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RED THERMOLUMINESCENCE OF ENSTATITE FROM THE CHAINPUR METEORITE

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Abstract: For most ordinary chondrites feldspar is mainly responsible for thermoluminescence [TL], but in type 3 ordinary chondrites, especially those which are most primitive, other minerals are important. We observed red TL with a ~660 nm spectral peak in an ordinary chondrite, Chainpur (LL3.4). The mineral responsible for the red TL was identified as iron-free enstatite. Spatial distribution of TL and cathodoluminescence [CL] for the same specimen was also investigated, and it was found that the red TL areas corresponded to the high-sensitivity areas of red CL.

1. Introduction

Thermoluminescence [TL] is a useful tool for studying meteorites. The TL sensitivity increases by a factor of 10^5 with petrologic type, namely with degree of metamorphism due to the crystallization of feldspar, and is an indicator for classification of type 3 ordinary chondrites and CO chondrites (SEARS *et al.*, 1980, 1990, 1991; SEARS, 1988). The TL of ordinary chondrites usually has spectral peaks at 450 and 400 nm (STRAIN *et al.*, 1985; NINAGAWA, 1989). Therefore the relationship between TL sensitivity and petrologic type has been investigated under TL detection wavelengths between 320 and 480 nm in the ultraviolet-blue region (SEARS *et al.*, 1990).

Primitive ordinary chondrites have been considered to have the lowest TL sensitivity, based upon the above TL petrologic classification. However, intense TL glow curves were observed for the primitive ordinary chondrites, Semarkona (LL 3.0) and Bishunpur (LL3.1) (NINAGAWA *et al.*, 1992a, b). It was found that these TLs were due to anorthite-normative mesostases and had a spectral peak at ~570 nm. Such yellow TL of ~570 nm had been outside of the detection wavelengths in the previous studies of TL petrologic classification. The yellow cathodoluminescence [CL] was also observed in the same specimens (NINAGAWA *et al.*, 1992b). Moreover it was found that an other phase, such as silica, was also responsible for the TL in unequilibrated chondrites (MATSUNAMI *et al.*, 1992).

Since then, we have been searching for the other spectral type of TL and for the other minerals responsible for the TL in meteorites, and we found red TL in an ordinary chondrite, Chainpur (LL3.4). In this paper, we report on the red TL observed for Chainpur. The mineral responsible for the red TL was identified by the results of EPMA analysis, and spatial distribution of TL and CL intensities for the same specimen was also measured.

2. Sample and Equipments

One of 3 fragments of the Chainpur meteorite (BM1915, 86; 112.53 mg) was cut by a wire saw and ground to ~1 mm thickness with alumina and polished with diamond paste for TL, CL and EPMA analysis. The specimen was irradiated to a dose of 13.2 kGy by Co-60 γ-rays. Then the specimen was heated to about 500°C at a rate of 1.7°C/s in a nitrogen atmosphere. The TL spectra were measured using a time-resolving spectroscopy system (NINAGAWA *et al.*, 1986) during the heating course, and were recorded on videocassettes as a function of temperature.

The spatial distribution of the induced TL was measured by substituting a microscope for the spectroscope (NINAGAWA *et al.*, 1990). For measurement of the red TL image, an image intensifier with multialkali photocathode was used with a Toshiba R-60 long pass filter, which transmitted photons longer than 600 nm. In a case of blue TL image, another image intensifier with bialkali photocathode was used with a Corning 4–96 band pass filter, which transmitted photons between about 400 nm and 580 nm. The TL images were also recorded on videocassettes during heating of the specimen at a rate of 0.25°C/s. For CL observations of the specimen, we used a Nuclide Corporation 'Luminoscope' attached to an optical microscope with an electron beam of 13±1 keV and 7±1 μA, Kodak ECTAR 1000 film and exposures of 150–1/500 s. Compositional analysis of the relevant minerals was performed with a JEOL-JCXA 733 electron microprobe operating at 15 kV accelerating voltage and 12 nA probe current. The data were corrected using the ZAF method.

