A Google Earth Grand Tour of the Terrestrial Planets

Declan De Paor,[1,a] Filis Coba,[2] and Stephen Burgin[3]

ABSTRACT

Google Earth is a powerful instructional resource for geoscience education. We have extended the virtual globe to include all terrestrial planets. Downloadable Keyhole Markup Language (KML) files (Google Earth's scripting language) associated with this paper include lessons about Mercury, Venus, the Moon, and Mars. We created "grand tours" of these bodies, guiding students to explore atmospheres, magnetospheres, landscapes, and interiors. The tours benefited from a study of 364 students in an introductory astronomy class. We compared learning outcomes for students using Google Earth versus static portable document format (PDF) files. In pre- and immediate posttests, there were small but statistically significant (p-value < 0.05) learning gains from the use of Google Earth; however, these did not persist in a long-term follow-up. There may have been insufficient differences between viewing text and images in Google Earth placemark balloons versus identical text and images in a PDF document. Consequently, we revised our tours, adding many more three-dimensional models, draped maps, and movies. We also assembled a table of links to virtual globes for other planets and moons, and a virtual solar system model, thus building a comprehensive teaching resource for introductory lunar and planetary science courses. © *2016 National Association of Geoscience Teachers*. [DOI: 10.5408/15-116.1]

Key words: Google Earth, Keyhole Markup Language, KML, planetary science

INTRODUCTION

For over a decade, avant garde geoscience instructors at primary, secondary, and tertiary levels have leveraged the three-dimensional (3D) visualization and active-learning affordances of Google Earth (Table I). Conference presentations describing Google Earth applications in geoeducation are too numerous to list. A search for "Google Earth" in the Geological Society of America's *Abstracts and Programs* yields 1,229 results, and there are 1,209 teaching resources listed in a search of the Science Education Resource Center (SERC, 2016). Google Earth is clearly a favorite teaching tool across a wide range of geoscience subdisciplines, and virtual globes are critical to professional geoscience research, especially with the ability of Google Earth Engine to analyze Big Geodata using tens of thousands of parallel processors (Hansen et al., 2013; Google Earth Engine, 2016). Our tours differ from prior work in comprehensively covering the terrestrial planets, efficiently delivering large image files via image tiling, and including multiple planet-scale 3D COLLADA models. (COLLADA is the format used for 3D building models in Google Earth, and models can be made up to twice Earth's diameter.)

Planetary science is one of the subdisciplines that potentially can benefit most from a Google Earth–based curriculum. The desktop application includes virtual globes only for Earth, the Moon,[4] and Mars, but Hirshon et al. (2010) created a tour of Mercury based on National Aeronautics and Space Administration (NASA) *Messenger* mission data, and De Paor et al. (2012a) created a Google Earth model of Venus using *Magellan*'s synthetic aperture radar (SAR) imagery. Both of these resources were designed with professionals and geoscience majors in mind. The tours presented here target introductory major and nonmajor general education students but could be readily adapted for primary, secondary, and informal education. Although the present paper is concerned with the terrestrial planets, for the sake of completeness, links to models of the outer planets and their moons are also listed in Table II. The latest addition to the collection is a Google Pluto model based on the *New Horizons* mission to that dwarf planet. Following the idea of Bennett (2016a, 2016b), we also created a virtual scale model of the solar system.

Our basic concept is a "grand tour" of the key features of each terrestrial planet (including our Moon, which can be thought of as a binary planet). Just as the elite social class of 19th century northern Europe embarked on a cultural grand tour to prepare for life in polite society, we want to send our students on a tour of places on terrestrial bodies about which scientifically literate citizens ought to know. Our argument is that, in the age of publicly funded space exploration involving several national space agencies, knowing about the highest mountain in the solar system is as basic to geospatial literacy as knowing about the highest mountain on Earth is to classical geography.

Each tour commences with an astronaut's overview from space, and then it zooms in on specific, media-rich placemarks, and ends with a concluding view from space. Surface imagery, geological maps, and other large draped images were processed through MapTiler™ software to

Received 15 August 2015; revised 13 April 2016 and 25 August 2016; accepted 6 September 2016; published online 02 November 2016.

[1]Department of Physics and Department of Ocean, Earth, and Atmospheric Sciences, Old Dominion University, Norfolk, Virginia 23529, USA.
[2]Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA.
[3]Department of Curriculum and Instruction, University of Arkansas, Fayetteville, Arkansas 72701, USA.
[a]Author to whom correspondence should be addressed. Electronic mail: ddepaor@odu.edu.

[4] We capitalize our Moon and refer to moons of other planets in lower case.

TABLE I: Prior literature referencing Google Earth in geoscience education includes a range of subdisciplines and topics as listed in the first column. Asterisks indicate primary (*) or secondary (**) school applications.

Topics	Papers
Assessment	Johnson et al. (2011)
Climate change	Chilcott and Haslett (2010)
Environmental science	Bodzin et al. (2014)**, Guertin and Neville (2011)**, Martínez-Graña et al. (2014)**
Field geology	Blenkinsop (2012), Boggs et al. (2012), De Paor et al. (2016), Dordevic and Wild (2012), Giorgis (2015), Granshaw and Duggan-Haas (2012), Kluge (2008), Lisle (2006), Treves and Bailey (2012), Whitmeyer et al. (2009a, 2009b, 2010)
Geological time	Parker (2011)
Geomorphology	Dolliver (2012)
Geophysics	De Paor (2008a, 2008b)
Hydrology	Habib et al. (2012)
Miscellaneous	Bailey and Chen (2011), Bailey et al. (2012), Goodchild (2008), Ratinen and Keinonen (2011), Rice et al. (2007)*,**, Whitmeyer et al. (2012)
Oceanography	Hochstaedter and Sullivan (2012), Zhang et al. (2013)
Physical geology	Monet and Greene (2012), Thorndycraft et al. (2009)
Lunar and Planetary geology	Brooks and De Paor (2009), De Paor (2009), Dordevic et al. (2009), Messenger (2016)
Plate tectonics	Almquist et al. (2012)**, Blank et al. (2012), De Paor et al. (2012b)
Regional geology	Hennessy et al. (2012)
Volcanology	Schipper and Mattox (2010)**

create tiled image pyramids that load sequentially upon zooming, similar to the way the Google Earth terrain itself loads. This ensures the highest possible resolution without loading multimegabyte image files that would slow computer responsiveness, as has been done frequently by others in the past. In each tour, we include an option to view the outlines of Earth's continents. This is intended to help students develop a sense of relative position and relative size of features on other planets.

GRAND TOUR OF THE TERRESTRIAL PLANETS

The Solar System to Scale

We recommend starting a classroom implementation with our Google Earth–based scale model of the solar system (available in the online journal and at http://dx.doi.org/10.5408/15-116s1). Almost all students grossly overestimate planetary radii in relation to the scale of planetary orbits. To

TABLE II: In addition to the four terrestrial tours discussed in this paper, this table contains links to virtual globes for all planets and major moons of the solar system. The first row links to a 1:1 million scale model of the solar system in Google Earth.

