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Thermoluminescence studies of ordinary chondrites in the Japanese Antarctic meteorite collection, II: New measurements for thirty type 3 ordinary chondrites

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Abstract: We have measured the thermoluminescence (TL) properties of thirty type 3 ordinary chondrites from the Japanese Antarctic meteorite collection. This brings to 73 the total number of Japanese type 3 ordinary chondrites examined in this way by the Arkansas-Okayama collaboration. Fifteen pairing groups were found using TL and geographical criteria. Most of the new meteorites are of petrologic types 3.6–3.9, but fourteen are of petrologic type ≤3.4. Six of the 73 meteorites (Yamato (Y)-790448, Y-793596, Y-793565, Y-791324, Y-791558, Y-74660) have petrographic types <3.2, and are therefore particularly valuable samples of primitive solar system material. Most of the meteorites with high TL sensitivity (petrologic type >3.5) tend to have higher induced TL peak temperature and peak width than those with low TL sensitivity, in confirmation of earlier work and consistent with peak temperature and width as well as TL sensitivity, being independent parameters of thermal history. Samples not obeying these trends (Y-75029, Y-86706, Y-793567 and Y-790787), are either heavily weathered or experienced atypical thermal histories.

1. Introduction

Thermoluminescence (TL) is the light emitted by a sample in response to heating. It is discrete from blackbody radiation and can be produced at almost any temperature depending on the solid state properties of the sample (McKeever, 1985). Natural TL is that produced by a sample in its "as received" state, induced TL is that produced after removal of the natural TL and exposure to a laboratory test dose of radiation. Thus while natural TL data can provide information on radiation and thermal history, and thus on the orbits, shock heating, and terrestrial history (Benoit *et al.*, 1991, 1992), induced TL reflects the mineralogy and structure of the sample, and thus the metamorphic history of the meteorites. The maximum amount of light produced as the sample is heated, normally normalized to an arbitrary standard like the Dhajala meteorite, is referred to as "TL sensitivity" and provides a direct determination of petrologic type and thereby metamorphic alteration of type 3 ordinary chondrites (Sears *et al.*, 1980, 1991a; Sears, 1988), CO chondrites (Sears *et al.*, 1991b), CV chondrites (Guimon *et al.*, 1995) and eucrites (Batchelor and Sears, 1991). Differences in induced TL peak temperature and width reflect disordering in the feldspar, the mineral responsible for the TL in most classes, and therefore provide independent information on metamorphic temperatures and cooling rates. Differences in induced TL peak temperature and width data for Antarctic and non-Antarctic H chondrites have been used to argue for short-term secular variation in the nature of the flux of H chondrite material reaching Earth from the 8 Ma break-up event for this parent object (Sears *et al.*, 1991c; Benoit and Sears, 1992).

A unique challenge of Antarctic meteorite studies is the large amount of "pairing", and TL data can also provide insights into this problem. "Paired" fragments are pieces of a single meteorite that fragmented in the atmosphere or on Earth. It has been suggested that more than half of the Japanese Antarctic collection (Ikeda and Kimura, 1992) and one-third the U.S. collection (Benoit *et al.*, 2000) is paired. Petrographic examination is of minimal utility in recognizing pairing among many classes because of their chemical and physical homogeneity.

The natural and induced TL of meteorites of the American Antarctic meteorite collection has been routinely measured at the University of Arkansas for over thirteen years. Systematic TL analysis of the Japanese Antarctic meteorite collection began in 1996. Last year we reported the properties of forty-three type 3 ordinary chondrites measured at the University of Arkansas (Ninagawa *et al.*, 1998). After rigorous interlaboratory comparison, we now report data for a further thirty type 3 ordinary chondrites obtained at the Okayama University of Science.

2. TL measurements and TL data

The thirty type 3 ordinary chondrites obtained for this study are listed in Table 1. Each sample was gently crushed to a grain size of about 20–200 μm and the metal removed by a hand magnet. The TL of the samples was measured with a custom built TL system with a Hamamatsu R762 photomultiplier, Corning 7–59 and 4–69 filters, nitrogen atmosphere and heating rate of 0.5°C/s. After measurement of the natural TL, and the sample drained of its TL signal, the sample was given 250 Gy dose of ^{60}Co γ radiation and the induced TL properties measured.

