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Thermoluminescence studies of ordinary chondrites in the Japanese Antarctic meteorite collection, IV: Asuka ordinary chondrites

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Abstract: We measured TL properties of ninety Asuka (A) ordinary chondrites (LL: 16, L: 27, H: 47) from Japanese Antarctic meteorite collection. Most of the chondrites had TL sensitivities over 0.1, corresponding to petrologic subtype 3.5–3.9. Eight chondrites, A-881244 (L3), A-881607 (LL3), A-881328 (LL3), A-881408 (LL3), A-881397 (LL3), A-881522 (L3), A-881357 (LL3 or L3), and A-881199 (LL3) were revealed to be primitive ordinary chondrites under petrologic subtype 3.4, and therefore they are particularly significant in understanding the nature of primitive material in the solar system. Twenty-one chondrites with low TL sensitivities below 0.1 (Dhajala = 1) had suffered remarkable shock and/or terrestrial weathering.

Samples were mainly from three different dirt bands south of the Sør Rondane Mountains at D1, D2, and D3 sites. LT/HT distribution at D1 site suggested that chondrites at D1 site had shorter terrestrial ages than those at D2 and D3. A-880709, A-88710, A-88774, A-881324 which had extremely low LT/HT ratio under 0.1, and A-881484 and A-881546 which might be heated over 400℃ were presumed to have small perihelia. We found 26 TL potential paired fragments, and 9 groups. A group of H3 at D1 site comprises a chain of paired fragments. A H3 chondrite might shower near the Asuka.

key words: ordinary chondrite, thermoluminescence, subtype, Asuka, Antarctic meteorite

1. Introduction

Thermoluminescence (TL) is light emitted by a phosphor in addition to intrinsic blackbody radiation during heating (McKeever, 1985). Induced TL, the response of a luminescent phosphor to a laboratory dose of radiation, reflects mineralogy and structure of the phosphor while providing valuable information on metamorphic and thermal history of meteorites. As one important utility, TL sensitivity is used to determine the petrologic subtype of type 3 ordinary chondrites (Sears *et al*., 1980, 1991a; Sears, 1988; Benoit *et al*., 2002), CO chondrites (Sears *et al*., 1991b), CV chondrites (Guimon *et al*., 1995), and eucrites (Batchelor and Sears, 1991). Differences in thermal histories of Antarctic and non-Antarctic H chondrites were distinguished by the induced TL peak temperature and width (Sears *et al*., 1991c; Benoit and Sears, 1992). Natural TL, luminescence of a sample that has received no irradiation in the laboratory, reflects the thermal history of the meteorite in space and on Earth. Natural TL data thus provide insights into such topics as meteoroid orbits, shock heating effects, and terrestrial histories of meteorites (Benoit *et al*., 1991, 1992).

Induced and natural TLs of meteorites of the American Antarctic meteorite collection have been routinely measured at the University of Arkansas. They have provided fundamental data of assignment of petrologic subtypes of ordinary chondrites and pairing. Systematic TL analysis of the Japanese Antarctic meteorite collection began in 1996. The TL properties of 121 type 3 ordinary chondrites have been measured; data were used for assignment of petrologic subtypes and pairing (Ninagawa *et al*., 1998, 2000, 2002). We now report TL data for an additional ninety Asuka ordinary chondrites in the Japanese Antarctic meteorite collection measured at the Okayama University of Science.

2. Samples and TL measurements

The Sør Rondane Mountains are located west of the Belgica Mountains in Queen Maud Land, East Antarctica. West Ragnhild Glacier flows between the two Mountains (Pattyn *et al*., 2004). The Sør Rondane Mountains form a substantial barrier to ice flow (Cassidy *et al*., 1992). The Asuka-87 and Asuka-88 meteorites over 2400 samples were recovered by the 29th Japanese Antarctic Research Expedition on the bare icefield around the Sør Rondane Mountains (Yanai, 1993). Samples of ninety Asuka ordinary chondrites (LL: 16, L: 27, H: 47) from Asuka-88708 to Asuka-881626 were obtained from the Japanese Antarctic meteorite collection for this study. Sampling sites are shown in Fig. 1. Thirty-eight of them were collected at D1 site from ~20 km south of Dirt Band A233, forty-three of them were collected at D2 site from ~15 km west of Dirt Band A233, and nine were at Dirt Band A233 (D3 site) south of the Sør Rondane Mountains. They were expected to be type 3 ordinary chondrites because percent mean deviations of low Ca pyroxenes are over 5%. Our procedures for preparing samples and measuring their induced and natural TL were described by Ninagawa *et al*. (2000).

3. Results and discussion

3.1. New TL data

Our new TL data for ninety Asuka ordinary chondrites from the Japanese Antarctic collection are presented in Table 1, along with ancillary information.

3.2. Induced TL data

All ninety samples were expected to be petrologic type 3 ordinary chondrites. However, eight of them were reported to be not type 3 in the Meteorite Newsletter 2002 and 2003 (Kojima and Imae, 2002, 2003). They are denoted by mark † in the Table 1.

Figure 2 compares Dhajala-normalized TL sensitivity with olivine and low Ca pyroxene heterogeneity of Asuka ordinary chondrites. It includes previously reported

