American Mineralogist, Volume 86, pages 780–789, 2001

The induced thermoluminescence and thermal history of plagioclase feldspars

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ABSTRACT

Feldspars are a common component in igneous and metamorphic rocks. Most feldspars exhibit luminescence, and this has proved useful in a number of mineralogical applications. In this paper, we concentrate on the thermoluminescence (TL) properties of feldspar, or the luminescence produced when a sample of feldspar is heated. We determined the induced TL properties of four feldspars of various compositions in their natural states, and after heating, and we compared the TL data with structural changes as determined by X-ray diffraction. The major TL peak at 120–240 °C in the TL glow curve, a plot of light intensity against temperature, varies significantly among feldspar-bearing samples. Meteorites and lunar samples with slow cooling histories of ~10 °C/My as determined by independent methods, have induced TL peak temperatures of ~120 °C, while samples with fast cooling histories (~100 °C/My) have induced TL peak temperatures of ~220 °C. This variation in TL peak temperature can be reproduced by heating the present feldspar samples, meteorites and lunar samples prior to the TL measurement. Most of the present samples in their natural state had TL peak temperatures of ~120 °C. Heating below 750 °C in the laboratory caused no change in TL peak temperatures or the structural disorder of the feldspar, while heating >750 °C caused TL peak temperatures to move to ~220 °C and disordered the feldspar structure. We suggest that induced TL peak temperature in feldspar is influenced by the degree of Al-Si ordering in the feldspar. Thus, induced TL peak temperature can be used as an indicator of cooling rate for igneous and metamorphic rocks.

INTRODUCTION

Feldspar exhibits a wide range of compositions and Al-Si ordering, which makes the mineral well-suited to recording evidence of the metamorphic and igneous history of rocks (e.g., Schandl et al. 1986). Feldspar is also one of the most-common mineral groups in terrestrial metamorphic and igneous rocks, and in lunar samples and the major meteorite groups (e.g., Smith 1974; Papike et al. 1991; Rubin 1997). However, their complexity results in difficulty in interpreting composition, crystallographic order, and macroscopic and microscopic texture and some features probably reflect metastability rather than equilibrium conditions (e.g., Grove et al. 1983; Carpenter 1994).

Feldspars commonly show intense luminescence under the appropriate stimulation. Cathodoluminescence (CL), the emission of light during exposure to an electron beam, has been described for feldspar by Marshall (1988) and Mora and Ramseyer (1992), for instance, whereas the CL of lunar samples and meteorites has been described by Sippel and Spencer (1971), DeHart et al. (1992) and Götze et al. (1999). Optically stimulated luminescence (OSL), that is, the emission of visible light under stimulation from discrete wavelengths of visible light, is likewise a common feature of feldspars (e.g., Poolton et al. 1996; Duller 1997; Krbetschek et al. 1997; Wintle and Murray 1997). Thermoluminescence (TL) is the emission of visible light stimulated by heating the samples (Chen and McKeever 1997). All the common feldspar species exhibit significant TL (Prescott and Fox 1993).

Over the past decade, the luminescence properties of feldspar have enabled dating of sediments, especially loess deposits (e.g., Rendell and Townsend 1988; Berger et al. 1992; Huntley et al. 1993; Prescott and Robertson 1997). The technique is based on the removal of previous luminescence by exposure to sunlight during transport and the subsequent buildup of "new" luminescence in feldspar due to exposure to ionizing radiation from radionuclides in the surrounding soil and cosmic rays. A similar technique is used in archeological dating where the TL was "initialized" when the pottery was fired (Aitken 1985; Roberts 1997). We have discussed the application of TL properties to the study of the thermal history of meteorites and lunar samples (e.g., Sears 1988; Benoit and Sears 1993; Batchelor et al. 1997). In the present paper, we report laboratory and heating studies of the TL properties of feldspars as a test of TL data as an indicator of state of structural order and thus thermal history.

EXPERIMENTAL METHODS

Three coarsely crystalline feldspar samples, including a single crystal of oligoclase from Muskwa Lake, Canada and a poly-crystalline sample of bytownite from Crystal Bay, Minnesota, (e.g., Miller and Weiblen 1990; Table 1) were obtained from Wards Scientific, the samples having been characterized by Ostertag (1983). A sample of pulverized orthoclase perthite

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of unknown provenance was obtained from the National Bureau of Standards. Eight coarsely crystalline feldspar samples covering the plagioclase series were also obtained from Wards Scientific (Table 1). These samples have been characterized to varying degrees by authors quoted in Smith (1974). A well-analyzed sample of bulk Apollo 16 lunar soil was also included (see McKay et al. 1991, for references). Meteorite samples were obtained as 250 mg chips from the Antarctic meteorite collection of NASA/NSF, Johnson Space Center (see Grossman 1994, for details of characterization).

Approximately 250–300 mg of each sample was ground to 100 mesh (150 micrometer diameter) in an agate mortar and pestle. In the case of meteorite samples, Fe-Ni metal, which is nonluminescent and heterogeneously distributed in the samples, was removed with a hand magnet. Three 4 mg aliquots were then placed in copper pans. Each pan was placed in the TL apparatus and heated to 500 °C to eliminate pre-existing thermoluminescence. The sample was then given a ~20 Gy dose from a 200 mCi ^{90}Sr-^{90}Y beta source and the induced TL measured. The sample was heated from room temperature to 500 °C at a heating rate of 7.5 °C/s in a nitrogen atmosphere and the TL measured as a function of temperature. Our TL apparatus is a Daybreak Nuclear and Medical Systems TL system fitted with blue bandpass and IR filters (Corning 7-59 and 4-69) with a wavelength sensitivity of 400–700 nm. Samples of the Dhajala H3.8 meteorite were measured at the beginning and end of each measurement period to monitor the performance of the equipment over time and to provide a laboratory normalization for TL intensity measurements. Data for the three aliquots were averaged, the uncertainties reflecting the precision of the measurement.

The heating experiments were performed on ~100 mg samples of powder in silica glass tubes, which had been flushed three times with dry N_2 and then evacuated and sealed. The tubes were placed in a wire-wound tube furnace in which thermal profiles were determined by independent thermocouples. After heating, samples were removed from the furnace and allowed to cool to room temperature in air, on the order of a few minutes or less. Samples were heated for times ranging from 1 hour to 100 hours and temperatures ~440–1080 °C.

X-ray diffraction (XRD) measurements were made on powdered samples using a Diano 8500 series diffractometer at the Department of Geology, University of Arkansas, Fayetteville. A 40 kV, 20 mA Cu*Ka* source was used. Duplicate XRD measurements were made with a Norelco diffractometer at the Johnson Space Center with the same conditions. Scans were made over 2θ angles of 29 and 32° at ~0.25 °C/min. The data were analyzed by determining the difference between the postitions of the (131) and ($1\bar{3}1$) diffraction peaks, as described by Kroll and Ribbe (1983).

RESULTS

All the feldspars in this study produced glow curves consisting of a single broad peak, typically with a shoulder on the higher temperature side of the peak (Table 2; Fig. 1; Haq et al. 1988; Batchelor et al. 1997). The position of the peak in the glow curve in each sample ranged from 120 to 280 °C but was highly reproducible for aliquants of the same sample. TL sensitivity, defined as the maximum intensity of the TL peak normalized to the maximum intensity of the peak of a laboratory standard, also varied significantly from sample to sample, but was reproducible for aliquants from the same sample. The TL sensitivity of our plagioclase samples generally decreased as a function of Ca content (Fig. 2; Table 2). A similar trend has been reported by Prescott and Fox (1993).

