

## Thermoluminescence and the shock and reheating history of meteorites: IV. The induced TL properties of type 4–6 ordinary chondrites

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**Abstract**—The induced thermoluminescence (TL) properties of 121 equilibrated ordinary chondrites have been measured. The samples were 74 H and 47 L chondrites, of which 33 H and 32 L were from Antarctica. The distribution of TL sensitivities for non-Antarctic L chondrites differs from that of non-Antarctic H chondrites, consistent with a greater proportion of the former class suffering post-metamorphic shock. Data on the effect of laboratory annealing on TL sensitivity, and step-wise Ar release measurements, enable the meteorites to be sorted into three shock-related temperature groups (<800°C, 800–1000°C, >1000°C). The distribution of TL sensitivities for Antarctic meteorites suggests that only a few of the present samples have suffered intense shock. Antarctic H chondrites have TL sensitivities typically one third those of non-Antarctic H chondrites; this may reflect a greater proportion of meteorites which have suffered mild shock levels or greater degrees of weathering. On a diagram of TL peak temperature against peak width, L chondrites produce tight clusters with minimal overlap between Antarctic and non-Antarctic meteorites. Antarctic H chondrites also produce a tight cluster, but non-Antarctic chondrites plot in a band in which peak temperature increases with peak width, and there is little or no overlap between the Antarctic and non-Antarctic meteorites. Because TL peak temperature and width reflect the thermal history of the feldspar, and changes in these TL parameters can be produced by laboratory annealing experiments, this implies significant differences in the thermal (probably metamorphic) history of the Antarctic and non-Antarctic ordinary chondrites.

### INTRODUCTION

CHONDRITIC METEORITES have experienced a series of events which have affected individual specimens to varying degrees. All chondrites were formed by aggregation in the primordial solar nebula (or primitive accretion disk) of components which themselves have experienced a variety of complex histories. Most suffered long-term static metamorphism and brecciation, although a few experienced regolith processing. Some chondrites, perhaps a third of the L class but a smaller proportion of the other classes, suffered dynamic metamorphism due to violent shock. All of these processes except aggregation are secondary, presumably having taken place predominantly on the meteorite parent bodies.

The induced thermoluminescence (TL) properties of ordinary chondrites are governed primarily by the amount and structural state of feldspar. Feldspar is particularly sensitive to thermal processes, being produced from primary glass during metamorphism of unequilibrated chondrites (GUIMON *et al.*, 1986) and destroyed during intense shock-related heating of equilibrated chondrites (SEARS *et al.*, 1984a; HARTMETZ *et al.*, 1986). Feldspar also undergoes temperature-dependent phase transformations which, probably indirectly, affect TL (GUIMON *et al.*, 1985). The induced TL properties of chondrites therefore provide a unique means of studying secondary processes in chondrites.

LIENER and GEISS (1968) and KOMOVSKY (1961) observed a relationship between TL sensitivity and K-Ar age, which the former interpreted in terms of the solid state processes involved in the TL mechanism. SEARS (1980) confirmed the relationship and suggested that it reflected the destruction of feldspar by shock processes. Annealing experiments (SEARS *et al.*, 1984b), TL, metallographic, optical and TEM studies of artificially shock-loaded Kernouvé meteorite (SEARS *et al.*, 1984a) and measurements on artificially shock-loaded ter-

restrial feldspar (HARTMETZ *et al.*, 1986) have confirmed that explanation.

Other previous work on shock and chondritic meteorites has focused on describing the effects of shock on meteorite structures and minerals, determination of peak shock pressures, post-shock temperatures, post-shock cooling rates, and the timing of shock events.  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  studies were made by BOGARD *et al.* (1976) and TURNER *et al.* (1978). Volatile and readily mobilized elements were discussed by WALSH and LIPSCHUTZ (1982) and HUSTON and LIPSCHUTZ (1984). Petrographic studies of metal, phosphide and sulfide have been reported by HEYMANN (1967), WOOD (1967), TAYLOR and HEYMANN (1969, 1970, 1971) and SMITH and GOLDSTEIN (1977). CARTER *et al.* (1968) and HEYMANN (1967) looked at shock effects in olivine, and shock-produced glassy veins have been described by FREDRIKSSON *et al.* (1963) and CARTER *et al.* (1968). BINNS *et al.* (1969), PRICE *et al.* (1979), and PUTNIS and PRICE (1979) found several high-pressure minerals in the veins. Such work has implications for the number of meteorite parent bodies, their fragmentation history, and the size of the meteorites after the shock.

DODD and JAROSEWICH (1979) described melt pockets in heavily shocked chondrites and proposed a shock classification scheme, now widely used, which encompasses much of the above data. This scheme is summarized in Table 1, which also includes our estimates for shock-related changes in TL and highly volatile elements. It should be stressed that most of the parameters in the Dodd and Jarosewich scheme reflect the thermal history (*i.e.* peak temperature and subsequent cooling rate) rather than shock pressure. The pressure estimates are, at best, rough guesses. In principle, laboratory shock experiments should enable a more quantitative version of Table 1 to be developed, notwithstanding the problems associated with uncertainties in chondritic cooling rates and the fact that most laboratory data are for pure minerals rather

**Table 1.** Definition and properties of 6 shock-heating facies in ordinary chondrites (after Dodd and Jarosewich, 1979).\*

| Shock-heating facies | Pressure (GPa) | Olivine†                                    | Plagioclase†                 | Melt pockets† | <sup>40</sup> Ar@ | TL Sensitivity** | Trace Elements‡ |
|----------------------|----------------|---|------------------------------|---------------|-------------------|------------------|-----------------|
| a                    | <5             | fractured                                   | <50% deformed                | None          | >2000             | normal           | normal          |
| b                    | 5-20           | fractured & undulose extinction             | <50% deformed                | None          | >2000             | normal           | normal          |
| c                    | 20-22          | fractured & undulose extinction             | >50% deformed                | None          | >2000             | 0.15-0.4         | Bi, Ag, Zn <0.8 |
| d                    | 22-35          | fractured & mosaic extinction               | 100% deformed or maskelynite | None          | <2000             | 0.0025-0.15      | In, Tl, Cd <0.5 |
| e                    | 35-57          | fractured, mosaicked & marginal granulation | >50% maskelynite             | Present       | <2000             | 0.0025-0.15      | Bi, Ag, Zn <0.5 |
| f                    | >57            | recrystallized                              | 100% maskelynite             | Present       | <2000             | 0.0025-0.15      | In, Tl, Cd <0.1 |

\* The criteria above generally reflect the thermal history of the samples (i.e. maximum temperatures and cooling rates) immediately following the shock event, rather than the pressure of the shock. The quoted pressures, which, at best, are only rough estimates assume that shock temperature and pressure are related, and that chondrites have broadly similar post shock cooling histories.

† Dodd and Jarosewich (1979).

@ Our estimates based on Fig. 4b. Units are 10<sup>-8</sup> cc STP/g.

‡ Our estimates based on data published by Dennison and Lipschutz (1986).

\*\* Our estimates based on Figs. 1 and 2. Units are Kernouve = 1.

than chondrites. The shock classification scheme, like the VAN SCHMUS and WOOD (1967) scheme for metamorphism, is essentially empirical and its value lies in its success as an aid to interpretation.

It is clear that the H and L chondrites have suffered significantly different shock histories. Perhaps one-third of the L chondrites were involved in a major shock event 500 Ma ago (HEYMANN 1967), and many are of shock facies d-f (DODD and JAROSEWICH, 1979). In contrast, H chondrites have not in general experienced intense shock, and shock facies d-f are very rare (LINGNER *et al.* 1986). Nevertheless, H chondrites did experience a number of events which caused loss of <sup>40</sup>Ar (BOGARD *et al.*, 1976) and highly volatile trace elements (DENNISON and LIPSCHUTZ, 1986).

The present study was undertaken to see if TL data could enhance our understanding of the shock-related thermal histories of the H and L classes, in a quantitative way if possible. We also wanted to see if meteorites collected in Antarctica had the same thermal histories as non-Antarctic meteorites. There are compositional and isotopic differences between Antarctic meteorites and those collected elsewhere, and there are also compositional differences between meteorites from different sites in Antarctica (MCGARVIE *et al.*, 1986; DENNISON *et al.*, 1986; LINGNER *et al.*, 1986). Furthermore, the distributions of terrestrial ages for meteorites from the Yamato Hills and Allan Hills are different (NISHIZUMI, 1986). Compositional distinctions between Antarctic and non-Antarctic meteorites, mainly for Cd and In, could be due to the leaching of trace elements by weathering (CASHORE *et al.*,

1988). However, the implications of secular variations in the properties of meteorites falling to earth are sufficiently important that the matter deserves thorough study by independent techniques. If differences in thermal history are involved, then there may well be differences in the TL properties of Antarctic and non-Antarctic chondrites.