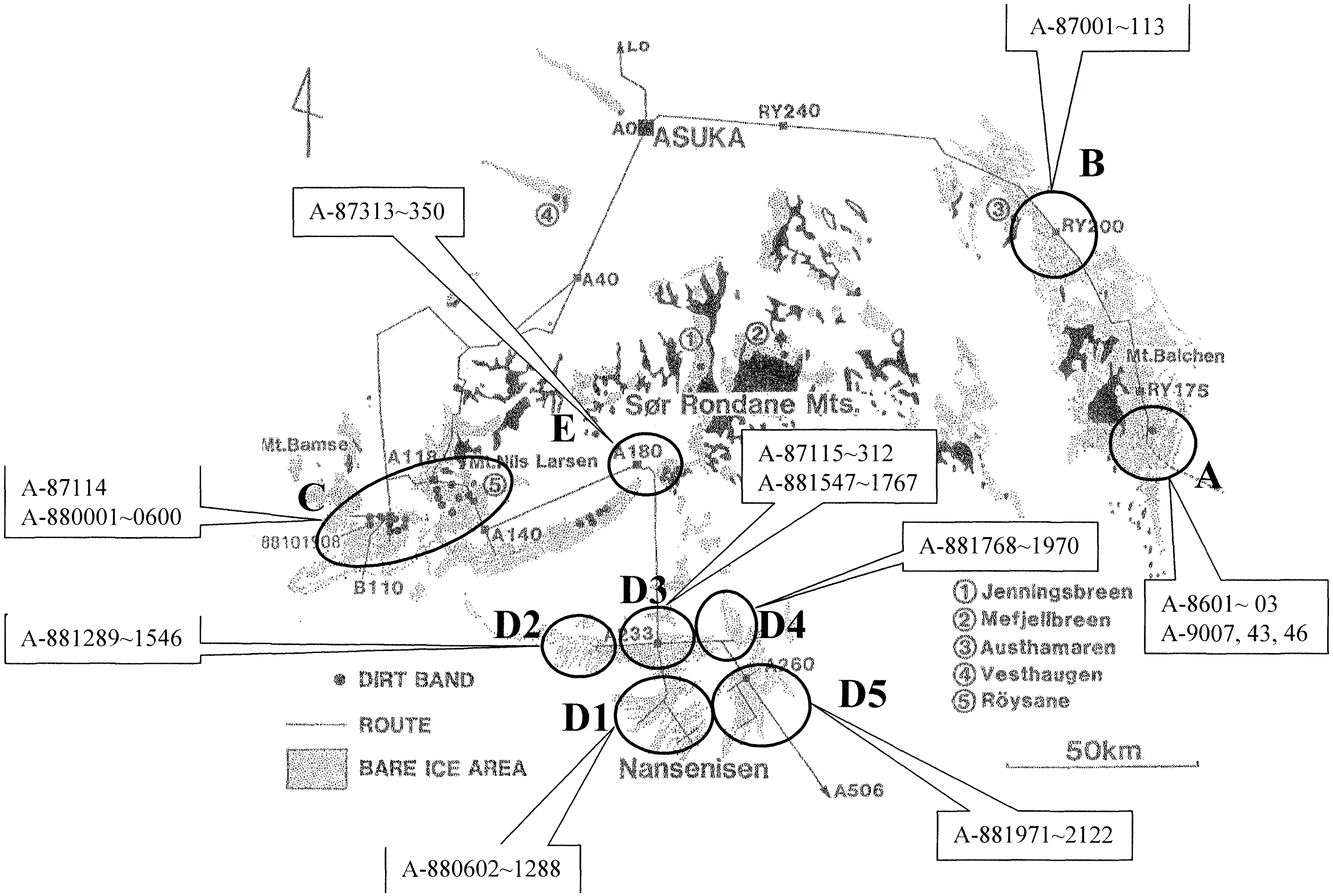

Fig. 1. Sampling sites of the Asuka-87 and Asuka-88 meteorites around the Sør Rondane Mountains.

Table 1. Thermoluminescence data for ninety Asuka ordinary chondrites.

Table 1 (continued).

