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Pilot Study Using the Augmented Reality Sandbox to Teach Topographic Maps and Surficial Processes in Introductory Geology Labs

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ABSTRACT

Spatial thinking is often challenging for introductory geology students. A pilot study using the Augmented Reality sandbox (AR sandbox) suggests it can be a powerful tool for bridging the gap between two-dimensional (2D) representations and real landscapes, as well as enhancing the spatial thinking and modeling abilities of students. The AR sandbox involves a real box of sand with virtual contour lines and a water flow model created using a three-dimensional (3D) scanning camera, visualization software, and a projector. It was used in undergraduate, physical geology courses to teach topographic maps and surficial features and processes. The instructor demonstrated topographic concepts (contour lines, topographic profiles, etc.), and students engaged in model building of coastal and fluvial environments (drainage basins, cutoffs, longshore transport, sea-level rise, spits, flooding, etc.). The virtual water flow model was used to illustrate water flow dynamics on surface features. With the AR sandbox connected to a computer monitor, students could simultaneously see 3D landscapes in the sandbox and their corresponding 2D images on the monitor. Students used camera phones to capture landscape models they built and submitted them via e-mail for grading. Exit surveys indicated students were overwhelmingly positive (97%) in their perception of how the AR sandbox improved their understanding of learning objectives. They also preferred AR sandbox activities when compared to traditional laboratories that used only topographic maps. Effective classroom use of the AR sandbox required developing student-modeling exercises that took advantage of real-time feedback, virtual water, and physical modeling activities. While data are limited and more research is needed, real-time feedback on student models by both the students and the instructor suggests sandbox models are particularly useful for dispelling student misconceptions. © *2016 National Association of Geoscience Teachers*. [DOI: 10.5408/15-135.1]

Key words: augmented reality sandbox, spatial thinking, embodied learning, topographic maps, geology labs, surficial processes

INTRODUCTION

Spatial thinking is a fundamental skill for discovery and problem solving in many disciplines, especially the geosciences. Spatial thinking abilities—such as describing the shape, position, and orientation of objects; creating and reading maps; and visualizing processes in three dimensions—are critical to understanding the complex processes that take place on Earth (NRC, 2006). Despite its importance, students often have difficulty with spatial thinking and face challenges such as understanding scale, symbology, and how to connect two-dimensional (2D) representations with their three-dimensional (3D) counterparts (Chang et al., 1985; Ishikawa and Kastens, 2005; Liben and Titus, 2012). Educators have used a variety of models—physical, virtual, and augmented reality (AR) models—in an effort to improve spatial thinking ability.

Physical models such as raised relief maps and sandboxes have been shown to improve understanding of topographic maps, help students understand the link between 2D representations and 3D objects, and improve student engagement (Lord, 1985; Feldman et al., 2010; Kuehn 2012; Atit et al., 2015). In addition, virtual models such as interactive stereoscopic visualizations like the GeoWall (Johnson et al., 2006) can also support spatial learning, for instance, by allowing students to see through an object and view objects from multiple angles, by providing environmental context, and by preparing students for outdoor field research (Johnson et al., 2006; Reynolds et al., 2006; Rapp et al., 2007; Keehner et al., 2008). While animations and interactive models are common in geosciences education, the uses of AR are relatively limited but expanding (e.g., an AR sea-level-rise tool has recently been developed for teaching geoscience; Kintisch, 2013). AR models may make it possible to combine the interactive benefits of physical models with the flexibility and diversity of virtual tools.

Caudell and Mizell (1992) coined the term "augmented reality (AR)" to describe overlaying computer-generated and computer-presented information onto the real world. AR (1) combines real and virtual images, (2) presents an interactive image in real time, and (3) displays a scene in 3D, where real and virtual objects are accurately aligned (Azuma, 1997). The presently pervasive navigational aids used in modern automobiles are examples of AR devices that superimpose digital sightlines onto a camera view of a road, while the plethora of popular video games exploits virtual reality. The former is closer to the real environment, and the latter is

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closer to the virtual environment. Many augmented or virtual reality devices use mobile computers, head-worn displays, and devices for global positioning system and wireless Web access. These systems often overlay computer-generated information and images onto real buildings, room interiors, and exterior landscapes, among other settings.

In a systematic review of research and applications of AR to education, Bacca et al. (2014) describe the uses, advantages, limitations, effectiveness, challenges, and features of AR in education by evaluating 32 studies published between 2003 and 2013. Their results indicate that only 40% of the uses of AR in education are in science and that 85% of these applications have been to explain a given topic and augment information about it, as opposed to only 12.5% for laboratory (lab) experiments. Cai et al. (2013) describe an AR 3D technique used in a physics course to conduct an interactive and integrated convex-lens, image-forming experiment and an application in chemistry enabling students to more readily envision the composition of substances in a microworld (Cai et al., 2014). Andújar et al. (2011) developed augmented online labs for use in engineering education at the University of Huelva. Their simulated lab experiences are aimed at giving the user the sensation that lab functions can be handled just as they would be in the physical lab classroom. Several European projects have also developed AR applications (apps) for educational purposes. For example, the Augmented Reality in School Environments (ARiSE) project is developing and piloting AR learning tools in classrooms to enhance student understanding of topics such as the human digestive tract and chemical reactions (ARiSE, 2015). In the realm of K–12 education, AR apps are becoming more readily available and include some Earth Science topics (astronomy is particularly popular). Kamarainen et al. (2013) described environmental-education activities with middle-school students combining AR and probeware technologies—computer-aided, data-collection devices that both capture data with sensors (e.g., temperature, pH, and force or acceleration probes) and analyze it with the connected computer—with a field trip to a local pond. Until the AR sandbox (Kreylos, 2015a), however, little AR technology has been readily applicable to the university geology classroom.

Many undergraduate students completing the lab section of geology courses have difficulty with interpreting topographic maps and other spatial thinking tasks (Chang et al., 1985; Ishikawa and Kastens, 2005; Rapp et al., 2007; Clark et al., 2008; Alles and Riggs, 2011). Besides the obstacle of the significant amount of math involved in understanding and using scales, determining elevations and relief, and interpolating latitudes and longitudes, the concept of representing 3D landscapes in two dimensions (i.e., contour lines symbolizing elevations and contour spacing indicating steepness of topography) is challenging for most students to grasp. The AR sandbox is a compelling tool for bridging the gap between 2D representations and the real world. When the modeled 3D landscape in the sandbox is juxtaposed with its 2D image projected on a screen, the connection between the two is more accessible to novices than when they study a topographic map and try to envision the real terrain. Another unique aspect of this particular AR visualization is the ability to study the movement of virtual water interacting with real modeled landscapes to envision the processes by which landscapes evolve.

In this paper, we first describe the background and origins for an AR sandbox designed for use in museums and science centers and then share information regarding its design, application, and use for an undergraduate geology lab course. We also provide a sample lesson plan (available in the online journal and at http://dx.doi.org/10.5408/15-135s1) and explanatory video (ECU, 2016), as well as a technical guide to the sandbox (available in the online journal and at http://dx.doi.org/10.5408/15-135s2). Because of significant recent upgrades to the AR sandbox software and online instructions, some of the issues we encountered when constructing and programming our sandbox in fall 2014 have been resolved. Still, this supplement provides insight on many important aspects of AR sandbox construction that new users might find helpful.

THE AR SANDBOX

Lake Visualization 3D (LakeViz3D, 2015b), a National Science Foundation–funded project, is a collaboration among the University of California (UC)–Davis W.M. Keck Center for Active Visualization in the Earth Sciences (KeckCAVES, 2015), UC Davis Tahoe Environmental Research Center (TERC, 2015), Lawrence Hall of Science (LHS, 2015), Ecology, Culture, History, and Opportunities Leahy Center for Lake Champlain (ECHO, 2015), and Audience Viewpoints Consulting. The project's primary objective is to increase understanding and stewardship of freshwater lake ecosystems using 3D visualizations. As part of the initiative, the interdisciplinary team built a real, hands-on sandbox exhibit, overlaid with virtual topography and water created using a motion-sensing input device (a Microsoft Kinect 3D camera; Kreylos, 2015b), visualization software, and a data projector. The first prototype AR sandbox was developed at UC Davis KeckCAVES and allows users to create topographic models by shaping real sand on which an elevation color map, topographic contour lines, and simulated water are projected in real time. As users move the sand, the camera perceives changes in the distance to the sand surface, and the projected colors and contour lines change accordingly. When an object (e.g., a hand) is sensed at a particular height above the sand surface, virtual rain appears as a blue, shimmering visualization on the surface below and a flow simulation moves the water across the landscape. The virtual water slowly disappears as if it was infiltrating the soil or can be drained rapidly with a push of a drain button. The LakeViz3D project (2015b) then created three AR sandbox exhibits (called Shaping Watersheds), which were installed at the three science-center partner sites (LHS, TERC, and ECHO) and one portable AR sandbox for Howard University Middle School. They continue to be used by the public and K–12 school programs to explore a variety of topics, including geomorphology, hydrology, environmental stewardship, and watersheds. The exhibit software was inspired by Czech researchers who demonstrated an early prototype called Sandy Station (SmartMania, 2011). Since its development in 2013, more than 100 versions of this sandbox have been created in the U.S. and internationally (LakeViz3D, 2015b; Reed et al., 2014). The original physical sandbox was made with plywood and mounting brackets with the help of an undergraduate student (Peter Gold). The driving visualization software (https://tinyurl.com/sandbox-download, under the GNU General Public License) was written by

Oliver Kreylos of the KeckCAVES at UC Davis and is based on the virtual reality user interface (VRUI) development toolkit (Kreylos, 2008; Kreylos, 2015c), the Kinect 3D video processing framework, the OpenGL shading language, and fluid flow models. The water flow simulation is based on the Saint-Venant set of shallow water equations, which are a depth-integrated version of the Navier-Stokes equations governing fluid flow (Kurganov and Petrova, 2007). The virtual sand surface is the boundary condition, and the simulation is run such that the water flows exactly at real speed, assuming a 1:100 scale factor. Details about the sandbox and its development can be found on the project Web site (Kreylos, 2015a) and in the technical supplement to this paper (available in the online journal and at http://dx.doi.org/10.5408/15-135s2).

