Geochimica et Cosmochimica Acta Vol. 50, pp. 1031–1038

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0016-7037/86/\$3.00 + .00

Thermoluminescence and the shock and reheating history of meteorites—III: The shergottites*

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(*Received May* 21, 1985; *accepted in revised form February* 14, 1986)

Abstract—The thermoluminescence (TL) sensitivities of the four shergottites are extremely low and display a 10-fold range (values are 0.15 to 1.8, where Dhajala = 1000), with the TL sensitivity decreasing with increasing peak temperature (from about 140 to 180°C) and peak width (from about 100 to 150°C). A mineral separation experiment indicates that the mineral producing the TL is associated with the maskelynite, presumably nanogram per gram quantities of crystalline feldspar are present in the maskelynite. Samples of Shergotty, Allan Hills A77005 and Elephant Moraine A79001 were annealed at 400–900°C for 24–98 h. For Shergotty, the peak increased in width and moved to higher temperatures in the glow-curve, while for Allan Hills A77005 and Elephant Moraine A79001, whose TL peaks were already broad and at high temperatures, remained unchanged. All samples showed a significant increase in TL sensitivity when annealed at >600–700°C. Apparently, the feldspar is present in varying proportions of high to low-temperature form and in amounts which vary from meteorite to meteorite. We conclude that the shergottites underwent post-shock recrystallization at a variety of cooling rates and that the order of increasing cooling rate was Shergotty, Allan Hills A77005, Zagami and Elephant Moraine A79001. The presence of a high-temperature phase implies peak post-shock cooling temperatures >600°C and that the size of the ejecta was <10 m. Current theories are well able to explain the ejection of such small objects from Mars.

1. INTRODUCTION

THE SHERGOTTITES are intensely shocked assemblages of pyroxene, maskelynite and sometimes olivine, with minor magnetite, pyrrhotite and whitlockite. The shock experienced by the class has caused the plagioclase originally present to be completely converted to maskelynite. Their young ages (1.3 Ga), igneous origin, Fe/Mn ratio and trapped gas composition has led many authors to conclude that the meteorites were ejected from Mars (see reviews by WOOD and ASHWAL, 1981, and MCSWEEN, 1984).

Many of the ordinary chondrites have also experienced an intense shock event and it is often assumed that this was associated with the break-up of their parent body; it is possible that it was ejection from Mars that caused the shergottites to be heavily shocked. Thermoluminescence (TL) has proved a useful technique for exploring the magnitude of the shock experienced by ordinary chondrites, since the residual temperatures associated with the shock caused significant changes in the nature and amount of the TL phosphor, feldspar (SEARS, 1980; SEARS *et al.*, 1984). In the present paper we report a TL study of the known shergottites, Shergotty, Allan Hills A77005, Zagami and Elephant Moraine A79001 (lithology A). Our hope was that such a study would shed further light on the shock history of this class.

2. EXPERIMENTAL

Two fragments or more from each meteorite, whose sources and masses are given in Table 1, were ground and 5 mg aliquots placed in a 5 mm copper dish for TL measurement. The apparatus described by SEARS and WEEKS (1983) was used. The TL sensitivity was measured by removing the natural TL by heating to 500°C in the TL apparatus and measuring the TL induced by exposure to a 250 mCi Sr-90 beta source. Samples of the Dhajala meteorite were used for normalization. Due to the very low TL sensitivity of the shergottites, 10 minute irradiation times were used instead of the 2 minutes used for ordinary chondrites, a heating rate of 15°C/sec was used rather than the usual 7.5°C/sec, and the 4 mm aperture was replaced by a 5 mm aperture. Each measurement was made at least three times and the data averaged. The uncertainties quoted are standard deviations, compounded with those of the Dhajala meteorite in the case of the TL sensitivity.

Mineral separation experiments were performed on Allan Hills A77005 in an attempt to identify the luminescing phase(s). A density gradient column was employed, with water and Clerici solution as the light and heavy density components, respectively (MULLER, 1977). Six fractions from a 20 mg sample were obtained, and these were prepared for TL measurement by filtering from the Clerici solution, washing in water and acetone, and depositing on 10 mm copper disks by evaporation of an acetone suspension (Table 2). No attempt was made to calibrate the density of the column, instead the