A-881093	H3	1.58 ± 0.00	11.9 ± 0.0	0.558 ± 0.004	168 ± 6	128 ± 1	3.7	21 ± 0	19%	5%	3.9		D1
A-881344	LL3	2.38 ± 0.02	56.4 ± 6.6	0.586 ± 0.034	161 ± 1	152 ± 4	3.7	96 ± 12	68%	51%	≦3.4		D2
A-881493	H3	0.20 ± 0.00	1.9 ± 0.1	0.589 ± 0.041	170 ± 0	138 ± 3	3.7	3.2 ± 0.2	20%	3%			D2
A-881622	L3	3.45 ± 0.07	54.4 ± 4.1	0.591 ± 0.048	183 ± 1	160 ± 2	3.7	92 ± 10	18%	14%	3.8		D3
A-881597	H3	0.23 ± 0.02	1.9 ± 0.0	0.599 ± 0.021	165 ± 0	164 ± 4	3.7	3 ± 0	22%	18%	3.8		D3
A-881249	H3	1.72 ± 0.12	21.1 ± 1.1	0.605 ± 0.051	172 ± 4	137 ± 2	3.7	35 ± 3	36%	24%	3.7	3.7	D1
A-881080	H3	5.48 ± 0.31	87.7 ± 1.3	0.628 ± 0.040	161 ± 0	135 ± 0	3.7	140 ± 9	8%	3%			D1
A-881412	L3	3.07 ± 0.02	40.1 ± 1.4	0.631 ± 0.001	151 ± 0	158 ± 3	3.7	64 ± 2	38%	3%			D2
A-881411	H3	6.92 ± 0.23	85.5 ± 10.5	0.655 ± 0.089	169 ± 5	140 ± 2	3.7	131 ± 24	9%	4%			D2
A-881069	H3	0.55 ± 0.03	6.8 ± 1.2	0.665 ± 0.038	179 ± 4	146 ± 0	3.7	10 ± 2	10%	2%			D1
A-881263	H3	1.26 ± 0.08	29.8 ± 1.8	0.678 ± 0.128	163 ± 2	148 ± 0	3.6-3.7	44 ± 9	30%	22%	3.7	3.7	D1
A-881616	LL3	3.60 ± 0.02	46.4 ± 2.4	0.705 ± 0.051	163 ± 2	160 ± 5	3.7	66 ± 6	16%	1%			D3
A-880925	H3	3.26 ± 0.48	78.6 ± 11.8	0.732 ± 0.105	165 ± 2	157 ± 5	3.7	107 ± 22	39%	19%	3.8		D1
A-881216	H3	1.14 ± 0.01	21.3 ± 1.6	0.735 ± 0.027	154 ± 0	133 ± 0	3.7	29 ± 2	26%	2%			D1
A-881350	L3	8.84 ± 0.12	147.4 ± 8.6	0.736 ± 0.044	160 ± 2	137 ± 1	3.7	200 ± 17	34%	2%			D2
A-881609	H3	0.24 ± 0.00	1.7 ± 0.1	0.752 ± 0.085	165 ± 3	169 ± 1	3.7	2 ± 0	25%	3%			D3
A-881621	L3	1.95 ± 0.00	46.7 ± 1.7	0.771 ± 0.018	174 ± 1	161 ± 0	3.7	61 ± 3	24%	8%	3.9		D3
A-881437	L3	8.07 ± 0.15	159.3 ± 0.1	0.801 ± 0.017	161 ± 1	155 ± 2	3.7	199 ± 4	30%	3%			D2
A-881402	L3	6.04 ± 0.16	161.0 ± 7.7	0.826 ± 0.096	153 ± 5	148 ± 1	3.7-3.8	195 ± 24	34%	4%			D2
A-881298	H3	2.38 ± 0.03	74.4 ± 0.1	0.870 ± 0.019	165 ± 5	142 ± 1	3.7	86 ± 2	31%	5%	3.9		D2
A-881538	H3	2.14 ± 0.05	26.1 ± 1.9	0.900 ± 0.010	168 ± 5	159 ± 5	3.7	29 ± 2	18%	2%			D2
A-881626	H3	0.15 ± 0.00	1.3 ± 0.0	0.931 ± 0.024	164 ± 1	161 ± 0	3.7	1 ± 0	13%	4%			D3
A-881079	L3	1.15 ± 0.00	39.8 ± 3.4	0.964 ± 0.077	157 ± 2	134 ± 2	3.7-3.8	41 ± 5	10%	4%			D1
A-881498	L3	5.17 ± 0.35	170.6 ± 6.4	0.990 ± 0.033	160 ± 17	162 ± 7	3.7-3.8	172 ± 9	49%	5%	3.9		D2
A-881320	L3	2.61 ± 0.03	54.1 ± 3.3	0.995 ± 0.136	178 ± 0	154 ± 0	3.7-3.8	54 ± 8	22%	3%			D2
A-881348	L3	8.04 ± 0.04	192.7 ± 2.2	1.014 ± 0.025	155 ± 12	145 ± 0	3.8	190 ± 5	31%	2%			D2
A-881436	L3	8.89 ± 0.46	171.4 ± 21.4	1.037 ± 0.090	159 ± 14	152 ± 5	3.7-3.8	165 ± 25	29%	9%	3.9		D2
A-881539	H3	2.32 ± 0.09	65.2 ± 1.0	1.238 ± 0.053	166 ± 4	164 ± 4	3.8	53 ± 2	21%	2%			D2
A-881387	H3	1.33 ± 0.07	46.8 ± 2.7	1.282 ± 0.155	167 ± 3	134 ± 1	3.8	37 ± 5	33%	17%	3.8	3.8	D2
A-881418	LL3	3.24 ± 0.03	95.6 ± 2.2	1.354 ± 0.003	160 ± 0	139 ± 2	3.8	71 ± 2	8%	5%	3.9		D2
A-881400	H3	0.65 ± 0.02	15.5 ± 0.3	1.362 ± 0.017	166 ± 6	130 ± 1	3.8	11 ± 0	11%	7%	3.9		D2
A-881386	H3	4.55 ± 0.02	195.2 ± 0.8	1.378 ± 0.138	165 ± 3	133 ± 0	3.8	142 ± 14	17%	4%			D2
A-881313	LL3	1.65 ± 0.06	80.9 ± 2.6	1.482 ± 0.078	160 ± 4	144 ± 1	3.8	55 ± 3	17%	11%	3.8	3.8	D2
A-881341	H3	4.34 ± 0.17	182.7 ± 11.9	1.579 ± 0.033	173 ± 1	137 ± 1	3.8	116 ± 8	18%	13%	3.8	3.8	D2
A-881146	LL3	1.39 ± 0.05	89.9 ± 1.4	1.881 ± 0.141	147 ± 1	134 ± 7	3.8-3.9	48 ± 4	8%	9%	3.9	3.9	D1
A-881567	LL3	4.46 ± 0.22	195.8 ± 23.5	1.881 ± 0.005	160 ± 2	162 ± 0	3.8	104 ± 12	27%	5%	3.9		D3
A-881420	H3	2.14 ± 0.08	73.4 ± 4.9	1.957 ± 0.188	161 ± 1	133 ± 0	3.8-3.9	37 ± 4	8%	2%			D2
A-881405	L3	6.77 ± 0.05	251.3 ± 0.7	2.039 ± 0.006	137 ± 4	138 ± 0	3.8	123 ± 0	26%	3%			D2
A-881105	LL3	2.20 ± 0.06	183.3 ± 16.3	2.073 ± 0.072	156 ± 0	129 ± 0	3.8-3.9	88 ± 8	11%	5%	3.9	3.9	D1
A-881287	LL3	2.15 ± 0.03	131.1 ± 6.5	2.191 ± 0.058	150 ± 3	139 ± 0	3.9	60 ± 3	16%	9%	3.9	3.9	D1

Table 1 (continued).