For the present study, we measured the TL properties of 121 H and L, Antarctic and non-Antarctic chondrites. The data reflect the well-known differences in shock history between H and L classes and, when considered with literature data, afford a new guide to temperatures associated with the shock processes. The data also show differences between Antarctic and non-Antarctic chondrites which must reflect non-trivial differences in thermal history.

## EXPERIMENTAL

**Samples.** Details of the samples and their TL data are listed in Table 2 (non-Antarctic samples) and Table 3 (Antarctic samples). The non-Antarctic H chondrites were provided by M. E. Lipschutz, and are chips from the samples studied by LINGNER *et al.* (1986). The Antarctic meteorites are those used in the studies of DENNISON *et al.* (1986) and DENNISON and LIPSCHUTZ (1986). These were chosen, on the basis of cosmogenic isotopes, to avoid paired meteorites. DENNISON and LIPSCHUTZ (1986) also reported Dodd's shock assignments for 6 of the present Antarctic H chondrites: ALHA76008, b; ALHA77262, a; ALHA78076, a; ALHA78108, c-d; ALHA79406, b-c; RKPA80230, c. The present Antarctic meteorites also include 30 samples chosen on the basis of <sup>26</sup>Al content by L. Rancitelli and provided by the MWG for a study of the natural TL levels in equilibrated ordinary chondrites of known Al-26 content (HASAN *et al.*, 1986).

Table 2. Thermoluminescence data\*\* and other details for the non-Antarctic chondrites used in the present study.

| Meteorite*           | Source and Catalog No.† | Class | Shock Facies‡ | <sup>40</sup> Ar/Ar§ | TL Sensitivity (Kernouve = 1) | Peak Temp (°C) | FWHM†† (°C) |
|----------------------|-------------------------|-------|---------------|----------------------|-------------------------------|----------------|-------------|
| Barratta             | BM1929,1284             | L4    | d             | 340                  | 0.046±0.005                   | 179±2          | 168±2       |
| Barwell              | BM1966,57               | L5    |               | 5140                 | 1.6±0.1                       | 180±3          | 145±2       |
| Bruderheim           | BM                      | L6    | c             | 1251                 | 1.1±0.1                       | 183±4          | 153±2       |
| Crumlin              | BM86115                 | L5    | c             |                      | 0.4±0.05                      | 185±2          | 148±6       |
| Farmington           | BM67016                 | L5    | e             | 341                  | 0.10±0.01                     | 191±7          | 149±3       |
| Holbrook             | BM1912,653              | L6    | c             | 6660                 | 0.33±0.03                     | 182±3          | 146±3       |
| Karkh                | BM(MEL)1915,85          | L6    | e             | 460                  | 0.0010±0.0002                 | 176±2          | 127±3       |
| Ladder Creek         | BM1959,999              | L6    | b             | 5800                 | 0.26±0.03                     | 179±2          | 143±2       |
| Lubbock              | BM1959,887              | L5    | d-f           | 690                  | 0.0016±0.0002                 | 191±10         | 144±4       |
| McKinney             | HES                     | L4    | e             | 1285                 | 0.020±0.001                   | 199±3          | 153±2       |
| Tenham               | BM1935,792              | L6    |               |                      | 0.023±0.001                   | 179±2          | 174±4       |
| Tennasfilm           | BM1913,218              | L4    | a             | 6500                 | 0.64±0.06                     | 138±4          | 129±2       |
| Wickenburg(stone)    | BM1959,1023             | L5    | f             | 900                  | 0.24±0.11                     | 192±2          | 147±2       |
| Wold Cottage         | BM1073                  | L6    |               | 5660                 | 1.1±0.1                       | 172±2          | 148±2       |
| Zomba                | BM84357                 | L6    |               | 820                  | 0.41±0.03                     | 191±3          | 163±2       |
| Allegan              | FMNH500                 | H5    | a             | 5700                 | 0.85±0.08                     | 173±2          | 136±2       |
| Ambapur Nagla        | BM(MEL)81117            | H5    | b             | 2280                 | 0.51±0.04                     | 192±3          | 153±2       |
| Ankoher              | USNM3399                | H4    | a             | 7100                 | 0.36±0.10                     | 186±3          | 150±2       |
| Avanhandava          | MPH0029A                | H4    | b             | 5760                 | 0.15±0.01                     | 179±2          | 133±3       |
| Barbotan             | BM(MEL)18582            | H5    | c             | 5160                 | 0.39±0.04                     | 177±2          | 137±2       |
| Beardsley            | ASU 134ax               | H5    | b-c           | 6800                 | 0.82±0.08                     | 172±8          | 132±7       |
| Beddgelert           | MPIM 11-1               | H5    |               | 2020                 | 0.055±0.011                   | 215±17         | 184±3       |
| Bielokrymskische     | FMNH 1394               | H4    |               | 1430                 | 0.11±0.06                     | 196±2          | 157±4       |
| Bur-Gheluai          | USNM 778                | H5    | c-d           | 4685                 | 0.27±0.02                     | 183±5          | 141±5       |
| Butsura              | BM(MEL)3443             | H6    |               | 3443                 | 0.50±0.05                     | 172±9          | 126±6       |
| Charsonville         | ASU 538-1               | H6    | d             | 420                  | 0.062±0.004                   | 172±3          | 151±2       |
| Dokachi              | ASU 624-1               | H5    | b-c           | 5450                 | 0.14±0.01                     | 184±2          | 136±3       |
| Doroninsk            | ASU 1103                | H6    | a-b           | 368                  | 0.41±0.04                     | 192±10         | 163±8       |
| Ehale                | USNM 2142               | H5    |               | 5280                 | 1.23±0.11                     | 171±3          | 132±2       |
| Eichsdt              | ETH                     | H5    |               | 5240                 | 0.49±0.12                     | 188±2          | 148±2       |
| Forrest Vale         | USNM 1749               | H4    | a             | 6340                 | 0.63±0.06                     | 178±9          | 134±7       |
| Forrest City         | ASU 49t                 | H5    | d             | 5560                 | 0.14±0.01                     | 174±8          | 141±7       |
| Glasatovo            | BM(MEL)1956,323         | H4    |               | 3700                 | 0.24±0.03                     | 185±4          | 149±12      |
| Kernouve             | BM(MEL)43400            | H6    | b-c           | 4430                 | 0.90±0.03                     | 190±4          | 156±2       |
| "                    | "                       | "     | "             | "                    | 1.01±0.15                     | 181±2          | 153±2       |
| "                    | "                       | "     | "             | "                    | 0.98±0.14                     | 183±1          | 152±2       |
| "                    | "                       | "     | "             | "                    | 0.95±0.12                     | 186±3          | 145±14      |
| "                    | "                       | "     | "             | "                    | 1.19±0.10                     | 177±2          | 147±2       |
| "                    | "                       | "     | "             | "                    | 1.01±0.01                     | 180±2          | 146±2       |
| "                    | "                       | "     | "             | "                    | 0.97±0.05                     | 189±3          | 144±2       |
| "                    | "                       | "     | "             | "                    | 0.92±0.07                     | 183±3          | 146±2       |
| "                    | "                       | "     | "             | "                    | 0.86±0.08                     | 183±2          | 147±2       |
| Kesen                | ASU 362-1               | H4    | a             | 4495                 | 0.10±0.02                     | 184±5          | 127±2       |
| Kiffa                | USNM 5490               | H4    | a-b           | 5550                 | 0.63±0.09                     | 186±4          | 150±2       |
| Limerick             | BM(MEL)1955,115         | H5    | c             | 4070                 | 0.19±0.02                     | 175±2          | 127±2       |
| Malotas              | USNM 1440               | H5    | b-c           | 4891                 | 0.32±0.04                     | 173±2          | 131±3       |
| Menow                | BM(MEL)150928           | H4    | a             | 4424                 | 0.21±0.02                     | 196±4          | 160±5       |
| Meruz                | BM(MEL)1924,135         | H5    |               | 2990                 | 0.29±0.03                     | 175±8          | 139±7       |
| Miller (Arkansas)    | MPIH 0200 B             | H5    | a-b           | 6095                 | 0.72±0.06                     | 170±2          | 131±2       |
| Monroe               | ASU 274b                | H4    | b-c           | 1290                 | 0.09±0.02                     | 200±5          | 174±4       |
| Mount Browne         | BM(MEL)86644            | H6    | a             | 5767                 | 0.51±0.07                     | 169±3          | 138±2       |
| Ochansk              | BM(MEL)1922,158         | H4    | d             | 5919                 | 0.045±0.005                   | 182±8          | 126±2       |
| Oesede               | ETH                     | H5    |               | 5200                 | 0.89±0.09                     | 175±9          | 133±7       |
| Olmedilla de Alarcón | USNM 1472               | H5    | b-c           | 6050                 | 0.42±0.08                     | 196±5          | 152±2       |
| Queen's Marcy        | MPIH 0247A              | H6    | b-c           | 4150                 | 0.29±0.09                     | 215±2          | 184±3       |
| Richardton           | FMNH 1995               | H5    | a             | 5385                 | 0.34±0.10                     | 185±3          | 146±3       |
| St. Germain-du-Pinel | ETH                     | H6    | c             | 6100                 | 0.24±0.02                     | 175±8          | 133±7       |
| Sena                 | USNM 1473               | H4    | a             | 4997                 | 0.81±0.08                     | 174±8          | 133±7       |
| Sindri               | ASU 6251                | H5    |               | 5070                 | 0.44±0.08                     | 184±2          | 154±2       |
| Sijathali            | BM(MEL)51186            | H5    | c             | 4665                 | 0.29±0.02                     | 171±2          | 133±5       |
| Stalldalen           | ETH                     | H5    | c             | 650                  | 0.110±0.007                   | 200±4          | 163±2       |
| Timochin             | BM(MEL)373              | H5    | c             | 4140                 | 0.095±0.008                   | 173±2          | 136±2       |
| Zhovtnevyi           | MPIH 0311A              | H5    | c-d           | 5700                 | 0.348±0.03                    | 166±8          | 130±7       |