Table 1. Thermoluminescence data on shergottite meteorites+

Meteorite	Source*	Maskelynite** (vol%)	Mass (mg)	TL sensitivity (Dhajala = 1000)	Peak temperature (°C)	FWHM@ (°C)
Shergotty,7	GSI	23.3	152	1.2 +/-0.4	155+/-8	117+/-17
Shergotty,20	GSI		172	1.8 +/-0.5	143+/-8	134+/-22
ALHA77005,67	MWG	8	81	0.60+/-0.2	169+/-9	128+/-20
ALHA77005,68	MWG		57	0.73+/-0.1	236+/-8	126+/-32
ALHA77005,74	MWG		3000	0.42+/-0.09	214+/-15	144+/-25
Zagami,1	BM	21.8	70	0.42+/-0.08	156+/-10	155+/-16
Zagami,2	BM		120	0.35+/-0.08	156+/-2	140+/-20
EETA79001\$,171	MWG	17	32	0.25+/-0.07	182+/-4	145+/-6
EETA79001\$,170	MWG		30	0.15+/-0.02	181+/-7	155+/-7
EETA79001\$,183	MWG		3000	0.81+/-0.29	168+/-10	140+/-24

+ Errors quoted are 1 sigma. ALHA refers to Allan Hills and EETA to Elephant Moraine.
* MWG: Meteorite Working Group of NASA/NSF
GSI: Geological Survey of India, Calcutta. (Curatorial fragment number indicated).
BM: British Museum (R. Hutchison, Catalogue number BM1966,54).
\$ Lithology A (See McSween and Jarosewich, 1983).
** From McSween and Jarosewich (1983); Stolper and McSween (1979) and Anon (1978).
@ Full width of the TL peak at half the maximum intensity.

* Presented at the Shergotty-Nakhla-Chassigny Symposia, 16th Lunar and Planetary Science Conference, 1985.

Table 2. Thermoluminescence sensitivity of 6 density separates from Allan Hills A77005.

Fraction	Density	TL sens. (arb)	Mass (%)	-----Mineral Composition*----- Pyrox.	Oliv.	Feld.	Phos.	Metal
A	heavy	4.9	62	4	7	1	-	-
B	↓	6.6	13	10	3	5	-	-
C	↓	8.3	10	6	4	3	-	-
D	↓	5.1	8	8	7	4	-	-
E	↓	12.5	5	4	10	4	1	-
F	light	36.0	2	2	2	13	-	1

* Number of grains identified by SEM/EDS

Table 3. Thermoluminescence sensitivity, peak temperature and peak width data for three shergottites annealed at various temperatures for 24 h +.

Meteorite	Anneal. Temp. (°C)	TL sens. (Dhajala =1000)	Peak Temp. (°C)	FWHM** (°C)
Shergotty*	400	0.83+/-0.13	195+/-22	165+/-30
	600	1.7 +/-1.1	216+/-12	172+/-12
	850@	45.0+/-10.0	198+/-11	157+/-1
	900@	23.3+/-4	228+/-12	176+/-3
ALHA77005,74	Unan.	0.42+/-0.09	214+/-15	144+/-25
	450	0.52+/-0.10	206+/-9	164+/-15
	500	0.68+/-0.10	219+/-27	136+/-3
	600	0.49+/-0.13	217+/-20	153+/-16
	700	1.11+/-0.24	192+/-12	184+/-17
	800	2.64+/-1.00	206+/-6	151+/-8
EETA79001,183	Unan.	0.81+/-0.29	168+/-10	140+/-24
	450	0.48+/-0.20	182+/-4	135+/-16
	500	0.50+/-0.10	196+/-15	172+/-5
	600	4.2 +/-3.2	176+/-14	147+/-31
	700	3.7 +/-3.0	201+/-14	148+/-26
	800	10.3+/-1.3	222+/-5	193+/-11

\+ Errors quoted are 1 sigma on measurements for 3 aliquants from a single vial.
* Mixture of Shergotty,20 and Shergotty,7.
** Full width of the TL peak at half its maximum intensity.
@ Annealed for 98 h.

minerals on each disk were identified by a Tracor Northern NS-880 X-ray analysis system attached to a Cambridge S600 Scanning Electron Microscope (SEM/EDS).

Interpretation of the data was helped considerably by experiments in which samples of three shergottites were annealed at various temperatures. Such annealing experiments have proved of great value in understanding the TL properties of type 3 ordinary chondrites, whose TL phosphor is also feldspar, and essentially the same procedures were used here as in the previous work (GUIMON *et al.*, 1985). Aliquants of Shergotty, Allan Hills A77005 and Elephant Moraine A79001 weighing 20 mg were sealed in a pure nitrogen atmosphere in quartz vials and annealed in wire-wound tube furnaces for the times and temperatures indicated in Table 3. Each value reported represents the mean (± 1 sigma) of three splits from the same vial.