A-881258	H4‡			0.004 ± 0.000	165 ± 9	183 ± 16			18%	10%	3.9		D1
A-881026	H3/4 br‡		0.03 ± 0.01	0.004 ± 0.000				9 ± 4	33%	16%	3.8		D1
A-881083	H3/melt br‡	0.40 ± 0.35	0.2 ± 0.2	0.006 ± 0.005	159 ± 16	139 ± 31		27 ± 46		2%			D1
A-881096	L4,5,6 br‡			0.007 ± 0.001	160 ± 7	122 ± 13			24%	3%			D1
A-881090	L3,4,5,6 br‡			0.007 ± 0.000	151 ± 1	230 ± 39			16%	3%			D1
A-881088	L3,4,5,6 br‡			0.018 ± 0.000	139 ± 14	164 ± 19			23%	5%	3.9		D1
A-881494	L6‡	1.07 ± 0.00	2.6 ± 0.2	0.022 ± 0.001	174 ± 0	166 ± 2		117 ± 11	10%	3%			D2
A-880941	H4†	0.47 ± 0.02	0.2 ± 0.0	0.025 ± 0.001	151 ± 2	136 ± 0		8 ± 1	16%	4%			D1
A-880916	H4†	0.62 ± 0.01	0.8 ± 0.2	0.031 ± 0.002	155 ± 5	139 ± 7		25 ± 7	21%	4%			D1
A-881381	L6‡	1.39 ± 0.02	8.2 ± 0.8	0.034 ± 0.000	179 ± 9	164 ± 7		244 ± 24	11%	9%	3.9		D2
A-880733	H4†	0.55 ± 0.03	0.4 ± 0.2	0.040 ± 0.003	153 ± 12	138 ± 7		10 ± 4	7%	4%			D1
A-880973	H4†	0.29 ± 0.01	1.9 ± 0.0	0.364 ± 0.000	163 ± 3	131 ± 1		5 ± 0	12%	2%			D1
A-880930	H4†	0.14 ± 0.00	2.3 ± 0.2	0.472 ± 0.034	153 ± 5	133 ± 1		5 ± 1	10%	6%	3.9		D1
A-880966	H4†	1.62 ± 0.02	20.8 ± 2.8	0.556 ± 0.100	166 ± 7	133 ± 1		37 ± 8	17%	3%			D1
A-880956	H†	0.52 ± 0.02	8.6 ± 0.0	0.766 ± 0.012	165 ± 1	135 ± 3		11 ± 0	8%	8%	3.9		D1
A-880951	H4†	2.04 ± 0.08	98.3 ± 4.4	1.068 ± 0.008	164 ± 5	142 ± 6		92 ± 4	3%	3%			D1

* :Coefficient of variation (σ as a percentage of the mean) of ferrosilite in the low Ca pyroxene.
**: Coefficient of variation (σ as a percentage of the mean) of fayalite in the olivine.
†: Meteorite Newsletter (2002, 2003)
‡: classified after observation of thin section
br: breccia

Asuka data, such as A-87319, A-9043 and A-9046 (Ninagawa *et al*., 2002). Most of the samples had TL sensitivities over 0.1, corresponding to petrologic subtype 3.5–3.9. Twenty-nine chondrites have very low TL sensitivities under or near 0.1. Primitive chondrites of petrologic subtype $\leqq$3.4 have coefficient of variations (σ as a percentage of the mean) over 50%, of fayalite in the olivine (Sears *et al*., 1991a). Eight chondrites, A-881244 (L3), A-881607 (LL3), A-881328 (LL3), A-881408 (LL3), A-881397 (LL3), A-881522 (L3), A-881357 (LL3 or L3), and A-881199 (LL3) satisfied coefficients of variation over 50%, as shown in Fig. 2. They are primitive ordinary chondrites. Petrography of them is not described here, but will be reported later as Meteorite Newsletter.

Residual twenty-one chondrites, however, have coefficients of variation under 50% with the inconsistency between TL sensitivity and olivine heterogeneity (Table 2). There are only two chondrites with this inconsistency in Yamato (Y) samples, Y-790787 (L3) and Y-75029 (H3)(Ninagawa *et al*., 2000). Y-790787 (L3) was found to be shock melted, and Y-75029 (H3) was to be highly weathered, respectively, from microscopic observation of thin sections. TL sensitivity decreases 10-fold after shock-loading to 25–32 GPa (Hartmetz *et al*., 1986), and terrestrial weathering makes TL sensitivity decrease 16-fold at maximum in Antarctic chondrites (Benoit and Sears, 1999). Thin sections of the Asuka twenty-one samples were observed to estimate shock degree and terrestrial weathering. Table 2 shows the detailed descriptions. Almost of these chondrite have suffered remarkable shock and/or terrestrial weathering. High shock and heavy weathering would make their TL sensitivities lower.

Ten chondrites, A-881283 (H3), A-881125 (L3), A-881399 (L3), A-881558 (H3), A-881236 (H3), A-880708 (L3), A-881329 (H3), A-881491 (H3), A-881124 (L3), and A-880713 (H3) were classified to be type 3 chondrites by the microscopic observation. However, eleven chondrites were classified to be H4 (A-880733, A-880916, A-880941), H3/4 breccia (A-881026), H3/melt breccia (A-881083), H4/5/6 breccia (A-881258), L3/4/5/6 breccia (A-881088, A-881090, A-881096), and L6 (A-881381, A-881494). Type 4, 5, and 6 ordinary chondrites usually have higher TL sensitivity. High shock and heavy weathering would make TL sensitivities lower under 0.1 (Dhajala = 1) even for type 4, 5, and 6 ordinary chondrites.

A-881026 was classified to H3/4 breccia in this observation, and a specimen of this chondrite showed a unique induced TL glow curve, as shown in Fig. 3. This unique TL glow curve resembles that of cristobalite, which has two peaks at 140℃ and 290℃ (Matsunami *et al*., 1992). A-881026 may include crystobalite.

3.3. *Natural TL data*

Ordinary chondrites usually have two natural TL peaks at low temperature (about 230℃) and at high temperature (about 360℃). Low temperature peak intensity (LT) is susceptive to heating, although high temperature peak intensity (HT) is relatively resistant to heating. TL glow curve profiles within several millimeter of fusion crust, which have suffered heating during atmospheric entry, demonstrate this heating property (Ninagawa *et al*., 1983). The LT have decreased in Antarctic ambient air temperature (*e.g.* -5℃) for several hundred thousand years, although the HT had kept almost same intensity for that period. Then low LT/HT ratio suggests shock reheating,

