Applications of airborne and terrestrial laser scanning to paleoseismology

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ABSTRACT

Paleoseismic investigations aim to document past earthquake characteristics such as rupture location, frequency, distribution of slip, and ground shaking intensity—critical parameters for improved understanding of earthquake processes and refined earthquake forecasts. These investigations increasingly rely on high-resolution (<1 m) digital elevation models (DEMs) to measure earthquake-related ground deformation and perform process-oriented analyses. Three case studies demonstrate airborne and terrestrial laser scanning (ALS and TLS) for paleoseismic research. Case 1 illustrates rapid production of accurate, high-resolution, and georeferenced three-dimensional (3D) orthophotographs of stratigraphic and fault relationships in trench exposures. TLS scans reduced the preparation time of the trench and provided 3D visualization and reconstruction of strata, contacts, and permanent digital archival of the trench. Case 2 illustrates quantification of fault scarp degradation rates using repeat topographic surveys. The topographic surveys of the scarps formed in the 1992 Landers (California) earthquake documented the centimeter-scale erosional landforms developed by repeated winter storm-driven erosion, particularly in narrow channels crossing the surface rupture. Vertical and headward incision rates of channels were as much as ~6.25 cm/yr and ~62.5 cm/yr, respectively. Case 3 illustrates characterization of the 3D shape and geomorphic setting of precariously balanced rocks (PBRs) that serve as negative indicators for strong ground motions. Landscape morphometry computed from ALS-derived DEMs showed that PBRs are preserved on hillslope angles between 10° and 40° and contributing areas (per unit contour length) between 5 and 30 m²/m. This situation refines interpretations of PBR exhumation rates and thus their effectiveness as paleoseismometers. Given that earthquakes disrupt Earth’s surface at centimeter to meter scales and that depositional and erosional responses typically operate on similar scales, ALS and TLS provide the absolute measurement capability sufficient to characterize these changes in challenging geometric arrangements, and thus demonstrate their value as effective analytical tools in paleoseismology.

INTRODUCTION

Determining the location, magnitude, rupture frequency, and associated ground motions of past earthquakes is a necessary step toward the formulation of accurate earthquake forecasts (e.g., Working Group on California Earthquake Probabilities, 2008). Earthquake ruptures disrupt Earth’s topography, and surface process responses (i.e., erosion and deposition) to this deformation operate at centimeter to meter scales. The accurate measurement of earthquake-induced topographic deformation and the associated geomorphic process response rates in complex geometrical arrangements is a necessary step toward characterizing earthquakes and refining earthquake forecasts.

The detail and accuracy of digital topographic data collected by light detection and ranging (lidar) instruments provide an opportunity to quantitatively analyze earthquake-produced surface deformation. In paleoseismology, two primary lidar platforms are employed: airborne and terrestrial laser scanning (Fig. 1). Airborne laser scanning (ALS) employs an aircraft-mounted laser scanner that scans topography in side-to-side swaths perpendicular to the aircraft’s flight path. Typical scan rates range from tens to several hundred kHz. The orientation (yaw, pitch, and roll) of the aircraft is monitored by an onboard inertial navigation measurement unit, and its location is determined by a high-precision kinematic global positioning system (GPS; El-Sheimy et al., 2005; Carter et al., 2007; Shan et al., 2007). Postprocessing places the lidar data in a global reference frame as a point cloud of the laser returns with typical shot densities >1 m⁻² (Fig. 1). Recent ALS campaigns have yielded digital representations of topography at resolutions sufficient to make measurements of earthquake-related surface deformation (e.g., Hudnut et al., 2002; Bevis et al., 2005; Oskin et al., 2007, 2010a, 2010b, 2012; Prentice et al., 2009; DeLong et al., 2010; Hilley et al., 2010, 2012). For example, ALS effectively depicts fault trace geometries and stream channels that are offset by structures such as the San Andreas fault (e.g., Arrowsmith and Zielke, 2009; DeLong et al., 2010). Systematic analyses of these data reveal geomorphic features that are barely perceivable in the field, but can fundamentally change our inferences about paleoseismic records and fault segmentation (e.g., Zielke et al., 2010). ALS also assists in characterizing paleoseismic study sites by defining the local tectonic geomorphology of paleoseismic trench data (e.g., offset alluvial fans, pressure ridges, sags; e.g., Akçiz et al., 2010; Toké et al., 2011) and aiding in the location of potential paleoseismic sites.

