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Thermoluminescence sensitivity and thermal history of type 3 ordinary chondrites: Eleven new type 3.0–3.1 chondrites and possible explanations for differences among H, L, and LL chondrites

P. H. BENOIT[1]*, G. A. AKRIDGE[1,3], K. NINAGAWA[2] AND D. W. G. SEARS[1]

[1]Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, USA
[2]Department of Applied Physics, Okayama University of Science, 1-1, Ridai-Cho, Okayama 700-0005, Japan
[3]Process Dynamics, Biomass Building, University of Arkansas, Fayetteville, Arkansas 72701, USA
*Correspondence author's e-mail address: pbenoit@uark.edu

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Abstract–We review induced thermoluminescence (TL) data for 102 unequilibrated ordinary chondrites (UOCs), many data just published in abstracts, in order to identify particularly primitive UOCs and further explore TL systematics that may have implications for the history of the chondrites and their parent body. We have identified 11 UOCs of petrologic types 3.0–3.1: Adrar 003, Elephant Moraine (EET) 90066, EET 90161, Grosvenor Mountains (GRO) 95502, Lewis Cliff (LEW) 88477, Meteorite Hills (MET) 96503, Yamato (Y)-790787, Y-791324, Y-791558, Y-793565, and Y-793596. These samples represent an important new resource for researchers interested in the nature of primitive solar system materials. Previously reported trends in which TL sensitivity increases with TL peak temperature and TL peak width, which we interpret in terms of crystallization of feldspar in the ordered or disordered forms during metamorphism, are confirmed by the new data. Importantly, the present data strengthen the trend described earlier in which the mean level of metamorphism experienced by UOCs increases along the series LL, L and H. This suggests either different burial depths for the UOCs from each class, or formation at similar depths in regoliths of different thickness.

INTRODUCTION

The unequilibrated ordinary chondrites (UOCs) are among the least altered meteorites and thus provide a unique opportunity to examine processes, such as chondrule formation and metal silicate fractionation, that occurred in the early solar system (*e.g.*, Grossman *et al.*, 1988; Scott *et al.*, 1996; Brearley, 1996; Huang *et al.*, 1996; Sears, 1998). These meteorites also provide an opportunity for examining the metamorphism of small solar system bodies (*e.g.*, Dodd, 1981; McSween *et al.*, 1988). Thus, the characterization of newly discovered UOCs is of much value.

Induced thermoluminescence (TL) has proven to be successful in evaluating degree of metamorphism for ordinary chondrites, CM, CV, and CO chondrites and eucrites (Batchelor and Sears, 1991; Sears *et al.*, 1991a,b, 1995, 1997; Guimon *et al.*, 1995). The TL sensitivity of a chondrite increases as feldspathic glass crystallizes during metamorphism and perhaps during aqueous alteration (Guimon *et al.*, 1985), and the peak temperature and peak width also appear to be related to thermal history. Chondrites of petrologic type 3.2–3.5 have sharp peaks at relatively low glow curve temperatures, while chondrites of type 3.5–3.9 have broad peaks at high glow curve temperatures. We have argued that this reflects the proportion of feldspar in the low-temperature (ordered) and high-temperature (disordered) forms (*e.g.*, Benoit *et al.*, 2001). Consistent with this interpretation, (1) heating UOCs and terrestrial feldspars in the laboratory can cause a shift in peak temperature similar to that observed naturally and (2) a suite of equilibrated H chondrites show a correlation between TL peak temperature and metallographic cooling rate (Benoit *et al.*, 1992, 2001).

Sears *et al.* (1991b) reviewed the database of induced TL data for 125 UOCs (106 when corrected for pairing) and found that very few were "primitive" (*i.e.*, type 3.0 or 3.1) or essentially unmetamorphosed (Bishunpur, Krymka, Lewis Cliff (LEW) 86018, LEW 86134, LEW 86270, Semarkona and Yamato (Y)-74660), although several additional meteorites appeared to be breccias containing primitive material (LEW 86549, LEW 86700, Thiel Mountains (TIL) 82408). They also found that the mean petrologic type of the UOCs increased along the series LL–L–H which they ascribed to differences in thermal history reflecting the different physical properties of the classes. In this paper, we review the induced TL data for a further 102 UOCs measured since 1991. Some of these data have been reported in the context of characterization of new specimens (*e.g.*,

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McCoy *et al.*, 1993; Rubin *et al.*, 1996; Ninagawa *et al.*, 1998) but they have not been discussed in the context of the larger database of UOCs We discuss the effects of weathering, shock processing, and pairing (identifying fragments of a single fall), since most of the samples are finds. We discuss at some length the implications of these data on our understanding of metamorphism of primitive materials. By quantifying the metamorphic history of these UOCs using their TL properties, we hope to better understand the nature of primitive solar system materials prior to metamorphic alteration and their meteorite parent bodies.

SAMPLES AND METHODS

The samples and their sources are listed in Table 1. Roosevelt County (RC) 075 (McCoy *et al.*, 1993), Adrar 003 (Hutchison *et al.*, 1991), the Acfer and Hamada al Hamra samples, Ilafegh 013 and Tanezrouft 006 (Bischoff *et al.*, 1992) were provided to us as parts of consortia studies of these meteorites. Many Antarctic meteorites were provided in connection with a study of the metal and sulfides in UOCs by Zanda *et al.* (1994) or as part of an interlaboratory comparison with Okayama University (Ninagawa *et al.*, 1998, 2000). The MacAlpine Hills (MAC), Meteorite Hills (MET), Queen Alexandra Range (QUE), Mount Wisting (WSG) and Wisconsin Range (WIS) samples were analyzed as part of the natural thermoluminescence survey of Antarctic meteorites (*e.g.*, Benoit *et al.*, 1992).

Chips of the UOCs weighing 50–300 mg were crushed in an agate mortar so as to pass through a 100 mesh sieve. Three 4 mg samples of the powder were placed in copper pans and, heated to 500 °C (to remove natural TL), and exposed to a 200 mCi ^{90}Sr-^{90}Y beta source for 2.5–7.5 min (dose rate of ~1 krad/min). The induced TL signal was measured by a Daybreak Nuclear and Medical Systems Inc. system, equipped with a EMI 9635 photomultiplier tube and Corning 7-59 and 4-69 filters to suppress black-body radiation. The filters restrict light measurement to wavelengths of 350 to 500 nm.

Splits of some samples were placed in 6M HCl and gently swirled for 45 s to remove weathering products and restore their natural pale gray color. The acid was then diluted by addition of ~3× the acid volume of water, and the mixtures were centrifuged, decanted, washed twice in distilled water and once in acetone, and allowed to dry in a desiccator.

For the TL measurement, each sample was heated to 500 °C in the TL apparatus at a rate of 7.5 °C/s. A powdered sample of the Dhajala meteorite was used as a day-to-day and long-term standard to monitor the apparatus and to provide a basis for interlaboratory comparisons. The maximum light produced (TL sensitivity, relative to the Dhajala standard), the temperature of maximum light production ("peak temperature") and the temperature range over which light is produced (or full-width at half-maximum of the TL peak, or "peak width") were measured (*e.g.*, Sears and Weeks, 1983).

RESULTS

Table 1 summarizes induced TL data for 102 UOCs measured since 1991. The present samples display the very large range of TL properties characteristic of UOCs. Their TL sensitivities cover over 4 orders of magnitude (0.001 to 3.6, where Dhajala = 1), while induced TL peak temperatures and widths cover a factor of ~2 (101 to 200 °C and 100 to 179 °C, respectively). In this section of our paper we will discuss pairing, weathering and the assignment of petrographic types.

