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The Sutter's Mill meteorite: Thermoluminescence data on thermal and metamorphic history

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Abstract–A piece of the Sutter's Mill meteorite, fragment SM2-1d, has been examined using thermoluminescence techniques to better understand its thermal and metamorphic history. The sample had very weak but easily measureable natural and induced thermoluminescence (TL) signals; the signal-to-noise ratio was better than 10. The natural TL was restricted to the high-temperature regions of the glow curve suggesting that the meteorite had been heated to approximately 300 °C within the time it takes for the TL signal to recover from a heating event, probably within the last 10^5 years. It is possible that this reflects heating during release from the parent body, close passage by the Sun, or heating during atmospheric passage. Of these three options, the least likely is the first, but the other possibilities are equally likely. It seems that temperatures of approximately 300 °C reached 5 or 6 mm into the meteorite, so that all but one of the small Sutter's Mill stones have been heated. The Dhajala normalized induced TL signal for SM2-1d is comparable to that of type 3.0 chondrites and is unlike normal CM chondrites, the class it most closely resembles, which do not have detectable TL sensitivity. The shape of the induced TL curve is comparable to other low-type ordinary, CV, and CO chondrites, in that it has a broad hummocky structure, but does not resemble any of them in detail. This suggests that Sutter's Mill is a unique, low-petrographic–type (3.0) chondrite.

INTRODUCTION

The Sutter's Mill meteorite currently consists of 78 fully crusted fragments, all but one being less than 50 g. For most of the fragments, the fusion crust is thick (almost 1 mm) and most of the pieces appear to have been oriented for at least the final portion of their atmospheric descent. The first fragments, including the present sample (SM-2), were collected within days of fall and before a storm passed through the area. Within weeks of the fall, an interdisciplinary consortium was established for the study of these meteorite fragments and their initial results were published in *Science* (Jenniskens et al. 2012). The major conclusions of the consortium were that Sutter's Mill was an unusual CM-like chondrite, which had the structure of a regolith breccia and had been aqueously altered and metamorphosed. However, at least one section from the present fragment contained the highly water-soluble mineral, oldhamite, suggestive of highly reducing formation conditions not expected in a CM-like chondrite.

As part of the consortium, we obtained a piece of SM2, subfragment number 1d, for study by thermoluminescence (TL) techniques. SM2 is one of three Sutter's Mill meteorites recovered before the storm. CM chondrites examined to date do not show measureable TL, but the consortium reported that the meteorite had been metamorphosed indicating to us that it should have a measureable TL signal. A major review of the thermoluminescence studies of meteorites was recently published by Sears et al. (2013). For several decades, thermoluminescence studies have proved useful in exploring the metamorphic history of chondrites and for investigating their recent thermal and radiation histories, including atmospheric heating. Given the small size and thick fusion crust of the fragments, we were also interested in determining the extent of atmospheric heating these fragments had experienced. A brief synopsis of these data appeared on pages 65 and 66 of the supplementary material published online with the Jenniskens et al. (2012) article. A progress report had also been published as a conference abstract, but this study supersedes both of those (Sears 2012).

EXPERIMENTAL METHODS

The SM fragment used in this study (SM2-1) is shown in Fig. 1, a fragment that had fusion crust. SM-2 was recovered by Peter Jenniskens in the parking lot of Henningsen Lotus Park and appeared to have been crushed into a dozen or so pieces by an automobile. The present subsample (SM2-1d) was broken into two pieces, weighing approximately 20 mg each, and each piece was examined under a low-powered optical microscope to ensure that both were clean interior material. They were located 5–6 mm into the original fragment. They were then crushed to approximately 200 μm grains with an agate pestle and mortar. A 4 mg aliquot from each fragment was placed in a copper pan 5 mm in diameter for TL measurement in a Daybreak Nuclear and Medical Inc. TL reader. This is a commercial instrument that we have modified to: (1) place the sample nearer the detector (an EMI 9635QB photomultiplier tube), (2) screen off black body from the heating strip using an aperture and heat filters, and (3) enable the PMT to remain on permanently by installation of a shutter.

The TL is measured in the blue-green region between room temperature and 500 °C, with a heating rate of 7.5° s^{-1}. The plot of light emitted as a function of laboratory heating temperature is referred to as the "glow curve." After measurement of the TL of the "as-received" sample (which we will refer to as the natural TL), the copper pan with the sample was placed in a radiation cell that exposed it to a 140 mCi ^{90}Sr source for 3 min. The sample was then returned to the TL rig and the induced TL measured in the same way as the natural TL. This was repeated twice more. Before removing the sample from the TL apparatus after the last measurement, the sample was heated once more and the curve for the background and black body was recorded. As there were 10–15 min between this control run and the previous run, this also served to check for spurious (nonradiation induced) TL; none was found.