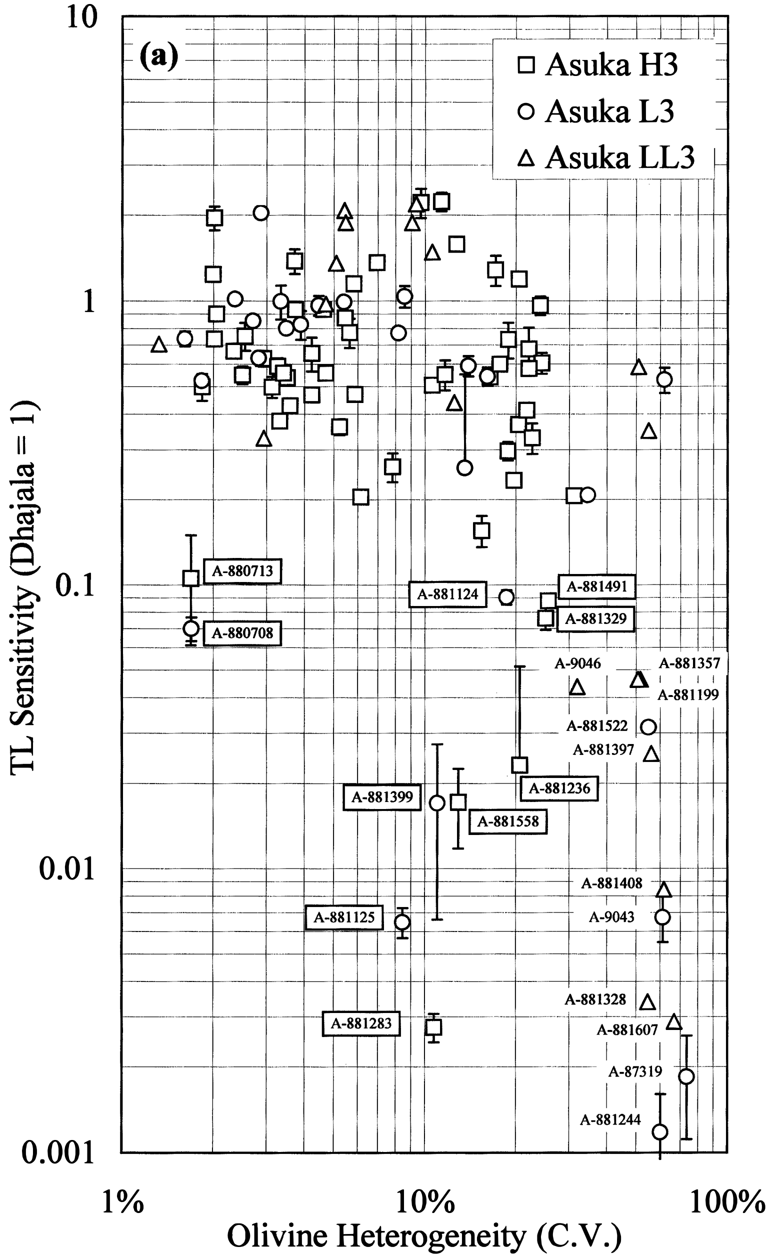

Fig. 2. Dhajala-normalized TL sensitivity vs. (a) olivine heterogeneity and (b) low Ca pyroxene heterogeneity of Asuka ordinary chondrites for the new seventy-four data set except sixteen classified to be not type 3, and data for previously analyzed Asuka type 3 samples, such as A-87319, A-9043 and A-9046 (Ninagawa et al., 2002). Type 3 chondrites with coefficients of variations under 50%, of fayalite in the olivine and TL sensitivities under or near 0.1 (Dhajala = 1) are surrounded by solid rectangle.

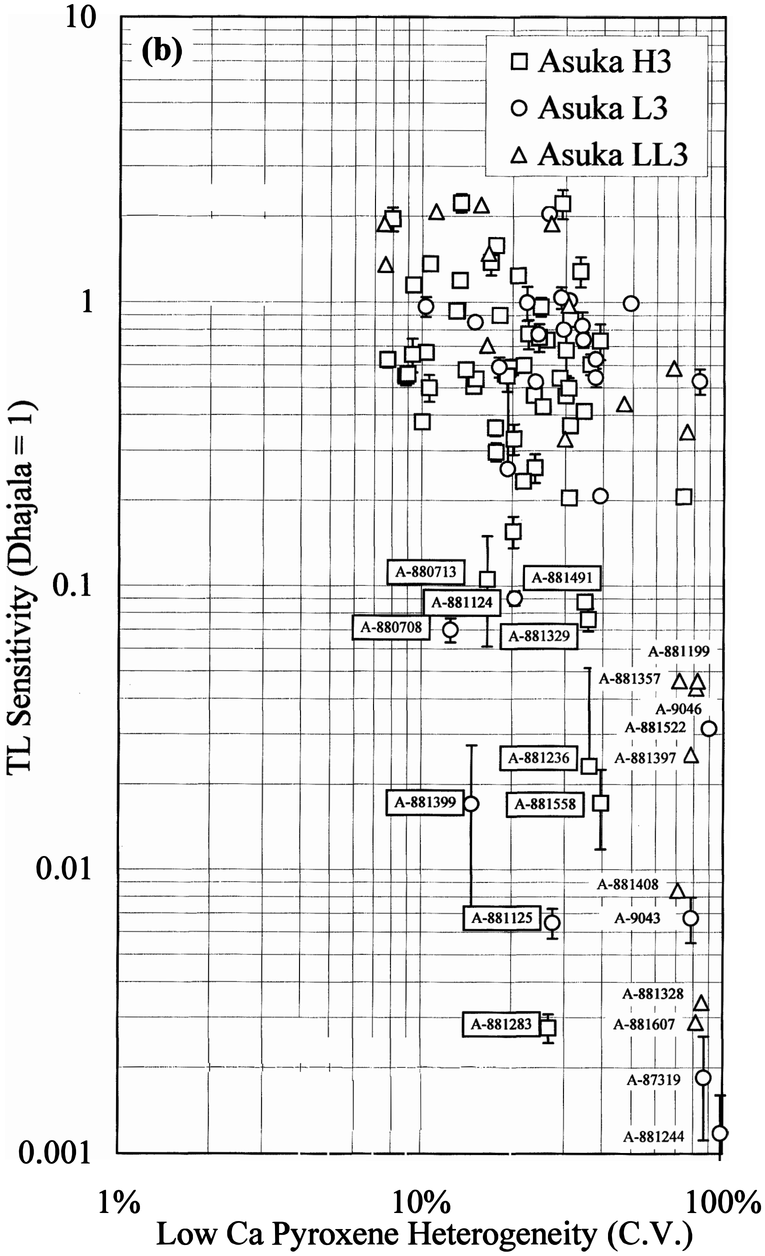

Fig. 2 (continued).

