

GEOCHEMISTRY AND ORIGIN OF ACHONDRITIC INCLUSIONS IN YAMATO-75097, -793241 AND -794046 CHONDRITES

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Abstract: We have performed instrumental and radiochemical neutron activation analyses of the host L6 chondrite and five splits of the Yamato (Y)-75097 achondritic inclusion, and achondritic inclusions from the Y-793241 (L6) and Y-794046 (H5) chondrites. The troctolitic inclusions from Y-75097 and Y-793241 show numerous compositional similarities, including low Sc contents, fractionated siderophile element patterns at low abundances, and commonly (though not always) depleted trivalent REE abundances but with Eu at near chondritic levels. The REE, however, are highly variable in the Y-75097 inclusion due to variations in modal merrillite. The lack of pyroxene in these inclusions is best explained by assuming the protolith was non-chondritic in bulk composition. However, it is not clear that nebular processes could produce a pyroxene-poor protolith. The siderophile element patterns in these inclusions can be modeled as residual metal left after partial melting of the Fe-FeS system.

The Y-794046 inclusion is compositionally and mineralogically different from the other inclusions. Abundances of refractory through moderately volatile lithophile elements are unfractionated relative to mean H chondrites. Similarly, abundances of refractory through moderately volatile siderophile elements are in H chondritic relative proportions, but at ~10% the abundance of mean H chondrites. This cosmochemical signature is most simply modeled as a result of impact melting of an H chondrite target, with loss of ~90% of the immiscible Fe-FeS melt.

1. Introduction

Stony meteorites are broadly divided into chondritic and achondritic varieties. The latter are mostly the result of parent body igneous processes in which major modifications to both texture and composition have occurred, for example, the basaltic eucrites. The former are nebular materials that have variably suffered textural modification (VAN SCHMUS and WOOD, 1967), but whose compositions have been little affected. Bridging these extremes are some texturally achondritic materials of various compositions which occur both as meteorites and as inclusions within chondrites. Some of these may be igneous, while others may be metamorphic in origin. For example, the Lodran-like achondrites may be partial melting residues (McCoy *et al.*, 1992), and hence suffered parent body igneous processes. Others, such

as the Acapulco-like achondrites, appear to be ultra-metamorphosed chondrites (PALME *et al.*, 1981), again the product of parent body-wide processes. A third type of achondritic material in between chondritic and classical achondritic meteorites are "igneous chondrites". These typically have igneous textures, but compositions that are clearly related to known chondrite classes, at least for the lithophile elements. Examples of "igneous chondrites" include PAT 91501, an igneous-textured meteorite of L chondrite composition (HARVEY, 1993; MITTFELDLT *et al.*, 1993), and many igneous textured clasts such as one described from the Plainview H5 chondrite (KEIL *et al.*, 1980). Many meteorites and clasts of this type appear likely to be impact melts, and hence do not reflect internal, parent body-wide processes.

More problematical are various inclusions in chondritic meteorites that have achondritic texture and non-chondritic bulk compositions. For many of these, the bulk composition cannot be easily understood in terms of classic igneous processes, such as partial melting, nor can their compositions be easily understood in terms of impact melting processes. For example, HUTCHISON *et al.* (1988) reported an igneous inclusion in the Barwell L6 chondrite of troctolitic bulk composition that has a fractionated rare-earth-element (REE) pattern. Similarly, the Hedjaz L3.7 chondrite has yielded pyroxenitic and noritic clasts with fractionated lithophile element patterns that suggest both nebular and igneous processes were responsible for their formation (MISAWA *et al.*, 1992; NAKAMURA *et al.*, 1990).

Large, achondritic inclusions were reported in several Yamato chondrites; Y-75097 L6 chondrite (YANAI *et al.*, 1983), Y-793241 L6 chondrite (PRINZ *et al.*, 1984) and Y-794046 H5 chondrite (YANAI and KOJIMA, 1993). The inclusions in Y-75097 and Y-793241 are troctolitic and have H chondrite oxygen isotopic compositions (NAKAMURA *et al.*, 1994a; PRINZ *et al.*, 1984; YANAI *et al.*, 1983). These clasts show similarities to the troctolitic clast from the Barwell chondrite (HUTCHISON *et al.*, 1988). The inclusion in Y-794046 is pyroxene-rich (SACK *et al.*, 1994; YANAI and KOJIMA, 1993), and hence, unlike the Y-75097 and Y-793241 inclusions.

In order to better understand the processes that produced such unusual materials, an international consortium was set up by N. NAKAMURA and K. YANAI to investigate a wide range of petrologic and geochemical properties of these three meteorites and their inclusions. We were recruited by them to perform radiochemical neutron activation analysis (RNAA) and instrumental neutron activation analysis (INAA) on various inclusion and host samples. We report here the results of our RNAA and INAA study of bulk inclusions from Y-793241 and Y-794046, a series of five subsamples of the Y-75097 inclusion from the center to the contact with the host, and the host Y-75097 chondrite. SACK *et al.* (1994), and WANG *et al.* (1994) have presented the results of a petrologic study of these samples and an RNAA study of chondritic host samples, respectively.

2. Samples and Analytical Methods

We received our samples from NIPR *via* K. YANAI and N. NAKAMURA. We received ~20 mg each of five splits of the Y-75097 inclusion, and ~67 mg of the Y-75097 host as partially crushed materials. Hence, we performed no processing on

these samples prior to analysis. We received chips of a few hundred mg each of the Y-793241 and Y-794046 inclusions. A portion of each of these inclusions was weathered, and therefore the inclusions were split prior to crushing to remove all weathered material. The remaining fresh material was crushed and split to provide separate samples for INAA and RNAA studies. For INAA, the samples, standards and ~50 mg samples of Allende and BHVO-1 reference materials were encapsulated in pure SiO₂ glass tubes, and irradiated at the University of Missouri Research Reactor (UMRR) Facility for 10 hours at a flux of 5.5×10^{13} n/cm²-s. A series of three counts about 1 week, 1½ weeks and 4 weeks after irradiation were performed in order to obtain data for elements of differing half-lives. Details of our INAA procedure are given in MITTLEFEHLDT and LINDSTROM (1993) and references therein. For RNAA, the inclusion samples, along with suitable flux monitors, were irradiated at the UMRR for 20 days at a flux of 8×10^{13} n/cm²-s. These samples therefore received ~70 times the neutron fluence they received for the INAA work, and corrections for pre-irradiation are unnecessary. The Y-75097 host sample (.52 F) was irradiated for 2 days at a flux of 8×10^{13} n/cm²-s; only about 7 times the fluence received for INAA work. Hence, this sample received about 14% more neutrons than the flux monitors used for RNAA. Details of our RNAA procedure are given in WANG *et al.* (1994) and references therein.

3. Results

Our INAA data for the Yamato inclusions and host are presented in Table 1 and our analyses of Allende and BHVO-1, along with a comparison to literature data for them, are given in Table 2. We also compare our Allende analysis to mean CV chondrites (Table 2), and our analysis of Y-75097 host with mean L chondrites (Table 1) (WASSON and KALLEMEYN, 1988). Our RNAA data for these samples are presented in Table 3, along with a comparison to a mean of Purdue data for unshocked to mildly shocked L4-6 chondrites (LINGNER, 1985) and to mean L chondrites (WASSON and KALLEMEYN, 1988) for the Y-75097 host. For the Y-75097 host sample, we have corrected the RNAA data for residual activity left over from the INAA irradiation that was done 125 days before the RNAA irradiation. This correction is only significant for nuclides with half-lives greater than about one month. Numbers in parentheses in Table 3 are the percent residual activity for each of the elements that required correction.