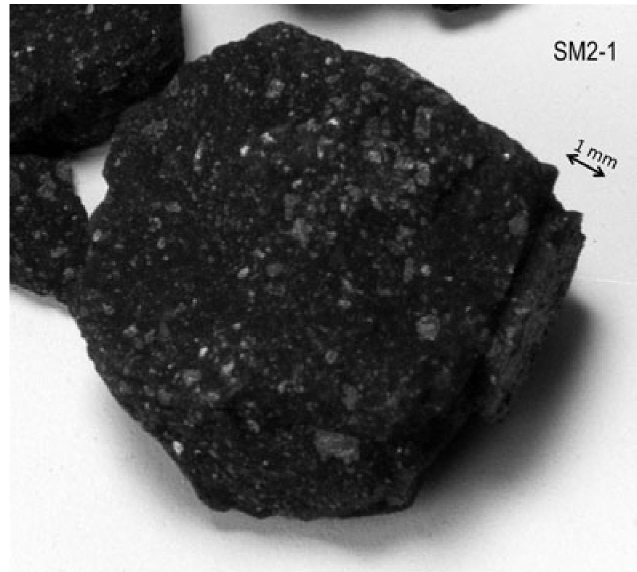

Fig. 1. Sutter's Mill meteorite (individual SM2) that was used for this study (subfragment SM2-1d). Note that the fragment contained a piece of fusion crust almost 1 mm thick. (Double-headed arrow is a 1 mm scale bar.)

Thus, the record for each sample consists of five glow curves, one for the sample in its natural state, three for the sample that had been exposed to beta radiation, and one for the background/black body measurement. At the beginning and end of each day, a sample of the Dhajala H3.8 chondrite, prepared in the same way as the Sutter's Mill meteorite samples (but with metal removed with a hand magnet), was run as a normalization standard for the induced TL measurement and to ensure long-term stability of the apparatus. The ratio of the induced TL of the low-temperature peak (in its absence, the TL at 250 °C) to the induced TL of Dhajala at the low-temperature peaks (approximately 250 °C) is referred to as the TL sensitivity.

RESULTS

Typical glow curves are shown in Fig. 2. The natural TL consists of a broad featureless emission beginning at about 300 °C and remaining significant until black body becomes comparable with the TL signal at approximately 470 °C. The signal-to-noise ratio is approximately 10. Also shown in Fig. 2 is a typical background and black-body curve, which starts at about 350 °C. Finally, Fig. 2 shows an example of the curve for the sample that had been exposed to a standard radiation dose. The induced curve is broad, hummocky, with obvious prominent peaks, starts at about 150 °C, and drops to essentially zero (when it

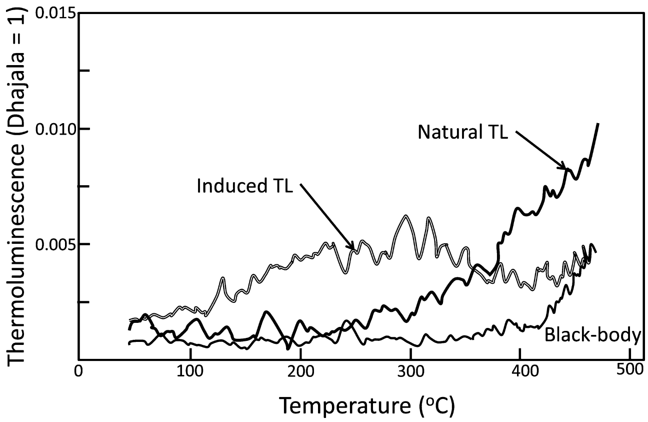

Fig. 2. Typical thermoluminescence glow curves for Sutter's Mill fragment SM2-1d. The luminescence produced (normalized to the TL-induced intensity of the Dhajala meteorite, which is used as a standard) is plotted against the temperature to which the sample is heated in the laboratory. The "natural TL" is the signal produced by the "as received" sample. The "induced TL" the signal is that produced by the sample after heating to 500 °C (to remove the natural signal) and then exposing to 140 mCi ^{90}Sr beta source for 3 min. Also shown is the black-body curve produced by the sample after its TL signal has been removed.