\* Finds in bold type.

§ References: Dodd and Jarosewich (1979) for L chondrites, Lingner *et al.* (1986) for H chondrites.

† ASU - Arizona State University via MEL (M.E. Lipschutz); BM - British Museum, London; BM(MEL) - British Museum, London, via M.E. Lipschutz; ETH - Eidgenössische Technische Hochschule, Zurich, via M.E. Lipschutz; FMNH - Field Museum of Natural History, via M.E. Lipschutz; HES - H.E. Suess and M. Herndon (University of California, San Diego); MPH - Max Planck Institute für Chemie, Mainz, via M.E. Lipschutz; NMV - Naturhistorisches Museum, Vienna, via M.E. Lipschutz; USNM - Smithsonian Institution, via M.E. Lipschutz.

§ Means for bulk meteorites from the compilation by Kruse and Schultz (1983). Units are 10<sup>-8</sup> cm<sup>3</sup> STP/g.

\*\* Uncertainties for the TL data are standard deviations of triplicate measurements.

†† Full width of the TL peak at half its maximum intensity.

**Pairing.** Because many of our observations concern the distributions of TL data, the presence of paired meteorites (individual stones from the same fall) could greatly influence our interpretations. We have therefore taken care to avoid paired meteorites. Several paired meteorites were accidentally included in our study, and others were included because they are rare examples of heavily shocked meteorites. Meteorites in the present study which may be paired according to literature data, and three meteorites with very similar and unusual

TL properties which we suggest are paired, are indicated in Table 3. For many of these samples, HASAN *et al.* (1986) report natural TL data which provide additional information on likely pairings. Natural TL and TL sensitivity data are consistent with pairing for ALHA77296 with ALHA77297, and for ALHA77004 with ALHA77191. For ALHA78112 and ALHA78114 the factor of 2 difference in both TL sensitivity and natural TL makes pairing seem unlikely, consistent with reservations expressed by NISHIZUMI *et al.* (1983) on the basis

Table 3. TL data for Antarctic chondrites.\*

| Meteorite <sup>a</sup> | Class | Weather-<br>Cat. <sup>b</sup> | Feld <sup>c</sup> | TL Sensitivity<br>(Kernouve-1) | Peak Temp<br>(°C) | Range <sup>d</sup><br>(°C) | Ref. to<br>pairing <sup>e</sup> |
|------------------------|-------|-------------------------------|-------------------|--------------------------------|-------------------|----------------------------|---------------------------------|
| ALHA 76008,21          | H5    | B                             | --(f)             | 0.16±0.02                      | 180±2             | 140±2                      |                                 |
| ALHA 77004,18          | H4    | C                             | --(a)             | 0.048±0.008                    | 186±2             | 141±4                      | g                               |
| ALHA 77004,19          | H4    | C                             | --(a)             | 0.046±0.003                    | 187±2             | 138±3                      | g                               |
| ALHA 77191,16          | H4    | C                             | --(a)             | 0.041±0.003                    | 172±3             | 128±3                      | g                               |
| ALHA 77012,13          | H5    | C                             | plag(a)           | 0.15±0.03                      | 172±3             | 128±3                      |                                 |
| ALHA 77014,17          | H5    | C                             | turb(a)           | 0.037±0.004                    | 186±5             | 139±2                      |                                 |
| ALHA 77177,21          | H5    | C                             | plag(a)           | 0.12±0.03                      | 176±3             | 132±2                      |                                 |
| ALHA 77182,28          | H5    | C                             | plag(a)           | 0.23±0.02                      | 195±11            | 136±2                      |                                 |
| ALHA 77258,28          | H6    | B                             | plag(a)           | 0.150±0.006                    | 188±2             | 142±4                      |                                 |
| ALHA 77259,11          | H5    | C                             | --(a)             | 0.065±0.007                    | 194±8             | 140±2                      |                                 |
| ALHA 77262,43          | H4    | BC                            | --(a)             | 0.14±0.02                      | 197±3             | 143±2                      |                                 |
| ALHA 77274,10          | H5    | C                             | --(a)             | 0.20±0.04                      | 195±4             | 144±4                      |                                 |
| ALHA 77294,36          | H5    | A                             | --(a)             | 0.29±0.04                      | 188±2             | 140±3                      |                                 |
| ALHA 77294,39          | H5    | A                             | --(a)             | 0.28±0.03                      | 169±2             | 133±4                      |                                 |
| ALHA 78075,9           | H5    | BC                            | --(a)             | 0.07±0.01                      | 191±2             | 139±3                      |                                 |
| ALHA 78076,24          | H6    | B                             | plag(a)           | 0.37±0.01                      | 182±2             | 142±3                      |                                 |
| ALHA 78102,17          | H5    | BC                            | --(a)             | 0.31±0.05                      | 186±2             | 141±2                      |                                 |
| ALHA 78108,9           | H5    | B                             | --(a)             | 0.056±0.012                    | 205±9             | 160±2                      |                                 |
| ALHA 78111,9           | H5    | BC                            | --(a)             | 0.20±0.05                      | 182±3             | 136±2                      |                                 |
| ALHA 78115,25          | H6    | B                             | plag(a)           | 0.60±0.06                      | 174±2             | 138±2                      |                                 |
| ALHA 79026,18          | H5    | B                             | dev.(a)           | 0.32±0.04                      | 205±4             | 139±2                      |                                 |
| ALHA 79029,16          | H5    | C                             | --(a)             | 0.068±0.008                    | 194±7             | 136±2                      |                                 |
| ALHA 79046,9           | H5    | B                             | --(a)             | 0.33±0.05                      | 195±7             | 141±7                      |                                 |
| ALHA 80132,14          | H5    | B                             | plag(b)           | 0.34±0.08                      | 195±9             | 134±2                      |                                 |
| ALHA 81015,12          | H5    | B                             | --(c)             | 0.045±0.006                    | 198±2             | 137±3                      |                                 |
| ALHA 81039,12          | H5    | AB                            | --(c)             | 0.27±0.05                      | 192±7             | 137±2                      |                                 |
| ALHA 82102,15          | H5    | BC                            | --(e)             | 0.25±0.05                      | 190±6             | 136±2                      |                                 |
| EETA 79007,12          | H5    | B                             | --(a)             | 0.074±0.024                    | 194±5             | 138±2                      |                                 |
| META 78006             | H6    | C                             | plag(a)           | 0.26±0.026                     | 187±5             | 139±3                      |                                 |
| META 78010,15          | H5    | B                             | --(a)             | 0.022±0.005                    | 186±5             | 140±2                      |                                 |
| RKPA 79004,21          | H5    | BC                            | plag(a)           | 0.23±0.05                      | 184±4             | 137±2                      |                                 |
| RKPA 8020,10           | H5    | BC                            | --(b)             | 0.15±0.02                      | 193±7             | 138±3                      |                                 |
| RKPA 80230,10          | H5    | B                             | plag(b)           | 0.20±0.03                      | 190±4             | 134±3                      |                                 |
| RKPA 80233,10          | H5    | BC                            | plag(b)           | 0.13±0.03                      | 184±5             | 136±2                      |                                 |
| ALHA 77002,46          | L5    | B                             | plag(a)           | 0.045±0.007                    | 195±2             | 141±2                      |                                 |
| ALHA 77002,47          | L5    | B                             | plag(a)           | 0.033±0.004                    | 180±2             | 143±2                      |                                 |
| ALHA 77155,24          | L6    | AB                            | plag(a)           | 0.39±0.13                      | 190±8             | 136±0                      |                                 |
| ALHA 77230,42          | L4    | C                             | turb              | 0.35±0.05                      | 186±7             | 138±5                      |                                 |
| ALHA 77264,14          | L5    | AB                            | --(a)             | 0.17±0.04                      | 196±3             | 141±2                      |                                 |
| ALHA 77261,24          | L6    | B                             | plag(a)           | 0.15±0.02                      | 177±3             | 142±2                      |                                 |
| ALHA 77231,36          | L6    | AB                            | plag(a)           | 0.60±0.13                      | 180±2             | 137±3                      | g                               |
| ALHA 77270,29          | L6    | AB                            | plag(a)           | 0.49±0.03                      | 182±3             | 145±2                      | g                               |
| ALHA 77284,18          | L6    | AB                            | plag(a)           | 0.37±0.07                      | 183±6             | 140±2                      | g                               |
| ALHA 77282,26          | L6    | B                             | --(a)             | 0.044±0.006                    | 188±3             | 143±3                      | g,h                             |
| ALHA 77296,19          | L6    | AB                            | plag(a)           | 0.40±0.07                      | 181±2             | 140±2                      | g                               |
| ALHA 77296,21          | L6    | AB                            | plag(a)           | 0.45±0.03                      | 186±6             | 136±4                      | g                               |
| ALHA 77297,31          | L6    | A                             | plag(a)           | 0.65±0.04                      | 183±3             | 138±2                      | g                               |
| ALHA 77297,33          | L6    | A                             | plag(a)           | 0.43±0.08                      | 173±3             | 138±2                      | g                               |
| ALHA 78043             | L6    | B                             | plag(a)           | 0.56±0.07                      | 183±2             | 146±2                      |                                 |
| ALHA 78044,17          | L4    | BC                            | plag(a)           | 0.12±0.02                      | 192±2             | 139±2                      |                                 |
| ALHA 78078,16          | L6    | AB                            | plag(a)           | 0.52±0.03                      | 182±3             | 137±2                      |                                 |
| ALHA 78105,26          | L6    | B                             | plag(a)           | 0.78±0.09                      | 179±3             | 139±2                      | g                               |
| ALHA 78251,25          | L6    | B                             | plag(a)           | 0.15±0.02                      | 176±4             | 140±2                      | g                               |
| ALHA 78251,26          | L6    | B                             | plag(a)           | 0.33±0.05                      | 182±6             | 138±2                      | g                               |
| ALHA 78106,25          | L6    | AB                            | plag(a)           | 1.5±0.3                        | 174±2             | 137±2                      | g                               |
| ALHA 78112,25          | L6    | B                             | plag(a)           | 0.066±0.001                    | 181±2             | 147±2                      | g,g,h                           |
| ALHA 78112,26          | L6    | B                             | plag(a)           | 0.12±0.01                      | 182±3             | 144±2                      | g,g,h                           |
| ALHA 78114,21          | L6    | BC                            | plag(a)           | 0.20±0.02                      | 189±2             | 151±3                      | g,g,h                           |
| ALHA 81017,13          | L5    | B                             | --(c)             | 1.00±0.2                       | 182±6             | 137±2                      |                                 |
| EETA 79009,11          | L5    | B                             | --(a)             | 0.26±0.10                      | 200±4             | 133±2                      |                                 |
| EETA 79010,9           | L6    | B                             | mask(a)           | 0.011±0.003                    | 146±4             | 105±13                     |                                 |
| META 78002,22          | L6    | B                             | plag(a)           | 0.31±0.10                      | 194±12            | 158±5                      | h                               |
| META 78003,23          | L6    | B                             | plag(a)           | 0.143±0.007                    | 195±2             | 160±2                      | h                               |
| META 78003,24          | L6    | B                             | plag(a)           | 0.191±0.0012                   | 191±2             | 161±2                      | h                               |
| META 78028,78          | L6    | B                             | plag(a)           | 0.078±0.02                     | 197±4             | 159±2                      | h                               |
| META 78028,81          | L6    | B                             | plag(a)           | 0.13±0.01                      | 192±2             | 159±2                      | h                               |
| META 78028,82          | L6    | B                             | plag(a)           | 0.16±0.03                      | 197±3             | 160±2                      | h                               |
| RKPA 79001,20          | L6    | B                             | mask(a)           | 0.087±0.018                    | 196±2             | 158±2                      | g,h                             |
| RKPA 79001,23          | L6    | B                             | mask(a)           | 0.065±0.006                    | 195±10            | 166±2                      | g,h                             |
| RKPA 79001,24          | L6    | B                             | mask(a)           | 0.15±0.02                      | 185±2             | 166±2                      | g,h                             |
| RKPA 80202,12          | L6    | B                             | mask(a)           | 0.015±0.001                    | --                | --                         | g,h                             |
| RKPA 80202,13          | L6    | B                             | mask(a)           | 0.0086±0.001                   | --                | --                         | g,h                             |
| RKPA 80216,12          | L4    | B                             | --(b)             | 0.27±0.06                      | 198±6             | 146±2                      |                                 |

