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Visualization techniques in field geology education: A case study from western Ireland

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ABSTRACT

Geoscience students often have difficulty interpreting real-world spatial relationships from traditional two-dimensional geologic maps. This can be partly addressed with direct, tactile field experiences, although three-dimensional (3-D) cognition can still be hampered by incomplete exposure of all spatial dimensions. Many of these barriers can be overcome by incorporating computer-based, virtual 3-D visualizations within undergraduate field-oriented curricula. Digital field equipment is fast becoming a standard tool in environmental, engineering, and geoscience industries, in part because of the increased accessibility of ruggedized computers equipped with global positioning system (GPS) receivers. Handheld computers with geographic information systems (GIS) software record and display data in real time, which

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increases the accuracy and utility of draft field maps. New techniques and software allow digital field data to be displayed and interpreted within virtual 3-D platforms, such as Google Earth. The James Madison University Field Course provides a field geology curriculum that incorporates digital field mapping and computer-based visualizations to enhance 3-D interpretative skills. Students use mobile, handheld computers to collect field data, such as lithologic and structural information, and analyze and interpret their digital data to prepare professional-quality geologic maps of their field areas. Student data and maps are incorporated into virtual 3-D terrain models, from which partly inferred map features, such as contacts and faults, can be evaluated relative to topography to better constrain map interpretations. This approach familiarizes students with modern tools that can improve their interpretation of field geology and provides an example of the way in which digital technologies are revolutionizing traditional field methods. Initial student feedback suggests strong support for this curriculum integrating digital field data collection, map preparation, and 3-D visualization and interpretation to enhance student learning in the field.

INTRODUCTION

Fieldwork has been the backbone of geologic investigation and presentation since William Smith produced the first recognized geologic map of England and Wales (Smith, 1815). Traditional geologic maps show three-dimensional (3-D) features on a two dimensional (2-D) surface, which requires observers to mentally visualize the vertical dimension of geologic structures and landforms depicted on maps. Smith displayed interpretations of geology in the vertical dimension by including cross sections on his map, a style of presentation that became standard on all geologic maps. More recent illustrative methods that expand on the basic map and cross-section depiction of geology include sequential cross sections (e.g., Dewey and Bird, 1970), block diagrams (e.g., Argand, 1922; Love *et al.*, 1972), and balanced cross sections (e.g., Dahlstrom, 1969; Elliott, 1983; Suppe, 1985; De Paor, 1988), among others. To a large extent, the basic methods of field data collection and map-based presentation of geologic interpretations have remained largely unchanged from Smith's day through the twentieth century. However, recent advances in computer hardware and software have revolutionized the collection, interpretation, and presentation of geologic field data, with direct applicability to field education and pedagogy.

An ongoing challenge for geoscience educators is to ensure that students are able to recognize and interpret real-world geologic structures from a range of perspectives. Many students have difficulty visualizing the 3-D geometries of geologic structures and landforms when presented with traditional paper maps and cross sections. In addition, classroom instruction often lacks the hands-on experience of working with real materials in their natural setting. As a result, field-based education is still viewed by many geoscience educators as a core component in the development of 3-D visual acuity (Butler, 2007). Our experience of teaching geology in field environments, both in Europe and the United States, suggests that the majority of undergraduate students have three main conceptual difficulties when visualizing landscape and its geologic influences:

(1) understanding and visualizing the 3-D nature of geologic structures and how they intersect topography, which is particularly apparent when students are confronted with geologic features on 2-D surfaces, such as outcrops or geologic maps, and are asked to extrapolate the features into the third dimension;

(2) extrapolating small-scale observations to larger scales (e.g., relating information from a field outcrop to a regional geologic map); and

(3) visualizing the evolution and modification of geologic structures and landforms through time, both forward into the future and backward into geologic history.

Modern, effective teaching and learning practices in the geosciences typically make use of appropriate visual displays and animations to demonstrate geologic structures, processes, and their interaction with the landscape. New technology has facilitated a dramatic change in the way geology is mapped, displayed, and evaluated because of the availability of ruggedized, handheld computers that easily log geological, geochemical, geophysical, and/or hydrological data in the field (e.g., Swanson and Bampton, this volume). These systems record and display data in real time, which increases the accuracy and utility of working field maps. Since most geologic maps are now produced digitally using integrated graphics programs, such as ArcGIS® and Adobe Illustrator®, the compatibility of handheld field computers with office and laboratory systems enables the seamless transfer of field data and interpretations. Removal of the time-consuming step of hand-drawing a field map while retaining accuracy between digital data and outcrop evidence means that digital field mapping will be the present and future method for geologic map preparation.