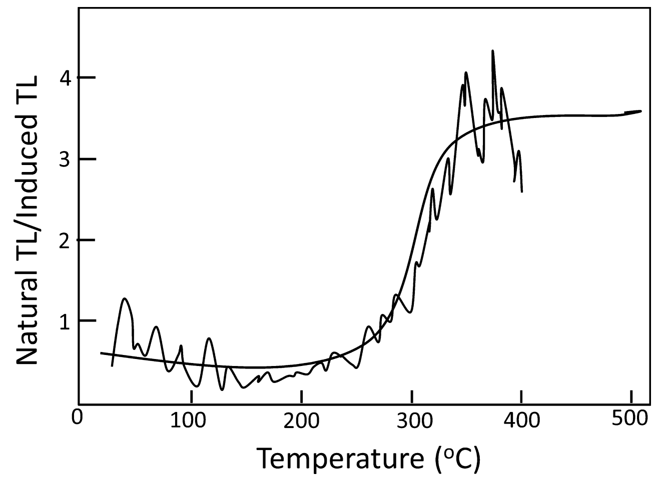

Fig. 3. Plot of the ratio of the natural TL to the ratio of the induced TL as a function of glow curve temperature. The position of the step in the ratio suggests that Sutter's Mill has been heated to approximately 300 °C.

intercepts the black-body curve) at approximately 470 °C.

Traditionally, the way to determine the level of stable natural TL in a sample is to determine the "plateau" (Fig. 3). This is a plot of the ratio of natural TL to induced TL as a function of glow curve temperature (e.g., Aitken 1985). This ratio is essentially zero until about 300 °C when it rises steeply and levels off. This behavior has been reproduced in the laboratory by heating a meteorite sample stepwise and running the glow curve in between steps (Sears 1975) and indicates that the sample has recently been heated to approximately 300 °C. We discuss this further below.

Dividing the maximum intensity of the induced curve by the intensity of the curve for induced Dhajala TL, the TL sensitivity of the two aliquots of Sutter's Mill SM2-1d measured in this study is 0.0032 ± 0.01 and 0.0032 ± 0.07 (where Dhajala = 1). These values are comparable to the values observed for Shergottites (Hasan et al. 1986), type 3 ordinary chondrites (Sears et al. 1980), and howardite–eucrite–diogenite meteorites (Sears et al. 1997).

DISCUSSION

To evaluate these results, we need to consider the history of the meteorites through the window of their quantitative TL properties.

The Natural TL History of Meteorites

The factors governing the natural TL level in meteorites were recently described in depth, with the quantitative relationships, by Sears et al. (2013). An idealized schematic of the history of a meteorite and how it affects natural TL was shown in fig. 4 of Sears et al. (2013), where a detailed explanation can be found. When buried at great depth in a parent object, and receiving essentially no cosmic radiation, the natural TL levels are essentially zero, but upon breakup to meter-sized fragments, the sample is exposed to cosmic radiation and starts to build up a TL signal. The rate of build-up depends on the dose rate and number of unfilled electron traps in the crystal lattice of the luminescent minerals. On the other hand, when the meteorite reaches Earth and is no longer exposed to cosmic radiation and the level of natural TL decays exponentially. This is the basis of terrestrial age determination using natural TL (Sears and Durrani 1980; Melcher 1981a).

Between these extremes in the post–break-up life of a meteorite, there is the longest period, which is interplanetary orbit as a meter-sized fragment. Cosmic ray exposure age data suggest that this is usually on the order of tens of millions of years. During this middle phase, the level of natural TL of a meteorite can be assumed to be at a level determined by equilibrium between (1) the rate of promotion of electrons from the ground state to metastable traps and (2) the rate of decay of electrons from the traps to the ground state. This situation can be described quantitatively by equation 11 of Sears et al. (2013). The two factors determining the level of natural TL in a meteorite are

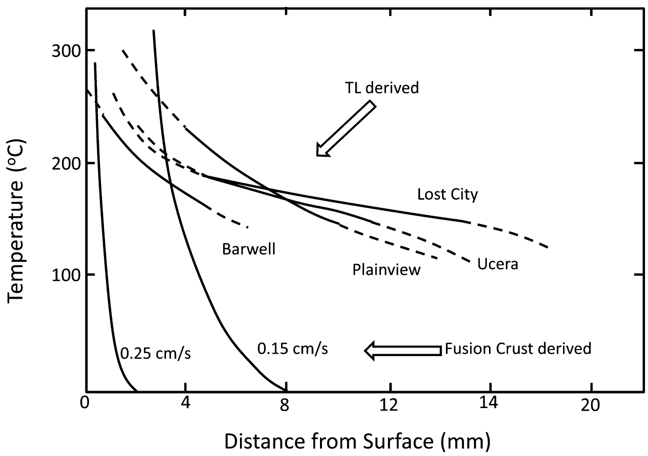

Fig. 4. Temperature gradients in meteorites caused by heating during atmospheric passage. The steep gradients at smallest distances into the meteorite are calculated from the thickness of various zones in the fusion crust, while the shallower gradients at larger distances are determined by thermoluminescence methods. (From Sears 1975.)

the temperature and the dose rate, the remaining factors being governed by the properties of the luminescent crystals in the meteorite. The temperature of a meteorite in orbit can be calculated by the inverse square law and Stefan's law and dose rates can be calculated from meteorite and spacecraft data (e.g., Biswas et al. 2011).