Footnotes

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Terrestrial laser scanning (TLS) systems employ a tripod-mounted laser scanner operated from various user-selected and near-field positions to ensure complete scan coverage of the feature of interest. Reflective targets with known geographic coordinates placed around the feature are used to align the final point cloud and place it in a global reference frame (Fig. 1). Shot densities for TLS point clouds can be $>10^4 \text{m}^{-2}$ and the acquisition geometry provides a true three-dimensional (3D) representation of the scanned feature. In addition, TLS systems employ high-resolution digital color photography where point attributes such as red-green-blue (RGB) values acquired by a TLS-mounted digital camera are used to color the point clouds and produce photorealistic images.

The utility of ALS and TLS data sets for visualization and analysis is often demonstrated using gridded digital elevation models (DEMs) that are generated from the spatially heterogeneous point clouds (El-Sheimy et al., 2005). Where the point spacing is less than the desired resolution of the DEM, a local binning algorithm is applied to compute values within a specified search radius, $r$, at each node and a predefined mathematical function (e.g., mean, minimum, maximum, inverse distance weighting [IDW]; El-Sheimy et al., 2005). For the ALS and TLS analyses presented here, we used IDW ($1/r^2$) and appropriate search radii to generate our high-resolution DEMs.

In this paper, we present three case studies to demonstrate the utility of ALS and TLS in paleoseismic research (Fig. 2). The first case study employs TLS in a paleoseismic investigation of the San Andreas fault in the Carrizo Plain. Trenches excavated perpendicular to the San Andreas fault reveal fractures and coseismically disrupted strata, while fault-parallel trenches are excavated across offset stream channels and alluvial fans to provide information about the history of aggradation, degradation, and channel geometry. Datable samples from both types of trenches constrain the timing of earthquakes and incision events. We next explore the utility of TLS in monitoring the geomorphic evolution of part of the 1992 $M_w$ 7.3 Landers, California, earthquake fault scarp. Coseismically generated fault scarps provide information about the timing, frequency, and extent of the earthquakes that produced them. By assessing the initial forms and tracking the subsequent morphologic modification of these landforms, information about the timing and recurrence of the earthquakes may be determined (e.g., Nash, 1980; Arrowsmith and Rhodes, 1994; Arrowsmith et al., 1996). We then present ALS and TLS data that characterize the geomorphic setting and 3D form of precariously balanced rocks (PBRs). By serving as negative indicators for earthquake-induced strong ground motions, fragile geologic features such as PBRs provide information about past ground motions, i.e., their geographic extent and intensity (Brune, 1993a, 1993b, 1994, 1996; Brune and Whitney, 2000; Brune et al., 2006). The geologic and geomorphic processes that operate in all of our case studies span spatiotemporal...
ALS and TLS applications to paleoseismology

scales that range from centimeters to hundreds of meters and decades to millennia. The case studies demonstrate TLS and ALS as promising technologies that provide a framework upon which the efficient and accurate characterization of earthquake processes may be constructed over a range of spatiotemporal scales.

BACKGROUND

Paleoseismic Trenches and Offset Geomorphic Markers

Conventional paleoseismic logging of structures, strata, and samples is typically conducted either manually (e.g., tape measure and pencil on millimeter-grid paper) or on digital photomosaics of trench walls (McCalpin, 2009). The latter method involves taking as many as hundreds of digital photographs perpendicular to the trench walls and creating a digital photomosaic of the stratigraphy and structures exposed in the trench walls. The footprint of each photograph depends on the aperture angle of the lens and the distance between the wall and the camera. In conventional 1-m-wide trenches, this footprint is ~1 m × 0.5 m. The final mosaics are then used as base maps on which the trench walls are logged. This method has several time-consuming drawbacks. For example, lens distortion introduces mismatches between photograph edges that lead to spatial distortions in the photomosaic. Similarly, unwanted parallax effects resulting from large vertical and horizontal photograph spacing lead to further spatial distortions in the final photomosaic. These problems are exaggerated by trench walls that have large surface irregularities, thereby introducing more geometrical inaccuracies in the final photomosaics. Issues such as these cannot be rectified without extensive postprocessing of the photographs.

Paleoseismic investigations also include topographic surveys of paleoseismic sites for context or offset geomorphic markers (e.g., stream channels and terraces) that provide information about earthquake-generated vertical and lateral displacements. Conventional methods for measuring these features include performing dense total station surveys. Such surveys may consume many person hours to acquire a sufficiently large number of point measurements from which an adequate surface model of the offset marker can be made.

