Applications of high-resolution topography in Earth science education

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ABSTRACT

High-resolution topography (HRT) provides Earth scientists the opportunity to measure landscapes at unprecedented meter to submeter resolutions. The spatial nature of HRT data and its active role in Earth science research complements education concepts such as visualization, Earth as a system, place-based learning, inquiry-based teaching, and active learning. There is a recognized need within the science education community for curricula that encourage spatial thinking and use two-dimensional and three-dimensional (3-D) environments (Hegarty, 2014; Kopcha et al., 2015). Despite the obvious applications of this technology to Earth science education, little work has been done to formally assess the effectiveness of HRT as an education tool. This discussion of HRT as a teaching tool for Earth science education is further motivated by science education initiatives and the science education community calling for integration of research-level data into the classroom (Taber et al., 2012). HRT data have the potential to address many of the established science educational standards, including the “Big Ideas” of the community-driven Earth Science Literacy Initiative (National Science Foundation, 2009) and the Next Generation Science Standards (NGSS) (Table 1).

To examine the effectiveness of HRT as a teaching tool, we conducted a study at Arizona State University (Tempe, Arizona, USA) in 2010 that tested the cognitive ability of undergraduate students to recognize the topographic signature of faulting and earthquakes in HRT. Based on these preliminary results, two targeted Earth science education resources were developed that use HRT to teach Earth systems. The goal of these developed resources was to determine whether undergraduate students would understand HRT, and if the addition of HRT within undergraduate Earth science laboratories would aid in the understanding of the earthquake cycle. The first is an exercise using HRT at the San Andreas fault (California, USA) to teach about landscape evolution and the earthquake cycle, core concepts in understanding plate tectonics.

INTRODUCTION

High-resolution topography (HRT; commonly derived from terrestrial or airborne lidar) has become an indispensable tool for providing insights into geologic phenomena such as faulting, earthquake and landslide hazards, surface morphology, ice sheet dynamics, and coastline evolution (Haagerud et al., 2003; Cunningham et al., 2006; Carter et al., 2007; Chan et al., 2007; Hilley and Arrowsmith, 2008; Arrowsmith and Zielke, 2009; Zielke et al., 2010; Meigs, 2013; Passalacqua et al., 2015). The diverse research and educational applications of HRT (which samples the ground at least once per square meter) have motivated the collection of data sets with large spatial extents spanning numerous geologic features. One important resource for free access to HRT data is the U.S. National Science Foundation (NSF)-funded OpenTopography Facility (www.opentopography.org). This web portal provides online access to >213,066 (as of October 2017) square kilometers of HRT data gathered by various groups for multiple applications, processing tools to generate derivative products and visualizations of the data, and educational products and tools for educators (Crosby et al., 2011; Krishnan et al., 2011).
TABLE 1. EDUCATION STANDARDS

