Radiation Measurements xxx (2017) 1–9

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

Can thermoluminescence be used to determine soil heating from a wildfire?

Francis K. Rengers [a,*], Vasilis Pagonis [b], Shannon A. Mahan [a]

[a] U.S. Geological Survey, 1711 Illinois St., Golden, CO 80401, USA
[b] Physics Department, McDaniel College, Westminster, MD 21157, USA

HIGHLIGHTS

- We investigated the use of thermoluminescence to distinguish between burned and unburned soil samples.
- Soil heated by a wildfire had a distinctly different luminescence glow curve shape than unburned soil samples.
- It was possible to see changes in the thermoluminescence signal as a function of soil depth in wildfire-heated samples.
- Soil heating occurred at depths less than 10 cm.

ARTICLE INFO

Article history:
Received 11 April 2017
Received in revised form
27 July 2017
Accepted 7 September 2017
Available online xxx

Keywords:
Thermoluminescence
Wildfire temperature
Quartz
Polymineral silt

ABSTRACT

The Silverado wildfire occurred from September 12 to 20, 2014, burning 960 acres in Orange County, California. Soil samples from within the burn area were obtained and the thermoluminescence (TL) properties of those samples were compared against a control sample to understand wildfire heating. We performed a series of experiments investigating the degree to which the control differed from the wildfire soil samples. This work showed that soil heated by a wildfire had a distinctly different glow curve shape than the unburned soil sample. Moreover, it was possible to see changes in the TL signal as a function of soil depth in wildfire-heated samples. Our experiments suggest that minimal soil heating occurred below approximately 10 cm. Estimates of wildfire temperatures, however, were nuanced.

Published by Elsevier Ltd.

1. Introduction

Many studies have observed increased erosion on hillslopes burned by wildfires (e.g. Benavides-Solorio and MacDonald, 2005; Wagenbrenner et al., 2010), which leads to sedimentation hazards both onsite and downstream of burned areas (Shakesby and Doerr, 2006). This is partially due to increased runoff in burned areas, and partially because wildfire heating can remove soil cohesion (Moody et al., 2005). Understanding how soil erosion changes after a wildfire is a crucial step toward estimating and predicting post-wildfire sedimentation and debris flow hazards. Several hypotheses have been developed to explain the increase in erodibility following wildfire. Nyman et al. (2013) present evidence that following a wildfire there is a non-cohesive layer of sediment on the top of the forest floor. The top of this non-cohesive layer is simply ash, and underneath the ash is soil that has been altered from the fire. This burned soil becomes non-cohesive due to the lack of aggregate stability following the fire. Nyman et al. (2013) find that this stability is primarily shaped by fine roots and cohesive fine sediment. This is consistent with the observation that temperatures above 60 °C are the lethal threshold for destroying plant tissue, roots, and soil microorganisms, which all play a part in soil cohesion and structure (Hungerford et al., 1991; Busse et al., 2010; Chief et al., 2012).

Soil aggregate stability is also influenced by heat effects on soil mineralogy and microbiology. Researchers have noted that expansive 2:1 clays are destroyed or altered during wildfires (Fitzpatrick, 1980; Chandler et al., 1983; Ulery et al., 1996; Arocena and Opio, 2003), which would reduce soil cohesion. Moreover, DeBano et al. (1979) demonstrated that when soils reach temperatures of 200–300 °C, 85% of the organic substances, a critical element of soil stability, are removed. Furthermore, bacteria and fungi, both important factors in soil stability, are killed when soils are heated to

* Corresponding author.
E-mail address: frengers@usgs.gov (F.K. Rengers).

http://dx.doi.org/10.1016/j.radmeas.2017.09.002
1350-4487/Published by Elsevier Ltd.

temperatures of 110–210 °C (bacteria) and 100–155 °C (fungi) (DeBano et al., 1979).

Because many factors that contribute to soil stability can be destroyed during wildfires (e.g. plant roots, clays, microorganisms, and organic matter), it is important to know the potential depth of soil that has been heated to critical temperatures. Numerous field experiments have sought to understand the depth of wildfire heating using laboratory experiments and prescribed fires (Hartford and Frandsen, 1992; Campbell et al., 1995; Robichaud, 2000; Preisler et al., 2000; Massman et al., 2003; Busse et al., 2010; Chief et al., 2012). However, the fundamental physics of heat conduction in a soil show that temperature propagation is strongly controlled by soil moisture (Campbell et al., 1995), consequently real-time monitoring during prescribed or experimental burning may not reflect the very dry soil conditions that are likely to precede a natural wildfire. In this study, we explored *a posteriori* what observations can be derived from thermoluminescence about wildfire heating as a function of soil depth.

Thermoluminescence (TL) is a phenomenon common to minerals such as quartz and feldspar that can be used to detect prior grain heating (e.g. Watson and Aitken, 1985). The luminescence signal of a grain or an aliquot of several grains is typically measured by heating the grains at known temperatures, and measuring the photons emitted from the grains; the resulting plot of the TL signal as a function of temperature is referred to as the TL glow curve. In the case of quartz, the TL glow curve shows a distinct peak at ~110 °C when measured with a heating rate of ~5 °C/s; in our experiments, this TL peak appears at ~90 °C since we are using a higher heating rate of 2 °C/s, although we acknowledge that the TL peak can occur anywhere between 90 and 110 °C when heating rates are between 1 K/s and 20 K/s. This TL peak has been used extensively for dosimetry and for dating of geological and archaeological samples (Aitken, 1985; Chen and Pagonis, 2011). When quartz samples are irradiated with a small test dose, the resulting TL signal at ~110 °C is known to depend on the prior thermal treatment of the sample and on the prior irradiation dose received by the sample. This rather complex phenomenon is commonly known as the “predose effect” in quartz.

There have been several attempts to use the height of the ~110 °C TL peak to interpret the thermal history of quartz (Rhodes et al., 2004; Polymeris et al., 2007, 2014; Brodard et al., 2012; Sanjurjo-Sánchez et al., 2016a; Sanjurjo-Sánchez et al., 2016b). Both TL signals and optically stimulated luminescence signals (OSL) have been used in these types of studies. Rhodes et al. (2004) specifically explored the use of TL to interpret past wildfire temperatures, but the broad applicability of their results is hindered by the fact that they did not know the date of the last fire at the sample site. Sanjurjo-Sánchez et al. (2016a) made considerable progress in investigating previous firing temperatures of ancient pottery, and importantly showed that low luminescence sensitivity can obscure results of the 110 °C TL peak in interpreting firing temperature. Herein, we add a new set of experiments to further test the ability of TL to reveal observations of wildfire soil heating.

In this study, we use a battery of experiments in order to test the following hypotheses:

1. TL can be used to differentiate soil samples that have been heated in a wildfire compared to nearby control samples that were unheated.
2. TL can identify if soils are heated at different depths.
3. Thermal stability of the TL signals from unheated and wildfire-heated soil samples from the same study site will show similar trends.
4. Laboratory heating of unburned soil samples can be used to estimate the temperature range at which a burned soil was heated.