Parts and Construction of the Sandboxes at East Carolina University

Guided by information from the LakeViz3D Web site (LakeViz3D, 2015a), staff and faculty at East Carolina University (ECU) Department of Geological Sciences constructed and calibrated two AR sandboxes (Fig. 1, see color versions of the figures in the online version of this manuscript) in fall 2014 for use in a university lab setting. The ECU team adapted the original sandbox components to construct two sandboxes (total cost of about $1,000), one for each of the two lab classrooms (see the supplemental materials on the construction, calibration, and programming process; available in the online journal and at http://dx.doi.org/10.5408/15-135s2). While the cost can vary enormously depending on the construction materials, projector, and computer used, a complete sandbox can be built for under $1,000 with used parts (not including staff time). For instance, the ECU team employed some materials already available in the department, including used computers, a donated video card, cables and wiring to connect camera and monitor, and woodworking tools. Alternatively, private design firms offer exhibit-grade sandboxes starting at $10,000. By not using all recommended equipment, the cost was minimized, but that savings resulted in somewhat compromised performance. For example, the water simulation is slightly slower than with the recommended GTX970 video card, and the less expensive sand used in the ECU sandboxes is not as good for this application as white Sandtastik sand, resulting in a projected image that is slightly less bright and true to color. The time required for sandbox construction can also vary widely depending on staff expertise. The ECU sandboxes were built, the software was installed, and the AR sandboxes were operational in 1 week.

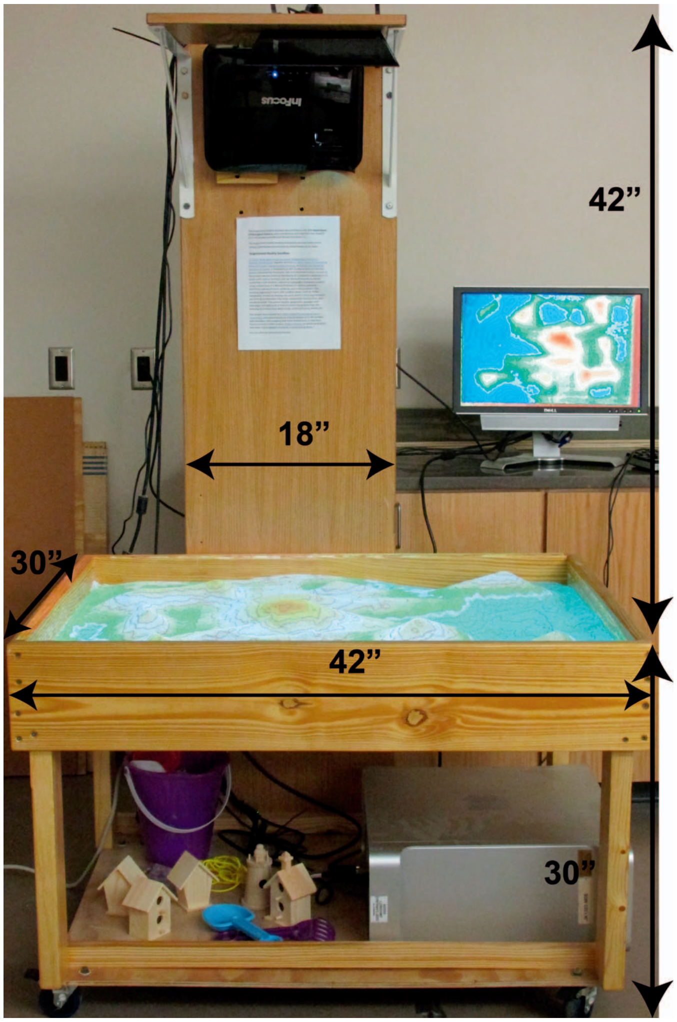

FIGURE 1: ECU AR sandbox linked to display monitor to permit viewing of both 2D and 3D images simultaneously. Wooden framework was designed to be sturdy and portable and to fit through classroom doors. The short-throw projector is mounted vertically on the upright wooden board to the back. The right end of the Microsoft Kinect camera (suspended at the front of the overhanging, forward-projecting, wooden mounting board) can be seen extending a bit to the right of the projector. Some key dimensions are indicated.

When configuring the operating system and software, the goal was to anticipate the most likely usage pattern for instructors and to remove probable obstacles. At ECU, most users of the AR sandbox will be graduate teaching assistants (GTAs)—usually master of science (MS) candidates, with varying degrees of familiarity with computers and usually no experience with the Linux operating system. To simplify sandbox operation (i.e., minimize unnecessary navigation and remove the need for operation using the command-line interface), adjustments were made after installing the sandbox software. Finally, the sandbox program was set to start automatically upon user login. With these adjustments, an instructor can simply walk into the classroom and turn on the projector and computer. The operating system then boots, logs in the correct user, and launches the sandbox software, all without requiring input from the user.

LOCATION AND CONTEXT OF THE PILOT STUDY

To understand the institutional and instructional context for this work, a brief description of ECU and its student body is provided here. This is followed by an overview of the exercises and an outline of the individual learning objectives for each of the three lab topics (topographic maps, rivers, and coastlines).

ECU is a regional, doctoral-granting (Carnegie classification: higher research activity), liberal-arts institution with

TABLE I: Topics historically covered in GEOL 1501, and syllabus revisions made to accommodate AR sandbox activities in summer 2015. Labs that were changed in summer 2015 are indicated in bold.

Typical Lab Syllabus Without Sandbox Exercises		Syllabus With Sandbox Exercises, Summer 2015	
Lab	Topic	Lab	Topic
1	Properties of minerals	1	Properties of minerals
2	Mineral identification	2	Mineral identification
3	Mineral exam and igneous rocks	3	Mineral exam and igneous rocks
4	More igneous rocks	4	More igneous rocks
5	Sedimentary rocks	5	Sedimentary rocks
6	Metamorphic rocks and geologic time	6	Metamorphic rocks and geologic time
7	Exam on rocks and geologic time and introduction to contouring spot elevations	7	**Exam on rocks and geologic time, 45-minute demonstration of the sandbox, and introduction to contouring spot elevations**
8	Basics of topographic maps	8	**Basics of topographic maps using topographic maps and the sandbox**
9	Studying rivers using topographic maps	9	**Studying rivers using the sandbox and topographic maps**
10	Quiz on topographic maps, hydrographs, flood-insurance rate maps, and flood recurrence diagrams	10	**Quiz on topographic maps and continuation of river exercises using topographic maps and the sandbox**
11	Groundwater	11	**Short exercise on stream hydrographs and continuation of river exercises using the sandbox**
12	Studying shorelines using topographic maps	12	**Groundwater exercises and shoreline exercises using topographic maps and the sandbox**
13	Crustal deformation and earthquakes	13	**Continuation of shorelines exercises using topographic maps and the sandbox**
14	Plate tectonics	14	Plate tectonics
15	Final lab exam	15	Final lab exam

an enrollment of ~28,000 students, of which about 80% are undergraduates and 20% are graduate students. Nearly 90% of ECU undergraduates (average age 22 years) are from North Carolina originally, and 32% qualify as low income. In 2015, composite SAT scores (reading and math) for degree- or certificate-seeking students ranged from 980 to 1,120 (Forbes, 2016).