\* Uncertainties refer to the standard deviations of triplicate measurements.

+ ALH, EET, MET and RKP refer to Allan Hills, Elephant Moraine, Meteorite Hills and Reckling Peak, respectively. Curatorial fragment number also indicated.

§ Weathering Category from Antarctic Meteorite Newsletter (see "feld" column for references).

θ Full-width of the TL peak at half its maximum intensity.

† Unusual glow curve shape makes peak temperature and FWHM impossible to measure.

\* Descriptions of feldspathic material (references below): plag = plagioclase present; mask = maskelynite present; turb = turbid glass present; -- meteorite described with no mention of feldspathic material. References: (a) Score *et al.* (1981), (b) Score *et al.* (1982), (c) Anon (1983), (d) Nishizumi *et al.* (1983), (e) Anon (1984), (f) Olsen *et al.* (1978), (g) Scott (1984), (h) This work.

of cosmogenic isotopes. For ALHA78105 and ALHA78251 the situation is less clear, because natural TL data is consistent with pairing, but the difference in TL sensitivities (they differ by a factor of ~4) are rather large for fragments from a single meteorite. The factor of 10 difference between RKPA80202 and RKPA79001 in natural TL and TL sensitivity also makes us think that these two are *not* paired, but because they are both heavily shocked chondrites, shock heterogeneity is also a possibility. SCOTT (1984) concluded that these two may not be paired on the basis of composition and <sup>26</sup>Al data, and here we treat them as separate meteorites.

ALHA77231, ALHA77270, ALHA77282, and ALHA77284 were paired in the Antarctic Meteorite Newsletter (SCORE *et al.*, 1981), but data on cosmogenic nuclides, petrology and composition led SCOTT (1984) to suggest that although 77270 and 77284 may be paired, the others are not paired with these or each other. TL sensitivity clearly indicates that 77282 is a discrete fall, but the remaining three have very similar induced TL properties; natural TL data have not yet been obtained for these meteorites.

META78002, META78003 and META78028 and all L6 chondrites of weathering category B and identical TL peak temperature and peak width which sets them apart from the other Antarctic L chondrites (see below). They also have similar macroscopic and microscopic properties and similar TL sensitivities. Their natural TL data are also very similar (natural TL peak height ratios of  $1.3 \pm 0.2$ ,  $2.4 \pm 0.1$  and  $1.61 \pm 0.03$ , respectively [HASAN *et al.*, 1986]; a factor of two can be attributed to shielding effects), and their <sup>26</sup>Al are the same within 2 sigma ( $47 \pm 3$ ,  $50 \pm 3$ , and  $56 \pm 3$  dpm/kg, respectively; EVANS *et al.*, 1982). It seems very likely, therefore, that they are fragments of the same meteorite, although there is no previous suggestion of this (SCOTT, 1984).

**TL measurement.** The procedures and apparatus were essentially those used by SEARS and WEEKS (1983), except that the Kernouve meteorite is used for normalization. Chips of 0.2–0.5 g were gently ground, the magnetic material removed with a hand magnet, and ground again so as to pass through a 100 mesh sieve. Aliquants of  $5 \pm 1$  mg were then placed in a Cu dish (5 mm dia., 2 mm deep, 0.01 mm base) and placed in a Daybreak Nuclear and Medical Inc. apparatus for TL measurement. The natural TL was drained by momentary heating to 500°C, and the sample exposed to a 250 mCi Sr-90 beta source until the absorbed dose was 2.0 krad. The induced TL for each sample was measured 3 times and the means and standard deviations calculated. TL sensitivity, peak temperature and peak width were measured from the glow curves in the manner described in Fig. 1 of SEARS and WEEKS (1983). The quoted uncertainties for TL sensitivity include the uncertainty in the normalization standard.