3. RESULTS

Figure 1 shows typical examples of the glow-curves (light emitted as a function of temperature) for Shergotty and Elephant Moraine A79001, where A79001 is presented on a 10 times more sensitive scale. The curves have similar overall structure, consisting of a broad band of TL between 100–300°C which is actually a composite of several smaller, individual peaks, but there are significant, and in some respects systematic, differences in the curves for the four meteorites.

The following three measurements were made from each glow-curve: (1) the intensity of the TL at maximum emission (*i.e.* the TL sensitivity); (2) the temperature at which the TL emission is at a maximum (the peak temperature); and (3) the width of the TL peak at half its maximum intensity (FWHM). The results are summarized in Table 1 and are plotted in Figs. 2 and 3. The TL sensitivity values for the shergottites are the lowest yet encountered in meteorite studies. They show a factor of 10 spread, but all are below the lowest type 3 ordinary chondrite in TL sensitivity (Fig. 2). Replicates from a given meteorite usually agree to within a factor of 1.5, but in the case of Elephant Moraine A79001 the individual fragments covered a factor of over 5 range in TL sensitivity. A plot of TL sensitivity, peak width and peak temperature is shown in Fig. 3. The fragment of Elephant Moraine A79001,183 has the highest TL sensitivity, and TL which is lower in peak temperature and narrower in peak width than the other fragments of this meteorite. The tendency for the peak to move to lower temperatures and broaden as the TL sensitivity increases is also present in the individual fragments from Shergotty and Zagami. With the exception of two fragments of Allan Hills A77005, there is a trend shared by all the samples in which peak temperature increases, from about 150 to 180°C, and peak width increases, from 110 to about 150°C, as the TL sensitivity decreases by

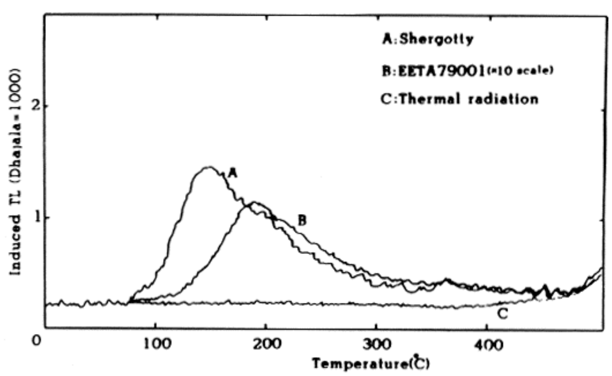

FIG. 1. Glow-curves (thermoluminescence against temperature) for samples of the Shergotty (curve A) and Elephant Moraine A79001 (curve B) meteorites induced by Sr-90 beta radiation. The curve for A79001 is shown on a 10 times more sensitive scale. Curve C is the thermal radiation from the sample and the heating pan on the same scale as Shergotty.

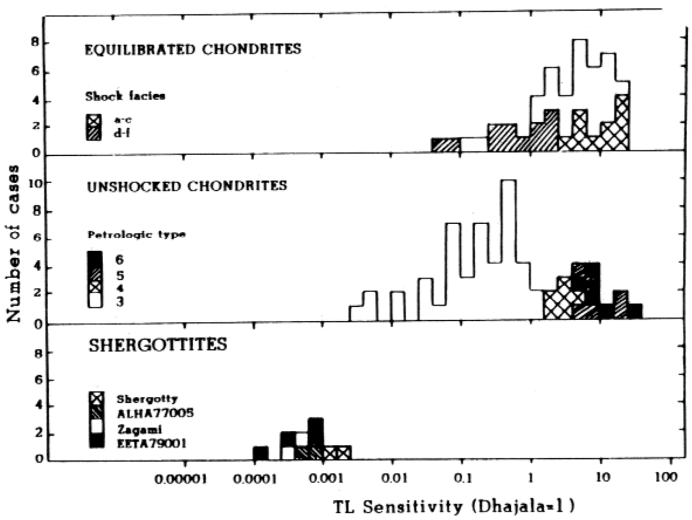

FIG. 2. Histograms comparing the TL sensitivities of the shergottite meteorites studied here with those ordinary chondrites (data taken from SEARS, 1980; LIENER and GEISS, 1968; SEARS *et al.*, 1980, 1982, and SEARS and WEEKS, 1983). The top histogram shows the TL sensitivities of equilibrated ordinary chondrites of various shock histories. Shock facies a–c (light to moderate shock) and d–f (heavy shock) are as defined by DODD and JAROSEWICH (1979). The middle histogram shows the TL sensitivities of unshocked ordinary chondrites of various petrologic types.

about an order of magnitude. The exceptions to this generalization, are two fragments of Allan Hills A77005 (74 and 68) which have conspicuously high peak temperatures.