Body	Link	Creators
Solar system	http://www.digitalplanet.org/APP/SolarSystem_1m.kmz	Declan De Paor. Concept: Jeff Bennett
Mercury	http://messenger-education.org/googletours.php	NASA *Messenger* mission website
Venus	http://www.digitalplanet.org/APP/VenusInteriorLocal.kml	Mladen Dordevic, Vicki Hansen, Declan De Paor
Earth	http://earth.google.com	Google, Inc.
Moon	http://earth.google.com	Google, Inc.
Mars	http://earth.google.com	Google, Inc.
Jupiter	http://bbs.keyhole.com/ubb/download.php?Number=372403	Frank Taylor, http://www.gearthblog.com
	http://services.google.com/earth/kmz/jupiter_cassini_n.kmz	
Io	http://www.geode.net/Io.kmz	Mladen Dordevic
Saturn	http://bbs.keyhole.com/ubb/download.php?Number=534324	James Stafford, http://www.barnabu.co.uk
Titan	http://www.digitalplanet.org/APP/Titan.kmz	Declan De Paor
Uranus	http://www.gearthhacks.com/forums/downloads.php?do=file&act=down&id=31517	http://www.gearthhacks.com
Neptune	http://www.gearthhacks.com/forums/downloads.php?do=file&act=down&id=31516	http://www.gearthhacks.com
Pluto	http://geode.net/Pluto_New_Horizons.kmz	Declan De Paor
Moons	http://www.barnabu.co.uk/the-many-moons-of-google-earth/	James Stafford, http://www.barnabu.co.uk/

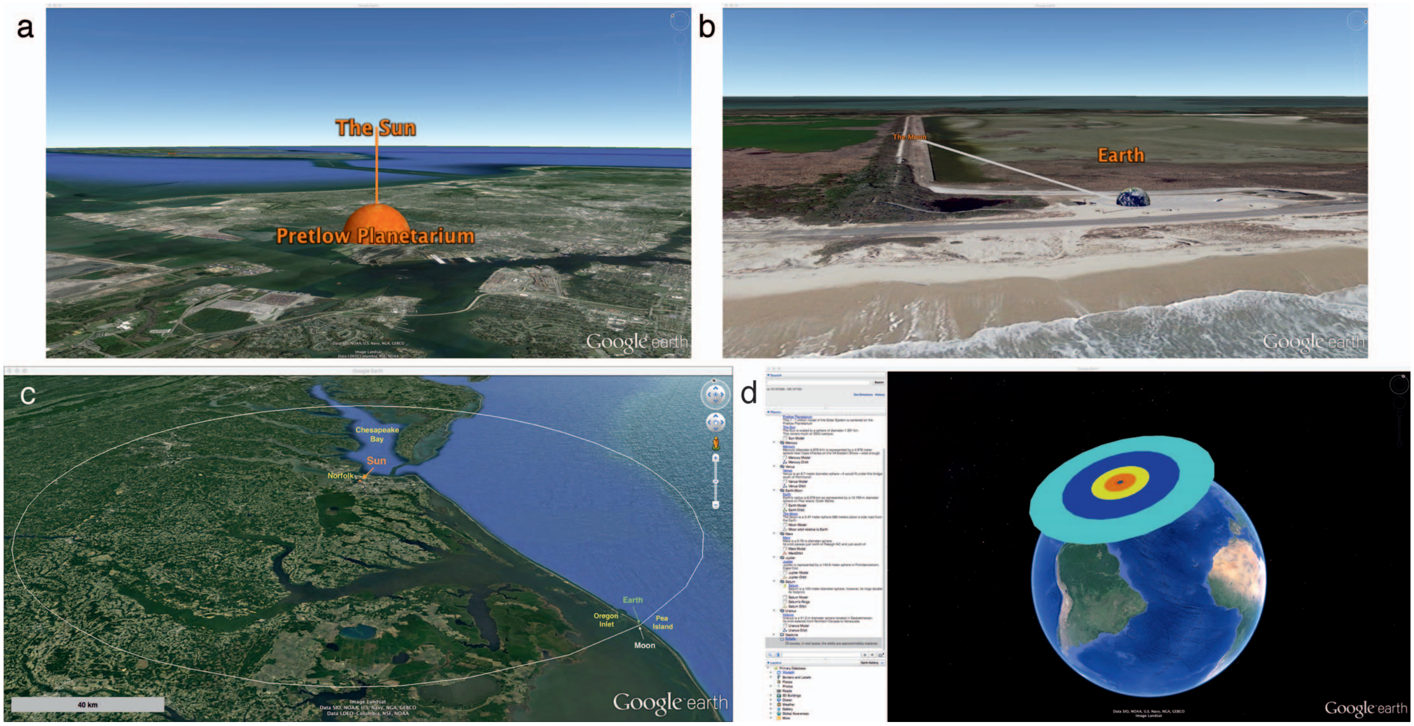

FIGURE 1: (a) In a 1:1 million scale model of the solar system on Google Earth, the Sun is represented by a 1.39-km-radius COLLADA model centered on the Pretlow Planetarium on the ODU campus. Students can actually fly into the model. It can be moved to a different location by editing the latitude and longitude attributes. (b) To the same scale, Earth is represented by a COLLADA model that fits in a parking lot on Pea Island in the Outer Banks of North Carolina. The Moon is on one side of a dirt road nearby. (c) Looking down upon the 1:1 million scale model of Earth's orbit, the orange Sun is just visible, but the model of Earth is smaller than the thickness of the line representing its orbit, and the model of the Moon is less than one pixel in diameter at this scale. (d) A COLLADA model of the ecliptic plane to the same scale. Orbits are color coded to the planets: red = Mars, orange = Jupiter, yellow = Saturn, blue = Uranus, cyan = Neptune. Google Earth is ©2016 Google, Inc. Data SIO, NOAA, US Navy, NGA, GEBCO, LDEO–Columbia, NSF. Image Landsat. Image ©2016 Digital Globe.

tackle this misconception, Bennett (2016a, 206b) described physical models constructed on the scale of 1 to 10 billion in Boulder, Colorado, the Washington, D.C., Mall, and elsewhere. In our courses, we previously used the Old Dominion University (ODU) Omniglobe™ to represent the Sun at approximately 1:1 billion scale, and a Skittle™ candy at 150 m distance to represent Earth. Using Google Earth, however, we were able to create a 1:1 million model without building the world's largest dome, or sending students on a long hike! The Sun is represented by a 1.39 km COLLADA model centered on ODU's Pretlow Planetarium in Norfolk, Virginia (Fig. 1a). To this scale, Earth fits in a parking lot on Pea Island in the Outer Banks of North Carolina, and the Moon is less than the width of a lane on a nearby dirt road (Fig. 1b). Figure 1c shows Earth's orbit to scale. Because of Google Earth's curvature, we created a flat COLLADA model of the ecliptic plane (Fig. 1d) to include the planets out to Neptune. Readers can move these models to their local regions by right-clicking in the Google Earth Places sidebar and editing their latitude and longitude. Future development could also include animating the migration of giant planets to demonstrate the Nice model of the Late Heavy Bombardment (Hahn, 2005).