In the Department of Geological Sciences, there are 10 faculty members who routinely teach the large (100 students) introductory lecture classes in basic physical geology (GEOL 1500: Dynamic Earth) and typically 10 graduate students (MS only—no doctoral candidates) who teach the accompanying lab course (GEOL 1501: Dynamic Earth Laboratory). The topics for which the sandbox was used are currently taught as part of GEOL 1501, which meets for 3 h each week of the semester. During the 5-week summer session, in which use of the AR sandbox was piloted, the lab course met three times a week for 3 h each class period. This course, along with its accompanying lecture, is dominantly populated by nongeology majors fulfilling the lab requirement of their general science-education curriculum. Most students take the lecture portion of the course during the same semester in which they take the lab, although some students enroll in the lab during a later semester. The lecture is taught by faculty members, and during the fall and spring semesters, labs are taught by graduate students. Typical enrollment in a lab is 23 students. Because lab students have not necessarily had the lecture material for a specific topic before entering lab, the graduate-student teaching assistant begins each class with a 15- to 20-minute introduction to the topic. Assessment for this course typically involves four in-class exams or quizzes (~67%) on minerals, rocks and geologic time, and basics of topographic maps (quiz) and the final exam covering the remaining topics (Table I). The remaining 33% of the lab grade is derived from prelab exercises submitted at the beginning of each lab period and daily exercises completed during the lab period. Other than taking the lecture portion of the course, prelab reading in the lab manual, and responses to prelab questions, students are not expected to have skills or knowledge related to the topics covered.

Topographic Maps Lab

Learning to use topographic maps can be challenging for college students, but facility with these maps is crucial to developing an understanding of surficial processes associated with rivers, glaciers, oceans, and groundwater. This skill can also help students in their everyday lives when using road maps, property maps, and navigational charts. The specific learning objectives for this lab include the following:

- Interpret information and understand symbols on maps
- Determine latitudes and longitudes for locations on Earth's surface
- Calculate distances between locations, as well as elevations and relief
- Determine contour spot elevations
- Construct topographic profiles

- Develop the ability to envision a terrain based on its topographic map

Rivers Lab

In a humid climate such as that in North Carolina, students seldom find themselves farther than a few hundred yards from running water. Understanding fluvial processes and features can help them avoid serious loss of life and property, such as that the state experienced following Hurricanes Dennis and Floyd in 1999. Due to the geographic diversity of North Carolina, all types of streams are found, ranging from high-gradient mountain rivers flowing in narrow, V-shaped valleys to low-gradient, coastal creeks on broad coastal plains. North Carolinians must, therefore, be familiar with the entire spectrum of fluvial systems. This knowledge permits potential property owners to make wise decisions before they purchase and empowers informed citizens to influence municipal officials as they make decisions regarding land use near rivers. As the population of the state increases, water-supply issues will require even more difficult choices to be made about North Carolina streams and rivers. Specific learning objectives for this lab include the following:

- Recognize factors that affect stream flow, velocity, and erosion
- Understand the concept of gradient
- Learn about flooding and how human development can affect it
- Use hydrographs to describe river flow
- Explore the work that rivers do: erosion, transportation, and deposition
- Recognize the erosional and depositional features created by rivers
- Develop the ability to envision the processes that create fluvial features

Coastlines Lab

Coastal change has significant political and social consequences for the U.S. in general and North Carolina in particular. If current trends in climate change continue, coastal regions will experience profound effects from sea-level rise. Flooding of low-lying coastal areas requires citizens to make hard decisions about preserving infrastructure and property in the coastal zone. As a result, it is important for voters to understand natural coastal processes and the impacts humans have on them. Specific learning objectives for this lab include the following:

- Learn the basic terminology and behavior of wind-formed waves
- Investigate the link between wave refraction and longshore transport
- Recognize the types of coastal features formed by erosion and deposition
- Learn ways humans have attempted to interfere with natural coastal processes
- Understand results of human interference with natural coastal processes
- Describe how the barrier islands of North Carolina originated
- Differentiate submergent, emergent, primary, and secondary coasts

TABLE II: Demographics of students participating in this pilot study.

Demographic	No. Students
Class rank	
Freshman	2
Sophomore	5
Junior	2
Senior	3
Major	
Social science	2
Science and technology	5
Fine arts	2
Health and human performance	1
Education	2
Gender	
Male	8
Female	4
Race/ethnicity	
White	11
African American	1

PREPARATION FOR SANDBOX LABS

The sandbox exercises were designed and taught by the first author (T.L.W.), who has been teaching this class (and other undergraduate and graduate geology classes) since 1988. The summer lab course had only 9 students, which offered an ideal situation for exploring the learning potential of the sandbox and developing sandbox lesson plans to pilot, especially when compared to the larger sections offered during fall and spring semesters. Three students who were enrolled in lecture but not lab also spent several hours working in the sandbox, thereby exposing a total of 12 students to this new teaching tool (Table II). All but 1 of these 12 students was of traditional college age. The faculty member teaches both lecture and lab during the summer semester, so the syllabus (Table I) was designed to allow lecture background on lab topics to be covered before students undertook the lab exercises on that topic. However, because several lab students had taken the lecture portion of the course in a previous semester, the instructor presented a 15- to 20-minute review of each lab topic.

Time is precious in 3-h university labs, and several weeks of lesson design, testing potential activities, and acquiring supplies were required to ensure course objectives were achieved and that AR sandbox activities would work and not take too long. A long list of potential features, processes, and terrains to be modeled in the sandbox was considered, but many were discarded as impractical. For example, the sandbox could potentially be used to explore (1) the impact of differing cross-sectional areas, wetted perimeters, and channel roughness on stream flow; (2) the concept of changing base levels; and (3) meandering versus braided streams, but it was discovered these would not work because the loose sand used in the ECU sandbox does not

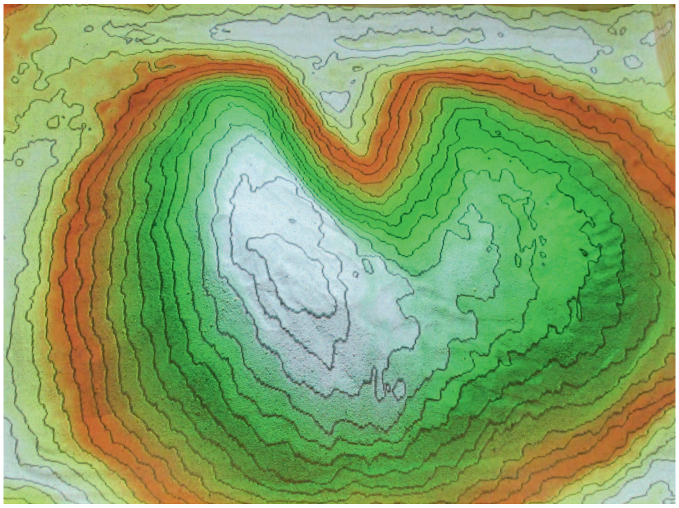

FIGURE 2: Top view of sandbox terrain constructed for an initial contour-line demonstration by instructor in a lab class. The mound was constructed with the steeper terrain on the left side and a valley carved at the top to demonstrate the Rule of Vs. Print version of the figure: Lightest shade in the center left indicates the highest elevation, whereas the other light shade at the edges of the image surrounding the central mountain represents lower elevations. Online version of the figure: Elevations are color coded, moving from highest to lowest as color changes from white to green, orange, yellow, and then gray. (Sandbox exterior dimensions are 28″ × 38″.)

hold the required shapes. (In the original use of the AR sandbox using white sand from Sandtastik, a spray bottle of water has been helpful to minimize dust and help with landform shaping.) Implements that were useful for generating sandbox models included large pieces of wood to smooth sand throughout the entire box, small shovels and buckets, thin sticks with cardboard squares taped to the end to generate rainstorms on limited areas, wooden models of buildings, rollers for smoothing sand, rocks and wood for jetties and groins, string, dowels, markers, and transparency film.

Sandbox activities take time that in the past was allocated for other exercises. Table I outlines the changes made to the previous lab syllabus to accommodate sandbox activities. Lab periods highlighted in bold on the right side of Table I involved significant use of the sandbox for demonstrations and exercises. To make time for sandbox activities, a portion of the questions students would previously have been answering (based on their individual study of topographic maps) was eliminated. Lab 7 is traditionally one of the shorter lab periods, so addition of the sandbox demonstration did not require elimination of any activities pursued in previous years. Sandbox exercises involving student construction of simple terrains (described later) were added to the standard topographic-map activities pursued in Lab 8, without requiring elimination of any map exercises. Time for sandbox activities was generated in Labs 9–11 by eliminating about one-fourth of the topographic-map questions and shortening the hydrology exercises in Lab 11 (by eliminating the flood recurrence activity). In Labs 12 and 13, time for sandbox activities was generated by eliminating about one-fourth of the topographic-map questions on shorelines and groundwater.

Sandbox activities did not serve as a replacement for crustal deformation and earthquake exercises pursued in Lab 13 in previous semesters; those activities were eliminated from the lab. In the past, the exercises relating to crustal deformation would have required approximately 1 h of a lab period, and the computer exercise developed to study the distribution of earthquakes worldwide required about 2 h. These were deemed the least crucial of the GEOL 1501 exercises for different reasons. Crustal deformation (faulting and folding of rocks usually occurring many miles beneath Earth's surface) generates features usually only exposed at Earth's surface following millions of years of weathering, erosion, and uplift. Furthermore, crustal deformation is difficult for most students to visualize, is perceived by them as irrelevant to their daily lives, and is not effectively dealt with in the time typically allotted for it, so it was deemed expendable. In contrast, earthquakes are a crucial aspect of internal Earth processes for people living in regions experiencing frequent earthquakes. However, these phenomena are not perceived as relevant in the everyday lives of most ECU students. Also, this topic is well covered in the lecture portion of the course, so most students finish GEOL 1500 with a reasonable idea of the distribution of regions experiencing frequent earthquakes.