Pairing

Although the type 3 ordinary chondrites exhibit significant petrographic diversity, it is often difficult to identify paired samples using only petrographic observations (Scott, 1984a,b). We have developed criteria including natural TL, TL sensitivity, induced TL peak temperature and induced TL peak width, petrography, hand specimen descriptions, and cosmic-ray exposure ages where available (Benoit *et al.*, 1992, 2000). Of course, TL sensitivity and TL peak temperature and TL peak width are related parameters but natural TL and TL sensitivity are independent phenomena. They have much value in pairing because separate falls display several orders of magnitude variation while duplicate samples from single large meteorites exhibit less than a factor of 3 range in TL sensitivity (Sears *et al.*, 1991b) and <10% variation in natural TL (Benoit and Chen, 1996; Benoit *et al.*, 2000).

Table 2 summarizes possible pairings for the present samples based only on natural and induced TL data, and petrographic descriptions. The 102 samples in the present sample probably represent only 93 separate meteorites, with four instances of two samples being paired, one instance of three paired samples, and the Grosvenor Mountains (GRO) 95502 group having four members. For the remainder of our discussion, paired fragments are considered a single meteorite.

Weathering

Sears *et al.* (1982) found that acid-washing of three highly weathered Antarctic type 3 chondrites caused an increase of a factor of ~3 in their TL sensitivity and restored the pale gray color typical of fresh meteorites. Induced TL peak temperature and width were unaffected by acid-washing. Similar results were obtained for Antarctic equilibrated ordinary chondrites (Benoit *et al.*, 1991; Benoit and Sears, 1999). It was suggested that TL phosphors were coated by rust during weathering and that this rust was removed by acid-washing.

Some of our present samples were acid-washed and the results are shown in Table 3 and Fig. 1. Again, the treatment did not affect induced TL peak temperature and width, any small effects being due to the reduction in measurement uncertainties (due to greater absolute TL intensity in the acid-washed samples).

TABLE 1. Induced thermoluminescence properties of unequilibrated ordinary chondrites.

Meteorite	Source*	Class	TL sensitivity, (Dhajala = 1.0)	Induced TL peak temperature (°C)	Induced TL peak width (°C)	Recommended petrologic type	Characterization reference
Acfer 022	MPI	H	0.084 ± 0.06	71 ± 3	168 ± 3	3.7	Bischoff *et al.* (1992)
Acfer 023	MPI	H	1.6 ± 0.1	150 ± 5	145 ± 2	3.8	Bischoff *et al.* (1992)
Acfer 028	MPI	H	2.2 ± 0.2	168 ± 4	144 ± 1	3.8	Bischoff *et al.* (1992); Otto (1992)
Acfer 039	MPI	L	1.8 ± 0.2	160 ± 7	148 ± 2	3.8	Bischoff *et al.* (1992)
Acfer 066	MPI	LL	1.9 ± 0.2	166 ± 5	8 ± 3	3.8	Bischoff *et al.* (1992)
Acfer 080	MPI	L	2.5 ± 0.2	181 ± 8	176 ± 12	3.9	Bischoff *et al.* (1992)
Acfer 129	MPI	H	0.46 ± 0.02	133 ± 1	129 ± 2	3.7	Bischoff *et al.* (1992)
Acfer 153	MPI	H	2.10 ± 0.02	133 ± 1	129 ± 2	3.6	Bischoff *et al.* (1992)
Acfer 159	MPI	H	1.13 ± 0.08	167 ± 8	141 ± 1	3.8	Bischoff *et al.* (1992)
Acfer 160	MPI	LL	1.6 ± 0.2	155 ± 3	129 ± 1	3.8	Bischoff *et al.* (1992)
Acfer 163	MPI	H	1.23 ± 0.07	165 ± 2	140 ± 3	3.8	Bischoff *et al.* (1992)
Acfer 169	MPI	H	1.2 ± 0.1	169 ± 4	134 ± 6	3.8	Bischoff *et al.* (1992)
Acfer 171	MPI	H	0.82 ± 0.07	169 ± 5	139 ± 4	3.7	Bischoff *et al.* (1992)
Acfer 178	MPI	H	0.48 ± 0.02	171 ± 2	n.m.	3.7	Bischoff *et al.* (1992)
Acfer 188	MPI	H	2.8 ± 0.2	162 ± 3	145 ± 1	3.9	Bischoff *et al.* (1992)
Acfer 192	MPI	H3	3.1 ± 0.4	167 ± 3	144 ± 1	3.9	Bischoff *et al.* (1992)
Acfer 210	MPI	H	0.46 ± 0.03	146 ± 6	143 ± 2	3.7	Bischoff *et al.* (1992)
Acfer 211	MPI	H	2.0 ± 0.2	143 ± 1	143 ± 2	3.9	Bischoff *et al.* (1992)
Adrar 003	MPI	L/LL	0.011 ± 0.005	190 ± 3	139 ± 14	3.1	Hutchison *et al.* (1991)
Adrar 003	OU	L/LL	0.0046 ± 0.0001	185 ± 5	n.m.	3.1	Hutchison *et al.* (1991)
ALH 90411	MWG	L	0.67 ± 0.02	162 ± 11	148 ± 6	3.7	AMN 14(2)[†]
Dar al Gani 369	AMNH	L(H)	0.123 ± 0.007	152 ± 2	n.m.	3.5	Grossman (1998)
EET 87726	MWG	H	1.33 ± 0.07	187 ± 4	156 ± 3	3.9	AMN 12(3)
EET 90066	MWG	L	0.003 ± 0.001	182 ± 4	169 ± 16	3.0	AMN 15(2)
EET 90161	MWG	L	0.004 ± 0.001	189 ± 8	156 ± 9	3.0	AMN 15(2)
EET 90628	MWG	H	0.081 ± 0.013	167 ± 6	161 ± 5	3.4	AMN 15(2)
GRA 95208	MWG	H	0.25 ± 0.01	184 ± 3	151 ± 4	3.7	AMN 20(1)
GRO 95502	MWG	L	0.001 ± 0.001	156 ± 7	n.m.	3.5	AMN 20(2)
GRO 95504	MWG	L	0.002 ± 0.001	122 ± 9	n.m.	3.5	AMN 20(2)
GRO 95505	MWG	L	0.014 ± 0.002	132 ± 9	78 ± 11	3.4	AMN 20(1)
GRO 95512	MWG	L	0.003 ± 0.001	121 ± 3	n.m.	3.5	AMN 20(2)
GRO 95536	MWG	L	0.029 ± 0.002	109 ± 1	80 ± 4	3.3	AMN 20(2)
GRO 95539	MWG	L	0.0040 ± 0.0001	114 ± 3	113 ± 4	3.1	AMN 19(2)
GRO 95544	MWG	L	0.003 ± 0.001	125 ± 14	89 ± 13	3.5	AMN 19(2)
GRO 95545	MWG	L	0.006 ± 0.001	116 ± 6	100 ± 13	3.5	AMN 19(2)
GRO 95546	MWG	L	0.97 ± 0.05	191 ± 4	141 ± 1	3.8	AMN 20(2)
HaH 004	MPI	H	3.6 ± 0.3	162 ± 3	141 ± 1	3.9	–
Hallingeberg	AMNH	L	0.13 ± 0.01	121 ± 4	94 ± 4	3.4	–
Hughes 021	Bart.	L	0.42 ± 0.01	194 ± 1	n.m.	3.6	–
Ilafegh 013	MPI	H	0.19 ± 0.04	177 ± 2	152 ± 3	3.5	Bischoff *et al.* (1992)
Ioka	BM	L	0.10 ± 0.01	146 ± 5	148 ± 4	3.5	–
LEW 87208	MWG	L	0.044 ± 0.003	153 ± 4	147 ± 2	3.4	AMN 12(1)
LEW 87284	MWG	L	0.026 ± 0.003	174 ± 8	153 ± 10	3.5	AMN 12(3)
LEW 88175	MWG	LL	0.09 ± 0.01	132 ± 5	122 ± 3	3.4	AMN 13(3)
LEW 88477	MWG	LL	0.005 ± 0.001	171 ± 18	155 ± 20	3.1	AMN 14(1)
LEW 88561	MWG	LL	0.025 ± 0.003	128 ± 1	94 ± 3	3.3	AMN 14(2)
LEW 88644	MWG	L	0.074 ± 0.005	110 ± 2	89 ± 1	3.5	AMN 14(2)
MAC 88174	MWG	H	0.09 ± 0.02	132 ± 8	86 ± 11	3.4	AMN 13(2)
MAC 88199	MWG	L	0.03 ± 0.01	144 ± 8	135 ± 1	3.3	AMN 13(3)
MET 96503	MWG	L	0.006 ± 0.002	200 ± 10	n.m.	3.1	AMN 21(2)
MET 96515	MWG	L	<0.004	n.m.	n.m.	3.0	AMN 21(2)
QUE 93030	MWG	H	0.31 ± 0.02	147 ± 2	143 ± 1	3.6	AMN 18(1)
QUE 93705	MWG	L	0.068 ± 0.003	131 ± 3	101 ± 12	3.4	AMN 18(2)
QUE 97008	MWG	L	0.003 ± 0.001	195 ± 8	n.m.	3.0	AMN 22(1)
QUE 97030	MWG	H	0.073 ± 0.006	163 ± 7	140 ± 10	3.4	AMN 22(1)
RC 075	UHaw.	H	0.022 ± 0.004	140 ± 1	140 ± 1	3.2	McCoy *et al.* (1993)
Richfield (dark)	UCLA	L	0.24 ± 0.01	177 ± 2	131 ± 4	3.7	Rubin *et al.* (1996)