Mercury

A virtual globe of Mercury is not built into Google Earth. The NASA *Messenger* mission outreach site does include a downloadable KMZ[5] file simulating Mercury on Google Earth (Messenger, 2016); however, that tour contains almost 1,000 places of interest—many more than can be accommodated in an undergraduate- or school-level course. Also, the KML code contains an error that causes Earth's terrain imagery to poke through on zooming. We created a more concise tour of key features of Mercury and overlaid it on Google Moon, which is much closer in size, does not have an atmosphere that students might neglect to turn off, and does not show tropics and polar circles on its grid in the View menu. This, and all other tours, is available for download from the supplemental documents (available in the online journal and at http://dx.doi.org/10.5408/15-116s1 through http://dx.doi.org/10.5408/15-116s7).

Hovering above the surface, students first see that there is effectively no atmosphere on Mercury, and they invariably note that the surface is quite similar to our Moon. In fact, instructors can challenge students to study the terrain and be able to tell whether they are looking at the Moon or Mercury. Students read about the dramatic difference in day and night temperatures, a consequence of Mercury's proximity to the Sun and slow rotation. The presence of ice in permanently shaded polar craters is highlighted and is

[5] A KMZ file is a zip archive of a Keyhole Markup Language (KML) document and dependent image and model files.

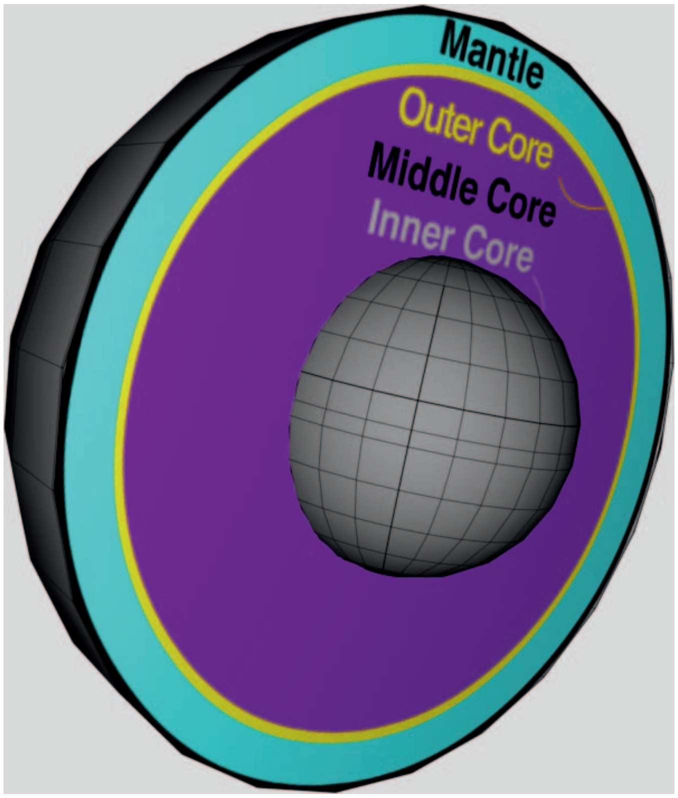

FIGURE 2: COLLADA models represent Mercury's cores. Gray = inner core, red = middle core, pyrite image = outer core.

explained by the planet's lack of axial tilt. Students also learn about 3:2 spin-orbit resonance and view Mercury's huge core. The inner, middle, and outer cores are represented by huge 3D COLLADA models (Fig. 2). Students can also manipulate a COLLADA model of the magnetic field and its interaction with the Sun's field.

In line with the classical European Grand Tour concept, the first tour stop on the surface is the Rembrandt Crater. Students then visit the Caloris Basin, including its faults and a volcano near its rim, and they follow a video ground wave to the antipodal crumpled terrain, a consequence of the entire planet ringing like a bell as a result of basin formation during the Late Heavy Bombardment 3.9 billion years ago.

Essential features of Mercury are the scarps called rupes resulting from ongoing cooling and shrinkage since core–mantle differentiation. A highlight of the tour is the large volcanic region that *Messenger* discovered near the north pole. Finally, students return to a satellite view of the planet and review its geological history.

Venus

Our Google Venus is built on Google Earth, which is similar in size. Here, instructors need to check that students do not display Earth's atmosphere or latitude and longitude grid. We created a graticule for Venus that displays longitude from 0° to 360° east of the prime meridian and does not have tropics or polar circles.

Hovering over Google Venus, students can compare and contrast the global features of Earth's so-called sister planet, including its bulk density, orbit, and spin. They view its atmosphere via an overlay and note the atmospheric superrotation. Next, the atmospheric overlay is turned off to reveal NASA SARS imagery, which is tiled over the surface, facilitating deep zoom. Placemarks point out the lack of an Earth-like division into land and sea, and the very different distribution of volcanic craters compared to Earth's mid-ocean ridges and volcanic arcs. The landscape is divided into Lowlands, Mesolands, and Highlands. Tour stops include Addams impact crater, with its melt apron, and pancake-like lava domes.

Students zoom in to two features unique to Venus—the Artemis superplume and the Ishtar terrain. They should be encouraged to debate the possibilities for past plate tectonics and discuss the concept of recent resurfacing. The tour ends again with an overview from space, a view of large COLLADA models of the interior (Fig. 3), and an account of the runaway greenhouse effect.

The Moon

The grand tour of our Moon is more detailed because we have more data from manned and unmanned missions and telescopic observations. Google Moon is built into Google Earth, and users are prompted to switch to it when they load the KML file. The tour begins with the familiar view of the near side from space. Students note dimensions, phases, tidal locking, and eclipses, and the division of the surface into heavily cratered terrain and smoother maria. They view hand specimens and thin sections of basalt, anorthosite, breccia, and orange soil, and a model of water–ice distribution. The tour of geological structures includes Hadley Rille, linear and arcuate fractures, volcanic domes, and wrinkle ridges. Students visit Tranquility Base, the place where the *Eagle* landed and Neil Armstrong took a giant leap for mankind. The stop includes historic video of this event, which surprisingly some students have not seen.

Students next compare the near and far sides of the Moon (Fig. 4), visiting prominent craters and maria. They compare gravity anomaly maps and are challenged to discuss the Big Whack theory of lunar formation, the possibility of a coalescence of two protomoons, and the Nice model explanation of the Late Heavy Bombardment and subsequent mare formation. The tour ends with the latest water–ice data suggesting true polar wandering.

Mars

Mars is also treated with considerable detail thanks to the amount of orbital and rover mission data available. To emphasize the difference in size of Mars and Earth, we created a semitransparent model of Earth's continents hovering high over the Martian surface and used the "extend to surface" feature to dramatize the scale difference (available in the online journal). Students view historic maps built into Google Mars and visit 3D models of its moons, Phobos and Deimos (Fig. 5a).