Final lab preparations included placing a whiteboard along the back of the sandbox to record sand elevations as students create a topographic profile of a 3D sandbox landscape. A corkboard and pushpins would serve the same purpose. In addition, a mound of sand (steeper at one end than the other) was built before the beginning of class. The mound was designed to fill most of the box, thereby minimizing the amount of time required to add the virtual water needed for the demonstration to follow (Fig. 2). Sand in the rest of the box was flattened to limit irregularities in the contour lines around the mound. In addition, a piece of transparency film was taped over the sandbox image on the computer monitor (Fig. 1) to record student observations of the changing positions of the shoreline around the mound as virtual water is drained from the sandbox. Finally, a single distinctive river valley was carved in one side of the mountain as a demonstration of the Rule of Vs (the Vs on a topographic map open toward lower elevations; Fig. 2).

In the typical introductory ECU lab on topographic maps, students are introduced to the rules of contour lines and the basic techniques of contouring spot elevation data and asked to produce a simple topographic map. Although many have seen contour maps before (e.g., atmospheric pressure maps on weather reports), most have not thought critically about what the maps show and have never been faced with the task of generating contour lines from individual data points. Their first attempts almost invariably contain numerous, significant errors. In the sandbox-based course, this contouring exercise was the initial activity; however, immediately afterward, the sandbox was introduced to clarify the concept of contour lines. The activities described next were pursued with the sandbox connected to a computer monitor so that students could see the 2D image on the monitor at the same time they were looking at the 3D landscape in the box (Fig. 1; see the detailed lesson plan for the demonstrations and exercises, available in the online journal and at http://dx.doi.org/10.5408/15-135s1). (With

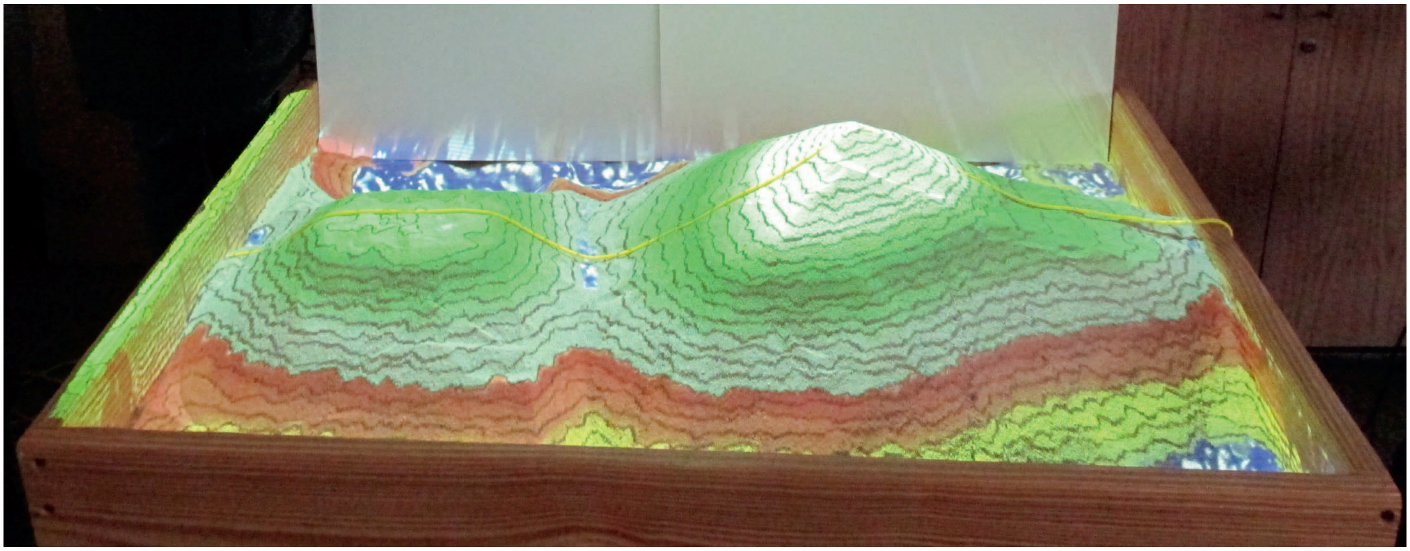

FIGURE 3: Oblique view of the instructor's model used to demonstrate the construction of a topographic profile. A whiteboard has been placed upright in the back of the box so that students can record changing elevations along the profile line. Print version of the figure: The light line along the center of the terrain (from left to right) is a string laid along the profile line at a point representing maximum elevation changes. The mottled gray-and-white pattern along some edges is virtual water. Online version of the figure: Elevations are color coded, moving from highest to lowest as color changes from white to green, gray, reddish orange, and then yellow. The mottled blue-and-white pattern along some edges is virtual water. (Sandbox interior dimensions are 28″ × 38″). The yellow line along the center of the terrain (from left to right) is a string laid along the profile line at a point representing maximum elevation changes.

ECU's hardware configuration [including the screen of a computer monitor or a projected image on a screen] the program crashed if the cursor was positioned on the monitor when a numerical key was pressed. Such random problems may result from using other than LakeViz recommended hardware configurations.) The computer was also connected to a printer for capturing screenshots, but the ubiquity of camera phones renders this largely unnecessary.

INITIAL DEMONSTRATION ON CONTOUR LINES AND TOPOGRAPHIC PROFILES

Contour Lines

Before beginning the demonstration on Contour Lines and Topographic Profiles (East Carolina University, 2016), the instructor gathered the students around the AR sandbox and explained its parts and how they work together to generate the projected images. Then students were asked for their observations about contour lines. This did not elicit any response, so they were asked to kneel down until their eyes were level with the rim of the sandbox and told to follow a single contour line all the way around the mound, noting how its position changed with respect to the rim of the sandbox. Then, to prompt observations, they were asked questions such as "Does the line's elevation change with respect to the rim of the AR sandbox?" "Do contour lines close to form loops?" "Do they cross?" and "Do they branch?" After establishing some of the basic characteristics of contour lines, students were asked, "What shape do the lines in the river valley remind you of?" and then "In which direction does the sharp end of the 'V' point—uphill or downhill?" Finally, they were directed to study the steeper and more gently sloping ends of the mound and asked to describe what was different about the spacing of contour lines at these two ends.

Subsequently, after rapidly flooding the area around the mound, the drain button was used to progressively dry up some of the water. Stopping the process after each water-level decline, successive student volunteers traced the edges of the mound-to-water contact onto the transparency film taped over the computer screen. When the transparency film was removed from the monitor, students recognized that they had generated a contour map. Many students commented immediately how easy it now was to see the relationship between the sandbox landscape and the lines on the transparency. They could quantify elevations or water depths by counting up or down from a reference point (e.g., the bottom of the sandbox) to the water surface or the contour line in question. Subsequently, with two mounds in the sandbox—one higher and steeper than the other—the instructor explained the concept of relief, both local and total, and asked, "Which mountain has the greater relief?" "Which mountain is steeper?" and "How would you determine local versus total relief for this landscape?" Then, after scraping off the top of the higher and steeper mound so that it was the same elevation as the smaller one, students were asked again, "Which has the higher relief?"

Topographic Profile

After building two mounds with different heights, reliefs, and shapes (Fig. 3), the instructor laid a brightly colored piece of string in the sand along a straight line across the features (parallel to the whiteboard at the back of the sandbox) to represent the trace of a topographic profile. Students took turns placing skinny dowels laid horizontally from the front to the back of the box—perpendicular to the string and parallel to successive contour lines. One student