Our previous work with the Arkansas TL system used an EMI 9636 photomultiplier, a heating rate of 7.5°C/s and a 20 Gy dose of β radiation dose from a ^{90}Sr source. Despite differences in equipment and procedures, the agreement between the two laboratories is excellent (Ninagawa *et al.*, 1998) and simple calibration expressions can be used to put the data on a common basis:

$$(\text{LT/HT intensity ratio})_{\text{O}} = 1.27 \times (\text{LT/HT intensity ratio})_{\text{A}},$$

$$(\text{TL intensity})_{\text{O}} = 50 \times (\text{TL intensity})_{\text{A}},$$

where the suffices A and O refer to Arkansas and Okayama, respectively, and the term LT/HT refers to the ratio of the low-temperature TL to the high-temperature TL, a parameter frequently used for natural TL measurements (Hasan *et al.*, 1989).

3. Results and discussion

3.1. New TL data

Our new TL data are presented in Table 1, along with ancillary information.

3.2. Pairing

We used the following criteria for pairing the meteorites: (1) the natural TL peak height ratios, LT/HT, of two potentially paired meteorites should be within 20%, (2) the ratio of the low-temperature natural TL signal to the induced TL signal (=LT intensity/TL sensitivity) should be within 50%, (3) the TL peak temperatures should be within 20°C and peak widths within 10°C. These criteria are based on the variation in these parameters among modern falls and within especially large meteorites (*e.g.*, Sears *et al.*, 1991a; Benoit and Chen, 1996; Ninagawa *et al.*, 1998). These criteria yield eighteen pairing groups among the 73 Antarctic meteorites in the Japanese collection we have analyzed, most involve only two samples, but two involve three samples (Tables 1 and 2). However, while satisfying the TL pairing criteria, three groups are probably not paired because their recovery positions are separated by ~80 km. Pairing analyses at other Antarctic sites suggests that paired fragments are rarely separated by more than 20 km (*e.g.*, Benoit *et al.*, 1992).

3.3. Petrologic type

Most of the samples are of petrologic subtype 3.6–3.8 based on TL sensitivity, but Y-74660, Y-86711, Y-74417, Y-75029 and Y-791856 have TL sensitivities equivalent to petrologic subtype ≤3.4. The induced TL peak temperatures and widths segregate the meteorites into two distinct clusters, which are also indicative of degree of metamorphism. Meteorites in the lower cluster are generally of petrologic subtype <3.5, a relationship noted in previous studies of type 3 ordinary chondrite modern falls and finds (Sears, 1988; Sears *et al.*, 1991a). Thus the clusters noted in the induced TL peak temperature and width plot (Fig.1) are also apparent in Fig. 2. Figure 3 compares TL sensitivity with olivine and pyroxene heterogeneity and they resemble similar plots in earlier studies so that our TL assignments would be in agreement with assignments based on mineral heterogeneity.

3.4. Unusual meteorites

A few samples, Y-74660 (LL3), Y-75029 (H3), Y-793567 (L3), Y-86711 (LL3) and Y-86706 (L3), plot outside these clusters. Petrographic observations indicate that Y-74660 (LL3) is exhibiting features of shock stage S2 in the classification system of Stöffler *et al.* (1991) and has a fine-grained matrix. The most unequilibrated meteorites such as Bishunpur, Krymka and Semarkona do not follow

Table 1. Thermoluminescence data of thirty unequilibrated Japanese ordinary chondrites measured in Okayama.