Perhaps the most revolutionary technological advancement in geologic fieldwork is the potential for integrated, virtual (computer-aided) 3-D visualization of field data. Digital elevation models (DEMs) are available for most regions of the developed world, and the universal access to global terrain models, through programs such as Google Earth and NASA World Wind, means that field researchers can use this data to evaluate and constrain working maps. Most geologic maps have a significant component of interpretation due to incomplete exposure of lithologies

in the field coupled with a lack of direct geologic evidence for all three spatial dimensions. Computer-facilitated visualization of 2-D geologic maps draped over virtual 3-D topography can improve interpretations, and these methodologies and cognitive implications are easily grasped by novice students as well as geoscience professionals.

In this paper, we advocate a new iterative approach to geologic fieldwork that uses handheld computers to record data and interpretations in the field. Working field maps and interpretations are draped over virtual 3-D terrains and continually evaluated throughout the mapping process. Data collection, digital mapping, and 3-D evaluation occur simultaneously as an iterative process during which working field interpretations are continuously updated at the outcrop. This process ultimately yields a well-constrained and field-tested geologic map. Exercises based on this iterative mapping approach are an important component of the James Madison University field course in Ireland, where upper-level undergraduate geoscience students receive capstone field-based education. Specific learning goals for the field course digital mapping exercises focus on the improvement of students' abilities to understand, visualize, and interpret 3-D geologic features from outcrop evidence. Broader goals include providing students with technical skills recognized as important by industry and academic geoscience professionals.

BACKGROUND

Digital Mapping in the Field

Geographic information systems (GIS) software has been widely used by the U.S. Geological Survey and other geoscience, environmental, and engineering industries (Longley et al., 2001) for many years as the storage and presentation medium of choice for geologic data. Early limitations of GIS software (Mies, 1996) and the lack of efficient mobile hardware slowed the adoption of GIS as a mapping tool by many field geologists. This all changed when civilian scrambling of the global positioning system (GPS) ceased in 2000, and inexpensive, accurate handheld GPS devices such as those made by Magellan™ and Garmin™ became readily available. Modern GIS software has geology-oriented toolkits for the preparation of geologic maps and, in many cases, functions effectively on mobile GPS-inclusive hardware (Kramer, 2000; Jackson and Asch, 2002). As a result, familiarity with GIS software and associated hardware has become an important skill for employment within geoscience-related industries, including fieldwork-intensive occupations such as state geological surveys, departments of environmental quality, and civil engineering (see www.agiweb.org/workforce).

Handheld field computers running GIS software allow the user to record a variety of geologic data digitally in the field. A geologist may view his or her location in relation to other data, such as topographic maps and/or aerial photos (Fig. 1A), and new geologic data can be stored in a spatial database designed for a specific field problem (Fig. 1B). The integration of hand-

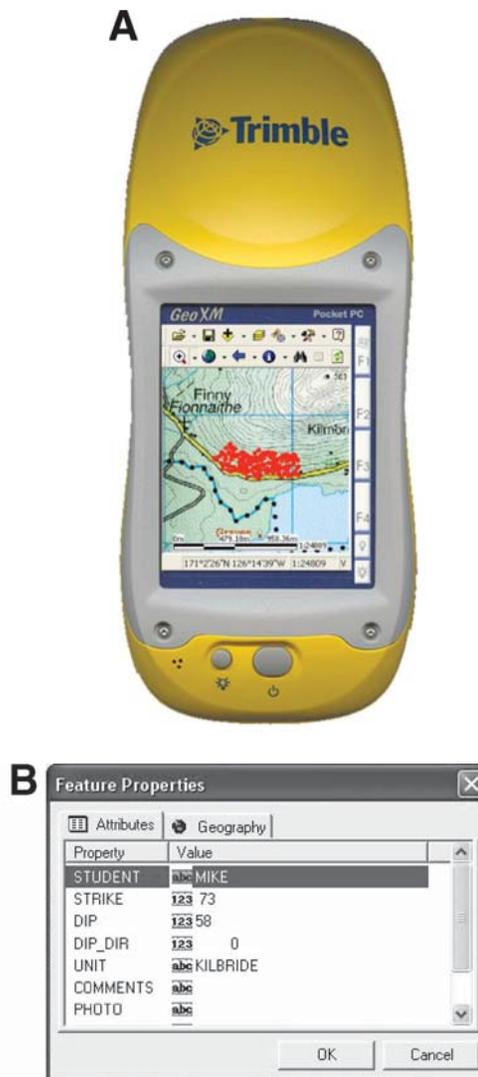


Figure 1. (A) In the field, students have access to topographic maps, historical fence maps, and aerial photos as background data on their handheld computers. (B) Using ArcPad software, the students' location was automatically recorded, and students entered relevant attribute data such as strike, dip, and lithologic unit. These data were available to them in real time for immediate assessment of the field geology.

held field computers with workstations running GIS software has facilitated a new era of geologic field mapping where data observed and recorded in the field are directly incorporated into a digital geologic map.