2. Background: study site, preliminary investigation, and sample preparation

We focus our study on a burned area in the Silverado Canyon, a large drainage within the Santa Ana Mountains of southern California (Fig. 1). The Silverado fire burned 960 acres from September 12 to 20, 2014. The study area is located within a high-severity burn area of the wildfire, where vegetation was completely incinerated. The study site is primarily underlain by meta-sedimentary bedrock with a dominantly sandy-loam soil type. Prior to the fire, the study location hosted chaparral vegetation. A Mediterranean climate dominates the region, with wet winters (December–February) punctuating warm dry periods the rest of the year. The terrain in the study area is steep, with mean slope angles of 31°.

We obtained our initial soil cores from the site in November 2014 in order to determine if the material was suitable for luminescence measurements. Our results indicated that the material was sourced from the meta-sedimentary bedrock, contained quartz and feldspar in adequate quantities, and that these minerals contained both TL and OSL in measurable quantities.

We analyzed three soil cores from the burned watershed as well as an unburned soil core that was used as a control (Fig. 1). These

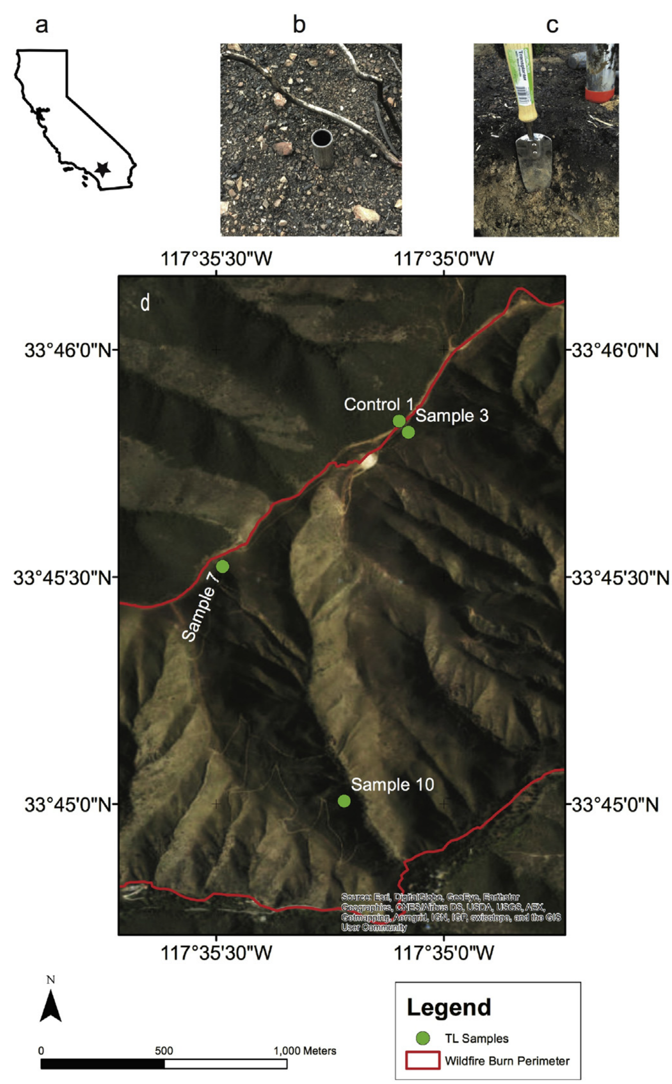

Fig. 1. (a) Site location (b) Sample core (c) View of the soil after sample core is removed (d) Study area map showing location of samples and control.

Please cite this article in press as: Rengers, F.K., et al., Can thermoluminescence be used to determine soil heating from a wildfire?, Radiation Measurements (2017), http://dx.doi.org/10.1016/j.radmeas.2017.09.002

will be referred to as sample 3, sample 7, sample 10 (S3, S7, S10 respectively), and control 1. The sample cores were slotted into 2-cm partitions up to a maximum depth of 14 cm in order to allow laboratory subsampling of the core in depth increments. For each sample, the tube had seven subsections, and we extracted at least four replicates for each subsection. For example, Sample 10-1a is the first replicate for the first subsample, and 10-1b is the second replicate for the first subsample. Using the silt fraction in each of the seven 2-cm segments, we performed several laboratory experiments, described subsequently, to test our hypotheses.

3. Experimental methods

All samples were prepared following U.S. Geological Survey standard protocols (Gray et al., 2015). Luminescence measurements were carried out using a Risø TL/OSL Reader (model TL/OSL–DA–20), equipped with a $^{90}Sr/^{90}Y$ beta particle source, delivering a nominal dose rate of 0.089 Gy/s for 180 min, which calculates to a dose of 16 Gy. A 9635QA photomultiplier tube with a Schott Blue (BG-39) filter was used for light detection (390–490 nm). All TL measurements and heatings were performed in a nitrogen atmosphere with a low constant heating rate of 2 °C/s, in order to avoid significant temperature lag between the sample heater and the top surface of the sample. TL measurements were performed from room temperature up to the maximum temperature of 500 °C. The grain size of the polymineral silt sample was 4–11 μm. The silt was obtained by Stoke's settling in a calibrated cylinder and then centrifuging the sample to remove clay particles. Methanol was added to the silt to create a slurry that could be pipetted onto the aluminum discs at the bottom of glass vials, and later evaporated off leaving the silt plated onto the discs. No preheat was applied to the samples, unless otherwise noted in the description of the experiments below. A 180 s N_2 purge was used, introducing a delay before measurement. The background counts of ~40 cts/s were subtracted and a satisfactory plateau was found (see description of pre-heat plateau in Gray et al. (2015)), where applicable. The black body counts were also ~50 cts/s.

For the thermal stability experiments, we used a Thermo Scientific programmable muffle furnace (240 cu in 120VAC), with a temperature uniformity of ±5 °C at 100 °C. Temperature preheats in the muffle furnace were 100, 150, 200, 250, 300, 325 (not all cases), 350, 400, and 500 °C, and the duration of temperature preheat was 20 min. We used 4–5 replicate disks for each preheat temperature.

4. Results

4.1. Experiment to differentiate between burned and unburned samples

In an initial experiment, we tested whether the natural TL signal (NTL) can be used to determine if a soil sample had been heated in a wildfire. We compared the glow curves of the unburned sample (control 1) with the burned samples (S3, S7, and S10). This was done to investigate if there was a systematic variation of the NTL signal with depth below the surface, and also to see how the height of the NTL signal in the wildfire-heated samples compare with the unburned control samples.