Figure 2. Seismotectonic settings of the studied paleoseismic sites. The Landers fault scarp (LFS) produced by the 1992 Mw 7.3 Landers, California, earthquake and the trenches and channels crossing the San Andreas fault (SAF) in the Carrizo Plain (CP) were scanned with terrestrial laser scanning (TLS). Both airborne laser scanning (ALS) and TLS were used to scan precariously balanced rocks in the Granite Dells precarious rock zone (GDPRZ). Digital topographic data provide physiographic context and were accessed from the U.S. Geological Survey (USGS) Seamless Data Warehouse (http://seamless.usgs.gov/). Fault data were acquired and modified from the USGS Quaternary Fault and Fold Database (http://earthquake.usgs.gov/hazards/qfaults/).
Fault Scarp Formation and Degradation

Surface-rupturing earthquakes often produce initially subvertical fault scarps that degrade to their angle of repose over time by diffusive processes (e.g., Wallace, 1977; Hanks et al., 1984; Pierce and Colman, 1986; Stewart and Hancock, 1990; Arrowsmith and Rhodes, 1994; Arrowsmith et al., 1998; Hanks, 2000). Stream channels crossing these scarps are steepened and the response is more vigorous than those portions of the landscape not dominated by surface runoff. Typical scarp modification occurs in three stages (Arrowsmith and Rhodes, 2000): (1) set-up: pre-earthquake drainage network upslope of the scarp (Arrowsmith and Rhodes, 2000); (2) integration: reestablishment of a connected drainage network via channel capture and multiple incisions that occurred across the scarp; and (3) development: establishment of the channel flow paths that extend headward into the drainage basin. The rate at which each stage modifies the fault scarp depends on climate, the complexity of the scarp’s initial form, and the geometry of the drainage basin. Postearthquake monitoring of scarp degradation provides an essential step toward understanding the evolution of fault scarps. In addition, it helps evaluate the veracity of landscape evolution models to quantitatively extract temporal information about the recurrence of earthquakes from landscape form (e.g., Gilbert, 1877, 1909; Davis, 1892, 1899; Hanks et al., 1984; Hilley and Arrowsmith, 2001, 2003).

PBRs

Fragile geologic features such as PBRs (Fig. 3) provide information about the timing of past ground motions, their geographic extent, and their intensity (Brune, 1993a, 1993b, 1994, 1996; Brune and Whitney, 2000; Brune et al., 2006). The exposure time of the basal contact of a PBR with its pedestal is a proxy for the time since the PBR has remained balanced following its exhumation to the ground surface. Knowing the exposure time of the PBR pedestal aids in reconstructing its exhumation history using surface exposure dating methods (e.g., Bell et al., 1998; Stirling et al., 2002; Stirling and Anooshehpoor, 2006; Rood et al., 2008, 2009; Stirling, 2008). However, a number of geomorphic factors can affect the surface exposure ages of a PBR and its pedestal (Heimsath et al., 2001; Haddad, 2010), and therefore the time since the PBR has been balanced. For example, the rates of soil production from bedrock and downslope soil transport are controlled by geomorphic parameters such as hillslope gradient and upslope drainage area (Gilbert, 1877, 1909; Penck, 1953; Schumm, 1967; Kirkby, 1971). These parameters are typically not considered in cosmogenically determined exhumation histories of PBRs. Therefore, assessing the local geomorphic settings of PBRs is important to defining their utility as physical validators of past ground motions.

The 3D form and geometry of a PBR control its static stability and survivability during earthquakes (Purvance, 2005; Purvance et al., 2008a). Furthermore, the stability of a PBR provides information about the upper limits of past earthquake-induced ground motions that have occurred since the exposure of the PBR pedestal (e.g., Shi et al., 1996). Conventional methods for estimating the 3D form of a PBR involve photogrammetry (e.g., Anooshehpoor et al., 2007, 2009). In this process, paper targets are attached to the PBR and as many as hundreds of photographs are acquired from multiple viewpoints. Photogrammetric alignment techniques are then used to generate surface models of the PBR from which its 3D stability may be computed. A drawback to this method is its inability to accurately document the basal contact between the PBR and its pedestal. Because the geometry of the basal contact is integral to the rocking response of the PBR to ground motions (Purvance, 2005; Purvance et al., 2008a, 2008b), uncertainties can be introduced in applying measured seismic waveforms to PBRs (e.g., Hudnut et al., 2009a, 2009b).