Development of new field mapping methods that take advantage of these advances in hardware and software has come from geoscientists who have research programs rooted in fieldwork, and who have a practical appreciation for advances in equipment (e.g., Walsh et al., 1999; Edmundo, 2002; Knoop and van der Pluijm, 2006; McCaffrey et al., 2008; De Paor and Whitmeyer,

this volume). Not surprisingly, many of the advances in digital mapping methods have resulted from geologic field courses (e.g., Brimhall, 1999; Knoop and van der Pluijm, 2006). The choice of equipment depends on the user's field environment and data collection goals. Given a mostly rain-free climate, field researchers can use tablet personal computers (PCs) with built-in GPS receivers running GIS software, such as ArcPAD and ArcGIS, to record data and build their maps in real time in the field. For inclement weather environments, ruggedized, handheld pocket PCs (e.g., Trimble GeoExplorer series) can run field-appropriate GIS software (ArcPAD) that performs many of the important data-entry tasks related to geologic map creation. Final map assembly requires a laboratory PC running ArcGIS, to which the field data can be uploaded.

3-D Visualization and Interpretation

One of the major challenges for geoscientists is the 3-D interpretation of geologic data, and the most effective means of displaying that data. The petroleum industry has long been a leader in 3-D display of subsurface seismic and ground-penetrating radar images, colloquially called fence diagrams. Attempts have been made to combine seismic and other subsurface data or cross-section interpretations with surface geologic maps in 3-D block diagrams (Karlstrom *et al.*, 2005). Virtual 3-D software, such as ArcScene, that displays digital elevation models (DEMs) has provided a new medium for presentation and interpretation of geologic maps and field data (Knoop and van der Pluijm, 2003; Johnston *et al.*, 2005). However, the full potential for evaluation of geologic maps using virtual 3-D software has been impeded somewhat by the cost and steep learning curve of popular GIS programs, such as GRASS and ArcGIS.

The advent of free web-based geobrowsers, for example, NASA World Wind and Google Earth, has put virtual 3-D terrains at the fingertips of professionals and novice users alike. Many educators have intrigued students by using Google Earth to display spectacular landforms in virtual 3-D, such as the incised meanders of Escalante Canyon or active volcanoes like Mt. Rainier. Ease of use, minimal cost, and universal availability have encouraged geoscientists to use Google Earth for 3-D display of geologic maps (Hennessy and Feely, 2008; USGS maps: <http://geomaps.wr.usgs.gov/sfgeo/geologic/downloads.html>) and other data sets (e.g., hurricane tracks and data: <http://bbs.keyhole.com/ubb/download.php?Number=110283>).

A more advanced use of Google Earth—to prepare and display professional-quality, interactive geologic maps—is now feasible due to recent software enhancements. The most recent versions of ArcGIS (9.3) and Google Earth Pro (4.3) can exchange data between their native formats: shapefiles and Keyhole Markup Language (KML), respectively. However, specialized display features within Google Earth, such as 3-D strike and dip symbols and cross sections, still require some external programming (see following). As the popularity of Google Earth and KML programming continues to grow, data-sharing capabilities among Google Earth, ArcGIS, and other spatial display programs

will certainly become easier. This will make the preparation of interactive digital geologic maps a standard skill that could be easily taught to geoscience students.

CASE STUDY: THE JAMES MADISON UNIVERSITY FIELD COURSE

The James Madison University field course is a senior-level, 6 wk, summer capstone experience that incorporates a variety of multiday group and independent field geology and mapping exercises. The course is based near the Connemara region of western Ireland, a strategic location that provides easy access to well-exposed outcrops of highly deformed Dalradian metasedimentary rocks, Paleozoic clastic and carbonate basin stratigraphy, and the fossiliferous Carboniferous carbonate stratigraphy of interior Ireland. Student enrollment is typically 25–35 individuals from universities across the United States. Faculty is similarly diverse and has included instructors from James Madison University, Boston University, National University of Ireland, Galway, and other universities.

The course has incorporated a digital mapping and visualization component since 2001 (De Paor *et al.*, 2004; Johnston *et al.*, 2005). We started with an introductory exercise that used handheld GPS units to log waypoints on a hiking traverse (De Paor *et al.*, 2004) and later added a laboratory component that used software, such as Bryce and Carrara, for 3-D terrain modeling and data draping. Basic 3-D interpretation concepts were addressed using a block diagram applet written in Flash Actionscript, which enabled students to project their own scanned sketch maps and cross sections on the sides of a block that can be rotated using the computer mouse, and that can be viewed against a backdrop of a relevant field area (Fig. 2A). More recently, we have provided students with examples of 3-D computer-based visualizations based on current field areas. These include virtual outcrop models of folded marbles at Streamstown and Cur, Connemara (Fig. 2B), that were generated using terrestrial laser-scanning techniques and are accessible as short AVI movies (McCaffrey *et al.*, 2008, and associated supplemental material, found at <http://dx.doi.org/10.1130/GES00147.S1>, <http://dx.doi.org/10.1130/GES00147.S2>). VRML (Virtual Reality Modeling Language) models have also been used to illustrate the Twelve Bens area (Fig. 2C), a mountainous region of Neoproterozoic Dalradian metasedimentary rocks in central Connemara (Hennessy and Feely, 2005). The current James Madison University field course curriculum incorporates field mapping using ArcPAD on handheld computers, professional geologic map construction using ArcGIS, and virtual 3-D map evaluation and presentation using ArcScene and Google Earth.