3.1. Y-75097

For some elements, we have determinations by both INAA and RNAA on the sample samples. Compared to our INAA analyses for Co, our RNAA data are low by ~17%. We have noted a systematic difference in Co determinations between the JSC lab and the Purdue lab before, but have no explanation for it. For other elements we each determine (Au, Sb, Se), agreement is generally within experimental error.

Our analysis of the Y-75097 host agrees well with the bulk analysis presented by YANAI and KOJIMA (1993); we agree within 10% for Na, Cr, Fe and Ni, and within 20% for K and Ca. We disagree by a factor of 7 on Co, but the value reported by

Table 1. INAA data for Y-75097, Y-793241 and Y-794046 inclusions and Y-75097 host (,52 F). Mean L chondrites data are from WASSON and KALLEMEYN (1988).

		Y-75097												L	Y-793241		Y-794046	
		,52 A1	±	,52 B1	±	,52 C1	±	,52 D1	±	,52 E1	±	,52 F	±	mean	,62	±	,97	±
wt	mg	21.48		18.77		23.17		25.42		21.19		66.82			49.04		49.16	
Na	mg/g	9.64	0.13	10.91	0.14	11.44	0.13	10.10	0.12	11.41	0.14	7.43	0.09	7	7.91	0.10	8.42	0.10
K	µg/g					880	240	770	200	860	190	810	180	825	380	170	1330	250
Ca	mg/g	20.6	2.1	27.2	2.9			3.2	1.6	7.6	1.9	15.5	1.9	13.1	3.9	1.3	12.7	1.0
Sc	µg/g	2.48	0.03	2.406	0.029	2.227	0.029	2.163	0.028	3.27	0.04	8.68	0.10	8.6	2.53	0.03	9.73	0.11
Cr	mg/g	2.86	0.03	4.07	0.05	9.14	0.11	6.74	0.08	6.14	0.07	4.42	0.05	3.88	3.72	0.04	4.52	0.05
Fe	mg/g	145	2	142	2	148	2	152	2	150	2	206	2	215	155	2	131	1
Co	µg/g	18.37	0.23	14.19	0.19	26.1	0.3	24.8	0.3	57.4	0.7	594	7	590	28.0	0.3	168.8	1.9
Ni	mg/g	0.27	0.03	0.217	0.027	0.39	0.03	0.346	0.027	1.08	0.04	12.9	0.4	12	0.233	0.019	3.24	0.07
As	µg/g											1.63	0.13	1.55			0.48	0.18
Se	ng/g									1000	400	6700	1300	9000			2100	300
Br	ng/g							320	140			270	90	800	180	60		
Sr	µg/g	70	30					45	22						44	14		
Sb	ng/g											68	20	68				
Cs	ng/g																90	40
La	µg/g	5.45	0.10	6.05	0.09	0.35	0.03			0.143	0.026	0.564	0.025	0.31	0.121	0.014	0.381	0.022
Ce	µg/g	15.1	0.6	17.1	0.6													
Sm	µg/g	2.87	0.04	3.15	0.05	0.172	0.007			0.052	0.006	0.318	0.008	0.195	0.0096	0.0018	0.243	0.007
Eu	µg/g	0.230	0.013	0.261	0.012	0.141	0.011	0.118	0.008	0.140	0.010	0.092	0.014	0.078	0.110	0.006	0.085	0.006
Tb	µg/g	0.72	0.04	0.69	0.04												0.066	0.015
Yb	µg/g	2.32	0.07	2.55	0.08	0.14	0.04					0.31	0.04	0.22	0.041	0.019	0.227	0.026
Lu	µg/g	0.294	0.013	0.326	0.013	0.024	0.007			0.014	0.006	0.052	0.008	0.033			0.040	0.004
Hf	µg/g														0.23	0.03	0.25	0.04
Ta	µg/g							0.082	0.029									
Ir	ng/g	70	4	80	4	74	5	91	5	169	8	600	40	490	31.4	1.9	176	7
Au	ng/g									10.7	1.6	168	3	162			41.4	1.6

Table 2. INAA data on standard rocks Allende and BHVO-1 and comparison to literature data. Literature data from: Allende-JAROSEWICH *et al.* (1987); BHVO-1-GLADNEY and ROELANDTS (1988); CV chondrite mean-WASSON and KALLEMEYN (1988).

	Allende			CV mean	BHVO-1		
	JSC	±	lit		JSC	±	lit
wt mg	49.58				47.15		
Na mg/g	3.43	0.04	3.4	3.3	16.9	0.2	16.8
K µg/g	220	80	330	310	4800	700	4300
Ca mg/g	14.9	1.4	18.4	19	76	4	81.5
Sc µg	10.90	0.12	11	11.4	31.3	0.3	31.8
Cr mg/g	3.66	0.04	3.6	3.6	0.289	0.003	0.289
Fe mg/g	238	2	235.7	235	85.4	0.9	85.5
Co µg/g	670	7	600	655	45.4	0.5	45
Ni mg/g	14.15	0.24	14.2	13.4	0.115	0.017	0.121
As µg/g	1.67	0.13		1.6	0.42	0.14	0.4
Se ng/g	8400	600		8300			
Br ng/g	1600	130		1500			
Sr µg/g					424	29	403
Sb ng/g	91	18		85	152	17	159
La µg/g	0.501	0.018	0.52	0.486	15.47	0.18	15.8
Ce µg/g	1.89	0.26	1.33	1.29	38.3	0.5	39
Sm µg/g	0.317	0.007	0.34	0.295	6.21	0.08	6.2
Eu µg/g	0.114	0.008	0.11	0.113	2.08	0.03	2.06
Tb µg	0.076	0.017	0.081	0.065	0.950	0.029	0.96
Yb µg/g	0.30	0.03	0.3	0.322	1.99	0.04	2.02
Lu µg	0.041	0.005	0.052	0.048	0.266	0.009	0.291
Hf µg/g	0.21	0.04	0.21	0.194	4.53	0.09	4.38
Ta µg/g					1.14	0.03	1.23
Ir ng/g	832	25	740	760			
Au ng/g	151.7	2.7	150	144	2.9	1.2	1.6

YANAI and KOJIMA (1993), 80 ppm, is very low compared to mean L chondrites (Table 1). Our results are in variable agreement with those of FUKUOKA (1994). For most lithophile elements, agreement is good. The most notable exception is Cr, for which FUKUOKA (1994) reports a concentration 35% lower than ours; likely due to heterogeneous distribution of chromite. For the REE, our results are systematically higher than those of FUKUOKA (1994), NAKAMURA *et al.* (1994a), and than mean L chondrites, probably indicating that our sample contained more phosphates. Our U determination on this sample (Table 3) is higher than mean L chondrites and than another host sample analyzed by WANG *et al.* (1994). Again, this is plausibly due to more merrillite in sample ,52 F. Indeed, SACK *et al.* (1994) noted merrillite at the inclusion-host contact. The siderophile element concentrations reported by FUKUOKA (1994) are about 20% lower than ours, except for Ir which is ~60% lower, indicating less metal in his sample. Our siderophile element data are similar to mean L chondrites, and therefore, our sample was representative. Last, FUKUOKA's (1994) Se

Table 3. RNAA data for Y-75097, Y-793241 and Y-794046 inclusions and Y-75097 host (.52 F). Mean *L. chondrites* data are from LINGNER (1985) (Purdue) and WASSON and KALLEMEYN (1988) (W&K).

