Antarct. Meteorite Res., **15**, 114–121, 2002

# Thermoluminescence studies of ordinary chondrites in the Japanese Antarctic meteorite collection, III: Asuka and Yamato type 3 ordinary chondrites

Kiyotaka Ninagawa[1], Masanori Ota[1], Naoya Imae[2] and Hideyasu Kojima[2]

[1]*Department of Applied Physics, Okayama University of Science, 1-1, Ridai-cho, Okayama 700-0005*
[2]*National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

***Abstract:*** We measured thermoluminescence (TL) properties of 37 Asuka and 13 Yamato type 3 ordinary chondrites from Japanese Antarctic meteorite collection for determining subtypes and pairing. Most of the meteorites are of petrologic type 3.6–3.9; however, we found three primitive ordinary chondrites (A-9043, A-87319 and Y-793384) of petrologic type ≦3.1.

We found 22 TL potential pairing groups in 26 Asuka H3 chondrites comprising a chain of pairing groups, which implies an H3 chondrite shower near the Asuka area.

## 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), CO chondrites (Sears *et al.*, 1991b), CV chondrites (Guimon *et al.*, 1995), and eucrites (Batchelor and Sears, 1991). Differing thermal histories of a subgroup of Antarctic and non-Antarctic H chondrites are apparent in 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 history of meteorites (Benoit *et al.*, 1991, 1992).

Induced and natural TL 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 73 type 3 ordinary chondrites have been measured; data were used for assignment of petrologic subtypes and pairing (Ninagawa *et al.*, 1998, 2000). We now report TL data for an additional 37 Asuka type 3 ordinary chondrites and 13 Yamato in the Japanese Antarctic meteorite collection measured at the Okayama University of Science.

## 2. Samples and TL measurements

Chips of 37 Asuka type 3 ordinary chondrites (LL3: 5, L3: 6, H3: 26) and 13 Yamato (LL3: 3, L3: 5, H3: 5) were obtained from the Japanese Antarctic meteorite collection for this study. They are almost new samples that have not been described in the Meteorite Newsletter of Japanese Collection of Antarctic Meteorites. Samples were treated for TL measurements as shown by Ninagawa *et al.* (2000) and their TLs were measured on conditions shown by Ninagawa *et al.* (2000).

## 3. Results and discussion

*3.1. New TL data*

Table 1 shows TL data for 37 Asuka type 3 ordinary chondrites from the Japanese Antarctic collection. Table 2 shows TL data for 13 Yamato type 3 ordinary chondrites. Five meteorites (A-9046, A-9043, A-87319, Y-793384, and Y-82007) have very low TL sensitivities equivalent to petrologic subtype ≦3.4. Some of these samples are discussed in greater detail below. Most of the samples are of petrologic subtype 3.6–3.9.

Figure 1 shows correlation between induced TL peak temperature and peak width for the Asuka samples. Induced TL peak temperatures and widths can be used to segregate meteorites into two distinct clusters which also indicate the degree of thermal 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); A-9046 (LL3) and A-9043 (L3) are plotted in the lower cluster. They have TL sensitivities corresponding to petrologic subtypes of 3.3–3.4 and 3.0–3.1, respectively. One other, Y-791656 (LL3), can also be plotted in the lower cluster.