Field Location

Digital mapping exercises are located on the southeastern slope of the mountain of Knock Kilbride, along the southern margin of the South Mayo region in County Mayo, western Ireland (Fig. 3). The geology consists of well-exposed, hillside outcrops

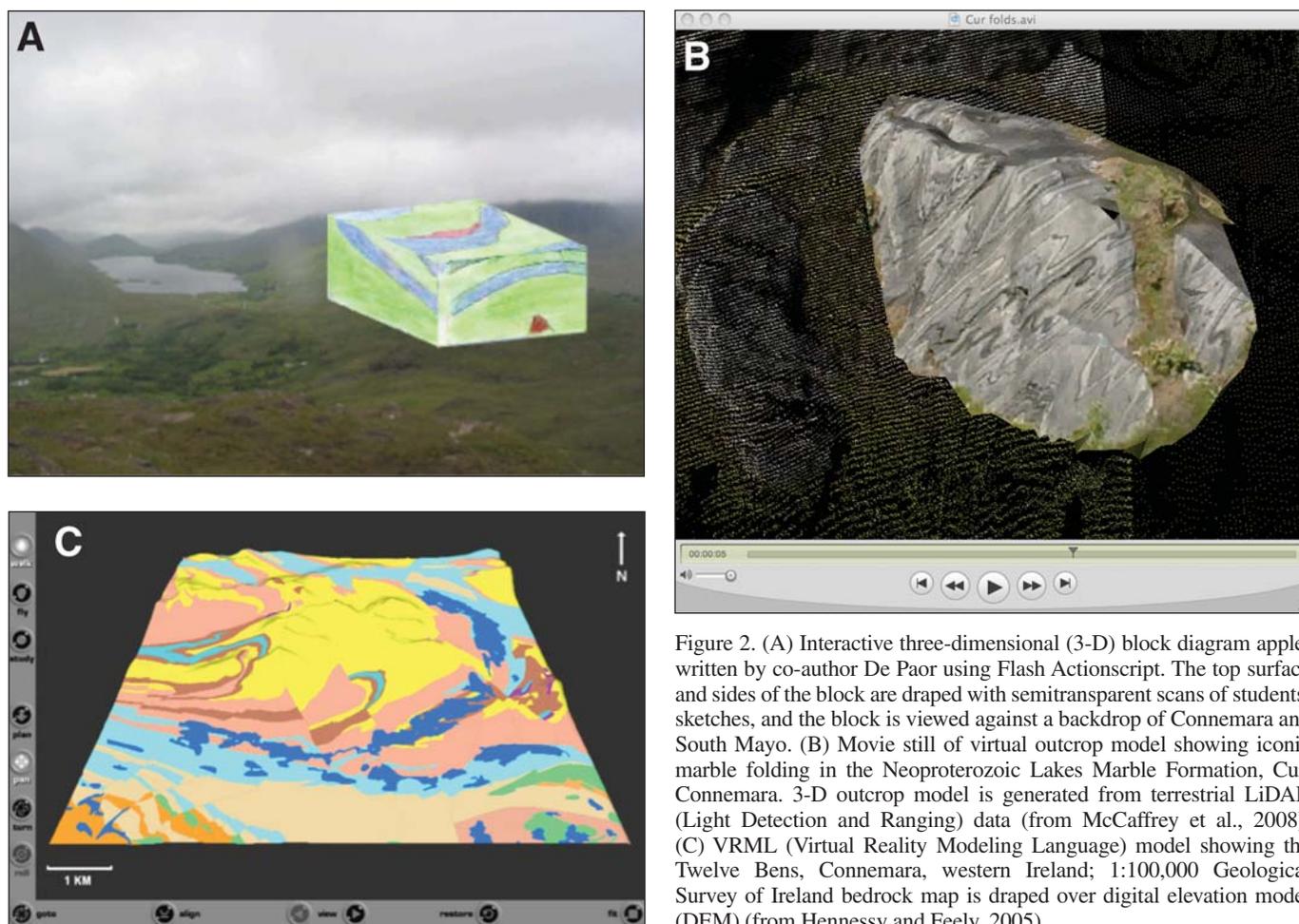


Figure 2. (A) Interactive three-dimensional (3-D) block diagram applet written by co-author De Paor using Flash Actionscript. The top surface and sides of the block are draped with semitransparent scans of students' sketches, and the block is viewed against a backdrop of Connemara and South Mayo. (B) Movie still of virtual outcrop model showing iconic marble folding in the Neoproterozoic Lakes Marble Formation, Cur, Connemara. 3-D outcrop model is generated from terrestrial LiDAR (Light Detection and Ranging) data (from McCaffrey et al., 2008). (C) VRML (Virtual Reality Modeling Language) model showing the Twelve Bens, Connemara, western Ireland; 1:100,000 Geological Survey of Ireland bedrock map is draped over digital elevation model (DEM) (from Hennessy and Feely, 2005).

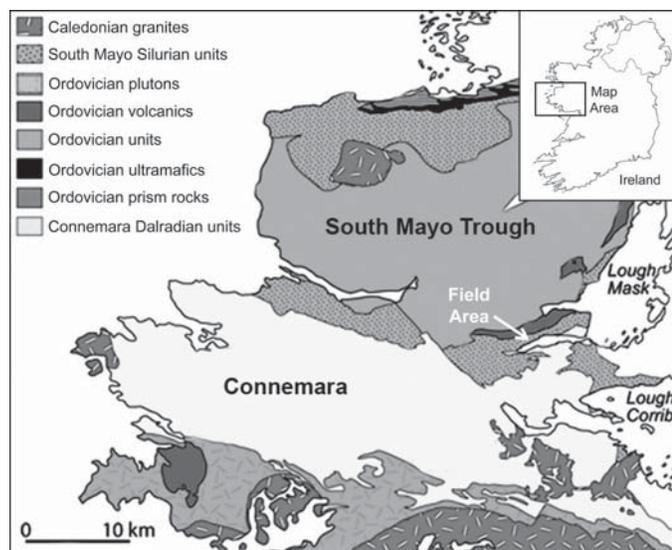


Figure 3. Generalized geologic map of the South Mayo and Connemara regions of western Ireland (modified from Chew et al., 2007); the Knock Kilbride field area is indicated by the white arrow. Inset shows map location on an outline of Ireland.

of mostly planar, moderately southeast-dipping Silurian sedimentary strata (Graham et al., 1989) that unconformably overlie Early Ordovician arc-related volcanic rocks (Chew et al., 2007). Tilting of the strata was likely the product of Caledonian oblique collisions (Dewey and Ryan, 1990; Williams, 1990) that sutured the Dalradian Connemara terrane to the southern margin of the South Mayo Trough (Williams and Harper, 1991). This suture zone can be seen just a few kilometers south of the field area along the north face of the mountain of Ben Levy (Williams and Rice, 1989; Whitmeyer and De Paor, 2008). Later deformation consists of decimeter- to decameter-scale offsets along crosscutting, oblique normal faults, which may have occurred during late Caledonian (Late Silurian–Early Devonian) transpressional terrane adjustment (Williams and Harper, 1991; Smethurst et al., 1994).