The tour addresses atmosphere and climate, surface features (Fig. 5b), rocks and outcrops, and the geophysics and geology of Mars. It is worth remembering that the current generation of senior high school and college students were young children when the NASA rovers first landed on Mars and may have a strong emotional connection to those exciting events. Tour stops include real surface imagery, dust devils, and a Martian sunset. Ending the tour, students are invited to discuss the possibilities for

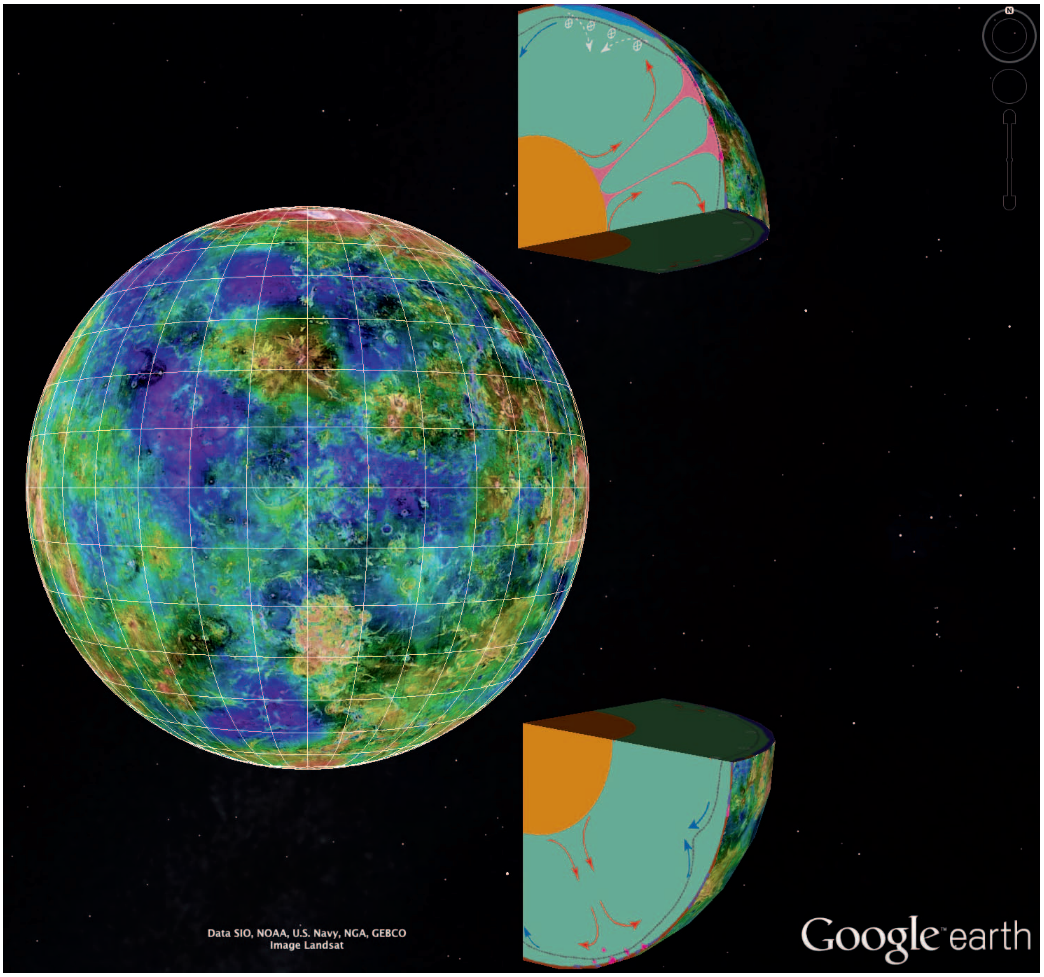

FIGURE 3: Google Venus was created by Hansen et al. (2011) by tiling NASA SARS imagery over Google Earth. Large COLLADA models represent the planet's interior. Cross sections of mantle plumes are courtesy of Vicki Hansen.

life on Mars and the probability that human life will reach the planet in current lifetimes.

Other Worlds and Other Times

Although the above concludes the resources that benefited from our classroom testing, we include, in Table II, links to the giant planets, moons, and the dwarf planet Pluto. In the near future, we plan a series of grand tours of planet Earth, highlighting ocean basins, Archean cratons, and younger rocks and regions. In addition to Google Earth, we are developing for the Cesium virtual globe.

Evaluation

The effectiveness of Google Earth as an instructional resource has been empirically investigated in the classroom (e.g., Coba et al., 2015). Using pre- and posttests, Giorgis (2015) found that Google Earth assignments improved students' spatial visualization skills and eliminated a pretest gender gap. There is evidence that putting students in charge of their learning experience is beneficial to learning outcomes (e.g., Herrington and Kervin, 2007). Laal and Ghodsi (2012) demonstrated the benefits of collaborative learning, as occurred in our three-person laboratory groups, versus teacher-lead instruction to a passive student audience.

As reported in Coba et al. (2015), the authors carried out a study comparing learning outcomes from 364 general education students at Old Dominion University, a large metropolitan public university on the mid-East Coast of the U.S. The undergraduate population of about 25,000 students is half female, a quarter African American, a third residential, and two thirds commuter/distance learners. All but a handful of students were nonscience majors.

The course topic was "The Solar System," with a strong emphasis on Earth and the terrestrial planets. Laboratory classes were divided into 12 sections with approximately 32 students per section and one 12-student honors section. Students worked in groups of three per computer, and groups were randomly given either a Google Earth–based KML tour (the treatment group) or a PDF document (the comparison group). The KML tours consisted of a series of placemarks on a planet's surface. Students flew to locations with a preset camera view, and a balloon displayed text and graphics (a few balloons contained a video clip or graphics interchange format [GIF] animation). Students were able to roam and explore surrounding areas using Google Earth's navigation controls.

The PDF tours consisted of identical text and graphic content, albeit without animated images and videos. The style was textbook-like, with two columns and embedded