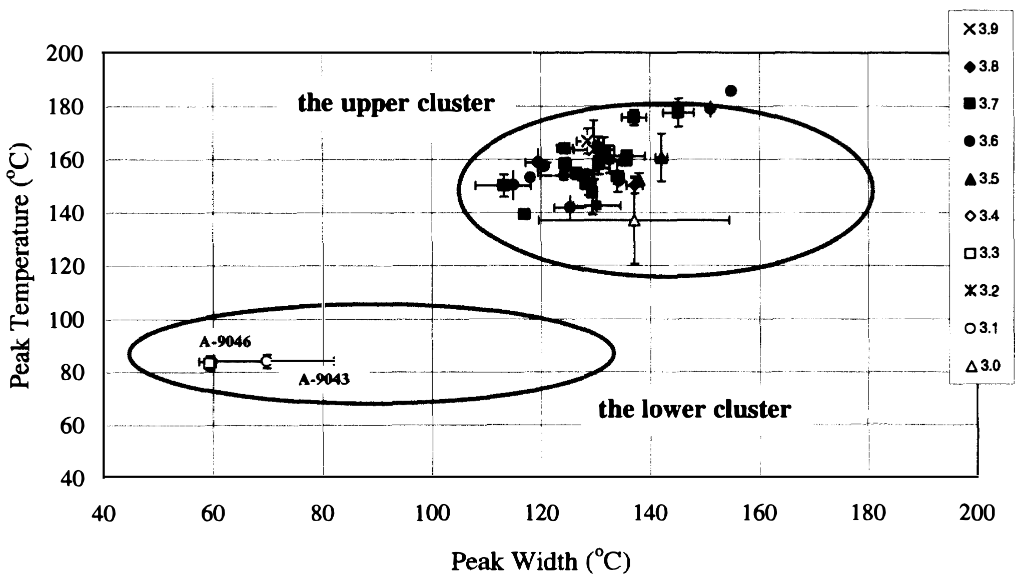


*Fig. 1. Induced TL peak temperature vs. peak width of Asuka type 3 ordinary chondrites from the Japanese Antarctic meteorite collection. Symbols express TL subtypes.*

*Table 1. Thermoluminescence data for 37 type 3 Asuka Japanese ordinary chondrites.*