The variation of the NTL signal does not systematically vary as a function of depth within the accuracy/precision of the experiment (for example, Fig. 2a–b). However, when viewed in detail, the NTL signal in the control sample is clearly higher by a factor of ~2–3 than the NTL signal in S7. Similarly, it was observed that the NTL signals for samples S3 and S10 were lower than the NTL for control 1. The average of the NTL signals from Fig. 2, with the error bars representing the standard deviation of the mean, shows that the

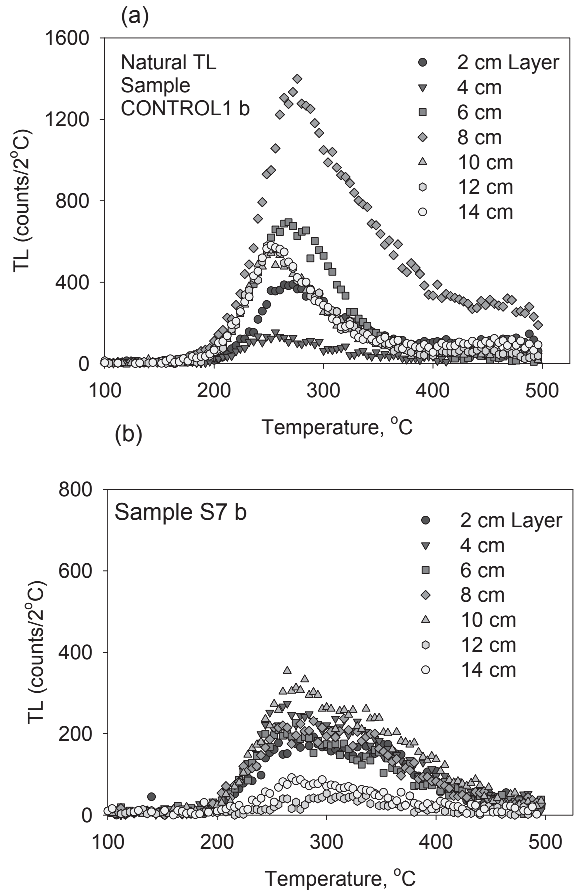

Fig. 2. (a) The NTL glow curve signal from the control 1b sample for different soil depths below the ground surface (b) The glow curve signal from sample S7b. N.B. Only every second experimental point is shown in this figure, for clarity.

average TL glow curve of the control and the wildfire-heated samples are markedly different within the statistical accuracy of these preliminary experiments (Fig. 3 and Fig. S1). However, the NTL glow curves indicate that the wildfire temperatures experienced by the samples (on average) could not have exceeded 400 °C, since in that case the NTL signal would be completely wiped out.

In addition to the difference between the heights of the average NTL and burned sample glow curves, differences in the *shape* of the NTL and sample curves were also found. For example, when the

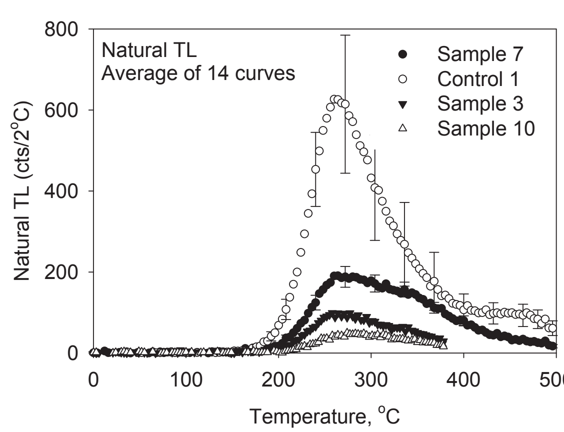

Fig. 3. Average of TL glow curves for the control and each sample. Error bars represent the standard error (standard deviation of the mean) with N = 14.

Please cite this article in press as: Rengers, F.K., et al., Can thermoluminescence be used to determine soil heating from a wildfire?, Radiation Measurements (2017), http://dx.doi.org/10.1016/j.radmeas.2017.09.002

glow curve for each sample depth is normalized by the maximum intensity in the control (Fig. 4a) and in sample 7 (Fig. 4b), we see that the average glow curve is different in shape (Fig. 4c). The average NTL glow curve for Sample 7 (solid circles) is much wider than the corresponding average NTL for control 1 (open circles), at least within the statistical accuracy of this experiment. This qualitative difference in shape indicates a fundamental change in the TL response of the materials due to heating. This type of change in the shape of TL glow curves has been associated in some experimental studies with thermally or optically transferred charges, from low temperature to higher temperature TL peaks in quartz and other materials. See, for example, the simulations by Pagonis et al. (2007).

We therefore conclude that the NTL glow curves in this preliminary experiment show that: 1) wildfire samples have a distinctly different height and shape of their TL signal compared to the unheated control, and 2) the samples were most likely heated to an average temperature less than 400 °C because they retained a TL signal, effectively bracketing the maximum range of potential heating.

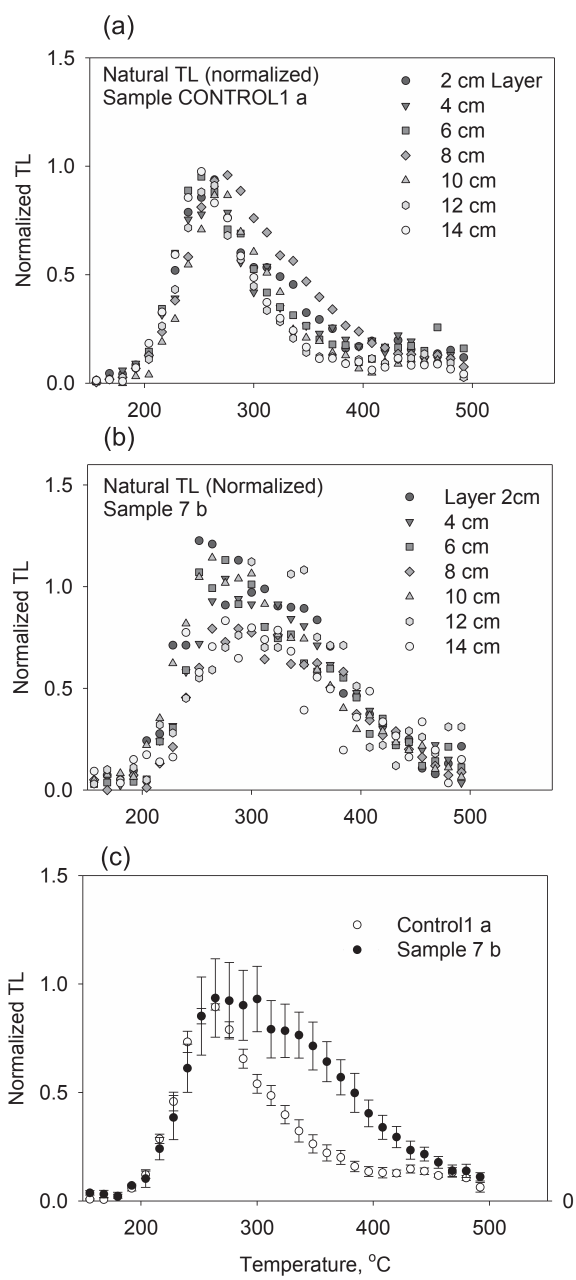

Fig. 4. (a) Experimental control 1 glow curves normalized to the maximum TL intensity. (b) Experimental Sample 7 glow curves normalized to the maximum TL intensity. (c) Comparison of the averages of the 7 control 1 and Sample 7 glow curves.