		Y-75097						corr*	L mean		Y-793241	Y-794046
		.52 A1	.52 B1	.52 C1	.52 D1	.52 E1	.52 F		Purdue	W&K	.62	.97
Co	µg/g	15.6	11.9	22.6	21.5	44.0	470	(14)	640	590	19.1	36.0
Zn	µg/g	54.4	63.3	107	91.5	82.3	60.5	(10)	64	50	69.6	42.3
Ga	µg/g	6.33	7.82	11.4	7.80	6.41	5.72		5.6	5.7	3.15	1.98
Se	ng/g	44.8	29.8	34.9	10.3	895	7890	(7)	8100	9000	37.3	1250
Rb	µg/g	1.86	1.95	1.70	1.30	1.68	1.17		2.7	3.1	0.93	3.11
Ag	ng/g	7.2	8.4	2.7	2.3	7.4	17.5	(10)	90	65	30.6	13.7
Cd**	ng/g	3.0±0.2	2.5±0.2	1.8±0.2	1.7±0.4	5.0±0.2	2.2±0.2		17	11	34.5	5.3±0.4
In**	ng/g	0.8±0.2	0.3±0.1	0.4±0.1	0.2±0.1	≤0.8	≤1	(7)	1.1	7.0	5.77	0.25±0.9
Sb	ng/g	2.8	1.9	2.4	22	8.2	63		300	68	12	12
Te	ng/g	55.3	50.6	34.1	291	177	494	(7)	440	480	42.4	48.6
Cs	ng/g	7.82	3.56	4.76	4.38	4.53	3.07	(13)	28	280	27.2	118
Au	ng/g	0.79	0.85	0.67	0.50	10.7	134		180	162	2.01	2.62
Tl**	ng/g	0.42	0.67	0.39	0.57	0.29	0.4±0.2	(13)	1.3	2.0	2.75	3.00
Bi**	ng/g	≤0.9	≤1.2	≤0.9	2.7±0.4	2.1±0.5	4.9±0.6		5.2	14	9.43	0.5±0.2
U**	ng/g	16.6	23.5	8.9	2.2±0.6	29.3	54.3			13	8.7	14.7

* Percent correction for residual activity from the INAA irradiation. See text.

** Uncertainties listed for these elements reflect only counting statistics. Upper limits are 2σ values based solely on counting statistics.

concentration is ~30% higher than ours, probably due to higher troilite content in his sample.

Our Y-75097 inclusion data are more difficult to compare with the literature data because we analyzed a series of samples designed to demonstrate the petrologic variability of the clast, rather than a bulk sample as has been done by others. If our samples represent the range of petrologic variability of the inclusion, then previous bulk analyses should fall within the ranges we find. YANAI *et al.* (1983) and YANAI and KOJIMA (1993) report analyses for inclusion core and mantle by modal recombination, and a bulk sample by wet chemistry. The core analyses should be most similar to our splits A1 and B1, while the mantle should be similar to split E1 and maybe D1. With the exception of Fe, there is relatively poor agreement between our analyses of inclusion splits and the core and mantle analyses of YANAI *et al.* (1983). However, this is almost certainly due to the highly heterogeneous nature of this inclusion; we find wide ranges in concentration between the different splits for Ca and Cr. Only for Na does there appear to be a systematic problem; none of our analyses are as low as those reported by YANAI *et al.* (1983). The bulk inclusion analysis reported by YANAI and KOJIMA (1993) agrees well with our split D1 for Ca, Cr and Fe, but is slightly lower for Na and K. The bulk inclusion analysis reported by FUKUOKA (1994) is within the wide range of concentrations represented by our five splits, except for Na which is slightly lower, and Ir which is a factor of 2 lower. The bulk inclusion analysis reported by WARREN and KALLEMEYN (1989) is also within the range of concentrations represented

by our five splits, except for Na and Ga which are slightly lower, and Fe which is higher.

We can more directly compare our Y-75097 inclusion data with those of NAKAMURA *et al.* (1994b), who ran samples of splits A through F. NAKAMURA *et al.* (1994b) did not present a data table, but our REE data are in qualitative agreement with the data they show in their Fig. 2. The only exception is that we find splits A and B to be more similar in REE abundances than do NAKAMURA *et al.* (1994b). This difference in REE between splits A and B in our study and those in NAKAMURA *et al.* (1994b) undoubtedly reflects minor variations in modal merrillite.

3.2. Y-793241

Our INAA results for the bulk inclusion from Y-793241 agree well with other data for this inclusion. Compared to the analysis by FUKUOKA (1993), our sample of Y-793241 inclusion is ~50% lower in Ca, and 40–70% lower in the siderophile elements Co, Ni and Ir. The latter is likely due to heterogeneous distribution in metal in this inclusion. The cause of the former is unclear. Calcium may be contained in diopside, plagioclase and/or phosphate. Diopside is not reported in this inclusion (YANAI and KOJIMA, 1993), and regardless, our Sc datum, which should be concentrated in any pyroxene that might be present, agrees well with that of FUKUOKA (1993). Similarly, phosphate is not reported in this inclusion (PRINZ *et al.*, 1984; SACK *et al.*, 1994; YANAI and KOJIMA, 1993), and again, our REE data, which should be dominated by merrillite if present, agree well with those of FUKUOKA (1993). Plagioclase is present in this inclusion, and is of variable composition (YANAI and KOJIMA, 1993). The combination of lower Ca concentration, with identical (within 7%) Na concentration in our sample compared to FUKUOKA's could be explained by a fortuitous combination of a more albitic plagioclase at lower modal abundance in our sample, but this seems rather farfetched. The bulk inclusion major element analysis presented by YANAI and KOJIMA (1993) has similar Ca, Cr, Fe and Na concentrations to our analysis.

3.3. Y-794046

Our INAA results on the inclusion from Y-794046 generally agree with those of YANAI and KOJIMA (1993) and FUKUOKA (1993). Our sample has slightly lower Ca and Na, suggesting lower modal plagioclase. FUKUOKA's results are slightly higher in REE than are ours. The most significant difference, however, is a much higher siderophile element component in our INAA sample. Our sample contained 5–6 times more As, Co and Ni, 10 times more Ir and 20 times more Au than that of FUKUOKA (1993). Our INAA sample also has higher Co by ~5 times, and Au by ~16 times than the split analyzed by RNAA (compare Table 3), while our Se datum is ~1.7 times that of the RNAA split. This comparison indicates heterogeneous distribution of metal in this inclusion, with an enrichment of metal in our INAA sample compared to the split we analyzed by RNAA or FUKUOKA's (1993) sample.

This detailed comparison of results on various splits of the inclusions shows that the inclusions are very heterogeneous on a small (few mm) scale. This could hamper interpretations of the genesis of these inclusions, and must be kept in mind.

Heterogeneity is also demonstrated by modal (YANAI *et al.*, 1983) and compositional (Table 1) information on the different splits of the Y-75097 inclusion.

4. Discussion

4.1. Siderophile elements

The siderophile elements determined in this study are shown in Fig. 1 normalized to ordinary chondrites; mean H chondrites for the inclusions and mean L chondrites for Y-75097 host. We have excluded Ag, the most highly volatile/mobile of the siderophile elements we analyzed, from this figure. Y-75097 host has a flat pattern at ~ 1 times mean L chondrites, indicating that our sample was representative of the siderophile element component of Y-75097 as mentioned above. The abundances of siderophile elements in the Y-75097 inclusion samples are much lower than in mean H chondrites, and exhibit fractionated siderophile element patterns, with Ir/Ni, Ir/Co, Ir/Sb and especially Ir/Au ratios greater than mean H chondrites. The siderophile element contents are somewhat correlated with position in the inclusion interior. Splits A1 and B1 from the center have the lowest siderophile element contents, while split E1 from the inclusion margin has the highest.