| Meteorite | Class | Natural TL | | Induced TL | | | LT | Low | | Subtype | | | Pairing, Shock Stage, |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LT/HT | LT ($10^3$ counts) | TL Sensitivity (Dhajala=1) | Peak Temp. (℃) | Width (℃) | /TL Sens. ($x10^3$) | Ca-Py. (C.V.)† | Ol. (C.V.)‡ | Olivine | TL | Recommended | Weathering Degree & Comments |
| A-87225 | LL3 | 0.24 ± 0.00 | 6.62 ± 0.19 | 0.974 ± 0.124 | 139 ± 0 | 117 ± 1 | 6.8 ± 0.9 | 31% | 5% | 3.9 | 3.7-3.8 | | |
| A-880833 | LL3 | 2.20 ± 0.00 | 156.25 ± 22.51 | 2.020 ± 0.158 | 143 ± 1 | 130 ± 4 | 77.3 ± 12.7 | 16% | 5% | 3.9 | 3.8-3.9 | | A-88795 |
| A-880795 | LL3 | 2.52 ± 0.02 | 141.00 ± 0.76 | 1.501 ± 0.022 | 154 ± 2 | 128 ± 1 | 94.0 ± 1.5 | 9% | 5% | 3.9 | 3.8 | | |
| A-87250 | LL3 | 4.18 ± 0.11 | 60.34 ± 4.03 | 0.330 ± 0.030 | 142 ± 4 | 125 ± 3 | 183.1 ± 20.7 | 30% | 3% | | 3.6 | | |
| A-9046 | LL3 | 2.30 ± 0.09 | 0.97 ± 0.39 | 0.044 ± 0.006 | 83 ± 3 | 59 ± 1 | 22.3 ± 9.4 | 82% | 32% | 3.6 | 3.3-3.4 | | |
| A-880774 | L3 | 0.08 ± 0.00 | 1.86 ± 0.08 | 0.851 ± 0.033 | 177 ± 5 | 145 ± 3 | 2.2 ± 0.1 | 15% | 3% | | 3.7 | | |
| A-880820 | L3 | 0.82 ± 0.01 | 18.30 ± 0.51 | 0.593 ± 0.055 | 176 ± 3 | 137 ± 2 | 30.9 ± 3.0 | 19% | 2% | | 3.7 | | |
| A-880908 | L3 | 1.19 ± 0.06 | 10.74 ± 1.09 | 0.527 ± 0.054 | 162 ± 6 | 132 ± 0 | 20.4 ± 2.9 | 83% | 62% | ≦3.4 | 3.6-3.7 | | |
| A-880870 | L3 | 1.33 ± 0.00 | 9.86 ± 0.11 | 0.217 ± 0.012 | 161 ± 9 | 142 ± 1 | 45.5 ± 2.5 | 9% | 2% | | 3.5-3.6 | | |
| A-87319 | L3 | 1.78 ± 0.69 | 0.05 ± 0.02 | 0.002 ± 0.001 | 165 ± 16 | 137 ± 17 | 24.4 ± 14.4 | 87% | 74% | ≦3.4 | 3.0 | 3.0 | S1, Weathering B/C |
| A-9043 | L3 | 2.76 ± 0.00 | 0.12 ± 0.01 | 0.007 ± 0.001 | 84 ± 3 | 70 ± 12 | 17.6 ± 3.4 | 79% | 61% | ≦3.4 | 3.0-3.1 | 3.0-3.1 | S1-S2, Weathering A |
| A-880709 | H3 | 0.04 ± 0.01 | 0.17 ± 0.00 | 0.468 ± 0.020 | 161 ± 0 | 136 ± 3 | 0.4 ± 0.0 | 30% | 4% | | 3.6-3.7 | | |
| A-880710 | H3 | 0.06 ± 0.00 | 0.15 ± 0.01 | 0.204 ± 0.005 | 152 ± 2 | 138 ± 0 | 0.7 ± 0.1 | 31% | 6% | 3.9 | 3.5-3.6 | | |
| A-880901 | H3 | 0.16 ± 0.01 | 0.71 ± 0.07 | 0.418 ± 0.020 | 179 ± 3 | 151 ± 0 | 1.7 ± 0.2 | 14% | 2% | | 3.6-3.7 | | |
| A-87216 | H3 | 0.20 ± 0.01 | 1.39 ± 0.08 | 0.498 ± 0.043 | 147 ± 8 | 129 ± 0 | 2.8 ± 0.3 | 31% | 3% | | 3.6-3.7 | | |
| A-880676 | H3 | 0.63 ± 0.03 | 4.26 ± 0.36 | 0.413 ± 0.004 | 152 ± 2 | 134 ± 1 | 10.3 ± 0.9 | 34% | 22% | 3.7 | 3.6 | | A-880620 |
| A-880793 | H3 | 0.64 ± 0.00 | 3.66 ± 0.21 | 0.361 ± 0.023 | 186 ± 1 | 155 ± 1 | 10.1 ± 0.9 | 18% | 5% | 3.9 | 3.6 | | |