Superimposed on this simple history is the possibility of stochastic events, like impacts, that would affect the natural TL level. These are discussed below.

Heating During Ejection from the Parent Body

We can infer the time since ejection from the parent body from its cosmic ray exposure, assuming this was the last major break-up event prior to Earth encounter. The cosmic ray exposure age of the CM meteorites are all low (Eugster et al. 2006), but the Sutter's Mill meteorite lies at the lowest end of the range. Determined from ^{26}Al, it is 0.10 ± 0.04 Ma, while ^{21}Ne abundances indicate a cosmic ray exposure age of 0.051 ± 0.006 Ma (Jenniskens et al. 2012). These values are comparable to the time it takes a meteorite to recover its natural TL in typical interplanetary conditions. It is therefore marginally possible that Sutter's Mill was heated to approximately 300 °C during its ejection from the parent body and not had time to restore its levels before fall on Earth. Another option to consider is heating due to a small perihelion.

Heating Due to Close Solar Passage

The idea that certain meteorites can have low natural TL due to close passage to the Sun has been discussed for many years (McKeever and Sears 1980; Melcher 1981b; Benoit et al. 1991). On the basis of plateau plots similar to Fig. 3, McKeever and Sears (1980) suggested that Olivenza (LL5) and Mangwendi (LL6) had small perihelia, say <0.6 AU. In fact, in every independent database assembled (observed falls, non-Antarctic finds, Antarctic finds, basaltic meteorites, and so on), about 20% have natural TL values suggestive of similarly small perihelia (Hasan et al. 1987; Benoit et al. 1992, 1993, 1994; Benoit and Sears 1993; Sears et al. 2011). The perihelion of the orbit of Sutter's Mill was 0.448 ± 0.024 AU for which the calculated temperature is 346 ± 5 °C (e.g., McKeever and Sears 1980). It seems therefore that the small perihelion observed for Sutter's Mill is also consistent with its natural TL data.

Heating During Atmospheric Passage

The temperature gradient in a meteorite during atmospheric passage is determined by the ablation rate, (Sears and Mills 1973; see also Sears et al. 2013):

$$\partial T/\partial y = v_w\, T_i\, K^{-1} \exp\left(-y v_w K^{-1}\right) \quad (1)$$

where T is temperature, y is depth, K is thermal diffusivity, and v_w is ablation rate, which depends on the orientation of the meteorite's local surface during flight. Beyond a few millimeters, the profile is no longer governed by ablation, but follows the normal path determined by the thermal conductivity of the meteorite (Sears 1975). It is possible to take samples of ordinary chondrite and heat them for 30 s in the laboratory to determine level of natural TL draining caused at various temperatures and thereby obtain a curve to calibrate the TL gradient observed near the fusion crust, after large-scale gradients have been removed. Figure 4 shows the resulting curves. The curves are quite steep initially. The TL at 250 °C in the glow curve, chosen because it is the location of a major TL peak, shows that a factor of two decreases after heating to 200 °C in the laboratory and is gone after heating to 250 °C. Applying this calibration curve to the natural TL profiles observed near the fusion crust produces the temperature gradients shown in Fig. 4, which also shows the results for an additional H5 chondrite, Plainview.

In addition to the gradients determined by natural TL in Fig. 4 are curves obtained from petrologic changes in the fusion crust (Lovering et al. 1960; Sears and Mills 1973). These inferred temperature gradients are much steeper and depend on the ablation rate. The overall temperature gradient is therefore a combination of a steep gradient determined by ablation and a shallower gradient determined by the conduction of heat into the meteorite. It is therefore perfectly reasonable that temperatures on the order of 300 °C penetrate to the 5 or 6 mm location of the present samples.

We emphasize that the Sutter's Mill meteorite fragments were all very small. Of the 78 stones recovered at the time of writing, only three are >30 g, and only one is >50 g (SM-78 is 205.2 g). All but one of the stones are small enough to have suffered temperatures of a few hundred degrees Celsius, 5 or 6 mm into the meteorite.