TABLE 1. *Continued.*

Meteorite	Source*	Class	TL sensitivity, (Dhajala = 1.0)	Induced TL peak temperature (°C)	Induced TL peak width (°C)	Recommended petrologic type	Characterization reference
Richfield (light)	UCLA	L	0.25 ± 0.02	180 ± 3	132 ± 3	3.7	Rubin *et al.* (1996)
Sahara 97210	AMNH	L/LL	0.016 ± 0.001	177 ± 4	179 ± 5	3.2	Grossman (1998)
Tanezrouft 006	MPI	H	0.52 ± 0.03	162 ± 2	143 ± 2	3.7	Bischoff *et al.* (1992)
Wells	Reed	LL	0.006 ± 0.002	125 ± 16	n.m.	3.3	Grossman (1997)
Willard (b)	Farrell	H	0.17 ± 0.02	176 ± 7	132 ± 1	3.6	Grossman (1997)
WIS 91627	MWG	H	2.0 ± 0.1	195 ± 20	139 ± 6	3.8	AMN 16(1)
WSG 95300	MWG	H	0.017 ± 0.001	113 ± 2	80 ± 6	3.3	AMN 20(1)
Y-82038	NIPR	LL	0.026 ± 0.004	110 ± 5	97 ± 10	3.2	Ninagawa *et al.* (1998)
Y-82055	NIPR	L	0.26 ± 0.01	148 ± 6	157 ± 5	3.6	Ninagawa *et al.* (1998)
Y-82056	NIPR	L	0.28 ± 0.01	179 ± 3	147 ± 5	3.6	Ninagawa *et al.* (1998)
Y-82058	NIPR	L	0.15 ± 0.01	171 ± 9	154 ± 3	3.6	Ninagawa *et al.* (1998)
Y-82095	NIPR	L	0.27 ± 0.01	161 ± 6	158 ± 2	3.6	Ninagawa *et al.* (1998)
Y-82096	NIPR	L	0.24 ± 0.01	148 ± 2	152 ± 2	3.6	Ninagawa *et al.* (1998)
Y-82133	NIPR	H	0.11 ± 0.01	130 ± 8	127 ± 4	3.4	Ninagawa *et al.* (1998)
Y-790138	NIPR	H	0.34 ± 0.02	179 ± 2	146 ± 3	3.6	Ninagawa *et al.* (1998)
Y-790167	NIPR	H	0.36 ± 0.01	188 ± 2	156 ± 2	3.7	Ninagawa *et al.* (1998)
Y-790333	NIPR	H	0.28 ± 0.04	157 ± 4	152 ± 1	3.5	Ninagawa *et al.* (1998)
Y-790443	NIPR	H	0.33 ± 0.02	172 ± 1	147 ± 4	3.7	Ninagawa *et al.* (1998)
Y-790448	NIPR	LL	0.008 ± 0.001	111 ± 4	104 ± 13	3.1	Ninagawa *et al.* (1998)
Y-790461	NIPR	H	0.55 ± 0.02	170 ± 3	138 ± 1	3.7	Ninagawa *et al.* (1998)
Y-790770	NIPR	L	0.6 ± 0.05	184 ± 3	158 ± 3	3.7	Ninagawa *et al.* (1998)
Y-790787	NIPR	L	0.003 ± 0.003	n.m.	n.m.	n.d.‡	Ninagawa *et al.* (1998)
Y-790986	NIPR	H	0.73 ± 0.03	170 ± 4	151 ± 2	3.7	Ninagawa *et al.* (1998)
Y-790994	NIPR	L	0.18 ± 0.02	179 ± 10	162 ± 8	3.7	Ninagawa *et al.* (1998)
Y-791057	NIPR	H	0.47 ± 0.04	182 ± 3	158 ± 2	3.6	Ninagawa *et al.* (1998)
Y-791087	NIPR	H	0.66 ± 0.03	176 ± 2	150 ± 3	3.7	Ninagawa *et al.* (1998)
Y-791148	NIPR	H	0.39 ± 0.02	179 ± 6	144 ± 3	3.6	Ninagawa *et al.* (1998)
Y-791324	NIPR	LL	0.005 ± 0.003	112 ± 4	n.m.	3.0	Ninagawa *et al.* (1998)
Y-791340	NIPR	H	0.58 ± 0.03	170 ± 2	146 ± 2	3.7	Ninagawa *et al.* (1998)
Y-791366	NIPR	L	0.51 ± 0.03	176 ± 4	149 ± 3	3.6	Ninagawa *et al.* (1998)
Y-791428	NIPR	H	0.60 ± 0.03	167 ± 2	151 ± 4	3.7	Ninagawa *et al.* (1998)
Y-791429	NIPR	L	0.64 ± 0.04	174 ± 4	145 ± 3	3.7	Ninagawa *et al.* (1998)
Y-791537	NIPR	H	0.32 ± 0.01	162 ± 6	146 ± 4	3.6	Ninagawa *et al.* (1998)
Y-791558	NIPR	LL	0.0065 ± 0.0006	112 ± 3	110 ± 7	3.1	Ninagawa *et al.* (1998)
Y-791828	NIPR	L	1.6 ± 0.1	188 ± 3	148 ± 2	3.8	Ninagawa *et al.* (1998)
Y-791835	NIPR	L	0.38 ± 0.02	172 ± 6	161 ± 5	3.6	Ninagawa *et al.* (1998)
Y-791961	NIPR	L	0.32 ± 0.01	194 ± 3	165 ± 5	3.6	Ninagawa *et al.* (1998)
Y-792670	NIPR	L	0.28 ± 0.02	157 ± 7	149 ± 4	3.6	Ninagawa *et al.* (1998)
Y-792947	NIPR	H	0.10 ± 0.01	121 ± 8	126 ± 6	3.4	Ninagawa *et al.* (1998)
Y-793272	NIPR	L	0.18 ± 0.01	155 ± 3	152 ± 3	3.5	Ninagawa *et al.* (1998)
Y-793369	NIPR	L	0.17 ± 0.01	164 ± 8	147 ± 2	3.5	Ninagawa *et al.* (1998)
Y-793374	NIPR	L	0.27 ± 0.01	150 ± 3	153 ± 3	3.6	Ninagawa *et al.* (1998)
Y-793375	NIPR	L	0.25 ± 0.01	171 ± 1	162 ± 1	3.6	Ninagawa *et al.* (1998)
Y-793396	NIPR	L	0.28 ± 0.02	189 ± 4	169 ± 4	3.6	Ninagawa *et al.* (1998)
Y-793408	NIPR	L	0.042 ± 0.003	101 ± 4	92 ± 11	3.3	Ninagawa *et al.* (1998)
Y-793565	NIPR	LL	0.0028 ± 0.0006	n.m.	n.m.	3.0	Ninagawa *et al.* (1998)
Y-93567	NIPR	L	0.028 ± 0.001	151 ± 1	158 ± 9	3.3	Ninagawa *et al.* (1998)
Y-93596	NIPR	LL	0.0025 ± 0.0006	n.m.	n.m.	3.0	Ninagawa *et al.* (1998)

Uncertainties are one standard deviation based on triplicate aliquots. Abbreviations: n.m. = poor resolved in glow curve; ALH = Allan Hills; EET = Elephant Moraine; GRA = Graves Nunataks; GRO = Grosvenor Mountains; HaH = Hammadah al Hamra; LEW = Lewis Cliff; MAC = MacAlpine Hills; MET = Meteorite Hills; QUE = Queen Alexandra Range; RC = Roosevelt County; WIS = Wisconsin Range; WSG = Mount Wisting; Y = Yamato.

