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A THERMOLUMINESCENCE STUDY OF EXPERIMENTALLY SHOCK-LOADED OLIGOCLASE AND BYTOWNITE

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Abstract. The thermoluminescence (TL) of samples of terrestrial oligoclase and bytownite shock-loaded to 10.5-45 GPa have been measured. The TL sensitivities of both feldspars decreased 10-fold after shock-loading to 25-32 GPa and, for the oligoclase, 25-fold after shock-loading to greater pressures. The shock-induced changes for oligoclase are very similar to those of the Kernouve meteorite, in which the TL phosphor is oligoclase, after similar shock-loading. The data indicate that ordinary chondrites of shock facies d-f have suffered shock pressures over 25 GPa, consistent with petrographic estimates. Petrographic studies on the shocked samples suggest that the lowering of TL sensitivity is caused by maskelynization (and, at the highest pressures, melting). The oligoclase samples shocked above 34 GPa showed changes in their glow curve shapes similar to those produced by annealing Amelia albite and a type 3.4 ordinary chondrite above 700°C; the dominant peak moves from 132 ± 8°C to 230 ± 12°C. Changes in the glow curve shape for bytownite resembled those produced by annealing certain shergottites. In addition to a major peak at 138 ± 3°C, a peak appeared at 178 ± 8°C. For albite, the changes were shown to be associated with small degrees of disordering, and we suggest that shock-induced disordering, or some process closely associated with the onset of disordering, is occurring in the trace amounts of feldspar that survive maskelynization after shock-loading to pressures >34 GPa.

Introduction

Feldspar is a ubiquitous rock-forming mineral of crustal rocks and meteorites. An important process in the history of most planetary surfaces and meteorites is shock metamorphism caused by impact. On the earth, some 80 impact features with associated shocked materials have been identified [Dence et al., 1977], while between one-third and two-thirds of the largest ordinary chondrite group, the L chondrites, have suffered violent shock. All of the shergottite class of achondrites have suffered intense shock. Most major minerals respond to shock, but feldspar is especially responsive. Effects have been described in feldspars from terrestrial craters [e.g., French and Short, 1968; Stöffler, 1974], the lunar surface [e.g., Chao et al., 1970; Engelhardt et al., 1970; Quaide and Bunch, 1970; Sclar, 1970; Short, 1970], and meteorites [e.g., Dodd and Jarosewich, 1979; Ostertag, 1985]. Quantitative interpretation of these data is possible with the help of artificially administered shocks on feldspar [e.g., Stöffler and Hornemann, 1972; Robertson, 1975; Gibbons and Ahrens, 1977; Syono et al., 1977]. Much of this work has been reviewed by Smith [1974] and Stöffler [1972, 1974]. With increasing shock pressure, and therefore temperature, the feldspar first fractures and then forms deformation lamellae. Vitrification occurs at higher pressures, through a solid state process that results in the formation of maskelynite at >30 GPa (300 kbar) and via melting at >45-50 GPa [Stöffler and Hornemann, 1972; Ostertag, 1983]. These changes may be monitored by a number of physical measurements, including refractive index determination, X ray diffraction and infrared spectroscopy [Stöffler, 1974].

Thermoluminescence (TL) is particularly sensitive to the amount and nature of feldspar in several meteorite classes, and its measurement may offer a further means of exploring the effect of shock on feldspar and the meteorites [Sears, 1980; Sears et al., 1984a,b]. Particularly useful is the ability of TL to detect very low abundances of crystalline feldspar and provide certain structural information, even when the mineral is predominantly amorphous [Sears et al., 1982; Guimon et al., 1986]. Thus metamorphism can be followed very precisely in type 3 ordinary chondrites, since it causes the formation of feldspar through the devitrification of glass [Sears et al., 1980]. Also, the postshock crystallization of feldspar in the maskelynite of the shergottites can be followed using TL [Hasan et al., 1986]. The structural information is provided by the details of the TL emission, since they are determined by thermally controlled, solid-state transformations occurring in the feldspar [Guimon et al., 1985]. Here we report measurements of the TL properties of samples of a terrestrial oligoclase and bytownite shock-loaded to pressures of 10.5-45 GPa. The shock-loading was performed by Ostertag [1983], who also reported a detailed petrographic, XRD, EPR, and IR study on the samples.

Experimental

The flying-plate technique was used to produce the pressures indicated in Table 1, with the shock pressures determined by a graphical impedance matching method (estimated uncertainties of ±3%). The present samples were a single crystal of oligoclase ($Or_{2.3}$, $Ab_{78.0}$, $An_{19.7}$) from Muskwa Lake, Canada, and a polycrystalline sample of bytownite ($Or_{0.4}$, $Ab_{22.0}$, $An_{77.6}$) from Crystal Bay, Minnesota, USA. Both minerals were originally in the low-temperature form (ordered Si,Al structure).

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TABLE 1. Thermoluminescence Data for the Shocked Oligoclase Samples

Pressure (GPa)	TL Sensitivity* (Unshocked = 1) Peak 1	Peak 2	Peak 3	Peak Temperature† (°C) Peak 1	Peak 2	Peak 3
0	1.00±0.05	1.00±0.04	1.0±0.1	142±4	---	315±12
10.5	0.21±0.02	0.17±0.02	0.15±0.01	133±4	---	285±2
10.5	0.27±0.02	0.24±0.02	0.20±0.02	132±3	---	295±6
14	0.22±0.02	0.168±0.009	0.15±0.01	135±5	---	293±6
14	0.29±0.02	0.24±0.02	0.20±0.02	130±2	---	298±1
18‡	0.033±0.002	0.034±0.003	0.030±0.003	146±3	---	301±1
18	0.030±0.001	0.034±0.002	0.044±0.009	135±3	---	317±5
22‡	0.025±0.002	0.026±0.002	0.020±0.002	135±6	---	---
22	0.021±0.002	0.021±0.002	0.015±0.002	121±1	---	---
26	0.08±0.01	0.10±0.01	0.069±0.007	132±2	211±1	---
26	0.08±0.01	0.10±0.01	0.068±0.006	120±3	239±1	---
28	0.058±0.004	0.077±0.002	0.062±0.006	131±1	---	---
28	0.097±0.005	0.127±0.004	0.094±0.008	122±2	---	---
30	0.107±0.005	0.12±0.01	0.08±0.01	143±1	235±4	---
30	0.16±0.02	0.20±0.02	0.13±0.02	133±3	---	---
32	0.063±0.007	0.08±0.01	0.050±0.004	132±3	222±3	---
32	0.15±0.01	0.19±0.01	0.12±0.01	117±5	---	---
34	0.045±0.007	0.063±0.008	0.045±0.004	149±1	228±2	---
34	0.05±0.01	0.07±0.01	0.044±0.006	132±3	214±1	---
39.5	0.05±0.01	0.088±0.008	0.063±0.005	132±1	245±7	---
39.5	0.031±0.008	0.06±0.01	0.038±0.008	143±5	234±14	---
45	0.05±0.02	0.121±0.003	0.07±0.01	135±1	243±1	---
45	0.04±0.01	0.09±0.02	0.034±0.003	150±3	215±4	---
glass§	0.031±0.002	0.063±0.008	0.021±0.003	132±3	204±5	296±3
glass§	0.075±0.003	0.121±0.006	0.05±0.01	121±1	210±4	292±4
Mean ±1σ				132±8	230±12	300±12