Samples heated at temperatures <600 °C showed no significant differences in TL peak temperature with those of unheated samples. Samples heated at 750 °C, however, had glow curves significantly different from those of unheated samples. In the case of the oligoclase sample, the glow curves of heated samples are characterized by the growth of the shoulder on the peak in the unheated sample (Figs. 3 and 4). Similar effects

TABLE 1. Samples used in our study and approximate feldspar composition

Type of Feldspar	Locality	Environment	Feldspar compostion*
Albite	Amelia Court House, VA	Pegmatite	$Or_{1.7}Ab_{98.3}An_{0.0}$
Albite	Keystone, SD	Pegmatite	
Albite	Bancroft, Ontario	Vein (plutonic?)	$Or_{0.5}Ab_{91.2}An_{8.3}$
Andesine	Essex Co., NY	Plutonic	$Or_{3.6}Ab_{48.3}An_{48.1}$
Anorthite	Grass Valley, CA	Plutonic	$Or_{0.2}Ab_{6.7}An_{93.1}$
Anorthite	Apollo 16 landing site	Lunar regolith	$Or_{0.2}Ab_{3.4}An_{96.4}$
Bytownite	Crystal Bay, MN	Plutonic	$Or_{0.4}Ab_{22.0}An_{77.6}$
Labradorite	Lake St. John, Quebec	Plutonic	$Or_{2.4}Ab_{42.6}An_{55.0}$
Oligoclase	Mitchell Co., NC	Pegmatite	$Or_{2.8}Ab_{76.5}An_{20.7}$
Oligoclase	Muskwa Lake, Canada	Plutonic	$Or_{2.3}Ab_{78.0}An_{19.7}$
Orthoclase	National Bureau of Standards	unknown	$Or_{41.2}Ab_{44.1}An_{14.7}$

* Data from compilations of Deer et al. (1963), Smith (1974), Smith and Brown (1988), and McKay et al. (1991).

TABLE 2. Induced thermoluminescence properties of a series of plagioclase feldspars

Sample, locality	Induced thermoluminescence peak temperature (°C)	Thermoluminescence sensitivity, relative to Dhajala = 1.0
Albite, Amelia Court House, VA	162 ± 1	17.8 ± 0.8
Albite, Bancroft, Ontario	121 ± 5	35 ± 2
Albite, Keystone, SD	146 ± 2	11.0 ± 0.6
Andesine, Essex Co., NY	118 ± 2	5.1 ± 0.3
Anorthite, Grass Valley, CA	129 ± 2	0.030 ± 0.002
Bytownite, Crystal Bay, MN	110 ± 2	0.056 ± 0.004
Labradorite, Lake St. John, Quebec	102 ± 4	0.42 ± 0.03
Oligoclase, Mitchell Co., NC	179 ± 7	2.8 ± 0.2

were present in the other samples, although the heating temperature required to produce significant changes in the glow curve varied among the samples, e.g., ~740 °C for perthite and bytownite, and ~800 °C for lunar soil 61501, in which the primary phosphor is anorthitic feldspar (Figs. 5, 6, and 7). No systematic changes in TL sensitivity were observed as a function of heating temperature, although some samples had higher TL sensitivity after heating to >800 °C.

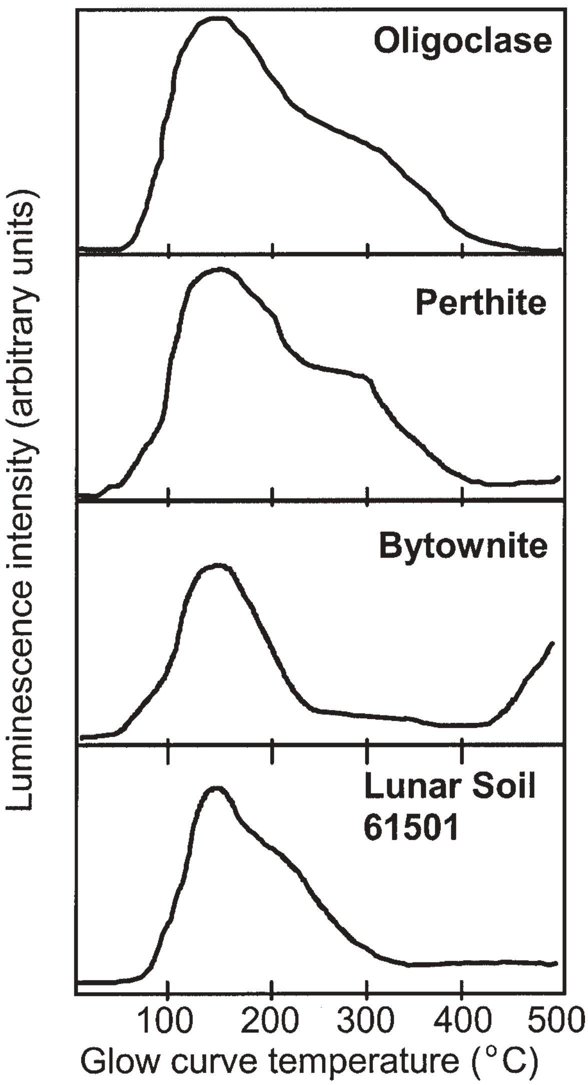

FIGURE 1. Thermoluminescence glow curves of feldspar samples. The glow curves consist of a single peak, typically with a shoulder in the high temperature portion of the peak. The slight rise at temperatures >450 °C reflects intrinsic black-body radiation.

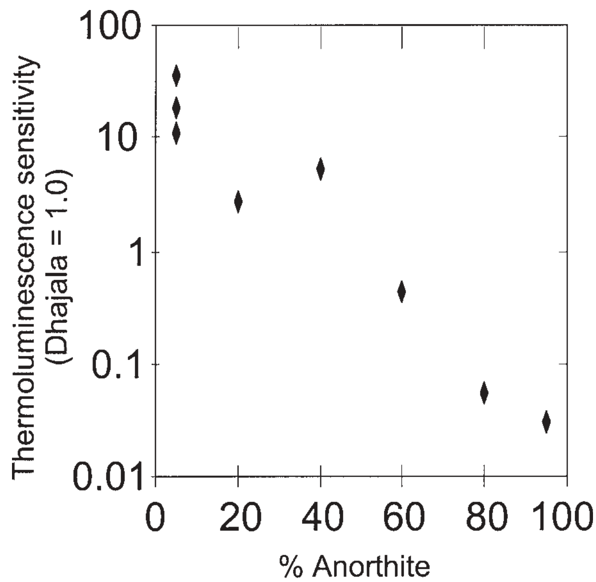

FIGURE 2. Thermoluminescence sensitivity of plagioclase feldspars. Compositional data are not available for these samples, so they are plotted in the middle of the compositional range of their classes. TL sensitivity generally decreases with increasing calcium content in this series. This change probably reflects filters used in the apparatus and changes in the peak wavelength of TL emission (Prescott and Fox 1993).

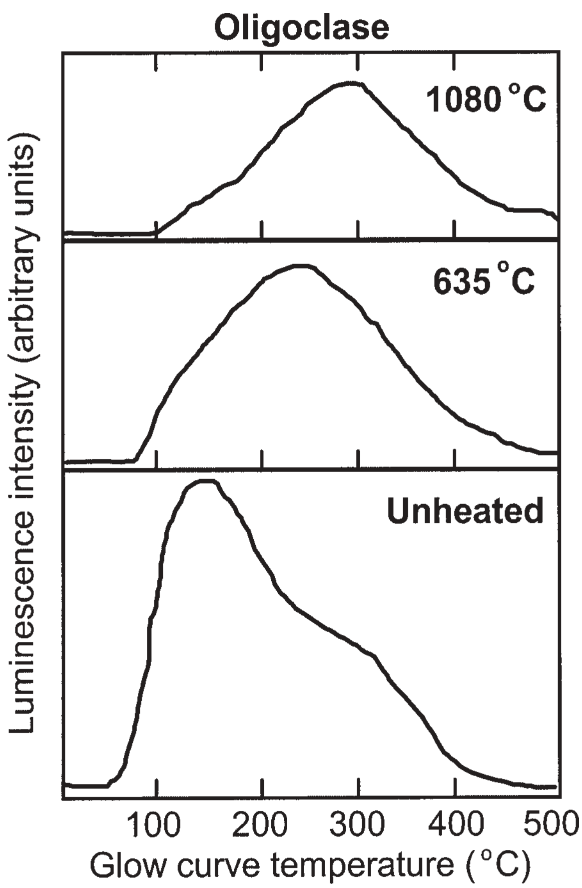

FIGURE 3. Thermoluminescence glow curve for heated and unheated oligoclase samples. Heated samples were heated for approximately 100 h. Heat treatment significantly alters the TL glow curve of oligoclase, resulting in an increase in glow curve peak temperature.