Table 2. Thin section observation of samples, which olivine hetero-

Meteorite	Class	Low Ca-Py Heterogenity (C.V.)†	Ol Heterogenity (C.V.)†	Ol Subtype	TL Subtype	Recom-mended Subtype	Polished Thin Section number
A-880713	H3	17%	2%	≥4	3.2-3.5		51-1
A-881236	H3	36%	21%	3.7	3.0-3.4	3.7	61-1
A-881283	H3	27%	11%	3.8	3.0	3.8	61-1
A-881329	H3	36%	25%	3.7	3.4	3.7	51-1
A-881491	H3	35%	26%	3.7	3.4	3.7	51-1
A-881558	H3	40%	13%	3.8	3.1-3.3	3.8	51-1
A-880708	L3	13%	2%	≥4	3.4		51-1
A-881124	L3	20%	19%	3.8	3.4-3.5	3.8	11-1
A-881125	L3	27%	8%	3.9	3.1	3.9	91-1
A-881399	L3	15%	11%	3.8	3.0-3.3	3.8	51-1
A-880733	H4†	7%	4%	≥4			51-1
A-880916	H4†	21%	4%	≥4			51-1
A-880941	H4†	16%	4%	≥4			51-1
A-881026	H3/4 br	33%	16%	3.8			61-1
A-881083	H3/melt br	11%	2%	≥4			61-1
A-881258	H4.5.6 br	18%	10%	3.9			71-1
A-881088	L3.4.5.6 br	23%	5%	3.9			51-1
A-881090	L3.4.5.6 br	16%	3%	≥4			51-1
A-881096	L4.5.6 br	24%	3%	≥4			61-1
A-881381	L6	11%	9%	3.9			91-1
A-881494	L6	10%	3%	≥4			91-1

†: Meteorite Newsletter (2002, 2003)
br: breccia

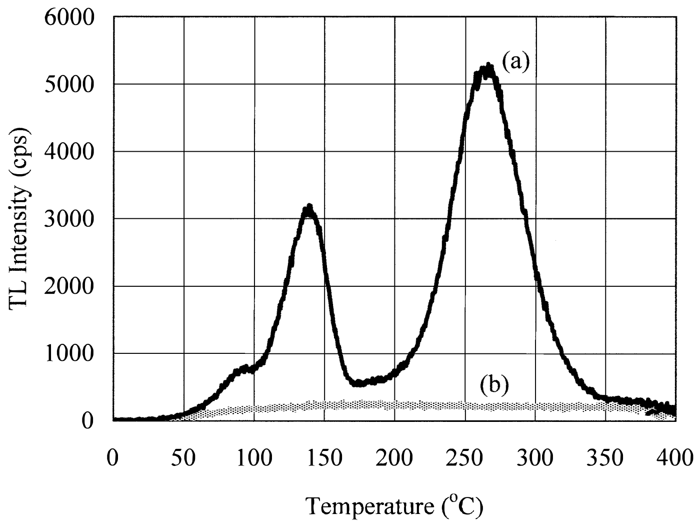

Fig. 3. TL glow curves of A-881026 (H3/4 breccia). (a) unique TL glow curve. (b) usual TL glow curve.

geneities are <50% and TL sensitivities are <0.1 (Dhajala=1).

Ol extinction	Shock darkening	Shock vein	Terrestrial weathering	Weathering size	Comments
mosaic	moderate	+	remarkable	50 μm	flattened chondrules
mosaic	remarkable	+	moderate	10-30 μm	partially fizzed troilite
mosaic	remarkable	-	remarkable	100 μm	
unduratory~mosaic	remarkable	+	moderate	20-30 μm	
unduratory~mosaic	moderate	-	remarkable	30 μm	
mosaic	remarkable	-	moderate	20 μm	
mosaic	moderate	-	fresh	-	flattened chondrules
mosaic	moderate	-	moderate	50 μm	fragmented chondrules, breccia
mosaic	remarkable	-	moderate	30 μm	
mosaic	remarkable	-	minor	10 μm	
mosaic	moderate	-	remarkable	100 μm	
mosaic	remarkable	-	moderate	20-30 μm	glassy bearing, breccia
mosaic	moderate	-	moderate	10 μm	flattened chondrules
unduratory~mosaic	remarkable	-	remarkable	<100 μm	
mosaic	remarkable	-	remarkable	100 μm	breccia with shock melted clast
mosaic	remarkable	-	moderate	20-30 μm	maskelynite rich, unique H
mosaic	remarkable	+	minor	10 μm	
mosaic	moderate	-	moderate	10-20 μm	
mosaic	remarkable	-	moderate	30-40 μm	
mosaic	absent	-	remarkable	100-200 μm	
mosaic	free	-	remarkable	20 μm	

heating due to small perihelion near Venus, or relatively long terrestrial age (Hasan *et al*., 1987).

Figure 4 shows ratio of the natural low temperature peak intensity (LT) to the Dhajala-normalized TL sensitivity vs. natural TL peak height ratio (LT/HT). Samples were mainly from three different dirt bands south of the Sør Rondane Mountains at D1, D2, and D3 sites. Figure 4 is plotted by sites. There are two clusters at D1 site as shown in Fig. 4a. A-88709, A-88710, and A-88774 comprise a group, and the others comprise another group with relatively high LT/HT ratio. The minimum of the group with relatively high LT/HT ratio is 0.55. Hasan *et al*. showed that minimum LT/HT ratio was 0.92 for ALHA 78043 chondrite, which had long terrestrial age of 490×10^3 years (Hasan *et al*., 1987). Although terrestrial ages of Asuka chondrites have not been measured, it seems to be difficult to attain to 0.1 due to long terrestrial TL draining. On the other hand LT/HT ratio distributes seriately to near 0.1 in Asuka D2 and D3 sites as shown Fig. 4b and 4c. The Sør Rondane Mountains form a substantial barrier to ice flow. Asuka D1 site has higher altitude than D2 and D3 sites. Then chondrites at D1 site may have relatively shorter terrestrial ages than those at D2 and D3 sites. This LT/HT ratio distribution at D1 site supports this shorter terrestrial ages of chondrites.