4.2. *Experiment to establish variations of the TL signal with soil depth*

We conducted an experiment to test the hypothesis that TL could be used to observe changes in wildfire temperature at different depths. For this experiment, we relied on the fact that when quartz is heated to high temperatures, the glow curve signal at ~90 °C will increase when the sample is subsequently irradiated with a small test dose (note we are using the silt fraction of sediment which contains quartz minerals). This is a well-known phenomenon related to the predose phenomenon in quartz, and is commonly termed “thermal activation” or “thermal sensitization” of the samples (Chen and Pagonis, 2003). The predose phenomenon is the observed change in sensitivity of the “110 °C” TL peak in quartz, caused by a combination of irradiation and higher temperature annealing. Extensive previous experimental and modeling research has established that quartz samples can become thermally activated by exposure to temperatures as low as 200 °C (Chen and Pagonis, 2003; Kitis et al., 2006).

We used the irradiated 90 °C glow curve peak to investigate if TL would show declines in temperature with soil depth. A test dose of 15–16 Gy was given to the samples before measuring their TL signal. Examining a single subsample (S10 at 4 cm depth) with five replicates, we found little variation among them (especially at the 90 °C glow curve peak), indicating good precision for this experiment (Fig. 5a–b). The five TL glow curves in Fig. 5a–b are then

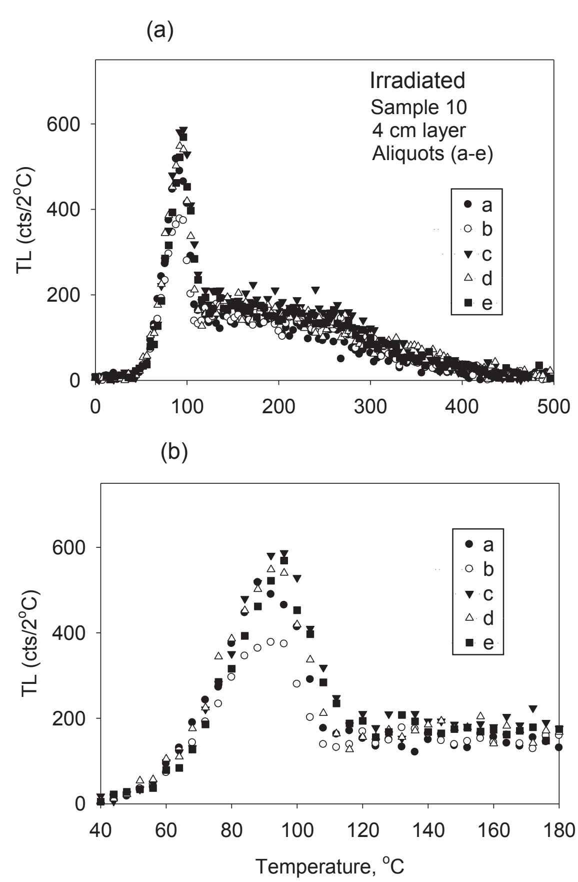

Fig. 5. (a) TL signal of the 4 cm deep layer in Sample 10 (irradiated) for five different aliquots, a-e. (b) Enlarged view of (a).

Please cite this article in press as: Rengers, F.K., et al., Can thermoluminescence be used to determine soil heating from a wildfire?, Radiation Measurements (2017), http://dx.doi.org/10.1016/j.radmeas.2017.09.002

averaged, and the process is repeated for each of the seven layers of sample S10 (2, 4, 6, 8, 10, 12, 14 cm) (Fig. 6a). The result of the averaging process for each layer shows a systematic variation of the TL maximum height with the depth of the layer (Fig. 6a). This systematic variation with depth can also be seen when one integrates the total TL area under each glow curve from Fig. 6a (Fig. 6b). As the depth increases, the maximum TL signal decreases systematically, with the exception of the deepest layer at 14 cm, which shows a higher signal (Fig. 6b). The reason for this discrepancy for the deepest layer is not clear; it is possible that it is due to inhomogeneities in the soil or to statistical fluctuations in the signal of the sample.

The similar behavior of the total TL area and the maximum height of the TL peak in Fig. 6b is due to the known stability of the 90 °C TL peak in quartz. This rather remarkable TL peak is known to have a very stable shape corresponding to first-order kinetics, and it has been found to have the same universal shape independent of the thermal and irradiation history of the quartz samples (Chen and Pagonis, 2011).

All three samples exhibit similar overall variations of the 90 °C TL peak with depth below the surface, at least within the accuracy and precision of the experiment (Fig. 7a). In addition, the TL signals from the deepest level of all three samples (12–14 cm depth) are very similar to each other, and also similar to the corresponding TL signal of the control 1 sample (Fig. 7b). By contrast, the control sample shows minimal variation of the 90 °C peak with soil depth, with the exception of the 8 cm layer that shows a much higher signal (Fig. 7). It is not clear what may have caused this discrepancy for the 8 cm layer. When the data in Fig. 7 are normalized to the first point representing the TL signal for the 2 cm layer (Fig. 8a), a declining trend is observed with depth. This trend is very clear when the irradiated samples are averaged (Fig. 8b).

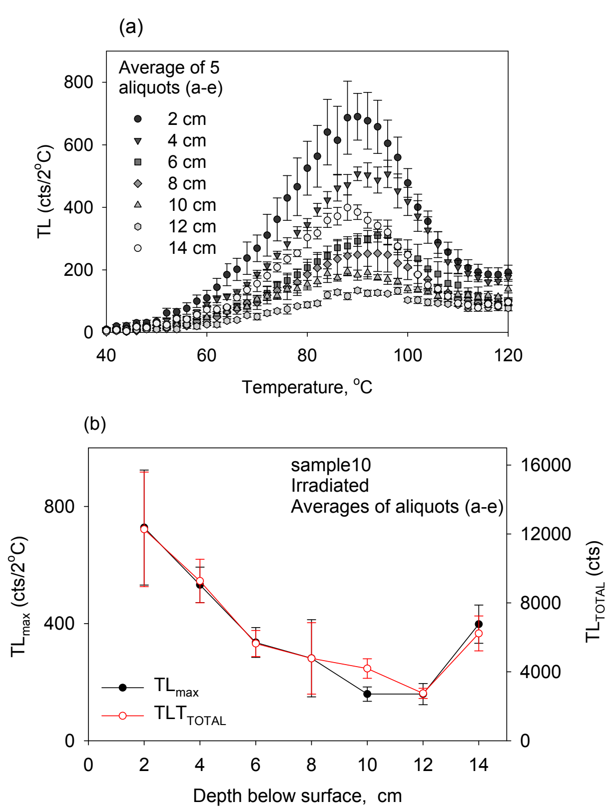

Fig. 6. (a) The glow curve for each depth in Sample 10 (irradiated), using the average of 5 aliquots. (b) The maximum TL height from Fig. 6a, as a function of the layer depth.