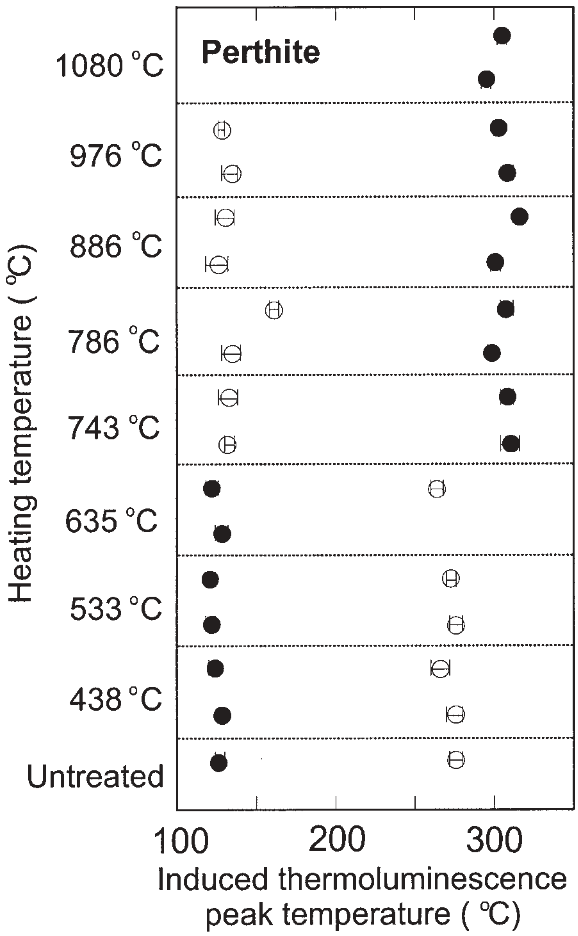

FIGURE 4. Induced thermoluminescence peak temperatures for orthoclase perthite after heating for various temperatures for 10 or 100 h. One sigma uncertainties for time and heating temperature are <1%, while uncertainties shown for TL data are one sigma based on measurements on three aliquants. Filled symbols are for the major peak, and open symbols are inflections on the major peak in the glow curve. Sample is a National Bureau of Standards orthoclase perthite ($Or_{41.2}Ab_{44.1}An_{14.7}$).

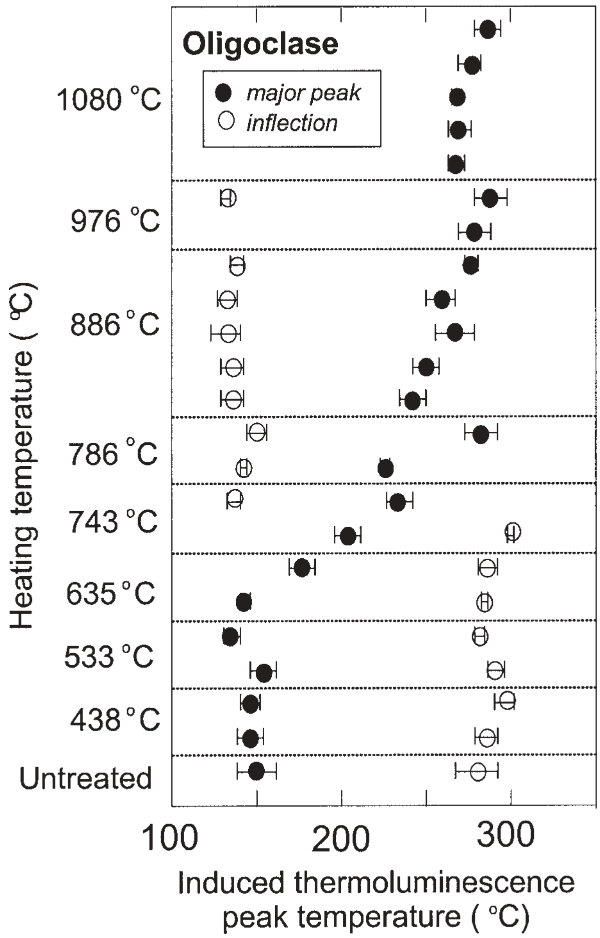

FIGURE 5. Induced thermoluminescence peak temperatures for oligoclase after heating for various temperatures for 10 or 100 h. One sigma uncertainties for TL data are shown based on average of three aliquots. If not shown, analytical uncertainties are within the size of the symbol. Filled symbols are for the major peak, while open symbols are inflections on the major peak in the glow curve. Sample is a crushed single crystal from Muskwa Lake, Canada ($Or_{2.3}$, $Ab_{78.0}$, $An_{19.7}$).

The heating experiments (Fig. 8) suggest that the activation energy (E_a) for changes in glow curve shapes, using an empirical fit to an Arrhenius equation (e.g., Guimon et al. 1985), is ~14 kcal/mol for lunar soil 61501. Guimon et al. (1985) found a similar activation energy of ~10 kcal/mole for the induced TL peak shift for an unequilibrated ordinary chondrite in which the TL was produced by a fairly sodic feldspar (approximately $Ab_{84}An_{10}Or_6$). Pasternak (1978) found a value of ~20 kcal/mol for the peak temperature change for Amelia albite.

The relative positions of the (131) and ($1\bar{3}1$) lines in the powder XRD pattern of sodic feldspars are interpreted as reflecting the degree of ordering of the feldspar structure, notably in Al-Si ordering (e.g., Kroll and Ribbe 1983; Meneghinello et al. 1999). As shown in Figure 9a, an oligoclase sample heated to >850 °C has a larger Δ131 and thus a higher degree of disorder than unheated samples. The data plotted in Figure 9b suggest a relationship between induced TL peak temperature and the degree of disorder indicated by the X-ray data (see also Table 3). Samples with high induced TL peak temperatures (~220 °C) exhibit significant degrees of disorder, whereas samples with low induced TL peak temperatures have higher degrees of order. Pasternak (1978) made a similar observation to those described here for samples of Amelia County albite. The correlation between TL peak temperature and the 2θ parameter is not linear, however, and the TL peak temperature shift occurs only after heating >750 °C, whereas significant alterations in the structure monitored by XRD require heating to >850 °C.

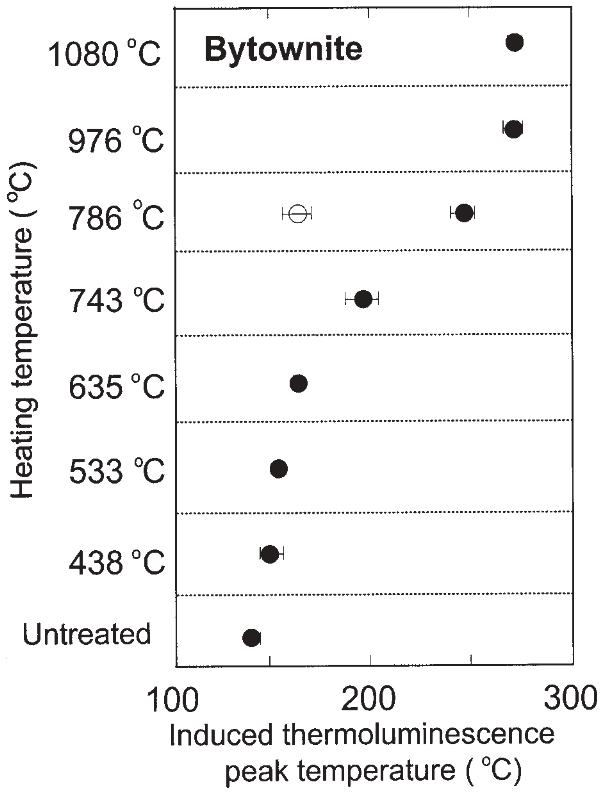

FIGURE 6. Induced thermoluminescence peak temperatures for bytownite after heating for 100 h at various temperatures. One sigma uncertainties are shown for induced TL data, based on averages for three aliquots. If not shown, analytical uncertainties are within the size of the symbol. Filled symbols are for the major peak, while open symbol is for an inflection on the major peak in the glow curve. Sample is a crushed polycrystalline sample from Crystal Bay, Minnesota, ($Or_{0.4}Ab_{22.0}An_{77.6}$).