Mineralogical changes in and just under the fusion crust can also be used to determine temperature gradients in Sutter's Mill. The fusion crust of Sutter's Mill consists of three petrographic zones (Fig. 5). These zones were readily identified in a cut face of Sutter's Mill meteorite using an SEM and their thickness measured in as many separate places as possible. On the outer edge is a glass coating with an average thickness of 1.37 ± 0.12 μm (four measurements). Underneath the glass layer is a scoriaceous or vesicular zone with an average thickness of 65 ± 15 μm (nine measurements). Finally, there is a much thicker zone where the crust spalls off to leave behind an orange/gold layer presumably of sulfides. This layer can readily been seen with the naked eye and it spalls easily during moderate handling. It is typically 625 ± 37 μm thick as can be seen from several slices cut from SM-48. If we assume that glass corresponds to fully melted material, then its temperature was approximately 1800 °C; the vesicular zone corresponds to complete dehydration and collapse of the phyllosilicate structure (approximately 1100 °C), and the sulfide layer corresponds to the metal-sulfide eutectic (say approximately 600 °C) as it penetrates into the meteorite (Fig. 5b), then we can derive a thermal gradient caused by atmospheric passage (Fig. 5c). By assigning temperatures to these boundaries (Fig. 5b), in the manner of Sears and Mills (1973), We can draw a temperature gradient through the meteorite (Fig. 5c).

Given the essentially logarithmic nature of the temperature gradient into the meteorite, then the gradient inferred from the fusion crust petrology is consistent with the natural TL result. We observe temperatures as high as 300 °C reached 5–6 mm in our sample, but these broader considerations, allowing, for example, for longer flight times and—more importantly—orientation of the face during flight, suggest that temperatures of several hundred degrees can sometimes reach up to 10 mm into the meteorite. It is also interesting to note that iron meteorites show a heat altered zone (corresponding to temperatures >400 °C) reaching 4–8 mm below the fusion crust (depending on orientation), which also enables ablation rates to be determined that are remarkably similar to those of stony meteorites (see, for example fig. 1330 in Buchwald 1975; and Lovering et al. 1960). Apparently, the lower fusion temperatures and higher thermal conductivity of iron meteorites are offset by their lower thermal capacities.

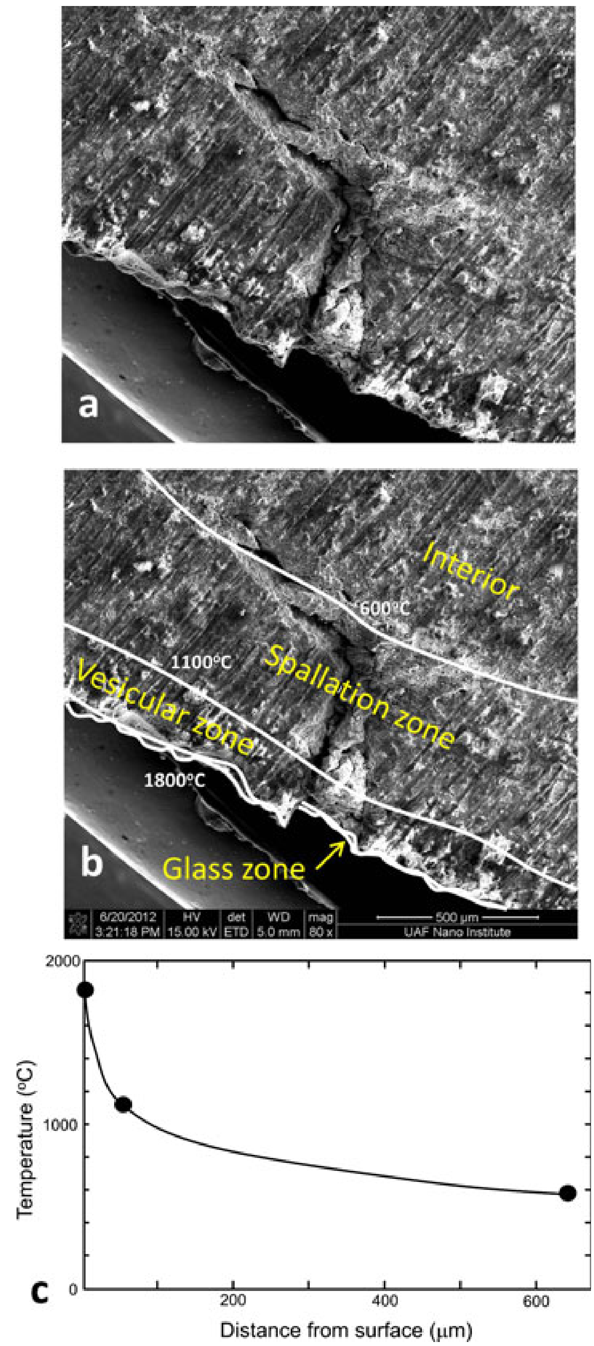

Fig. 5. The fusion crust of Sutter's Mill consists of an outer edge of glass (with an average thickness of 1.37 ± 0.12 μm), a scoriaceous or vesicular zone (65 ± 15 μm) and a much thicker zone (625 ± 37 μm) where the crust spalls off to leave behind an orange/gold layer presumably of sulfides. If we assume that glass corresponds to fully melted material, then its temperature was approximately 1800 °C; the vesicular zone corresponds to complete dehydration and collapse of the phyllosilicate structure (approximately 1100 °C), and the sulfide layer corresponds to the metal-sulfide eutectic (say approximately 600 °C) as it penetrates into the meteorite, then we can derive a thermal gradient caused by atmospheric passage.