*Sources: MWG = Meteorite Working Group of NASA, Johnson Space Center, Houston, Texas, USA; NIPR = National Institute for Polar Research, Japan; UCLA = University of California, Los Angeles, California, USA; UHaw. = University of Hawaii-Manoa, Honolulu, Hawaii, USA; Farrell = Ron Farrell; Reed = Blaine Reed, Durango, Colorado, USA; R. Bartoschewitz, Gifhorn, Germany.

†AMN = *Antarctic Meteorite Newsletter*.

‡TL sensitivity may reflect extensive shock processing, as shown by prominent shock features (Ninagawa *et al.*, 1998).

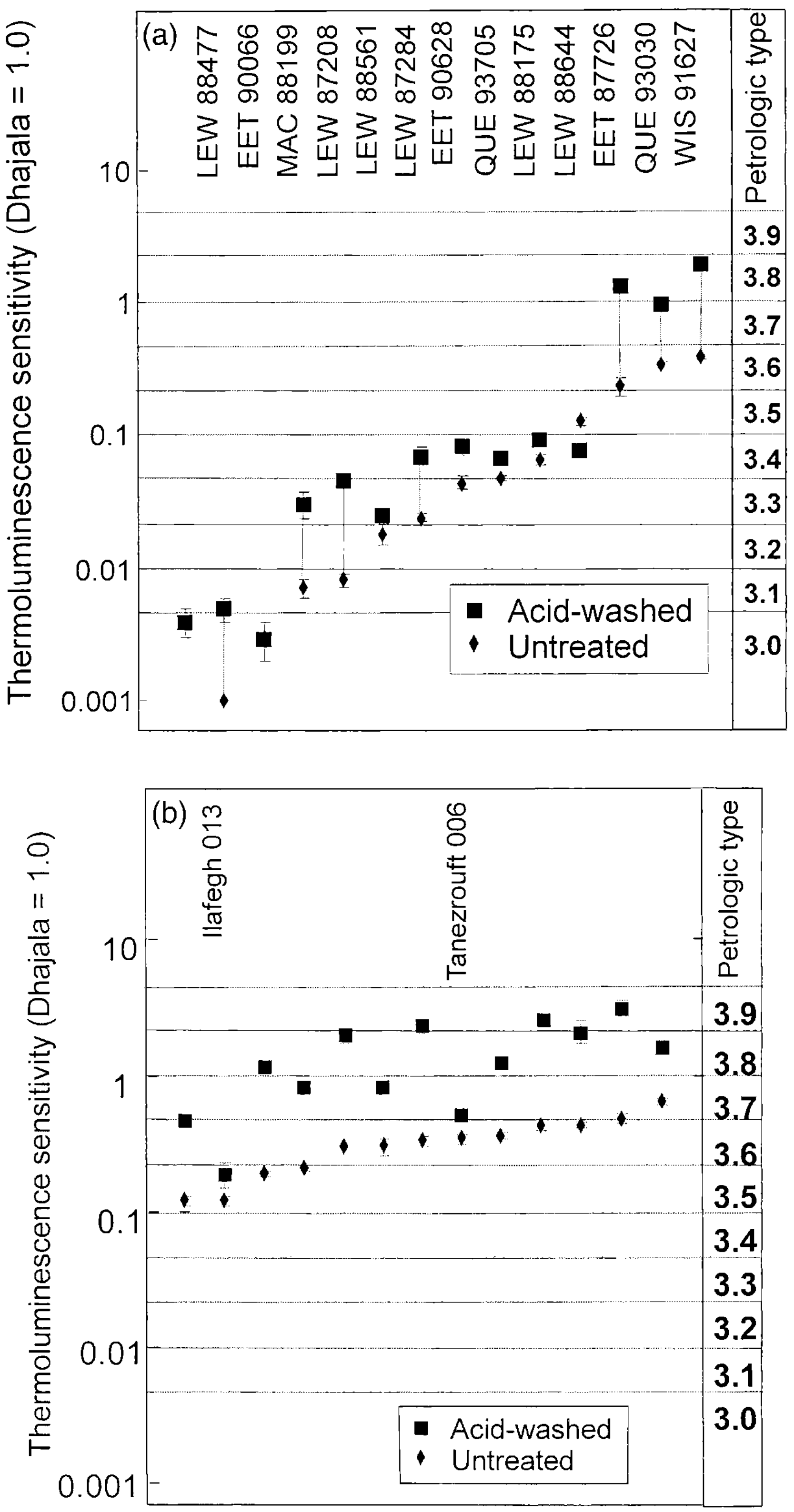

FIG. 1. Comparison of TL sensitivities of untreated and acid-washed type 3 ordinary chondrites. (a) Antarctic meteorites, (b) Saharan meteorites. TL sensitivity increases significantly after acid washing in most cases and reflects weathering. Axis on right shows petrologic divisions on the basis of TL sensitivity (*e.g.*, Sears *et al.*, 1991b). Uncertainties are 1σ on triplicate measurements of a single aliquot. Acid-washed samples are taken from the same aliquot.

TABLE 2. Possible pairing groups based on TL sensitivity and induced TL peak temperature and width.

Acfer 022
Afer 211

Acfer 028
Acfer 153
Acfer 171

Acfer 178
Acfer 210

Grosvenor Mountains 95502
GRO 95504
GRO 95512
GRO 95539

Grosvenor Mountains 95544
GRO 95545

Meteorite Hills 96503
MET 96515

TABLE 3. TL sensitivity of acid-washed unequilibrated ordinary chondrite finds.

Meteorite	TL sensitivity (Dhajala = 1.0)	Induced TL peak temperature (°C)	Induced TL peak width (°C)
Acfer 022	0.84 ± 0.06	191 ± 3	168 ± 3
Acfer 028	2.2 ± 0.2	188 ± 4	144 ± 2
Acfer 066	1.9 ± 0.2	186 ± 5	158 ± 3
Acfer 080	2.5 ± 0.2	201 ± 8	176 ± 12
Acfer 129	0.46 ± 0.02	153 ± 1	129 ± 2
Acfer 153	2.1 ± 0.4	197 ± 11	144 ± 1
Acfer 159	1.13 ± 0.08	185 ± 9	141 ± 1
Acfer 160	1.6 ± 0.2	175 ± 4	129 ± 1
Acfer 163	1.23 ± 0.07	185 ± 2	140 ± 3
Acfer 171	0.82 ± 0.07	185 ± 5	139 ± 4
Acfer 192	3.1 ± 0.4	187 ± 3	144 ± 1
Adrar 003	0.02 ± 0.01	184 ± 3	140 ± 20
EET 87726	1.33 ± 0.07	207 ± 4	156 ± 3
EET 90066	0.003 ± 0.001	202 ± 4	170 ± 20
EET 90161	0.004 ± 0.001	209 ± 8	156 ± 9
EET 90628	0.081 ± 0.01	187 ± 6	161 ± 5
Ilafegh 013	0.19 ± 0.04	197 ± 2	152 ± 3
LEW 87208	0.044 ± 0.003	173 ± 4	147 ± 2
LEW 87284	0.07 ± 0.01	194 ± 8	153 ± 9
LEW 88175	0.09 ± 0.01	152 ± 5	122 ± 3
LEW 88477	0.005 ± 0.001	190 ± 20	150 ± 20
LEW 88561	0.025 ± 0.003	148 ± 1	94 ± 3
LEW 88644	0.074 ± 0.005	130 ± 2	88 ± 2
MAC 88199	0.030 ± 0.007	164 ± 8	130 ± 20
QUE 93030	0.962 ± 0.042	178 ± 3	151 ± 5
QUE 93705	0.068 ± 0.003	151 ± 3	100 ± 10
Tanezrouft 006	0.52 ± 0.03	182 ± 2	143 ± 2
WIS 91627	2.0 ± 0.1	220 ± 20	139 ± 6

Uncertainties are 1σ based on triplicate aliquots. Abbreviations: EET = Elephant Moraine; LEW = Lewis Cliff; MAC = MacAlpine Hills; QUE = Queen Alexandra Range; WIS = Wisconsin Range.

