Portable optically stimulated luminescence age map of a paleoseismic exposure

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ABSTRACT

The quality and quantity of geochronologic data used to constrain the history of major earthquakes in a region exerts a first-order control on the accuracy of seismic hazard assessments that affect millions of people. However, evaluations of geochronological data are limited by uncertainties related to inherently complex depositional processes that may vary spatially and temporally. To improve confidence in models of earthquake timing, we use a high-density suite of radiocarbon and optically stimulated luminescence (OSL) ages with a grid of 342 portable OSL samples to explore spatiotemporal trends in geochronological data across an exemplary normal fault colluvial wedge exposure. The data reveal a two-dimensional age map of the paleoseismic exposure and demonstrate how vertical and horizontal trends in age relate to dominant sedimentary facies and soil characteristics at the site. Portable OSL data provide critical context for the interpretation of ¹⁴C and OSL ages, show that geochronologic age boundaries between pre- and post-earthquake deposits do not match stratigraphic contacts, and provide the basis for selecting alternate Bayesian models of earthquake timing. Our results demonstrate the potential to use emergent, portable OSL methods to dramatically improve paleoseismic constraints on earthquake timing.

INTRODUCTION

Radiocarbon (¹⁴C) and luminescence ages provide geochronological context to paleoseismic investigations; constrain the timing and rates of sedimentary, pedogenic, and geomorphic processes; and provide the basis for quantifying earthquake timing, recurrence, and fault slip rate (e.g., Weldon et al., 2004; Dolan et al., 2016; Galli et al., 2019; Scharer and Yule, 2020; Nelson et al., 2021). However, substantial uncertainties in these dating methods relate to the depositional and geomorphic setting of the paleoseismic site and the dominant processes of sediment transport and accumulation, pre-depositional age inheritance, and post-depositional modification and soil development that may vary spatially and temporally and in relation to surface ruptures. These factors can lead to an order of magnitude of variability in the number of ages per paleoseismic investigation reported across a region (e.g., Streig et al., 2020), poor understanding of contextual uncertainties related to different dating methods and environments (e.g., Gavin, 2001), “noisy” geochronological data sets, and inconsistent methods of deriving Bayesian models of earthquake-timing probabilities (e.g., Lienkaemper and Bronk Ramsey, 2009; DuRoss et al., 2018). This leads to a problem that is universally relevant to paleoseismic investigations: given the inherently complex processes of sedimentation and pedogenesis, how do we develop geochronological sampling strategies that maximize the accuracy and reproducibility of paleoseismic rupture histories?

We employ dense ¹⁴C and traditional optically stimulated luminescence (OSL) sampling with a new application of portable OSL (Gray et al., 2021) to explore spatiotemporal trends in geochronological data and develop a robust interpretation of the sedimentary, pedogenic, and tectonic processes that underlie a paleoseismic exposure. Portable OSL (Sanderson and Murphy, 2010) yields rapid measurements of bulk luminescence from small, mostly unprocessed sediment samples and can be used as a proxy for apparent depositional age when calibrated with numeric ages (Stone et al., 2015; Gray et al., 2018). We used portable OSL to generate a high-resolution, geochronological relative age map of a paleoseismic exposure. Our focus was on the depositional history of a normal fault scarp that formed in a late Holocene surface rupture of the Wasatch fault zone (Schwartz and Coppersmith, 1984; Machette et al., 1992) and was revealed in a natural exposure at the Deep Creek site (Utah, USA; Fig. 1). Our overall goal was to develop a panoptic view of a fault exposure in order to increase confidence in earthquake timing, which impacts estimates of rupture extent, earthquake probability forecasts, and seismic hazard models (e.g., Petersen et al., 2019; Field et al., 2020).

DEEP CREEK SITE, WASATCH FAULT ZONE

At the Deep Creek site, a natural exposure of Holocene alluvial fan sediments reveals a surface-rupturing earthquake on the Wasatch fault zone (Fig. 1). Similar to previous investigations of the site (Jackson, 1991; Hylland and Machette, 2008), we found a 20–30-cm-thick and organic-rich paleosol (buried A horizon) formed within alluvial fan sediments that are vertically faulted 1.8 m and buried by a ≤1.5-m-thick, wedge-shaped package of scarp-derived colluvium. The colluvial wedge includes two facies (Fig. 2A): a coarse, laterally discontinuous, and mostly massive basal debris facies (after Nelson, 1992; unit 2a), and a finer-grained and more laterally extensive wash facies that buried the debris facies and includes centimeter-scale finer-grained interbeds that have an apparent dip of ~30–50° west (unit 2b). Moderately cemented alluvial fan gravel and scarp colluvium are juxtaposed across a steeply dipping (locally overhanging) and eroded fault-scarp–free face. The Deep Creek paleoearthquake likely occurred after ca. 1 ka based on a bulk ¹⁴C age and thermoluminescence age for the paleosol (Jackson, 1991; Hylland and Machette, 2008).