| A-880620 | H3 | 0.73 ± 0.01 | 7.77 ± 0.51 | 0.540 ± 0.014 | 161 ± 2 | 131 ± 1 | 14.4 ± 1.0 | 29% | 16% | 3.8 | 3.7 | | |
| A-880729 | H3 | 0.87 ± 0.03 | 22.52 ± 1.47 | 1.148 ± 0.013 | 160 ± 5 | 133 ± 1 | 19.6 ± 1.3 | 9% | 6% | 3.9 | 3.8 | | A-880746 |
| A-880746 | H3 | 0.88 ± 0.01 | 18.92 ± 0.51 | 0.933 ± 0.047 | 158 ± 4 | 131 ± 0 | 20.3 ± 1.2 | 13% | 5% | 3.9 | 3.7-3.8 | | |
| A-880711 | H3 | 1.14 ± 0.03 | 10.59 ± 0.27 | 0.507 ± 0.001 | 164 ± 4 | 131 ± 1 | 20.9 ± 0.5 | 13% | 3% | | 3.7 | | A-880613 |
| A-880613 | H3 | 1.28 ± 0.04 | 60.40 ± 1.39 | 2.216 ± 0.261 | 163 ± 11 | 130 ± 4 | 27.3 ± 3.3 | 29% | 10% | 3.9 | 3.8-3.9 | | A-880624 |
| A-880624 | H3 | 1.51 ± 0.03 | 31.11 ± 1.92 | 0.962 ± 0.072 | 153 ± 6 | 134 ± 1 | 32.3 ± 3.1 | 25% | 24% | 3.7 | 3.7-3.8 | | A-880724, 684, 840 |
| A-880724 | H3 | 1.68 ± 0.00 | 47.39 ± 2.38 | 1.192 ± 0.018 | 150 ± 3 | 137 ± 1 | 39.7 ± 2.1 | 13% | 20% | 3.8 | 3.8 | | A-880684, 840, 641 |
| A-880684 | H3 | 1.68 ± 0.06 | 103.40 ± 5.65 | 2.229 ± 0.165 | 167 ± 5 | 129 ± 2 | 46.4 ± 4.3 | 13% | 11% | 3.8 | 3.8-3.9 | | A-880840, 788, 641 |
| A-880840 | H3 | 1.74 ± 0.06 | 22.97 ± 1.66 | 0.704 ± 0.006 | 154 ± 2 | 128 ± 1 | 32.6 ± 2.4 | 11% | 5% | 3.9 | 3.7 | | A-880788, 863 |
| A-880788 | H3 | 1.90 ± 0.00 | 51.71 ± 1.02 | 1.262 ± 0.145 | 154 ± 1 | 124 ± 4 | 41.0 ± 4.8 | 14% | 3% | | 3.8 | | A-880641 |
| A-880641 | H3 | 1.94 ± 0.00 | 40.72 ± 3.14 | 0.773 ± 0.090 | 159 ± 1 | 136 ± 1 | 52.7 ± 7.4 | 23% | 6% | 3.9 | 3.7 | | A-880863 |
| A-880863 | H3 | 2.05 ± 0.06 | 21.56 ± 0.49 | 0.470 ± 0.007 | 150 ± 4 | 129 ± 1 | 45.9 ± 1.2 | 24% | 6% | 3.9 | 3.7 | | |
| A-882004* | H3 | 2.06 ± 0.01 | 36.37 ± 0.87 | 0.558 ± 0.032 | 150 ± 4 | 113 ± 5 | 65.2 ± 4.1 | 9% | 3% | | 3.7 | | |
| A-87274 | H3 | 2.73 ± 0.05 | 26.23 ± 3.28 | 0.321 ± 0.036 | 153 ± 0 | 118 ± 0 | 81.7 ± 13.7 | 27% | 7% | 3.9 | 3.6 | | A-87286 |
| A-87286 | H3 | 3.21 ± 0.01 | 17.15 ± 0.51 | 0.234 ± 0.007 | 159 ± 5 | 119 ± 2 | 73.3 ± 3.2 | 22% | 20% | 3.8 | 3.6 | | A-880869 |
| A-880869 | H3 | 3.57 ± 0.01 | 77.42 ± 5.28 | 0.941 ± 0.091 | 155 ± 2 | 127 ± 0 | 82.3 ± 9.8 | 18% | 4% | | 3.7-3.8 | | |
| A-9007* | H3 | 4.75 ± 0.09 | 63.72 ± 1.14 | 0.367 ± 0.016 | 150 ± 5 | 115 ± 1 | 173.5 ± 8.4 | 31% | 20% | 3.8 | 3.6 | | |
| A-87278 | H3 | 5.72 ± 0.04 | 80.67 ± 9.92 | 0.551 ± 0.067 | 164 ± 1 | 124 ± 1 | 146.4 ± 25.3 | 19% | 12% | 3.8 | 3.6-3.7 | | A-87283, 277 |
| A-87283 | H3 | 5.76 ± 0.13 | 54.27 ± 0.67 | 0.297 ± 0.022 | 157 ± 1 | 121 ± 0 | 183.0 ± 13.8 | 18% | 19% | 3.8 | 3.6 | | A-87277 |
| A-87277 | H3 | 6.41 ± 0.16 | 97.84 ± 1.49 | 0.579 ± 0.031 | 158 ± 2 | 124 ± 1 | 169.0 ± 9.3 | 14% | 22% | 3.7 | 3.7 | 3.7 | |