An interesting aspect of the field area is that homoclinal Silurian strata dip to the south-southeast at $\sim 60^\circ$, more steeply than the topographic slope. Students are faced with a situation where a northward uphill walk from the lakeshore takes them down-section stratigraphically. Many students find this inversion of stratigraphy with respect to elevation challenging to visualize and interpret correctly.

Equipment and Methodology

Students work in groups of two to three, and each group has one handheld computer. Over the past few years, we have tried a variety of handheld units, including PDAs (Personal Data Assistants) (NAVMAN®, HP iPAQ®) and Trimble® GeoXMs (2003 and 2005 versions; Fig. 1A). The PDAs were less expensive (approximately \$800 with GPS plug-in card and waterproof Otterbox®, versus \$2000 for the Trimbles), but we found the GeoXM to be much faster at acquiring a steady GPS signal, and better in handling persistent, and often horizontal, Irish rain. The handheld field computers are equipped with ArcPAD, a portable version of ArcGIS, loaded with topographic maps, historical fence maps, and aerial photos of the field area. On the first day of the exercise, students create a shapefile to record data such as strike, dip, and lithologic unit (Fig. 1B). In the field, this expanding data set is available to students for immediate evaluation of the area geology while they collect data at each outcrop. The geographic coordinates (in whatever format the user desires: latitude and longitude, UTM, Irish grid, etc.) are automatically recorded by ArcPAD at each sample location when students enter their attribute data.

Following a full day in the field, students upload data from their handheld computer to a laboratory computer running ArcGIS. Invariably, there are some mistakes and omissions in the field data the students collected, and this is their chance to fix that prior to resuming fieldwork the next day. Students quickly learn the critical importance of recording their data by hand in a field book as a backup for the handheld computer. Even if they have not lost any data themselves, the word-of-mouth from a team that will have to spend much of the next day retracing their steps to replace lost data is convincing.