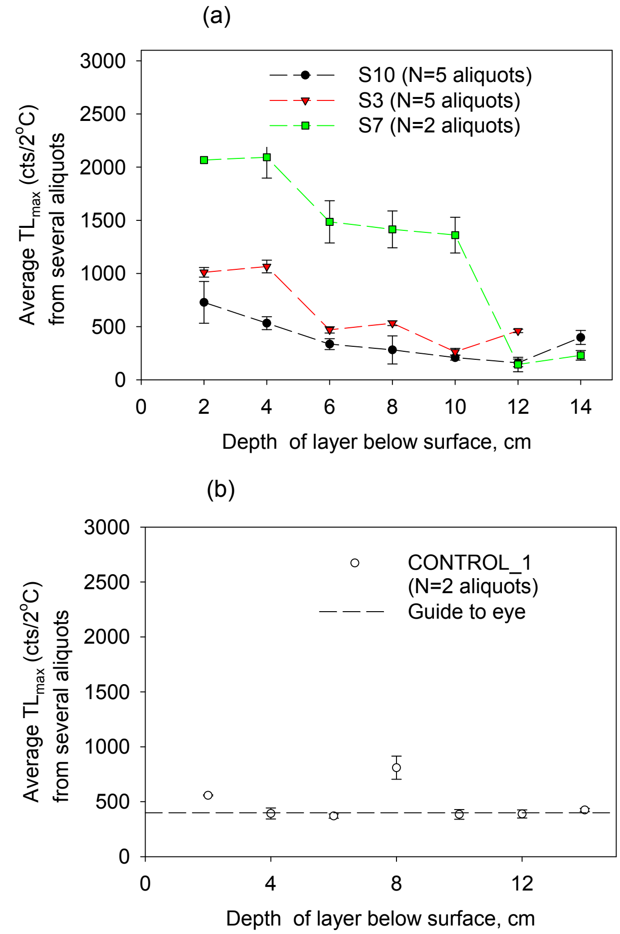

Fig. 7. (a) The maximum 90 °C TL height for the three irradiated samples studied here (S10, S7 and S3). (b) The maximum TL height for control 1 (unheated sample). (N.B. For sample 7 the subsample at depth 14 cm was contaminated during a laboratory accident, therefore there is no measurement for that sample.)

The results in Figs. 7 and 8 show that the TL signal was highest in burned soil samples at the ground surface, and the signal decreased with soil depth toward the level of the control signal. These results also suggest strongly that there is a difference between the irradiated control and irradiated burned samples (Fig. 7).

4.3. Experiment to determine thermal stability of the natural TL signal

The thermal stability of the NTL signal in our samples can be assessed by integrating the area under a TL glow curve, and plotting that area as a function of the known temperature to which the sample was heated in the muffle furnace (see list of temperatures in Section 3). We obtained a glow curve for the control and the samples at each unique depth, and for each annealing temperature. The glow curves for each soil depth were integrated by summing the TL counts, and these areas were subsequently averaged for two subsamples (a and b), and for each furnace temperature (Fig. 9).

The thermal stability of the NTL signal in the control and in the burned samples were quite similar, declining as the samples are heated to higher furnace temperatures (Fig. 9). The general behavior for the control and for the three samples shows that heating the samples to 400 °C causes the glow curve area to drop to as much as 0.5% of the initial glow curve area (Fig. 9). This is consistent with the previous discussion of the TL glow curves in

ARTICLE IN PRESS

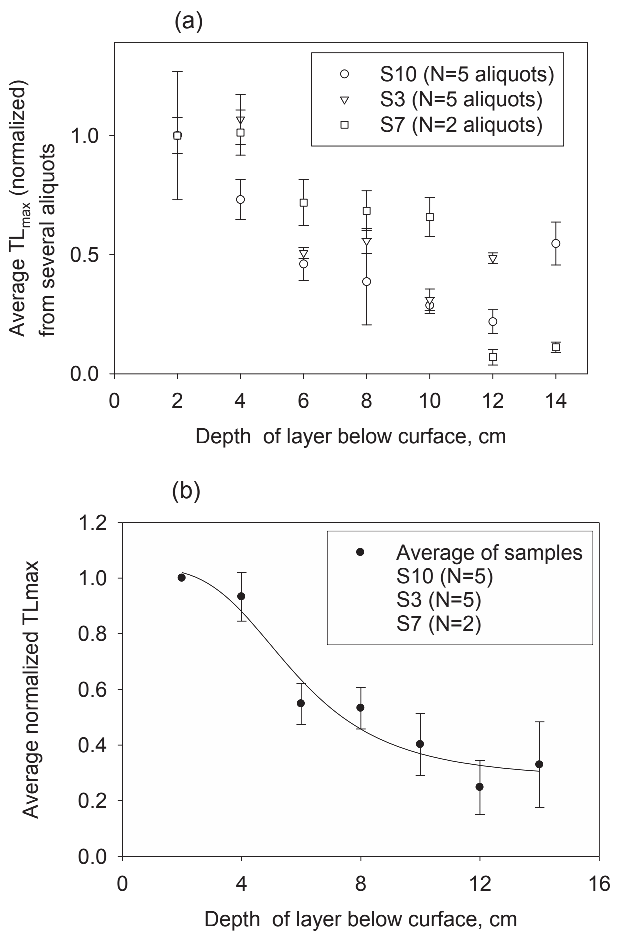

Fig. 8. (a) The average irradiated TL maximum value plotted as a function of depth. (b) The average TL max of all samples in Fig. 8a plotted as a function of soil depth (cm). The error bars represent the average and standard error of the normalized TL signals for the 3 samples. The parameter N in these figures represents the number of aliquots used for each sample during this averaging procedure. The solid line is a guide to the eye.