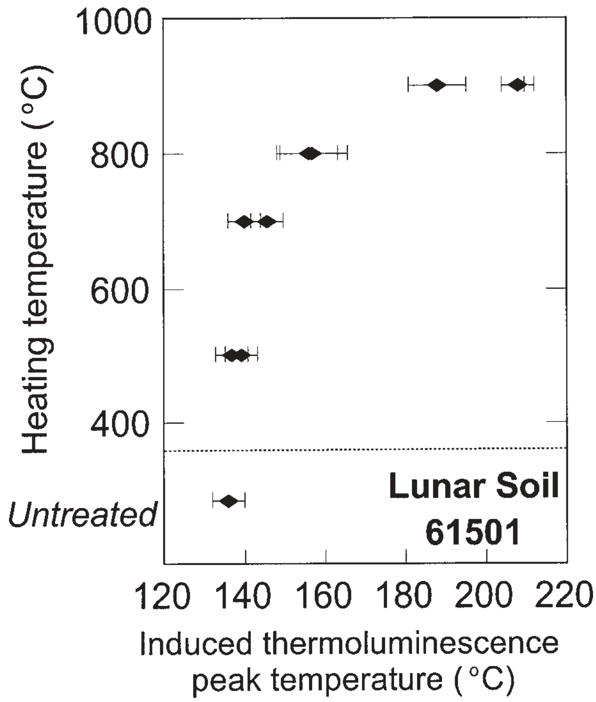

FIGURE 7. Induced thermoluminescence peak temperatures for Apollo 16 lunar soil 61501 after heating to various temperatures for 10 or 100 h. One sigma uncertainties are shown for the induced TL data, based on averages for three aliquots. If not shown, analytical uncertainties are within the size of the symbol. This sample is a mixture of anorthitic plagioclase, glass, shocked plagioclase, and minor amounts of pyroxene and olivine (McKay et al. 1991).

DISCUSSION

Induced TL and the role of structure

The mechanism for TL production in feldspars is uncertain, but TL emissions of wavelengths detectable with the present apparatus are typically ascribed to Fe^{2+}, Cu^{2+}, and Ti^{4+} impurities in the feldspar structure (Huntley et al. 1988; Prescott and Fox 1993) or to Al-O$^-$-Al electron hole luminescence centers (see Krbetschek et al. 1997, and references therein), although other impurities such as Mn^{2+} and Fe^{3+} may also play a role (Telfer and Walker 1978). Since TL sensitivity is not radically changed by laboratory heating, it is unlikely that the changes in TL peak temperature can be ascribed to significant changes in the types of luminescence centers, unlike the changes observed in calcite where the development of translation gliding is probably involved (Bergues and Chayé d'Albissin 1990).

A more likely explanation for the heating results is relatively minor alteration of the feldspar structure around luminescence centers (Sears et al. 1984, 1990). The influence of feldspar structure on luminescence has not been studied in detail, although changes in TL properties due to phase changes

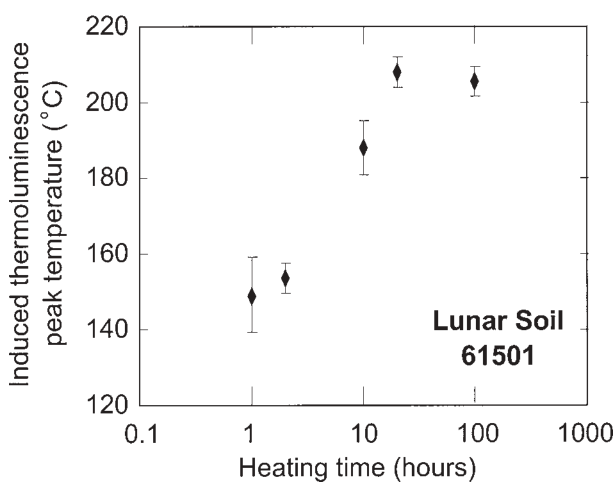

FIGURE 8. Induced thermoluminescence peak temperatures for Apollo 16 lunar soil 61501, after heating for various times. At 900 °C samples heated for <5 h exhibit peak temperatures similar to unheated material (Fig. 7).

TABLE 3a. Induced thermoluminescence and powder XRD properties of heated and unheated samples of feldspar and Apollo 16 lunar soil

Heating Temperature (°C)	Heating Duration (hours)	Thermoluminescence sensitivity*	Peak Temperature (°C)	Thermoluminescence sensitivity*	Peak Temperature (°C)	$\Delta 2\theta$, (131)–(1$\bar{3}$1)
			Oligoclase Muska Lake			
0	0	1 ± 0.09	150 ± 12	1 ± 0.09	280 ± 12	1.51 ± 0.04
438	11	0.78 ± 0.02	146 ± 8	0.65 ± 0.03	286 ± 7	1.51 ± 0.02
438	100	0.79 ± 0.04	146 ± 6	0.64 ± 0.05	296 ± 6	1.52 ± 0.03
533	10	0.5 ± 0.2	154 ± 8	0.45 ± 0.04	291 ± 5	1.52 ± 0.03
533	100	0.48 ± 0.06	135 ± 5	0.43 ± 0.01	282 ± 3	1.51 ± 0.03
635	10	0.56 ± 0.03	143 ± 3	0.58 ± 0.09	285 ± 2	1.51 ± 0.04
635	96	0.61 ± 0.05	177 ± 7	0.73 ± 0.1	287 ± 6	1.54 ± 0.03
743	10	0.61 ± 0.03	204 ± 7	0.86 ± 0.09	300 ± 1	1.54 ± 0.04
743	96	0.51 ± 0.05	137 ± 4	4.45 ± 0.2	234 ± 8	1.54 ± 0.05
786	10	0.57 ± 0.05	142 ± 2	1.07 ± 0.2	226 ± 3	1.53 ± 0.03
786	96	0.8 ± 0.07	150 ± 6	1.76 ± 0.3	280 ± 10	1.61 ± 0.04
886	1	0.46 ± 0.03	136 ± 7	1.55 ± 0.5	242 ± 8	1.54 ± 0.05
886	2	0.47 ± 0.04	136 ± 7	1.7 ± 0.2	250 ± 7	1.55 ± 0.05
886	11	0.49 ± 0.02	132 ± 8	2.39 ± 0.2	267 ± 11	1.64 ± 0.03
886	20	0.43 ± 0.04	133 ± 6	2.2 ± 0.3	259 ± 9	1.66 ± 0.08
886	100	0.45 ± 0.05	139 ± 4	2.59 ± 0.4	277 ± 4	1.72 ± 0.03
976	10	0.36 ± 0.08	–	2.53 ± 0.3	279 ± 9	1.77 ± 0.07
976	96.2	0.27 ± 0.07	131 ± 3	2.01 ± 0.4	290 ± 10	1.83 ± 0.03
1080	1	0.41 ± 0.03	–	2.2 ± 0.1	268 ± 5	1.73 ± 0.05
1080	2	0.36 ± 0.05	–	2 ± 0.3	270 ± 6	1.78 ± 0.08
1080	10	0.4 ± 0.07	–	2.53 ± 0.2	268 ± 3	1.85 ± 0.02
1080	20	0.55 ± 0.05	–	4 ± 0.5	276 ± 6	1.85 ± 0.04
1080	100	0.77 ± 0.2	–	6.99 ± 0.4	286 ± 8	1.82 ± 0.07
			Orthoclase National Bureau of Standards			
0	0	1 ± 0.1	127 ± 3	–	–	–
438	10	1 ± 0.09	128 ± 2	–	–	–
438	100	1.2 ± 0.1	124 ± 3	–	–	–
533	10	0.84 ± 0.06	122 ± 3	–	–	–
533	100	0.9 ± 0.1	121 ± 3	–	–	–
635	10	0.51 ± 0.05	128 ± 4	–	–	–
635	100	0.58 ± 0.05	122 ± 4	–	–	–
743	10	0.56 ± 0.07	133 ± 3	1.1 ± 0.3	311 ± 6	–
743	100	0.51 ± 0.05	132 ± 6	1.1 ± 0.3	308 ± 4	–
786	10	0.49 ± 0.06	134 ± 6	2.7 ± 0.3	299 ± 2	–
786	100	0.85 ± 0.06	161 ± 3	3.1 ± 0.3	309 ± 4	–
886	10	1.08 ± 0.03	126 ± 7	9 ± 2	301 ± 3	–
886	100	1.7 ± 0.3	130 ± 6	19 ± 3	316 ± 2	–
976	10	0.8 ± 0.2	134 ± 5	10 ± 2	309 ± 3	–
976	100	4.5 ± 0.5	128 ± 2	56 ± 5	304 ± 3	–
1080	10	–	–	15 ± 3	296 ± 3	–
1080	100	–	–	46 ± 6	306 ± 3	–