METHODS

Case Study I: Carrizo Plain

Our first study site is located on the Bidart Fan in the Carrizo Plain section of the southern San Andreas fault (Figs. 2 and 4), which last ruptured in 1857. Data from more than 20 trenches that have been excavated since the late 1980s (Grant and Sieh, 1994; Akçiz et al., 2009, 2010) suggest that earthquakes along the San Andreas fault that ruptured the Carrizo Plain section were on average every 90 yr and caused surface displacements that ranged between ~1 and ~5.5 m, at least during the past 700 yr (Grant Ludwig et al., 2010; Zielke et al., 2010). These results call into question whether earthquake recurrence along the San Andreas fault strictly follows the characteristic earthquake model (e.g., Schwartz and Coppersmith, 1984; Sieh and Jahns, 1984). The first goal of this case study is to demonstrate the utility of TLS at efficiently producing an accurate base image of paleoseismic trench walls. The second goal of this case study is to demonstrate how TLS can aid in measuring very subtle geomorphic markers by scanning a low-relief channel that crosses the San Andreas fault.

We implemented two TLS setups at the Bidart Fan site in 2009. The first included scanning a 5-m-wide section of the southwest wall of a 3.5-m-deep fault-parallel trench that exposed the stratigraphy of an offset stream channel (BDT18 in Fig. 4). The second setup included scans of a stream channel that crosses the San Andreas fault (BDT19 in Fig. 4). Both setups employed the short-range Zoller + Fröhlich Imager 5006i TLS. Trench BDT18 was scanned at three equally spaced depths at which sets of four scans were performed. All scans were aligned to a single point cloud in the Zoller + Fröhlich LaserControl point cloud registration software. Scan alignments were aided by targets that were strategically placed in the trench so that at least four targets were...
visible from each scan viewpoint. Each scan also included the acquisition of high-resolution digital photographs of the trench walls. For BDT19, the scanner was mounted on a standard survey tripod and employed in 10 scan positions. All scans were registered using the Zoller + Fröhlich LaserControl software to a single point cloud that totaled more than \(21 \times 10^6\) points. A 0.1 m DEM was generated from the point cloud using IDW binning and a 1 m search radius. We also employed a low-altitude (~200 m above ground level) camera lofted by balloon to provide high-resolution color photographs of the channel.

### Case Study II: Landers Earthquake Fault Scarp

This case study presents our observations of the initial form and subsequent geomorphic modification of the Landers fault scarp with the goal of evaluating the TLS method for measuring the scarp’s erosion rates, upstream drainage network evolution, and knickzone migration rates nearly two decades after the 28 June 1992 Landers, California, earthquake (\(M_w 7.3\); Figs. 2 and 5). Repeat surveys of the scarp were begun three days following the earthquake, followed by surveys in late 1992, mid-1993, mid-1994, mid-1995, mid-1997, late 1998, and early 2000 using conventional fault scarp measurement techniques (e.g., morphologic mapping, ground stereo photography, topographic, and channel profile surveys with an optical total station; Arrowsmith and Rhodes, 1994, 2000). In mid-2008 we repeated our monitoring efforts using TLS scans of the scarp.

In 1992, we established a control network and over the years focused on several channels that crossed the scarp (Fig. 5). In 2008, we used a Reigl LPM 321 TLS to scan the study site; 11 scan positions were tied together with as many

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Figure 5. Terrestrial laser scan (TLS) (2008) of the Emerson fault zone surface rupture from the 1992 $M_w$ 7.3 Landers, California, earthquake (Fig. 2). (A) Overview of a 0.1 m digital elevation model (DEM) and hillshade showing ~20 m local relief along the drainage basins, the lower ends of which were elevated ~1 m by the vertical component of offset in the earthquake. (B) Gully 2 shot density map overlain on hillshade from the 0.1 m DEM showing high density of points on incising channel. (C) Gully 6 shot density map over hillshade from the 0.1 m DEM (see Fig. 11 for detailed analysis of erosion at this site). (D) 1998 balloon platform digital camera image georeferenced to the TLS DEM. Both C and D show the incising and headward cutting knickpoints. The DEM was prepared in the OpenTopography portal (http://www.opentopography.org).
as 18 control points, and $8.8 \times 10^6$ points were collected. Shot densities varied from $\sim 1$ to $3.8 \times 10^4$ m$^{-2}$ (Fig. 5). Given the absolute GPS control from 2008, we rotated and translated the prior survey data into the 2008 UTM zone 11 NAD83 (Universal Transverse Mercator, North American Datum) coordinate system using least squares ($<10$ cm error in the network adjustments). Despite the numerous advantages of the TLS system for topographic survey (e.g., scanning in a few seconds what normally takes an entire day to do manually), the TLS could not illuminate the walls or floors of the narrow (few decimeters wide), incised, and tortuous knick channels in the most rapidly eroding portions of the scarps. We augmented the scans in the knickpoint channels with kinematic GPS measures of points ($\sim 1$ cm accuracy) using a plumb pole. Our study focuses on Gully 6 (Fig. 5), which has the greatest erosion signal and highest quality network adjustment of pre-2008 survey points. We extracted 416,000 points from the point cloud (TLS and GPS) and compared them with the 100 points measured at Gully 6 in the summer of 1993 (after modest winter erosion of the fault scarp). These comparisons were made in both projected cross sections of the points with knowledge that the GPS points indicated the local minima along the knick channels and by subtracting 5 cm DEMs with the same grid node positions to produce a 1993–2008 erosion map.