The errors are standard deviations from triplicate measurements. Peaks 1, 2 and 3 refer to the glow peaks that have mean peak temperatures of 132°C, 230°C and 300°C, respectively. Peak widths were not measured because of peak interference.

* When there was no peak or inflexion, the sensitivity refers to the TL measured at the mean temperature for that peak.

† A hyphen indicates no well developed peak.

‡ The 18 and 22 GPa samples were contaminated, resulting in low TL sensitivity values, so these data are excluded from the plots.

§ Unshocked oligoclase that was heated at 1500°C for 6 hours.

Measurement of the TL properties was by the apparatus and procedures described by Sears and Weeks [1983]. The samples were ground, two 4-mg aliquots were placed in Cu dishes, and their natural TL was removed by momentary heating to 500°C in the TL apparatus. The TL induced by a test dose of radiation from a ^{90}Sr beta source was then measured three times. The source is uncalibrated, but it is thought that the dose absorbed is on the order of 3 krad (assuming an absorption coefficient of unity). The TL sensitivity data were normalized to that of the appropriate peak in the unshocked powder. The data quoted are means for the triplicate measurements and the uncertainties are the standard deviations, compounded with those of the unshocked samples in the case of TL sensitivity.

Results

Oligoclase

Several glow curves (plots of TL as a function of temperature) for the oligoclase samples are presented in Figure 1. The shock caused changes in both the level of TL and the shape of the glow curves. The temperatures at which peaks occur, or inflections corresponding to partially resolved peaks appear, are plotted in Figure 2. The unshocked and lightly shocked (<18 GPa) samples have curves whose dominant peak is at 132 ± 8°C, while the samples shocked at higher pressures have curves with a dominant peak at 230 ± 12°C. There is also a peak at 300 ± 12°C that is present as an inflection in several

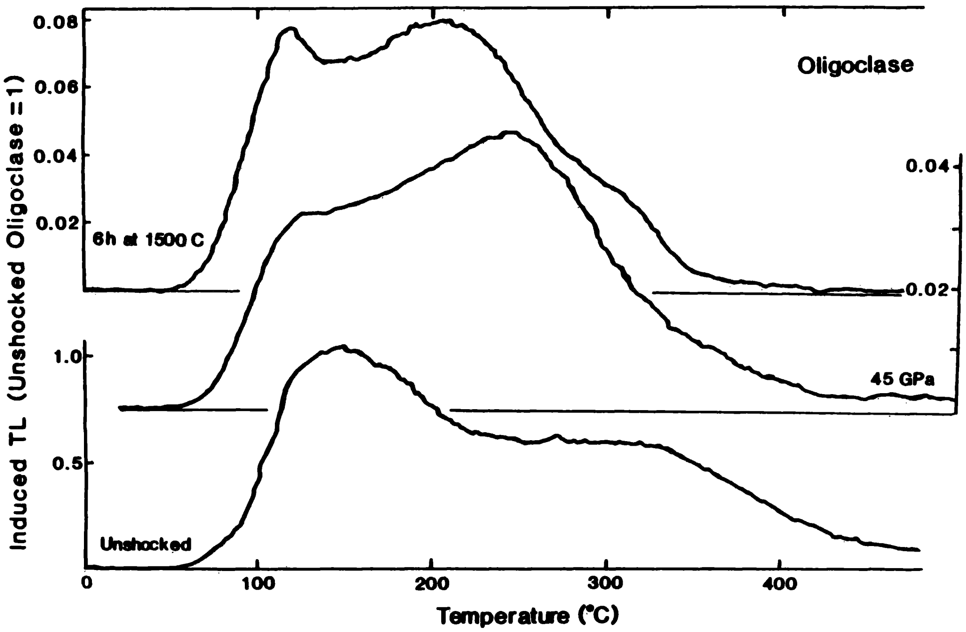

Fig. 1. Induced glow curves from the oligoclase series before and after shock loading. The TL level has been normalized to that of the unshocked material. The open circles with error bars refer to the mean $\pm 1\sigma$ for the three peaks observed in these samples (see Figure 2). The lightly shock-loaded samples (unshocked and shocked to <30 GPa) have a dominant peak at 132 ± 8°C, whereas the samples shock loaded above 34 GPa have a dominant peak at 230 ± 12°C. Also shown is the glow curve for a sample of glass made by heating oligoclase at 1500°C for 6 hours.

samples. We will refer to these as peaks 1, 2, and 3, respectively.

The TL sensitivity of the three oligoclase peaks (Table 1) is plotted as a function of shock pressure in Figures 3-5. All three peaks dropped in TL sensitivity by a factor of about 5 after the 10.5 and 14 GPa shocks, while the samples shocked at 26-32 GPa had TL sensitivities about an order of magnitude below the unshocked value. Peak 1 for the samples shocked at >32 GPa was a factor of 25 lower in TL sensitivity than the original powders. Our data for the 18 and 22 GPa samples have not been plotted on Figures 3-5 because the powders appeared brown and responded to the grinding process in an unusual manner; their very low TL could reflect some kind of contamination.