3. Results

3.1. TL emission spectra

Figure 1 shows TL emission spectra of the specimen, measured by the time-resolving spectroscopy system: (a) Distribution of the TL intensity as a function of

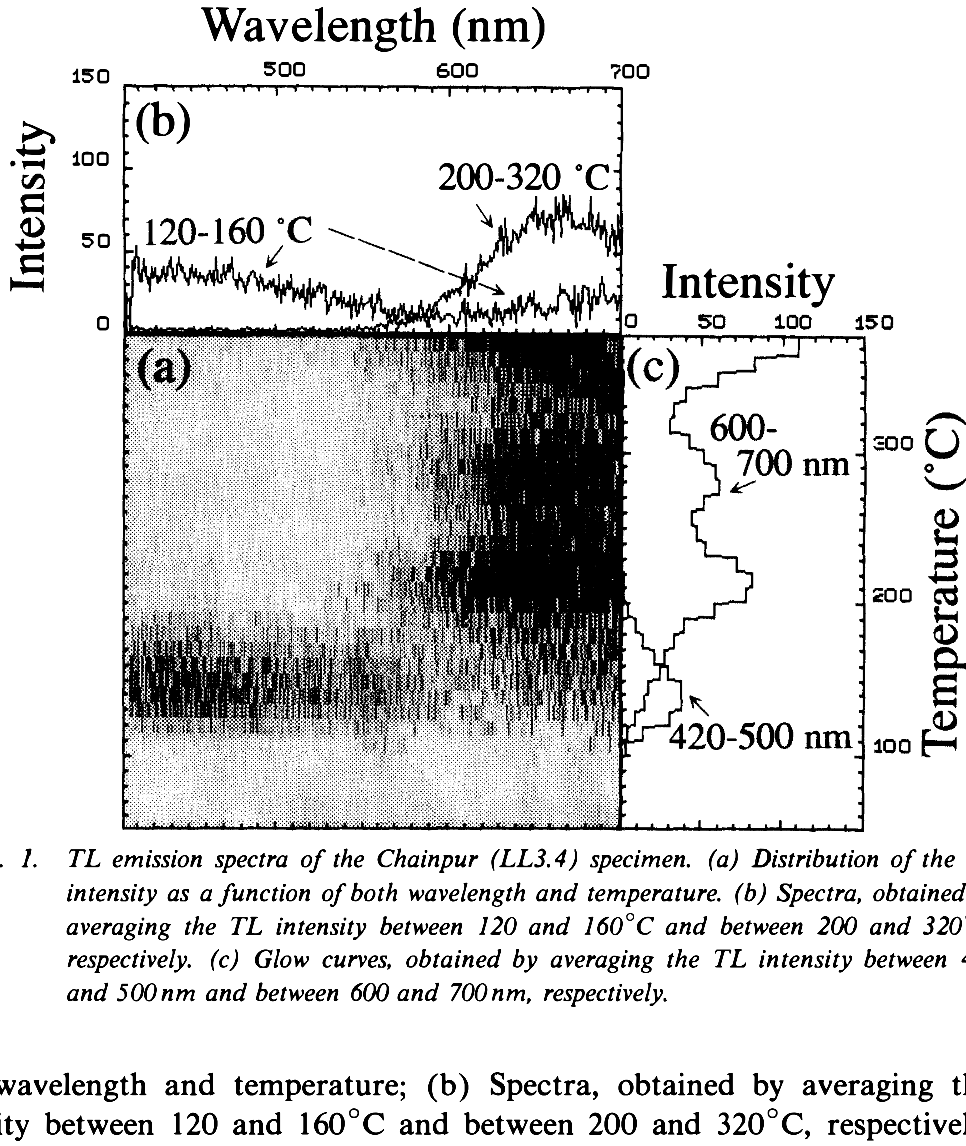

Fig. 1. *TL emission spectra of the Chainpur (LL3.4) specimen. (a) Distribution of the TL intensity as a function of both wavelength and temperature. (b) Spectra, obtained by averaging the TL intensity between 120 and 160°C and between 200 and 320°C, respectively. (c) Glow curves, obtained by averaging the TL intensity between 420 and 500 nm and between 600 and 700 nm, respectively.*

both wavelength and temperature; (b) Spectra, obtained by averaging the TL intensity between 120 and 160°C and between 200 and 320°C, respectively; (c) Glow curves, obtained by averaging the TL intensity between 420 and 500 nm and between 600 and 700 nm, respectively. The TL of the specimen has spectral peaks at wavelengths of ~660 nm and ~450 nm. This is the first recognition of the red TL of ~660 nm from meteorites.