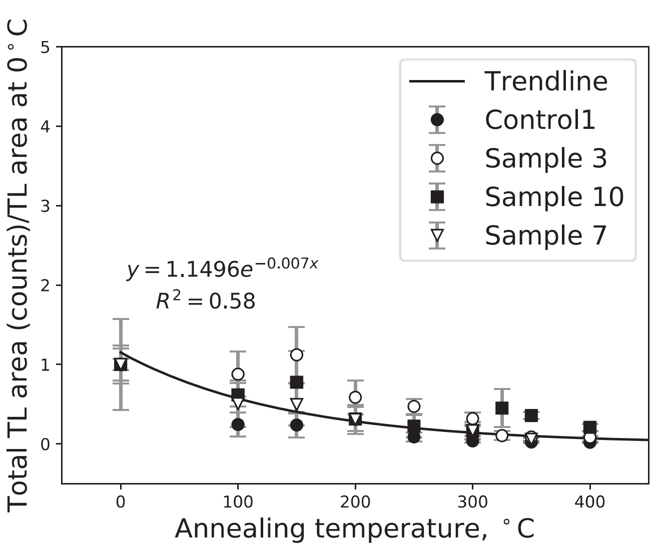

Fig. 9. Each point in this figure represents the average integrated area under TL glow curves at each soil depth that were heated at a known muffle furnace temperature. The integrated area is normalized by the sample that did not undergo heating in the muffle furnace. The error bars represent the standard error (standard deviation of the mean). (N.B. The total TL at 500 °C is not displayed, because it is about an order of magnitude higher than the signals shown here. This is due to the phase transition that quartz is known to undergo at ~500 °C).

Figs. 2–4, in which it was concluded that the samples were likely exposed to average wildfire temperatures of less than 400 °C because at those temperatures the TL signal is nearly wiped out completely.

4.4. Experiment to estimate wildfire temperatures

In order to estimate the temperature range that soil was heated at different depths, we attempted to simulate what happened during the wildfire by exposing the unfired control 1 sample to different annealing temperatures for 20 min in a muffle furnace. After annealing for 20 min, the samples were irradiated with the same test dose, and thus we studied the combined effect of heating *plus* test dose on the TL signal. The TL signals from two sample replicates (a and b) from each 2 cm portion of the control 1 sample were measured and averaged, in order to examine the average variation of the TL signal with the furnace temperature (Fig. 10).

The height of the 90 °C TL peak stays the same for all annealing temperatures in the range 100–400 °C (Fig. 10a). However, the annealing process causes changes in the height and shape of the TL peak at ~270 °C (Fig. 10b). As the annealing temperature increases, the 270 °C peak for each glow curve decreases and moves to the right (Fig. 10). There are no changes taking place in the TL height after an annealing temperature of 300 °C.

We explored the possibility of using the 270 °C peak in sample control 1 at known muffle furnace temperatures to develop a relationship between the 270 °C peak height and firing temperature. We used the NTL 270 °C peak value from the wildfire samples to interpolate a temperature of heating, and the results show a rather complex pattern (Fig. 11). Temperatures interpolated from

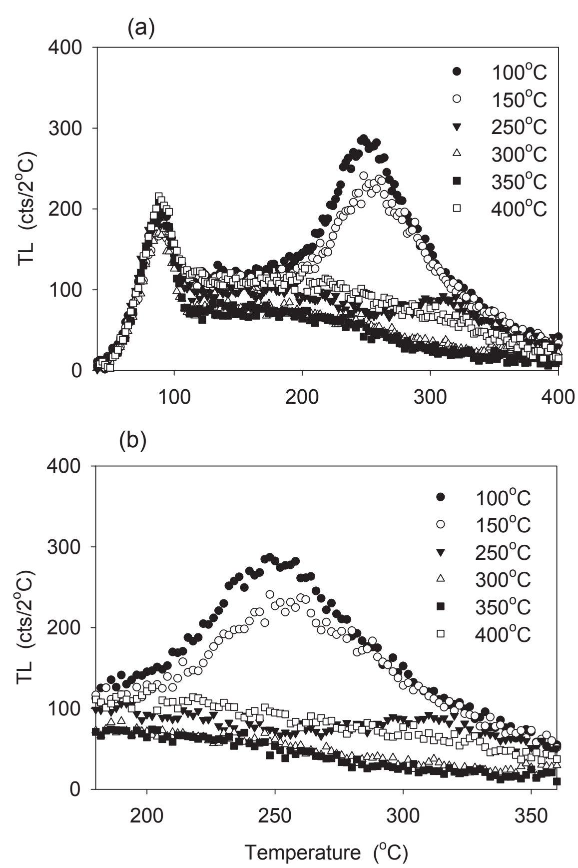

Fig. 10. (a) Control 1 glow curves after heating in the muffle furnace and irradiating the samples. (b) The detailed behavior of the TL peak around 270 °C.

Please cite this article in press as: Rengers, F.K., et al., Can thermoluminescence be used to determine soil heating from a wildfire?, Radiation Measurements (2017), http://dx.doi.org/10.1016/j.radmeas.2017.09.002

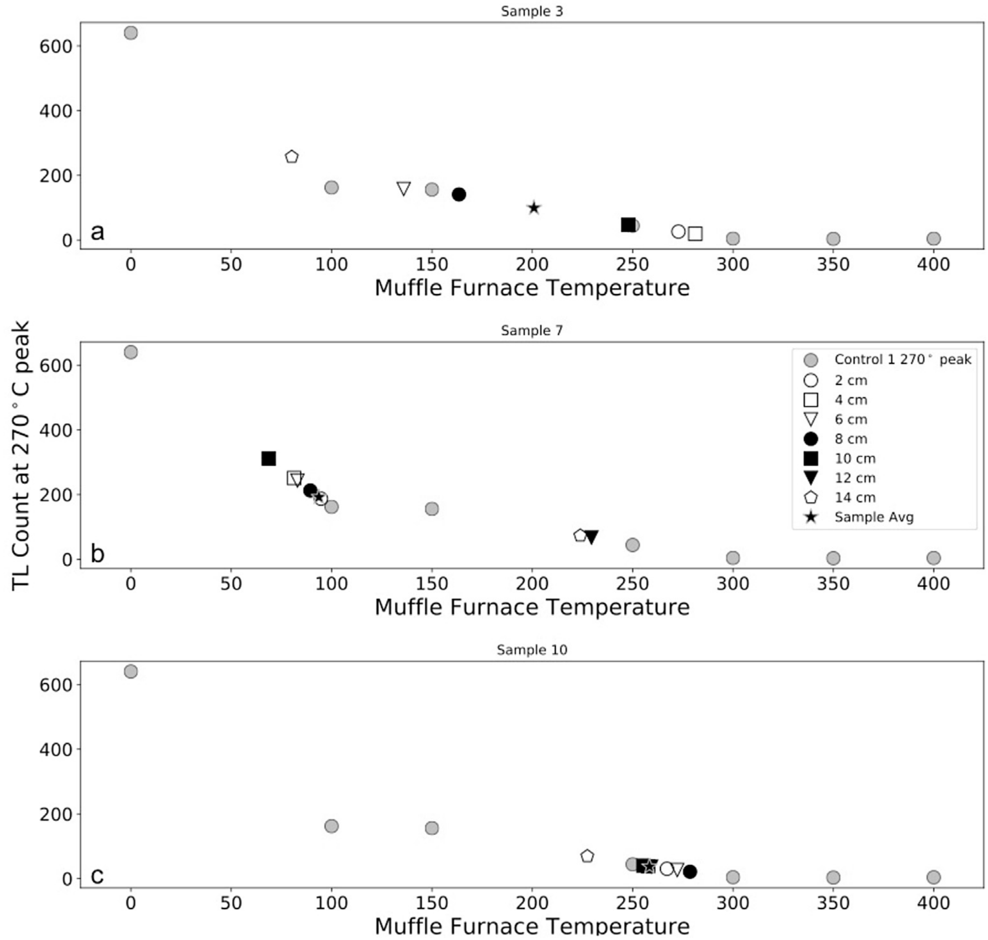

Fig. 11. The "curve" in a-c represents the 270 °C peak TL count for the control 1 at known muffle furnace temperatures. The ordinate value for each point in a-c represents the 270 °C peak TL count measured from the wildfire samples from at a specific depth, and the abscissa value is linearly interpolated using the "curve" from control 1. (a) Sample 3, (b) Sample 7, (c) Sample 10.

