Proc. NIPR Symp. Antarct. Meteorites, 7, 144–149, 1994

LABILE TRACE ELEMENTS AND COSMOGENIC RADIONUCLIDES IN CHONDRITIC HOSTS OF THREE CONSORTIUM IGNEOUS INCLUSIONS

Ming-Sheng WANG*, Edward S. MICHLOVICH†, Stephan VOGT* and Michael E. LIPSCHUTZ*§

Departments of Chemistry and Physics†, Purdue University, W. Lafayette, IN 47907-1393, U.S.A.*

Abstract: Three ordinary chondrites from the Yamato Mountains (Y) region of Antarctica contain cm-sized igneous inclusions being studied by a consortium. RNAA data for the labile elements Ag, Bi, Cd, Cs, Ga, In, Rb, Sb, Se, Te, Tl and Zn, and refractory Au and U in the L6 hosts of Y-75097 and Y-793241 indicate that each experienced at least one preterrestrial, high-temperature episode. This heating occurred during formation of the igneous inclusions and/or as a result of the severe shock that affected most equilibrated L chondrites. Cosmogenic 720 ka ^{26}Al, and 301 ka ^{36}Cl (which are determined by AMS) in metal from these two meteorites and nominal terrestrial ages (based on ^{36}Cl) hint that the L6 chondrites are not paired but are inconclusive in this regard. RNAA data for the H chondrite host of Y-794046 generally resemble those of other H4-6 chondrites: its contents of cosmogenic radionuclides in general, and its ^{36}Cl content, in particular, correspond to a nominal terrestrial age of 70±60 ka.

1. Introduction

The discovery of large (cm-sized) igneous inclusions in three ordinary chondrites—the L6 chondrites Yamato (Y)-75097 and Y-793241, and the H chondrite Y-794046 (YANAI and KOJIMA, 1987)—offers a unique opportunity to study achondrite-chondrite relationships. The resemblance of one inclusion (in Y-75097) to the rare brachinites (YANAI *et al.*, 1983) is particularly intriguing. Since the masses of these inclusions are 10–25 g, they can be studied in great detail by a consortium and we are grateful to have received an invitation from the consortium leaders, N. NAKAMURA and K. YANAI, to join such an effort. Here, we report results obtained by radiochemical neutron activation analysis (RNAA) for 14 trace elements—Ag, Au, Bi, Cd, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U, Zn—most of which are moderately- to highly-volatile, in the chondrite hosts. We also report results for cosmogenic ^{26}Al and ^{36}Cl, obtained by accelerator mass spectrometry (AMS), in metal from the hosts and the corresponding terrestrial ages that these data imply. We had hoped to be able to include data for 1.6 Ma ^{10}Be but instrumental problems prevented this. We hope to include these data in another study (in progress), in

[§] Author to whom correspondence should be addressed.

which we report RNAA and INAA (instrumental neutron activation analysis) results for labile and refractory trace elements in the inclusions, and mineral-chemical data for both hosts and inclusions.

2. Experimental

For our RNAA and AMS studies we received the following samples of host: Y-75097,107 (1.683 g); Y-793241,87 (1.955 g); Y-794046,62 (1.894 g). After removal of potentially contaminated surfaces, 200–260 mg aliquants of each meteorite were taken for RNAA. Each was sealed in a quartz vial and irradiated with monitors for 48 h at a flux of 8×10^{13} n cm^{-2} s^{-1} at the University of Missouri Research Reactor. Chemical processing, counting and data reduction were as described by WOLF (1993). Chemical yields for samples exceeded 40% except for Sb in Y-75097,107 (35%) and Au in the other two samples (38 and 39%, respectively). Monitor yields exceeded 50% for all elements but Bi (47%).

Samples for AMS were obtained by grinding 500 mg aliquants of each meteorite in an agate ball mill, reserving 100 mg of homogenized bulk material for ^{10}Be and ^{26}Al measurements. Metal was removed from the remaining material with a hand magnet and etched repeatedly with HF to remove adhering silicaceous material. Clean separates of about 15 mg each were used to determine ^{36}Cl: calcium was also separated in the presence of 20 mg of carrier for future determination of ^{41}Ca. Chemical procedures to separate AgCl are described by VOGT and HERPERS (1988). We used our AMS facility to determine the ^{36}Cl content of each sample by determining its ratio relative to inert carrier (ELMORE *et al.*, 1992). We normalized the measured ratios using standards prepared at Purdue (VOGT *et al.*, 1993). Each sample was measured several times, and the weighted mean and its standard deviation were determined by the propagation-of-errors method described by ELMORE *et al.* (1984).