3.2. Petrologic description of the specimen

As shown in Fig. 2, the Chainpur clast has a granular texture and consists of an assemblage of enstatite, minor forsteritic olivine and interstitial matrix. The petrologic characteristics of the specimen are not representative of Chainpur, but were similar to some regions in Bishunpur. Opaque minerals embedded in the matrix are kamacite and troilite. Calcic plagioclase and Ca-rich pyroxene commonly occur as interstitial phases. Euhedral enstatite crystals contain fine granular olivine inclusions. The enstatite and olivine are almost homogeneous in composition. Enstatite is nearly iron-free ($En_{98.4-99.4}Fs_{0.1-0.5}Wo_{0.4-1.2}$), while FeO and CaO contents of olivine range from 3.18 to 5.30 wt% ($Fa_{3.2-5.5}$) and from <0.03 to 0.16 wt%, respectively.

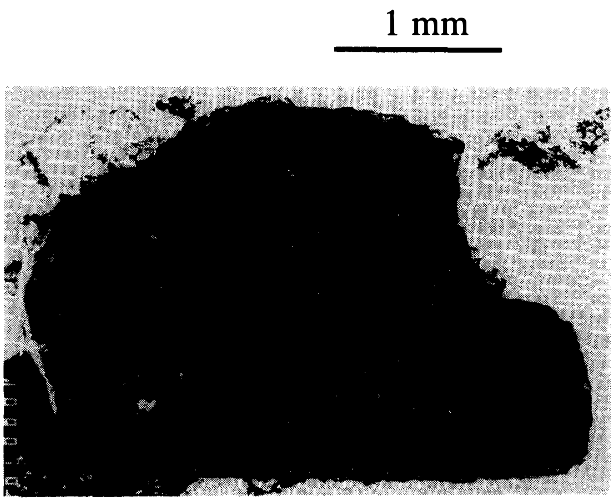

Fig. 2. BSE image of the Chainpur (LL3.4) specimen.

Table 1. Mean compositions of mineral phases in the Chainpur (LL3.4) specimen, obtained by EPMA analysis.

Mineral	Enstatite	Olivine	Calcic plagioclase	Ca-rich pyroxene
$N^{\#1}$	17	19	4	4
SiO_2	60.20	41.97	50.15	53.50
TiO_2	0.06	0.04	0.04	0.86
Al_2O_3	0.35	0.12	31.56	7.11
Cr_2O_3	0.01	0.22	0.01	0.03
FeO	0.18	4.36	0.15	0.21
MnO	0.10	0.26	0.03	0.07
MgO	39.27	52.75	0.04	18.18
CaO	0.36	0.02	15.21	20.57
Na_2O	0.06	0.05	2.83	0.52
NiO	0.01	0.02	0.02	0.07
Total	100.60	99.81	100.04	101.12
$X_{Fe}^{\#2}$	0.003	0.044		0.007
$En^{\#3}$	99.1			55.0
$Fs^{\#4}$	0.2			0.4
$Wo^{\#5}$	0.7			44.7
$X_{Ca}^{\#6}$			0.748	

#1 number of averaged analyses; #2 Fe/(Mg+Fe); #3 100×Mg/(Mg+Fe+Ca); #4 100×Fe/(Mg+Fe+Ca); #5 100×Ca/(Mg+Fe+Ca); #6 Ca/(Ca+Na).

The interstitial plagioclase and Ca-rich pyroxene show a range of compositions, $An_{67.1-88.2}$ and $En_{47.0-60.3}Fs_{0.3-0.5}Wo_{39.2-52.7}$, respectively. The Al_2O_3 concentration in Ca-rich pyroxene ranges from 3.2 to 13.8 wt%. Mean compositions of the minerals in the specimen are given in Table 1.