For the samples shocked >32 GPa, the TL sensitivity of a given sample increased each time its TL was measured (Table 2). The effect is shown in Figure 6, where the ratio of the TL sensitivity after second and third measurement against that of the first measurement is plotted against shock pressure. For peak 1 and 2, the effect is probably present in samples shocked >25 GPa but much stronger for samples shocked >32 GPa, while peak 3 does not show the effect. This increase in TL sensitivity after each measurement will be referred to as "sensitization."

Oligoclase Glass

The glow curve for the oligoclase glass had a broad peak at 207 ± 4°C, a much narrower peak at 127 ± 2°C and an inflexion at 294 ± 3°C (Figure 1

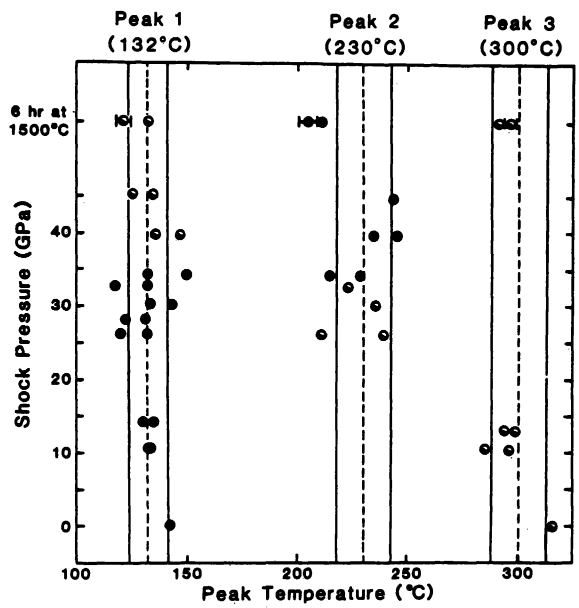

Fig. 2. Peak temperatures for oligoclase after shock-loading to various pressures and an oligoclase sample that was heated at 1500°C for 6 hours. Filled circles refer to discrete peaks, half-filled circles to inflections, and open circles to the TL sensitivity in the absence of a peak or inflexion. The 1 σ uncertainty for the shock pressure data in all cases is ±3%, while typical 1 σ uncertainty based on triplicate measurements for the TL data are shown on the data for the glass sample. The vertical lines indicate mean and 1 σ uncertainties.

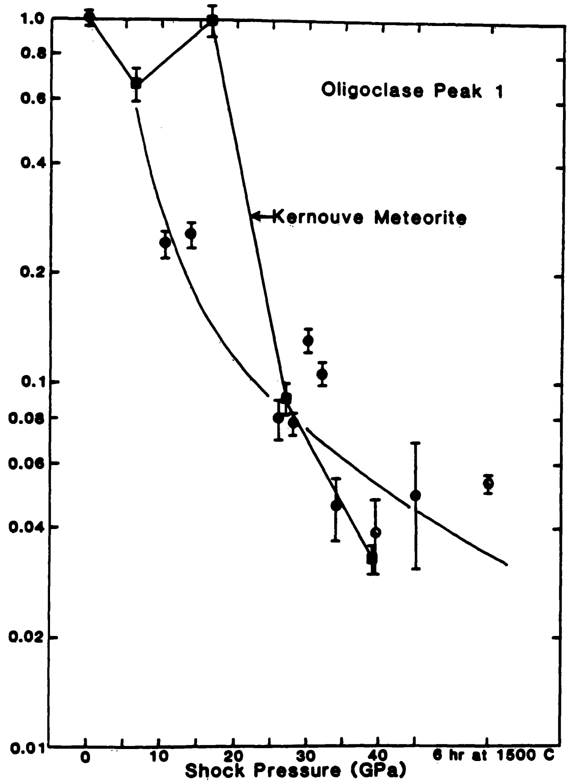

Fig. 3. Plot of TL sensitivity against shock pressure for oligoclase peak 1 (132 ± 8°C). Data from an oligoclase sample heated at 1500°C for 6 hours are also indicated. Samples shock-loaded in the 26 to 32 GPa range experience a 10-fold loss in TL sensitivity compared to the unshocked samples, while samples shock-loaded above 32 GPa showed a 25-fold loss in TL sensitivity. The squares are data for shock-loaded Kernouve meteorite [Sears, 1980]. The similarity in the behavior of the shock-loaded oligoclase and the meteorite is because the main TL phosphor in meteorites is oligoclase [Lalou et al., 1970]. The 10.5 and 14 GPa data may be low due to contamination (see text). Symbols as in Figure 2. The error bars for TL sensitivity due ±1 σ of triplicate measurements. The curve is a least-squares fit assuming a log-log relationship (see Appendix for parameters).

and 2). The sensitivity of the three peaks was comparable to the samples that had received shock-loading of 30 GPa or more (Figures 3-5). The samples differed from the heavily shocked samples, however, in not showing sensitization of any of the peaks (Figure 1).

Bytownite

Glow curves for two bytownite samples are shown in Figure 7. Bytownite also underwent changes in TL sensitivity and glow curve shape in response to the shock-loading, but the changes in shape were more subtle. The peak broadened, and an inflection appeared on the high-temperature side of the peak indicating the appearance of a new peak at about 180°C. Figure 8 shows the positions of the peaks and inflections in the bytownite samples [the two peaks have positions of 138 ± 5 (peak 1) and 178 ± 7°C (peak 2)], and Figure 9 shows how the width of the peak increases from about 110° to 150°C with increasing shock pressure. The increase in width precedes the appearance of the peak at 180°C, and it is this extra peak that is responsible for the broadening of the composite peak.

The TL sensitivity of the bytownite samples (Table 3) is plotted as a function of shock pressure in Figure 10 and 11. The TL sensitivity of peak 1 decreased by a factor of 5 after shock-loading at 18-22 GPa, and after loading at higher pressures had values of about a factor of 10 lower than the unshocked figure. The 39.5 GPa sample showed a decrease in TL sensitivity less than expected on the basis of similarly shocked samples, and its width increased more than the others.