Meteorite	Class	Weight (g)	Natural TL LT/HT	Natural TL LT (10^3 counts)	Induced TL TL Sensitivity (Dhajala=1)	Induced TL Peak Temp. (°C)	Induced TL Width (°C)	LT /TL Sens. ($\times 10^3$)	Low Ca-Py. C.V.(%)†	Ol. C.V.(%)‡	Subtype Olivine	Subtype TL	Subtype Recommended	Pairing (○:paired), Shock Stage & comments
Y-74660	LL3	27.2	*	*	0.0014 ± 0.0003	133 ± 1	148 ± 7		103	85	≦3.4	3.0	3.0	S2, fine matrix
Y-86711	LL3	37.6	0.85 ± 0.03	2.2 ± 0.7	0.06 ± 0.01	174 ± 6	150 ± 16	40 ± 14				3.3-3.4		
Y-82033	LL3	21.1	2.42 ± 0.01	78.4 ± 2.4	0.74 ± 0.03	167 ± 1	158 ± 1	106 ± 6	35	25	3.7	3.7	3.7	
Y-82179	LL3	56.0	3.61 ± 0.09	20.3 ± 0.1	0.147 ± 0.003	163 ± 1	146 ± 1	138 ± 3	54	41	3.5	3.5	3.5	
Y-82195	LL3	25.2	6.24 ± 0.05	146.8 ± 5.5	0.71 ± 0.06	166 ± 1	158 ± 1	206 ± 20	84	27	3.7	3.7	3.7	
Y-86332	L3	4.7	0.07 ± 0.01	0.26 ± 0.03	0.24 ± 0.01	143 ± 5	145 ± 1	1.1 ± 0.1				3.6	3.6	
Y-86055	L3	137.5	2.77 ± 0.11	55.0 ± 0.5	0.50 ± 0.04	162 ± 2	131 ± 2	109 ± 8	30	12	3.8	3.6-3.7	3.8	
Y-86631	L3	33.9	2.77 ± 0.07	16.3 ± 0.2	0.35 ± 0.01	120 ± 2	135 ± 2	47 ± 1	35	5	3.9	3.6	3.6/3.9	
Y-86706	L3	42.0	4.80 ± 0.24	27.2 ± 1.9	0.63 ± 0.04	102 ± 4	103 ± 1	43 ± 4	41	6	3.9	3.7	3.7/3.9	S2, recrystalized matrix.
Y-86705	L3	202.7	6.45 ± 0.02	41.1 ± 1.0	0.21 ± 0.02	151 ± 2	139 ± 1	197 ± 17	45	9	3.9	3.5-3.6	3.9	
Y-794064	H3	43.2	0.090 ± 0.002	0.54 ± 0.05	0.38 ± 0.01	153 ± 1	147 ± 1	1.4 ± 0.1	33	4		3.6	3.6	○
Y-794011	H3	19.0	0.11 ± 0.02	0.3 ± 0.1	0.28 ± 0.01	148 ± 1	147 ± 2	1.2 ± 0.4	29	4		3.6	3.6	○
Y-794008	H3	19.8	0.21 ± 0.01	0.4 ± 0.1	0.312 ± 0.004	155 ± 1	146 ± 1	1.2 ± 0.2	42	3		3.6	3.6	
Y-794009	H3	54.2	1.00 ± 0.00	38.0 ± 0.1	0.92 ± 0.03	154 ± 1	130 ± 1	41 ± 1	6	3		3.7-3.8	3.8	
Y-81015	H3	55.8	2.14 ± 0.02	27.1 ± 0.8	0.35 ± 0.02	162 ± 1	138 ± 8	78 ± 4	22	12	3.8	3.6	3.6/3.8	
Y-75106	LL3	15.8	6.07 ± 0.09	171.9 ± 5.1	0.89 ± 0.02	163 ± 1	123 ± 1	194 ± 7	31	12	3.8	3.7	3.8	
Y-793573	L3	14.2	0.55 ± 0.01	19.6 ± 2.5	1.17 ± 0.01	159 ± 2	125 ± 1	17 ± 2	7	2		3.8	3.9	○
Y-8014	L3	13.9	0.58 ± 0.01	4.67 ± 0.02	0.39 ± 0.01	159 ± 6	135 ± 2	11.9 ± 0.4	19	8	3.9	3.6	3.9	○
Y-793255	L3	29.9	1.97 ± 0.04	25.0 ± 2.1	0.45 ± 0.06	156 ± 2	128 ± 1	55 ± 8	27	13	3.8	3.6-3.7	3.8	
Y-793571	L3	26.0	2.12 ± 0.05	25.3 ± 1.3	0.247 ± 0.002	165 ± 3	121 ± 1	103 ± 5	9	4		3.6	3.6	
Y-74417	L3	44.5	3.94 ± 0.16	7.2 ± 0.3	0.16 ± 0.03	92 ± 12	87 ± 3	46 ± 9	60	53	≦3.4	3.4-3.6	3.4	
Y-793370	L3	206.9	5.40 ± 0.18	89.4 ± 0.5	0.90 ± 0.06	133 ± 1	119 ± 1	100 ± 7	39	9	3.9	3.7-3.8	3.9	○
Y-793325	L3	41.7	5.88 ± 0.01	27.1 ± 2.5	0.28 ± 0.04	144 ± 4	126 ± 1	97 ± 15	35	9	3.9	3.5-3.6	3.9	○
Y-74441	L3	27.4	8.24 ± 0.15	19.8 ± 0.2	0.12 ± 0.01	120 ± 3	144 ± 2	158 ± 8	69	52	≦3.4	3.5	3.5	S2, recrystalized matrix
Y-75029	H3	83.9	*	0.13 ± 0.01	0.009 ± 0.002	194 ± 9	311 ± 7	14 ± 2	10	3		3.1-3.2		S3, recrystalized matrix, heavily weathered.
Y-791856	H3	26.1	*	0.8 ± 0.1	0.031 ± 0.002	94 ± 15	113 ± 7	26 ± 2	69	53	≦3.4	3.3	3.3	S1, heavily weathered matrix.
Y-792927	H3	25.8	0.71 ± 0.03	5.5 ± 0.2	0.260 ± 0.003	151 ± 1	128 ± 2	21 ± 1	25	12	3.8	3.6	3.6/3.8	
A-882004	H3	375.5	2.06 ± 0.01	36.4 ± 0.9	0.56 ± 0.03	150 ± 4	113 ± 5	65 ± 4	9	3		3.7	3.7	
Y-74142	H3	29.5	4.30 ± 0.04	221.1 ± 11.1	1.27 ± 0.04	153 ± 1	130 ± 2	174 ± 10	34	16	3.8	3.8	3.8	
A-9007	H3	94.3	4.75 ± 0.09	63.7 ± 1.1	0.37 ± 0.02	150 ± 5	115 ± 1	174 ± 8	31	20	3.8	3.6	3.6/3.8	