The “digital inking-in” evening session is also a time to assess the quality of the group’s data and their coverage of the field area. While reviewing and troubleshooting their field data, students locate areas where they may have misidentified lithologies or missed important contacts or potential faults. At the end of the evening session students devise a work plan to enhance the efficiency of their data collection for the next day in the field, and the fixed field data is downloaded back to the students’ handheld computer. Thus, the laboratory computer functions as a backup for students’ field data. In this respect, it is similar to the hand drawn “fair copy” map that field geologists would keep in the office as a backup to their field slip.

After 3 to 4 d of field mapping, depending on the size of the field area and the weather, students have two full days on a GIS workstation in a state-of-the-art computer laboratory at the National University of Ireland, Galway. During this time, the students use ArcGIS to interpret their field data and prepare a professional-quality geologic map of the field area. The experience of using ArcPAD and watching the ArcGIS upload process increases students’ exposure to GIS prior to using ArcGIS on their own. Building on their preliminary interpretations at earlier evening sessions, students identify and highlight lithologic contacts and stratigraphic offsets of the contacts to accurately

determine the location of normal faults in the region. Each team produces, prints, and turns in a professional-quality GIS map of their field area (Fig. 4), along with a description of the geology they mapped, and a plausible history of how it was formed.

3-D Interpretation and Presentation

Valuable tools that have recently become available and practical for display and evaluation of geologic maps and field data include virtual 3-D terrain models, such as DEMs generated within ArcScene (Fig. 5), and virtual globes, such as Google Earth (Figs. 6A and 6B), NASA World Wind, and ArcGlobe. Georeferenced geologic maps can be draped over 3-D surfaces, and software controls allow the user to rotate, pan, and zoom the 3-D maps. This allows the user to appraise geologic map elements and data from any angle and at any point in the fieldwork and map preparation process. Students can reevaluate their field interpretations to better constrain contacts and faults across the terrain, and they can do this every evening before heading back out to their field area the next day. This iterative approach to evaluating geologic maps, while fieldwork is ongoing, permits a level of self-evaluation that only field researchers who were very experienced at 3-D visualization could have achieved in the past.

In summer 2008, we incorporated an extra day of laboratory-based computer exercises in order to acquaint students with the capabilities of Google Earth as a medium for displaying and evaluating geologic data. Following a general introduction to Google Earth, students exported jpeg images of their geologic maps from ArcGIS. Within Google Earth, students used the “Add – Image Overlay...” function to upload their jpeg maps and then positioned them at the correct latitude and longitude using the “Location” tab. This simple step allowed students to view their geologic maps draped over the Google Earth virtual terrain, with full access to Google Earth’s zoom, rotate, and pan capabilities. Students also incorporated specific point data information, such as orientation measurements, lithologic features, and outcrop photos, within their Google Earth maps by using the “Add – Placemark...” function. After only a couple of hours, most groups had truly interactive Google Earth-based geologic maps of their fieldwork that incorporated field data and photos georeferenced to their proper field coordinates.

We finished this exercise by demonstrating the capabilities of Google Earth for presenting cutting-edge geologic research. Examples included four-dimensional visualizations of the emplacement stages of the Devonian Galway Granite, western Ireland (Fig. 6A; Hennessy and Feely, 2008), and our ongoing work on an interactive 3-D geologic map of the Knock Kilbride field area with student data collected over the past four years (Fig. 6B). Each year, field course students have digitally mapped a different section of the southeastern slope of Knock Kilbride. By the end of the 2008 field season, digital data covered the full southeastern slope of the mountain. This visualization demonstration showed our students that their collective data were a vital part of an active research project that utilized modern digital methods and equipment.