The TL sensitivity of the samples, however, was sometimes increased by a factor of 10, although the typical increase was a factor of 2–3 for Antarctic meteorites (in agreement with Sears *et al.*, 1982), and ∼5 for Saharan meteorites. Saharan meteorites also tend to look more weathered than Antarctic meteorites and seldom does the acid-washing restore their pale gray color. Nevertheless, compared with the 5 orders of magnitude range in TL sensitivity shown by the type 3 ordinary chondrites (Sears *et al.*, 1980, 1991b), the effects of weathering are quite modest.

Induced Thermoluminescence Peak Temperature and Width

The samples in this study exhibit the same trends as observed by Sears *et al.* (1991b) (Fig. 2). Meteorites of petrologic type >3.5 exhibit higher peak temperatures and widths than the type <3.5 meteorites. There is not, however, a direct relationship between petrologic type and peak temperature and width and there is significant overlap of petrologic types within the groups.

DISCUSSION

Classification and New Primitive Unequilibrated Ordinary Chondrites

TL sensitivity is affected by metamorphism at all levels throughout the UOCs, although it is especially sensitive to the lowest levels of metamorphism (petrologic types <3.5). Compositional heterogeneity of olivine, abundance of ^{36}Ar, bulk C abundance (reflecting abundance of interstellar diamond) (Huss and Lewis, 1994; Russell *et al.*, 1996) are also sensitive to metamorphism, although for restricted ranges within the type 3 meteorites (*e.g.*, Sears *et al.*, 1991b). Metal and sulfide compositions are also affected by metamorphism (Afiatallab and Wasson, 1980; Zanda *et al.*, 1994), but the exact details of variation within UOCs are not known.

Using the petrographic type boundaries of Sears *et al.* (1980, 1991b), the present samples range from 3.0 to 3.9, and thus cover the full range of the UOCs (Table 1; Fig. 3). There is generally a good correlation between petrographic type assigned by TL sensitivity and other methods, especially for petrologic types >3.5.

Sixteen of our present samples representing 11 separate falls have TL sensitivities equivalent to petrographic type 3.0–3.1 (Table 4; Sears *et al.*, 1991b). Adrar 003 has been described as a highly unequilibrated ordinary chondrite with petrographic similarities to Semarkona (LL3.0) (Hutchison *et al.*, 1991). Olivine crystals have overgrowths similar to those found in Krymka (LL3.1) and Chainpur (LL3.2), and it has a D/H ratio similar to that of Krymka. The abundance of diamond is slightly less than in Krymka and is more similar to that of Tieschitz (H3.6) and the carbon isotopic composition of the meteorite is similar to that of Krymka (Russell *et al.*, 1996). The TL sensitivity of Adrar 003 is similar to the TL sensitivity of Krymka, but acid-washing increases TL sensitivity to just above the border of the 3.2 boundary (Table 3; Sears *et al.*, 1991b). Considering all the data, and the similarities between this meteorite and Krymka, Adrar 003 is best described as type 3.1.

We suggest that the petrologic type of GRO 95502 and samples paired with it is type 3.1–3.2. These samples have a

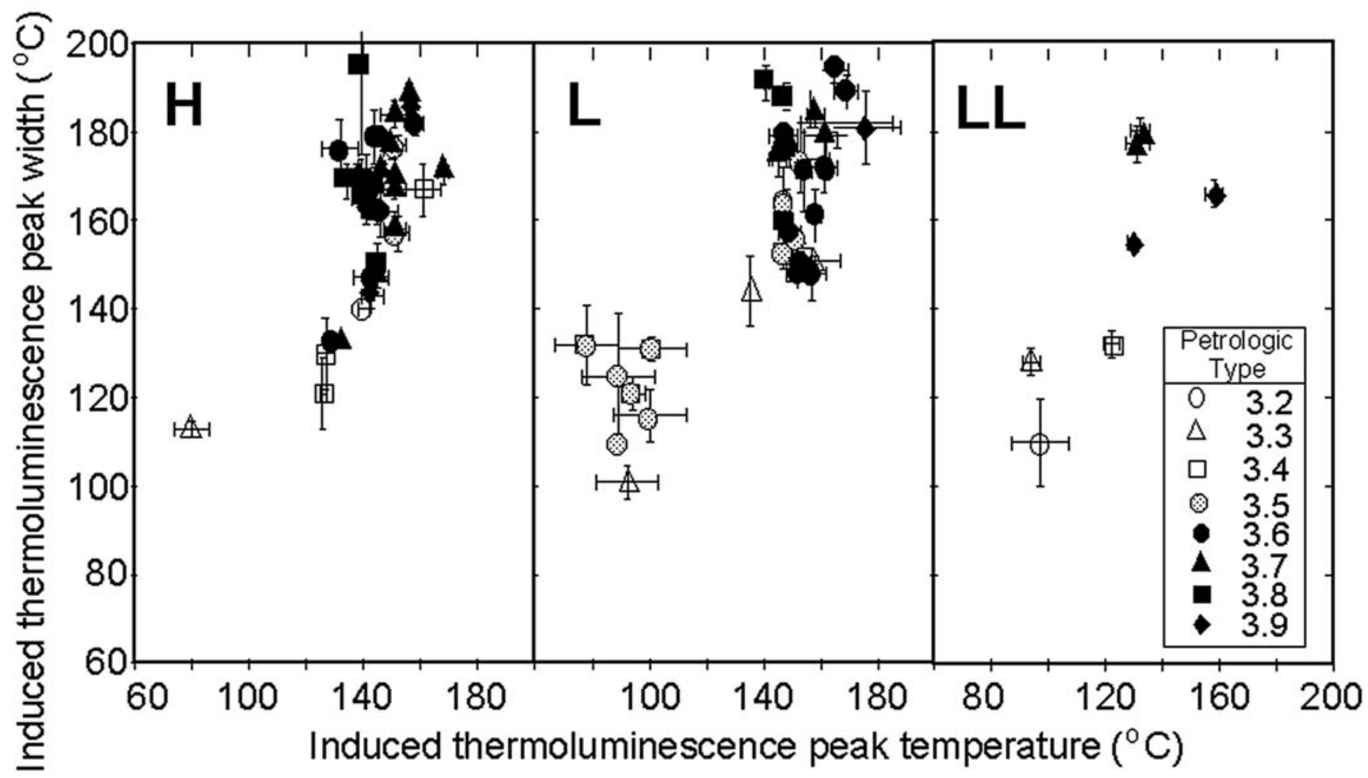

FIG. 2. Induced TL peak temperature *vs.* peak width for type 3 ordinary chondrites. There are two distinct clusters. Meteorites of petrologic type >3.5 (filled points) tend to plot in the upper cluster, while those of type <3.5 (open points) tend to plot in the lower cluster. Petrologic type 3.5 meteorites plot in both clusters. Includes data from this study and Sears *et al.* (1991b).

TABLE 4. Candidates for petrologic type 3.0 and 3.1.