* Natural TLs were not detected.

† 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.

Table 2. Paired fragments satisfying the TL pairing criteria.

Class	Paired fragments satisfying the TL pairing criteria		Time difference of gathering	Geographical distance of gathering position	Geographical consideration & comment
L3	Y-793573	Y-8014	1 year	unknown	
	Y-790770	Y-790994	1 day	< 2～3 km	
	Y-86055	Y-791366	7 years	～80 km	X**
	Y-793369	Y-793272	2 days	< 10 km	
	Y-791366	Y-793272	2 months	～80 km, different ice flow.	X**
	Y-82058	Y-82056	the same day	< 5 km	
	Y-793370*	Y-793325*	the same day	< 5 km	
	Y-82058*	Y-793325*	3 years	< 5 km	
	Y-82056	Y-86705	4 years	unknown	
	Y-82055	Y-82095	1 week	unknown	triplet 1
	Y-82055	Y-793374	2 years	unknown	triplet 1
	Y-793374	Y-82095	2 years	unknown	triplet 1
H3	Y-794064*	Y-794011*	2 days	unknown	
	Y-790443	Y-790461	the same day	< 2～3 km	triplet 2
	Y-790443	Y-794009	3 months	unknown	triplet 2
	Y-790461	Y-794009	3 months	unknown	triplet 2
	Y-790167	Y-790986	1 week	15～20 km	X**
	Y-790986	Y-74142	5 years	～30 km	△***

* These couples are shown in Table 1.
** These couples are probablely not paired in veiw of geography.
*** Whether they were in the same ice flow or not can not be determined.