Notes: Sample sources: Orthoclase perthite, National Bureau of Standards, Washington, D.C.; Oligoclase, Muskwa Lake, Canada, (Ostertag 1983).
* For oligoclase and perthite the TL sensitivity is normalized to the sensitivity of the original, unheated, sample.

have been noted in other materials (Townsend et al. 1997), in part due to the difficulty of monitoring structure in K-rich feldspar, the most common phosphor in TL sediment dating applications (Garcia-Guinea et al. 1996). Measurements of electron spin resonance, a related phenomenon, stress the importance of Al-O^--Al electron hole defects, that is, an O^- atom bonding two Al tetrahedra, as the major source of luminescence centers in feldspar (Petrov et al. 1989; Petrov 1994). The diffusion of Al in tetrahedral sites in feldspar is known from laboratory experiments to be very slow, especially at temperatures <1000 °C. This is reflected in our heating data, our results indicating that there is not a direct link between TL properties and Al-Si ordering (Fig. 9). Activation energies for the TL changes are much lower than for Al-Si ordering in albite (10–15 kcal/mol vs. ~75 kcal/mol, respectively, McKie and McConnell 1963). The two phenomena are therefore not simply related, or TL is a more sensitive indicator of the onset of crystallographic disordering than X-ray measurements. Pasternak (1978) suggested that the TL shift reflected defect formation preceding the structural transition. Petrov et al. (1989) noted variations in the ESR spectra of albite after heat treatments of ≥700 °C, which they attributed to localized increases in Al-Si disorder around Fe^{3+} sites. Notably, however, the changes are apparently not reversible under laboratory conditions, as repeat measurements on samples after heat treatments >750 °C do not show shifts of TL parameters back to original values. This stability has also been noted in X-ray-determined structural studies of laboratory-heated feldspar samples. (e.g., Ribbe 1983). As our heating experiments were conducted with dry powers, it is unlikely that Al (and thus TL center) mobility was enhanced by hydrogen (Goldsmith 1987).

Induced TL and the thermal history of feldspars

If induced TL peak position in feldspar is related to ordering in the feldspar structure, the TL peak temperature should reflect cooling history. The thermal history of igneous bodies can be examined by application of radiometric dating techniques (e.g., Dalrymple et al. 1999) or by various “geospeedometers”

TABLE 3b. Induced thermoluminescence and powder XRD properties of heated and unheated samples of feldspar and Apollo 16 lunar soil

Heating Temperature (°C)	Heating Duration (hours)	Thermoluminescence sensitivity*	Peak Temperature (°C)	Thermoluminescence sensitivity*	Peak Temperature (°C)	$\Delta 2\theta$, (131)–($\bar{1}31$)
			Bytownite Crystal Bay, Minnesota			
0	0	1 ± 0.3	140 ± 3	–	–	–
438	100	0.74 ± 0.07	150 ± 5	–	–	–
533	100	1.65 ± 0.07	153 ± 2	–	–	–
635	100	1.24 ± 0.2	163 ± 3	–	–	–
743	100	–	–	1.41 ± 0.05	196 ± 8	–
786	100	0.59 ± 0.1	164 ± 7	0.9 ± 0.1	246 ± 6	–
976	100	–	–	5.4 ± 0.6	272 ± 5	–
1080	100	–	–	7.7 ± 0.8	273 ± 3	–
			Lunar Soil 61501			
0	0	– 0.11 ± 0.01	136 ± 4	–	–	
500	10	0.21 ± 0.03	137 ± 4	–	–	–
500	100	0.28 ± 0.06	139 ± 4	–	–	–
700	10	0.25 ± 0.05	146 ± 4	–	–	–
700	100	0.26 ± 0.04	140 ± 4	–	–	–
800	10	0.23 ± 0.06	156 ± 7	–	–	–
800	100	0.4 ± 0.1	157 ± 9	–	–	–
900	1	0.22 ± 0.06	149 ± 10	–	–	–
900	2	0.3 ± 0.04	154 ± 4	–	–	–
900	10	0.44 ± 0.09	188 ± 7	–	–	–
900	20	0.39 ± 0.05	208 ± 4	–	–	–
900	100	0.61 ± 0.05	206 ± 4	–	–	–

Notes: Sample sources: Bytownite, Crystal Bay, Minnesota, (Ostertag 1983); Lunar soil 61501, Apollo 16 collection, NASA, Johnson Space Center, Houston, Texas. TL data include sensitivity and peak position of the two major peaks found in these samples.
* For bytownite, the TL sensitivity is normalized to the sensitivity of the original, unheated, sample. For lunar soil 61501, TL sensitivity is normalized to a sample of the Dhajala (H3.8) meteorite.