Sample	Class[*]	Mass (g)	Fa CV	Fs CV	Petrographic notes[§]
Adrar 003	L/LL3.1	287	50[#]	60[#]	Fe-carbide veins (?), non-stoichiometric overgrowth on olivine.
EET 90066	L3.0	9.8	80[#]	N.A.	Close-paced aggregate of chondrules and chondrule fragments, black matrix.
EET 90161	L3.0–3.1	9.7	70[#]	N.A.	Close-paced aggregate of chondrules and chondrule fragments, black matrix, minor weathering.
GRO 95502 group[†]	L3.0	10491.2	80[#]	N.A.	Numerous chondrules, up to 3.2 mm across, black matrix. Estimated type 3.5.
LEW 88477	LL3.1	12.3	50[#]	N.A.	N.A.
MET 96503 group[‡]	L3.0	308.7	N.A.	N.A.	Weakly shocked. Numerous large chondrules, abundant polysynthetically twinned pyroxene. Estimated type 3.5–3.6.
Y-790787	≥L3.1	46.1	15	17	Regions of shock melt.
Y-791324	LL3.0–3.1	20.7	54	102	N.A.
Y-791558	LL3.1	101.6	53	78	N.A.
Y-793565	LL3.0	16.2	60	96	N.A.
Y-793596	LL3.0	62.9	49	101	N.A.

Abbreviations: N.A. = not available; EET = Elephant Moraine; GRO = Grosvenor Mountains; LEW = Lewis Cliff; MET = Meteorite Hills; Y = Yamato.

[*] Chemical classification from mineral composition and petrography. Type based on TL sensitivity (Sears *et al.*, 1991b). Fayalite and ferrosilite coffiecient of variation from data in compilation of Koblitz (1998).

[†] Pairing group members: GRO 95502, GRO 95504, GRO 95512, GRO 95539, GRO 95544.

[‡] Pairing group members: MET 96503 and MET 96515.

[§] Petrographic notes from Hutchison *et al.* (1991), Ninagawa *et al.* (2000), and the *Antarctic Meteorite Newsletter*.

[#] Converted from range and mean data (*e.g.*, Sears and Weeks, 1983).

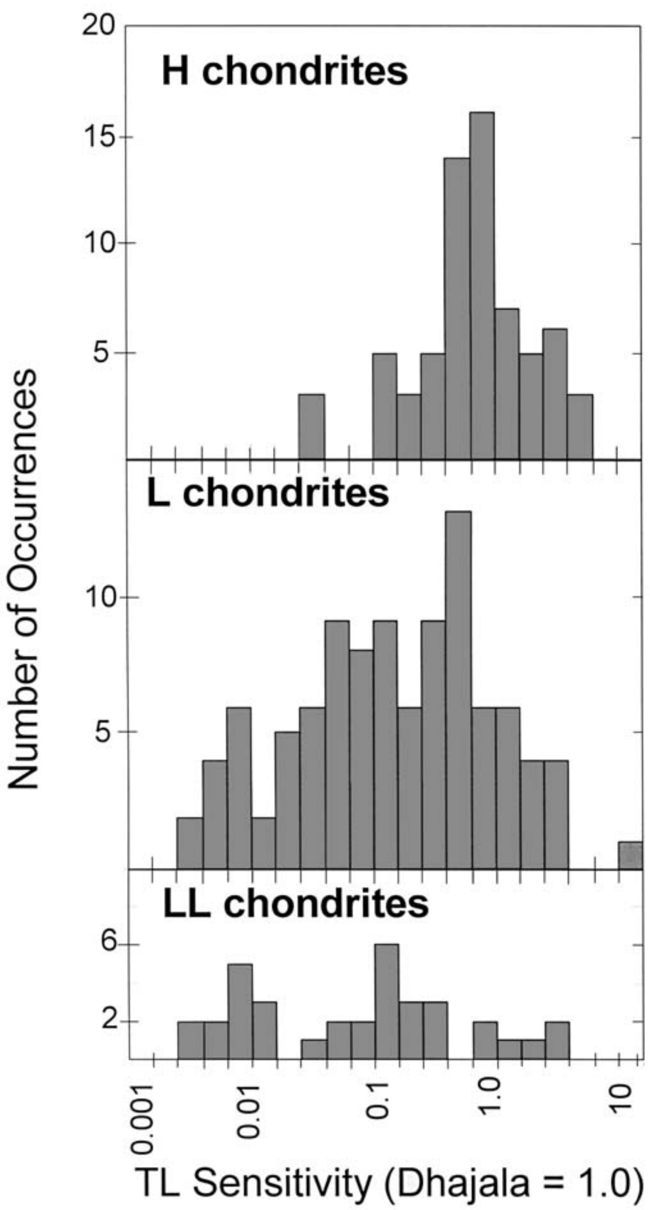

FIG. 3. Thermoluminescence sensitivity of type 3 ordinary chondrites, divided by chemical class. Compared to the L and LL chondrites, H chondrites exhibit a preferred TL sensitivity of ~0.8 relative to Dhajala and do not extend to low TL sensitivities. Data from current study and Sears *et al.* (1991b).

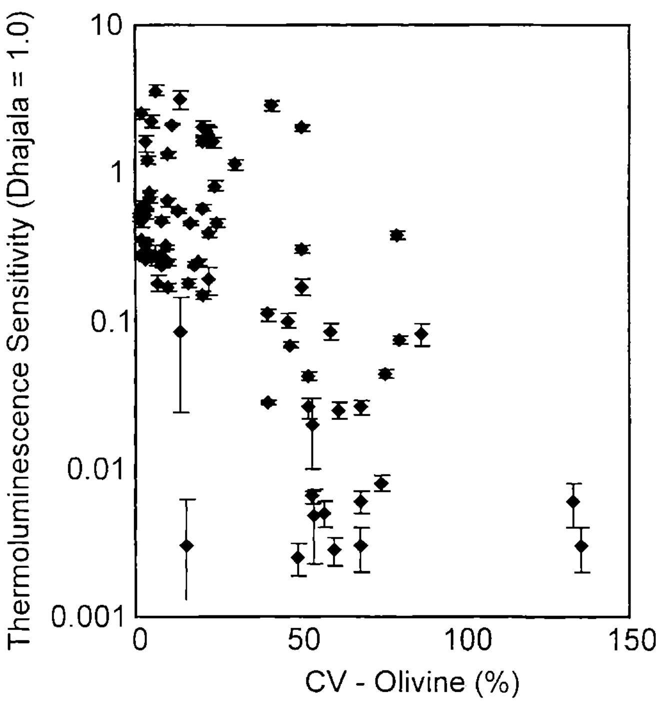

FIG. 4. Thermoluminescence sensitivity of type 3 ordinary chondrites against olivine heterogeneity (Table 1). Olivine heterogeneity tends to increase with decreasing TL sensitivity, although the data exhibit significant scatter. These data can be compared with those of Sears *et al.* (1991b). The lone sample with TL sensitivity <0.01 and olivine heterogeneity <25 is Y-790787, and this meteorite contains significant amount of melt glass, suggesting its TL sensitivity has been lowered by shock processing. Olivine heterogeneity data from sources listed in Table 1.

total mass of ~10 kg, making this one of the most important meteorites discovered in Antarctica, being extremely primitive and available in large amounts. GRO 95502, GRO 95504, and GRO 95512 have similar petrographic textures and similar olivine and pyroxene composition ranges and were suggested to be of petrologic type ~3.5 (Mason, 1997). However, GRO 95539 has not been analyzed in detail. The TL sensitivity of these samples is too low by almost 2 orders of magnitude to fit the suggested petrologic type of ~3.5. Shock pressures >30 GPa cause feldspar, the TL phosphor, to melt, thus lowering TL sensitivity by ~2 orders of magnitude (Haq *et al.*, 1988), but evidence for such intense shock is absent in thin sections of these meteorites. Weathering would not lower the TL sensitivity by the 2 orders of magnitude required, and the agreement between paired fragments (Table 2) suggests that we did not sample atypical lithologies. We therefore have no grounds for questioning the TL petrographic type assignment of GRO 95502, but clearly further work on this sample would be justified for a number of reasons. However, we note that olivine heterogeneity is a poor guide to subclassification for petrologic types <3.5 (Fig. 4).