Some of our data are described surprising well by regression lines fitted by the method of least-squares assuming a log-log relationship between the TL properties and shock-pressure (see Appendix and Figures 3-5 and 9-11). These provide a convenient means of describing the data quantitatively, but there is no reason to assume that TL sensitivity or FWHM should vary continu-

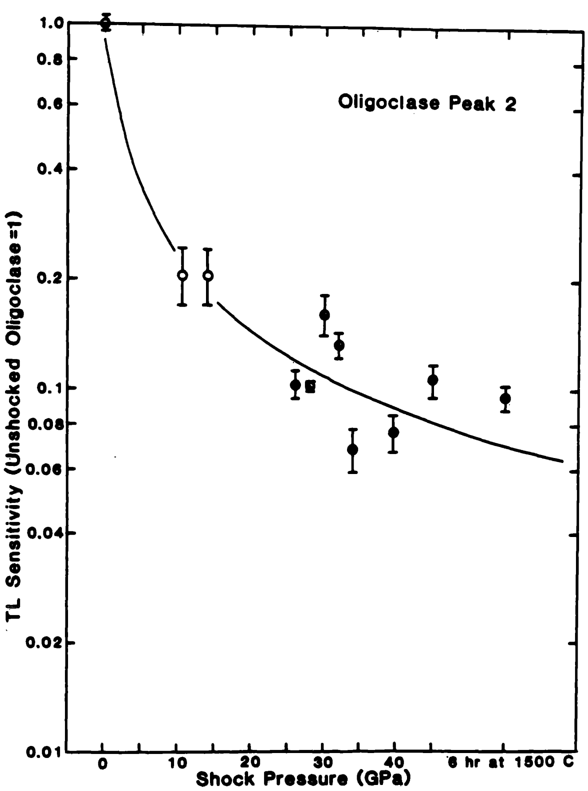

Fig. 4. Plot of TL sensitivity against shock pressure for oligoclase peak 2 (230 ± 12°C). The data from a sample of oligoclase heated at 1500°C for 6 hours are also included. Shock-loading at pressures above 25 GPa causes approximately a 10-fold decrease in TL sensitivity compared to the unshocked sample. The TL sensitivity error bars indicate 1 σ uncertainties from triplicate measurements. Shock-pressure errors and symbols as in Figure 2, curve as in Figure 3.

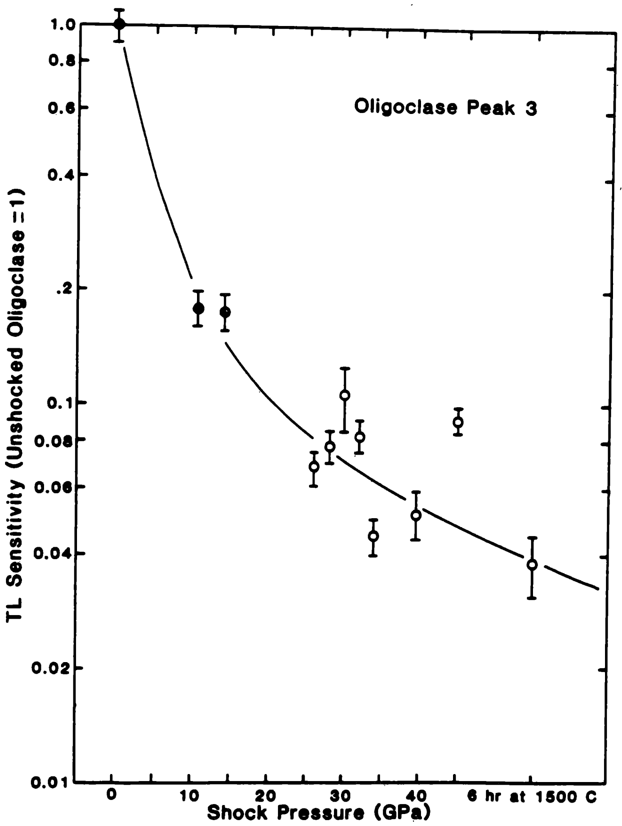

Fig. 5. Plot of TL sensitivity against shock-pressure for oligoclase peak 3 (300 ± 12°C). The data from a sample of oligoclase heated at 1500°C for 6 hours is also included. Shock-loading at pressures above 32 GPa causes approximately a 25-fold decrease in TL sensitivity. Shock pressure errors and symbols as in Figure 2, curve as in Figure 3.

ously with shock pressure. In fact, if, as we suppose, TL sensitivity depends on maskelynization and peak width on feldspar disordering, then the relationships are discontinuous.

Discussion

Causes of the Decrease in TL Sensitivity with Shock

The lowest TL sensitivities observed in the oligoclase and bytownite are for samples shocked to pressures >32 GPa. These are also the samples in which Ostertag [1983] observed extensive maskelynization, and the destruction of the crystalline feldspar is presumably the cause of low TL sensitivities in these samples. In fact, the process has also affected samples that have been shock-loaded at 26-32 GPa, since their TL sensitivities have fallen to one-tenth of their unshocked values. As far as the resulting TL levels are concerned, it is unimportant whether the destruction of feldspar results in the formation of maskelynite or melt glass, since the oligoclase melt glass also has very low TL sensitivity. However, loss of TL due to maskelynization can occur at much lower pressures, and melt glass is only observed in the samples shocked at 45-50 GPa [Stöffler, 1974; Ostertag, 1983].

Four of the oligoclase samples shocked to less than 26 GPa had a TL sensitivity significantly lower than the unshocked samples (Figure 3). Two of these (the 18 and 22 GPa samples) were discussed above and their TL sensitivity data rejected. The 10.5 and 14 GPa samples were much smaller in grain size than the others, but not as obviously contaminated as the 18 and 22 GPa samples, and it is possible that a lower TL sensitivity is a grain-size effect; we found that finely ground unshocked samples had lower TL sensitivity than those which had been normally prepared. On the other hand, Ostertag [1983] has argued that maskelynite is a mixture of an isotropic phase with identical structure to melt glass and a crystalline phase, and that the proportion of crystalline material decreases with increasing shock pressure. Thus the TL is moni-

TABLE 2. Thermoluminescence Sensitivity of the Second and Third Glow Curve Measurements for Oligoclase, Normalized to the First Measurement