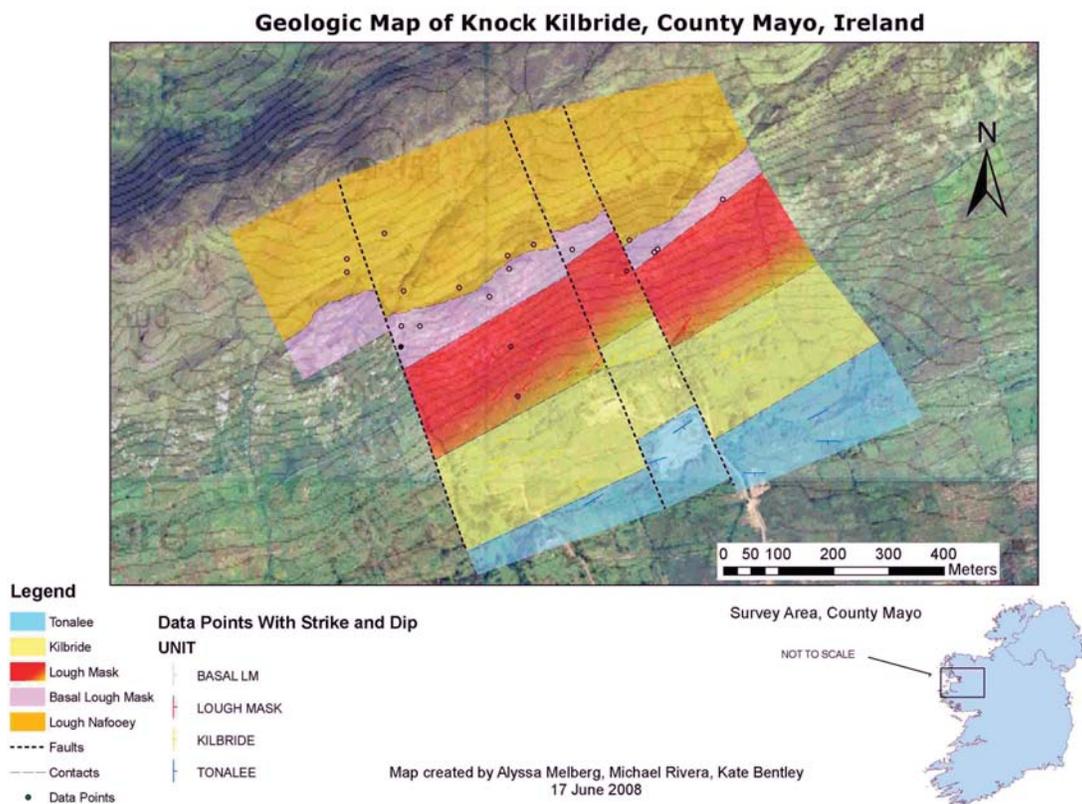


Figure 4. Student map of field area produced within ArcGIS with data collected from handheld computers.



Figure 5. Student's geologic map of the Knock Kilbride field area, draped over a digital elevation model (DEM) of the mountain of Knock Kilbride (view to the northeast). By using a virtual 3-D model that incorporates high-resolution aerial photos, students can reevaluate their initial field interpretations to better constrain contacts and faults across the terrain.