SACK *et al.* (1994) suggested that the siderophile element content in split E1 was enhanced by reaction with the host chondrite. However, our data suggest that this is unlikely because of the fractionated nature of the siderophile elements. Shown in Fig.

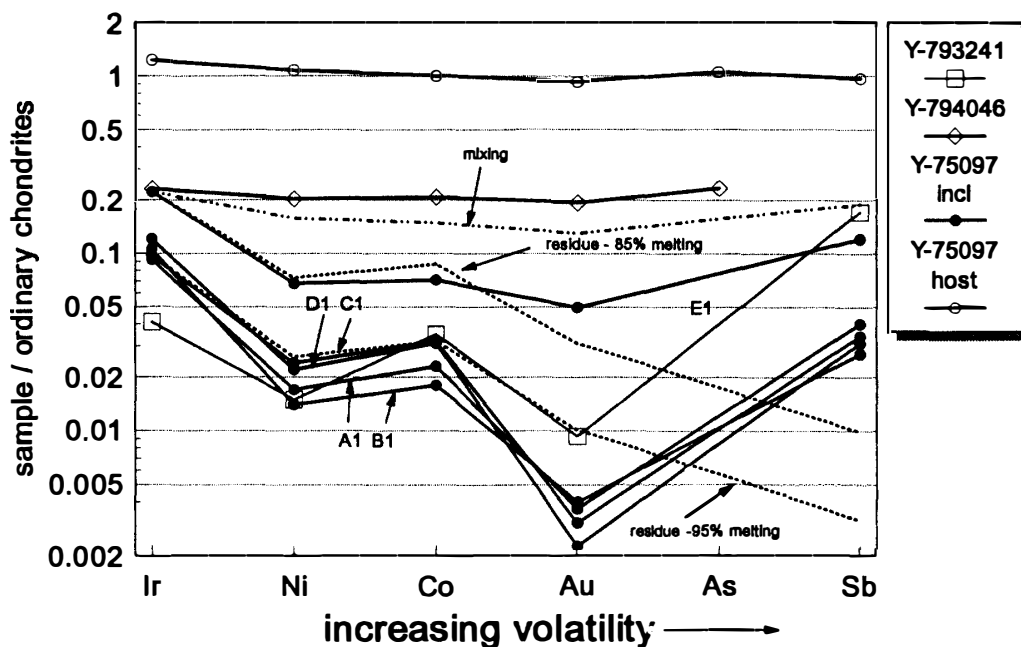


Fig. 1. Ordinary chondrite normalized siderophile element contents of Yamato chondrite igneous inclusions and Y-75097 host. Inclusions are normalized to mean H chondrites, while the host is normalized to mean L chondrites (WASSON and KALLEMEYN, 1988). Inclusion Y-794046 has an unfractionated siderophile element pattern, while inclusions Y-75097 and Y-793241 have fractionated patterns suggesting the metal in these clasts is residual after partial melting in the Fe-FeS system (see text).

1 is a mixing pattern between the mean of splits A1 and B1 and the host chondrite, split F. A mixing match to Ir in split E1 produces too much Ni, Co, Au and Sb in it.

The siderophile element patterns and contents of split E1 can be semi-quantitatively modeled as arising from residual metal trapped in it (Fig. 1). In this model, we assumed the inclusion protolith contained about 18% metal and 5.5% troilite by weight before melting, *i.e.* like mean H chondrites (JAROSEWICH, 1990). We used the metal-nonmetal avoidance model of JONES and MALVIN (1990) to calculate Ir, Ni, Co, Au and Sb partition coefficients at various fractions of melting of the metal+troilite system. Mass balance was then used to determine the trace element content of the residual solid metal, assuming equilibrium. Shown in Fig. 1 is the result for 85% melting of the metal+troilite system, normalized to Ir for split E1. This normalization implies ~6% metal in split E1, while the melting model implies that the residual metal should be ~3.5% of the total original silicate+metal+troilite system. This may be adequate agreement, considering uncertainties in the melting model (equilibrium vs. fractional melting), partition coefficients and that we cannot estimate changes to the total mass of the silicate system. Also shown in Fig. 1 is the result for 95% melting of the metal+troilite system normalized to average Ir for splits A1 through D1. The normalization here implies ~2.5% metal in these splits, while the melting model implies ~1.2%. Again, it is difficult to evaluate whether this is adequate agreement.

Excluding Sb for the moment, the resulting siderophile element pattern for residual metal (85% melting) is a fair match to the observed pattern for split E1, except that Au in the model is too low. Residual metal after 95% melting is a fair match for splits C1 and D1, except that Au in the model is too high. These models are qualitatively similar to the patterns of the other splits. The other splits have higher Co/Au ratios than split E1, but this could result from higher degrees of melting in the Fe-FeS system for these splits; Au becomes increasingly depleted relative to Co as the amount of residual metal decreases. This is consistent with the lower siderophile element contents of these splits as well. The systematic variations in siderophile element abundances from inclusion core to rim would then reflect the distribution of this metal within the inclusion.

Gold is not well matched in the model just described. However, we have used a simple, equilibrium melting model. Fractional melting will result in larger Au/Ir or Au/Co fractionations than equilibrium melting. Hence, the very low Au contents of splits A1 through D1 could possibly reflect fractional melting. The partition coefficients are very sensitive to the S content of the melt (JONES and MALVIN, 1990), and therefore, can lead to uncertainties in the model when the initial S content is only an estimate. In spite of these uncertainties, we believe that it is likely that the siderophile element content of the Y-75097 inclusion is contained in residual metal left after melting. This fits with petrographic and lithophile element evidence from this inclusion indicating that it is an igneous rock.

Antimony is overabundant in the inclusions compared to what the residual metal model would suggest. Antimony is a highly incompatible siderophile (JONES and CASANOVA, 1993), and should be more depleted than Au in residual metal (Fig. 1). Antimony is also one of the volatile/mobile elements that can be redistributed by

shock or other heating processes affecting chondritic material. Possibly, the high Sb content of the inclusions is due to transport from the highly shocked host L chondrite. This is not demanded by consideration of the full suite of volatile/mobile elements, but neither is it excluded (see Subsection 4.3, below). Other than this conjecture, we have no obvious explanation for the high Sb content relative to Au for the Y-75097 inclusion.

It is unlikely that the siderophile element pattern could instead be due to nebular siderophile element fractionation. Excluding Sb again, the siderophile element patterns do show a coherent signature that might be caused by volatility control (Fig. 1) as would be expected of a metal fraction formed in equilibrium with a hot nebular gas. In this case, metal in split E1 would have equilibrated to a lower temperature than the other splits judging by its lower Ir/Ni and Ir/Au ratios. In high temperature nebular materials, a volatility-controlled nebular signature in the siderophile elements is also associated with a similar signature in the lithophile elements (*e.g.*, see EKAMBARAM *et al.*, 1984). For the Y-75097 inclusion, this is not the case. The high Na content, for example, indicates that the moderately volatile lithophile elements are not depleted, while the low Au content would indicate severe depletion of the moderately volatile siderophile elements. Because of this mismatch, we do not favor a nebular origin for the siderophile element pattern displayed in Fig. 1.

The inclusion from Y-793241 shows a pattern similar to that of the Y-75097 inclusion, although the Ir/Ni ratio is lower, and the Co/Ni and Sb/Ni ratios are much higher (Fig. 1). We have not attempted to model this pattern explicitly, but we suggest that the metal in this inclusion has the same origin as that in Y-75097. The petrologic characteristics of the Y-793241 host chondrite indicate that it has also been heated, which could have caused redistribution of volatile/mobile elements like Sb (SACK *et al.*, 1994).