So, the Small Sutter's Mill Meteorites Have Been Heated to Approximately 300 °C, but How?

The natural TL data show that SM2 has been heated to approximately 300 °C, 6 or 7 mm into the meteorite, and in a stone, a little over a 1 or 2 cm in size, this means that probably much of the interior of the stone has been heated. As all but one of the Sutter's Mill are under 50 g, this conclusion probably applies to most of them. This needs to be kept in mind in interpreting the properties of the Sutter's Mill meteorite. Unfortunately, from the purpose of understanding the history of this meteorite, all of the mechanisms normally considered for draining natural TL (except a long terrestrial age) seem to work for explaining the low natural TL of Sutter's Mill. Heating during parent body ejection is hardest to defend as the exposure ages are comparable to natural TL recovery times. The meteorite certainly had a small perihelion, so this is a viable explanation. However, the meteorite also passed through a fiery atmospheric passage to the point of producing a plasma trail in the atmosphere.

The Classification and Metamorphic History of the Sutter's Mill Meteorite

Sears et al. (1980) pointed out that the TL sensitivity of ordinary chondrites was a highly sensitive indicator of metamorphic alteration, the TL sensitivity increasing by a factor of 10^5 through the petrographic type 3–6. Throughout type 3 alone, there was a 10^3 fold increase, which led to the subdivision of type 3 into type 3.0–3.9. It was subsequently realized that similar metamorphic subdivision is possible for CO chondrites (Keck and Sears 1987), CV chondrites (Guimon et al. 1995), and eucrites (Batchelor and Sears 1991), although the mechanism for eucrites was different from that responsible for the metamorphism-dependent TL sensitivity of the chondrites. Although the major factor driving the relationship between TL sensitivity and metamorphism in chondrites is the formation of crystalline feldspar, in eucrites it is the diffusion of Fe^{2+} out of the feldspar that increases the TL sensitivity of eucrites. Any number of other mechanisms are conceivable, such as the formation of luminescent crystalline phases from the phyllosilicates and amorphous mixtures in CI and CM chondrites.

There has been no systematic study of the TL properties of CM chondrites, because the first few examined, including Murchison, showed no detectable TL. In the light of the weak but significant induced TL of Sutter's Mill, and the realization that CM chondrites have experienced a wide variety of metamorphic and aqueous alteration histories (Browning et al. 1996; Hanowski and Brearley 2001; Rubin et al. 2007), this topic should be revisited.

The presence of a measureable induced TL signal from Sutter's Mill distinguishes this meteorite from the CM chondrites measured to date, and this is consistent with petrographic observations that suggest that Sutter's Mill has experienced some minor level of metamorphic alteration. The TL sensitivity of Sutter's Mill is very low, equivalent to that of a low type 3 chondrite. (A detailed discussion of the petrographic type assignments of low type 3 chondrites using TL sensitivity and other techniques is beyond the scope of this study and will be published elsewhere. Suffice to say that for the present purposes by "low," we mean type 3.0–3.2.)

Figure 6 is reproduced from Keck and Sears (1987) and shows the TL sensitivity range of UOCs and CO chondrites and the petrographic type boundaries assigned. The data for duplicate chips for the present Sutter's Mill sample are indicated. For type 3.0, Sears et al. (1980) provide only an upper limit; so on this basis, we can describe Sutter's Mill as type 3.0. A study of the several metamorphosed and anomalous CM chondrites that have been discovered in recent years would be of value. On a different, but related, topic, it would also be of value to explore the relationships between TL sensitivity and aqueous alteration for the carbonaceous chondrites—as aqueous alteration influences the abundances of crystalline luminescence phases (feldspar, other Ca minerals, forsterite, and enstatite)—to see if TL provides a sensitive and quantitative means of describing this process. Sutter's Mill is a regolith breccia of diverse clasts in a matrix and some samples have been described as CM2.0 and some as CM2.1 (Jenniskens et al. 2012). The present sample was taken early in the study and its detailed lithology is not known. On the basis of cathodoluminescence images of Murchison (Akridge et al. 2004), we can speculate that the minerals causing the TL signal are Ca minerals, like anorthite, gehlenite, akermanite, even oldhamite, and possibly enstatite, but we stress that the amounts are miniscule.