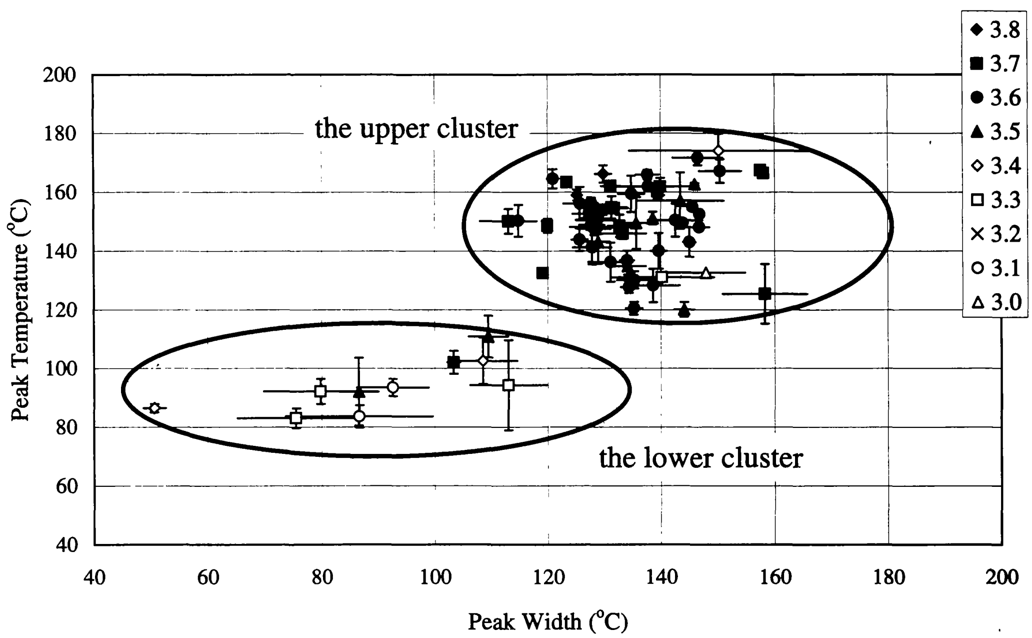

Fig. 1. Induced TL peak temperature vs. peak width of type 3 ordinary chondrites from the Japanese Antarctic meteorite collection. Symbols express TL subtypes.

the trends of two clusters possibly because the dominant TL phosphor is not crystalline plagioclase (Sears *et al.*, 1982) and Y-74660 may exhibit similar properties.

Y-75029 (H3) is of shock stage S3 and is also highly weathered. Figure 3 shows the relationship between Dhajala-normalized TL sensitivity and olivine heterogeneity and pyroxene heterogeneity. It seems likely that this meteorite was once

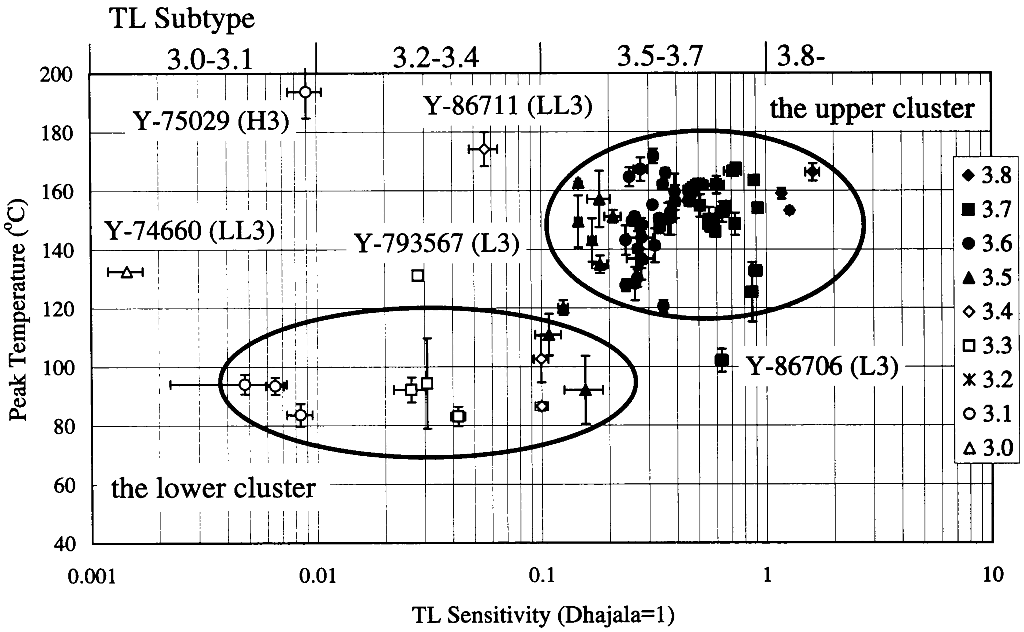

Fig. 2. Induced TL peak temperature vs. TL sensitivity of the type 3 ordinary chondrites from the Japanese Antarctic meteorite collection. Symbols express TL subtypes.

part of the upper cluster but had its TL sensitivity lowered by abnormally heavy weathering.