The Y-794046 inclusion is different. It shows a flat siderophile element pattern at about 20% that of mean H chondrites. (Only our INAA data are shown, as the split used for RNAA was depleted in metal, see Subsection 3.3, above.) There are three ways to explain this siderophile element pattern: (i) that this inclusion contains a siderophile element component derived by reaction with the host, as suggested by SACK *et al.* (1994) for split E1 of the Y-75097 inclusion, (ii) that our sample was composed of ~80% inclusion and ~20% host chondrite, or (iii) that this inclusion was depleted in metal by physical separation of about 80% of its original metal without chemical fractionation. We can rule out option (ii) because no host material was observed on the sample during preparation. We cannot specifically exclude option (i), but because of the similarity in compositional characteristics between this inclusion and the impact melted L chondrite PAT 91501 (MITTFELDLT *et al.*, 1993), we favor option (iii). This latter scenario will be discussed in more detail in Subsection 4.4 below.

4.2. Lithophile elements

The rare earth elements (REE) for the inclusions and Y-75097 host are shown normalized to the appropriate ordinary chondrite type (H chondrite for inclusions, L chondrite for the Y-75097 host) in Fig. 2. As noted by other researchers, the REE

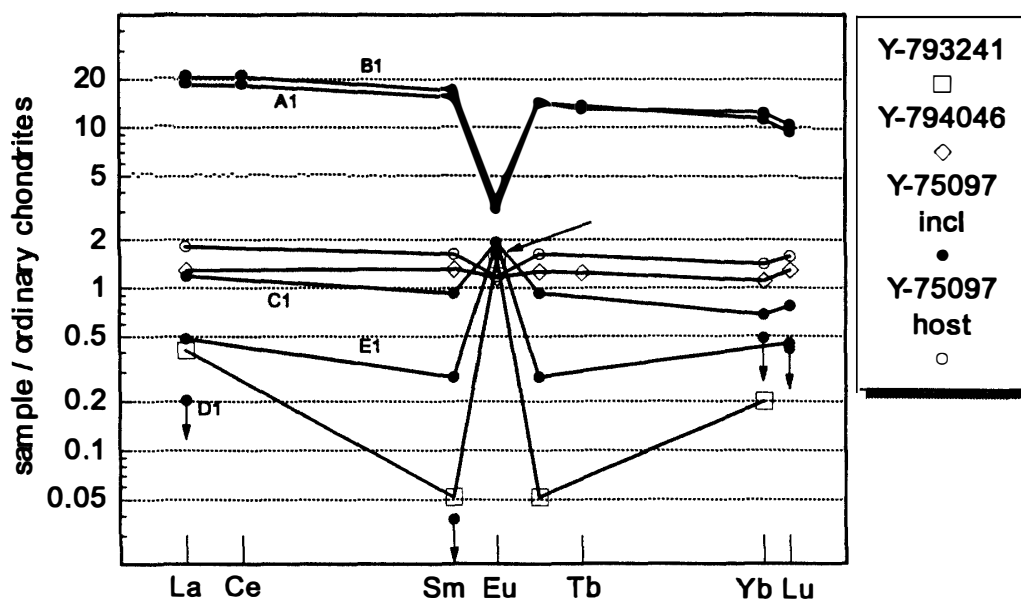


Fig. 2. Ordinary chondrite normalized REE patterns for Yamato chondrite igneous inclusions and Y-75097 host. Normalization as in Fig. 1. Inclusions Y-75097 and Y-793241 have fractionated REE patterns, while that of Y-794046 is chondritic. Slightly elevated REE in the host sample probably indicate an excess of merrillite in split F compared to typical L chondrite material, in accord with petrographic observations (SACK *et al.*, 1994). Only upper limits were determined for split D1 (spots with arrows), except for Eu which is at slightly lower concentration than in splits C1 and E1 (see Table 1).

contents of splits of the Y-75097 inclusion are highly variable, undoubtedly related to the distribution of phosphates (*e.g.* NAKAMURA *et al.*, 1994a, b). Our samples A1 and B1 from the core of the inclusion have essentially identical REE patterns enriched about 20 times mean H chondrites in LREE, about 10–12 times H chondrites in HREE, and have a chondrite normalized Eu/Sm ratio of about 0.2. Split D1 is very depleted in REE except for Eu; only upper limits were determined for all but Eu, which is ~1.6 times H chondrites. Split C1 is also low in trivalent REE and is enriched in Eu relative to Sm. These two splits, D1 and C1, must be poor in phosphates, but because Eu is at near chondritic abundance levels, depletion of plagioclase is not evident. SACK *et al.* (1994) suggested that the region of split D1 was a “feldspar-depleted, cumulate dunite”, but this is not evident in our Eu or Na data; split D1 is not substantially lower in these elements compared to the other splits (Table 1). Split E1 has near chondritic LREE, a slight depletion of HREE, and a modest enrichment of Eu (Fig. 2).

As noted above, SACK *et al.* (1994) inferred that split E1, from near the contact between the inclusion and the host, suffered partial chemical equilibration with the host chondrite which increased the siderophile and lithophile element contents compared to the adjacent D1 split. Above we showed that it is more likely that the enrichment in siderophile elements in split E1 is the result of higher modal metal from the inclusion, rather than interaction with the chondritic host. Of the lithophile elements, only Ca, Sc and U are enriched in split E1 relative to splits D1 and C1 (Fig. 3a, b) which could signify interaction with the host. Note, however, that Ca in split E1

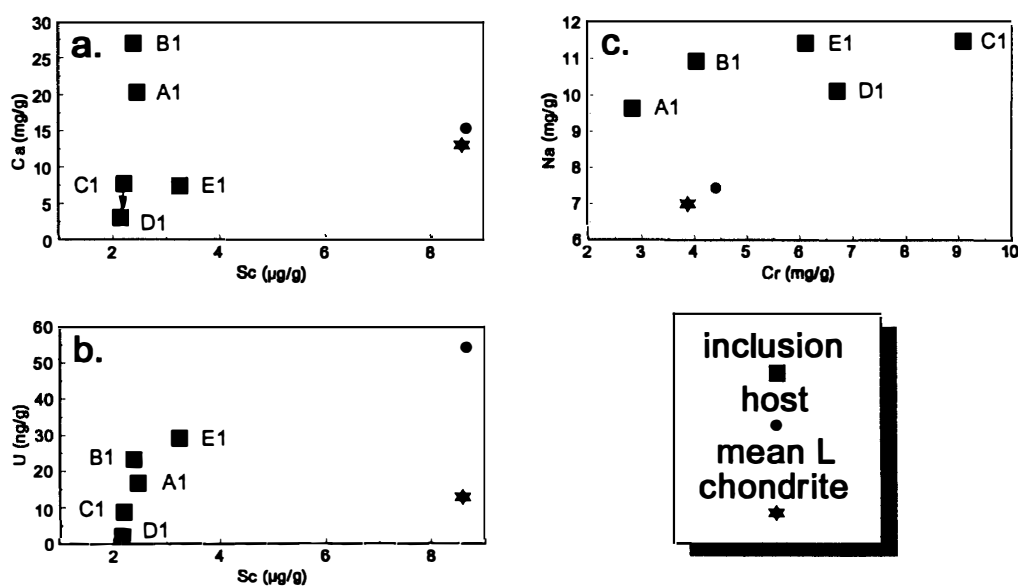


Fig. 3. *a.* Ca vs. Sc for Y-75097 inclusion samples, host and mean L chondrites (WASSON and KALLEMEYN, 1988). Split E1 has high Sc and Ca compared to adjacent splits D1 and C1, which has been taken as evidence for chemical interaction with the host (F) chondrite (SACK *et al.*, 1994). Uranium is also enriched in E1 compared to the other splits, but so is host F compared to both mean L chondrites and to host sample ,107 analyzed by WANG *et al.* (1994) (not shown). The U enrichments in these samples are likely due to merrillite present at the inclusion-host contact (SACK *et al.*, 1994). Other lithophile elements, such as Na and Cr (*c.*) do not show evidence for interaction.