the subsamples do not show a direct pattern of heating temperature with depth in most samples. For sample 3, soil heating temperature appears to alternate around an average sample temperature of 200 °C (Fig. 11). In sample 7, the majority of sample depths are heated to temperatures less than 100 °C, excluding the two deepest subsamples, which appear to have been heated to nearly 230 °C (Fig. 11). Sample 10 shows a clustering near the average temperature of 260 °C. Sample 10 was taken on a very steep slope, which might have burned at higher temperatures because of the slope angle.

This experiment suggested that it might be possible to estimate wildfire temperatures based on the height of the 270 °C peak in the heated soil samples. However, the accuracy and precision of this experiment will have to be improved significantly before any *quantitative* conclusions can be drawn about the temperatures occurring in the wildfire.

5. Discussion and conclusions

The set of experiments performed here show how the TL signals from silt can be used to estimate the impacts of wildfire heating on soils. The experiment to differentiate between burned and unburned soils demonstrates a strong distinction between the control and the fire-exposed soil samples (Figs. 3 and 4), confirming our original hypothesis 1. The small number of samples (3) restricts a rigorous statistical test; however, the differences in the *heights* and *shapes* of the NTL glow curves between the control and the samples suggests that the TL glow curves can qualitatively differentiate between the two populations.

The experiment to determine heating differences with soil depth also provides a promising result (Figs. 6 and 7). It appears that the 90 °C TL peak declines with depth in a systematic fashion, whereas the control sample has a nearly uniform TL count. This supports our original hypothesis 2. Moreover, this suggests that heating was minimal beyond approximately 10 cm. This depth of heating is at the high end of the range observed in prior studies (Table 1), but is likely to be accurate because a natural wildfire should be drier and propagate heat deeper than wet soils. Unlike prior studies (Table 1), this work provides a novel addition because it constrains heating depth after a natural wildfire. Prior studies measuring soil-heating depths failed to reflect completely natural conditions because observations were only conducted in controlled environments (laboratories) or in known wet conditions (prescribed burns) (Table 1).

The experiment of thermal stability confirms that exposure to higher temperatures reduces the entire glow curve (Fig. 9), lending support to hypothesis 3. However, the individual samples show a high degree of variability.

The final experiment to estimate wildfire temperature using the 270 °C peak shows mixed results (Fig. 11). Within the statistical

Table 1
Measured soil temperatures during fires in prior studies.

Author	Depth Measured Greater than 100 °C	Conditions
Busse et al. (2010)	2.5–5 cm	outdoor experiment
Campbell et al. (1995)	3.5–6.5 cm	lab experiment
Chief et al. (2012)	1-3 cm	grass/shrubland prescribed
Hartford and Frandsen (1992)	4 cm	prescribed burn
Massman et al. (2003)	10-30 cm	slash pile prescribed
Massman et al. (2003)	2 cm	meadow prescribed
Massman et al. (2003)	0 cm	forest prescribed
Odion and Davis (2000)	2 cm (for more than an hour)	prescribed burn
Preisler et al. (2000)	30 cm max (most were much shallower)	prescribed burn
Robichaud (2000)	2 cm	prescribed burn

accuracy and precision of the current experiments, samples 3 and 10 seem consistent with an estimated wildfire temperature in the range 200–300 °C. However, the wildfire duration at our sample sites is unknown and the change of sensitivity of the TL signal due to the heating duration in quartz samples has been reported to be a very complex phenomenon (Bailey, 2001; Adamiec, 2005). The response of the samples to a test dose depends in a complex manner on both the annealing temperature and on the cumulative annealing time. For example, Adamiec (2005, their Fig. 4) shows detailed experimental data on the change of sensitization for annealing temperatures in the range 180–250 °C and for cumulative times up to 6000 s. Their results show that the sensitization depends on both the annealing temperature and annealing time. In view of these previously reported experimental data, we feel that the laboratory heating experiment described in section 4.4 may not be reproducing the actual conditions during the wildfire, so it is only possible to draw qualitative conclusions from this experiment.

Overall, the accuracy and precision of the final experiment is influenced by several effects. One might expect, for example that soil temperatures should be the highest at the soil surface and decline with depth; however, the samples are not always consistent with this pattern, although they become more consistent when one takes the average of several samples (Fig. 11). This may indicate different heat transport mechanisms; however, the statistics in this experiment and the fact that we are not sure about the duration of the fire preclude us from making any definitive statements about specific transport mechanisms. In addition, grain mixing may be a factor, either during sample collection or sample extraction. The samples were obtained by pounding a tube into the ground, and some compaction of the soil was noted. It is then possible that during this process soil mixing did occur in the wildfire-heated samples. Alternatively, the variability in the glow curves may reduce the precision in temperature estimations. Sanjurjo-Sánchez et al. (2016a) show that temperatures may only be estimated to ± 50–100 °C, and this wide range may be influencing our interpretations. Finally, the temperature variation may be due to a complex soil-heating processes and the soil water/vapor distribution during heating. Despite this inconsistency, each of the samples show a mean soil-heating temperature that is realistic, non-zero, and distinctly different than the control sample (Fig. 11).

Acknowledgements

We would like to acknowledge Luke McGuire for help in sample preparation, as well as U.S. Geological Survey (USGS) reviewer, Harrison Gray, and anonymous journal reviewers. We thank the USGS Landslide Hazards Program for funding. Data used in this paper are available in USGS ScienceBase (Rengers and Mahan, 2017). Any use of trade, product or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.radmeas.2017.09.002.