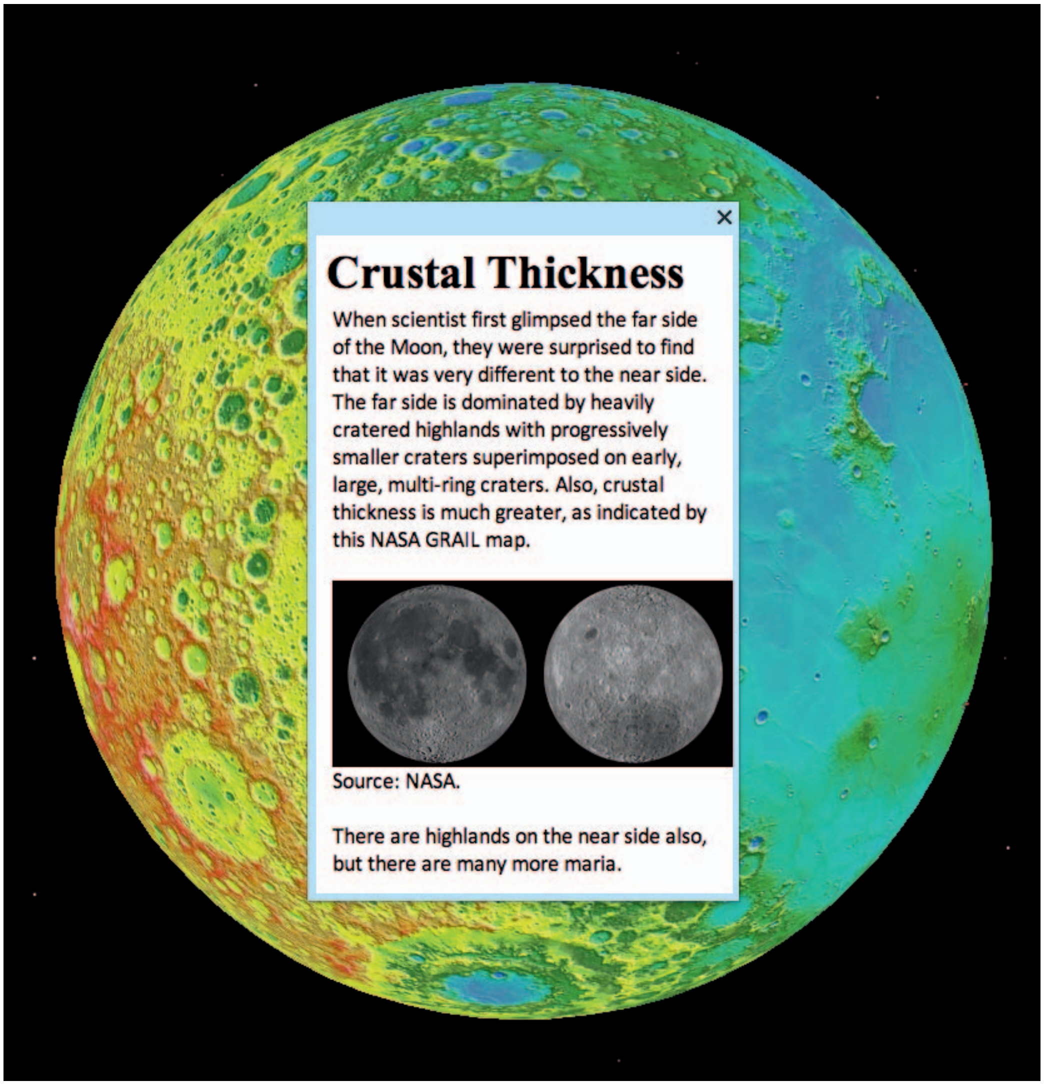

FIGURE 4: A NASA crustal thickness map helps students to compare the Moon's far side (left) and near side (right).

figures. Students were asked to take turns reading the PDF text aloud to their group.

Assessment included a pretest, immediate posttests, follow-up posttests, instructor's anecdotal observations, and a few semistructured student interviews (available in the online journal and at http://dx.doi.org/10.5408/15-116s7). Test questions were designed to limit guessing and encourage critical thinking rather than memorization. For instance, the use of multiple correct answers, although difficult to score, was formulated to encourage reasoning skills.

Data Analysis

Pre-, post-, and follow-up tests were scored using two rubrics, an M-rubric for multiple-choice questions and a C-rubric for critical thinking or short-answer questions (available in the online journal). A 2×2 repeated measures analysis of variance (ANOVA; Everitt, 2014) was used to test the short-term results. Test scores were converted into z scores[6] to make the results for different planets comparable. Data were screened for underlying assumptions of ANOVA (normal distribution, equality of variances, etc.) and no significant violations were found. To investigate long-term effects, we used a 3×2 repeated measures ANOVA, which assessed the change in test scores of treatment versus comparison groups from pretest to posttest to follow-up.

RESULTS

The outcome was a small but statistically significant learning gain in the posttest (p-value < 0.05); however, this dissipated in the follow-up posttest (Table III and Figs. 6a–6b). Figure 6c shows estimated marginal means (i.e., deviation from average scores) versus time. The KML group scored higher than the class average (indicated by 0.00), whereas the average PDF posttest score was below the average for all students. There was a significant difference between pre- and posttest ($p = 0.041$) but not between pretest and follow-up test ($p = 0.069$). Results of the 2×2 multivariate repeated measures ANOVA indicated a significant multivariate interaction between time and treatment condition: Wilks's $\lambda = 0.98$, $F(1, 200) = 4.22$, $\eta^2 = 0.02$, $p < 0.05$ (e.g., Mardia et al., 1979). This

[6] A z-score is the number of standard deviations between a score and the mean of a set of scores, positive being above, negative below, and zero equal to the mean.

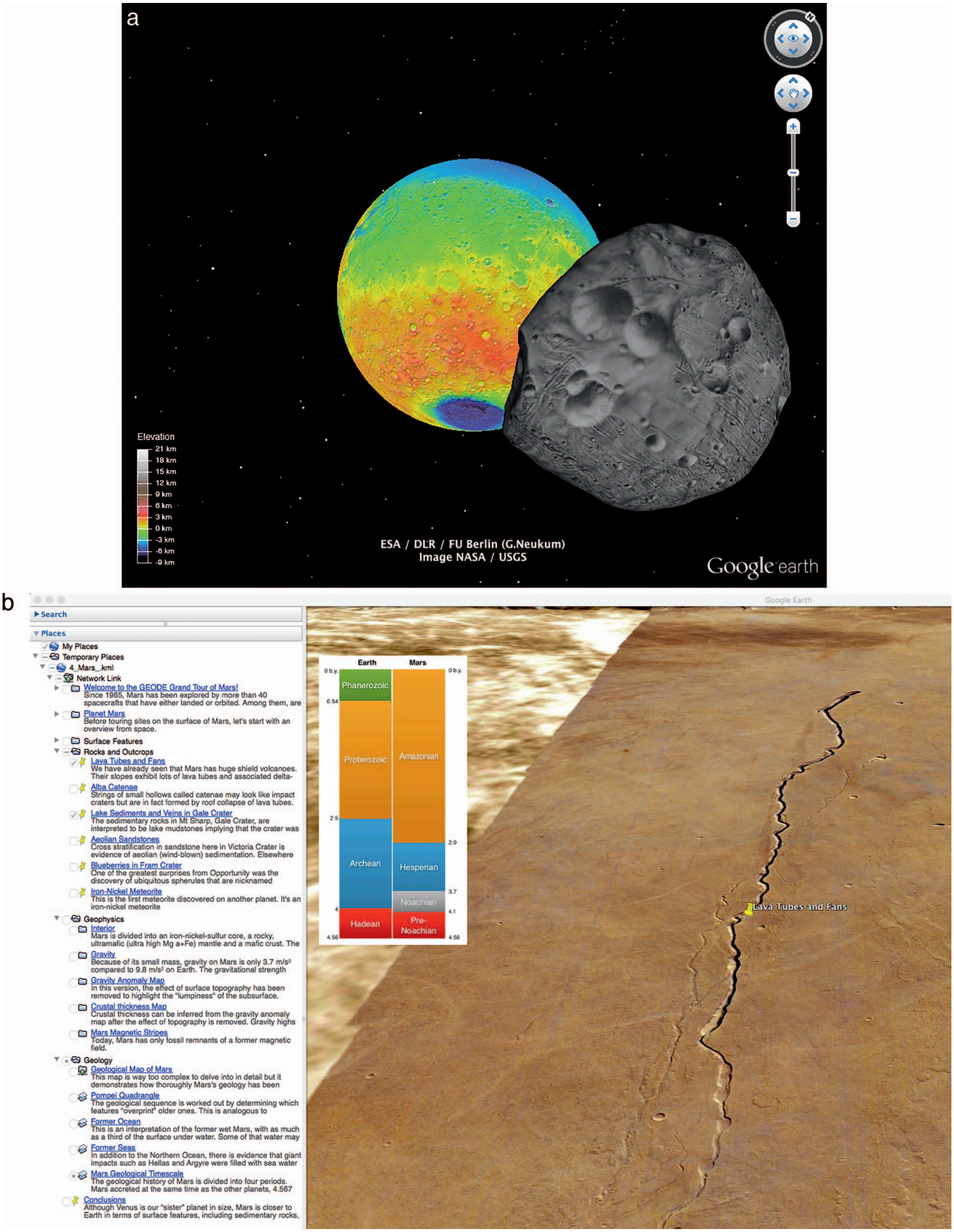

FIGURE 5: (a) COLLADA model of Mars's moon Phobos. Source: http://www.barnabu.co.uk and http://publish.uwo.ca/~pjstooke/. (b) Surface imagery in Google Mars has excellent quality, as illustrated by this lava tube. Data: ESA, DLR, FU Berlin (G. Neukum). Image NASA, USGS.