3.3. *TL and CL images*

After the same specimen was irradiated again to a dose of 13.2 kGy, spatial distribution of blue (~450 nm) and red (~660 nm) TL was measured. Figures 3a and b show an induced blue TL image integrated between 40–150°C and a red TL image between 40–300°C, respectively. Brightness of gray points in the TL image is proportional to the logarithm of TL intensity. The areas of the red TL are different from those of the blue TL. Figures 3c and d show CL images taken with long (50 s) and short (1/15 s) exposure times, respectively.

4. Discussion

The blue TL image (Fig. 3a) corresponds to blue-colored CL areas in Fig. 3c. The red TL image (Fig. 3b) resembles the red CL image of short exposure time (Fig. 3d). These observations imply that the colors of the TL are consistent with those of the CL, and that the red TL areas correspond to the high-sensitivity areas of the red CL.

These TL and CL images were compared with the results of compositional analysis by EPMA. The blue TL and CL areas were attributed to interstitial calcic plagioclase. The red TL and CL were attributed to iron-free enstatite. The iron-free enstatite has been known as a mineral responsible for the red CL in primitive ordinary chondrites (SEARS *et al.*, 1992). No CL area corresponded to forsteritic

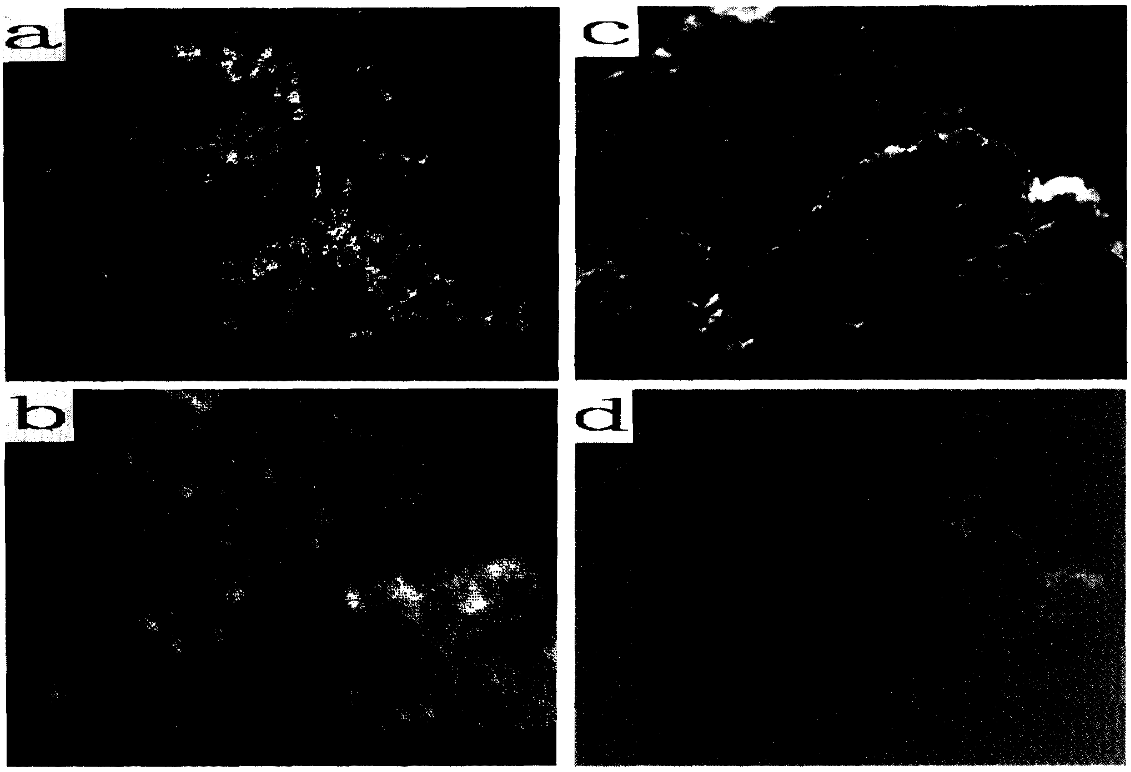

Fig. 3. Induced TL images and CL images of the specimen of Chainpur (LL3.4). (a) blue TL image in 40–150°C region. (b) red TL image in 40–300°C region.* (c) CL image taken with long exposure time (50s).** (d) CL image taken with short exposure time (1/15 s).***

** Brightness of gray points in the TL image is proportional to the logarithm of TL intensity.*

*** The specimen was cracked after the TL measurements.*

olivine ($Fa_{3.2-5.5}$); this was because the FeO was too high. Thus three kinds of CL areas correspond to three kinds of minerals. Red TL areas, however, seem to correspond only to the CL areas of short exposure time. This may be attributed to the narrow detection range of light intensity by the photograph, and the brightness of the red CL area may be saturated in Fig. 3c.