References

Adamiec, G., 2005. Investigation of a numerical model of the pre-dose mechanism in quartz. Radiat. Meas. 39, 175–189.
Aitken, M.J., 1985. Thermoluminescence Dating. Academic Press, London, p. 359.
Arocena, J., Opio, C., 2003. Prescribed fire-induced changes in properties of sub-boreal forest soils. Geoderma 113 (1), 1–16.
Bailey, R.M., 2001. Towards a general kinetic model for optically and thermally stimulated luminescence of quartz. Radiat. Meas. 33, 17–45.
Benavides-Solorio, J., MacDonald, L.H., 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. Int. J. Wildland Fire 14 (4), 457–474.
Brodard, A., Guibert, P., Leveque, F., Mathe, V., Carozza, L., Burens, A., 2012. Thermal characterization of ancient hearths from the cave of Les Fraux (Dordogne, France) by thermoluminescence and magnetic susceptibility measurements. Quat. Geochronol. 10, 353–358.
Busse, M.D., Shestak, C.J., Hubbert, K.R., Knapp, E.E., 2010. Soil physical properties regulate lethal heating during burning of woody residues. Soil Sci. Soc. Am. J. 74 (3), 947–955.
Campbell, G., Jungbauer Jr., J., Bristow, K.L., Hungerford, R., 1995. Soil temperature and water content beneath a surface fire. Soil Sci. 159 (6), 363–374.
Chandler, C., Williams, D., Trabaud, L., Thomas, P., Cheney, P., 1983. Fire in Forestry. Vol. 1: Forest Fire Behavior and Effects. John Wiley & Sons, New York, NY, p. 450.
Chen, R., Pagonis, V., 2003. Modelling thermal activation characteristics of the sensitization of thermoluminescence in quartz. J. Phys. D Appl. Phys. 36, 1–6.
Chen, R., Pagonis, V., 2011. Thermally and Optically Stimulated Luminescence: a Simulation Approach. Wiley and Sons, Chichester, UK, p. 434.
Chief, K., Young, M.H., Shafer, D.S., 2012. Changes in soil structure and hydraulic properties in a wooded-shrubland ecosystem following a prescribed fire. Soil Sci. Soc. Am. J. 76 (6), 1965–1977.
DeBano, L.F., Rice, R.M., Eugene, C.C., et al., 1979. Soil Heating in Chaparral Fires: Effects on Soil Properties, Plant Nutrients, Erosion, and Runoff. U.S. Forest Service Research Paper (RP-145), Berkeley, CA.
Fitzpatrick, R., 1980. Effect of forest and grass burning on mineralogical transformations in some soils of natal. Soil Irrigat. Res. Inst. Rep. 952 (139), 80.
Gray, H.J., Mahan, S.A., Rittenour, T., Nelson, M., 2015. Guide to luminescence dating techniques and their application for paleoseismic research. In: Lund, W.R. (Ed.), Basin and Range Province Seismic Hazards Summit III. Utah Geological Survey Miscellaneous Publication.
Hartford, R.A., Frandsen, W.H., 1992. When it's hot, it's hot... or maybe it's not! (surface flaming may not portend extensive soil heating). Int. J. Wildland Fire 2 (3), 139–144.
Hungerford, R.D., Harrington, M.G., Frandsen, W.H., Ryan, K.C., Niehoff, G.J., 1991. Influence of fire on factors that affect site productivity. In: Proceedings of the Symposium on Management and Productivity of Western-montane Forest Soils, pp. 32–50.
Kitis, G., Pagonis, V., Chen, R., 2006. Comparison of experimental and modelled quartz thermal-activation curves obtained using multiple- and single-aliquot procedures. Radiat. Meas. 41, 910–916.
Massman, W., Frank, J., Shepperd, W., Platten, M., Omi, P.N., Joyce, L.A., 2003. In situ soil temperature and heat flux measurements during controlled surface burns at a southern Colorado forest site. In: USDA Forest Service Proceedings, RMRS-P-29 (Fort Collins, CO).
Moody, J.A., Smith, J.D., Ragan, B.W., 2005. Critical shear stress for erosion of cohesive soils subjected to temperatures typical of wildfires. J. Geophys. Res. 110. F01004.
Nyman, P., Sheridan, G.J., Moody, J.A., Smith, H.G., Noske, P.J., Lane, P.N., 2013. Sediment availability on burned hillslopes. J. Geophys. Res. Earth Surf. 118 (4), 2451–2467.

Odion, D.C., Davis, F.W., 2000. Fire, soil heating, and the formation of vegetation patterns in chaparral. Ecol. Monogr. 70 (1), 149–169.
Pagonis, V., Chen, R., Wintle, A.G., 2007. Modelling thermal transfer in optically stimulated luminescence of quartz. J. Phys. D Appl. Phys. 40, 998–1006.
Polymeris, G.S., Kiyak, N.G., Koul, D.K., Kitis, G., 2014. The firing temperature of pottery from ancient Mesopotamia, Turkey, using luminescence methods: a case study for different grain-size fractions. Archaeometry 56, 805–817.
Polymeris, G.S., Sakalis, A., Papadopoulou, D., Dallas, G., Kitis, G., Tsirliganis, N.C., 2007. Firing temperature of pottery using TL and OSL techniques. Nucl. Instr. Meth. Phys. Res. A 580, 747–750.
Preisler, H.K., Haase, S.M., Sackett, S.S., 2000. Modeling and risk assessment for soil temperatures beneath prescribed forest fires. Environ. Ecol. Stat. 7 (3), 239–254.
Rengers, F.K., Mahan, S.A., 2017. Silverado California thermoluminescence data: U.S. Geological Survey data release. https://doi.org/10.5066/F7XP7351.
Rhodes, E., Farwig, V., Chappell, J., Pillans, B., et al., 2004. Luminescence of single quartz grains to determine past movement and heating. In: Roach, I.C. (Ed.), Regolith. CRC LEME, pp. 295–298.
Robichaud, P., 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain Forests, USA. J. Hydrol. 231, 220–229.
Sanjurjo-Sánchez, J., Fenollós, J.L.M., Polymeris, G.S., 2016a. Technological aspects of Mesopotamian Uruk pottery: estimating firing temperatures using mineralogical methods, thermal analysis and luminescence techniques. Archaeol. Anthropol. Sci. 1–16.
Sanjurjo-Sánchez, J., Gomez-Heras, M., Fort, R., de Buergo, M.A., Benito, R.I., Bru, M.A., 2016b. Dating fires and estimating the temperature attained on stone surfaces. The case of Ciudad de Vascos (Spain). Microchem. J. 127, 247–255.
Shakesby, R., Doerr, S., 2006. Wildfire as a hydrological and geomorphological agent. Earth Sci. Rev. 74 (3), 269–307.
Ulery, A., Graham, R., Bowen, L., 1996. Forest fire effects on soil phyllosilicates in California. Soil Sci. Soc. Am. J. 60 (1), 309–315.
Wagenbrenner, J., Robichaud, P., Elliot, W., 2010. Rill erosion in natural and disturbed forests: 2. Modeling approaches. Water Resour. Res. 46 (W10507).
Watson, I., Aitken, M., 1985. Firing temperature analysis using the 110°C TL peak of quartz. Nucl. Tracks Radiat. Meas. (1982) 10 (4), 517–520.

Please cite this article in press as: Rengers, F.K., et al., Can thermoluminescence be used to determine soil heating from a wildfire?, Radiation Measurements (2017), http://dx.doi.org/10.1016/j.radmeas.2017.09.002