TABLE III: Average scores and ranges for the treatment and comparison groups in pretests, immediate posttests, and delayed follow-up tests.

	Pretest (%)	Posttest (%)	Follow-up (%)
Whole class	36 ± 12	47 ± 13	43 ± 14
Treatment (KML)	35 ± 13	48 ± 12	42 ± 13
Comparison (PDF)	37 ± 12	44 ± 14	44 ± 14
Change	Statistically significant gain for KML versus PDF		Not significant

means that the treatment students who used Google Earth were, on average, 0.13 standard deviations above average test grade at posttest, while comparison students were 0.16 standard deviations below average test grade. Both KML and PDF groups made modest gains from pre- to posttest.

The multivariate results for the time × condition interaction (pre-, post-, follow-up) were marginally significant: Wilks's $\lambda = 0.97$, $F(2, 164) = 2.71$, $\eta^2 = 0.03$, $p = 0.069$. While the linear within-subjects univariate test was nonsignificant [$F(1, 165) = .005$, $\eta^2 < 0.00$, $p = 0.945$], the quadratic interaction effect was significant [$F(1, 165) = 5.33$, $\eta^2 < 0.03$, $p < 0.05$]. Specifically, the treatment (KML) group increased in test z score from pre- to posttest and then decreased in test z score from posttest to follow-up, while the comparison group decreased in test z score from pre- to posttest and

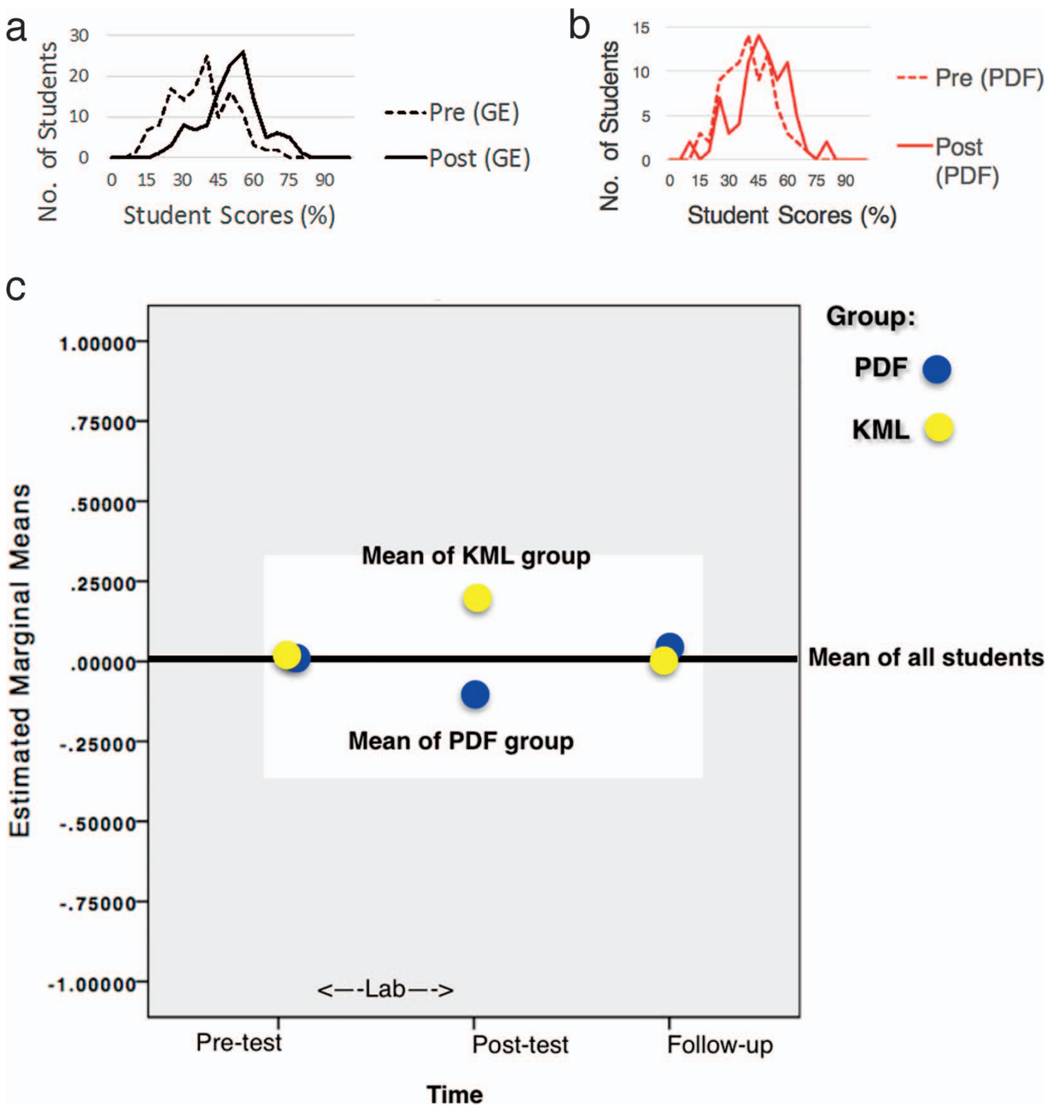

FIGURE 6: Distribution of pretest and immediate posttest scores. (a) treatment group using Google Earth (GE), and (b) comparison group using PDF files with identical content. (c) Plot of estimated marginal means versus time. Both groups did better on immediate posttest, but Google Earth group did significantly better. Then both groups reverted on follow-up test. They were still better than their pretest scores. Note that absolute performance is not shown, as it is not relevant.

then increased in test *z* score from posttest to follow-up. Details of our study methods are available in the supplemental documents (available in the online journal). but the take-home message is that the effect of using Google Earth (KML) was short-term, since significant differences between the groups disappeared in the follow-up tests.

DISCUSSION AND CONCLUSIONS

The test results are not entirely surprising given the similarity of the content presented to the two groups,[7] the low level of nonmajor student motivation, and the fact that our institutional review board (IRB) approval required that students get 100% credit regardless of performance. The main outcome of the study was to cause us to revise the tours, adding much more interactivity, including 3D models, draped maps, and movies, in order to widen the gap between KML and PDF versions.