The results of our mineral separation experiments are shown in Table 2. The dominant phases in the four highest density fractions were pyroxene and olivine and these fractions accounted for 93% of the total mass used for the separation. Of the remaining two separates, one contained a mixture of minerals and was predominently olivine while the other contains only a feldspathic material, presumably maskelynite. The proportion of pyroxene, olivine and maskelynite indicated by the separation data is in reasonable agreement with SCORE *et al.*'s (1981) modal abundances (35% pyroxene, 5% olivine and 8% maskelynite), although our sample seems to be higher in pyroxene. The TL sensitivity of the separates showed a 7-fold range, with the low density fractions having considerably higher values than the high density fractions. The TL sensitivity per unit mass shows an even larger range, being 0.079 and 18 for the highest and lowest density fractions, respectively. The phosphor responsible for the TL of the shergottites is clearly associated with the maskelynite.

The results of our annealing experiments are shown in Figs. 4–6. The peak temperature for Shergotty (Fig. 4) increased from the unannealed value of 140–160 to 195 ± 22°C after annealing for 24 h at 400°C,

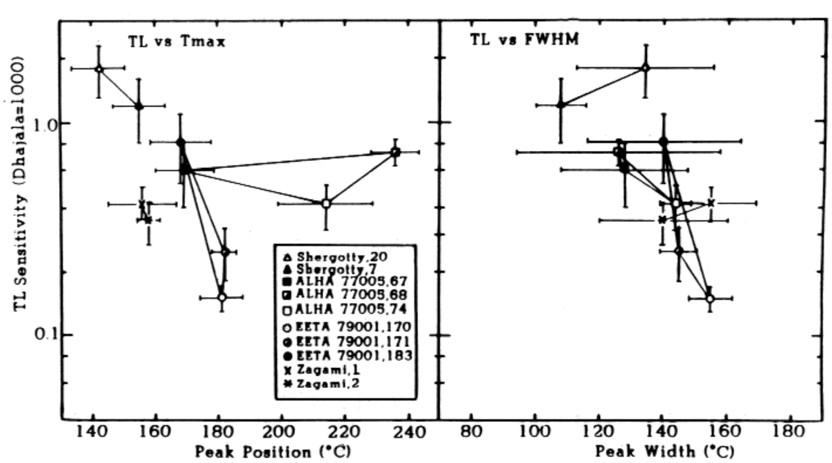

FIG. 3. Thermoluminescence sensitivity (normalized to Dhajala = 1000) plotted against the temperature at which TL emission is at a maximum (left diagram) and the width of the peak at half its maximum intensity, FWHM (right diagram). Fragments of the same meteorite are linked by tie-lines. The error bars refer to the standard deviation calculated from 3–5 glow-curves.

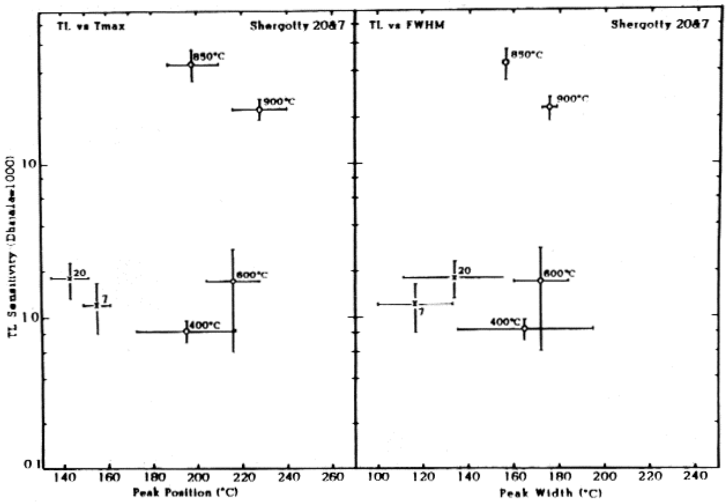

FIG. 4. TL sensitivity, peak width and peak temperature data for samples of the Shergotty meteorite annealed in an inert atmosphere for 24 h (98 h in the case of the 900°C datum). The sample used for the annealing was a mixture of samples Shergotty,20 and Shergotty,7. The crosses refer to unannealed samples, and the fragment number is indicated. The circles refer to the annealed samples; the annealing temperature is indicated alongside each data point. The annealing treatment caused the temperature of the peak to increase from approximately 150 to 200°C, and widen from 110 to 160°C, and the TL sensitivity to increase by over an order of magnitude.