3. Results and Discussion

We list trace element data for the 3 chondritic hosts in Table 1, together with population means and standard deviations for the corresponding groups of ordinary chondrite falls. As can be seen from Table 1, data for highly mobile trace elements in Y-75097 and Y-793241 more closely resemble those of strongly-shocked (>22 GPa) L4-6 chondrite falls than they do mildly-shocked (<22 GPa) ones. We do not necessarily infer from this resemblance that the two Yamato specimens were strongly-shocked, although they may well have been. Loss by vaporization of highly mobile trace elements from strongly-shocked L4-6 chondrite parent material apparently occurred during extended cooling of massive debris shock-heated in a massive collision 0.5 Ga ago (KACZARAL *et al.*, 1989 and references therein). Hence, it is possible that mobilization of trace elements from parent materials of Y-75097 and Y-793241 host occurred during the heating event that produced the igneous inclusions in them. It is also possible that both processes were operative.

Table 1. Labile trace element contents (ordered by increasing mobility) in chondritic hosts of three large igneous inclusions compared with data for falls of the corresponding chemical groups.

	U (ppb)	Au (ppb)	Sb (ppb)	Ga (ppm)	Se (ppm)	Rb (ppm)	Cs (ppb)
Y-75097,107	12.1	117	51	5.24	8.82	1.77	3.19
Y-793241,87	10.1	131	74	5.24	8.98	3.02	9.49
L4-6 mildly-shocked falls*		184±25 (13)	300^{+820}_{-220} (6)	5.55±0.73 (14)	8.13±1.71 (10)	$2.60^{+0.65}_{-0.52}$ (12)	28^{+80}_{-21} (14)
L4-6 strongly-shocked falls*		157±36 (24)	120^{+110}_{-60} (9)	5.00±0.82 (25)	9.05±2.30 (17)	$2.05^{+1.1}_{-0.70}$ (25)	$9.5^{+2.5}_{-6.9}$ (24)
Y-794046,62	12.4	175	71	5.78	8.14	1.01	39.8
H4-6 falls†		210±48 (26)	77^{+38}_{-25} (45)	5.90±0.80 (55)	8.1 ±1.2 (58)	$2.2^{+1.1}_{-0.7}$ (58)	32^{+105}_{-25} (58)

	Te (ppb)	Bi‡ (ppb)	Ag (ppb)	In‡ (ppb)	Tl‡ (ppb)	Zn (ppm)	Cd‡ (ppb)
Y-75097,107	437	1.0±0.3	11.6	≤0.41	0.23±0.08	60.7	≤0.19
Y-793241,87	401	0.46±0.13	12.3	0.12±0.06	0.53	48.3	1.03±0.07
L4-6 mildly-shocked falls*	480±230 (14)	$5.2^{+15}_{-3.8}$ (14)	90^{+120}_{-51} (13)	$1.08^{+2.8}_{-0.78}$ (14)	$1.3^{+9.4}_{-1.1}$ (14)	64±31 (14)	17^{+70}_{-14} (10)
L4-6 strongly-shocked falls*	388± 94 (25)	$1.7^{+6.8}_{-1.3}$ (25)	60^{+40}_{-24} (25)	$0.35^{+0.27}_{-0.24}$ (25)	$0.41^{+2.11}_{-0.35}$ (25)	48±16 (24)	$8.8^{+48}_{-7.4}$ (25)
Y-794046,62	280	0.94±0.22	62.4	≤0.49	0.99	38.1	2.3±0.1
H4-6 falls†	360±120 (58)	$1.6^{+3.7}_{-1.1}$ (58)	34^{+37}_{-18} (58)	$0.43^{+1.05}_{-0.30}$ (58)	$0.33^{+1.73}_{-0.05}$ (58)	48±17 (58)	$4.8^{+29.8}_{-4.1}$ (53)

* Data from KACZARAL *et al.* (1989). Arithmetic means and associated standard deviations are indicated if one uncertainty value is listed. Otherwise, the mean is a geometric one. Numbers in parentheses are the number of data averaged to obtain the mean and 1σ uncertainties listed.

† Data from sources listed in LIPSCHUTZ *et al.* (1993). Means, standard deviations and numbers in parentheses have the same meaning as for L4-6 chondrites.