## RESULTS

Histograms of the TL sensitivities of equilibrated chondrites are shown in Figs. 1 and 2; both literature and the present data are included, but, except for non-Antarctic L chondrites, literature data are very sparse. Chondrites of petrologic type 4 tend to have lower TL sensitivities than types 5 and 6 due to differences in the levels of metamorphism experienced (SEARS *et al.*, 1980). For types 5 and 6, facies c and especially d, have lower TL sensitivities than those of facies a and b. The Antarctic H chondrite distribution is skewed to lower values by a factor of about 3 compared with non-Antarctic H chondrites; excluding type 4, the number of H chondrites having TL sensitivities greater than 0.4 is 15/31 for non-Antarctic and 1/29 for Antarctic meteorites, respectively.

The range of TL sensitivities for the L chondrites is much greater than for the H chondrites, especially for the non-Antarctic meteorites. This reflects the presence of many heavily shocked (facies d–f) specimens. Shock-heating facies assignments are not available for the Antarctic L chondrites. However, three (RKPA79001, EETA79010 and RKPA-80202) are reported to contain maskelynite and are therefore facies d–f (Table 3), and they all have low TL sensitivities (<0.15). We suspect that the other Antarctic L5, 6 chondrites with TL sensitivities less than 0.15 are facies d–f (ALHA78112, ALHA77282 and ALHA77002; ALHA77261 is marginal). Of these, plagioclase has been observed in ALHA78112 and ALHA77002, but there was no mention

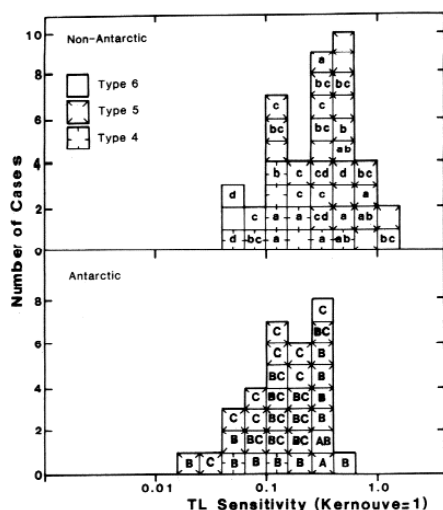


FIG. 1. Histograms for the TL sensitivities of H chondrites. Data are from the present study (Tables 2 and 3) and from the literature (SEARS, 1980 and LIENER and GEISS, 1968, normalized to Kernouze in the manner described by SEARS *et al.*, 1984b). Shock-heating facies, a–f, as defined by DODD and JAROSEWICH (1979), is indicated where known. Petrologic type 4 tend to have lower TL sensitivities than types 5 and 6 due to differences in the levels of metamorphism experienced, but within types 5–6 facies c and especially d, have lower TL sensitivities than those of facies a and b. The Antarctic H chondrite distribution is skewed to lower values by a factor of about 3; the number of H5, 6 chondrites having TL sensitivities greater than 0.4 is 15/31 for non-Antarctic and 1/29 for Antarctic meteorites, respectively. The capital letters A–C are weathering categories assigned to Antarctic meteorites on the basis of macroscopic weathering; H chondrites tend to be more highly weathered than L chondrites (Fig. 2) and weathering lowers TL sensitivity by a factor of  $\sim 3$  (SEARS *et al.*, 1982).

of feldspathic material in any form in the description of ALHA77282 (Table 3). The distributions for the Antarctic and non-Antarctic L chondrites in Fig. 3 are similar; excluding type 4, the number of L chondrites having TL sensitivities greater than 0.4 are 16/39 for non-Antarctic and 8/21 for Antarctic meteorites.

Plots of TL peak temperature against peak width appear in Fig. 3. The non-Antarctic H chondrite data show a significant ( $>99.9\%$ ) correlation between peak temperature and width ( $r = 0.90$ ,  $n = 30$ ; Fig. 3a). The distribution of data does not appear to be related to shock reheating, except that facies d–f may be showing greater scatter. The Antarctic H chondrites plot in a cluster (generally with peak widths and peak temperatures in the range 135–145°C and 180–195°C, respectively) which lies above the non-Antarctic H chondrite regression line (Fig. 3b). There is no tendency for the two parameters to correlate in this case.

There is also a difference in peak temperature and peak width distributions between Antarctic and non-Antarctic L chondrites, although the distinction is more subtle. Non-Antarctic L chondrites of facies a–c plot in a group with peak widths around 140–150°C and peak temperatures of around 180°C, while the 8 chondrites of facies d–f spread over the

diagram. Three of these lie to higher temperature values than those of facies a–c, but with similar peak widths, and the others well-removed (Fig. 3c). There is no indication that peak temperature and width are related to shock facies, except that shock-reheating may cause scatter. The diagonal line in Fig. 3c is a regression line through the Antarctic L chondrite data; the non-Antarctic L chondrites show no tendency to plot along this line. The Antarctic L chondrites plot largely in a cluster with peak widths of 136–149°C and temperatures 174–190°C, but with outliers which produce a smaller cluster at higher values (RKPA79001, META78028, META78003, and META78002; width about 158°C and temperature around 195°C) and a solitary sample (EETA79010) at a very low value; the outliers cause a significant correlation ( $>99.0\%$ ) between peak temperature and width ( $r = 0.75$ ,  $n = 18$ ; Fig. 3d). EETA79010 and RKPA79001 are, with RKPA80202, the only Antarctic L chondrites in the present suite which contain maskelynite (Table 3), but shock cannot be the cause of the displacement from the main cluster, because the three META meteorites which plot alongside RKPA79001 contain normal plagioclase.

## DISCUSSION

### TL sensitivity variations in equilibrated chondrites

It is known from a number of studies that shock or, more precisely, shock-related heating, causes a considerable re-

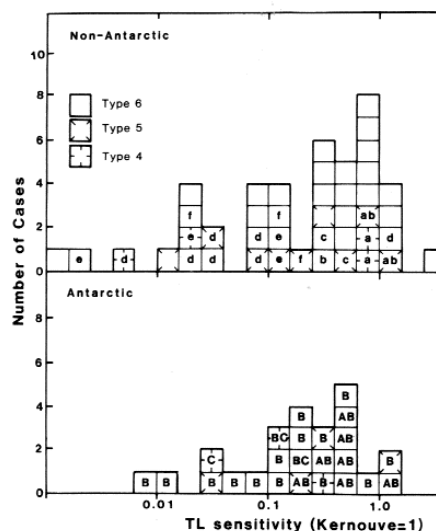


FIG. 2. Histograms for the TL sensitivities of L chondrites. The sources of data are as in Fig. 1. The range of TL sensitivities is much greater than for the H chondrites, especially for the non-Antarctic L chondrites, reflecting the presence of many heavily shock-heated (facies d–f) individuals. Shock-heating facies data are not available for the Antarctic meteorites, but three (RKPA79001, EETA79010, and RKPA80202) are reported to contain maskelynite and all have low TL sensitivities. The distributions for the Antarctic and non-Antarctic L chondrites are similar; the number of type 5, 6 L chondrites having TL sensitivity greater than 0.4 are 16/39 for non-Antarctic and 8/21 for Antarctic meteorites, respectively.