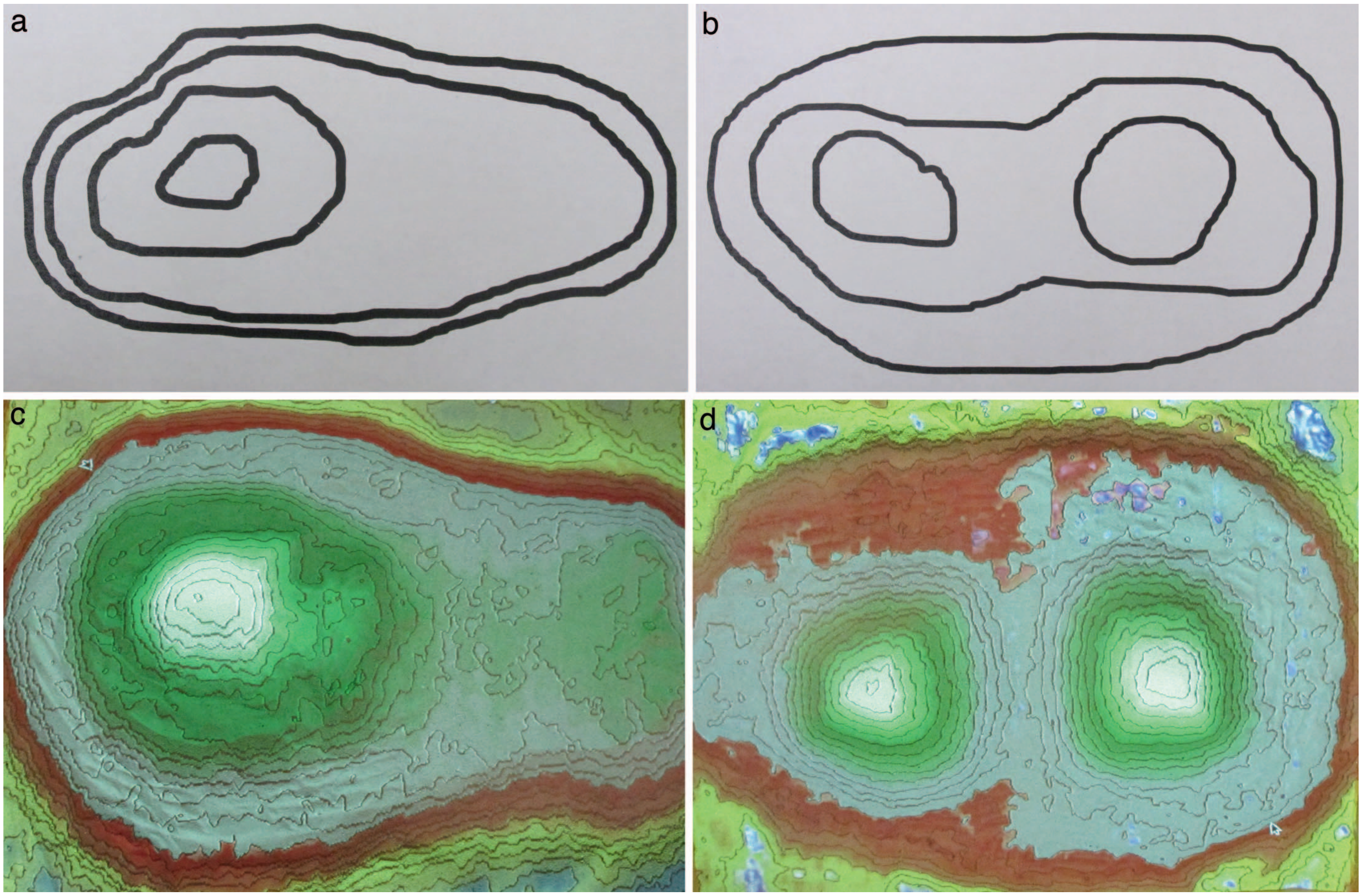

FIGURE 4: (a and b) Map views of simple terrains and (c and d) student models of these terrains. Print version of the figure: In (c) and (d), the lightest shade in the center of the mountains indicates the highest elevation, whereas the other light shade at the edges of the image represents the lowest elevations. The mottled gray-and-white pattern in some corners of (d) is virtual water. Online version of the figure: In (c) and (d), elevations are color coded, moving from highest to lowest as color changes from white to green, gray, reddish orange, yellow, and then bluish gray. The mottled blue-and-white pattern in some corners of (d) is virtual water. (Sandbox interior dimensions are 28″ × 38″).

kneeled in front of the box and sighted toward the whiteboard at the back, keeping the dowel horizontal at the elevation of the contour line. A second student placed a dot on the whiteboard where the dowel touched it. Finally, the students connected the dots to complete the profile. Later in lab, the instructor explained how to create topographic profiles for different traverses across the paper topographic maps.

CLASS EXERCISES

Constructing Terrains From Simple Contour Maps

As graded exercises, students constructed simple terrains in the sandbox using 2D diagrams of these terrains as a guide [Figs. 4(a) and 4(b)]. This part of the exercise was done when the students could get a timeslot, in pairs, with the sandbox, while other students were working on the standard topographic-map exercises. Students took photos of their resultant terrains and e-mailed them to the instructor as part of their daily lab grade.

For the purposes of grading, the detailed shape of the feature and its absolute relief were not of primary concern. Instead, if the landforms were properly oriented; if their size, relief, steepness, and location were generally correct; and if the extent of low- and high-relief sections was generally correct, students received full credit. Figures 4(c) and 4(d) are typical of the models constructed, indicating that most students could correctly interpret these simple contour maps [Fig. 4(a) and 4(b)] and visualize the 3D terrain they represent. As time allowed, the instructor also checked with students working in the sandbox to address questions or misconceptions that arose as they worked.

Modeling Fluvial Features and Processes

For the subsequent lab on rivers, the sandbox was used for two different but intimately interwoven purposes: (1) to have students build different fluvial features and (2) to help them better understand the interaction of river water with the landscape. They were encouraged to use the water flow feature to make their models more realistic and more useful as representations of the natural world. They based their models on lecture materials, class readings, textbooks, and lab manuals about these features and processes, as well as what they were seeing on the topographic maps of rivers they were studying. Again, students worked in pairs, taking photos of their efforts and

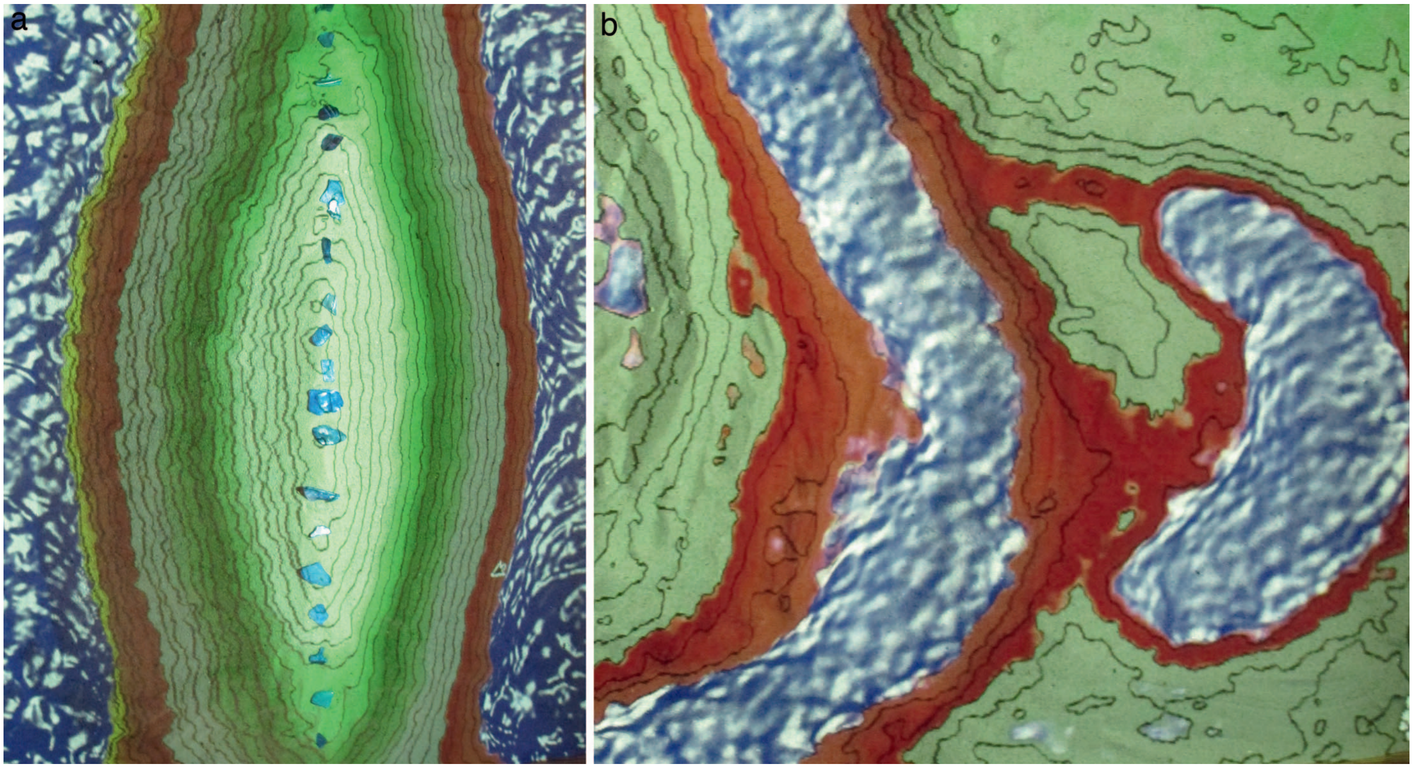

FIGURE 5: Print version of the figure: Top views of student models built to represent (a) stream divide and (b) meander (left) with an oxbow lake (right). (a) Objects running top to bottom down the center of the stream divide are rock chips marking the points of maximum elevation along the stream divide. Elevations increase up and away from both the meandering stream and the oxbow lake in all directions. The mottled dark-and-light patterns to the left and right of the stream divide and within the meandering channel and oxbow represent virtual water. Online version of the figure: Top views of student models of fluvial features. (a) Stream divide with elevations color coded, moving from highest to lowest as color changes from greenish white to green, gray, reddish orange, and then yellow. Blue rock chips mark the points of maximum elevation along the stream divide. (b) Meander (left) and oxbow lake (right) with elevations color coded, moving from highest to lowest as color changes from green to reddish orange. The mottled blue-and-white pattern in both photos is virtual water. (Sandbox interior dimensions are 28″ × 38″.)