<table>
<thead>
<tr>
<th>Science topic</th>
<th>Next Generation Science Standards performance expectations for high school (NGSS Lead States, 2013)</th>
<th>Earth Science Literacy Initiative (National Science Foundation, 2009)</th>
<th>Content in exemplary introductory geoscience textbooks*</th>
<th>How exploration of high-resolution topography links to these ideas†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Record of repeating earthquakes in the landscape</td>
<td>Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks (HS-ESS1-5).</td>
<td>• Earth is a continuously changing planet (Big Idea 4).</td>
<td>• Tectonic geomorphology of the San Andreas fault and offset stream channels as evidence of repeated earthquakes.</td>
<td>Fault system—specific acquisitions provide exquisite images and topography of western U.S. active faults, some of which cross heavily populated areas. Tectonic and geomorphic signals in topography are often readily apparent.</td>
</tr>
<tr>
<td></td>
<td>• Develop a model to illustrate how Earth’s internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features (HS-ESS2-1).</td>
<td>• Landscapes result from the dynamic interplay between processes that form and uplift new crust and processes that depress and break it down (Supporting Concept 4.7).</td>
<td>Fault types (normal, reverse, strike-slip) explained in terms of effect on landscape.</td>
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<td></td>
<td>• Analyze geoscience data to make the claim that one change to Earth’s surface can create feedbacks that cause changes to other Earth systems (HS-ESS2-2).</td>
<td>• Humans are threatened by Earth’s natural hazards (Big Idea 8).</td>
<td>Humans are threatened by Earth’s natural hazards (Big Idea 8).</td>
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</tr>
<tr>
<td></td>
<td>• Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes (HS-ESS2-5).</td>
<td></td>
<td>• Tectonic geomorphology of the San Andreas fault and offset stream channels as evidence of repeated earthquakes and long-term slip rates.</td>
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<td></td>
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<td>• Importance of knowledge of Earth science for mitigation of hazards.</td>
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<tr>
<td>Earthquake cycle</td>
<td>Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks (HS-ESS1-5).</td>
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<td></td>
<td>• Develop a model to illustrate how Earth’s internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features (HS-ESS2-1).</td>
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<tr>
<td></td>
<td>• Analyze geoscience data to make the claim that one change to Earth’s surface can create feedbacks that cause changes to other Earth systems (HS-ESS2-2).</td>
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<tr>
<td></td>
<td>• Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes (HS-ESS2-5).</td>
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<tr>
<td></td>
<td>• Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity (HS-ESS3-1).</td>
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<tr>
<td>Manifestation of plate tectonics along faults at and near plate boundaries</td>
<td>Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal rocks (HS-ESS1-5).</td>
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</tr>
<tr>
<td></td>
<td>• Develop a model to illustrate how Earth’s internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features (HS-ESS2-1).</td>
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<tr>
<td></td>
<td>• Analyze geoscience data to make the claim that one change to Earth’s surface can create feedbacks that cause changes to other Earth systems (HS-ESS2-2).</td>
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<tr>
<td></td>
<td>• Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity (HS-ESS3-1).</td>
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<tr>
<td>Geometry and processes of fluvial systems and hillslopes</td>
<td>Develop a model to illustrate how Earth’s internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features (HS-ESS2-1).</td>
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<tr>
<td></td>
<td>• Analyze geoscience data to make the claim that one change to Earth’s surface can create feedbacks that cause changes to other Earth systems (HS-ESS2-2).</td>
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<tr>
<td></td>
<td>• Plan and conduct an investigation of the properties of water and its effects on Earth materials and surface processes (HS-ESS2-5).</td>
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<tr>
<td></td>
<td>• Earth is the water planet (Big Idea 5).</td>
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<td></td>
<td>• Water shapes landscapes (Supporting Concept 5.6).</td>
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<tr>
<td>Earth as a system of which humans are a significant part</td>
<td>Develop a model to illustrate how Earth’s internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features (HS-ESS2-1).</td>
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<tr>
<td></td>
<td>• Analyze geoscience data to make the claim that one change to Earth’s surface can create feedbacks that cause changes to other Earth systems (HS-ESS2-2).</td>
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<tr>
<td></td>
<td>• Construct an explanation based on evidence for how the availability of natural resources, occurrence of natural hazards, and changes in climate have influenced human activity (HS-ESS3-1).</td>
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<td></td>
<td>• Evaluate or refine a technological solution that reduces impacts of human activities on natural systems (HS-ESS3-4).</td>
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<td></td>
<td>• Humans have become a significant agent of change on Earth (Big Idea 9).</td>
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<td></td>
<td>• Humans are the most significant agents of change in surficial Earth processes (Supporting Concept 9.3).</td>
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<tr>
<td></td>
<td>• Appreciation of effects of alteration of surface processes by humans.</td>
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<tr>
<td></td>
<td>• Importance of knowledge of Earth science for sustainability.</td>
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<tr>
<td></td>
<td>• Lidar data are recently gathered and will continue to be so. This data type measures topography, vegetation, and anthropogenic structures equally well and provides detailed and synoptic perspective. Data integration via digital globes and GIS enables students to spatially relate natural and human systems and assess effects and hazards.</td>
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</tbody>
</table>

Note: This table shows the alignment of lidar high-resolution topography (HRT) exploration with Earth science topics and educational standards. Important science topics that are outlined in the NGSS, ESLI, and geoscience textbooks can all be addressed through the exploration of HRT.

*For example, Tarbuck and Lutgens (2015); Marshak (2015); Reynolds et al. (2007); Chernicoff and Whitney (2007); Abbott (2008); and Keller and DeVecchio (2015).

†In addition to the basic power of active learning enabled by these data and the associated tools. Students can view imagery from anywhere where the data are available and find features of interest.

second is a video titled “Lidar: Illuminating Earthquake Hazards”, which was developed to provide an audio-visual introduction to using lidar-derived HRT for studying active tectonics. These resources demonstrate the value of HRT as a teaching tool for novice Earth science students and provide a template for additional resource development.

### BACKGROUND

#### Overview of Lidar and High-Resolution Topography

Lidar is a remote sensing technology capable of creating 3-D models of Earth's surface at the meter to submeter scale, enabling scientists to examine, interpret, and quantify Earth surface processes and landscapes (e.g., Carter et al., 2007; Crosby et al., 2011; Passalacqua et al., 2015). To show the inherent difference between lidar-derived imagery and other types of surface imagery, we show in Figure 1 a hillshade image from a lidar-derived digital elevation model with 1 m resolution (Fig. 1C) alongside a hillshade derived from the 10 m (Fig. 1B) and 30 m (Fig. 1A) U.S. Geological Survey (USGS) National Elevation Dataset (https://lta.cr.usgs.gov/NED) for the same spatial extent. One of the advantages of using high-resolution visualizations created from lidar data to study Earth's surface is that post-processing of data allows the “digital stripping” of vegetation and infrastructure to see the underlying topographic surface (Jaboyedoff et al., 2012; Meigs, 2013). This allows researchers to eliminate “distractors” and focus on the topographic surface.