Y-86706 (L3) also plots outside the data clusters (Fig. 2), having a relatively low induced TL peak temperature and narrow peak width but a relatively high TL sensitivity. The matrix in Y-86706 is recrystallized. The TL data suggest that either this meteorite did not experience metamorphic temperatures $>750^\circ C$ (Guimon *et al.*, 1985) or it cooled at much slower rate than most ordinary chondrites. The latter cause is probable because plagioclase, which belongs to the low cluster, has a low temperature form (Sears, 1988).

Y-793567 (L3) plots outside the data clusters (Fig. 2), having a relatively high induced TL peak temperature and wide peak width but a relatively low TL sensitivity. Its matrix is fine and is of shock stage S3. These data suggest that this meteorite experienced metamorphic temperatures $>750^\circ C$ for short time and cooled at a much more rapid rate than most ordinary chondrites.

Y-790787 (L3) has a very low TL sensitivity, and was reported to be 3.0–3.1 of TL subtype (Ninagawa *et al.*, 1998). However, it was found to be shock melted in the classification system of Stöffler *et al.* (1991) from microscopic observation of thin section. The TL sensitivity of oligoclase decreased 25-fold after shock-loading to 45 GPa by maskelynization (Hartmetz *et al.*, 1986). Y-790787 also plots off the main trend in Fig. 3. Its recommended subtype is 3.8 from olivine heterogeneity.

Y-790448, Y-793596, Y-793565, Y-791324, Y-791558 (Ninagawa *et al.*, 1998) and Y-74660 have TL sensitivities corresponding to petrologic types less than or equal to 3.1. Petrographic studies of these meteorites have not been completed but these meteorites are the best candidates for histories involving minimal metamorphism.

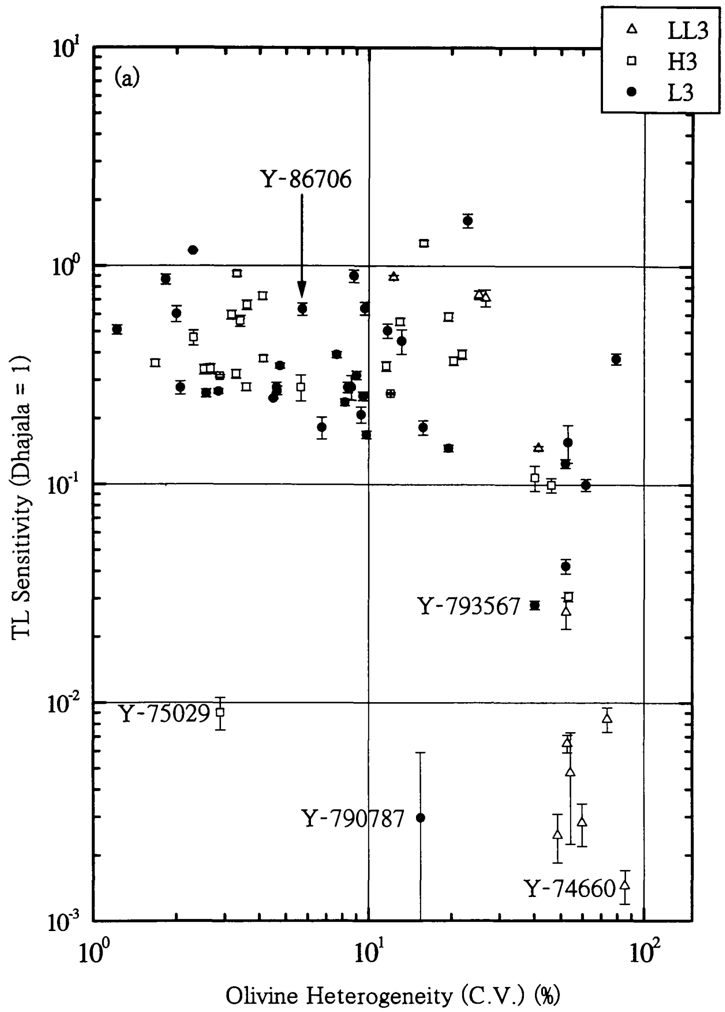

Fig. 3. Dhajala-normalized TL sensitivity vs. (a) olivine heterogeneity and (b) pyroxene heterogeneity of the type 3 ordinary chondrites from the Japanese Antarctic meteorite collection.