Pressure (GPa)	Measurement	Peak 1	Peak 2	Peak 3
0	Second	0.97	0.97	1.04
	Third	0.94	0.95	1.14
10.5	Second	0.93	0.88	0.95
	Third	1.02	1.01	1.04
14	Second	0.93	0.93	0.98
	Third	0.86	0.90	0.97
18†	Second	0.98	1.05	1.10
	Third	0.97	1.00	1.20
22†	Second	0.93	0.91	0.96
	Third	1.08	1.02	1.05
26	Second	1.16	1.07	0.96
	Third	1.29	1.23	1.02
28	Second	1.06	0.97	1.04
	Third	1.07	0.98	1.04
30	Second	1.08	1.13	1.16
	Third	1.08	1.11	1.21
32	Second	1.03	0.99	1.11
	Third	1.19	1.08	1.03
34	Second	1.24	1.18	1.04
	Third	1.45	1.36	1.15
39.5	Second	1.54	1.27	1.10
	Third	1.94	1.44	1.11
45	Second	1.44	1.17	1.03
	Third	1.83	1.37	1.14
glass*	Second	1.02	0.93	0.80
	Third	0.94	0.92	0.71

Peaks 1, 2 and 3 refer to the three peaks with mean temperatures of 132°C, 230°C, and 300°C, respectively.

* Unshocked oligoclase heated at 1500°C for 6 hours.

† Excluded from plots (see Table 1).

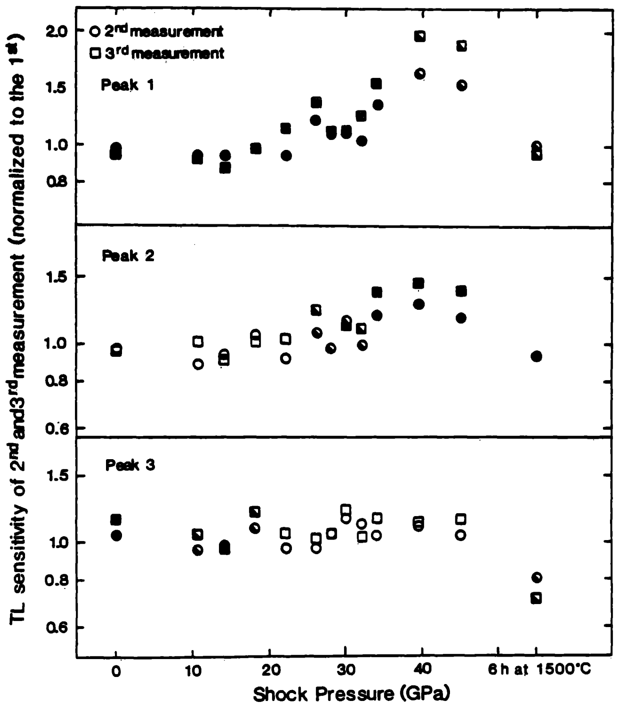

Fig. 6. Ratios of the second and third measurement of TL sensitivity to the first measurement against shock-pressure. There is an increase in TL sensitivity for oligoclase samples shock-loaded above 30 GPa, apparently caused by heating in the TL apparatus. The effect is weak or absent for the 300 ± 12°C peak. Shock pressure errors and symbols as in Figure 2.

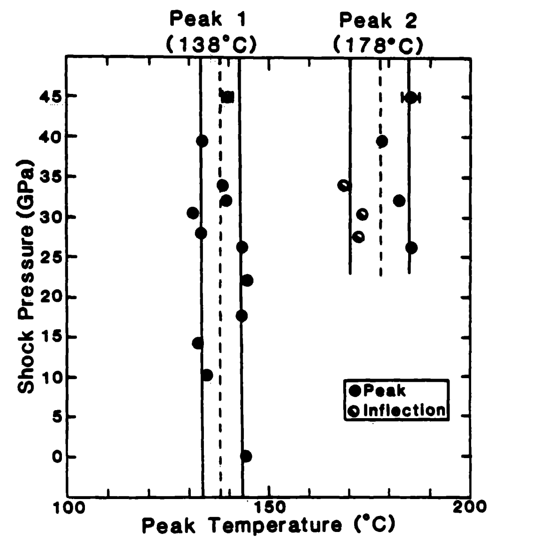

Fig. 8. Plot of shock pressure against peak temperature for bytownite. Typical 1 σ error from triplicate measurements are shown on the 45 GPa datum for each peak. The vertical lines are mean ±1 σ for all the data. Symbols and shock-pressure errors as in Figure 2.

toring the amount of that crystalline phase. This process could begin to occur at much lower pressures than those at which maskelynite is optically present, and Müller [1969] has reported planar elements that TEM data suggest contain amorphous phases.

Sensitization

The increase in TL sensitivity caused by measuring its TL (sensitization) is only observed at pressures in excess of about 25 GPa and is most notable in samples that have been shock-loaded to pressures above 32 GPa. From these pressures we infer that the effect is associated with the maskelynization of the feldspar. Since measurement of the TL glow curve requires an exposure to radiation and heating, this sensitization may be either due to radiation damage or thermal processes. It is known that maskelynite crystallizes rather readily; the maskelynite in Shergotty completely crystallizes after an hour