is within the range of splits A1 through D1; only Sc and U in split E1 among the lithophile elements are outside the range of the other splits. As mentioned above, merrillite at the inclusion-host contact (SACK *et al.*, 1994) is the likely cause of elevated U in split E1. Other lithophile elements, such as Na and Cr (Fig. 3c), do not display evidence for interaction between split E1 and the host chondrite. Therefore, we believe that the composition of split E1 reflects variation in modal mineralogy and/or mineral composition within the inclusion, rather than reaction with the host. We recognize that olivine compositions in the inclusion indicate that this mineral equilibrated Fe-Mg with the host (SACK *et al.*, 1994), but this doesn't necessitate that other lithophile elements exchanged with the host.

Because of the highly variable compositions of the various splits of the Y-75097 inclusion, we cannot calculate with any degree of confidence the bulk inclusion composition. However, because the ranges of many lithophile elements span the abundances of mean H chondrites, it is possible that the inclusion is near H chondritic in composition. Exceptions to this are Na, Eu and Sc. Sodium and Eu are enriched in all splits measured (this work; FUKUOKA, 1994; NAKAMURA *et al.*, 1994a; WARREN and KALLEMEYN, 1989) over H chondrite abundances, even after correcting for depletion of metal in the inclusions. This demonstrates that either the protolith for Y-75097 inclusion was enriched in plagioclase relative to H chondrites, or there is an unsampled portion of the inclusion poor in plagioclase. Scandium in all splits measured (this work; FUKUOKA, 1994; WARREN and KALLEMEYN, 1989) is about a

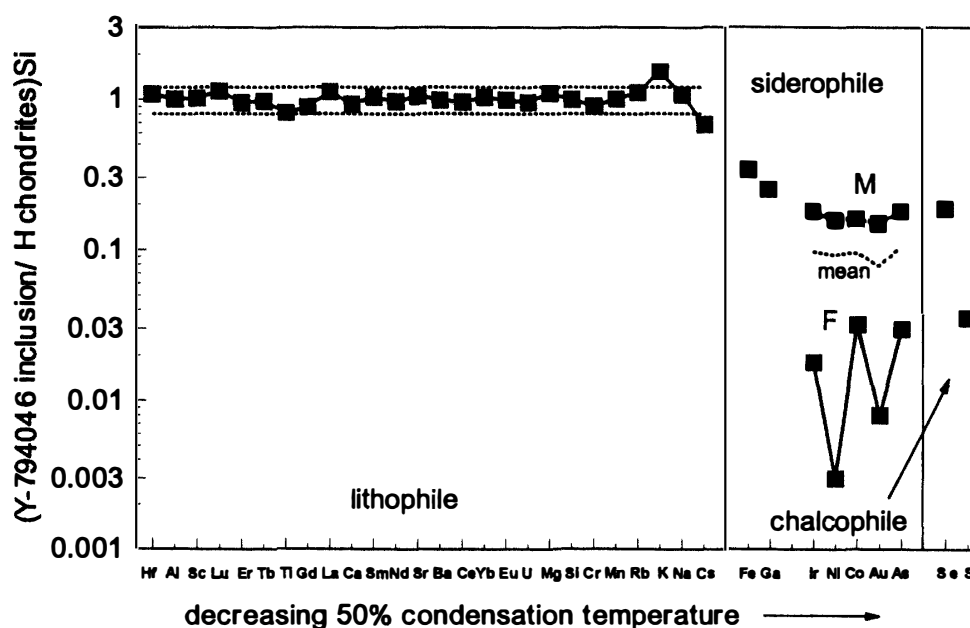


Fig. 4. *H* chondrite and Si normalized lithophile, siderophile and chalcophile element abundances for the Y-794046 inclusion. Lithophile elements are chondritic within 20% (dashed lines) except for K and Cs, while the highly siderophile elements (i.e. excluding Fe and Ga) have an unfractionated pattern depleted to about 0.095 times that of H chondrites (dashed line, mean of this work, INAA only, labeled M, and FUKUOKA, 1993, labeled F). Chalcophile elements are also depleted. The element patterns indicate that Y-794046 is an impact melt of H chondritic material that lost most of its metal+troilite. Data are from this work, FUKUOKA (1993), NAKAMURA *et al.* (1994a) and YANAI and KOJIMA (1993). Only the lithophile Rb and Cs, and chalcophile Se of our RNAA data were used because the siderophile element content of our RNAA sample was very different from our INAA sample, and because highly volatile/mobile element data show enormous variations in chondrites.

factor of three lower than mean H chondrites. As pyroxene is the major carrier of Sc in equilibrated ordinary chondrites (e.g. CURTIS and SCHMITT, 1979), the low Sc abundance is in accord with the low modal pyroxene in the inclusion, and implies that either the protolith was low in pyroxene, or that an unsampled portion of the inclusion is pyroxene-rich. This is discussed in more detail in Subsection 4.5 below.

The inclusion from Y-793241 has a REE pattern similar to those of splits C1 and D1 of the Y-75097 inclusion. Similar REE patterns have been determined by FUKUOKA (1994) and NAKAMURA *et al.* (1994a) on their splits of the Y-793241 inclusion. This inclusion shows a zonal petrographic structure (YANAI and KOJIMA, 1993), but detailed petrographic study has not yet been done. Therefore, it is not yet possible to infer whether the common REE patterns of the splits analyzed (this work; NAKAMURA *et al.*, 1994a; FUKUOKA, 1994) are representative of the whole inclusion, or just a portion of it.

The lithophile element abundances in the Y-794046 inclusion are different from those of the other inclusions studied. The REE pattern is relatively flat and unfractionated at about mean H chondrites abundances (Fig. 2), as has been remarked upon earlier (FUKUOKA, 1993; NAKAMURA *et al.*, 1994a). NAKAMURA *et al.* (1994a) noted, however, that the alkali elements K and Rb are enriched in their

sample of the Y-794046 inclusion relative to mean H chondrites. Using all available data, the similarity in mean lithophile element abundances extends to all elements except K and Cs (Fig. 4): all are within 20% of mean H chondrite lithophile element/Si ratios. This shows that inclusion Y-794046 is unfractionated relative to a chondritic precursor, unlike the Y-75097 and Y-793241 inclusions.

4.3. Volatile/mobile elements

The volatile/mobile elements are those that are predicted to condense out of the solar nebula at low temperatures, just prior to condensation of ices. Some of these elements are highly susceptible to mobilization in chondrites due to heating resulting from shock or other causes. As a result, these elements tend to be highly variable in concentration in chondrites. Figure 5 shows the volatile/mobile elements we determined by RNAA normalized to Purdue means for ordinary chondrites (H chondrites for the inclusions, unshocked to mildly shocked L chondrites for Y-75097 host) in order of estimated volatility in the solar nebula. Not shown are our data for U and Co, the two most refractory of the RNAA suite of elements.