In view of the small size of the Sutter's Mill fragments, and the thickness of the fusion crust, it seems prudent to ask whether the heat of atmospheric entry—which is easily capable of affecting natural TL—could also change induced TL by producing luminescent minerals in Sutter's Mill by dehydrating and crystallizing the normal CM chondrite mineral assemblages. The same question was asked by Sedaghatpour and Sears (2009) in their study of micrometeorites. These authors heated samples of MAC 88100 and Jilin for 30 s and measured their induced TL properties. After this short-term heating to temperatures as high at 1100 °C, the samples showed no sign of an increase in induced TL; this is no surprise as electron

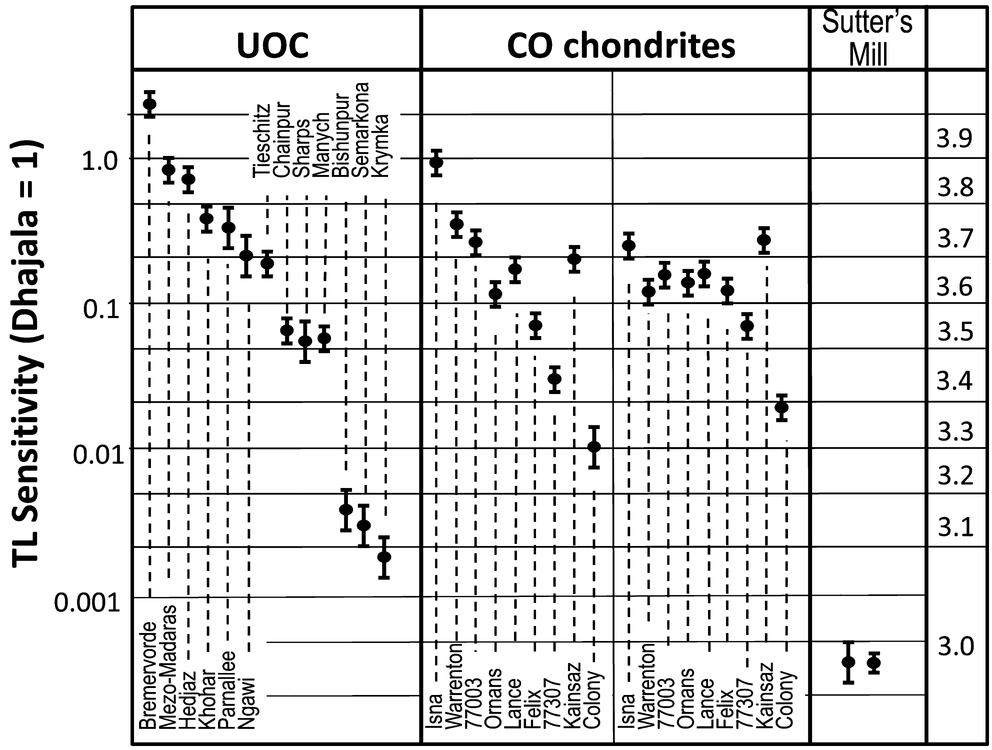

Fig. 6. The TL sensitivity of the Sutter's Mill meteorite compared with the TL sensitivity of CO and unequilibrated ordinary chondrites (modified from Keck and Sears 1987).

trap depths involved in natural TL are approximately 1 eV, while chemical bond energies involved induced TL are approximately 40 keV. Thus, the TL sensitivity of Sutter's Mill was not caused by atmospheric heating. Rather, the presence of a TL signal from the Sutter's Mill samples indicates important mineral and phase differences between this meteorite and normal CM chondrites. Experience with other meteorite classes and petrographic properties of this meteorite suggest that this reflects the slight metamorphic overprint.

These TL results seem to be consistent with Raman spectra of macromolecular carbon (which measures the level of ordering in graphitic carbon) that indicates a heating temperature of 153 ± 27 °C for SM2-9 and 268 ± 42 °C for SM12 experienced on a million-year time scale (Jenniskens et al. 2012). These temperatures and times are sufficient to dehydrate and induce small amounts of mineralization.