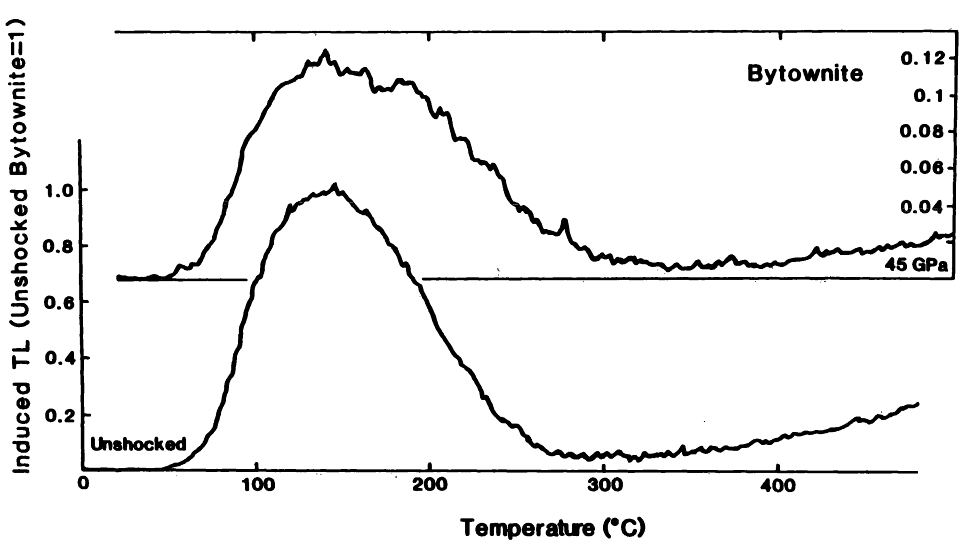

Fig. 7. Induced-glow curves for bytownite before and after shock-loading to 45 GPa. The lightly shock-loaded samples (0 to 22 GPa) have a dominant peak at 138 ± 5°C and the heavily shock-loaded samples (26 to 45 GPa) have peaks at 138 ± 5°C and 178 ± 7°C.

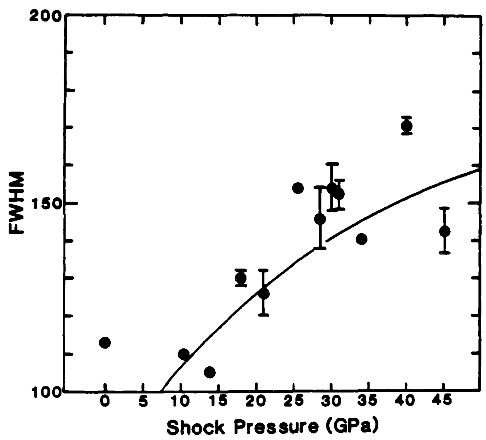

Fig. 9. Plot of the full width of the peak(s) at half the maximum height of the peak (FWHM) against shock pressure for the bytownite data. The widening of the peak is caused by the appearance, at higher shock pressures, of a new peak at 178 ± 7°C. The error bars are 1 σ uncertainties from triplicate measurements. Shock-pressure errors as in Figure 2, curve as in Figure 3.

at 1100°C, while the maskelynite from the terrestrial crater Manicouagan crystallizes completely after an hour at 800°C [Bunch et al., 1968]. Annealing experiments on the shergottites have resulted in significant increases in TL sensitivity, presumably reflecting the formation of crystalline feldspar, after annealing at temperatures as low as 600°C [Hasan et al., 1986]. However, we were able to identify radiation damage processes in the maskelynite as the probable cause by three sets of measurements, that are summarized in Table 4: (1) One of the 30 GPa samples was subjected to 8 cycles of 3.1 krad exposure in the radiation cell, and TL measurement. (2) Another 30 GPa sample was given 31 krad and its TL measured, and then the following cycle repeated 3 times; the sample was given a 25 krad and its TL drained, then given a 3.1 krad dose and its TL measured. (3) One of the 14 GPa samples was given the same treatment as in experiment 2. In this way, the sample in measurement 1 received a cumulative dose of 22 krad and 7 heatings in the apparatus, while the samples in measurements 2 and 3 received a cumulative dose of 86 krad and experienced 7 heatings. Experimental uncertainties for these data have not been

TABLE 3. Thermoluminescence Data for the Shocked Bytownite

Pressure (GPa)	TL Sensitivity* (Unshocked=1) Peak 1	TL Sensitivity* (Unshocked=1) Peak 2	Peak Temperature† (°C) Peak 1	Peak Temperature† (°C) Peak 2	Peak Width‡ (°C)
0	1.0±0.07	1.0±0.012	141±1	---	113±1
10.5	1.19±0.06	1.1±0.1	135±1	---	110±1
14	0.56±0.03	0.54±0.08	132±3	---	105±1
18	0.20±0.02	0.24±0.03	143±3	---	131±2
22	0.21±0.02	0.26±0.03	145±2	---	126±6
26	0.35±0.02	0.49±0.04	143±5	185±6	154±3
26	0.35±0.03	0.49±0.05			
28	0.39±0.02	0.47±0.04	133±1	173±2	146±8
28	0.33±0.05	0.39±0.07			
30	0.16±0.01	0.19±0.02	131±1	173±1	154±6
32	0.080±0.005	0.10±0.01	139±1	183±5	153±4
34	0.083±0.005	0.10±0.01	138±4	169±1	141±1
39.5	0.47±0.04	0.60±0.07	134±2	178±2	171±2
45	0.12±0.06	0.14±0.02	140±2	185±2	142±6
Mean ±1σ			138±5	178±7	

The errors are standard deviations from triplicate measurements. Peaks 1 and 2 refer to the two glow peaks that have mean temperatures of 138°C and 178°C, respectively.

* In the absence of a peak or inflexion the TL sensitivity refers to that measured at the mean temperature.

† A hyphen indicates no well developed peak.

‡ Peaks 1 and 2 are not resolved and the values quoted refer to their combined width.

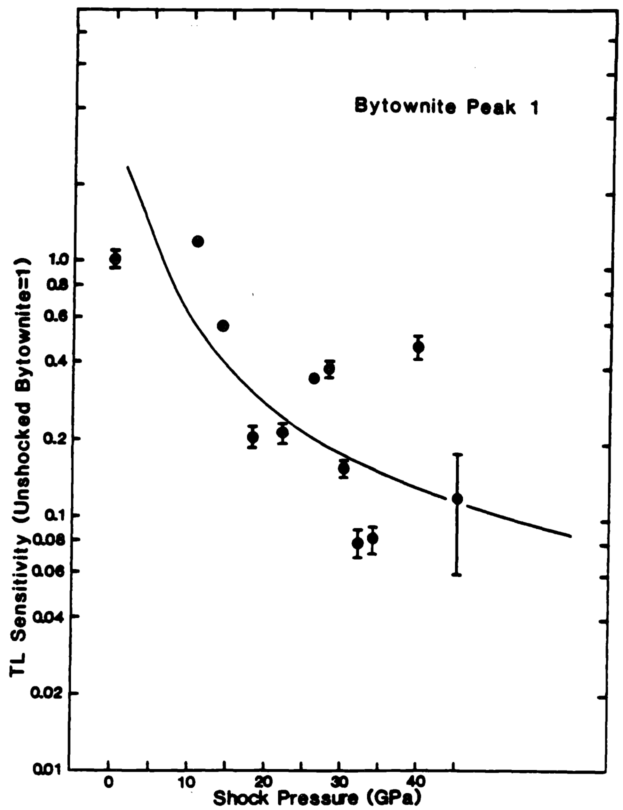

Fig. 10. Plot of TL sensitivity against shock pressure for the bytownite 138 ± 5°C peak. A 10-fold decrease in TL sensitivity is observed in the samples shock-loaded above 30 GPa. Error bars as in Figure 2, curve as in Figure 3.