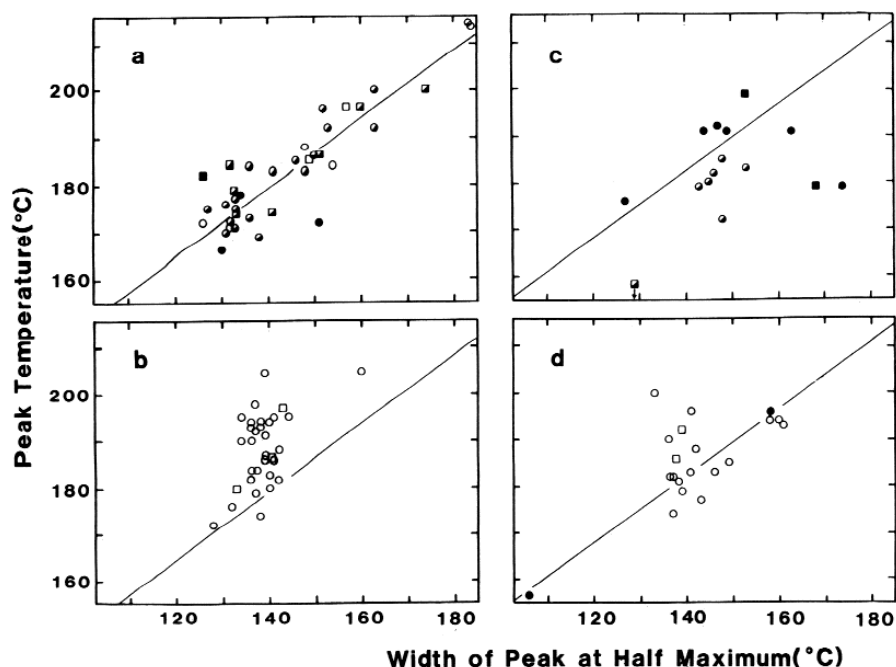


FIG. 3. Plots of TL peak temperature against width for type 4–6 ordinary chondrites. Filled symbols refer to shock-heating facies d–f, half-filled to facies a–c, open symbols to individuals of unknown shock-heating facies. Circles refer to type 5, 6 and squares to type 4. Meteorites for which there is any evidence for pairing have been averaged; for most samples in the present data set there is good evidence against pairing. For non-Antarctic H chondrites (Fig. 3a), there is a significant correlation between peak temperature and width ( $r = 0.90$ ,  $n = 30$ , significance  $>99.9\%$ ), while this is not the case for Antarctic H chondrites which plot in a cluster above the non-Antarctic H chondrite regression line (Fig. 3b). The data for non-Antarctic L chondrites (Fig. 3c) are meagre, but the facies a–c plot in a cluster around with peak width  $\sim 150^\circ\text{C}$  and peak temperatures  $\sim 180^\circ\text{C}$ ; samples of facies d–f scatter considerably. The diagonal in Fig. 3c is a regression line ( $r = 0.75$ ,  $n = 18$ , significance  $>99.9\%$ ) through the Antarctic L chondrite data (Fig. 3d) which owes its existence to the outliers. In contrast to the non-Antarctic L chondrites, the Antarctic L chondrites form a cluster in the same region of the plot as the Antarctic H chondrites.

duction in TL sensitivity which is related to melting of feldspar or its transformation to maskelynite. Thus, facies d–f meteorites have lower TL sensitivity than facies a–c (Fig. 2), and samples of the Kernouvé H6 chondrite and terrestrial feldspars shocked to pressures above 30 GPa have TL sensitivities 0.1–0.01 times their original values (SEARS, 1980; HARTMETZ *et al.*, 1986). Such heavily shocked samples show optical and other petrographic evidence for partial fusion or maskelynitization of the feldspar (DODD and JAROSEWICH, 1979; OSTERTAG, 1983; SEARS *et al.*, 1984a). Variations in TL sensitivity might also be expected as a result of variations in feldspar abundance due to sample heterogeneity. Changes in feldspar composition could also produce TL sensitivity variations because bytownite typically has a TL sensitivity  $<0.01$  times that of albite, (HASAN *et al.*, 1986). However, this possibility is probably not significant as equilibrated chondrites have remarkably uniform feldspar compositions (VAN SCHMUS and RIBBE, 1968). Meteorites of petrologic type 3 and 4 have low TL sensitivities since some or most of their feldspathic material is present in the form of primary igneous

glass; thus type 4 meteorites cannot be included in the present discussion.

The difference in the histograms of TL sensitivity for Antarctic and non-Antarctic H chondrites (Fig. 1) could be attributed to differences in shock history; temperatures associated with shock pressures of 15–20 GPa would suffice to lower the Antarctic H chondrites TL sensitivities a factor of  $\sim 3$  compared to non-Antarctic H chondrite values. However, pressures this low produce few petrographic changes which could be used to test this idea, and there are other plausible means of lowering TL sensitivity by the observed amount. Coincidentally, severe weathering also lowers TL sensitivity by a factor of  $\sim 3$  (SEARS *et al.*, 1982).

Weathering categories assigned to Antarctic meteorites by the JSC curator's laboratory on the basis of the appearance of the hand-specimen (this is governed mainly by the corrosion of metal and sulphide), are indicated in Figs. 1 and 2. Because all of the non-Antarctic H chondrites and all but a few of the non-Antarctic L chondrites are observed falls, these can probably be considered as category A. The prevalence

of category B and C individuals in the Antarctic data is then consistent with the lower TL sensitivities of Antarctic H chondrites being due to weathering; the Antarctic L chondrites not showing lower TL sensitivities than non-Antarctic L chondrites because of their small abundances of metal. However, one problem with this otherwise straightforward interpretation is that within the H and L classes there is no simple correlation between TL sensitivity and weathering category; other factors are also clearly affecting the TL data.

An independent indicator of the intensity and duration of heating following shock for an equilibrated chondrite is the amount of radiogenic  $^{40}\text{Ar}$  it contains. In Fig. 4 we compare the TL sensitivity of the non-Antarctic H and L chondrites with their  $^{40}\text{Ar}$  contents. Inert gas contents were taken from the compilation of KRUSE and SCHULTZ (1983); in about 1/3 of the cases the chip used here was the same as that used for  $^{40}\text{Ar}$  determinations. Most of the H chondrites, type 4 omitted, plot in a region with TL sensitivities 0.2–1.0 and  $^{40}\text{Ar}$  of 4000–6500 (Fig. 4a). However, 5/41 of the samples have lost more than 30% of their  $^{40}\text{Ar}$  ( $<2000 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1}$ ) and 4 out of 5 of these have TL sensitivities  $\sim 0.1$ ; values this low are very rare among those which contain  $^{40}\text{Ar} > 2000 \times 10^{-8} \text{ cm}^3 \text{ g}^{-1}$  (only 4 out of 36). There is no strong relationship between shock facies and position on this plot. There are very few facies d–f samples in the data base, but the 5 that are present (including those classified as facies c, d) scatter over the diagram.

The L chondrite plot is very different from the H chondrite plot, due mainly to a higher proportion of heavily shocked chondrites. The facies a–c chondrites show a distribution similar to that of the H chondrites; TL sensitivity decreases by a factor of 2–10, while  $^{40}\text{Ar}$  content decreases by a factor of 5–10. Shock facies d–f produce a “tail” in which TL sensitivities are 1/10 to 1/500 those of the unshocked chondrites, and have  $^{40}\text{Ar}$  contents a factor of 5–10 lower than those of the unshocked chondrites.

Interpretation of these plots in a semi-quantitative way is possible using laboratory data for the thermal (diffusive) release of Ar and the decrease in TL sensitivity with annealing. In Fig. 5 we compare the TL sensitivity of the Kernouve meteorite after annealing for 100 h (SEARS *et al.*, 1984b), as a function of annealing temperature, with the amount of  $^{40}\text{Ar}$  remaining after step-wise heating of a typical chondrite (BOGARD and HIRSCH, 1980; TURNER *et al.*, 1978). The TL sensitivity drops gradually by a factor of  $<2$  after annealing at temperatures up to 1000°C, and at higher temperatures drops abruptly to 1/100 of its unannealed value. The  $^{40}\text{Ar}$  decrease initially follows a similar pattern to TL sensitivity, but at 800°C drops suddenly to about 1/10 the original value. It remains at this value as annealing temperature is increased, until  $\geq 1000^\circ\text{C}$  when it drops abruptly again. The choice of chondrites whose  $^{40}\text{Ar}$  data are plotted (Wellman) is arbitrary, but the release patterns are fairly similar for a variety of chondrites of the H, L and LL classes: at 800°C the fraction of  $^{40}\text{Ar}$  remaining ranges between 20 and 95%, while at 1000°C these figures are 6 and 32%. To some degree, both patterns should reflect the behavior of feldspar, since feldspar is the TL phosphor and much of the  $^{40}\text{K}$  (the parent of  $^{40}\text{Ar}$ ) is located in the feldspar. Thus, in both cases the abrupt de-

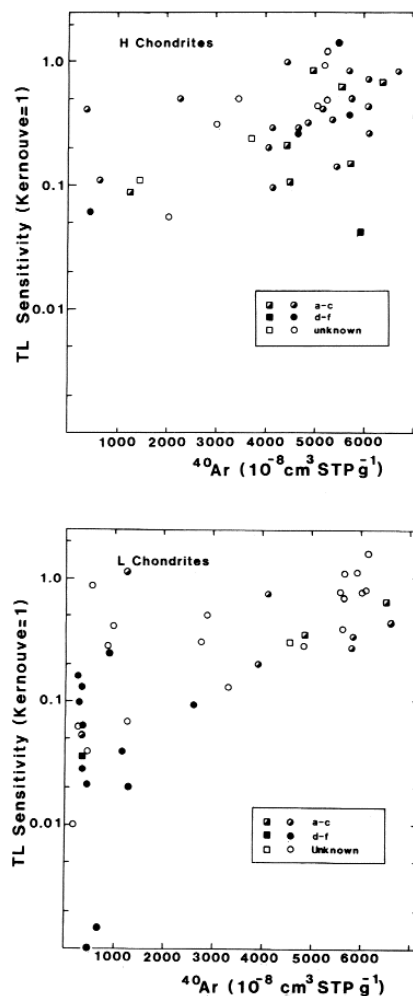


FIG. 4. TL sensitivity against  $^{40}\text{Ar}$  content for non-Antarctic (a) H chondrites and (b) L chondrites. TL data are from the sources described in Fig. 1 and the  $^{40}\text{Ar}$  data are from the compilation by KRUSE and SCHULTZ (1983). Squares refer to samples of petrologic type 4, circles to type 5, 6. Both classes of meteorite show a factor of 2 decrease in TL sensitivity for  $>80\%$   $^{40}\text{Ar}$ -loss, and the heavily shocked L chondrites show 10–100 fold decreases in TL sensitivity. The shock facies is indicated by the shading of the symbol.