e-mailing them to the instructor for grading. Each pair had to construct a model showing a drainage divide and had to use the water flow model to study effects of rain events and flooding [Fig. 5(a)]. A primary goal was to encourage students to think about how water moves through drainage basins and whether water can naturally move on the surface from one drainage basin to the neighboring one. Subsequently, they had a choice of which features to model, such as follows:

- The contiguous 48 states, its two major continental divides, and the Mississippi River Basin
- Point bars, relict point bars, and bars within streams
- Stream with natural levees and a yazoo tributary
- Difference between channel length and valley length to explain sinuosity
- Cutoff, oxbow lake [Fig. 5(b)], and abandoned meanders
- Various drainage patterns

Their choices for processes included the following:

- Formation of a meander, starting with a straight channel and putting an impediment in the way of water flow
- Erosion and deposition on the outside and inside of meanders
- Formation of an oxbow lake
- Formation of deltas and alluvial fans
- Headward erosion and stream piracy

Some of those modeling flooding built a stream with a wide floodplain and a stream with virtually no floodplain and then investigated how far flood water moves away from these two streams. They also modeled two paths for a hurricane (perpendicular and parallel to drainages) to show different flooding patterns resulting from different storm paths. In addition to submitting images to the instructor for grading, a model-building competition between groups of students was introduced into these activities as an instructional device. This teaching tool was effective in the small summer lab (only nine students), during which it was possible to use both sandboxes for the same class. Two pairs of students at a time were charged with modeling a specified terrain or process. Students not involved in building that particular landscape then studied the models and selected the winner. All students in the class were building models in the box and studying topographic maps showing landforms, so no rubric was provided for their determination of the

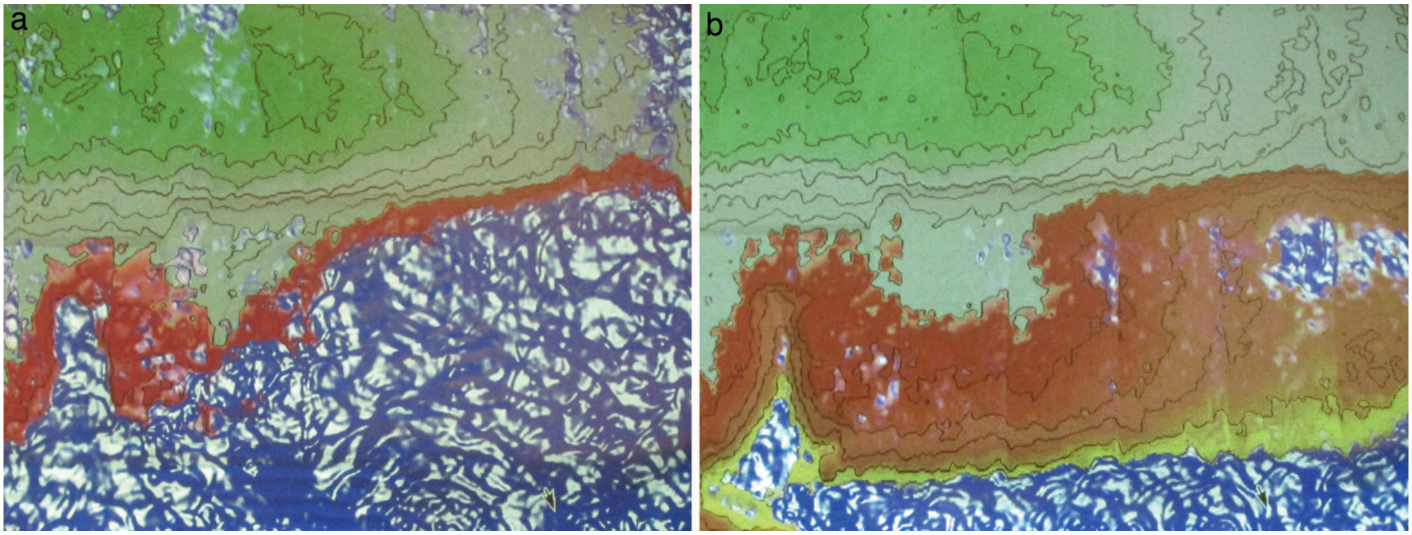

FIGURE 6: Top view of student models of backshore and foreshore regions along a beach at (a) high tide and (b) low tide. Print version of the figure: The mottled dark-and-light pattern in both images is virtual water projected onto the sandbox. Beach elevations increase toward the top of the photograph, and the ocean is at the bottom. Online version of the figure: Elevations are color coded, moving from highest to lowest as color changes from green to pale green, reddish orange, and then yellow. The mottled blue-and-white pattern in both photos is virtual water. (Sandbox interior dimensions are 28″ × 38″.)

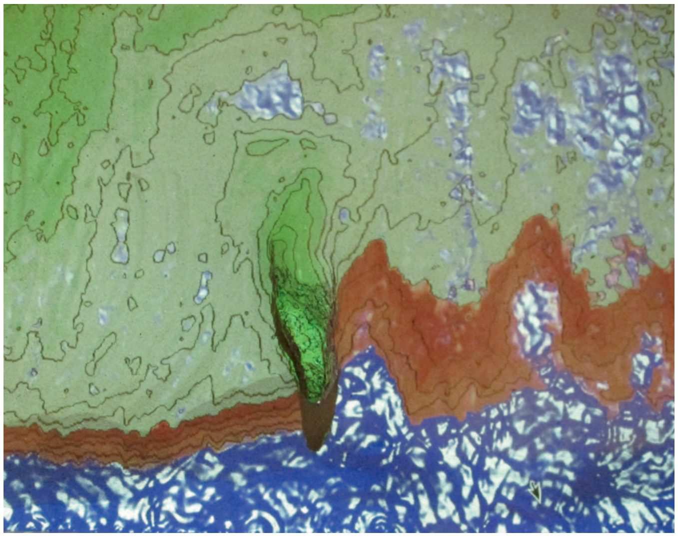

FIGURE 7: Top view of student model showing the effect on beach width of longshore transport in the surf zone. Print version of the figure: Model shows sand buildup on the upstream side (left) of a coastal groin (represented by a piece of granite) and beach erosion on the downstream side (right). The mottled dark-and-light pattern to the bottom of the image is virtual water. Higher beach elevations are at the top of the photograph. Online version of the figure: Model shows sand buildup on the upstream side (left) of a coastal groin (represented by a piece of granite that appears green because the camera senses it as a region of higher elevation). Beach erosion on the downstream side (right) is indicated by the beach migrating landward (toward top of photo). The mottled blue-and-white pattern is virtual water. (Sandbox interior dimensions are 28″ × 38″.)

winners of these competitions. They were asked to decide based on which model was generally the most recognizable, accurate, and complete. Somewhat surprisingly, although they were not provided with a rubric, the decision in all cases was unanimous.

Modeling Coastal Features and Processes

Students followed the same approach for coastal geology as they did for fluvial features and processes. They constructed models of features such as follows:

- Barrier islands of North Carolina with major inlets
- Shoreline showing backshore, foreshore, and offshore and their appearance during high tide [Fig. 6(a)] versus low tide [Fig. 6(b)]
- Western U.S. coast with sea stacks, tombolos, headlands, and bays
- Coastline with barrier islands, ebb and flood tide deltas, and spits

Coastal processes modeled included the following:

- Groins and their effect on beach width upstream and downstream (Fig. 7)
- Cape Hatteras National Seashore, North Carolina, showing where the sand eroded from the former lighthouse location goes as it is carried southward by longshore transport
- Sea-level rise eroding the shallowly sloping North Carolina mainland faster than the barrier islands migrate landward
- Longshore transport closing the mouth of an inlet
- Conversion of a spit into a bay-mouth bar
- Barrier island migration by sediment overwash
- Evolution of a coastal river into an estuary as sea level rises

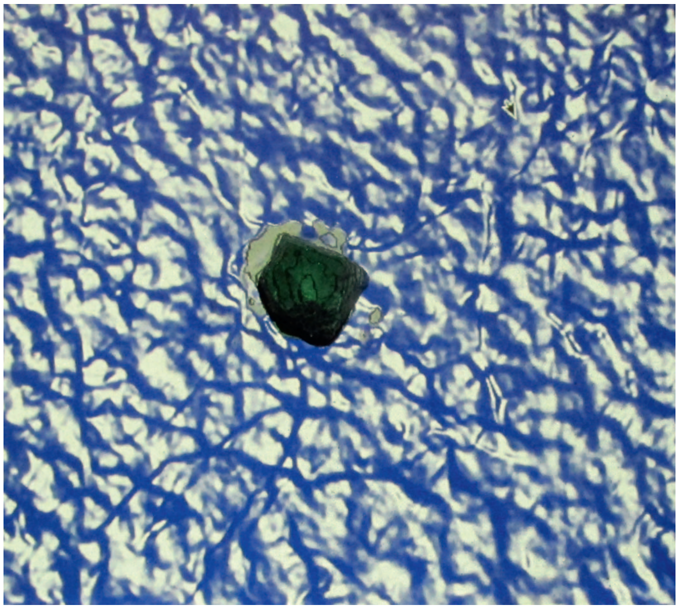

FIGURE 8: Top view illustrating wave refraction pattern projected onto sand by water flow software. The sandbox has been completely flooded with virtual water for this image. Wave fronts can be seen to refract around the rock island in the center, especially above and below the island. Print version of the figure: Longer, dark curving lines represent wave fronts. Online version of this figure: Longer, dark-blue, curving lines represent wave fronts. (Image measures approximately 27″ × 36″.)