One area of Earth science notably revolutionized by high-resolution (<1 m) topographic data is the study of earthquakes and faulting (e.g., Hudnut, et al., 2002; Haugerud et al., 2003; Sherrod et al., 2004; Carter et al., 2007; Kondo et al., 2008; Prentice et al., 2009; Arrowsmith and Zielke, 2009; Haddad, et al., 2012; Lin et al., 2013; Meigs, 2013; Nissen, et al., 2014; Donnellan et al., 2016). These data help scientists to map the locations of active faults, reconstruct fault offsets from past earthquakes, study landscape evolution by understanding the interaction between faulting and surface processes at the meter scale, and compute topographic differences in surveys made spanning events such as earthquakes and landslides. Similarly, allowing undergraduate Earth science students to use these HRT images will advance student understanding of Earth science concepts by removing visual distractions so that the student can focus on the topographic surface at the appropriate fine scale.

#### Meter-Scale High-Resolution Topography and Earth Science Education Standards

Traditionally, Earth science education has used a combination of verbal description and visual representation to communicate important concepts. Verbal description is most effective at communicating linear ideas such as methods, while visual representation is most effective at communicating nonlinear information such as real-world observations (Libarkin and Brick, 2002). Much research has been aimed at understanding how visual learning occurs (e.g., Ekstrom et al., 1976; Leach and Gull, 1990; Baker and Dwyer, 2000; Maltese et al., 2015) and what types of visual cues are best for promoting visual learning (Braukmann and Pedras, 1993; Lin and Atkinson, 2011; Jamet, 2014). Recent studies in the education community have demonstrated the importance of spatial learning and visualizations as an aid to science education (Kali and Orion, 1996; Ryoo and Linn, 2012; McElhaney et al., 2015). It has also become

![Figure 1. Variable spatial resolution. These images cover the same section of the San Andreas fault in northern California (USA [38.504093, –123.221017]). (A,B) U.S. Geological Survey digital elevation models (DEMs) at 30 m per pixel (A) and 10 m per pixel (B) (National Elevation Dataset, https://lta.cr.usgs.gov/NED). (C) DEM created using lidar data with a resolution of 2 m per pixel (EarthScope Northern California LiDAR Project, doi:10.5069/G9057CV2).](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/13/6/1887/3990862/1887.pdf)
increasingly apparent that using first-hand data and graphs in science learning can influence comprehension and understanding within the classroom (Friel et al., 2001; Hug and McNeill, 2008; Ryoo and Linn, 2012). Little work has been done examining what types of images are most suitable for teaching basic geologic concepts, in particular, topographic or landscape feature identification. Because of its broad applicability in these areas, it is natural to evaluate HRT in Earth science education to enhance visual learning.

The integration of HRT into the broad vision for Earth science education is motivated by the science literacy initiatives from several educational sources. For example, the 2010 Earth Science Literacy Initiative “Big Ideas” have outlined the importance of introducing Earth as both a continuously changing planet and a natural hazard to humans. The NGSS outline the importance of learning about plate tectonics and large-scale system interactions (NGSS Lead States, 2013). Although the NGSS are learning standards for grades K–12, it is important to evaluate and understand these recent standards particularly when thinking about lower-level undergraduate education as there is often concept overlap from high school into the first years of undergraduate education. The NGSS K–12 concepts also provide an excellent foundation for undergraduate Earth science education using the 3-D learning style that combines disciplinary core ideas, crosscutting concepts, and practices—a style easily adaptable to undergraduate classrooms.

Science topics such as “record of repeating earthquakes in the landscape” and “geometry and processes of fluvial systems and hillslopes” are topics that are important across various science standards and undergraduate textbooks (Table 1). HRT can be used to address each of the concepts and others outlined in these Earth science educational standard rubrics. For example, the NGSS high school performance expectations ask students to “analyze geoscience data to make the claim that one change to Earth’s surface can create feedbacks that cause changes to other Earth systems.” Students can analyze HRT for Earth’s surface changes in order to make evidence-based claims about how and why these changes occurred. By using HRT, a student can be both analyzing data and constructing a scientific model using concepts from geography, hydrology, climate, ecology, and other scientific fields in order to interpret the history of the landscape. Because a major emphasis of the NGSS is to use science and engineering practices alongside crosscutting concepts in order to gain an understanding of various disciplinary core ideas, using HRT can be seen as a beneficial addition to curricula and learning tools. HRT can help link ideas and address standards through visual exploration of the landscape at the appropriate fine scale (meter to submeter) for each of these Earth science topics.

The insight that HRT provides to Earth science education covers a wide variety of important Earth science topics beyond earthquakes and plate tectonics. Tools for using HRT have been built to facilitate exploration, measurement, and analysis. Briefly, HRT can be used in the study of the geometry and processes of fluvial systems and hillslopes, as well as the study of volcanic activity (e.g., Mount St. Helens [Washington State, USA] dome growth in repeat lidar), landslide hazard analysis, coastline evolution, and human activity as a significant agent of change on Earth (White and Wang, 2003; Vaughan et al., 2005; James et al., 2007; Jaboyedoff et al., 2012). The thousands of square kilometers of freely available lidar HRT along plate boundaries and active faults can aid students in investigations of the earthquake cycle, plate boundaries, and natural hazards (Prentice et al., 2009; Crosby et al., 2011; Crosby, 2012). Although not every region of the world has HRT yet, vast amounts of data are being collected, and many of these data sets are accessible to students and educators online.