determined, but are probably 15 - 20%. Of the two samples that received the higher dose, that which had been shocked to 30 GPa showed an increase in sensitivity while the 14 GPa sample did not, consistent with the sensitization being associated with maskelynite. The 30 GPa sample that received a cumulative dose of only 22 krad did not show any sensitization, even though it had received the same number of heatings in the apparatus. The sensitization effect is clearly associated with exposure of maskelynite to high radiation doses.

Causes of Peak Temperature and Width Variations

The position of the dominant peak in oligoclase changed from 132 ± 8°C to 230 ± 12°C, and a new peak appeared at 178 ± 7°C in addition to that at 138 ± 5°C in bytownite, after shock loading at >30 GPa (Figure 2). Based on Ostertag's [1983] descriptions of the mineralogical changes accompanying the shock-loading, we can identify no feasible mineralogical explanation for these changes. The dominant TL peak in Amelia albite moved from about 135° to 200°C after annealing at 1100°C for 24 hours [Pasternak, 1978] and that for Allan Hills A77011 changed from 139 ± 9°C to 206 ± 6°C after annealing at 1000°C for 24 hours [Guimon et al., 1985]. In fact, Guimon et al. [1985] found that the change in peak temperature occurred between 600° and 700°C, and suggested that it was associated with the onset of disordering. Pasternak [1978] found that the change in peak position for Amelia albite was associated with an increase in the 2θ(131-1$\bar{3}$1) parameter from 1.0 (ordered) to 1.2, where totally disordered albite has a value of 2.0 for this parameter. One difference between the TL changes and the disordering is that the TL changes occur much more readily (the activation energy is ~8 kcal/mole, compared with about 80 kcal/mole for disordering), although it is possible that the kinetics could be strongly influenced by any catalysts present in the TL samples, such as water. It seems clear that the movement in the peak position for our shocked samples is reflecting either a small degree of disordering, or some process associated with disordering of the trace amounts of feldspar present in the samples shocked at pressures >30 GPa. The difference in the peak position for the disordered bytownite may be due to compositional differences between it and oligoclase and albite; annealing experiments on terrestrial bytownite would readily resolve this point. Annealed shergottite samples (Shergotty, Elephant Moraine A79001, and Allan Hills A77005), in which the TL is associated with feldspar crystallizing in maskelynite of labradorite composition, also produce glow curves with peaks around 180°C [Hasan et al., 1986].

Al,Si Disordering and Shock

Aitken and Gold [1968], Dworak [1969], Sclar and Usselmann [1970], Ostertag and Stöffler [1982], and Ostertag [1983] have discussed the possibility of shock-induced disordering of the Al,Si chain in feldspars. For the present samples, Ostertag [1983] found that the optic axial angle provided no evidence for disordering of oligoclase in samples shocked up to 30 GPa, although there was an increase in scatter in the data for samples shocked above 22 GPa that Ostertag attributed to lattice strain. The absence of sufficient crystalline material prevented the technique being applied to samples shocked to higher pressures. Similarly, X ray diffraction data could only be obtained for samples shocked <30 GPa and it too provided no indication for disordering. Samples shock-loaded to higher pressures suffered broadening and weakening of the X ray lines, which made their measurement impossible. On the other hand, samples of several alkali feldspars annealed at 1000°C for 100 hours after shock-loading at pressures greater than 22 GPa readily disordered [Ostertag and Stöffler, 1982].

The present data may also indicate disordering in samples shocked at pressures <30 GPa. However, at higher pressures, where optical, X ray and infrared techniques are difficult to apply because the amount of crystalline material is too small, we detected changes that we attribute to the onset of disordering at 26 GPa for oligoclase and as low as 18 GPa for bytownite. In principle, the detection limit for TL is exceedingly small, and is usually governed by the appearance of competing phosphors. The main limitation for TL at present is, at least as far as feldspars are concerned, that the technique is less well understood. It is clear from existing data, however, that the peak temperatures (and

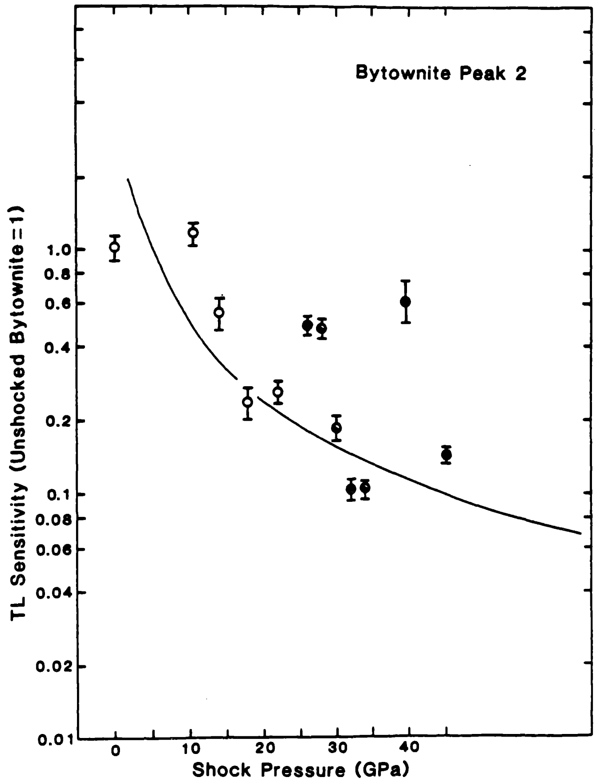

Fig. 11. Plot of TL sensitivity against shock pressure for the bytownite 178 ± 7°C peak. A 5-fold decrease in TL sensitivity is observed in the samples shock-loaded to >30 GPa. Error bars as in Figure 2, curve as in Figure 3.

widths, where their measurement is possible) are somehow related to the early stages of disordering. The main problem that remains to be resolved concerns the small size of the activation energy for the TL peak temperature and width changes compared with that of disordering as measured by the 2θ parameter; however, current data are rather meager and the influence of potential catalysts poorly constrained. Whatever the details behind the changes in glow curve shape, the present data provide an independent method of assessing shock levels of feldspar-bearing samples when the amount of crystalline material surviving the shock makes the application of other techniques difficult.