As described above, the profiles of TL and CL images are similar; however, some differences are observed in detail. This may be attributed to two causes as follows: (1) A TL image contains information on deeper surface regions (more than several 10 μm depth) of a solid, whereas a CL image is limited to that of less than about 3 μm depth because of the short penetration depth of the electron beam. (2) Even though the luminescence centers of CL and TL are identical, luminescence intensity of CL may not be directly proportional to that of TL because of difference in the excitation mechanism.

Recently red and blue CL of enstatite have been studied in connection with relict enstatite in enstatite chondrite chondrules (LOFGREN and DEHART, 1992a; LOFGREN *et al.*, 1992b). A proton-excited luminescence spectrum of the Bustee meteorite (aubrite) was reported to have a red peak at ~670 nm and a blue peak at ~400 nm (DERHAM *et al.*, 1964). STEELE also reported near infrared CL with a 742 nm spectral peak as well as red CL with a 664 nm spectral peak and blue CL in an enstatite chondrite, ALHA-77295. These near infrared and red CL had good correspondence in CL spectra with those of synthetic Cr and Mn doped enstatites, respectively (STEELE, 1988). As described previously, we observed red TL for iron-free enstatite for which red CL was observed, so that the near infrared, red and blue TL may be observed for enstatites in the enstatite chondrite, ALHA-77295.

The induced glow curves of the blue and red TL in Figs. 3a and b are shown in Fig. 4. The red TL from iron-free enstatite gives three glow peaks at 140, 190 and 270°C. The blue TL gives a glow peak at 100°C with narrow width, which is usually characteristic of anorthite-normative mesostasis of ordinary chondrites (NINAGAWA *et al.*, 1991). So far only one TL measurement of enstatites has been reported in enstatite chondrites and aubrites (GREER, 1970). The glow peak at 270°C in our

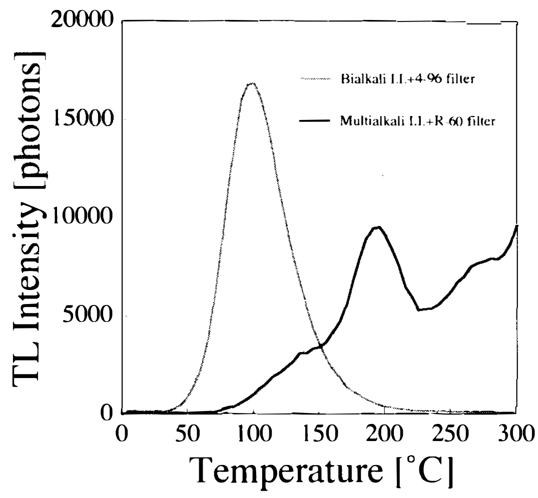

Fig. 4. Induced TL glow curves of the Chainpur (LL3.4) specimen.

TL measurements should correspond to that at 290°C of GREER's two major peaks. However, he measured the TL in a wide ultraviolet-red range, 300–660 nm, using a RCA 6199 photomultiplier tube, so there is a possibility that he measured red and blue TL together. Such TL measurements of the wide wavelength region should be refined because the red and blue TL may have different glow curves.

In general, CL gives information on luminescence centers. The analysis of TL glow curves which reveal depths of traps in a solid specimen may provide more information to distinguish the history of the specimen. The TL glow curves from enstatite may be applied to enstatite chondrites and aubrites as well as ordinary chondrites; these reflect mineralogy, formation and metamorphism of these meteorites. Furthermore, it should be noted that TL glow curves measured at various locations in a specimen may give detailed information about the structure of the specimen.

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