High-Resolution Topography Resources and Availability

In the past 20 yr, the so called “lidar revolution” (Meigs, 2013) has instigated the collection and use of lidar topography data by many public agencies and organizations. The broad multidisciplinary application encourages the sharing of data. An important aspect enabling research data use in educational curricula is free access. In the U.S., there are several portals available to distribute free HRT data including the USGS’s Earth Explorer (http://earthexplorer.usgs.gov/), the National Oceanic and Atmospheric Administration’s (NOAA) Digital Access Viewer (http://www.coast.noaa.gov/dataviewer/), and others run by state governmental agencies. In the academic Earth sciences, OpenTopography (http://www.opentopography.org/) is the most visible source for high-resolution lidar topography because it allows free access to research-oriented lidar point cloud data, derived products, tools, and educational resources for the scientific and educational community. One notable educational resource at OpenTopography is the OpenLandform catalog, a collection of geologic features within HRT such as faults, landslides, and volcanoes. For more information about the OpenLandform catalog, see the Supplemental Materials, section E.1.

EXPLORATORY STUDY

Background

Experts and novices looking at a photo will subdivide a landscape into categories, but novices do not have the experience to subdivide the area into geologically relevant subsections (Manduca et al., 2008). An eye-tracking study designed to see how students manage distractors in images found that they would focus primarily on the distractor and not on the entire image (Coyan et al., 2008). Thus, when teaching geologic concepts to novice learners using images, it may be advantageous to remove distractors such as land use and vegetation patterns to allow students to focus entirely on the underlying landscape, improving their ability to subdivide the area into geologically relevant topographic features. In this study, we show that lidar-derived HRT data displayed as a hillshade, as opposed to more traditional aerial photography (in this case, the base imagery of Google Earth), allows novice learners to focus
more directly on the landscape, enabling faster and more accurate interpretations of geologic features.

Methods

Images of two different parts of the San Andreas fault were utilized in this experiment: the Wallace Creek (WC) and San Bernardino (SB) areas (Fig. 2). The Wallace Creek area of the San Andreas fault in central California is a textbook example of strike-slip faulting (Wallace, 1968; Sieh and Jahns, 1984; Sieh et al., 1989). This site was selected because of spectacular fault expression and to support the instructive educational materials produced in relation to this location, like the Wallace Creek Interpretive Trail guide produced by the Southern California Earthquake Center (http://scecinfo.usc.edu/wallacecreek/). The area has minimal infrastructure, distinctive vegetation patterns, and clear right-lateral stream offsets (Figs. 2A and 2B).

The San Bernardino, southern California, area image used in this study shows a larger and more complex area (Figs. 2C and 2D). There is significant

Figure 2. Imagery given to students for distractor study. (A,B) Wallace Creek at the San Andreas fault (SAF, California, USA [35.271681, –119.827691]) shown in both Google Earth imagery (A) and lidar-derived hillshade (B). (C,D) The SAF near San Bernardino (34.216817, –117.364555) shown in both Google Earth imagery (C) and lidar-derived hillshade (D). The hillshades have significantly less distracting landscape-relevant detail. The lidar image of the Wallace Creek area (B) was slightly modified by executing a “smart blur” in Adobe Photoshop software in order to diminish the “corduroy” lidar data collection artifact. The resulting image looks slightly softer in the southwestern corner, but no major structures or landscape features were altered by the modification.
infrastructure, including houses, roads, parking lots, and water tanks, as well as
more diverse types of land use. The San Andreas fault has a more complicated
topographic expression, making it harder to distinguish than at Wallace Creek.
This site was chosen because of the diverse land use, different types of infrastruc-
ture, and subtle but clear fault expression.

Forty-six non-major geology students were each given one of the four images
of the San Andreas fault (Figs. 2A–2D). Class 1 (n = 21) looked at lidar-derived
hillshades. Part of the class (n = 12) was given a lidar hillshade of the Wallace
Creek area of the San Andreas fault in central California (Fig. 2B) and the other
part (n = 9) was given lidar-derived HRT of the fault in the San Bernardino area
of southern California (Fig. 2D). Class 2 (n = 25) was given Google Earth images. Part
of the class (n = 10) was given a Google Earth image of the Wallace Creek area
(Fig. 2A) while the other part (n = 15) received the Google Earth image of the San
Bernardino area (Fig. 2C). Each student was asked a series of questions about
their observations of the image. They were also asked to support their answers
by annotating directly on the images. They were given no information about the
image location or about fault-related landforms. For additional methodological
information, see the Supplementary Material [footnote 1].