**Case Study III: Precariously Balanced Rocks**

Our PBR study site is located in the Granite Dells precarious rock zone, central Arizona (Figs. 2 and 6). The primary PBR-forming rock unit is the Proterozoic Dells Granite (1.110–1.395 Ga; DeWitt et al., 2008; see Fig. 6). With the exception of local compositional variations,
the Dells Granite is a massive, medium- to coarse-grained locally porphyritic granite. It forms a prominent pediment surface that is dissected by angular, joint-controlled drainage networks. A large number of PBRs is in the Granite Dells precarious rock zone on bedrock hillslopes that flank these drainages (Haddad, 2010). The first goal of this case study is to use ALS-generated DEMs to document the geomorphic setting of PBRs; the second is to demonstrate the effectiveness of TLS in illuminating the basal contacts of PBRs.

Landscape Morphometry
ALS data for this site were collected by the National Center for Airborne Laser Mapping (NCALM) and covered the entirety of the Granite Dells precarious rock zone. The average aircraft elevation was 850 m above ground level. More than $350 \times 10^6$ laser returns were collected, covering ~35 km$^2$ and an average point density of 11.4 m$^{-2}$. A 0.25 m DEM was then generated from the ALS data using the IDW algorithm and a 1 m search radius (DeMers, 2002). Ground examinations were performed on 261 PBRs that were located using a handheld GPS unit ($\pm 2$ m horizontal accuracy). The resolution of the DEM was fine enough to locate only large (>1 m diameter) PBRs. However, small PBRs were severely smoothed out by the DEM algorithm and thus not recognizable without the aid of high-resolution color aerial photographs.

Local hillslope angles were computed from the DEM by fitting a plane to a $3 \times 3$ pixel computation window around each DEM and calculating the maximum slope value of the plane and assigning it to the node. The computation window then moves to the adjacent central cell and this process is repeated (DeMers, 2002). Stream channels were defined as grid cells using an upslope contributing area >100 m$^2$ and the $D^\infty$ flow routing algorithm (Tarboton, 1997). The local hillslope angle and contributing area of each PBR $x$-$y$ coordinate were then extracted from the gradient and contributing area rasters and plotted.

PBR Basal Contact Imaging
We used TLS to scan one of the surveyed PBRs in the Granite Dells precarious rock zone (Fig. 7). This provided a preliminary assessment of the PBR 3D static stability and tested the effectiveness of TLS in capturing the PBR basal contact. We used a tripod-mounted Riegl LPM 321 terrestrial laser scanner and scanned the PBR from six positions. All scans were aligned using the Riegl RiProfi le software and the aid of six reflective targets. The final point cloud totaled $\sim 3.4 \times 10^6$ points.

RESULTS AND DISCUSSION

Case Study I: Carrizo Plain

Trench BDT18 Scans
The final point cloud of our BDT18 trench scans totaled more than $129 \times 10^6$ points and was used to produce seamless color orthorectified base images of the trench walls (Fig. 8). Even though the scanner used a 5 megapixel (MP) digital camera, compared to our 8 MP point-and-shoot camera, with which we compared the results, overall image quality at 1:10 scale image printouts were not noticeably different (Fig. 8). While the TLS-produced images did not provide new insight or help to automate the identification of individual stratigraphic units, the efficiency and ease of orthomosaic production was greatly appreciated by the trench loggers. For example, the need for setting up reference grids was eliminated because the orthomosaics were automatically

Figure 7. (A) Location map of the terrestrial laser scanned (TLS) precarious balanced rock (PBR) (Fig. 6). It was scanned from six positions to fully capture its three-dimensional form. The underlying hillshade was prepared from a 0.25 m airborne laser scanning–generated digital elevation model. (B) Photographs of the TLS setup used for this PBR. Six 1.5-m-long polyvinyl chloride pipes with reflective tape attached to their tops were used as targets.
scaled by the scanner. Also, the subjectivity that is normally present when logging continuous contact traces that cross multiple mismatched photographs (by as much as 1–3 mm at the 1:10 scale) was significantly reduced (Fig. 8). Furthermore, total station surveys of contacts and locations of important features such as samples were not needed because the TLS-generated base image was locally georeferenced by the scanner. The paleoseismic logs, contacts, and sample locations can be placed in a global coordinate system such that a complete integration of these data with other paleoseismic data sets is possible. This high-accuracy geometric control is important for the 3D reconstruction of deformed features by retrodeforming offset channels and measuring vertical and horizontal components of displacement.