We see evidence for the value of Google Earth and other virtual globes, such as Cesium and NASA World Wind, in lunar and planetary science education. First, they allow students to interact with an authentic tool utilized by practicing geoscientists when asking and seeking answers to questions about our place in the solar system. For example, students participating in our test classes had the opportunity to discuss and ask questions about present and past tectonic activity on planets and moons. This is similar to what NASA scientists do when they receive new images from space missions and try to make sense of the data that they have collected. Additionally, Google Earth can be conceptualized as an example of a scientific model. Recent reform documents for K–12 science education have emphasized the importance of modeling as a scientific practice to which students should be introduced prior to their undergraduate studies (Schweingruber et al., 2012). The 3D models allow science learners to visualize concepts and interact with them in ways that might allow for explanation building (Coll and Lajium, 2011). Coll and Lajium (2011) also pointed out the strong links between modeling and the nature of scientific knowledge.

Our tours of terrestrial planets through interactive virtual globes offer an innovative way for geoscience educators to take their teaching to the next level. They can promote the authentic use of models by their students in ways that offer opportunities for meaningful and engaging learning. We are encouraged by our students' enthusiastic response to these activities. We encourage readers to use all of the virtual globe resources in the supplemental documents (available in the online journal) and provide feedback. We can all work together to build a stronger and more innovative teaching environment for the next generation.

In our study, we identified a significant hindrance in the lack of student familiarity with basic Google Earth navigation controls. Instructors can easily overestimate the technical savvy of students. Despite their expertise in communicating via Facebook or Twitter, students needed lots of help with very basic aspects of Google Earth, especially changing the camera view. To mitigate this issue, a detailed set of navigational instructions was compiled. It is essential that students know how to "look around" by a combination of arrow keys and modifiers (shift/control, etc.). Although Google Earth is available for mobile devices, that version has limited functionality. We have therefore concentrated on the desktop client.

While the authors are principally involved with undergraduate education and public outreach, there is every reason to believe that elementary, middle, and high school students could benefit from interactions with our virtual tools in their respective classrooms. Primary and secondary science teachers are encouraged to test these resources with their own students, modifying the tour stop balloons to suit the age group. Many schools in the U.S., and worldwide, have mobile computer carts that can be brought into the classroom. However, according to teachers, obtaining permission to install desktop applications such as Google Earth can be a challenge. Some teachers have to obtain permission at school district or even state level. We anticipate that the next version of Google Earth will be accessible via web browsers, replacing the deprecated Google Earth API and browser plug-in. If so, teachers will be able to overcome the problem of software installation restrictions in schools.

Museums that hold summer camps and informal education laboratory classes could benefit from the tours by allowing visitors to use them directly or pairing them with a planetarium show. The user guide and lesson plans allow instructors from all backgrounds to choose topics appropriate to their students or audiences.

Acknowledgments

This work was supported by National Science Foundation (NSF), grant 1323419, "Google Earth for Onsite and Distance Education (GEODE)" and by a Google Geo Curriculum Award. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation or Google, Inc. Thanks are due to Dr. Anthony Perez, who helped us analyze and report the pre- and posttests, and the editors and anonymous reviewers for detailed suggestions that improved the manuscript.

REFERENCES

Almquist, H., Blank, L., and Estrada, J. 2012. Developing a scope and sequence for using Google Earth in the middle school earth science classroom. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 403–412.

Bailey, J.E., and Chen, A., eds. 2011, The role of virtual globes in science. *Computers and Geosciences*, 37(1):1–110.

Bailey, J.E., Whitmeyer, S.J., and De Paor, D.G. 2012. Introduction: The application of Google Geo Tools to geoscience education and research. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. vii–xix.

Bennett, J. 2016a. Colorado scale model solar system. Available at http://www.jeffreybennett.com/model-solar-systems/colorado-scale-model-solar-system/ (accessed 25 August 2016).

[7] This conclusion was actually prompted by an anonymous reviewer of this paper.

Bennett, J. 2016b. Voyage scale model solar system. Available at http://www.jeffreybennett.com/model-solar-systems/voyage-scale-model-solar-system/ (accessed 25 August 2016).

Blank, L.M., Plautz, M., Almquist, H., Crews, J., and Estrada, J. 2012. Using Google Earth to teach plate tectonics and science explanations. *Science Scope*, 35(9):41–48.

Blenkinsop, T.G. 2012. Visualizing structural geology: From Excel to Google Earth. *Computers and Geosciences*, 45:52–56.

Bodzin, A.M., Anastasio, D., and Kulo, V. 2014. Designing Google Earth activities for learning Earth and environmental science. *In* MaKinster, J., Trautmann, N., and Barnett, M., eds., Teaching science and investigating environmental issues with geospatial technology. Dordrecht, Netherlands: Springer, p. 213–232.

Boggs, K.J., Dordevic, M.M., and Shipley, S.T. 2012. Google Earth® models with COLLADA and WxAzygy® transparent interface: An example from Grotto Creek, Front Ranges, Canadian Cordillera. *Geoscience Canada*, 39(2):56–66.

Brooks, W.D., and De Paor, D.G. 2009. Construction and presentation of Google Earth models for undergraduate education. *Geological Society of America Abstracts with Programs*, 41(7):92.

Chilcott, M., and Haslett, S.K. 2010. Climate change and sustainable development education through the lens of Google Earth. *Teaching Earth Sciences*, 35(1):20.

Coba, F., Burgin, S., and De Paor, D. 2015. KML versus PDF: An examination of student learning associated with non-traditional Earth and planetary geology laboratory activities. *Geological Society of America Abstracts with Programs*, 47(3):48.

Coll, R.K., and Lajium, D. 2011. Modeling and the future of science learning. *In* Khine, M.S., and Saleh, I.M., eds., Models and modeling. Dordrecht, Netherlands: Springer, p. 3–21.

De Paor, D.G. 2008a. Enhanced visualization of seismic focal mechanisms and centroid moment tensors using solid models, surface bump-outs, and Google Earth. *Journal of the Virtual Explorer*, 29(2):100.

De Paor, D.G. 2008b. Using Google SketchUp with Google Earth for scientific applications. Google Tech Talk. San Francisco, CA: Google. Available at https://www.youtube.com/v/6cVJqvsfxvo (accessed 25 August 2016).

De Paor, D.G. 2009. Visualizations of stellar, planetary, and lunar interiors using Google Earth. *In* Seaton, P., ed., Proceedings of Middle Atlantic Planetarium Society. Bowie, MD: Middle Atlantic Planetarium Society. Available at http://www.mapsplanetarium.org/category/conference/conference-archive/2009-conference/ (accessed 25 August 2016).

De Paor, D.G., Dordevic, M.M., Karabinos, P., Tewksbury, B.J., and Whitmeyer, S.J. 2016. The fold analysis challenge. *Journal of Structural Geology*, 85:85–94.

De Paor, D.G., Hansen, V.L., and Dordevic, M.M. 2012a. Google Venus. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 367–382.

De Paor, D.G., Wild, S.C., and Dordevic, M.M. 2012b, Emergent and animated COLLADA models of the Tonga Trench and Samoa Archipelago: Implications for geoscience modeling, education, and research. *Geosphere*, 8(2):491–506; doi: 10.1130/GES00758.1.

Dolliver, H.A. 2012. Using Google Earth to teach geomorphology. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 419–429.

Dordevic, M.M., De Paor, D.G., and Whitmeyer, S.J. 2009. Understanding volcanism on terrestrial planets and moons using virtual globes and COLLADA models. *Geological Society of America Abstracts with Programs*, 41(7):260.

Dordevic, M.M., and Wild, S.C. 2012. Avatars and multi-student interactions in Google Earth–based virtual field experiences. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 315–321.