The Y-75097 host shows concentrations of Au, Ga, Se, Te, Zn, Bi and In within 30% of mean unshocked to mildly shocked L chondrites (LINGNER, 1985). Depletion factors of between 0.1 to 0.4 are observed for all other elements (Fig. 5). Although this may seem at first glance to indicate that our sample may not have been representative, in fact, our data for all elements in the Y-75097 host are within the uncertainty limits of the means (LINGNER, 1985), except for Ag which is a factor of 2

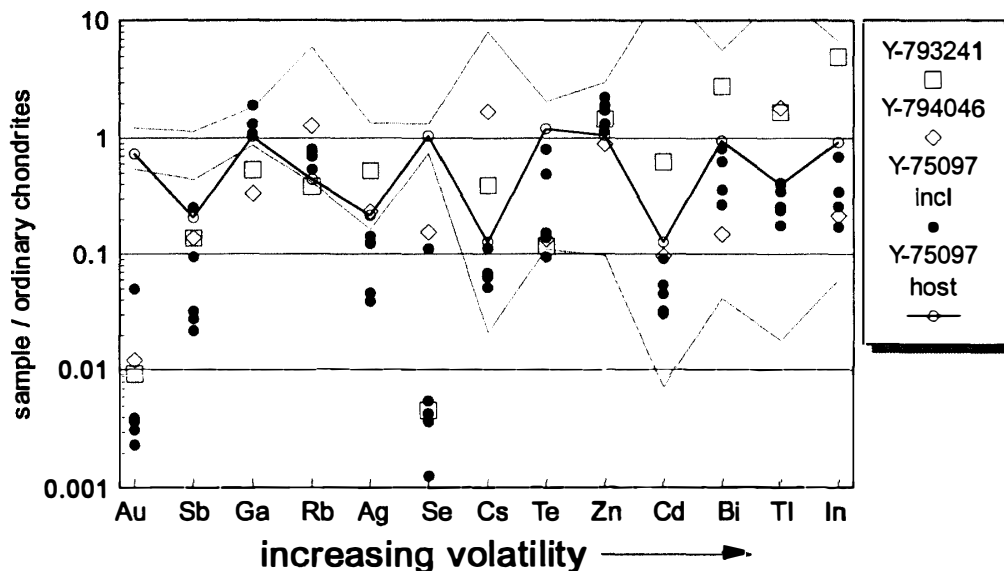


Fig. 5. Chondrite normalized volatile/mobile elements determined by RNAA for the Yamato chondrite igneous inclusions and the Y-75097 host. Chondrite normalizations are to Purdue means for unshocked to mildly shocked L chondrites (LINGNER, 1985) for the Y-75097 host, and mean H chondrites (S. WOLF, personal communication) for the inclusions. The dashed lines enclose the ranges observed for H5-6 chondrites from LINGNER et al. (1987). Data for the Y-75097 L6 chondrite host are within the ranges for L4-6 chondrites (not shown) except for Ag, which is only slightly lower.

below the lower uncertainty limit. Nevertheless, Ag is only 7% lower than the minimum measured for L chondrites (HUSTON and LIPSCHUTZ, 1984). In summary, we find no unusual compositional features for the Y-75097 host, either in lithophile, siderophile or volatile/mobile elements.

The troctolitic inclusions, Y-75097 and Y-793241, are within the ranges of H5-6 chondrites for all volatile/mobile elements except the siderophile elements Au, Sb and Ag (for Y-75097), and the chalcophile element Se. As previously discussed, we believe the siderophile and chalcophile elements were depleted in the troctolites by partial melting in the Fe-FeS system. Why then, are Ga (in Y-75097), nominally siderophile, and Zn, nominally chalcophile, in near chondritic abundances in these inclusions? Among the siderophile elements, Ga can show considerable lithophile tendency in chondrites (*e.g.*, CHOU and COHEN, 1973; CHOU *et al.*, 1973). Similarly, Zn can be lithophile, and indeed, HUTCHISON *et al.* (1988) found it to be so in the petrologically similar troctolite inclusion in the Barwell L6 chondrite. We suspect then, that Ga and Zn are largely lithophile in these inclusions.

Excluding the depletions in some of the siderophile and chalcophile elements, none of the other volatile/mobile elements show enhancements or depletions outside the rather wide ranges exhibited by H5-6 chondrites. Therefore, these elements provide no evidence for element mobilization during formation of the troctolitic inclusions. Based on our samples, however, the Y-793241 inclusion appears to be enriched in the most volatile elements, Cd, Bi, Tl and In, by a factor of ~ 10 relative to the Y-75097 inclusion. We cannot determine whether this is due to differences in the inclusions' protoliths, or formation processes.

Volatile/mobile element concentrations in the Y-794046 inclusion are within or near the ranges for the troctolitic inclusions. Like them, Y-794046 has volatile/mobile element concentrations generally within the ranges of H5-6 chondrites except for the siderophile elements Au and Sb, and the chalcophile element Se. Unlike in the Y-75097 inclusion, Ag is within the H chondrite range, while Ga is depleted. Based on volatile/mobile elements, the Y-794046 inclusion is not distinguishable from the troctolitic inclusions.

4.4. *Petrogenesis of the Y-794046 inclusion*

The composition of the Y-794046 inclusion is characterized by lithophile element/Si ratios unfractionated relative to mean H chondrites and unfractionated siderophile element pattern with mean siderophile element/Si ratios approximately 0.095 times mean H chondrites (Fig. 4). Chalcophile element/Si ratios are also low, but the abundances of Se and S are not similar (Fig. 4). Probably, this is due to heterogeneity as S was not determined for the same samples as Se. This pattern for lithophile, siderophile and chalcophile elements is similar to that determined for PAT 91501, an L chondrite with an igneous texture (MITTFEHLDT *et al.*, 1993). PAT 91501 is believed to be an impact melt of L chondritic material that did not undergo igneous fractionation as it cooled, with the exception of segregation of immiscible Fe-FeS melt from the silicate melt (MITTFEHLDT *et al.*, 1993; and unpublished). This can result in unfractionated lithophile element abundances relative to Si, and unfractionated siderophile element patterns at low abundance levels. Small amounts

of the immiscible Fe-FeS melt trapped in the silicate melt while it cooled provide the minor siderophile element contents of the impact melt. This model can explain the compositional data for the Y-794046 inclusion, and therefore, we conclude that this inclusion is an impact melt of the H chondrite parent body. This model is in accord with the petrologic study of this inclusion, which concluded that the inclusion crystallized rapidly from a melt produced by shock heating (SACK *et al.*, 1994).

4.5. *Petrogenesis of the Y-75097 and Y-793241 inclusions*

Previous studies have come to conflicting conclusions regarding the genesis of these inclusions. PRINZ *et al.* (1984) felt the Y-793241 inclusion was related to H chondritic barred olivine chondrules and discussed the inclusion in terms of nebular components. WARREN and KALLEMEYN (1989) considered the Y-75097 inclusion to be igneous in origin, specifically a metamorphosed olivine-plagioclase-phosphate cumulate. NAKAMURA *et al.* (1994a, b) believed both inclusions are metaigneous rocks, and suggested the inclusion precursors may have been large troctolitic chondrules with chondritic REE abundances. They suggested these cm-sized inclusions were formed as discrete objects in space, not as parts of larger igneous bodies.

The genesis of these clasts are difficult to define because of their unusual mineralogy and composition, and because of their highly variable modes. The low pyroxene abundances in these clasts are difficult to ascribe to igneous processes acting on chondritic precursors. Igneous fractionation processes can easily yield dunitic, harzburgitic, pyroxenitic or basaltic lithologies from chondritic precursors, but because of low-pressure phase relations in the olivine-plagioclase-silica pseudoternary system, formation of troctolites is difficult to envision.