Results

Students were able to identify familiar landscape features, such as moun-
tains, rivers, and valleys, on both the lidar HRT and the Google Earth images.
However, when looking at Google Earth images, students selected distractors
such as land use, vegetation, and infrastructure rather than the landscape it-
self. This is substantiated by a 40%–70% increase in students describing land-
scape or topographic features as the most prominent features in the image
when looking at HRT images (Table 2). The features labeled directly on the
images support this. When the students were asked to list features that they
recognized (geologic or otherwise), there was a 30%–40% decrease in the
mention of non-landscape-related features (houses, roads, water tanks, cars,
trees, shrubs, fences) when looking at the HRT. In both the San Bernardino
and Wallace Creek areas, students looking at HRT images were able to more
accurately identify faults (as much as 38%) compared with students looking
at Google Earth images, despite being given no additional information about
faulting, fault landforms, or fault identification. The results of this study pro-
vided motivation to design undergraduate educational tools that utilized HRT

<table>
<thead>
<tr>
<th>Total participants</th>
<th>WC Google Earth</th>
<th>WC lidar</th>
<th>SB Google Earth</th>
<th>SB lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students’ previous map experience</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lots</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>Some</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>None</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

A. Percentage of total number of students who noticed each feature type in the imagery

<table>
<thead>
<tr>
<th></th>
<th>WC Google Earth</th>
<th>WC lidar</th>
<th>SB Google Earth</th>
<th>SB lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landscape</td>
<td>20.0%</td>
<td>58.3%</td>
<td>60.0%</td>
<td>66.7%</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>10.0%</td>
<td>0.0%</td>
<td>26.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Land Use/Vegetation</td>
<td>80.0%</td>
<td>8.3%</td>
<td>6.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Other</td>
<td>0.0%</td>
<td>0.0%</td>
<td>6.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fault</td>
<td>0.0%</td>
<td>16.7%</td>
<td>0.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

B. Percentage of students who recognized features in the imagery

<table>
<thead>
<tr>
<th></th>
<th>WC Google Earth</th>
<th>WC lidar</th>
<th>SB Google Earth</th>
<th>SB lidar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountains and/or ridges</td>
<td>30.0%</td>
<td>58.3%</td>
<td>100.0%</td>
<td>88.9%</td>
</tr>
<tr>
<td>Valleys</td>
<td>40.0%</td>
<td>75.0%</td>
<td>53.3%</td>
<td>77.8%</td>
</tr>
<tr>
<td>Structures</td>
<td>0.0%</td>
<td>0.0%</td>
<td>73.3%</td>
<td>22.2%</td>
</tr>
<tr>
<td>Roads</td>
<td>30.0%</td>
<td>0.0%</td>
<td>66.7%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fault</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marked the fault</td>
<td>20.0%</td>
<td>58.3%</td>
<td>0.0%</td>
<td>11.1%</td>
</tr>
<tr>
<td>Marked a road as the fault</td>
<td>20.0%</td>
<td>0.0%</td>
<td>13.3%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Marked a valley or ridge as the fault</td>
<td>60.0%</td>
<td>41.7%</td>
<td>20.0%</td>
<td>88.9%</td>
</tr>
</tbody>
</table>

Note: The table shows the results for students who looked at Google Earth versus lidar imagery at Wallace Creek (WC) and San Bernardino (SB) locations on the San Andreas fault (California, USA). See Figure 2 for the imagery and see the Supplemental Materials [see text footnote 1] for assessment questions.
for teaching Earth science concepts. The increase in a student’s ability to identify topographic features in HRT over Google Earth imagery demonstrates that HRT is appropriate for classroom activities that require the evaluation and interpretation of landscape features.

NEWLY DEVELOPED EDUCATIONAL CONTENT STUDIES

Motivated by the results of the exploratory study, new educational resources using HRT have been developed. An introductory video on lidar and an undergraduate-level activity addressing earthquake cycle concepts were created and assessed in the classroom. The educational video, “Lidar: Illuminating Earthquake Hazards” (available for free viewing online at http://www.youtube.com/watch?v=dwGT9B4s6lw), and the San Andreas fault earthquake cycle structured activity are described in detail here. Both of these resources were developed and tested in the classroom to determine (1) whether the video could teach undergraduate novice Earth science students about lidar HRT and its uses for studying earthquakes and (2) whether the San Andreas fault earthquake cycle activity could increase their understanding of landscape evolution and the earthquake cycle through the use of HRT.

“Lidar: Illuminating Earthquake Hazards” Video

Concisely and accurately defining lidar topography and its uses in Earth science motivated the development of the video “Lidar: Illuminating Earthquake Hazards.” The primary goal of producing the video was to create a freely available resource that introduced airborne lidar and its applications to Earth science, specifically to the study of faulting and earthquakes.

The development of the video included a team of Earth scientists to ensure the accuracy of the narration content. Using a combination of videography and computer animation, the video was filmed, edited, and completed in the summer of 2010 at the Southern California Earthquake Center at the University of Southern California. Figure 3 shows examples of video content.

Figure 3. Content examples from the “Lidar: Illuminating Earthquake Hazards” video. (A) Frame from an animation demonstrating how aerial lidar is collected (from Ian Madin, Oregon Department of Geology and Mineral Industries). (B) Comparison of lidar-derived three-dimensional topography with video footage. (C) Clip from an interview with Dr. Ken Hudnut (U.S. Geological Survey) explaining strike-slip fault behavior.
The “Lidar: Illuminating Earthquake Hazards” video is composed of several parts. The first part is an introduction to earthquake science and the motivation for studying faulting and active tectonics. This section introduces the need for the most up-to-date technology for studying earthquakes because of the hazard that earthquakes pose. The second part of the video is an introduction to lidar technology and data collection. Key concepts are introduced, terminology is defined, and examples of technology and data collection are shown (Fig. 3A). Lidar digital elevation models and hillshades are compared alongside field views of the landscape demonstrating the versatility and usefulness of lidar’s 3-D capability (Fig. 3B). The next part of the video demonstrates the importance of lidar topography for studying earthquakes through interviews with earthquake scientists who use lidar (Fig. 3C).