*These samples have been already reported in Ninagawa et al. 2000.

†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. Thermoluminescence data for 13 type 3 Yamato Japanese ordinary chondrites.*

| Meteorite | Class | Natural TL | | Induced TL | | | LT | Low | | Subtype | | | Pairing, Shock Stage, |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | LT/HT | LT | TL Sensitivity | Peak Temp. | Width | /TL Sens. | Ca-Py. | Ol. | | | Recom- | Weathering Degree & |
| | | | ($10^3$ counts) | (Dhajala=1) | (℃) | (℃) | ($x10^3$) | (C.V.)† | (C.V.)‡ | Olivine | TL | mended | Comments |
| Y-82007 | LL3 | 6.03 ± 0.05 | 6.91 ± 0.36 | 0.040 ± 0.011 | 169 ± 4 | 148 ± 1 | 173.3 ± 46.9 | 72% | 52% | ≦3.4 | 3.2-3.4 | 3.2-3.4 | Y-82195 |
| Y-791656 | LL3 | | 0.73 ± 0.09 | 0.182 ± 0.004 | 85 ± 2 | 53 ± 0 | 4.0 ± 0.5 | 84% | 49% | 3.5 | 3.5 | 3.5 | S2, Weathering B/C |
| Y-793384 | LL3 | | | 0.002 ± 0.001 | 195 ± 6 | | | 87% | 52% | ≦3.4 | 3.0 | 3.0 | S1-S2, Weathering B/C |
| Y-8340 | L3 | 0.04 ± 0.00 | 0.42 ± 0.02 | 0.673 ± 0.183 | 156 ± 7 | 141 ± 2 | 0.6 ± 0.2 | 12% | 2% | | 3.6-3.8 | | |
| Y-74024 | L3 | 1.17 ± 0.05 | 43.38 ± 0.48 | 0.639 ± 0.103 | 164 ± 6 | 156 ± 2 | 67.9 ± 11.0 | 55% | 26% | 3.7 | 3.6-3.7 | 3.7 | |
| Y-8411 | L3 | 2 89 ± 0 07 | 37 74 ± 2 61 | 0 257 ± 0 003 | 157 ± 10 | 146 ± 1 | 146 7 ± 10.3 | 83% | 59% | ≦3.4 | 3.6 | | |
| Y-86712 | L3 | 7.97 ± 0.03 | 58.72 ± 2.48 | 0.158 ± 0.001 | 147 ± 17 | 148 ± 1 | 371.2 ± 16.0 | 36% | 10% | 3.9 | 3.5 | | Y-82059, 055, 095 |
| Y-82059 | L3 | 8.21 ± 0.35 | 51.24 ± 4.36 | 0.189 ± 0.028 | 150 ± 18 | 141 ± 2 | 271.8 ± 46.1 | 44% | 11% | 3.8 | 3.5-3.6 | | Y-82095 |
| Y-793275 | H3 | 0.08 ± 0.01 | 4.58 ± 1.20 | 0.937 ± 0.085 | 155 ± 2 | 138 ± 1 | 4.9 ± 1.4 | 4% | 2% | | 3.7-3.8 | | |
| Y-794007 | H3 | 0 76 ± 0 01 | 14 48 ± 0.77 | 0 435 ± 0 060 | 129 ± 0 | 144 ± 1 | 33.3 ± 5.0 | 32% | 3% | | 3.6-3.7 | | |
| Y-793574 | H3 | 1.05 ± 0.16 | 4.30 ± 0.12 | 0.130 ± 0.010 | 137 ± 4 | 134 ± 1 | 33.0 ± 2.6 | 39% | 40% | 3.6 | 3.5 | | Y-794009<br>Y-790443 (>20km: not paired) |
| Y-8454 | H3 | 2.22 ± 0.50 | 0.14 ± 0.01 | 0.134 ± 0.012 | 189 ± 2 | 150 ± 1 | 1.0 ± 0.1 | 10% | 2% | | 3.5 | | S1 |
| Y-790460 | H3 | 3.47 ± 0.05 | 21.68 ± 0.36 | 0.185 ± 0.009 | 132 ± 3 | 132 ± 1 | 117.1 ± 5.9 | 49% | 25% | 3.7 | 3.5 | | |

†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.

### *3.2. Pairing for all type 3 ordinary chondrites*

The following criteria for potentially paired meteorites are used: 1) average natural TL peak height ratio, LT/HT, of one meteorite should agree with that of another meteorite within a factor from 1.0 to 1.2; 2) ratios of raw natural TL signal to induced TL signal (=LT intensity/TL sensitivity) should agree within a factor from 1.0 to 1.5; 3) coincidences of TL peak temperatures and peak widths should be within 20°C and within 10°C, respectively. These criteria are based on observed heterogeneity with modern falls and petrographically paired finds (*e.g.*, Sears *et al.*, 1991a; Benoit and Chen, 1996; Ninagawa *et al.*, 1998). Pairing criteria were applied to the new data set and data for previously analyzed samples (Ninagawa *et al.*, 1998, 2000). We found 22 TL potential pairing groups in 26 Asuka H3 chondrites (Table 1). They comprise a chain of pairing groups, implying an H3 chondrite showered near the Asuka area. However, there are no detailed geographical expedition notes in Asuka samples. We were unable to estimate pairing under geographical consideration for Asuka samples. We also found one TL potential pairing group in Asuka LL3 (Table 1) and new six TL potential pairing groups in Yamato type 3 chondrites (Table 2). Both Y-793574 and Y-790443 satisfied TL criteria. However, they are probably not paired because their recovery positions were separated by over 20 km.