Shock in Ordinary Chondrites

Also plotted on Figure 3 are data obtained by Sears [1980] for the Kernouve H6 chondrite after shock-loading in a manner similar to that used here. The Kernouve meteorite displayed a 10-fold TL sensitivity decrease after shock-loading at 27 GPa and a 25-fold decrease after shock-loading at 39 GPa, very similar behavior to that displayed by the oligoclase sample in the present work. Mineral separation experiments have shown that the major TL phosphor in the equilibrated St. Severin chondrite is feldspar of oligoclase composition [Lalou et al., 1970; Van Schmus and Ribbe, 1968]. The shocked Kernouve samples also contained abundant maskelynite when shocked >25-30 GPa [Sears et al., 1984a]. Trace amounts of maskelynite were also found in samples shocked to only 7 GPa, but were attributed to the severe heterogeneity of shock effects in chondrites caused by the interaction between the shock wave and metal and sulfide. Heterogeneity effects in the chondrite (which contains chondrules, metal, and sulfide grains) may also explain the difference in the 17 GPa samples of Kernouve and oligoclase. The similarity in the response of the TL sensitivity of Kernouve and oligoclase (except for the 17 GPa datum) is evidence that the phosphor is feldspar and that the TL is monitoring its shock response.

Dodd and Jarosewich [1979] defined the scheme

TABLE 4. Effect of Radiation Exposure and Heating in the TL Apparatus on TL Sensitivity of Two Shocked Samples

Sample	Cumulative Dose (krad)	Number of Heatings	Normalized TL Sensitivity Peak 1	Peak 2	Peak 3
30 GPa	3.1	1	1.00	1.00	1.00
	6.2	2	0.93	1.09	1.09
	9.3	3	1.07	1.09	1.19
	13	4	1.00	1.17	1.22
	16	5	1.13	1.09	1.19
	19	6	0.93	1.04	1.16
	22	7	0.96	1.13	1.22
30 GPa	3.1	1	1.00	1.00	1.00
	31	3	1.26	1.26	1.22
	59	5	1.49	1.40	1.39
	86	7	1.64	1.42	1.46
14 GPa	3.1	1	1.00	1.00	1.00
	31	3	0.92	1.00	1.21
	59	5	0.94	1.00	1.21
	86	7	0.86	0.94	1.14

Data normalized to first measurement.

TABLE A1. Parameters for Curves Fitted to the Data in Figures 3-5 and 9-11, for y = log TL and x = log P

		Figure	Slope	Inter-cept	Corr. Coef.	No. of Points	Sig. Level
Oligoclase	peak 1	3	-1.289	0.790	-0.88	9	>95%
	peak 2	4	-0.686	0.0469	-0.79	9	>95%
	peak 3	5	-0.960	0.275	-0.91	9	>99%
	FWHM	9	-0.251	1.776	0.71	11	>95%
Bytownite	peak 1	10	-0.959	0.778	-0.52	11	>90%
	peak 2	11	-0.899	0.775	-0.53	11	>90%

most frequently used to describe naturally shocked chondrites. They utilized petrographic criteria to establish shock facies a to f such that facies d-f contain maskelynite while a-c generally do not. Incipient melting is observed only in the most intensely shocked chondrites (facies f). Dodd [1981, p. 109] estimates that shock facies a-c have suffered pressures of 0-22 GPa, while shock facies d-f have suffered pressures of 22-70 GPa.

Equilibrated ordinary chondrites that have suffered from natural shock events in space also have lower TL sensitivity than unshocked chondrites [Liener and Geiss, 1968; Sears, 1980; Sears et al., 1984b]. Meteorites of shock facies d-f have TL sensitivities 0.1-0.01 times those of shock facies a-c, consistent with shock pressures in excess of 25 GPa, and reflecting maskelynization of the feldspar. This estimate is in agreement with previous petrographic estimates of shock levels in chondrites. Based on olivine deformation and comparisons with artificially shock-loaded olivines, Carter et al. [1968] found that shocked chondrites have suffered a variety of shock pressures up to 100 GPa. Heymann [1967] estimated that shock-blackened ordinary chondrites (shock facies c and greater) had suffered pressures of a few tens of GPa to 100-150 GPa while Taylor and Heymann [1971] suggested that several facies e-f chondrites had suffered 50->80 GPa.

Summary and Conclusions

Samples of oligoclase and bytownite that have been shock-loaded to pressures up to 45 GPa show decreases in their TL sensitivity and changes in the shapes of their glow curves. The decreases in sensitivity appear to be correlated with the formation of maskelynite at the expense of crystalline feldspar, which is the mineral producing the TL emission. The decrease in TL with increasing shock is very similar to that observed for the Kernouve meteorite, and implies that ordinary chondrites of shock facies d-f have experienced pressures >25 GPa. The changes in glow curve shape, which occur after shock-loading >30 GPa, are similar to those induced by annealing Amelia albite and a type 3.4 ordinary chondrite above the order/disorder transformation temperature; for albite the changes were associated with small increases in the degree of disorder in the Al,Si structure. We therefore suggest that feldspars shocked >30 GPa have undergone a certain amount of disordering or solid state changes associated with disordering. Optical, X ray, and infrared techniques are unable to provide information on the structure of the feldspar after shock >30 GPa, because the amount of crystalline material that survives is too small, although they confirm that there was no disorder in these samples after shock-loading <30 GPa.

Appendix

For the sake of completeness, curves were fitted to the data in Figures 3-5 and 9-11 by the method of least squares assuming log-log relationships (see Table A1). The extent to which the curves describe our data can be judged from the correlation coefficient and the figures, but there is reason to believe that the relationship between TL properties and shock is discontinuous (see text).

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