4. Summary

We have now measured the TL properties of additional thirty type 3 ordinary chondrites at the Okayama University of Science and determined their petrologic subtypes. Four meteorites (Y-74660, Y-86711, Y-74417 and Y-791856) in our new dataset exhibit very low TL sensitivities, comparable with unequilibrated ordinary chondrites of petrologic type $\leq$3.4. We have completed natural and induced TL measurements, bringing our data set to 73 samples. Most of the meteorites are of petrologic type 3.6–3.9, but fourteen (LL3: Y-790448, Y-82038, Y-793596, Y-793565, Y-791324, Y-791558, Y-74660, Y-86711, L3: Y-793408, Y-793567, ALH-77214, Y-74417, H3: Y-792947, Y-791856) are of petrologic type $\leq$3.4. Y-86706 (L3) has a TL sensitivity comparable with type 3.7 ordinary chondrites, but has lower induced TL peak temperature and peak width than other meteorites of this type, and we suggest this may reflect a metamorphic history of slow cooling. On the

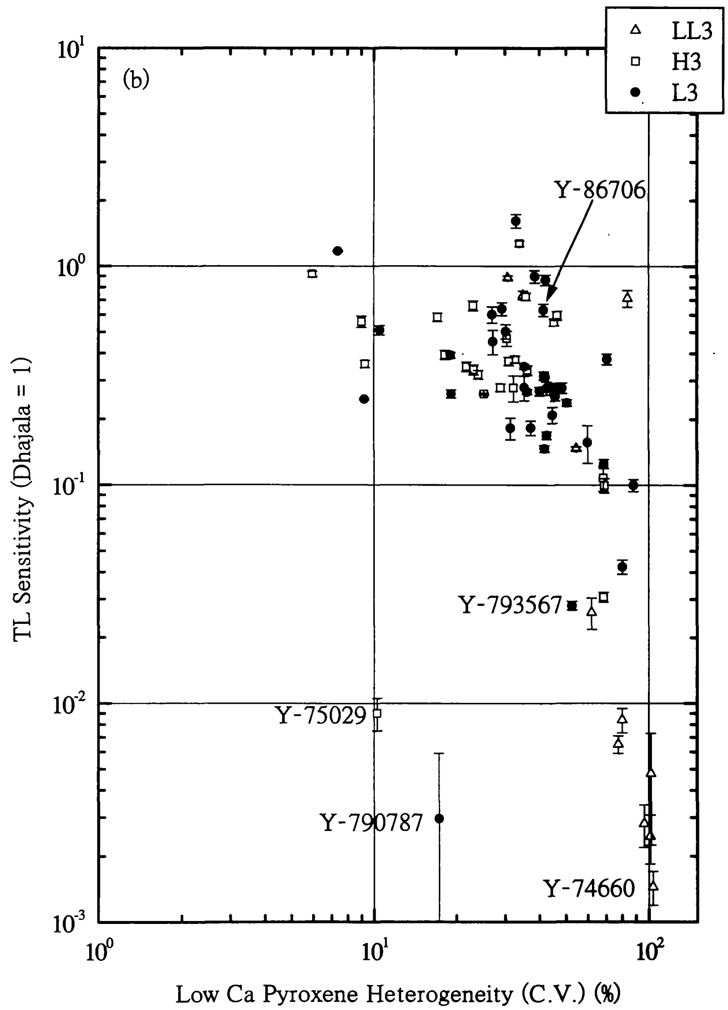

Fig. 3. (continued).

basis of our natural and induced TL data, it appears that our data set of 73 samples represents no more than 54 meteorite falls.

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