crease at  $>1000^\circ\text{C}$  probably reflects fusion of the feldspar. The decrease in  $^{40}\text{Ar}$  at 800°C is less straightforward and could indicate physical changes in the feldspar, or that most of the  $^{40}\text{Ar}$  is located in another phase. On the basis of inferred K/Ca ratio, BOGARD and HIRSCH (1980) argued that two phases (feldspar and pyroxene) are involved.

The factor of 2 decrease in TL sensitivity and  $^{40}\text{Ar}$  observed in the moderately shocked chondrites could therefore imply post-shock heating to  $<800^\circ\text{C}$ , all else being equal, whereas those with an order of magnitude or so decrease in  $^{40}\text{Ar}$  but

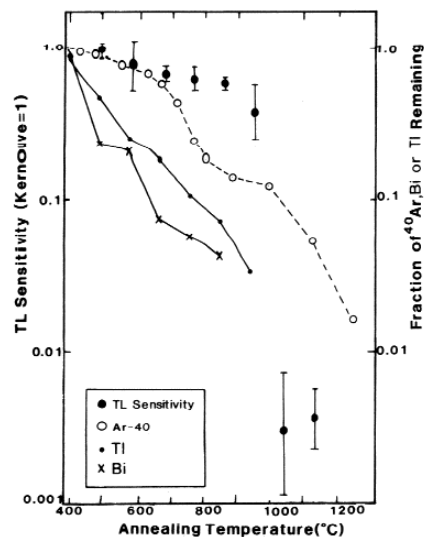


FIG. 5. Plot of TL sensitivity for the Kernouve meteorite (filled symbols, left-hand scale, data from SEARS *et al.*, 1984b) and fraction of  $^{40}\text{Ar}$  remaining in the Wellman meteorite (open symbols, right-hand scale, data from BOGARD and HIRSCH, 1980) as a function of annealing temperature. According to these laboratory results, heating to less than 800°C causes less than a factor of 2 decrease in TL sensitivity and  $^{40}\text{Ar}$  content, heating to 800–1000°C causes less than a factor of 2 decrease in TL sensitivity but about an order of magnitude loss in  $^{40}\text{Ar}$  content, while heating >1000°C causes an order of magnitude or more loss in both  $^{40}\text{Ar}$  and TL sensitivity. Data for Bi and Tl from IKRAMUDDIN *et al.* (1977a,b) are also indicated; both are more readily lost than TL sensitivity and  $^{40}\text{Ar}$  during the annealing experiments.

with a <2-fold decrease in TL sensitivity have experienced post-shock temperatures of 800–1000°C. The heavily shocked chondrites, with more than an order of magnitude decrease in both  $^{40}\text{Ar}$  and TL sensitivity, have apparently experienced >1000°C. Figure 6 summarizes these relationships. The percentages of samples in the present study in each of the three categories, <800, 800–1000, and >1000°C are 49, 24, 27 for the L chondrites, and 81, 16 and 3 for the H chondrites. Of course, the laboratory annealing experiments are only a crude approximation to true post-shock annealing conditions; for  $^{40}\text{Ar}$ -loss especially the post-shock cooling rate is of prime importance. More importantly, if the shock occurred 4.6 Ga ago,  $^{40}\text{Ar}$  contents would have returned to their “normal” values, but to restore TL sensitivity would require a period of metamorphism following the shock event indicated by the shock facies; we return to this point below. However, the present conclusions are in good agreement with petrographic estimates of post-shock temperatures for the few L chondrites for which estimates have been made (SEARS *et al.*, 1984b), suggesting that for the L chondrites, at least, the simplest interpretation of our data which is summarized in Fig. 6 is realistic.

This may not be the case for 4 of the 5 H chondrites which have experienced severe shock (Zhovtnevyi, c-d; Bur-Ghel-

uai, c-d; Forest City, d; Charsonville, d; Ochansk, d). Charsonville has a TL sensitivity and  $^{40}\text{Ar}$  content consistent with a shock-heating history much like that experienced by L chondrites of facies d, and we would infer a history involving recent shock-heating to ~1000°C for this meteorite. There are no facies c-d L chondrites with which to compare Zhovtnevyi and Bur-Gheluai, which plot in the high TL-high  $^{40}\text{Ar}$  cluster along with facies a-c meteorites. Forest City (H5) and Ochansk (H4) are noteworthy for being facies d yet having high  $^{40}\text{Ar}$  contents. The TL sensitivities for both meteorites are low relative to most H chondrites with comparable  $^{40}\text{Ar}$ , consistent with their shock classification, but Ochansk's value is also expected to be low due to its relatively low petrologic type. A possible interpretation of Forest City and Ochansk data is that the shock-heating which lowered their TL sensitivities and gave them the petrography of facies d yet occurred >4.0 Ga ago, so that  $^{40}\text{Ar}$  has had time to build up again. If this is the case, then one should expect trace elements with high volatility to be depleted in these chondrites, because stepwise heating experiments suggest that In and Tl are more labile than  $^{40}\text{Ar}$  (Fig. 5; IKRAMUDDIN *et al.*, 1977a,b).

#### TL peak temperature and width variations in equilibrated chondrites

The differences between the H and L, Antarctic and non-Antarctic chondrites in their TL peak temperature vs. width plots (Fig. 3) have major implications for our understanding of their thermal histories and thereby the relationship between these various categories of meteorite. The difference between the Antarctic and non-Antarctic H chondrites is especially significant in view of the nature of the differences and size of the data base.

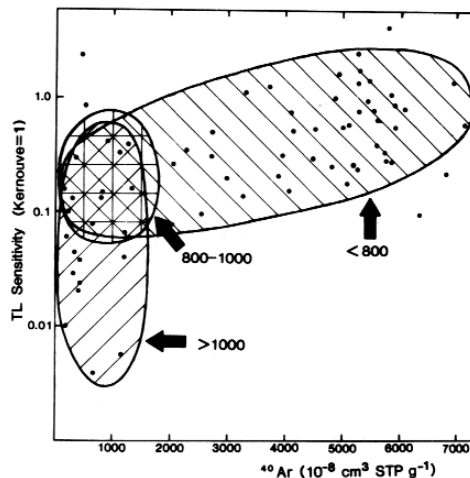


FIG. 6. Sketch indicating post-shock residual temperatures based on TL sensitivity,  $^{40}\text{Ar}$  and the annealing data in Fig. 5, assuming uniform post-shock cooling rates and that the shock event occurred recently (<1 Ga). The meteorites plotted can be divided into three post-shock temperature categories.



A variety of studies have shown that the TL phosphor in ordinary chondrites is feldspar and that this mineral undergoes thermally controlled transformations which affect TL peak temperature and width; the transformations indirectly involve the degree of disorder in the Al-Si chain, but the details are poorly understood (LALOU *et al.*, 1970; PASTERNAK, 1978; GUIMON *et al.*, 1984; 1985; HARTMETZ and SEARS, 1987). Thus a type 3.4 chondrite, which is thought to contain feldspar in the low form, has a narrow TL peak at low temperatures which broadens and moves to relatively high temperatures after annealing above the order/disorder transformation temperatures. The TL peak temperature and width changes caused by annealing a type 3.4 are rather large. Smaller changes in peak temperature and width are observed when chondrites of type >3.5 are annealed; for example, the TL peak of Dhajala H3.8 chondrite increases from  $169 \pm 7$  to  $212 \pm 5^\circ\text{C}$  in width and from  $172 \pm 9$  to  $231 \pm 8$  in peak temperature after annealing at  $1000^\circ\text{C}$  for 10 h (SEARS *et al.*, 1984c; KECK *et al.*, 1986). In the Dhajala case, measurements on separated chondrules show that the original peak temperature and width are determined by the relative proportions of chondrules whose feldspar is predominantly in the "low" and "high" state. The obvious interpretation of the Dhajala annealing data is therefore that the peak parameters changed as a result of annealing due to conversion of the "low" form to the "high" form.