Finally, we point out that the broad hummocky glow curve shape we observe for Sutter's Mill is reminiscent of many low-petrographic–type meteorites (Fig. 7). Metamorphosed C chondrites like ALH 82101, Y-791717, and Allende tend to have TL peaks at approximately 100 °C or approximately 200 °C due to feldspar, but unmetamorphosed or only very slightly metamorphosed chondrites like MAC 87300/301, ALHA77307, Colony, and Kaba, or ordinary chondrites of type 3.0–3.2 (Sears et al. 1980) have broad hummocky glow curves with many unresolved peaks, often including a peak at 350 °C due to refractory minerals. Kaba, Colony, Y-791717, and MAC 87300 and 301 all have weak induced TL with broad hummocky glow curves, as do several very low-type ordinary chondrites. However, the glow curve is significantly different from any previously reported meteorite, which signals unique mineralogical characteristics for this meteorite. In passing, we also note that in the Raman G-band center–versus-width diagram, SM2-9 plots between CM2 and CO3 chondrites, whereas SM12 trends closer to polycrystalline C were observed in CV3 chondrites (Jenniskens et al. 2012), which seems to lead to conclusion similar to that drawn from the TL data.

CONCLUSIONS

Both natural and induced TL signals were detected in Sutter's Mill fragment SM2-1d, which is unusual for a CM chondrite. The natural TL signal was present at high glow curve temperatures, but missing from low glow curve temperatures (where it is expected to be strongest). This indicates that the fragment was heated to approximately 300 °C within the last 100 ka or so, the time for TL to recover in typical interplanetary conditions. Three opportunities for such heating are

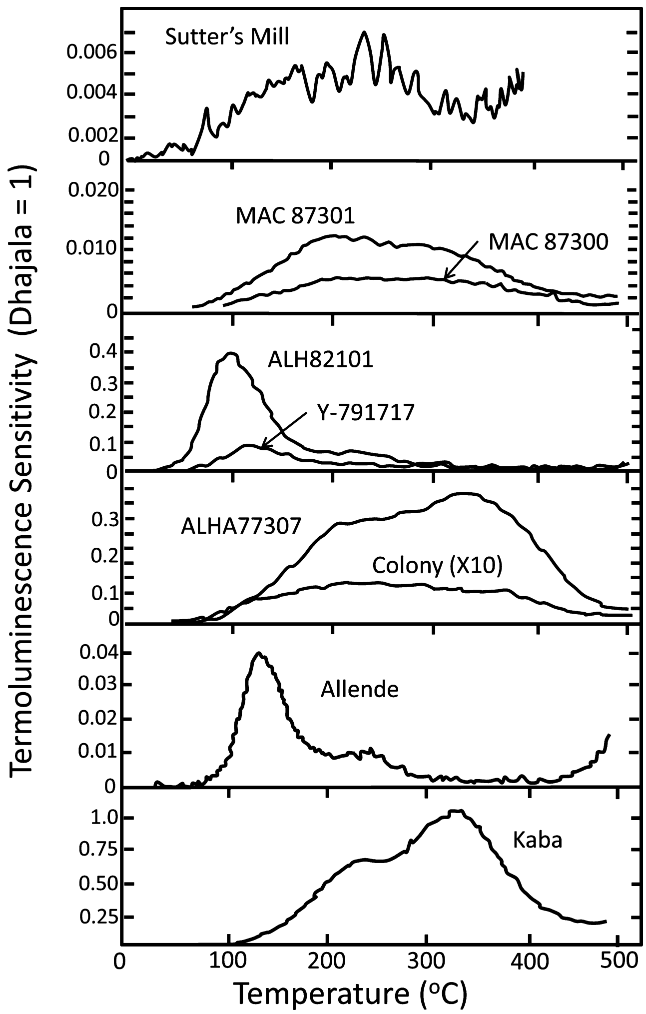

Fig. 7. Using induced thermoluminescence glow curves to "finger-print" primitive (i.e., un- or little-metamorphosed) solar system materials (modified after Sears et al. 1991). Glow curves for meteorites of the CV (Guimon et al. 1995) and CO classes (Keck and Sears 1987) and the anomalous C2 meteorite MAC 87300/301 (Sears et al. 1991), compared with the glow curve for Sutter's Mill. Sutter's Mill has a glow curve resembling the low-type 3 chondrites (MAC 87300/301, ALHA77307, Colony, and Kaba), but is not an exact match to any other C2 or C3 chondrite suggesting a unique mineral mixture.

discussed, ejection from the parent body, small perihelion, and heating during atmospheric passage. None of these possibilities can be eliminated, although the first is less likely than the others. In any event, the properties of the Sutter's Mill meteorite should be interpreted with this fact in mind. The presence of a weak but significant (S/N ~ 10) induced TL signal gives a TL sensitivity in the range of type 3.0 chondrites and the glow curve structure is similar, but not identical, to low-type UOC, CO, and CV chondrites and unlike CM chondrites examined to date. This is consistent with petrographic evidence for the unusual nature of this meteorite.

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