A-880709, A-88710, A-88774, and A-881324 have extremely low LT/HT ratio under 0.1, as shown in Fig. 4. In case of shock heating, TL sensitivity is also decreased (Hartmetz *et al*., 1986). However, their TL sensitivities are over 0.1, and not so weak

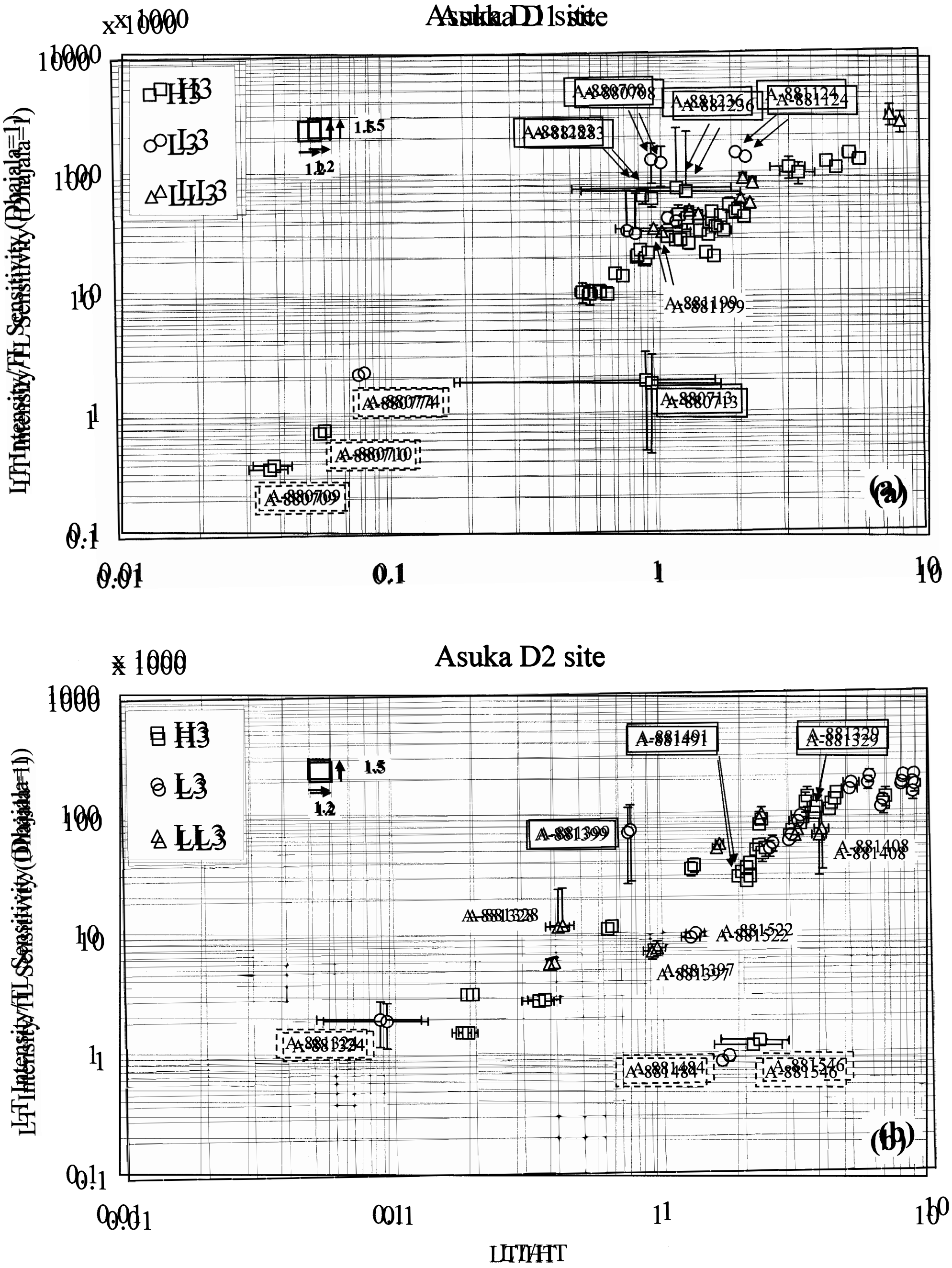

Fig. 4. Ratio of the natural low temperature peak intensity (LT) to the Dhajala-normalized TL sensitivity vs. natural TL peak height ratio (LT/HT), (a) for Asuka D1 site, (b) for Asuka D2 site, and (c) for Asuka D3 site. Type 3 chondrites with coefficients of variations under 50%, of fayalite in the olivine and TL sensitivities under or near 0.1 (Dhajala=1) are surrounded by solid rectangle.