while the width increased from 110–140 to 165 ± 30°C. This annealing treatment also caused a slight (about 50%) decrease in TL sensitivity. Higher annealing temperatures caused the peak to increase in TL sensitivity by up to a factor of about 40 with no further change in TL peak temperature or width. The sample of Elephant Moraine A79001 did not change in peak temperature or width, but at temperatures above 600°C the TL sensitivity increased by up to an order of magnitude. An exception to this is the 800°C sample which appears broader and at higher peak temperatures than the other samples. In fact, its TL glow-curves are very similar to those of Allan Hills A77005,68 and 74 and it may be that they contain an additional phosphor to that normally encountered, perhaps high temperature oligoclase. The data for Allan Hills A77005,74 are shown in Fig. 6. There were no significant changes in the TL properties of the samples after annealing at temperatures below 700°C, but at 700 and 800°C there were significant increases in TL sensitivity and the peak

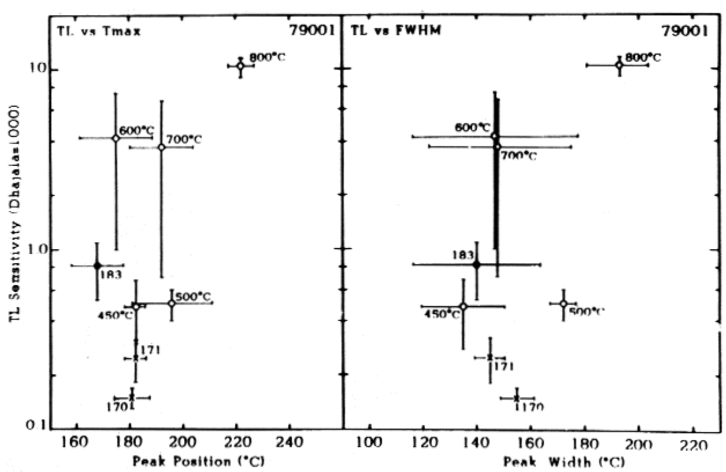

FIG. 5. TL sensitivity, peak width and peak temperature data for samples of the Elephant Morraine A79001 meteorite annealed for 24 h in an inert atmosphere. The filled circle refers to the unannealed sample used for the annealing treatments (fragment number indicated), other symbols as in caption to Fig. 4. The annealing treatment caused no change in peak temperature or width, although samples annealed >500°C showed a significant increase in TL sensitivity.

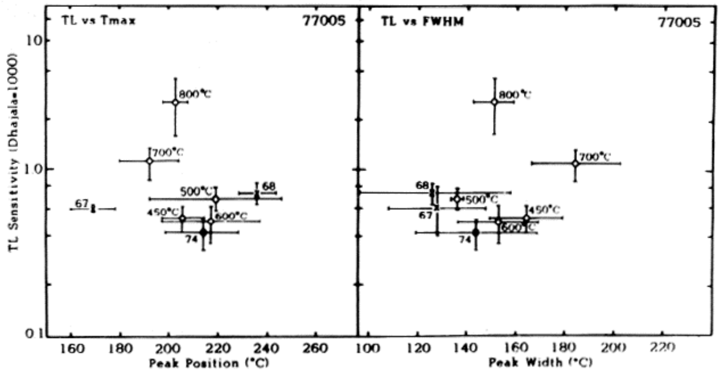

FIG. 6. TL sensitivity, peak width and peak temperature data for samples of Allan Hills A77005 annealed in an inert gas for 24 h. Symbols as in captions to Figs. 4 and 5. The annealing treatment caused no change in the TL properties of the fragment annealed, which prior to annealing had a peak which was relatively broad and at high temperatures, however another fragment of this meteorite (67) does show a narrow peak at low temperatures.

had moved down slightly to 190–200 from 200–220°C. The 700°C sample may also have broadened slightly.