‡ Uncertainties listed for these highly labile elements in individual chondrite hosts are uncertainties reflecting only counting statistics. Upper limits are 2σ values based solely on counting statistics.

Table 2. Cosmogenic ^{26}Al and ^{36}Cl and nominal terrestrial ages of chondritic hosts of three consortium igneous inclusions.

Meteorite	^{26}Al* (dpm/kg metal)	^{36}Cl* (dpm/kg metal)	Terrestrial Age†* (ka)
Y-75097,107	53.2±1.8	21.9±1.2	50±50
Y-793241,87	55.2±2.2	18.3±0.8	100±60
Y-794046,62	33.9±1.4	19.5±0.9	70±60

† Based on an average ^{36}Cl saturation activity of 22.8±3.1 dpm/kg metal (NISHIIZUMI *et al.*, 1989).
* Uncertainties listed are 1σ values.

Trace element data for Y-794046 agree reasonably well with averages of non-Antarctic H chondrite falls. The elements Rb, Tl and Cd differ at the factor of 2 level traditionally accepted as indicating compositional differences (Table 1). Contents of these elements, particularly Tl and Cd, often differ by an order of magnitude or more in replicate chips of even the same fall. Hence, the variations in Y-794046 do not seem to signal a problem other than normal chemical heterogeneity. The low Rb content of Y-794046 could be taken to indicate loss by terrestrial weathering. However, the agreement of the Cs datum with its mean concentration in falls, coupled with the known variability of Rb in falls, suggests, again, that the difference (Table 1) reflects normal chemical heterogeneity. Of course, chemical differences observed between Antarctic and non-Antarctic meteorites (*cf.* MICHLOVICH *et al.*, 1993 and references therein; WOLF and LIPSCHUTZ, 1993) may also be playing a role.

The ^{26}Al and ^{36}Cl contents of the three Yamato host samples are listed in Table 2 together with ^{36}Cl-derived nominal terrestrial ages. The ^{36}Cl data and inferred terrestrial ages hint that the two L6 chondrites, Y-75097 and Y-793241, are not paired, especially when one considers the insensitivity of the ^{36}Cl production rate to shielding over a wide range of conditions (REEDY *et al.*, 1993). These results and the ^{26}Al data do not preclude pairing of these two L6 chondrites with certainty. However, this inconclusive hint is consistent with our RNAA, INAA, and mineral-chemical data for the inclusions (in preparation: *cf.* SACK and LIPSCHUTZ, 1993; WANG *et al.*, 1993) and with results of others (YANAI and KOJIMA, 1993; NAKAMURA *et al.*, 1993; FUKUOKA, 1993).

4. Conclusions

Contents of labile trace elements in the two L6 chondrite hosts of Y-75097 and Y-793241 are quite similar to each other and to L4-6 chondrite falls that lost some proportion of their volatile complement by preterrestrial shock heating. We interpret the Yamato chondrite data as indicating a high-temperature episode(s) in their histories, perhaps during formation of the igneous inclusions in them and/or during the massive collision that disrupted the L chondrite parent(s) 0.5 Gy ago. The ^{26}Al and ^{36}Cl data (and consequent nominal terrestrial ages) for these two chondrites hint that the two L6 chondrites are not paired but are inconclusive in this regard.

Contents of labile trace elements in the H chondrite Y-794046 generally resemble those of H4-6 chondrites although small compositional differences exist, reflecting differences in preterrestrial thermal histories. The nominal terrestrial age of Y-794046 derived from ^{36}Cl data is 70 ± 60 ka, *i.e.* consistent with ages determined for other Yamato meteorites. A future paper will focus on compositional data for the igneous inclusions in these chondrites and will discuss their thermal histories in some detail.

Acknowledgments

We thank Prof. N. NAKAMURA and Dr. K. YANAI for inviting us to join their consortium and for providing material for our study. This research was supported by NASA grants NAG 9-48, NAG 9-580 and NAGW-3396 with aid from DOE grant DE-FG07-80ER1 0725J for support of irradiations.

References

ELMORE, D., CONARD, N., KUBIK, P. W. and FABRYKA-MARTIN, J. (1984): Computer controlled isotope ratio measurements and data analysis. Nucl. Instrum. Methods, **B5**, 233–237.

ELMORE, D., RICKEY, F. A., SIMMS, P. C., LIPSCHUTZ, M. E., MUELLER, K. A. and MILLER, T. E. (1992): PRIME lab: A dedicated AMS facility at Purdue University. Radiocarbon, **34**, 447–451.