- Straightening of a coastline by erosion of headlands and deposition in bays
- California beach compartments and offshore flow of sand to submarine canyons

One particularly useful aspect of the water flow simulation is that it is possible to show how waves are reflected from vertical surfaces and refracted around shallow spots (Fig. 8).

STUDENT LEARNING AND COMMENTS

At the end of the semester, the 12 students (9 from the lab and 3 from the lecture only) were asked to complete an exit survey (Table III), providing feedback on their perception of the value of the AR sandbox, as well as insights on how to improve the activities and scale them up for the normal enrollment of 23 students. The objective of the survey was to help improve instruction to maximize student learning using this new technology. Seven of the nine lab students and all three lecture-only students responded, for a total of 10 replies.

None of the respondents had ever seen an AR model like the sandbox. When asked to describe the AR sandbox, some responses were fairly explicit, such as "The sandbox is basically a projection of hundreds of still images recorded and projected from above onto a sand area below. Contour elevation lines (and different colors for different elevations) are projected according to how you shape the sand. It is helpful if you are a visual, 3-dimensional learner." Others were enthusiastic, if not very informative: "It is a box with sand and a thing is on top of it to measure the height of the sand. This can create topography maps. (It's awesome)," and "A sandbox with a brain!"

To quantify students' overall response to this new teaching tool, numerical evaluations (1 = strongly disagree through 5 = strongly agree) of their responses to Questions 3–6 were solicited (Table III). Students were universally positive (97%) in their perception of the helpfulness of the AR sandbox for understanding topographic maps and

TABLE III: Exit survey administered to lab and lecture students in summer 2015.

Questions (N = 10, 7 From Lab and 3 From Lecture)
1. Have you ever seen an augmented reality model such as this? Specifically, have you ever seen anything about this particular model on the Web?
2. How would you describe the sandbox to someone who has never seen it?
3–6. Students were asked to respond with 1–5, where 1 = strongly disagree and 5 = strongly agree
3. The sandbox helped me learn about topo maps, contour lines, relief, etc.
4. The box helped me learn about Earth surface features and processes such as barrier islands, point bars, longshore transport of sediment, floods, etc.
5. I learned some things using the box that will help me in my everyday life.
6. I will tell others about the exercises I did with the sandbox.
7. If you chose 4 or 5 for question 3 above, how in particular has it helped you understand topo maps better? Specifically, what are your most vivid recollections of how the sandbox allowed you to better understand them?
8. If you chose 4 or 5 for question 4 above, how in particular has it helped you understand them better? Specifically, what are your most vivid recollections of how the sandbox allowed you to better understand these features and processes?
9. If you chose 4 or 5 for question 5 above, what in particular have you learned that will help in your everyday life?
10. What did you like best about the sandbox exercises?
11. What did you like least about the sandbox exercises?
12. What would make this more useful for future students?
13. What would make this more interesting for future students?
14. Do you have any suggestions on how the sandbox activities could be adapted for a larger lab class (23 students) taught by a single graduate-student teaching assistant? During a normal 3-h lab, the teaching assistant has trouble answering all questions and helping that large number of students. Any ideas on how the teaching assistant could enhance student learning without input of excessive amounts of time?
15. Did you enjoy the sandbox exercises more than working with hard copies of the topographic maps, and do you think you learned more with the sandbox activities?
16. Which of the activities was the most affective? Which the least?
17. Please write any other comments you have about these exercises.

surficial features and processes. A score of 4.6 out of 5 suggests they would tell others about these exercises, and 4 out of 5 indicated they perceived they had learned something using the AR sandbox that would help them in their everyday life. Comments related to the latter included "Where to build a house! Definitely not on the beach or the bottom of a valley," and "As elementary as it might sound, it helped me to grasp elevations better. I would like to hike more with my father whose eyesight is starting to fail him. If I am better equipped at reading maps, it could aid us in our journeys together."

Students also expanded on their numerical evaluations, giving specific information about how they perceived the sandbox helped them learn. Many of the more general responses indicated how well they thought the sandbox allowed them to visualize what the 2D contour lines were trying to describe about the 3D landscape. Some mentioned specifically that they believed the AR sandbox made it easier to visualize flow direction of streams and steepness of slopes compared to contour lines on maps. Two student comments are particularly illustrative of this outcome:

> *"The first time we were introduced to the sandbox, something clicked in my brain. I was able to learn and interpret contour lines and elevations more accurately in that 15 minute introduction than in an hour by myself just using a topographic map. I am a visual learner, and it was such an asset having this tool in the classroom."*

> *"The sandbox helped me better understand topo maps from a visual perspective. Sometimes it's hard to picture what the terrain of the land actually looks like based on a bunch of lines on a map. The sandbox allowed [me] to actually visualize how the contour lines matched up with hills, mountains, etc."*

Any perceived or actual learning gains resulting from use of the AR sandbox are likely in part due to the direct link between the 3D landforms and processes and their 2D representations that the sandbox makes possible. In particular, the sandbox may help with spatial learning by providing an opportunity for embodied learning. The impact of action on learning has long been recognized by developmental psychologists (Piaget, 1952; Held and Hein, 1963). Embodied cognition refers to the notion that an individual's abstract representations of a concept are often based on a somatic experience of the concept (Niedenthal, 2007). Research is demonstrating that embodied learning shows promise to support powerful learning experiences (Lindgren and Johnson, 2013; Abrahamson and Lindgren, 2014). Being able to interact with real (model) landscapes may help students develop a sense of scale, experiment with changing reference points, improve penetrative ability, and recognize a range of slopes (Birchfield and Megowan-Romanowicz, 2009; Liben and Titus, 2012; Atit et al., 2015). It may also prove to be a useful tool in helping novice users more carefully investigate and partition complex 2D to 3D translation tasks (Ishikawa and Kastens, 2005).

Furthermore, the sandbox may support the development of model building, one of eight core practices in science education recently identified by the Natural Research Council (Schweingruber et al., 2012) and deeply integrated in the Next Generation Science Standards (NGSS; NGSS Leads States, 2013). Scientific modeling is a process that involves producing concrete representations of abstract ideas and evaluating and revising the representations based on testing and observations (Gobert and Buckley, 2000). Because the sandbox is a mixed-reality environment in which students can interact with a physical model overlaid with abstract diagrams, while testing and exploring specific science concepts, it may support the development of scientific model-building skills. That is, because the sandbox experience can merge scientific content, practice, and knowledge development, it may be an important tool for helping students understand how scientists create models that explain Earth systems and begin to practice model building themselves (Louca and Zacharia, 2012; Bryce et al., 2016). The sandbox, then, may also be a useful means by which to address the focus on model-development practices outlined in the NGSS. These practices are developed via the means of learning progressions: "research-based cognitive models of how the learning of scientific concepts and practices unfolds over time" (Duncan and Rivit, 2013). Because research on learning progressions is in the early stages, the AR sandbox could not only become a productive tool for geoscience education but also could be used to understand the development and evolution of scientific reasoning.

Many students were particularly intrigued by the water flow model, and their comments suggested they believed it had helped them better understand surficial processes and features. Instructor observations and student comments clearly indicated students enjoyed the sandbox exercises more than the traditional topographic-map exercises. Speaking for herself, the first author can state that using the sandbox in summer 2015 vastly improved her enjoyment teaching this portion of GEOL 1501. Selected responses on this and other topics are compiled in Table IV. Most students used the word "fun" somewhere in their other comments on sandbox activities, and many descriptions included these adjectives: refreshing, incredible, creative, interactive, hands-on, and realistic. Not surprisingly, when asked whether (1) they enjoyed the sandbox exercises more than working with hard copies of the topographic maps and (2) they thought they learned more with the sandbox activities than with the maps, the response was a unanimous "Yes." Comments such as this one were common: "The sandbox activity was most effective for me. Looking at regular diagrams can be confusing and boring." One of the lecture-only students remarked, "Looking forward to lab in order to use the sandbox again!" When asked what they liked least about the sandbox, a few students mentioned it was "messy." Others mentioned an issue with the rain function in that it takes practice locating the "cloud" (as represented by the user's hand or a cardboard cutout on the end of a stick) to get the rain to fall in a particular spot. In addition, if students left the sandbox program (e.g., to transfer files to thumb drives), when they returned, they had trouble reactivating the water features using number keys 1–4 that drain and add water throughout the box. A few comments described the software as "sensitive"; in actuality, the program is quite stable, although it is occasionally necessary to wiggle the mouse to get the projection back.