4. DISCUSSION

a. TL sensitivity variations in shergottites

The TL sensitivities of the shergottites and ordinary chondrites are compared in Fig. 2. The top histogram shows data from SEARS (1980) and LIENER and GEISS (1968) for 54 equilibrated chondrites which have experienced a variety of shock histories. The unshocked, or relatively lightly shocked, chondrites (facies a–c according to DODD and JAROSEWICH, 1979) have TL sensitivities 10–100 times those of the moderately to heavily shocked chondrites (facies d–f). SEARS *et al.* (1984) found that the TL sensitivity of the Kernouve equilibrated chondrite decreased sharply after annealing at or above 1100°C and suggested that this was because a significant proportion of the TL phosphor, feldspar, had melted. Metallographic studies also indicate that many chondrites of shock d–f have experienced post-shock residual temperatures around 1100°C (SMITH and GOLDSTEIN, 1977).

The middle histogram in Fig. 2 shows the variation of TL sensitivity caused by metamorphism. SEARS *et al.* (1980, 1982) found that the TL sensitivity displayed by petrologic types 3–6 showed a 10^5-fold range. The type 3 ordinary chondrites have experienced a wide range of metamorphic alteration, which is reflected in the 10^3-fold range of TL sensitivity they display. The mechanism behind the metamorphism-related TL sensitivity range appears to be associated with the production of the TL phosphor, feldspar, through the devitrification of the primary igneous glass abundant in the low petrologic types (LOFGREN *et al.*, 1985; DEHART and SEARS, 1985).

The TL sensitivity values for the shergottites are extremely low and display a 10-fold range (lower histogram in Fig. 2). They are lower than even the lowest known TL sensitivity for very heavily shocked and type 3 ordinary chondrites. If we assume on the basis of the mineral separation experiment that the TL phosphor in the shergottites is feldspar, then the extremely low sensitivities presumably reflect the thorough maskelynization of feldspar during the shock event. In fact, the TL levels would indicate that only nanogram per gram amounts of feldspar are now present in the meteorite. It follows that the TL sensitivity range reflects variation in the amount of feldspar present. The 10-fold range in TL sensitivity is not due to sample heterogeneity because, except for Elephant Moraine A79001, we observe good agreement in TL sensitivity between duplicates. This seems reasonable since in general the samples are homogeneous on a macroscopic scale, inhomogeneities occurring predominantly on a micron-to-submicron scale. Neither does the amount of maskelynite (ANON, 1978) in the meteorite appear to be responsible for the TL range, since Allan Hills A77005 contains only 8 percent maskelynite but has the second highest TL sensitivity, while Shergotty and Zagami contain 23.3 and 21.8 percent maskelynite (STOLPER and MCSWEEN, 1979) but have very different TL sensitivities.

We suggest that the range in TL sensitivity observed for the shergottites reflects differing amounts of crystalline material now present in the maskelynite and that the amount is determined by one of the following mechanisms. (i) Some of these meteorites were shocked more than others, so that the TL is measuring the amounts of feldspar which survived the conversion to maskelynite. (ii) Maskelynization during shock was complete, but the glass underwent post-shock recrystallization to produce varying amounts of feldspar. (iii) The trace amounts of feldspar now present in the meteorite are a mixture of that surviving the shock event and that produced by post-shock recrystallization. It is difficult, but probably not impossible, to choose between these alternatives on the basis of TL sensitivity variations and petrographic data. However, the observed variations in TL peak temperature and width must also be taken into account and they bear strongly on the question.

b. The temperature and width of the TL peak

An interpretation of the TL sensitivity *versus* peak width and peak temperature trends is suggested by studies of the TL sensitivity of type 3 ordinary chondrites and terrestrial feldspars. GUIMON *et al.* (1984, 1985) reported annealing experiments on the little-metamorphosed type 3.4 ordinary chondrite, Allan Hills A77011. It was found that changes in the TL properties are associated with the transformation from a low-temperature form to a high-temperature form of feldspar, and it was presumed that these are associated with the ordered and disordered forms. The TL peak is relatively broad in the high-form, and appears at a higher temperature in the glow-curve, than the TL peak of the low-form. The peak shape changes we observe in the shergottites may be interpreted as reflecting relative amounts of a high-temperature and a low-temperature form of the phosphor which is probably, though not necessarily, identified with the ordered and disordered feldspar structures. A difference between these data and those for the type 3 ordinary chondrites is that for the shergottites the peak for the high temperature-phase is at 180°C and has a width of 150°C, while for the ordinary chondrites the peak and width are 210 and 240°C, respectively. This probably reflects compositional differences in the feldspar. HARTMETZ *et al.* (1986) found that shock loading bytownite in the low-temperature form to >25 GPa causes its TL peak to move from 140 to 180°C and broaden from 100 to 150°C, implying the same high-temperature phase is involved in both systems. In contrast, shock loading low-temperature oligoclase >34 GPa moved the TL peak from 132 ± 8 to 230 ± 12°C.