San Andreas Fault Earthquake Cycle Exercise (Structured Activity)

The educational motivation for developing the San Andreas fault earthquake (SAF EQ) cycle activity is multifaceted. There is a need for an undergraduate-level geology classroom activity that teaches the earthquake cycle and elastic rebound theory (Robinson, 2011). Lidar HRT of Wallace Creek, a channel offset repeatedly by earthquakes along the right-lateral strike-slip San Andreas, allows for easy identification of the geomorphologic features associated with fault movement due to its visual simplicity and the resolution at which the landscape is represented (Fig. 4). The SAF EQ cycle activity is a hands-on exercise that teaches students about the earthquake cycle, strain accumulation and release, and earthquake recurrence intervals (Fig. 5). For additional discussion on the science motivation, see the Supplemental Materials [footnote 1].

Figure 4. Hillshade of lidar topography of Wallace Creek along the San Andreas fault in the Carrizo Plain, California (USA [35.271681, –119.827691]) with annotated fault zone tectonic geomorphologic features (cf. Sieh and Jahns, 1984; Sieh and Wallace, 1989). Such high-resolution data allow for easy visual identification of features that indicate strike-slip faulting such as linear ridges, scarps, etc.
Figure 5. San Andreas fault earthquake cycle activity. (A–D) Evolution of the topography at Wallace Creek (California, USA [35.271681, −119.827691]) using lidar topography as a base (cf. Sieh and Jahns, 1984). Repeated earthquakes along the San Andreas fault have offset the creek creating its bend. Red line in panels A–C shows the location of strike-slip movement along the fault at the surface. (C) The creek has abandoned the original channel and carved a new path for water flow. (D) The creek’s present condition. (E) An example of using lidar within the Google Earth environment. Students can use Google Earth to measure various offsets as part of the activity. (F) GPS station velocity vector data as part of the activity (data used is from UNAVCO Plate Boundary Observatory, http://pbo.unavco.org/data/gps). Students use the vectors to measure the strain accumulation rate across the San Andreas fault plate boundary spanning the Wallace Creek section.
The SAF EQ cycle activity is divided into two parts. The first part uses Google Earth as a platform to view B4 (named B4 to reflect that it is lidar data collected before the expected fault rupture) lidar-derived high-resolution topography images of the San Andreas fault in California at Wallace Creek (Bevis, et al., 2005). Students use the “measure” tool in Google Earth to measure the main offset at Wallace Creek (Fig. 5E), along with smaller offsets south of the main creek that would be difficult to see without HRT. Students are told that the age of the creek is 3700 yr (Sieh and Jahns, 1984) and are then asked to calculate the long-term slip rate along the San Andreas fault at Wallace Creek. The second part of the SAF EQ cycle activity uses EarthScope Plate Boundary Observatory GPS station velocity data (e.g., http://pboweb.unavco.org/products/velocity/pbo_final_frame.kmz and http://www.unavco.org/software/visualization/GPS-Velocity-Viewer/GPS-Velocity-Viewer.html) which students plot graphically and then use to calculate the strain accumulation rate along the San Andreas fault spanning the Wallace Creek section (Fig. 5F).

Methods and Analysis

In April 2011, both resources were assessed for effectiveness in freshman-level introductory geology labs at Arizona State University (ASU). The introductory lab is a supplementary for-credit lab to the Introduction to Geology lecture counterpart in which students learn the basics about minerals, the rock cycle, plate tectonics, geologic time, geologic hazards such as earthquakes and volcanoes, and other basic topics. About 250 students in 2011 took this introductory course at ASU. In order to calculate an appropriate sample size, a confidence level of 95% allowing for a margin of error at 10% estimates a statistically appropriate sample size to be 70 students. This experiment pulled from a total pool of 133 students: 45 in the control group and 88 in the experimental group. These students represent typical non-major Earth science students at ASU. According to the National Center for Education Statistics (2011), the ASU undergraduate student body is 52% white, and 19% Hispanic or Latino of the total population. ASU students are predominantly full-time (91%) and age 24 or under (88%). Fifty-seven percent (57%) are male.

We may assume that results here could be duplicated at other similar universities across the United States. Testing was administered over a two-week period in lab sections that met once a week. The control group consisted of three sections of the introductory geology lab (course GLG 103) under the same lab teaching assistant (TA). The experimental group consisted of four sections of the same introductory geology lab (GLG 103) but under a different lab TA. Although the lab TAs were different, the lab manual and methodology for each lab were the same, maximizing the consistency of the assessment.

Both the control and experimental groups were administered the SAF EQ cycle activity assessment and the “Lidar: Illuminating Earthquake Hazards” video assessment (discussed below) during week 1 as pretests. No additional activities were given to either the control or experimental groups during week 1. During week 2, control groups were not shown the video or asked to complete the SAF EQ cycle exercise. The experimental group students, on the other hand, were shown the “Lidar: Illuminating Earthquake Hazards” video and then administered the posttest assessment for the video. After completion of the assessment, experimental group students worked together on the SAF EQ cycle exercise in groups of three to four. After completion of the exercise, they were administered the SAF EQ cycle exercise posttest assessment.