The Deep Creek site presents ideal conditions for a high-density geochronological study. First, the stratigraphic units are distinct...
and contacts between them are clear. A relatively thick package of stratified scarp-derived colluvium forms an abrupt contact with the paleosol, which lacks evidence of post-depositional disturbance or burrowing. We extracted 35 samples of bulk sediment, which yielded discrete charcoal fragments for \(^{14}\)C dating and facilitated single-aliquot quartz OSL dating (Gray et al., 2015). In total, 34 ages (excluding three modern ages) include one \(^{14}\)C and four OSL ages for the alluvial fan, \(^{14}\)C and two OSL ages for the paleosol, and \(^{14}\)C and five OSL ages for the scarp colluvium (Tables S1 and S2 in the Supplemental Material); Gray et al., 2021).

Second, the stratigraphic and structural interpretation is simple: only a single surface rupture postdates the alluvial fan gravel and paleosol. Third, the site offers ideal conditions for relating changes in portable OSL to age. We extracted 342 samples for portable OSL in a grid across the exposure (Fig. 2A). Measurements of luminescence correspond to the time since sediment transport, last exposure to sunlight, and burial (Rhodes, 2011). Although

![Deep Creek site](https://doi.org/10.1130/G49472.1)
luminescence is affected by the rate of background radiation, we observed a near-uniform dose rate across the exposure from the alluvial fan source (1.99 ± 0.16–1σ Gy/k.y.; Table S2). Our portable OSL samples consisted of bulk sediment rather than a mineral separate (e.g., quartz) used in traditional OSL dating. However, the near-uniform lithology, and our pre-treatment of sieving to a 90–250 µm grain size and weighing aliquots to 0.5 ± 0.005 g, helped maximize the comparability of samples (Gray et al., 2018, 2021). We interpolated the results into a 10-cm-cell raster to assess spatial variability in portable OSL across the exposure; we plotted the logarithm of the photon counts to account for variance in the luminescence measurements (Fig. 2B). To estimate the apparent age of each portable OSL sample, we generated a statistically significant linear regression (adjusted $R^2 = 0.9$) between portable OSL photon counts (normalized by sample weight) and the $^{14}$C and OSL ages (Fig. 2).

**SPATIAL TRENDS IN GEOCHRONOLOGICAL CONSTRAINTS**

The portable OSL results (Fig. 2B) are a proxy for the age distribution of sediment across the exposure. First-order observations are consistent with our geologic interpretations: pronounced changes in portable OSL values occur vertically across the unconformable paleosol–colluvium (units 1A–2b) contact and horizontally across the eroded fault-scarp free face. The scarp colluvium exhibits less portable OSL signal than that in the paleosol and alluvial fan, which generally increases with depth. However, in the fault-proximal part of the colluvial wedge (<1.5 m west of the fault; Fig. 2B), increased bulk luminescence suggests that partially bleached sediment has a residual or incompletely reset luminescence signal and a possible inherited age component. As a result, the apparent age of the fault-proximal colluvium is closer to that of the paleosol and alluvial fan, which generally increases with depth. The $^{14}$C and traditional OSL ages (Fig. 2B) confirm the robustness of the portable OSL spatial relations. The alluvial fan age increases with depth from 5 ka to 8 ka in the hanging wall (Fig. 3B) and from 7 ka to 13 ka where it is more deeply exposed in the footwall. Six groupings of vertically stacked ages within the paleosol (Fig. 2B) show that soil age increases consistently with depth, for example, from $\leq 0.7$ ka near its contact with overlying scarp colluvium to ca. 2–4 ka near its center and base (Fig. 3B). The paleosol is slightly younger at fault-distal (0.1–0.6 ka) rather than fault-proximal (0.4–0.7 ka) positions. The fault-distal colluvial wedge is $\leq 0.4$ ka; however, seven ages for fault-proximal colluvial sediment range from 1 ka to 6 ka and correspond spatially with the area of increased portable OSL signal. A single $^{14}$C age for debris-facies colluvium (2.3 ka) is similar to the age of the paleosol.

Spatial relations in the geochronology show that vertical trends in age dominate in the
alluvial fan and paleosol, and horizontal trends in age are most prominent in the scarp colluvium (Fig. 3). Although these relations appear in the 14C and OSL ages (Figs. 3A and 3B), they are more pronounced in the portable OSL ages (Figs. 3C–3F) that were modeled using the linear regression (Fig. 2). The alluvial fan sediments exhibit the most consistent modeled portable OSL age (ca. 6 ka) laterally; the paleosol may decrease in age slightly with distance from the fault but is similar laterally within error (Figs. 3C and 3E). Modeled ages for the colluvial wedge facies decrease strongly from the fault in a fault-proximal position, whereas the wash-facies colluvium has a more uniform age laterally beyond ~1.0–1.5 m from the fault. Vertical trends are more apparent in the alluvial fan and soil (Figs. 3D and 3F), where the modeled portable OSL age increases consistently with depth below the top of the paleosol. The portable OSL age of the colluvium is mostly constant vertically above the paleosol but has considerable scatter (Fig. 3D).