FUKUOKA, T. (1993): Chemistry of the lithic inclusions in Yamato-793241 and -794046 meteorites (abstract). Papers Presented to the 18th Symposium on Antarctic Meteorites, May 31–June 2, 1993. Tokyo, Natl Inst. Polar Res., 71–73.

KACZARAL, P. J., DODD, R. T. and LIPSCHUTZ, M. E. (1989): Chemical studies of L chondrites—IV. Antarctic/non-Antarctic comparisons. Geochim. Cosmochim. Acta, **53**, 491–501.

LIPSCHUTZ, M. E., WOLF, S. F., VOGT, S., MICHLOVICH, E., M. M. *et al.* (1993): Consortium study of the unusual H chondrite regolith breccia, Noblesville. Meteoritics, **28**, 528–537.

MICHLOVICH, E. S., WOLF, S. F., WANG, M.-S., VOGT, S., ELMORE, D. and LIPSCHUTZ, M. E. (1993): Chemical studies of H chondrites—V. Temporal variation of sources. submitted to J. Geophys. Res.

NAKAMURA, N., HUTCHISON, R., YANAI, K., MORIKAWA, N. and OKANA, O. (1993): Consortium study of three inclusions in Yamato ordinary chondrites: A progress report (abstract). Papers Presented to the 18th Symposium on Antarctic Meteorites, May 31–June 2, 1993. Tokyo, Natl Inst. Polar Res., 61–64.

NISHIIZUMI, K., ELMORE, D. and KUBIK, P. W. (1989): Update on terrestrial ages of Antarctic meteorites. Earth Planet. Sci. Lett., **93**, 299–313.

REEDY, R. C., MASARIK, J., NISHIIZUMI, K., ARNOLD, J. R., FINKEL, R. C., CAFFEE, M. W., SOUTHON, J., JULL, J. T. and DONAHUE, D. J. (1993): Cosmogenic-radionuclide profiles in Knyahinya: New measurements and models (abstract). Lunar and Planetary Science XXIV. Houston, Lunar Planet Inst., 1195–1196.

SACK, R. O. and LIPSCHUTZ, M. E. (1993): Mineral chemistry and formation of igneous inclusions from consortium samples Y-75097, Y-793241, and Y-794046 (abstract). Papers Presented to the 18th Symposium on Antarctic Meteorites, May 31–June 2, 1993. Tokyo, Natl Inst. Polar Res., 65–68.

VOGT, S. and HERPERS, U. (1988): Radiochemical separation techniques for the determination of long-lived radionuclides in meteorites by means of accelerator mass-spectrometry. Fresenius Z. Anal. Chem., **331**, 186–188.

VOGT, S., WANG, M.-S. and LIPSCHUTZ, M. E. (1993): Chemistry operations at Purdue's Accelerator Mass Spectrometry Facility. submitted to Nucl. Inst. Methods.

WANG, M.-S., MICHLOVICH, E. S., VOGT, S., LINDSTROM, M. M., MITTELFEHLDT, D. W. and LIPSCHUTZ, M. E. (1993): Contents of trace elements and cosmogenic radionuclides in consortium samples Y-75092, Y-793241 and Y-794046 (abstract). Papers Presented to the 18th Symposium on Antarctic Meteorites, May 31–June 2, 1993. Tokyo, Natl Inst. Polar Res., 69–70.

WOLF, S. F. (1993): Trace Element Study of H Chondrites: Evidence for Meteoroid Streams. Thesis, Purdue.

WOLF, S. F. and LIPSCHUTZ, M. E. (1993): What's hot and what's not: Multivariate statistical analysis of ten labile trace elements in H chondrite population-pairs (abstract). Meteoritics, **28**, 461–462.

YANAI, K. and KOJIMA, H. (1987): Photographic Catalog of Antarctic Meteorites. Tokyo, Natl Inst. Polar Res., 298 p.

YANAI, K. and KOJIMA, H. (1993): General features of unique inclusions in Yamato ordinary chondrites (abstract). Papers Presented to the 18th Symposium on Antarctic Meteorites, May 31–June 2, 1993. Tokyo, Natl Inst. Polar Res., 57–60.

YANAI, K., MATSUMOTO, Y. and KOJIMA, H. (1983): A Brachina-like inclusion in the Yamato-75097 L6 chondrite: A preliminary examination. Mem. Natl Inst. Polar Res., Spec. Issue, **30**, 29–35.

(Received August 9, 1993; Revised manuscript received January 27, 1994)