TABLE IV: Selected student responses to exit survey.

Comments on the Water Flow Feature of the AR Sandbox and What Students Learned From It
• It was also really helpful to show how water reacted to different terrains, especially w/ ocean features.
• The sandbox helped me better understand the earth's processes because of the water features. Modeling different structures and adding water to it, allowed me to visualize how water flows in relation to landforms.
• By creating different land formations you can get real-time response on what the resulting effect will be. If I built a mountain with a valley I can see free flow of water.
• Specifically longshore current and how water reacts to certain coastal features.
• I liked the feelings of clarity that I received after working with the sandbox, but in particular I thought the way it modeled water flow was incredible!
• The sandbox helped me to understand water run-off and river flow. The flooding function is very accurate. It was also beneficial in demonstrating shorelines.
What Students Liked Least About the AR Sandbox
• Sand got into my shoes. But it's a sacrifice I was willing to make.
• I kept spilling the sand.
• I wish it was bigger.
• That the technology was a little sensitive.
• It was very difficult to make anything other than a round hill because the dry sand doesn't form well.
• It might be useful if it were a bit easier to control the "rain" function.
• Having an updated computer attached to it, so that the software wasn't so sensitive.

LIMITATIONS TO STUDY

This paper presents a pilot study that tests the use of the AR sandbox in an introductory geology lab and summarizes self-reported assessments of student engagement and learning. While the results suggest that the AR sandbox may increase student understanding of complex geologic processes and enhance spatial thinking skills, to objectively assess sandbox learning gains, the following limitations to the study design would need to be addressed. Student comments were collected from only a small group of 10 students. A larger number of students responding in a similar pattern could give more validity to the positive responses received. In addition, limited data were collected from the students (in the form of a short exit survey). Conducting follow-up interviews and focus groups with students was difficult because the course was in a summer intensive session, significantly limiting time available for assessments and additional data collection about student perceptions of learning. This second limitation can be remediated in future studies of students who take the regular course during the academic year by integrating the assessments and research into the course activities. In addition, incentives can be offered to students to encourage them to be interviewed in depth about specific ideas and concepts they gained from interacting with the AR sandbox. Finally, because the data collected were self-reported, there is no external objective test of the impact of the sandbox on learning and engagement. In the future, we would implement pretests and posttests of introductory geology knowledge and course engagement, using an appropriate sample size.

LESSONS LEARNED AND PLANS FOR FUTURE USE

As mentioned previously, many potential activities could not be pursued because loose sand does not sufficiently hold the shape of certain terrains. When asked which of the sandbox exercises were the most effective, students commented, "The creation of ocean features [was most effective], the way rivers behaved for me was just challenging to actually make happen," and "Oceans most, rivers least 'cause [sand] wouldn't hold together well enough to form river features." Upgrading the sandboxes by replacing regular sand with more moldable sand should permit construction of many additional models and features. Other ideas include having a potter make clay models of landscapes for the box or using a 3D printer to generate such landscapes from paper topographic maps. ECU is currently generating features with a 3D printer to be used for the introductory demonstration described previously.

Several issues must be resolved to incorporate these activities into fall- and spring-semester labs that typically have 23 students and are taught by a GTA. GTAs sometimes struggle to answer all standard topographic-map questions that are asked, so introducing open-ended sandbox exercises, which will probably generate a lot of unpredictable questions, may be difficult for them. Therefore, to use the sandbox successfully in introductory geology labs, GTAs will need to feel comfortable in this less prescribed setting—for instance, by developing a database of potential student questions and answers and by faculty members coaching GTAs on how to work through questions for which they don't immediately have an answer. However, at the least, the basic introductory contour line and topographic profile demonstration described earlier should work well. For this introductory demonstration, the GTAs can be given the detailed lesson plan and shown how to set up the sandbox. This approach was implemented by GTAs in large labs at ECU in the fall 2015 and spring 2016 semesters, and anecdotal feedback from them suggests it worked well. For example, here are two comments volunteered by GTAs after they used the sandbox in lab:

> *"The sand box exercise was not only personally my favorite class to teach, but also for the students to learn. For my final exam extra credit question I asked, 'What was your favorite experience in my class?' Almost all of the students incorporated one way or another how useful the sandbox was, both visually and conceptually, understanding geologic process and topographic maps. Incorporating the sand box into the lesson plan is by far the best idea and I cannot wait to see where this model goes into the future because its potential is beyond belief. Lastly, thanks for involving me with this experience, it has been very rewarding!! I love it."*

> *"I introduced the class by guiding them through drawing topographic lines. I used the whiteboard and they followed on their own papers. After we had drawn about 6 topo lines, I asked them to describe to me the landscape we were looking*

> *at. Silence. We had drawn a stream valley between two ridges, but the most detailed responses I got were, 'A hill.' Or 'A creek.' Then we went to the sandbox and replicated the map on the whiteboard. This is where it really clicked for them. They could see the connection between the topo lines and the actual topography. For the next ~20 minutes, I would draw a new topo map on the whiteboard and pairs of students would do their best to replicate in the sandbox what I had drawn. Their interest was captured. From there, I showed them on the sandbox how to draw a topographic profile, then passed out practice topo profiles for them to draw themselves. They performed beautifully."*

Students in the summer 2015 lab provided several good suggestions for scaling up these exercises to larger classes: "It might be cool to have a question box set up, with the sandbox. Maybe that way, even if all questions can't be answered at the time, the GTA can address them later with the whole class," and "Create a series of YouTube videos answering possible FAQs. This could benefit an ECU classroom as well as any other school with this technology."

One exercise students enjoyed was the model-building competition. This teaching tool was effective in the small summer lab (nine students), during which it was possible to use both the sandboxes for the same lab class. Two teams of students at a time were charged with modeling a specified terrain or process. The whole class then studied these and voted on which model was the most effective and correct. It would probably be beneficial to expand the use of this strategy whenever multiple sandboxes are available. However, during the fall and spring semesters, ECU teaches two introductory-geology labs at once in different rooms, so as of now, it will not be possible for a lab class to use more than one box. Another exercise worth trying in the future would be to choose sections from local topographic maps for the students to re-create in the sandbox. In addition, combining the use of model building with Google Earth Timelapse (which highlights imagery showing the effects of fluvial and coastal processes over time) may help students compare their models with the actual processes. For instance, Google Earth Timelapse (Ferrell, 2013) portrays erosion of the Outer Banks. Additional processes can be explored at https://earthengine.google.org/timelapse.

CONCLUSIONS

Using instructions and software downloaded from the LakeViz3D Web site (LakeViz3D, 2015a), it was possible to construct and implement a version of the AR sandbox at a teaching university with faculty and staff members who have basic knowledge of carpentry, computer hardware and software, and Linux operating systems. Then, several weeks of preparation were required to develop, pilot, and evaluate which potential activities fit into the existing course structure and to work through issues associated with landform building and software and hardware challenges. A sandbox demonstration lasting about 45 minutes appears to be an extremely valuable addition to introductory geology labs on topographic maps and surficial processes, especially to clarify the concepts of contour lines, terrain steepness, Rule of Vs, and topographic profiles. Based on a self-reported student survey given to 10 students (Table III), students perceive that hands-on time spent with the sandbox significantly enhances learning about fluvial and coastal features and processes and the ability to visualize 3D landscapes from 2D maps. Another invaluable aspect of the sandbox is the opportunity for students to study movement of virtual water interacting with modeled landscapes.

Small labs of 10 or fewer students are probably the optimal size to make most effective use of the sandbox, and it will be necessary to adapt exercises, which were successful with small groups, to benefit larger lab sections. The ubiquity of camera phones is an advantage in terms of saving time and submitting lab exercises for grading. Retraining of teaching assistants will be required to improve their comfort level with these open-ended activities and allow them to make effective use of the technology.

Students were unanimous in their perception that sandbox activities helped them understand topographic maps and surficial features and processes better than just studying topographic maps alone. A comment of one student summarizes the overall response of many:

> *"I felt so lucky that we were given the time and opportunity to experiment with this helpful tool. If sandboxes like the one we were exposed to were put in every public school, I feel it would go leaps and bounds in helping students of all ages more easily grasp some of the basic concepts of geology. Fund this! The cost seems so low to construct the model, it should open up many opportunities in the educational community. And this is coming from someone who has really struggled with geology!!"*

Acknowledgments

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