The assessment tools designed for both the video and the SAF EQ cycle exercise were created in order to test our research questions. Both tests were short (the lidar video quiz was 10 questions for 10 points total, and the SAF EQ cycle quiz was 6 questions for 6 points total) and were multiple choice. The tests were designed to take less than ten minutes each, with one correct answer and at least three other distractors. Questions and phrasing used minimal “jargon” outside of what was presented and defined within the activity and video in order to minimize the amount of outside knowledge of the field needed to complete the assessment. The tests were given in multiple class-rooms (each ~15–25 students) with two different TAs in order to ensure repeatable results. Test questions were specifically aimed at gaining an in-depth analysis of a student’s understanding of the learning goals.

For the SAF EQ cycle exercise, the assessment tool had questions aimed at a student’s increased knowledge of the Wallace Creek landscape evolution during repeated ground-rupturing earthquakes. One of the questions, “How was the landscape at Wallace Creek formed?” (see the Supplemental Materials [footnote 1]), was a key part of the quiz, aimed at assessing a student’s understanding of the earthquake cycle as it pertains to the San Andreas fault at Wallace Creek after the completion of the SAF EQ cycle exercise.

For the video, we assessed if the video increased an undergraduate Earth science student’s understanding about lidar and how it is used to study earthquakes. For the SAF EQ cycle exercise, we assessed if the activity (which incorporates HRT) increased an understanding about the earthquake cycle and how landscapes change by repeating earthquakes.

In order to assess understanding, the lidar video assessment included multiple choice questions such as the following, shown with the answer choices: What is lidar as it is used for the study of earthquakes?

- High-resolution aerial photography that produces very detailed topographic maps. (correct answer)
- A remote-sensing technology that produces very detailed topographic maps.
- A remote-sensing technology that uses both satellites and radar.
- High-resolution aerial photography that uses both satellites and radar. Which of the following is the BEST reason to use lidar for the study of earthquakes?
- The data can be used to image the Earth’s surface at a resolution of a meter or smaller. (correct answer)
- The data can create 3-D models of the Earth’s surface in real color with hillshading.
- The data can create 3-D models of the Earth’s surface with exaggerated topography.

The tests were designed to take less than ten minutes each, with one correct answer and at least three other distractors. Questions and phrasing used minimal “jargon” outside of what was presented and defined within the activity and video in order to minimize the amount of outside knowledge of the field needed to complete the assessment. The tests were given in multiple class-rooms (each ~15–25 students) with two different TAs in order to ensure repeatable results. Test questions were specifically aimed at gaining an in-depth analysis of a student’s understanding of the learning goals.

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- The data can create 3-D models of the Earth’s surface in real color with hillshading.
- The data can create 3-D models of the Earth’s surface with exaggerated topography.
• The data can be used to image the Earth's surface at a resolution of millimeters or smaller.

See the full assessment in the Supplemental Materials [footnote 1]. These select questions test the understanding of the student's knowledge gained about lidar as it differs from other technologies, and how or why it is used for the study of earthquakes (checking their understanding that the submeter scale at which lidar data images Earth's surface is important). Students were given the same assessment tool before and after they watched the video in order to determine if their understanding increased significantly by watching video content.

Results

Both assessment tools are valid in that the questions were designed to reflect the learning goals for each tool (the SAF EQ cycle exercise and the lidar video). Questions were phrased so that the correct answer would not be intuitive to those who had not completed the exercise or video. The experimental group's superior performance over the control group on the posttest quiz speaks to the validity of the assessment tool as a good predictor of a student's increased knowledge of the learning goals (Table 3).

Results show an increase in experimental group participant scores for both the lidar video assessment and SAF EQ cycle assessments from pre- to posttest (Table 3). Participant scores for the lidar video assessment experimental group (n = 88) ranged between 0 and 6 correct out of a possible 10 on the pretest (standard deviation for the fraction of questions correctly answered [SD] = 0.18) and between 1 and 9 correct on the posttest (SD = 0.22), with a mean fraction of the questions answered correctly of 0.32 for the pretest and 0.62 for the posttest. A one-tailed t-test was performed on the results in order to evaluate the relationship between the pre- and posttests and determine statistical significance of the score increase. The t value was shown to be 0.41 with a p value of 0.34. The effect size using Cohen's d was 0.82 at a 95% confidence interval. The score here is not statistically significant using the t-test, but the effect size is still large. This will be addressed further in the Discussion section. The control group for the SAF EQ cycle exercise did not show a significant increase in scores, which is expected.

### DISCUSSION

This exploratory study demonstrates that HRT data effectively allow novice learners to more quickly and easily identify important landscape features. Proper identification of these features aids in geologic interpretation and allows for a better understanding of landscape evolution. The decrease in the student's mention of non-landscape-related features when looking at the HRT imagery suggests that students are less distracted by elements in the landscape such as infrastructure and land-use patterns on the HRT images. The increase in a student's ability to correctly identify faults when using HRT implies that they have an intuitive knowledge of the general concept of a fault and how to recognize its expression in the topography. Thus, when distractors are stripped away, students are able to focus entirely on the topography and more effectively use their previous knowledge or geologic intuition to correctly identify particular landscape features.