**Trench BDT19 Scans**

A 0.1 m DEM was prepared using the point cloud data obtained from the combined BDT19 scans (Fig. 9). The TLS-generated DEM is superior to the ALS-generated DEM in the clarity with which the stream channel is shown (cf. Figs. 4 and 9). An ~5 m dextral bend in the channel is observable from the TLS-generated DEM as it crosses the San Andreas fault. However, whether this bend is a result of the most recent earthquake to rupture this section of the San Andreas fault or a deflection that occurred after this earthquake is inconclusive. Our TLS-generated DEM will aid in planning future 3D excavations across this channel to investigate its stratigraphy and relationship with past earthquakes in greater detail. Unlike the setup inside the trenches described here, our TLS scans of the channel could not automatically assign an RGB value for each scan point to generate a photomosaic of the offset channel. Our inability to keep the camera in the shade at all times caused sharp contrasts in the digital images during 360° scans and did not provide enough RGB data points to be locally referenced. However, the TLS-generated DEM provided a detailed topographic surface to which our low-altitude balloon aerial photographs were georeferenced and draped (Fig. 10).

**Case Study II: Landers Earthquake Fault Scarp**

The 2008 topographic survey provides a spectacular view of the original forms and initial modifications of the 16-yr-old fault scarps produced in the Landers earthquake (Arrowsmith and Rhodes, 1994; Fig. 5). The discontinuous main and secondary scarps and the erosional responses to the ~1 m uplift of the northeastern block are well illustrated by the TLS data. Where runoff is poorly channelized, the scarps have begun to fail by block-scale and grain-scale diffusive processes. The largest changes are evident in the channels that cross the scarp. Gully 6 is representative of that response (Fig. 11); the knick channels are ~10–20 cm wide and have incised ~1 m into the displaced block, indicating a vertical incision rate of ~6.25 cm/yr of the knickpoint formed in Gully 6. The long profiles of the gully thalwegs now approach their pre-seismic forms. At Gully 6, the vertical displacement of the channel across the fault created a knickpoint that has moved upslope ~10 m.
from the scarp, which corresponds to a headward incision rate of ~62.5 cm/yr. The thalweg profile remains irregular, with the upslope knickpoint accommodating most of the relief change. Above the knickpoint, an erosional zone of a few tens of centimeters communicates the knickpoint erosion headward (e.g., Gardner, 1983).

**Case Study III: PBRs**

**Geomorphic Characterization of PBRs**

We plotted the values of local hillslope angle versus upslope contributing area for all of the surveyed PBRs (Fig. 12). Only slope-area values that were extracted from the PBR locations are plotted (green dots). The remaining slope-area values are binned into a 2D histogram to reduce clutter, and the density of the slope-area values is plotted as a color map. The surveyed PBRs are clustered in the bottom-right corner of slope-area space. Contributing areas per unit contour length for PBRs range between 5 and 30 m²/m. Local hillslope angles on which PBRs are situated range between 10° and 40°.

The stark difference between the slope-area plot of the PBR landscape and that of a soil-mantled landscape likely reflects the differences in the geomorphic processes that operate in either setting. Slope-area plots for soil-mantled landscapes exhibit a boomerang pattern that captures convexo-concave hill-slopes bounded by stream channel elements. This pattern consists of slope values that vary inversely with contributing area for convergent parts of the landscape, and vice versa for divergent landscape elements (Dietrich et al., 1992; Roering et al., 1999). However, the wide range of slope-area values that we extracted from our DEM is indicative of the etched topographic nature of the Granite Dells precariously rock zone, which is dominated by joint-controlled angular drainage networks and hillslope gradients that range between near vertical and near horizontal (e.g., Twidale, 1982). Therefore, our application of the slope-area threshold approach (e.g., Dietrich et al., 1992) must be made with caution because it assumes that the landscape is in dynamic denudational equilibrium. As a result, present-day geomorphic processes bounded by the landform process thresholds may not apply to our PBRs because they are preserved in preexisting etched landscapes. However, the slope-area approach allows us to extract fundamental information about the present-day geomorphic situation, and the preservation and exhumation histories of PBRs on a first-order basis.