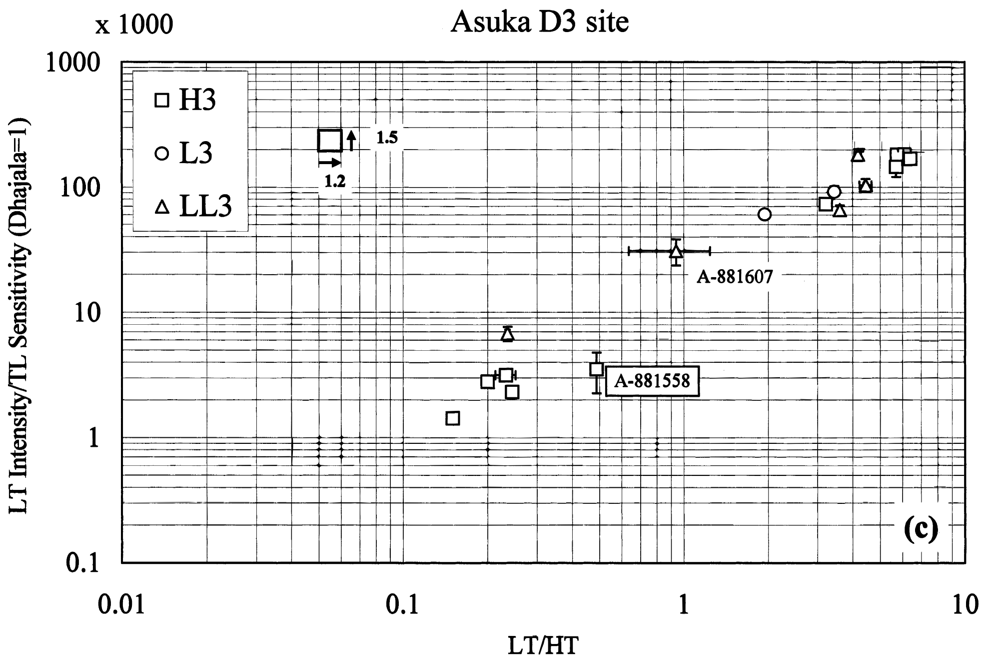

Fig. 4 (continued).

(Table 1). Shock heating may not be cause of their low LT/HT ratios. Then these chondrites have possibility that their meteoroid orbits had small perihelia. A-881484 and A-881546 stand from the other chondrites in Fig. 4b. Their natural high temperature peaks (HT) are also very weak as well as their natural low temperature peaks (LT) are. Their TL sensitivities are over 0.2, also not so weak. These samples may be heated over 400°C in the past, and their meteoroid orbits were presumed to have more small perihelia than the group of A-880709.

Four pairing criteria (Ninagawa *et al.*, 1998) were applied to the new seventy-four data and data of previously analyzed Asuka type 3 chondrites (Ninagawa *et al.*, 2000; Table 1), considering sampling sites. Samples in a rectangle in Fig. 4 satisfy the two of the pairing criteria. We found 26 TL potential paired fragments, and 9 groups (Table 3) after applying more two residual criteria. A group of H3, group 4 in Table 3, comprises a chain of paired fragments at D1 site. A H3 chondrite might shower near the Asuka.

The ten type 3 chondrites with inconsistency between TL sensitivity and olivine heterogeneity are surrounded by solid rectangle in Fig. 4. They are located above main trend in Fig. 4a. On the other hand the primitive chondrites are located below main trend in Fig. 4b. Plot of ratio of the natural low temperature peak intensity (LT) to the Dhajala-normalized TL sensitivity *vs.* natural TL peak height ratio (LT/HT) gently distinguish primitive chondrites from high shock and heavy weathered chondrites.

Talbe 3. Paired specimens of type 3 chondrite, satisfying the TL pairing criteria.

Class	Sampling Site	Meteorite	Paired fragments satisfying the TL pairing criteria.	Group
H3	D1	A-881069	A-880793	1
	D1	A-880676	A-880620	2
	D1	A-880729	A-880746	3
		A-880746	A-881240	
	D1	A-880711	A-881216 A-880613	4
		A-881216	A-880613	
		A-880613	A-880624	
		A-880624	A-880724 A-880684 A-881249	
		A-881242	A-880684	
		A-880724	A-880684 A-880641	
		A-880684	A-881249 A-880641	
		A-880641	A-880863	
	D2	A-881382	A-881329	5
	D2	A-881341	A-881386	6
	D3	A-881597	A-881609	7
	D3	A-87278	A-87283 A-87277	8
		A-87283	A-87277	
L3	D2	A-881348	A-881350 A-881436	9
		A-881437	A-881436	

4. Summary

We measured TL properties of ninety Asuka ordinary chondrites (LL: 16, L: 27, H: 47). Their percent mean deviations of low Ca pyroxenes are over 5%. Most of the samples had TL sensitivities over 0.1, corresponding to petrologic subtype 3.5–3.9.

Twenty-nine chondrites had very low TL sensitivities under or near 0.1. The eight chondrites, A-881244 (L3), A-881607 (LL3), A-881328 (LL3), A-881408 (LL3), A-881397 (LL3), A-881522 (L3), A-881357 (LL3 or L3), and A-881199 (LL3) were primitive ordinary chondrites with coefficient of variations over 50% of fayalite in the olivine. The ten chondrites, A-881283 (H3), A-881125 (L3), A-881399 (L3), A-881558 (H3), A-881236 (H3), A-880708 (L3), A-881329 (H3), A-881491 (H3), A-881124 (L3), and A-880713 (H3) were type 3 chondrites with coefficient of variations under 50% of fayalite in the olivine. Almost of them had suffered remarkable shock and/or terrestrial weathering. All samples were expected to be petrologic type 3 ordinary chondrites. However, the eleven chondrites were classified to be H4 (A-880733, A-880916, A-880941), H3/4 breccia (A-881026), H3/melt breccia (A-881083), H4/5/6 breccia (A-881258), L3/4/5/6 breccia (A-881088, A-881090, A-881096), and L6 (A-881381, A-881494), by the microscopic observation. They also had suffered remarkable shock and/or terrestrial weathering. A-881026 showed the unique TL glow curve. It resembled that of cristobalite. A-881026 may include crystobalite.

Samples were mainly from three different dirt bands south of the Sør Rondane Mountains at D1, D2, and D3 sites. There are two clusters in plot of ratio of the natural low temperature peak intensity (LT) to the Dhajala-normalized TL sensitivity *vs.* natural TL peak height ratio (LT/HT) at D1 site. This LT/HT ratio distribution at D1 site supports shorter terrestrial ages of chondrites than those at D2 and D3 sites.

A-880709, A-88710, A-88774, and A-881324 have extremely low LT/HT ratio under 0.1. Then these chondrites have possibility that their meteoroid orbits had small perihelia. A-881484 and A-881546 stand from the other chondrites in Fig. 4b. These samples might be heated over 400℃ in the past, and their meteoroid orbits were presumed to have more small perihelia than the group of A-880709.

Four pairing criteria were applied, considering sampling sites. We found 26 TL potential paired fragments, and 9 groups. A group of H3 at D1 site comprises a chain of paired fragments. A H3 chondrite might shower near the Asuka.

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