### *3.3. Primitive ordinary chondrites*

Figure 2 compares TL sensitivity and induced TL peak temperature for Asuka samples. Clusters noted in induced TL peak temperature and width plot (Fig. 1) are also apparent in Fig. 2. While A-87319 (L3) is plotted outside these clusters, both Y-793384 (LL3) and Y-82007 (LL3) can also be plotted outside these clusters.

Both A-87319 (L3) and Y-793384 (LL3) have TL sensitivities corresponding to petrologic type 3.0. Petrographic observations indicate that they exhibit features of shock stage S1-S2 in classification system of Stöffler *et al.* (1991). Their chondrules are also rounded, not flat. This is further evidence of very weak shock. Most unequilibrated meteorites such as Bishunpur, Krymka, and Semarkona do not follow the trends of two clusters possibly because the dominant TL phosphor is not crystalline plagioclase (Sears *et al.*, 1982). They, like Bishunpur, Krymka, and Semarkona, also do not follow trends of two clusters. There is a trace of hot accretion of chondrules in A-87319. Some chondrules contact with another one without orientation and have a common area on their boundary. This suggests that chondrules in hot conditions accreted in a slight compaction. This textural feature is different from that of compound chondrules (Wasson *et al.*, 1995). Figure 3 compares Dhajala-normalized TL sensitivity with olivine and pyroxene heterogeneity and they resemble similar plots in earlier studies.

This study found that A-87319 (L3), Y-793384 (LL3) and A-9043 (L3) are primitive ordinary chondrites which have low TL sensitivities corresponding to petrologic types less than or equal to 3.1, just as Y-790448, Y-793596, Y-793565, Y-791324, Y-791558 (Ninagawa *et al.*, 1998), and Y-74660 (Ninagawa *et al.*, 2000). Petrographic studies of these meteorites are not completed, but these meteorites are the best candidates for histories involving minimal metamorphism.

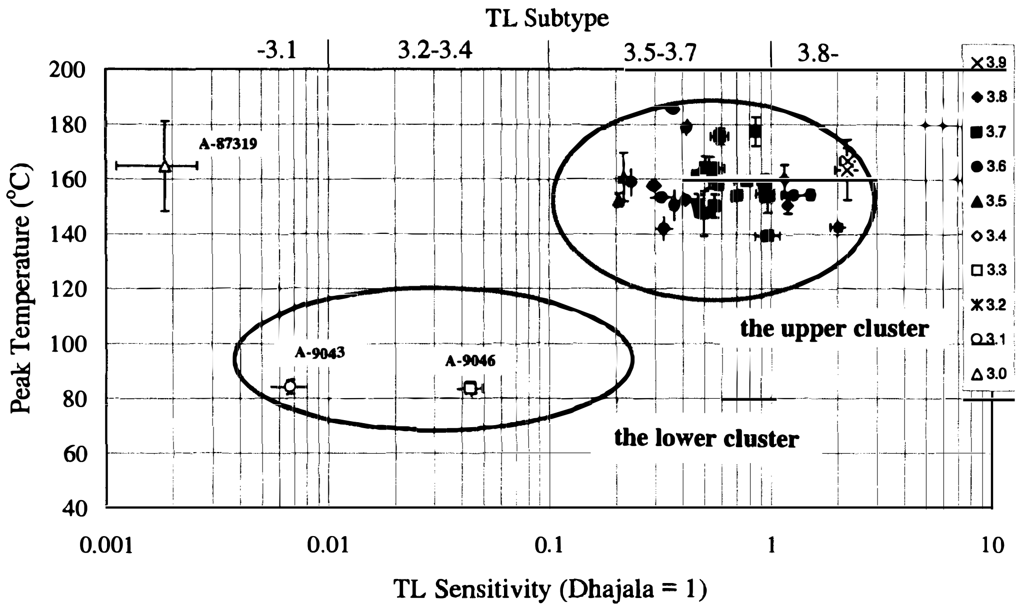


*Fig. 2. Induced TL peak temperature vs. TL sensitivity of Asuka type 3 ordinary chondrites from the Japanese Antarctic meteorite collection. Symbols express TL subtypes.*