The preservation potential of PBRs appears to be controlled by their location in a drainage basin. Most of the PBRs in the Granite Dells precariously rock zone are located in the upper reaches of catchments near drainage divides. This may indicate that the geomorphic conditions in the upper reaches of a drainage basin are conducive to forming and preserving PBRs. Because spatially variable soil production and transport rates affect the subsurface formation of corestones from bedrock (e.g., Heimsath et al., 2001), geomorphic rates in the upper reaches of catchments may be ideal for PBRs to survive subsurface chemical attack and their subsequent exhumation. After exhumation, the survival of the PBRs is controlled by the local geomorphology (e.g., hillslope gradient and upslope drainage area) during the evolution of the catchment. These geomorphic complexities illustrate that caution should be taken when PBR exhumation histories are reconstructed from surface exposure ages because these histories do not account for the overall geomorphic setting of the PBRs in a drainage basin, and thus do not provide a complete understanding of the processes that act to exhume the PBRs.

**PBR Basal Contact Assessment**

The 3D form of PBRs is captured with great detail that shows the intricacies of the basal contacts (Fig. 13). Closer examination of this contact shows that a significant overhang exists between the PBR width and its basal contact. Detailed inspection of this contact would not have been possible with the use of conventional photogrammetry. Therefore, an overestimation in the width of the basal contact of the PBR, and thus its stability, may have likely resulted from photogrammetric methods. Our scans, however, show that careful documentation of this contact is made possible using TLS and that uncertainty about the 3D stability of PBRs can be significantly reduced.

**CASE STUDY CONCLUSIONS**

Our TLS work in the Carrizo Plain demonstrates that, with careful consideration to the scanner setup and lighting conditions, TLS is an effective tool for imaging subtle paleoseismic features. TLS-generated images produce superior base maps (in both function and geometric accuracy) on which trenches can be logged when compared to their photomosaic counterparts. For both sets of scans, TLS proved to be an efficient alternative to conventional surveying techniques and base image production from mosaics of photographs. In addition to its analytical value, a significant potential for TLS is in its utility as a digital archival and educational tool in paleoseismic research. Digital archives of trench records will facilitate reviews of paleoseismic interpretations by other members of the paleoseismological community. Furthermore, digital records of the trenches provide valuable educational tools for students who are...
Figure 9. Comparison between airborne laser scanning (ALS) and terrestrial laser scanning (TLS) generated digital elevation models (DEMs) of BDT19 (see Fig. 4 for location). (A) A hillshade prepared from a 0.25 m ALS-generated DEM of BDT19. Dashed white arrows show the trace of the San Andreas fault (SAF). White half arrows indicate dextral motion along the SAF. (B) A color hillshade of a 0.1 m TLS-generated DEM of the same area shown in A. Linear local highs around BDT19 box trenches are spoil piles that were excavated from the trench. Other features are vehicles and people. The white dashed lines outline a bend in a channel that crosses the SAF. Solid white arrows indicate the directions of the oblique viewpoints in Figure 10.
engaged in paleoseismic trench interpretations and exercises.

Our results from the Landers fault scarp demonstrate that TLS is an effective tool for the rapid and detailed characterization of the original forms and evolution of earthquake-produced surface ruptures. Initially steep fault scarps begin to fail by block-scale and grain-scale diffusive processes. Vertical and headward incision rates of knickpoints in stream channels that cut across fault scarps can be as great as several centimeters/yr and several decimeters/yr, respectively. This underlines the importance of rapidly documenting surface ruptures using TLS prior to their complete geomorphic degradation. Recent scans of the El Mayor–Cucupah Mw 7.2 earthquake in northern Baja California (Oskin et al., 2010a, 2010b; Gold et al., 2012) alone and nested within ALS (Oskin et al., 2010a) have shown the exquisitely fine original character of the brittle deformation along the surface rupture. Repeat scans with TLS can also be used to measure the surface process response to the change in base level of local stream channels and postseismic surface deformation. Unlike our study, in which the original forms of scarps were represented crudely with manual surveys and roughly matched to decimeter-accuracy network adjustments, centimeter-accurate ultra-high-resolution repeat TLS will measure those changes in an unprecedented manner. Not only can the original forms and initial geomorphic modifications be measured, but postseismic changes can be measured in future high-resolution surface rupture studies with TLS (e.g., Wilkinson et al., 2010).