Paired fragments MET 96503 and MET 96515 (total weight ~0.3 kg) are type 3.5 based on olivine heterogeneity data of McCoy (1998) but 3.1–3.2 based on TL sensitivity. As with GRO 95502, we do not think that the TL sensitivity is low because of shock, weathering or unfortunate sampling, and suggest that this meteorite is also very primitive.

Y-790787 exhibits TL sensitivity similar to type 3.0–3.1 UOCs, but a limited range of olivine and pyroxene composition compared with other meteorites of petrologic type <3.5 (Table 4; Sears *et al.*, 1991b). Extensive shock melting is observed in thin section (Ninagawa *et al.*, 2000) which, depending on its original value might have considerably reduced the TL sensitivity (*e.g.*, Hartmetz *et al.*, 1986; Stöffler *et al.*, 1991). TL sensitivity of this sample is not suited to the assignment of a petrographic type for this sample.

The remaining meteorites in Table 4 have not been described in the primary literature and the only available descriptions are the discovery announcements in newsletters and catalogues. Elephant Moraine (EET) 90066 is a close-packed aggregate of chondrules and chondrule fragments, the chondrules being up to 2.4 mm in diameter and set in a black matrix (Mason, 1992). EET 90151 has chondrules up to 1.5 mm in diameter and minor abundances of weathering products were noted in thin section (Mason, 1992). LEW 88477 has chondrules up to 2.4 mm in diameter, set in a black opaque matrix and also has small amounts of weathering products (Mason, 1991). Aside from the presence of shock melt in Y-790787, no textural notes are available for the Yamato samples.

Thermal History and Parent Bodies

The present data (Fig. 3) support the observation of Sears *et al.* (1991b) that H chondrites exhibit significantly different TL sensitivity distributions than L and LL chondrites. The present data confirm that the H chondrites exhibit a smaller range of metamorphism and tend to be more metamorphosed than the L and LL chondrites.

Models of parent bodies of meteorites often start with the assumption that the distribution of petrographic types reflects the thermal profile in the parent bodies, and also assume that meteorites of the same class came from one (or a few) parent bodies (*e.g.*, Grimm, 1985). Much of our discussion is based on these assumptions as well, but we stress that the relative abundances of petrographic types and subtypes in the ordinary chondrite classes could reflect sampling biases rather than parent-body metamorphism. The meteorite population is not representative of the asteroid population, being heavily influenced by a few meteoroid-producing impacts, the self-limiting nature of orbital transfer using resonances with Jupiter and Saturn, and atmospheric passage (*e.g.*, Sears and Akridge, 1998). The H-chondrite meteorites, in particular, are dominated by samples from a few large impacts (*e.g.*, Graf and Marti, 1995) and thus the lack of highly unequilibrated H chondrites (Fig. 3) may merely indicate that they were not sampled during these events.

It is also possible that the observed distribution of petrologic subtypes is an artifact of the petrographic classification process. Assignment of chemical class to ordinary chondrites of low petrologic type is a difficult, and at least partly qualitative, process. For example, assignment of chemical class to RC 075, one of the least metamorphosed H chondrites (type 3.2), was largely on the basis of oxygen isotopic composition, a procedure not typically part of ordinary chondrite classification (McCoy *et al.*, 1993). Possibly some of the L and LL chondrites of petrologic type <3.5 are unrecognized H chondrites, and thus the distributions of petrologic type are similar among the chemical classes.

Sears *et al.* (1991b) proposed three explanations for this distribution (not considering the possibility that the distribution was skewed by sampling or chemical classification uncertainties): (1) the major heat source was decay of ^{26}Al and the H-chondrite parent body formed before the L and LL parent bodies, and was thus heated to higher peak temperatures, (2) the major heat source was internal heating and the H chondrites in the collection came from greater depths in their parent body than the L and LL chondrites, and (3) the H parent body differed in physical properties from the L and LL parent bodies. They suggested that the first two explanations were contradicted by other data, and thus that differences in physical properties might be important in determining the thermal histories of meteorite parent bodies. Subsequent suggestions of other sources of heat, such as the decay of ^{60}Fe (Shukolyukov and Lugmair, 1993), do not significantly change their argument. Possible support for their explanation was noted in the tendency for equilibrated H chondrites to have higher metallographic cooling rates than equilibrated L and LL chondrites (*e.g.*, Wood, 1979; Lipschutz *et al.*, 1989; McCoy *et al.*, 1990). Direct comparison of metallographic cooling rates of the UOCs is not presently possible due to the requirement that the metal be initially homogenized by heating >900 K (Herpfer *et al.*, 1994).

The available data do not provide definitive support for a strong dependence in physical properties with thermal history among the ordinary chondrites, but neither do the data rule out such a dependence. The H chondrites have essentially the same porosity as L and LL chondrites, but it is unclear whether porosity should reflect internal structure for asteroidal-sized bodies (Consolmagno *et al.*, 1998). H chondrites may also have higher electrical conductivity, by a factor of ~100×, than L and LL chondrites (Fig. 5; Evernden and Verhoogen, 1956; Brecher *et al.*, 1975). The present TL sensitivity data (Fig. 5) could thus be explained as reflecting an electric-based heat source, the H-chondrite parent body being heated to higher temperatures due to higher electrical conductivity (*e.g.*, Herbert and Sonett, 1979) and the scarcity of least metamorphosed H chondrites might thus reflect the inherent greater sensitivity of the H-chondrite body to heating compared to L and LL chondrites.

Other bulk sample data are sparse and may be partially compromised by weathering in finds, but H chondrites may have greater thermal diffusivities than those of L chondrites, on average (Yomogida and Matsui, 1983). The thermal diffusivities of three L chondrite falls (Bruderheim, New Concord, Leedey) of shock stage <S4 (Stöffler *et al.*, 1991; Rubin, 1994) are ~10% lower than those of H chondrites. L chondrites of shock stage S4 or greater (Arapahoe, Farmington, Kunashak) have thermal diffusivities similar to, or slightly higher than, H chondrites. Insufficient data are available for LL chondrites, but we assume their thermal diffusivities are similar to L chondrites. The apparent difference in diffusivities could result in significantly different metamorphic histories for L, LL and H chondrites.

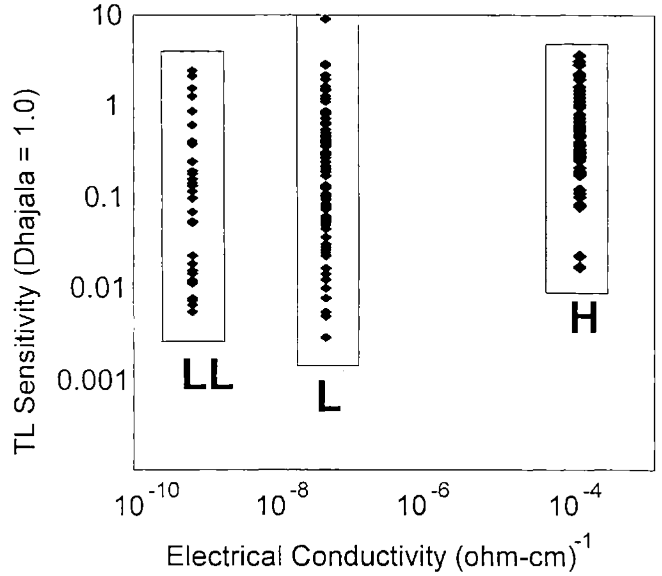

FIG. 5. Comparison of induced thermoluminescence sensitivity and electrical conductivity at 300 K. H chondrites, which tend to have higher TL sensitivity values compared to L and LL chondrites, have significantly higher electrical conductivities, although the database of electrical conductivity data is limited to 2–4 samples per group. Data points are present TL data (Table 1) and boxes indicate the range of electrical conductivity for each group. Electrical conductivity data are from Evernden and Verhoogen (1956) and Brecher *et al.* (1975).