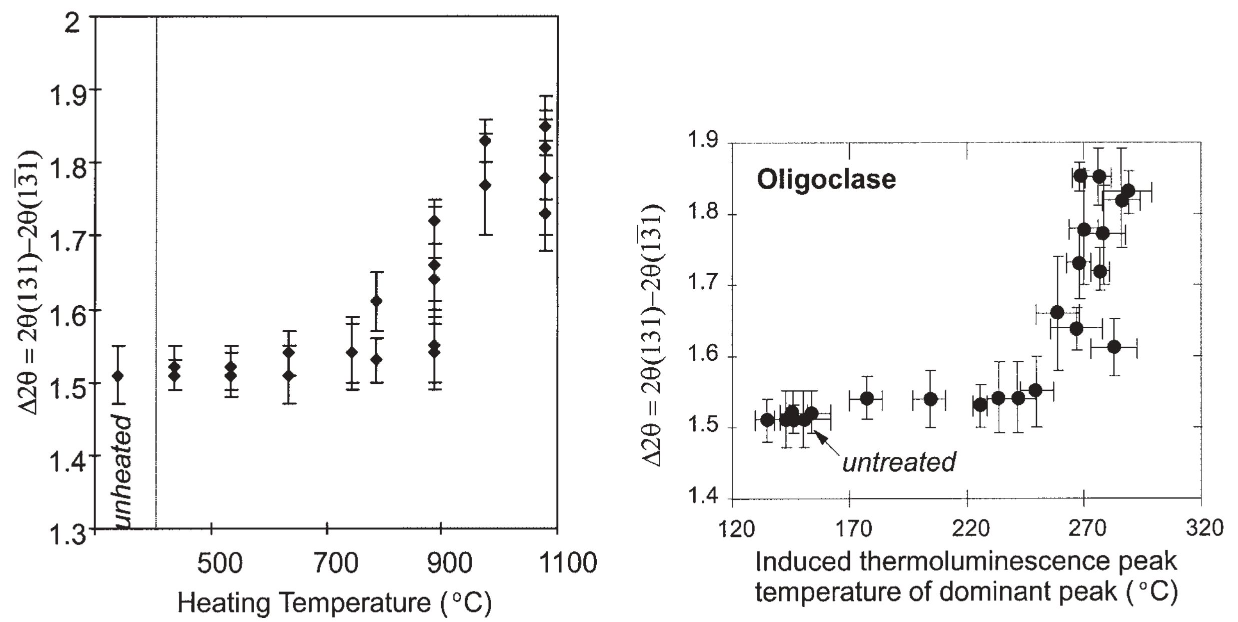

FIGURE 9. Plot of the difference between XRD peak positions for the 131 and $\bar{1}31$ reflections and induced TL peak positions for heated samples of oligoclase (see Fig. 5). The $\Delta 2\theta$ parameter is used as an indicator of crystallographic ordering, with values of ~2.0 being disordered, and values of ~1.5 being ordered (Kroll and Ribbe 1983).

(e.g., Domeneghetti et al. 2000), but the extensive sampling and analysis required by these techniques can be prohibitive. Our samples were chosen for the presence of large feldspar crystals and thus were typically taken either from large igneous bodies or pegmatites (Table 1). Samples from large igneous bodies might be expected to have experienced slow post-crystallization cooling histories, and we find that these samples generally exhibit low induced TL peak temperatures compared with heated feldspar samples (Table 3; Fig. 5). Samples from pegmatites, including the Amelia albite and Mitchell County oligoclase (Lemke et al. 1952; Lesure 1968) have a largely unknown thermal history (e.g., Webber et al.

1997; Baker and Freda 1999), but it is likely that these small bodies had significantly faster cooling rates than large plutonic bodies at ~750 °C, the temperature of TL "closure" (Fig. 5). Crystals of Amelia albite are well-ordered (Harlow and Brown 1980; Yang et al. 1986), which would seem to contradict our interpretation of our TL as indicative of rapid cooling. However, as noted above, the connection between crystallographic order and induced TL properties is indirect, and we suggest that the data can be interpreted as indicating conditions suitable for formation of highly ordered crystals, but with relatively rapid cooling compared to plutonic bodies. Other possible interpretations, however, might emphasize the role of trace element composition in pegmatitic feldspars. Trace "dopants" are often used in TL radiation dosimetry to alter the TL properties of synthetic crystals, such as various Mg-, Ti-, Na-, Cu-, and P-doped LiF crystals used in variety of personnel and environmental radiation dosimetry measurements (e.g., McKeever 1985), and pegmatitic feldspars commonly contain minor amounts of a variety of trace elements (Smith 1983). The influence of trace elements on TL properties of feldspar is a complex, and poorly documented, phenomenon (e.g., Poolton et al. 1996; Krbetschek et al. 1997).

One way to examine the possible role of cooling history on TL properties of feldspar is to examine lunar samples and meteorites with igneous and metamorphic histories (Table 4). These samples have been extensively studied, and in some cases contain mineral phases suitable for independent cooling rate estimation. The cumulate eucrite meteorites, igneous meteorites thought to come from the asteroid Vesta, have low induced TL peak temperatures (of ~130 °C) and had slow post-igneous cooling rates of ~6 K/Ma (Warren et al. 1989; Batchelor and Sears 1991). Lunar mare basalts have high induced TL peak temperatures (~220 °C in the glow curve) and thus apparently disordered feldspars, and have inferred cooling rates of ~30 °C/h (Stewart et al. 1970; Onorato et al. 1978; Batchelor et al. 1997).

Equilibrated ordinary chondrites, which did not experience melting but did experience significant degrees of metamorphism and have microcrystallites of sodic feldspar in glass, have intermediate induced TL peak temperatures (~190 °C in the glow curve) (Haq et al. 1988). For these meteorites, cooling history can be inferred from compositional profiles in Fe-Ni metal grains (Wood 1967; Willis and Goldstein 1981) and cooling rates are on the order of 10–1000 °C/My (Lipschutz et al. 1989; Table 4). Although the range of induced TL peak temperatures exhibited by equilibrated ordinary chondrites is relatively small, TL peak temperature correlates with cooling rate determined from the composition and structure of Fe-Ni metal grains (Fig. 10).

Our study has shown that induced TL properties of feldspar may be associated with structural order, perhaps degree of Al-Si ordering in tetrahedral sites. However, there is clearly not a direct linkage between the two phenomena. Induced TL can be used as a qualitative indicator of thermal history of feldspars, or perhaps as a semi-quantitative indicator of thermal history if correlated against other cooling rate indicators. Unlike XRD methods, induced TL measurements do not require large single crystals or mineral separates, and, in comparison with other cooling rate determinations, induced TL requires less sample processing and instrumentation. In addition, induced TL data

TABLE 4. Induced thermoluminescence properties and cooling rates for lunar and meteorite samples

Sample	Induced thermoluminescence peak temperature (°C)*	Cooling rate, temperature range	Source of cooling rate estimate†
	Cumulate Eucrite Meteorites		
ALH 85001	115 ± 2	~6 K/My, 1600–1000 °C	A
Moore County	118 ± 3	~6 K/My, 1600–1000 °C	A
Serra de Mage	102 ± 3	~6 K/My, 1600–1000 °C	A
	Lunar Mare basalts		
10020	220 ± 20	0.1 – 30 °C/h, ~1200 °C	B
10049	200 ± 10	0.1 – 30 °C/h, ~1200 °C	B
12021	225 ± 10	0.1 – 30 °C/h, ~1200 °C	B
15449	200 ± 10	0.1 – 30 °C/h, ~1200 °C	B
	Equilibrated ordinary chondrite meteorites		
ALH A76008	180 ± 2	5 K/My, ~550 °C	C
ALH A77012	172 ± 2	10 K/My, ~550 °C	C
ALH A77014	186 ± 5	2 K/My, ~550 °C	C
ALH A77262	197 ± 3	100 K/My, ~550 °C	C
ALH A77274	195 ± 4	150 K/My, ~550 °C	C
ALH A77294	188 ± 2	25 K/My, ~550 °C	C
ALH A78076	182 ± 2	10 K/My, ~550 °C	C
ALH A78111	182 ± 3	40 K/My, ~550 °C	C
ALH A78115	174 ± 2	10 K/My, ~550 °C	C
ALH A78134	190 ± 1	50 K/My, ~550 °C	C
ALH A79026	205 ± 4	200 K/My, ~550 °C	C
ALH A79035	184 ± 1	100 K/My, ~550 °C	C
ALH A80121	187 ± 1	50 K/My, ~550 °C	C
ALH A80131	193 ± 4	150 K/My, ~550 °C	C
ALH A81015	198 ± 2	10 K/My, ~550 °C	C
ALH A81092	195 ± 11	130 K/My, ~550 °C	C
ALH A81105	192 ± 1	10 K/My, ~550 °C	C
ALH A82102	190 ± 6	100 K/My, ~550 °C	C

* Induced thermoluminescence data from Batchelor and Sears (1991), Benoit and Sears (1993), and Batchelor et al. (1997).
† Data type and source. A = Sm–Nd isotopic system. (Warren et al. 1989; Tera et al. 1987). B = Olivine compositional profiles (Onorato et al. 1978). C = Metal composition/structure (Benoit and Sears 1993, 1996).