SEDIMENTARY AND PEDOGENIC PROCESSES AND IMPLICATIONS FOR PALEOSEISMIC RESEARCH

Our work offers an unprecedented view into sedimentary and pedogenic processes at a paleoseismic site, and their influence on age...
variability. The Deep Creek 14C and OSL ages show that the paleosol began forming at ca. 3–4 ka and soil-development processes continued as late as ca. 0.4–0.7 ka. Portable OSL data indicate that the paleosol decreases in age with distance from the fault. This likely results from the time-transgressive nature of colluvial wedge deposition, which accommodates continued soil development and the addition of carbon to the upper (<0.2 m) and most fault-distal (>1.5 m) part of the soil prior to burial, as well as the mixing of organic matter across the paleosol–colluvium contact. As a result, the minimum age of the paleosol in a fault-proximal position (Fig. 4) is likely most representative of its initial burial age. Charcoal 14C, OSL, and portable OSL ages for the scarp-derived colluvium fall into two distinct groups: (1) old (ca. 1–6 ka) ages within 0.5–1.6 m of the fault and (2) young (<0.4 ka) ages for the more distal parts of the wedge. The fault-proximal ages likely reflect recycled charcoal and sediment from the footwall alluvial fan and paleosol; a limited (<2 m) transport distance and/or coherent block failure (e.g., Nelson, 1992) could explain the partially bleached sediment. The young, fault-distal colluvial ages are likely related to periods of soil formation between episodes of scarp degradation and wedge sedimentation.

To address whether portable OSL data can be used to refine estimates of earthquake timing, we compare stratigraphic and chronological event horizons that separate pre- and post-earthquake sediments (Fig. 4). Stratigraphic event horizons have long served as the basis for interpreting geochronological data (Pantosti et al., 1993; McCalpin, 2009) and, more recently, for establishing prior information used in Bayesian models of earthquake-timing probabilities (Bromk Ramsey, 2008, 2009). The paleosol–colluvium unconformity forms the stratigraphic event horizon within the Deep Creek exposure. We also defined apparent chronological boundaries using the 14C and OSL results in three Bayesian models that imply earthquake times at 0.7 ± 0.2 ka, 0.5 ± 0.08 ka, and 0.4 ± 0.04 ka (see the Supplemental Material). We compared equivalent portable OSL contours for these earthquake times to the stratigraphic event horizon (Fig. 4). The 0.5–0.7 ka portable OSL age contours have the greatest spatial overlap with the stratigraphic event horizon and are most consistent with the sedimentary and pedogenic processes interpreted across the exposure.

Consequently, we exclude the 0.4 ka Bayesian model and infer a Deep Creek earthquake time of 0.6 ± 0.2 ka, which combines the 0.5 ka and 0.7 ka models and refines the previous ≤1 ka rupture estimate. Thus, portable OSL facilitates the exploration of age variability and context as well as the evaluation of alternate Bayesian models and definition of a defensible chronologic event horizon. This is especially critical at the Deep Creek site, where the divergence of the 0.5–0.7 ka chronologic horizons from the stratigraphic event horizon in a fault-proximal position (Fig. 4) demonstrates that a stratigraphic boundary alone is insufficient for interpreting a limited suite of geochronological data.

Although geochronological insight into a paleoseismic exposure provided by portable OSL may help improve Bayesian models of earthquake timing, the application of these methods may be limited by factors such as the exposure extent, luminescence characteristics, available material for dating, and time and budgetary constraints. However, real-time portable OSL, conducted during the field component of a trench investigation but at a reduced sampling density (see the Supplemental Material), offers a practical solution for paleoseismic exposures that are suitable for traditional OSL dating. A real-time portable OSL age map could yield a more comprehensive understanding of spatiotemporal age variability across the exposure and support the mapping of detailed wedge facies that are not resolvable from sediment characteristics alone. Field-based portable OSL could also inform strategies of 14C and traditional OSL sampling at resource-limited sites, provide context for the interpretation of the resulting ages or existing geochronological data in a re-occupied site, and yield more nuanced and defensible Bayesian models of earthquake timing.

CONCLUSIONS

At the Deep Creek paleoseismic exposure, a high-density geochronological sample suite and portable OSL age map yield insight into how spatiotemporal age variability relates to intricate sedimentary and pedogenic processes. We demonstrate that a high-resolution portable OSL age map of the exposure has the potential to resolve vertical to horizontal age trends in sedimentary and pedogenic units, improve our understanding of dominant processes of colluvial sedimentation and soil formation, and assess alternate Bayesian models of earthquake timing. Our work challenges the concept of geochronological sampling strategies based on stratigraphy alone (the stratigraphic event horizon) and shows that portable OSL, even in a moderate-density field application, has the potential to provide insight into pre-, syn-, and post-earthquake depositional processes and improve the accuracy of paleoseismic rupture histories.

Figure 4. An apparent chronologic event horizon derived from portable optically stimulated luminescence (OSL) age contours corresponding to an earthquake at 0.5–0.7 ka marks the transition from pre- to post-event sediment and soil. The chronologic event horizon diverges from the stratigraphic event horizon within the fault-distal paleosol and fault-proximal colluvium, and demonstrates that sampling strategies integrating both horizons are likely to yield more accurate and reproducible results than those based on stratigraphy alone.
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