Numerical calculations of the thermal history of parent bodies using the decay of ^{26}Al as a heat source show that, using the "shocked" L-chondrite and H-chondrite diffusivities results in parent-body histories of rapid heating, with cooling rate dependent on depth (Fig. 6a; Miyamoto *et al.*, 1981; Akridge *et al.*, 1998). The same calculation using the less shocked L-chondrite diffusivities shows rapid temperature rise followed by very slow cooling in the interior of the body (Fig. 6b). In accord with the results of Akridge *et al.* (1998), addition of a thin (2.5 km thick) regolith results in higher peak temperatures and slower cooling rates regardless of model (Fig. 6a,b). Figure 6a,b reflect extremes in the thermal diffusivity data, and it is likely that cooling histories for H chondrites were somewhat slower than Fig. 6a, and those for L chondrites were faster than Fig. 6b, in better accord with cooling rate indicators (*e.g.*, Scott and Rajan, 1981; Lipschutz *et al.*, 1989; Keil *et al.*, 1994).

Thus, one possible interpretation of the data (Fig. 3) is that the H and L (and possibly LL) parent bodies had different thermal histories due to a combination of physical properties and regolith thickness. The H-chondrite parent body had a significant regolith (>1 km in thickness) which was sufficient to counterbalance its higher diffusivity compared to L and LL chondrites, thus resulting in virtually uniform peak metamorphic temperatures throughout the body and moderate cooling rates compared to a regolith-free body (Akridge *et al.*, 1998). Due to the insulation effect of the regolith, highly

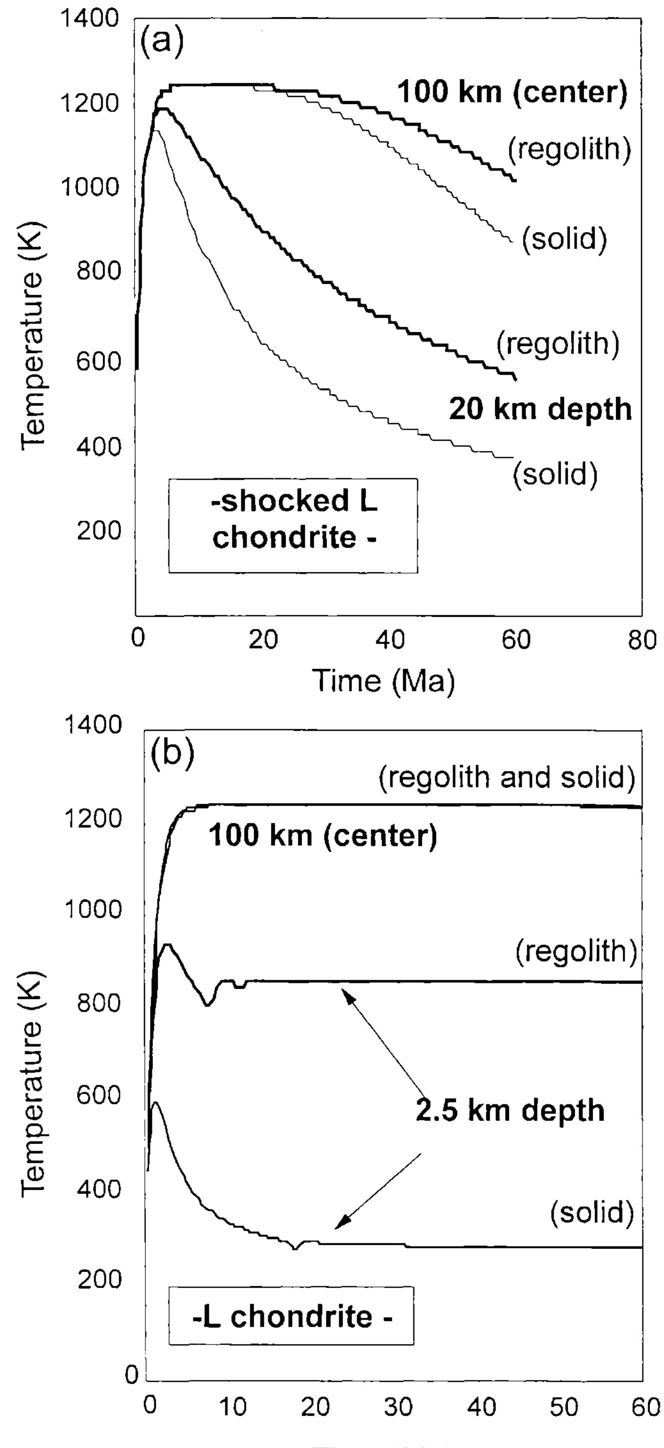

FIG. 6. Calculated thermal histories of L/LL chondrite parent bodies. Calculations are for 100 km diameter bodies, modeled as solid rock and with 2.5 km thick regoliths. Calculation procedures are described by Akridge *et al.* (1998). In (a), the thermal conductivity of an L chondrite of shock stage >S4 (Kunashak) is used, with a conductivity similar to H chondrites (Fig. 5) while in (b) an L chondrite of shock stage <S4 (Leedey) is used (data from Yomogida and Matsui, 1983; shock classification data from Stöffler *et al.*, 1991 and Rubin, 1994). The results in (a) resemble calculated thermal histories for H chondrites (Akridge *et al.*, 1998).

unequilibrated H chondrites would form only at the very surface of the body (assuming an internal heat source), the remainder of the body being equilibrated. In contrast, the L and LL parent bodies can be described as nearly regolith-free or as "onion skin" bodies (*e.g.*, Miyamoto *et al.*, 1981). The lower thermal diffusivity of these bodies relative to H chondrites result in the formation of equilibrated material at depth in the body, and this material cools slowly relative to the H-chondrite body (Fig. 6b). The outer rim of the body, however, would exhibit a significant temperature profile, including a multi-kilometer thick unequilibrated zone with peak metamorphic temperatures <600 °C. If these bodies were then sampled volumetrically, a greater percentage of L and LL chondrites would be highly unequilibrated, compared to H chondrites. An additional observation in support of this concept is cooling rates for chondrites, inferred from compositional profiles in metal and ^{40}Ar-^{39}Ar ages. Equilibrated L and LL chondrites tend to exhibit lower cooling rates than H chondrites, in agreement with the models based on thermal diffusivity differences (Fig. 6b); they also exhibit a greater range in cooling rates and a trend of decreasing cooling rate with petrologic type, unlike the H chondrites which have fairly homogeneous cooling rates, supportive of a classical "regolith-free" onion skin interpretation for these bodies (Lipschutz *et al.*, 1989).

Our interpretation applies only to the critical metamorphic period of parent-body history. Regolithic breccias are common among all three ordinary chondrite classes (*e.g.*, Bunch and Rajan, 1988), but this does not invalidate the interpretation. L and LL chondrites, are likely to have been mantled by extensive regoliths after metamorphism due to impact processing, as shown by the prevalence of thick regoliths among modern asteroids (*e.g.*, Veverka *et al.*, 1999).

CONCLUSIONS

Like other thermal history indicators, induced TL data does not fully resolve the issue of parent-body structure and metamorphic heat sources. However, these data do place a number of constraints on the thermal history of UOCs:

(1) The unequilibrated H chondrites exhibit a more limited range of metamorphism and tend to have been more metamorphosed than L and LL chondrites.

(2) Weathering does not change induced TL peak temperatures and widths. Weathering does reduced TL sensitivity, but the effect is typically no more than a factor of 0.1 petrologic type units for Antarctic meteorites and 0.2 for meteorites from hot deserts.

(3) Eleven additional candidates for least degrees of metamorphism (types 3.0–3.1) have been identified. These samples are of special interest as sources for material (chondrules, matrix) representative of the early solar system.

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