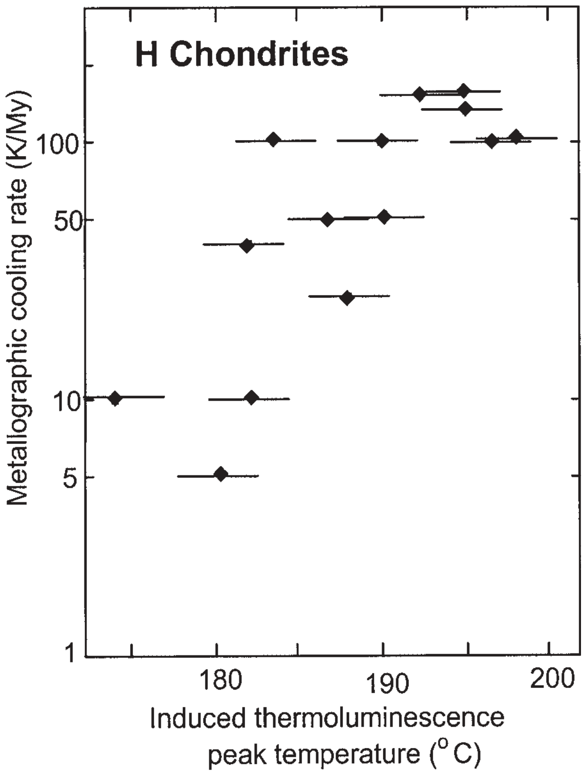

FIGURE 10. Induced TL peak temperature and metallographic cooling rates for equilibrated H chondrites. The metallographic cooling rates are estimated from compositional profiles in Fe-Ni metal grains as discussed by Willis and Goldstein (1981), the raw data presented in Benoit and Sears (1993). Petrologic type refers to the degree of metamorphism exhibited by the meteorites, type 6 being the most metamorphosed. Induced TL peak temperature tends to increase with increasing metallographic cooling rate even within the limited range of peak temperatures and metallographic cooling rates noted for this class of meteorites (e.g., Lipschutz et al. 1989).

can be used for samples covering the full range of plagioclase feldspar compostions, whereas XRD studies are limited to Na-rich feldspars. An obvious application of induced TL as a thermal history indicator is examination of the cooling history of large differentiated igneous intrusions.

ACKNOWLEDGMENTS

We thank Brad Jolliff, Steve Sutton, Alan Rubin, and an anonymous reviewer for their constructive comments. This study was supported by the National Aeronautics and Space Administration of the United States.

REFERENCES CITED

Aitken, M.J. (1985) Thermoluminescence Dating. Academic Press, New York.

Baker, D.R. and Freda, C. (1999) Using models of undercooled binary system crystallization: Comparison with experimental and pegmatite textures. American Mineralogist, 84, 725–732.

Batchelor, D. and Sears, D.W.G. (1991) Thermoluminescence constraints on the metamorphic, shock, and brecciation history of basaltic meteorites. Geochimica et Cosmochimica Acta, 55, 3831–3844.

Batchelor, J.D., Symes, S.J.K., Benoit, P.H., and Sears, D.W.G. (1997) Constraints on the thermal and mixing history of lunar surface materials and comparisons with basaltic meteorites. Journal of Geophysical Research, 102, 19321–19334.

Benoit, P.H. and Sears, D.W.G. (1993) Breakup and structure of an H-chondrite parent body: The H-chondrite flux over the last million years. Icarus, 101, 188–200.

Benoit, P.H., Sears, D.W.G., and Symes, S.J.K. (1996) The thermal and radiation exposure history of lunar meteorites. Meteoritics and Planetary Science, 31, 869–875.

Berger, G.W., Pillans, B.J., and Palmer, A.S. (1992) Dating of loess up to 800 ka by thermoluminescence. Geology, 20, 403–406.

Bergues, J. and Chayé d'Albissin, M. (1990) Thermoluminescence as a scalar measure of plastic strain in experimentally and naturally deformed crystalline limestones. Tectonophysics, 172, 223–234.

Carpenter, M.A. (1994) Subsolidus phase relations of the plagioclase feldspar solid solution. In Feldspars and their Reactions, Kluwer Academic, 221–269.

Chen, R. and McKeever, S.W.S. (1997) Theory of Thermoluminescence and Related Phenomena, 559 p. World Scientific, Singapore.

Dalrymple, G.B., Grove, M., Lovera, O.M., Harrison, T.M., Hulen, J.B., and Lanphere, M.A. (1999) Age and thermal history of the Geysers plutonic complex (felsite unit), Geysers geothermal field, California: A $^{40}Ar/^{39}Ar$ and U-Pb study. Earth and Planetary Science Letters, 173, 285–298.

Deer, W.A., Howie R.A., and Zussman, J. (1963) Rock-forming Minerals, Vol. 4., Framework Silicates, Longmans, London.

DeHart, J.M., Lofgren, G.E., Lu, J., Benoit, P.H., and Sears, D.W.G. (1992) Chemical and physical studies of chondrites: X. Cathodoluminescence and phase composition studies of metamorphism and nebular processes in chondrules of type 3 ordinary chondrites. Geochimica et Cosmochimica Acta, 56, 3791–3807.

Domeneghetti, M.C., Molin, G.M., Triscari, M., and Zema, M. (2000) Orthopyroxene as a geospeedometer: Thermal history of Kapoeta, Old Homestead 001, and Hughes 002 howardites. Meteorites and Planetary Science, 35, 347–354.

Duller, G.A.T. (1997) Behavioral studies of stimulated luminescence from feldspars. Radiation Measurements, 27, 663–694.

Garcia-Guinea, J., Rendell, H.M., and Sanchez-Muñoz, L. (1996) Luminescence spectra of alkali feldspars: Some relationships between structural features and luminescence emission. Radiation Protection Dosimetry, 66, 395–398.

Goldsmith, J.R. (1987) Al/Si interdiffusion in albite: Effect of pressure and the role of hydrogen. Contributions to Mineralogy and Petrology, 95, 311–321.

Götze, J., Habermann, D., Kempe, U., Neuser, R.D., and Richter, D.K. (1999) Cathodoluminescence microscopy and spectroscopy of plagioclases from lunar soil. American Mineralogist, 84, 1027–1032.

Grossman, J.N. (1994) Meteoritical Bulletin, No. 76, 1994 January: The U.S. Antarctic meteorite collection. Meteoritics, 29, 100–143.

Grove, T.L., Ferry, J.M., and Spear, F.S. (1983) Phase transitions and decomposition relations in calcic plagioclase. American Mineralogist, 68, 41–59.

Guimon, R.K., Keck, B.D., Weeks, K.S., DeHart, J.M. and Sears, D.W.G. (1985) Chemical and physical studies of type 3 chondrites—IV: Annealing studies of a type 3.4 ordinary chondrite and the metamorphic history of meteorites. Geochimica et Cosmochimica Acta, 49, 1515–1524.

Haq, M., Hasan, F.A., and Sears, D.W.G. (1988) Thermoluminescence and the shock and reheating history of meteorites: IV. The induced TL properties of type 4–6 ordinary chondrites. Geochimica et Cosmochimica Acta, 52, 1679–1689.

Harlow, G.E., and Brown, G.E., Jr. (1980) Low albite: An X-ray and neutron diffraction study. American Mineralogist, 65, 986–995.

Huntley, D.J., Godfrey-Smith, D.I., Thewalt, M.L.W., and Berger, G.W. (1988) Thermoluminescence spectra of some mineral samples relevant to thermoluminescence dating. Journal of Luminescence, 39, 123–136.

Huntley, D.J., Hutton, J.T., and Prescott, J.R. (1993) The stranded beach-dune sequence of south-east South Australia: A test of thermoluminescence dating, 0–800 ka. Quaternary Science Review, 12, 1–20.

Krbetschek, M.R., Götze, J., Dietrich, A., and Trautmann,T. (1997) Spectral information from minerals relevant for luminescence dating. Radiation Measurements, 27, 695–748.

Kroll, H. and Ribbe, P.H. (1983) Lattice parameters, composition and Al, Si order in alkali feldspars. In Mineralogical Society of America Reviews in Mineralogy, 2, 57–100.