The ALS-derived DEMs allowed us to characterize PBRs geomorphically at the drainage basin scale. They showed that PBRs are preserved in the upper reaches of drainage basins on moderately steep hillslope gradients. Gentle hillslopes may not promote sufficient soil production rates to form the corestones prior to their exhumation as PBRs. Conversely, steep hillslopes may drive transport rates too high for the PBRs to remain preserved in a landscape. At a finer scale, surface and volumetric analyses from TLS may be used to validate the accuracy of 2D static stability estimators (e.g., Haddad, 2010) versus their 3D implementations (e.g., Purvance, 2005; Anooshehpoor et al., 2007, 2009). Because the stability and survivability of PBRs during ground motion events are controlled by the geometry of the PBR basal contact, TLS scans of PBRs provide valuable views into the complexity of the basal contact. Therefore, high-resolution TLS-derived surface models of PBRs can refine simulations of coseismic ground motions (e.g., Hudnut et al., 2009a, 2009b).

Figure 10. (A) Oblique views of a low-altitude aerial photograph of BDT19. The photograph was taken from a balloon-mounted digital camera and draped over the 0.1 m terrestrial laser scanning (TLS) generated digital elevation model (DEM) to provide topographic context. The San Andreas fault (SAF) is shown as a narrow zone of deformation (red). (B) Comparison between an oblique view of the aerial photograph and a photograph that was taken at ground level from the same viewing direction. Such three-dimensional representations of paleoseismic sites can be beneficial for peer reviews of paleoseismic interpretations, digital archival of trenches, and virtual field trips for educational activities.
SUMMARY

Paleoseismic research is significantly enhanced by the use of airborne and terrestrial lidar data. Our three case studies include examples of these data at different spatial scales. A nested combination of ALS and TLS will become an integral paleoseismic tool to study meter- and centimeter-scale fault-related deformation. In addition, ALS and TLS can refine our understanding of the geologic and geomorphic processes that act within the earthquake cycle by allowing us to study these processes at multiple spatiotemporal scales and at the appropriately fine (centimeter to decimeter) scales at which the relevant surface and deformational processes operate. The work presented here should aid paleoseismologists in planning ALS and/or TLS campaigns for future investigations.

A challenging yet important task in using a nested lidar approach for paleoseismic research is the multiscale integration of DEM preparation and distribution capabilities. Facilities such as OpenTopography (most of the data discussed here are available at http://www.opentopography.org) facilitate this task for ALS data and are spearheading the integration of TLS data sets to produce customized DEM products (e.g., Krishnan et al., 2011). The integration of these data sets with short-range photographic and multispectral imaging provides detailed material property information with excellent geometric control (e.g., Xu, 2000; Ragona et al., 2006). These integrated products enhance the interpretation and analysis of the 3D targets while allowing for their virtual reviews and digital archiving. This integration will therefore be an important step toward the management of scientifically meaningful lidar data sets that have high resolution, accuracy, density, and spatial coverage. Such data sets will become impor-

Figure 11. Point cloud map and repeat topographic survey at Gully 6 (see Fig. 5 for location). (A) Points extracted from the 2008 terrestrial laser scan (TLS) (black dots) were combined with kinematic global positioning system (GPS) measurements from the tortuous and narrow knick channels (blue dots) to represent the 2008 topographic surface and compared to the 1993 survey points (red dots). (B) A narrow swath of the point cloud data was extracted and projected to a common reference plane. The kinematic GPS points (blue dots) indicate the minimum elevations along the channel profile within the swath and show the erosion in 15 yr relative to the red points (1993 survey) and the black points showing relatively uneroded channel margins. (C) The 2008 digital elevation model (DEM) computed from the extracted TLS and GPS points (white dots) was subtracted from the 1993 survey points to produce an erosion map (5 cm/pixel). Maximum erosion in the 10–20-cm-wide knick channels is ~1 m and they have cut >10 m upstream between 1993 and 2008.
Figure 12. Hillslope angle versus upslope contributing area per unit contour length of landscape elements containing precariously balanced rocks (PBRs). Black dots are slope-area values for the landscapes plotted every 25th point. Green dots are slope-area values for each PBR computed from a 5 m airborne laser scanning (ALS) derived digital elevation model (DEM). Most of the surveyed PBRs are located in contributing areas between 5 and 30 m/m² and local hillslope angles between 10° and 40° (indicated by dashed blue lines).

Figure 13. Oblique views of the point cloud representing the precariously balanced rock (PBR) scanned using terrestrial laser scanning (TLS). The total point count shown is $\sim 3.4 \times 10^6$. TLS illuminates the three-dimensional complexities of the PBR form and its basal contact (outlined in white at right).
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Enhances student learning.

For example, bringing a surface rupture or an outcrop of the San Andreas fault into an educational setting in three dimensions significantly enhances student learning.

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Haddad et al.