The annealing experiments provide evidence that devitrification of the maskelynite increases the TL sensitivity of shergottites, and that the temperature and width of the peak are governed by thermal history. All our samples showed an increase in TL sensitivity after annealing above 600 or 700°C, which we ascribe to crystallization of the maskelynite. BUNCH *et al.* (1967) found that terrestrial maskelynite formed sufficient feldspar for detection by X-ray diffraction after annealing for 2 hours at 900 ± 20°C, while Shergotty maskelynite partially crystallized after 1 h at 1100°C. Since TL has considerably lower detection limits than XRD, one would expect it to detect crystallization after milder conditions than those used by BUNCH *et al.*

Shergotty, whose feldspar, it is argued, is predominantly in the low-temperature form, showed an increase in TL peak temperature and width after annealing which brought both parameters close to those of Elephant Moraine A79001. On the other hand, Elephant Moraine A79001, whose TL phosphor is already in the high-temperature form, underwent no changes in its peak temperature and width after the annealing treatments. This is in agreement with our idea that the width and temperatures are governed by thermal history. The sample of Allan Hills A77005,74 used for the annealing study already had a broad high-temperature peak and, not surprisingly showed no changes upon annealing. Presumably, Allan Hills A77005,67 would have shown changes similar to those of Shergotty, were sufficient material available for annealing. In any event, there is evidence in the present data that whatever thermal events distinguish one shergottite from another, also distinguish certain fragments of Allan Hills A77005 and Elephant Moraine A79001 from others.

c. The thermal history of the shergottites

The co-existence for low and high-temperature forms of feldspar in the shergottites, and the relative proportions of the two phases, has certain implications for their thermal history and for which of the explanations (i)–(iii), described above, is closest to reality. For example, explanation (ii) would explain the peak temperature and width trends in the following way. If a meteorite cooled rapidly following the shock event which caused maskelynization, and if the residual temperature was high enough, then the few feldspar crystals which had the chance to form would be in the high-form and produce a TL glow-curve similar to that of Elephant Moraine A79001. On the other hand, a meteorite which experienced high residual temperature and which cooled relatively slowly would (1) experience greater recrystallization and the TL sensitivity would be much higher, and (2) would undergo greater recrystallization in the stability field of the low-form. Transformation of the high-temperature feldspar to the low-temperature form is extremely sluggish and the high-temperature form frequently exists in the stability field of the low-form, so the TL peak produced would be a composite of both forms. This could be the case for the Shergotty meteorite. The explanation is described schematically in Fig. 7. This explanation explains well all of the features in our data.

If the feldspar in the meteorites reflects the amount that survived maskelynization, and there was no post-shock recrystallization (explanation i above), then the TL sensitivity reflects the intensity of the shock and the peak temperatures and widths reflect a variety of pre-shock cooling rates. However, the trends between TL sensitivity, peak width and peak temperature would be difficult to explain in such a scenario. If the feldspar in the meteorites is a mixture of that surviving maskelynization and that produced by post-shock recrystallization (explanation iii), then again it would seem difficult to explain the TL sensitivity *versus* peak width and temperature trends, if the residual feldspar were anything but a minor component. However, residual feldspar could well be a cause for some of the scatter in our data and for the particularly severe heterogeneity sometimes observed (*e.g.* the data for Allan Hills A77005).

There is independent evidence that residual feldspar is not the major component of the trace amounts of feldspar now in the meteorite. There is no relationship between the TL sensitivity of the shergottites and the intensity of the shock they have suffered as determined by petrographic studies, especially refractive index measurements of the maskelynite. Shergotty and Za-