Lemke, R.W., Johns, R.H., and Griffitts, W.R. (1952) Mica deposits of the Southeastern Piedmont, Part 2, Amelia District, Virginia. U.S. Geological Survey Professional Paper, 248B, 121–125.

Lesure, F.G. (1968) Mica deposits of the Blue Ridge in North Carolina. U.S. Geological Survey Professional Paper, 577, 124 p.

Lipschutz, M.E., Gaffey, M.J., and Pellas, P. (1989) Meteoritic parent bodies: Nature, number, size and relation to present-day asteroids. In Asteroids II, R.P. Binzel, T. Gehrels, and M.S. Matthews, Eds., Univ. Arizona Press, Tucson, Arizona, 740–777.

Marshall, D.J. (1988) Cathdoluminescence of Geological Materials. 146 p. Allen Unwin, Boston.

McKay, D.S., Heiken, G., Basu, A., Blanford, Simon, S., Reedy, R., French, B.M., and Papike, J. (1991) The lunar regolith. In The Lunar Sourcebook, Cambridge University Press, Cambridge, p. 285–356.

McKie, D. and McConnell, J.D.C. (1963) The kinetics of the low-high transformation in albite. I. Amelia albite under dry conditions. Mineralogical Magazine, 33, 581–588.

McKeever, S.W.S. (1985) Thermoluminescence of Solids. 376 p. Cambridge Univ. Press, Cambridge.
Meneghinello, E., Alberti, A., and Cruciani, G. (1999) Order-disorder process in the tetrahedral sites of albite. American Mineralogist, 84, 1144–1151.
Miller, J.D. and Weiblen, P.W. (1990) Anorthositic rocks of the Duluth Complex: Examples of rocks formed from plagioclase crystal mush. Journal of Petrology, 31, 295–339.
Mora, C.I. and Ramseyer, K. (1992) Cathodoluminescence of coexisting plagioclases, Boehls Butte anorothosite: CL activators and fluid flow paths. American Mineralogist, 77, 1258–1265.
Onorato, P.I.K., Taylor, L.A., Coish, R.A., and Gamble, R.P. (1978) Olivine cooling speedometers. Proceedings of the 9th Lunar and Planetary Science Conference, 613–628.
Ostertag, R. (1983) Shock experiments on feldspar crystals. In Proceedings of the 14th Lunar and Planetary Science Conference, Journal of Geophysical Research Supplement, 88, B364-B376.
Papike, J., Taylor, L., and Simon, S. (1991) Lunar minerals. In G.H. Heiken, D.T Vaniman, and B.M. French, Eds., Lunar Sourcebook, 121–182, Cambridge University Press, Cambridge, U.K.
Pasternak, E.S. (1978) Thermoluminescence of Ordered and Thermally Disordered Albite. Ph.D. Thesis, University of Pennsylvania, Philadelphia.
Petrov, I. (1994) Lattice-stabilized CH_3, C_2H_5, NO_2, and O^{1-} radicals in feldspar with different Al-Si order. American Mineralogist, 79, 221–239.
Petrov, I., Yude, F., Bershov, L.V., Hafner, S.S., and Kroll, H. (1989) Order-disorder of Fe^{3+} ions over the tetrahedral positions in albite. American Mineralogist, 74, 604–609.
Poolton, N.R.J., Bøtter-Jensen, and Johnsen, O. (1996) On the relationship between luminescence excitation spectra and feldspar mineralogy. Radiation Measurements, 26, 93–101.
Prescott, J.R. and Fox, P.J. (1993) Three-dimensional thermoluminescence spectra of feldspars. Journal of Physics D: Applied Physics, 26, 2245–2254.
Prescott, J.R. and Robertson, G.B. (1997) Sediment dating by luminescence: A review. Radiation Measurements, 27, 893–922.
Rendell, H.M. and Townsend, P.D. (1988) Thermoluminescence dating of a 10 m loess profile in Pakistan. Quaternary Science Review, 7, 251–255.
Roberts, R.G. (1997) Luminescence dating in archaeology: From origins to optical. Radiation Measurements, 27, 819–892.
Rubin, A.E. (1997) Mineralogy of meteorite groups. Meteoritics and Planetary Science, 32, 231–247.
Schandl, E.S., Martin, R.F., and Stevenson, J.S. (1986) Feldspar mineralogy of the Sudbury igneous complex and the Onaping Formation, Sudbury, Ontario. Canadian Mineralogist, 24, 747–759.
Sears, D.W.G. (1988) Thermoluminescence of meteorites: Shedding light on the cosmos. Nuclear Tracks and Radiation Measurements, 14, 5–17.
Sears, D.W.G., Bakhtiar, N., Keck, B.D., and Weeks, K.S. (1984) Thermoluminescence and the shock and reheating history of meteorites II: Annealing studies of the Kernouve meteorite. Geochimica et Cosmochimica Acta, 48, 2265–2272.
Sears, D.W.G., Myers, B.M., Hartmetz, C.P., and Hasan, F.A. (1990) Structural state and anomalous fading of thermoluminescence of oligoclase. Nuclear Tracks and Radiation Measurements, 17, 583–586.
Sippel, R.F. and Spencer, A.B. (1971) Luminescence petrography and properties of lunar crystalline rocks and breccias. Proceedings of the Apollo 11 Lunar Science Conference, 2, 2413–2426.
Smith, J.V. (1974) Feldspar Minerals, vol. 1, Springer-Verlag, New York.
———(1983) Some chemical properties of feldspars. In Mineralogical Society of America Reviews in Mineralogy, 2, 281–296.
Smith, J.V. and Brown, W.L. (1988) Feldspar Minerals, vol. 1 (2nd edition). Springer-Verlag, New York.
Stewart, D.B., Appleman, D.E., Huebner, J.S., and Clark, J.R. (1970) Crystallography of some lunar plagioclases. Proceedings of the Apollo 11 Lunar Science Conference, 927–930.
Telfer, D.J. and Walker, G. (1978) Ligand field bands of Mn^{2+} and Fe^{3+} luminescence centers and their site occupancy in plagioclase feldspars. Modern Geology, 6, 199–210.
Tera, F., Carlson, R.W., and Boctor, N.Z. (1987) Just how old are cumulate eucrites? Meteoritics, 22, 513–514.
Townsend, P.D., Rowlands, A.P., and Corradi, G. (1997) Thermoluminescence during a phase transition. Radiation Measurements, 27, 31–36.
Warren, P.H., Haack, H., and Rasmussen, K.L. (1989) Effects of megaregolith insulation on Sm-Nd coolng ages of deep-crustal cumultes from the moon and large asteroids. Lunar and Planetary Science Conference, 20, 1179–1180.
Webber, K.L., Falster, A.U., Simmons, W.B., and Foord, E.E. (1997) The role of diffusion-controlled oscillatory nucleation in the formation of line rock in pegmatite-aplite dikes. Journal of Petrology, 38, 1777–1791.
Willis, J. and Goldstein, J.I. (1981) A revision of metallographic cooling rate curves for chondrites. Proceedings of the 12th Lunar and Planetary Science Conference, 1135–1143.
Wintle, A.G. and Murray, A.S. (1997) The relationship between quartz thermoluminescence, photo-transferred thermoluminescence, and optically stimulated luminescence. Radiation Measurements, 27, 611–624.
Wood, J.A. (1967) Chondrites: Their metallic minerals, thermal histories, and parent planets. Icarus, 6, 1–49.
Yang, W-H., Kirkpatrick, R.J., and Henderson, D.M. (1986) High-resolution ^{29}Si, ^{27}Al, and ^{23}Na NMR spectroscopic study of Al-Si disordering in annealed albite and oligoclase. American Mineralogist, 71, 712–726.

MANUSCRIPT RECEIVED OCTOBER 27, 1999
MANUSCRIPT ACCEPTED FEBRUARY 10, 2001
MANUSCRIPT HANDLED BY BRAD L. JOLLIFF