Everitt, B.S. 2014. Repeated measures analysis of variance. Wiley StatsRef: Statistics Reference Online. Hoboken, NJ: John Wiley & Sons, Ltd.; doi: 10.1002/9781118445112.stat06585.

Giorgis, S. 2015. Google Earth mapping exercises for structural geology students—A promising intervention for improving penetrative visualization ability. *Journal of Geoscience Education*, 63(2):140–146.

Goodchild, M.F. 2008. The use cases of digital earth. *International Journal of Digital Earth*, 1(1):31–42.

Google Earth Engine. 2016. A planetary-scale platform for Earth science data & analysis. Available at https://earthengine.google.com (accessed 25 August 2016).

Granshaw, F.D., and Duggan-Haas, D. 2012. Virtual fieldwork in geoscience teacher education: Issues, techniques, and models. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 285–303.

Guertin, L., and Neville, S. 2011. Utilizing Google Earth to teach students about global oil spill disasters. *Science Activities: Classroom Projects and Curriculum Ideas*, 48(1):1–8.

Habib, E., Ma, Y., and Williams, D. 2012. Development of a web-based hydrologic education tool using Google Earth resources. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 431–439.

Hahn, J. 2005. Planetary science: When giants roamed. *Nature*, 435:4432–4433; doi: 10.1038/435432a.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., and Kommareddy, A. 2013. High-resolution global maps of 21st-century forest cover change. *Science*, 342:850–853.

Hansen, V.L., Dordevic, M.M., De Paor, D.G., and Bannister, R.A. 2011. A virtual field trip to Venus's Artemis—Our solar system's largest plume/super-plume: A journey across the crust and to the core. *Geological Society of America Abstracts with Programs*, 43(5):476.

Hennessy, R., Arnason, T., Ratinen, I., and Rubensdotter, L. 2012. Google Earth geo-education resources: A transnational approach from Ireland, Iceland, Finland, and Norway. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 413–418.

Herrington, J., and Kervin, L. 2007. Authentic learning supported by technology: Ten suggestions and cases of integration in classrooms. *Educational Media International*, 44(3):219–236.

Hirshon, B., Chapman, C.R., Edmonds, J., Goldstein, J., Hallau, K.G., Solomon, S.C., Vanhala, H., Weir, H.M., and the Messenger Education Public Outreach (EPO) Team. 2010. Google Mercury: The launch of a new planet. San Francisco, CA: American Geophysical Union, Fall Meeting, abstract ED31A-0605.

Hochstaedter, A., and Sullivan, D. 2012. Oceanography and Google Earth: Observing ocean processes with time animations and student-built ocean drifters. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 441–451.

Johnson, N.D., Lang, N.P., and Zophy, K.T. 2011. Overcoming assessment problems in Google Earth–based assignments. *Journal of Geoscience Education*, 59(3):99–105.

Kluge, S. 2008. Encounter Earth: Interactive geoscience explorations. New York: Pearson Education, p. 72.

Laal, M., and Ghodsi, S.M. 2012. Benefits of collaborative learning. *Procedia—Social and Behavioral Sciences*, 31:486–490.

Lisle, R. J. 2006. Google Earth: A new geological resource. *Geology Today*, 22(1):29–32.

Mardia, K.V., Kent, J.T., and Bibby, J.M. 1979. Multivariate analysis. San Diego, CA: Academic Press.

Martínez-Graña, A.M., González-Delgado, J., Pallarés, S., Goy, J.L., and Llovera, J.C. 2014. 3D virtual itinerary for education using Google Earth as a tool for the recovery of the geological heritage of natural areas: Application in the "Las Batuecas Valley" Nature Park (Salamanca, Spain). *Sustainability*, 6(12):8567–8591.

Messenger, 2016. Explore Mercury in Google Earth. Available at http://www.messenger-education.org/googletours.php (accessed 25 August 2016).

Monet, J., and Greene, T. 2012. Using Google Earth and satellite imagery to foster place-based teaching in an introductory physical geology course. *Journal of Geoscience Education*, 60(1):10–20.

Parker, J.D. 2011. Using Google Earth to teach the magnitude of deep time. *Journal of College Science Teaching*, 40(5):23–27.

Ratinen, I., and Keinonen, T. 2011. Student-teachers' use of Google Earth in problem-based geology learning. *International Research in Geographical and Environmental Education*, 20(4):345–358.

Rice, M., Ezell, B., Johnson, D., Sullivan, S., Edgington, W., Robinson, K., and Robinson, G. 2007. Google Earth: A tool to assist pre-service teachers in learning to effectively implement interdisciplinary units. *In* Carlsen, R., McFerrin, K., Price, J., Weber, R., and Willis, D., eds. Proceedings of Society for Information Technology and Teacher Education International Conference. Chesapeake, VA: Association for the Advancement of Computing in Education (AACE), p. 3134–3138.

Schipper, S., and Mattox, S. 2010. Using Google Earth to study the basic characteristics of volcanoes. *Science Scope*, 34(3):28–37.

Schweingruber, H., Keller, T., and Quinn, H., eds. 2012. A framework for K–12 science education: Practices, crosscutting concepts, and core ideas. Washington, DC: National Academies Press. p. 400.

Science Education Resource Center (SERC). 2016. Science Education Resource Center. Available at http://serc.carleton.edu/serc/search.html?search_text=google+earth (accessed 25 August 2016).

Thorndycraft, V.R., Thompson, D., and Tomlinson, E. 2009. Google Earth, virtual fieldwork and quantitative methods in physical geography. *Planet*, 22(1):48–51.

Treves, R., and Bailey, J.E. 2012. Best practices on how to design Google Earth tours for education. *In* Whitmeyer, S.J., Bailey, J.E., De Paor, D.G., and Ornduff, T., eds., Google Earth and virtual visualizations in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America, p. 383–394.

Whitmeyer, S.J., Bailey, J., De Paor, D.G., and Ornduff, T., eds. 2012. Google Earth and virtual visualization in geoscience education and research. Geological Society of America Special Paper 492. Boulder, CO: Geological Society of America. p. 468.

Whitmeyer, S.J., Feely, M., De Paor, D., Hennessy, R., Whitmeyer, S., Nicoletti, J., Santangelo, B., Daniels, J., and Rivera, M. 2009a. Visualization techniques in field geology education: A case study from western Ireland. In Whitmeyer, S.J., Mogk, D.W., and Pyle, E.J., eds., Field geology education: Historical perspectives and modern approaches. Geological Society of America Special Paper 461. Boulder, CO: Geological Society of America, p. 105–115.

Whitmeyer, S.J., Mogk, D.W., and Pyle, E.J., eds. 2009b. Field geology education: Historical perspectives and modern approaches. Geological Society of America Special Paper 461. Boulder, CO: Geological Society of America, p. 45–56.

Whitmeyer, S.J., Nicoletti, J., and De Paor, D.G. 2010. The digital revolution in geologic mapping. *GSA Today*, 20(4/5):4–10.

Zhang, X., Dong, W., Jiang, X., Shi, S., and Chi, T. 2013. "Digital earth" in support of an online oceanic educational public service and popularization. *Acta Oceanologica Sinica*, 32(5):82–86.