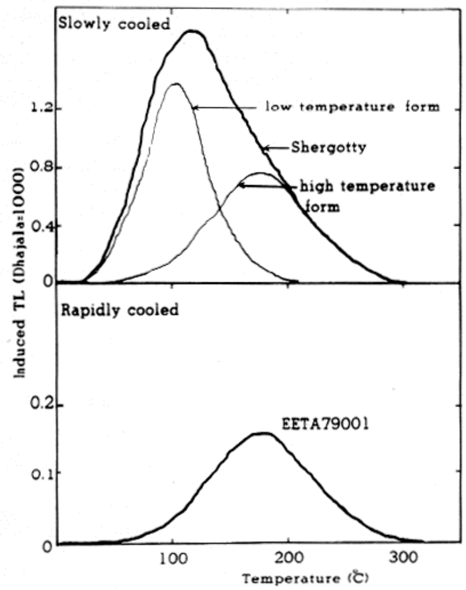

FIG. 7. Schematic diagram illustrating how the glow-curve shapes for Shergotty and Elephant Moraine A79001 may be governed by the presence of two forms of the TL phosphor, a high-temperature form and a low-temperature form whose relative abundance was determined by the rate at which the meteorites cooled after the shock event.

gami appear to have suffered peak shock pressures of 30–35 GPa (STEELE and SMITH, 1982; SMITH and HERVIG, 1979; OSTERTAG *et al.,* 1985). Allan Hills A77005 and Elephant Moraine A79001 have generally experienced peak shock pressures of 35–45 GPa, but melt veins and pockets indicate local pressures in excess of 80 GPa for these meteorites (MCSWEEN and STOFFLER, 1980; MCSWEEN and JAROSEWICH, 1983). The TL sensitivity data, if the TL level reflects the amount of residual feldspar, would require that Shergotty and Allan Hills A77005 experienced the lowest shock pressures, and Zagami and Elephant Moraine A79001 the highest.

d. Implications for a Mars origin

There is now a considerable body of data consistent with an origin on Mars for the shergottites, but the details of ejection from the planet remain obscure (WOOD and ASHWAL, 1981; MCSWEEN, 1984). Crucial to the question is the size of the ejecta blanket in which the meteorites were located before their ejection. Several mechanisms have been proposed, but none are effective for masses larger than 10–100 m. The chronological data provides evidence for a number of events which also relate to ejecta size; the various possible histories for these meteorites were described by BOGARD *et al.* (1984). On the basis of the Ar retained after the last shock, BOGARD *et al.* (1979) attempted to determine ejecta size, and found a value of >300 m. The calculation is highly dependent on the assumed post-shock temperature and BOGARD *et al.* (1979) used a value of 400°C. This value was based on the refractive index of the maskelynite in Shergotty which undergoes major changes if annealed at or above 400°C for an hour or so (DUKE, 1968). LAMBERT and GRIEVE (1984) pointed out that Shergotty may have experienced a second, milder shock to which the 400°C values really applies. In this case, the post-shock temperature associated with maskelynization may have been higher, consistent with much smaller ejecta. However, there is no petrographic evidence for a second shock. (OSTERTAG *et al.,* 1985).

If our conclusions concerning the TL sensitivity trends and their association with post-shock recrystallization are correct, then the present data provide independent evidence that the post-shock temperature was in excess of the order-disorder transformation temperature (>600°C). According to the calculations of BOGARD *et al.* (1979), this value corresponds to an ejecta size of <10 m. Current theories have no difficulty explaining the ejection of objects this small from the surface of Mars.

5. CONCLUSIONS

The level of TL sensitivity in the shergottites varies by a factor of 10 but is always low and, we suggest, reflects the amount of crystalline material in the maskelynite. There are trends in the TL peak temperature, peak width and TL sensitivity, which appear to be associated with different proportions of feldspar in high and low-temperature forms. The changes induced in the TL properties of samples of Shergotty, Allan Hills A77005 and Elephant Moraine A79001 by annealing at 400–900°C for 24–98 h are consistent with this interpretation. We argue that the trends were produced during post-shock crystallization at a variety of cooling rates, the increasing order of cooling rate being Elephant Moraine A79001, Zagami, Allan Hills A77005 and Shergotty, and that there is high-temperature feldspar present in all the samples. This implies a post-shock temperature of >600°C and that the size of fragments following the maskelynization was <10 m. Current theories are well able to explain how objects this small could have been ejected from Mars.

Acknowledgements—We are grateful to the Geological Survey of India, the Meteorite Working Group of NASA/NSF and the British Museum for providing samples, J. C. Laul and R. Hutchison for encouraging us to make the study and H. Y. McSween, G. E. Lofgren, F. Horz, J. M. DeHart, R. K. Guimon, B. D. Keck, C. Hartmetz and K. S. Weeks for discussions and help in manuscript preparation. An extremely stimulating review by H. Y. McSween greatly improved the paper, as did the reviews of C.-Y. Shih and E. R. D. Scott. Financial support was partially provided by grant NAG 9-81 from NASA.

Editorial handling: R. A. Schmitt

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