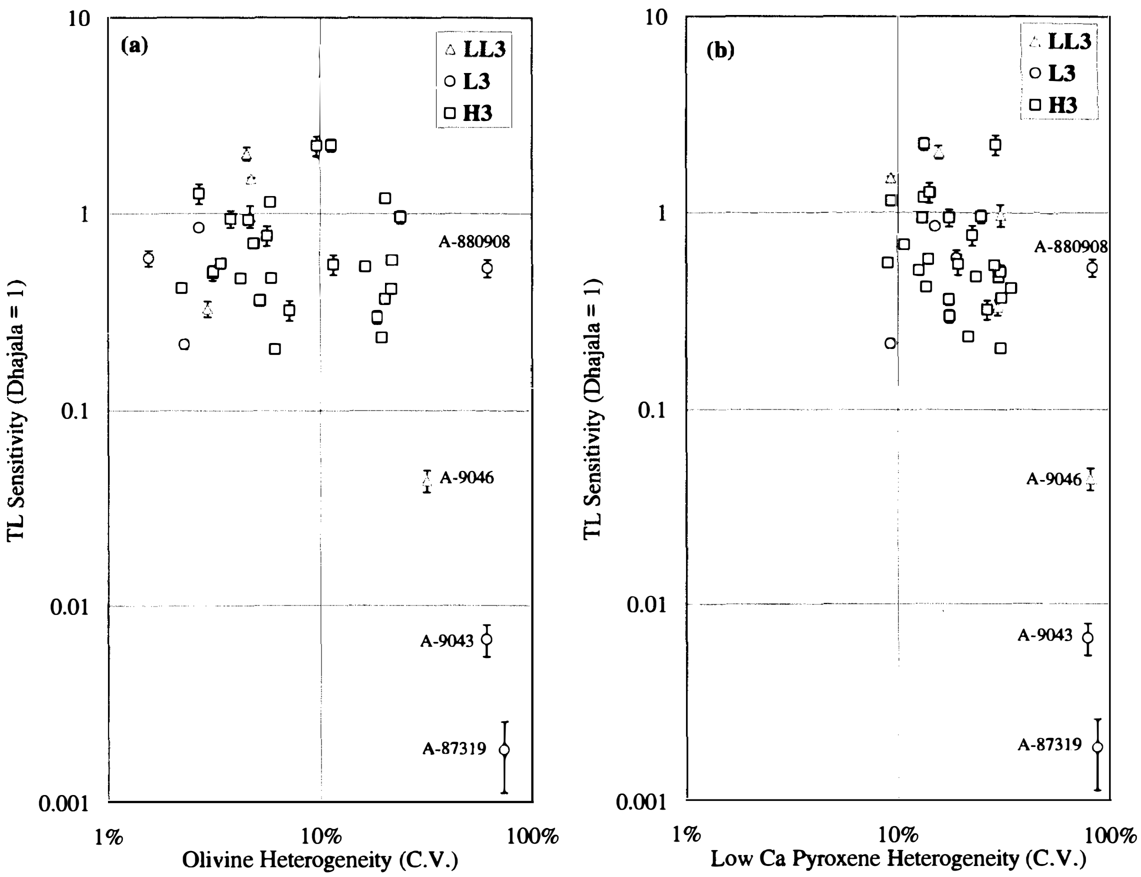


*Fig. 3. Dhajala-normalized TL sensitivity vs. (a) olivine heterogeneity and (b) pyroxene heterogeneity of Asuka type 3 ordinary chondrites.*

## 4. Summary

We measured TL properties of an additional 37 Asuka and 13 Yamato type 3 ordinary chondrites at the Okayama University of Science and determined their petrologic subtypes. Three meteorites (A-9043, A-87319 and Y-793384) in our new dataset exhibit very low TL sensitivities, comparable with unequilibrated ordinary chondrites of petrologic type ≦3.1. We completed induced and natural TL measurements, bringing our data set to 121 samples. Most meteorites studied in this work are of petrologic type 3.6–3.9.

We found 22 TL potential pairing groups in 26 Asuka H3 chondrites. They comprise a chain of pairing groups implying an H3 chondrite shower near the Asuka area.