Low pressure (1 bar) melting of ordinary chondrites yields basaltic compositions saturated in pyroxene and plagioclase at the peritectic point in the olivine-plagioclase-silica pseudoternary (JUREWICZ *et al.*, 1995). With increasing pressure, however, the peritectic will migrate toward the olivine-plagioclase join (LONGHI and ASHWAL, 1985; WARREN and WASSON, 1979). If liquids formed under modest pressure (a few kbars) were intruded to shallower depths (lower pressure) in an asteroid, these melts would crystallize troctolitic cumulates along the olivine-plagioclase cotectic. Eventually, however, the low pressure peritectic would be reached and norites would crystallize. Hence, troctolites could in principle be formed on a Ceres-sized asteroid (central pressure ~ 5 kbar, WASSON, 1974), however, these should be quite rare relative to other magmatic rock types, such as basalts, and this doesn't seem like a likely model for production of the troctolitic inclusions in L chondrites. This model would also require that the inclusions were only fragments of their parent igneous rocks as the complementary noritic material is not present. This is at odds with the near chondritic bulk REE pattern calculated for the Y-75097 inclusion (NAKAMURA *et al.*, 1994b), and the abundance of merrillite in the inclusion core, which ought to be a late crystallizing phase and be associated with abundant pyroxene. Because of this, we believe it likely that the precursors of these inclusions did not have chondritic bulk compositions.

Textural evidence also suggests that these inclusions were not formed by parent body igneous processes. A remnant barred-olivine chondrule is reported from the

core of the Y-793241 inclusion, although detailed descriptions are not available (PRINZ *et al.*, 1984; YANAI and KOJIMA, 1993). This suggests that the inclusion was not part of a large magma body derived by igneous processes similar to those that produced the eucrites, for example. Petrographic descriptions of the Y-75097 inclusion suggest (but don't clearly state) that it may be concentrically zoned (SACK *et al.*, 1994; YANAI and KOJIMA, 1993; YANAI *et al.*, 1983). If so, this would suggest that the inclusion is essentially complete, and that it does not represent a fragment of a much larger magma body.

All analyzed samples of Y-75097 and Y-793241 are low in Sc, a refractory lithophile element. Because there is little variation in Sc content, we assume that the average of all analyses (this work; FUKUOKA 1994; WARREN and KALLEMEYN, 1989), 2.5 $\mu\text{g/g}$ for Y-75097, is that of the bulk inclusion. This estimated bulk Sc content is identical to that measured on the Y-793241 inclusion (this work; FUKUOKA, 1993). Using the average Si content of the Y-75097 inclusion, 179 mg/g (WARREN and KALLEMEYN, 1989; YANAI and KOJIMA, 1993; YANAI *et al.*, 1983), we estimate that this inclusion has an H chondrite normalized Sc/Si ratio of ~ 0.3 . With the exception of some CAIs, refractory lithophile elements are normally in chondritic relative ratios in nebular materials. Hence, one might take the low inferred Sc/Si ratio to indicate that all refractory elements were depleted in this precursor material. This appears incorrect, as it implies that the Al/Si ratio would also be low, and therefore, the albite content of plagioclase (the major host for Al and Na) should be much higher than typical for chondrites. In fact, plagioclase in the Y-75097 inclusion is similar in composition to that of the Y-794046 H chondrite, while plagioclase in the Y-793241 inclusion is substantially more calcic than that of the Y-794046 chondrite (SACK *et al.*, 1994). The Eu/Si ratio should also be low if the precursor was depleted in refractory elements. In contrast, we calculate an H chondrite normalized Eu/Si ratio of 2.1 using the average of all available Eu determinations (this work, FUKUOKA, 1994; NAKAMURA *et al.*, 1994a; WARREN and KALLEMEYN, 1989). Because of this, it seems unlikely that the precursor materials for the inclusions obtained their unusual compositions by nebular processes.

Consideration of data from chondrules from ordinary chondrites also indicates that a nebular origin for the inclusion precursors is unlikely. GROSSMAN and WASSON (1983) have inferred that there are two lithophile element precursors to ordinary chondrite chondrules; refractory, olivine-rich silicates low in FeO, and a non-refractory, SiO₂- and FeO-rich, pyroxene-rich component. They also infer a third component needed for the matrix of ordinary chondrites; a volatile-rich component. This third component is also rich in Al (GROSSMAN and WASSON, 1983). It may be possible to form pyroxene-poor precursor materials for the troctolitic inclusions by mixing olivine-rich chondrule and matrix precursors. However, this seems unlikely to satisfy the low Sc content, as the olivine-rich chondrule precursor is also rich in refractory elements. Indeed, we are unaware of any chondrules from any chondrite type with measured Sc contents as low as those of the Y-75097 and Y-793241 inclusions. It appears that concentration of Sc in pyroxene in chondrites (CURTIS and SCHMITT, 1979) occurs as a result of parent body metamorphic processes, and not a result of nebular processes. It is not obvious how one could physically remove

pyroxene from an equilibrated chondrite in order to produce a suitable precursor for the troctolitic inclusions.

This is a major conundrum; the composition of these troctolitic inclusions does not obviously appear to be the result of either igneous or nebular processes. HUTCHISON *et al.* (1988) similarly wrestled with interpreting the genesis of the troctolitic inclusion from the Barwell chondrite and similarly met an impasse. They suggested a "planetary process" was required to form the inclusion, but this was mostly because they felt confident that they could exclude impact melting or nebular processes. HUTCHISON *et al.* (1988) could not provide a plausible planetary process that could have formed the inclusion, however. At present, all that can be said of these troctolitic inclusions is that they crystallized from melts, their precursors had H chondrite oxygen isotopic composition, and that they probably formed early in solar system history because of the observed excess of ^{129}Xe from short-lived ^{129}I (HUTCHISON *et al.*, 1988; NAGAO, 1994; OTT *et al.*, 1993).

5. Conclusions

Although all inclusions studied here are from H chondritic materials based on O isotopic analyses (*e.g.* NAKAMURA *et al.*, 1994a), the compositions of the Y-75097 and Y-793241 inclusions are distinct from that of the Y-794046 inclusion. The former two troctolitic inclusions share numerous compositional and mineralogical similarities, and likely formed from similar protoliths by similar processes. The results of our studies can be summarized as follows:

- 1) The Y-75097 and Y-793241 inclusions share several compositional similarities, *viz.* low bulk Sc contents, fractionated siderophile element ratios at low abundances, and fractionated REE patterns. The Y-75097 inclusion also has highly variable lithophile element concentrations reflecting variations in modal mineralogy, principally merrillite.

- 2) The siderophile element patterns of the Y-75097 and Y-793241 inclusions can be modeled as arising from residual metal left after extensive melting in the Fe-FeS system. The most volatile/mobile siderophile elements do not follow this trend, which we believe indicates mobilization of these elements after incorporation of the inclusions in the host chondrites.

- 3) These inclusions do not have chondritic bulk compositions; they lack a pyroxene component. The origin of this composition is unclear, but it does not seem possible to form it by igneous processes starting with H chondrite material. However, there is also no obvious way to produce the protolith by nebular processes, either.

- 4) The Y-794046 inclusion, in contrast, has H chondritic bulk composition for refractory through moderately volatile lithophile elements. Refractory through moderately volatile siderophile elements are in H chondritic relative proportions, but at low abundance levels. This cosmochemical signature indicates that the Y-794046 inclusion is an impact melt of H chondritic material.

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