The lidar video assessment showed that this tool gave students a statistically significant increase in understanding of lidar collection and the applications of HRT to studying earthquakes. There was not a strong increase in

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Note: The table shows the one-tailed t-test performed to determine statistical significance for score increases. For assessment questions, refer to the Supplemental Materials [see text footnote 1]. n—sample size, df—degrees of freedom. Statistical parameters are values for the fraction of questions answered correctly.
assessments scores for the SAF EQ cycle exercise assessment. After reevaluation of the assessment questions for the SAF EQ cycle exercise, some of the assessment questions may not have been phrased appropriately in order to test the hypothesis that the exercise increased the student’s understanding of landscape evolution and the earthquake cycle. However, one question on the assessment asked students how the landscape at Wallace Creek was formed. On this question (question 2), students showed a 38% increase in understanding overall. Students understood that the creek itself had been repeatedly offset by earthquakes along the San Andreas fault, encompassing the concepts of landscape evolution and the earthquake cycle. As this question addresses our research focus of determining whether the activity would increase a student’s understanding of landscape evolution and the earthquake cycle using HRT, we are confident that the SAF EQ cycle exercise is an appropriate model for the implementation of HRT into undergraduate Earth science educational tools. This activity, paired with GPS velocity data analysis, allowed students to gain an overall understanding of the earthquake cycle by comparing the long-term slip rate at Wallace Creek with the short-term strain accumulation. Using lidar HRT to remove distractors alongside recent GPS data enhances exploration of the earthquake cycle.

The scope of this study was limited to a rather small student body. In the initial study, the sample size was small but the results seemed to be repeatable (Table 2). Although all student lab sections used in the lidar video and SAF EQ cycle exercise study showed score increases in the experimental group compared with the control group, more work may be done in order to assess the validity of the instruments. Further refinement of the assessment tools and more classroom testing could help to verify the validity. The assessment tools used have a few shortcomings in that the questions asked might not have been phrased in a way that clearly accentuate learning goals. Future studies on HRT educational tools should use larger sample sizes from a broad range of universities, and assessment tools refined to reflect learning goals by using several sets of questions for each learning goal. However, this initial study has provided valuable insight into the benefits of using HRT in undergraduate classrooms.

The possible applications of using HRT for education are far reaching. The ability to use these freely available data sets within free software such as Google Earth not only makes the data accessible to non-expert science users and graduate and undergraduate students, it also makes the data accessible to K-12 students and the general public in a way that extends the impact of a research-oriented data set (Crosby, 2012). As lidar HRT becomes increasingly common in research and industry, the applications to education are also broadened. The ability for an Earth science student to think spatially has been emphasized by Earth science educators (e.g., Ormand et al., 2014), and lidar or other HRT imagery allows for the possibility to view landscapes and think spatially without being distracted by infrastructure or vegetation (Crosby, 2012). Although much of the content developed so far has used hillshade images of lidar topography, lidar data have much more analytical information associated with them than these hillshade “pretty pictures.” The xyz point cloud data could provide an opportunity for 3-D analysis of landscapes, tree canopy, and the built environment. Recent research advances into HRT data and availability of repeat lidar have excellent classroom potential. Structure from motion, or SfM, is a photogrammetric technique that uses overlapping photos taken from different positions to create a HRT model. SfM photos can be taken from the ground of something as simple as an outcrop (Bemis et al., 2014), or from an airborne platform like a balloon (Johnson et al., 2014) or unmanned aerial vehicle (UAV). The value in using this technique in teaching is the ability for a student to approach a problem, collect data, process the data, and perform an analysis, all at a low cost. Repeat lidar could also provide room for educational activities that look at long-term landscape analysis of landslides (Travelletti et al., 2014) or landscape evolution before and after a ground-rupturing earthquake (e.g., Nissen, et al., 2012, 2014). There is an unprecedented opportunity for HRT to be integrated the educational materials for Earth science—a field where the ability to think spatially and with a process perspective is imperative.

Conclusions

The results of these studies show that integrating HRT into Earth science educational resources helps make Earth science concepts more conceptually accessible to students. The Earth science education community should consider integrating HRT into future resource development. The exploratory study shows that an undergraduate Earth science student’s ability to identify landscape features and utilize their spatial and geology skills is greatly increased when using HRT over traditional aerial photography. The opportunity to address important Earth science topics with HRT such as the earthquake cycle and the record of repeating earthquakes in the landscape (and others outlined in Table 1) is reinforced within the “Lidar: Illuminating Earthquake Hazards” video and the SAF EQ cycle exercise. These are templates for the development of additional undergraduate educational content integrating lidar-derived HRT into Earth science learning. This also serves as a starting point for the integration of HRT into all educational platforms that tackle Earth science topics, including K-12 education and informal education. The increasing volume of aerial lidar data that are freely available online through OpenTopography and elsewhere makes it an easy-to-use, accessible, and valuable visualization tool for scientists, educators, and students.

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