## Acknowledgments

The authors are indebted to the National Institute Polar Research for meteorite samples. The authors would like to thank Prof. H. Hase, the Research Reactor Institute, Kyoto University, for kindly helping with $^{60}$Co $\gamma$-ray irradiation. This work was carried out in part under the Visiting Researcher's Program of the Research Reactor Institute, Kyoto University. We thank Prof. D. W. G. Sears and Prof. N. Takaoka for their helpful reviews of the manuscript.

### References

Batchelor, J.D. and Sears, D.W.G. (1991): Metamorphism of eucrite meteorites studied quantitatively using induced thermoluminescence. Nature, **349**, 516–519.

Benoit, P.H. and Chen, Y. (1996): Galactic cosmic-ray-produced thermoluminescence profiles in meteorites, lunar samples and a terrestrial analog. Radiat. Meas., **26**, 281–289.

Benoit, P.H. and Sears, D.W.G. (1992): The breakup of a meteorite parent body and the delivery of meteorites to earth. Science, **255**, 1685–1687.

Benoit, P.H., Sears, D.W.G. and McKeever, S.W.S (1991): The natural thermoluminescence of meteorites: II. Meteorite orbits and orbital evolution. Icarus, **94**, 311–325.

Benoit, P.H., Sears, H. and Sears, D.W.G. (1992): The natural thermoluminescence of meteorites: 4. Ordinary chondrites at the Lewis Cliff Ice Field. J. Geophys. Res., **97**, 4629–4648.

Guimon, R.K., Syems, S.J.K., Sears, D.W.G., and Benoit, P.H. (1995): Chemical and physical studies of type 3 chondrites, XII: The metamorphic history of CV chondrites and their components. Meteoritics, **30**, 704–714.

McKeever, S.W.S (1985): Thermoluminescence of Solids. Cambridge, Cambridge University Press, 376 p.

Ninagawa, K., Hoshikawa, Y., Kojima, H., Matsunami, S., Benoit, P.H. and Sears, D.W.G. (1998): Thermoluminescence of Japanese Antarctic chondrite collection. Antarct. Meteorite Res., **11**, 1–17.

Ninagawa, K., Soyama, K., Ota, M., Toyoda, S., Imae, N., Kojima, H., Benoit, P.H. and Sears, D.W.G. (2000): Thermoluminescence studies of ordinary chondrites in the Japanese Antarctic meteorite collection, II: New measurements for thirty type 3 ordinary chondrites. Antarct. Meteorite Res., **13**, 112–120.

Sears, D.W.G. (1988): Thermoluminescence of meteorites: Shedding light on the cosmos. Nucl. Tracks Radiat. Meas., **14**, 5–17.

Sears, D.W.G., Grossman, J.N., Melcher, C.L., Ross, L.M. and Mill, A.A. (1980): Measuring metamorphic history of unequilibrated ordinary chondrites. Nature, **287**, 791–795.

Sears, D.W.G., Grossman, J.N. and Melcher, C.L. (1982): Chemical and physical studies of type 3 chondrites-I: Metamorphism related studies of Antarctic and other type 3 ordinary chondrites. Geochim. Cosmochim. Acta, **46**, 2471–2481.

Sears, D.W.G., Hasan, F.A., Batchelor, J.D. and Lu, J. (1991a): Chemical and physical studies of type 3 chondrites-XI: Metamorphism, pairing and brecciation of type 3 ordinary chondrites. Proc. Lunar Planet. Sci., **21**, 493–512.

Sears, D.W.G., Batchelor, J.D., Lu, J. and Keck, B.D. (1991b): Metamorphism of CO and CO-like chondrites and comparisons with type 3 ordinary chondrites. Proc. NIPR Symp. Antarct. Meteorites, **4**, 319–343.

Sears, D.W.G., Benoit, P.H. and Batchelor, J.D. (1991c): Evidence for differences in the thermal histories of Antarctic and non-Antarctic H chondrites with cosmic-ray exposure ages <20 Ma. Geochim. Cosmochim. Acta, **55**, 1193–1197.

Stöffler, D., Keil, K. and Scott, E.R.D. (1991): Shock metamorphism of ordinary chondrites. Geochim. Cosmochim. Acta, **55**, 3845–3867.

Wasson, J.T., Krot, A.N., Lee, M.S. and Rubin, A.E. (1995): Compound chondrules. Geochim. Cosmochim. Acta, **59**, 1847–1869.

*(Received September 6, 2001; Revised manuscript accepted December 25, 2001)*