It is significant that this strong dependence of peak temperature and width on thermal history is observed in feldspars from a variety of sources. Terrestrial feldspars, ordinary chondrites and shergottites behave very similarly, with respect to their TL properties, when annealed. Additionally, the Antarctic H and L chondrites in the present study resemble each other in their peak temperature and width distributions more closely than they do their chemically more similar non-Antarctic counterparts. It seems, therefore, that the major structural changes associated with disordering have a stronger influence on these TL characteristics than the numerous detailed differences in these feldspars.

The equilibrated chondrite Kernouve (H6) also undergoes small changes in TL peak temperature and width when annealed in a manner similar to Dhajala, presumably because it also contains feldspars in both high and low forms. However, because it has experienced much higher metamorphic intensities than Dhajala, feldspar would be predominantly in the high form, the low form being produced in a relatively restricted temperature range during cooling. X-ray diffraction data on feldspar separated from equilibrated chondrites confirm that it is in the high state (VAN SCHMUS and RIBBE, 1968). For the purpose of the present study, new measurements were made on samples of Kernouve which were annealed by SEARS *et al.* (1984b). The new data are shown in Fig. 7 and Table 4; better temperature calibration and several modifications in our technique have reduced the uncertainties and produced small changes in the data, but not enough to affect our earlier conclusions. The series of samples annealed at a variety of temperatures for 10 h showed an increase in peak temperature and width which followed fairly closely the non-Antarctic H chondrite regression line. Annealing at  $500$  or  $600^\circ\text{C}$  caused a 10% increase in peak temperature and

width, while annealing at  $700$ ,  $800$  or  $900^\circ\text{C}$  caused a 20% increase in peak temperature and width. The series of samples annealed at  $1000^\circ\text{C}$  showed a slightly more complicated behavior: 1 or 2 h at  $1000^\circ\text{C}$  also caused the peak temperature and width to increase along the non-Antarctic H chondrite regression line. Longer periods of annealing also caused an increase in peak temperature with peak widths compared to the unannealed sample, but the increase in both parameters was  $15$ – $20^\circ\text{C}$  less than for the samples annealed at  $700$ – $900^\circ\text{C}$  for 10 h.

The Kernouve data in Fig. 7 seem to confirm the presence of a low feldspar component which is destroyed as the meteorite is annealed above the transformation temperature. The position of a meteorite on the non-Antarctic H chondrite regression line is therefore governed by the relative proportions of high- and low-feldspar. This in turn will be governed by either (1) peak metamorphic temperature and post-metamorphic cooling rate, or (2) peak-shock temperature and post-shock cooling rates. It seems unlikely that post-shock cooling rates are fast enough for the low form to be produced during post-shock cooling, but shock-heating above the order/disorder temperature could produce the observed correlation. However, we would then observe a relationship between shock facies and position on the plot. It seems more plausible that shock heating was too transient to change peak position and temperatures, except perhaps some scatter due to the production of new phosphors and similar processes, and that the position on the plot is governed by the metamorphic

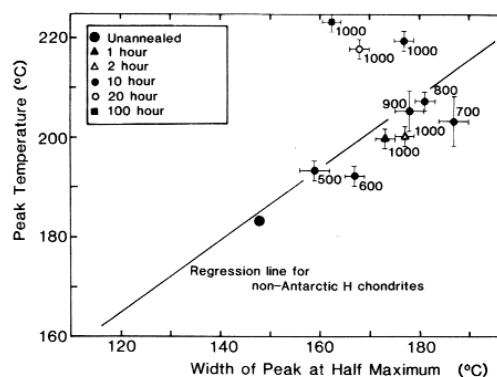


FIG. 7. Peak temperature vs. width diagram for samples of the Kernouve meteorite annealed at a variety of temperatures for various times. The values alongside each data point refer to annealing temperatures (in  $^\circ\text{C}$ ), and the symbols indicate the duration of annealing. The data appear in Table 4. The diagonal line is the non-Antarctic H chondrite regression line from Fig. 3a. Annealing for 10 h causes the temperature and width to increase with increasing annealing temperatures along the non-Antarctic regression line, as does annealing for 1 or 2 h at  $1000^\circ\text{C}$ . Annealing at  $1000^\circ\text{C}$  for longer times caused the peak temperature to become  $220^\circ\text{C}$  and the peaks to eventually narrow. These data are interpreted in terms of the TL phosphor (feldspar) consisting of two components (possibly related to the ordered and disordered phases) whose proportions can be adjusted by annealing. They clearly indicate that the position of the non-Antarctic H chondrites on the regression line may be controlled by thermal history.

**Table 4.** TL data for samples of the Kernouve meteorite annealed by Sears *et al.* (1984b).\*

| Annealing Temperature (°C) | Time Annealed (h) | TL sensitivity (Unannealed Kernouve = 1) | Peak Temp. (°C) | FWHM (°C) |
|----------------------------|-------------------|--|-----------------|-----------|
| 500                        | 10                | 1.11±0.13                                | 193±2           | 159±3     |
| 600                        | 10                | 1.06±0.11                                | 192±2           | 167±2     |
| 700                        | 10                | 0.9±0.1                                  | 203±5           | 187±3     |
| 800                        | 10                | 1.06±0.14                                | 207±2           | 181±2     |
| 900                        | 10                | 1.07±0.13                                | 205±4           | 178±3     |
| 1000                       | 1                 | 0.69±0.08                                | 199±2           | 173±2     |
| 1000                       | 2                 | 0.62±0.07                                | 200±2           | 177±2     |
| 1000                       | 10                | 0.44±0.05                                | 219±2           | 177±2     |
| 1000                       | 20                | 0.57±0.07                                | 215±2           | 168±2     |
| 1000                       | 100               | 0.24±0.03                                | 223±2           | 162±2     |

\* Uncertainties and symbols as in Table 2.

history of the meteorite. Laboratory experiments on terrestrial feldspars in the low form have shown that shock pressures equivalent to shock facies c and f are required to convert peak temperatures and widths from those we associate with the low form to those associated with the high form (HARTMETZ *et al.*, 1986).

If these interpretations of our TL data are correct, they provide significant insights into the metamorphic history of the H and L, Antarctic and non-Antarctic chondrite parent bodies. The non-Antarctic H meteorites apparently suffered a variety of post-metamorphic cooling rates, whereas the Antarctic H chondrites cooled at a fairly uniform rate which was a little slower than that experienced by most of the non-Antarctic H chondrites. The L chondrite data base is smaller than for the H chondrites, especially for the non-Antarctic L chondrites, so the situation is less clear. However, on the basis of existing data, L chondrites from both sources cooled at a fairly uniform rate with the Antarctic chondrites cooling more slowly. The post-metamorphic cooling history of the H and L chondrites from Antarctica are more similar to each other than either are to their non-Antarctic counterparts.

The most reasonable first-order interpretations for differences in peak temperatures and width must involve thermal history. Whatever the details, it seems fairly clear that there were significant differences in the thermal history of the Antarctic and non-Antarctic meteorites, especially for the H chondrites.

### CONCLUSIONS

The range of TL sensitivities observed for the non-Antarctic H and L chondrites reflects the variety of shock-related thermal histories suffered by the classes. The covariations of TL sensitivity with  $^{40}\text{Ar}$  and highly volatile trace element abundance, and laboratory annealing data concerning the relative stability of TL sensitivity,  $^{40}\text{Ar}$  and trace elements, are consistent with a greater proportion of the L class having suffered intense shock. The data enable some crude estimates of post-shock residual temperatures, which are consistent with petrographic estimates, and it is possible to divide ordinary chondrites into three categories on the basis of post-shock temperature (<800, 800–1000 and >1000°C).

The Antarctic H chondrites have a TL sensitivity distribution which is skewed to lower values by a factor of about 3, compared to the other chondrites. A greater proportion of the Antarctic H chondrites are heavily weathered, compared

with the Antarctic L chondrites, and weathering is probably responsible for the low TL sensitivity. However, mild shock of the Antarctic H chondrites to slightly higher levels than the non-Antarctic H chondrites cannot be ruled out.

The Antarctic and non-Antarctic H and L chondrites show distinctive behavior on TL peak temperature vs. width diagrams. Annealing experiments on the Kernouve (H6) chondrite are consistent with the position on the temperature-width plot being governed by differences in the small amount of low feldspar in equilibrated chondrites. The unique temperature-width plots therefore suggest unique thermal (probably metamorphic) histories for the Antarctic and non-Antarctic H chondrites and, possibly, the Antarctic and non-Antarctic L chondrites. The Antarctic H and L chondrites resemble each other more than they do their non-Antarctic equivalents.

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