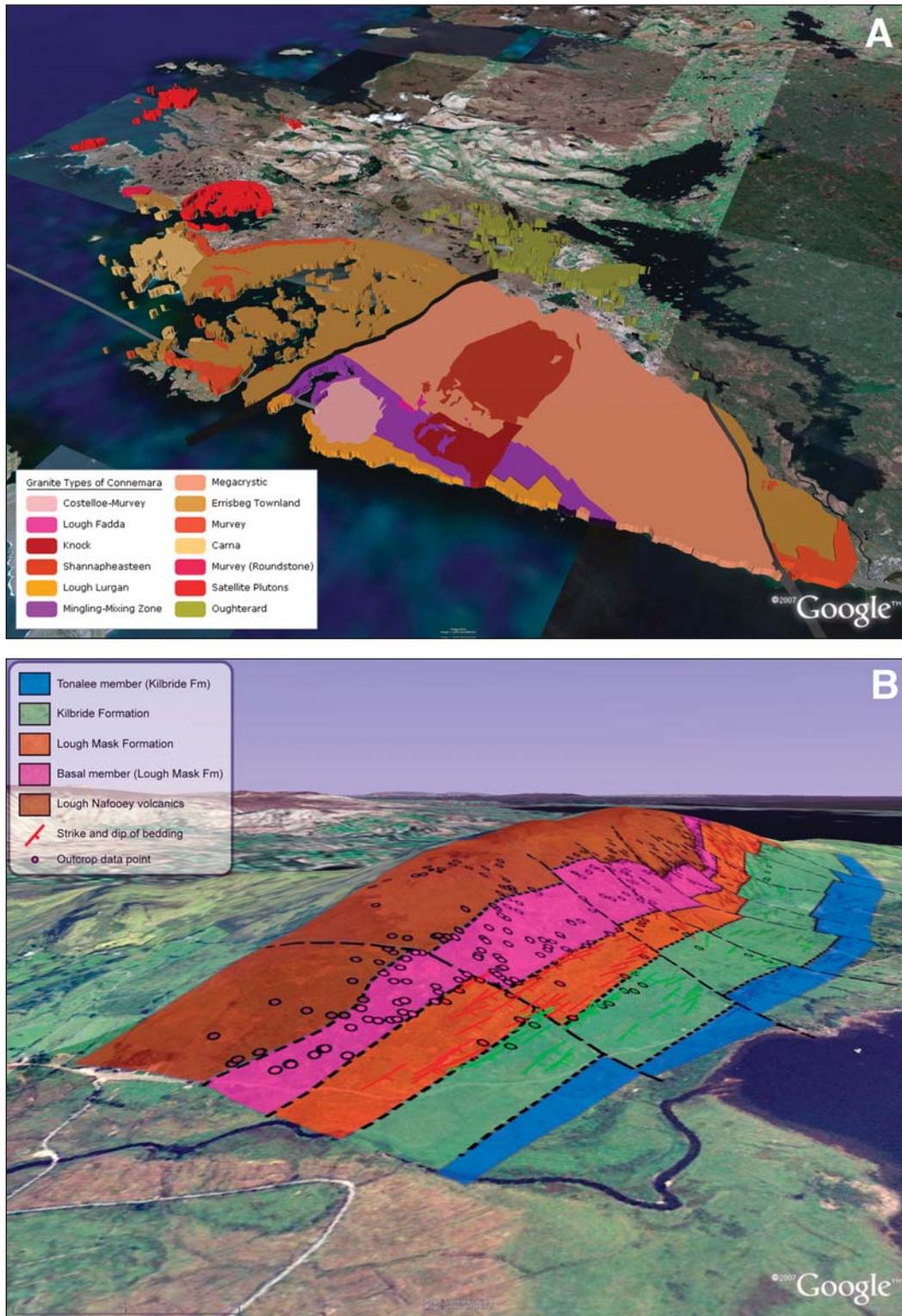


Figure 6. (A) Google Earth image of the Galway Granite batholith. The emplacement stages of the granite units are controlled through the time-slider function visible at the top of the image (from Hennessy and Feely, 2008). (B) Google Earth image of the composite Knock Kilbride geologic map, compiled from 4 yr of student data from the Ireland field course. View is to the northeast, similar to Figure 5. Data points, line work (faults and contacts), and each unit (as polygons) can be turned on or off for viewing. Resolution of terrain underlying the geologic map has been enhanced by overlaying aerial photos on the standard (poor-resolution) Google Earth terrain.

The collective Google Earth geologic map incorporated more advanced features than the students had included in their individual Google Earth maps, such as selectable layers of lithologic units, contacts, faults, or point data that the user could turn on or off. Our map used high-resolution aerial photos of the field area as overlays on the native Google Earth terrain images to overcome Google Earth's poor image resolution of this region. By editing the Image Overlay tag to make the colors of the unit layers slightly transparent, we demonstrated how field researchers could evaluate mapped geology against a high-resolution 3-D topographic base map. This is correlative with the map evaluation exercise that the students had recently completed using their GIS maps of the field area and ArcScene, which allowed students to compare digital, interactive geologic maps assembled in two different software platforms.

We concluded our "Google Earth Day" by demonstrating future components of Google Earth-based interactive geologic maps that were not yet fully developed. These included 3-D strike and dip symbols as Collada models (www.collada.org) positioned in the proper spatial orientation above the outcrop location where the data were collected. The current complexities involved in properly displaying orientation symbols in Google Earth were apparent to students after we explained that, in order to transfer the relevant location and orientation data from ArcGIS point shapefiles into Google Earth Collada models, it was necessary to write a Linux-based bash script (see Appendix 1). We also demonstrated vertical cross sections that users can "pull up" from the Google Earth ground surface (Whitmeyer and De Paor, 2008), and superoverlays of the geologic maps that allow users to zoom to outcrop-scale details without using large, high-resolution files that cause Google Earth to dramatically slow down (Whitmeyer et al., 2008).

Preliminary Feedback of the Digital Mapping Exercise

Student feedback of the continually developing digital mapping and visualization exercise indicates a strongly positive

response to both digital field mapping and map preparation using ArcGIS (Table 1). Interesting trends over the past four years include a general increase in students' incoming familiarity with GPS and ArcGIS. Four years ago, the use of handheld GPS units in the field was a novelty for many students, whereas now many students have GPS units in their cars. When we began the digital mapping project, few students had much exposure to ArcGIS, whereas in recent years ~40% of the students had already taken a full semester GIS class. This increased experience with GIS prior to the field course has allowed us to include more advanced material within allotted laboratory days. However, we found that the experienced GIS students tended to usurp control of the computer during the laboratory sessions, and we had to enforce an "equal-opportunity" policy at the computer keyboard so that all group members had a hand in preparation of the final map product.

As students have entered the Ireland field course with a stronger GIS background, their opinion of the value of the laboratory GIS component has decreased (Table 1). Student opinion of the field GIS component has not decreased as much as the laboratory exercise, perhaps due to less prior familiarity with the equipment and techniques. In 2008, all field camp students had used Google Earth to "fly" around to familiar locations, like their homes and college campuses, but none of them had viewed or evaluated geologic maps using Google Earth. Our demonstration of the potential capabilities of interactive geologic maps built within Google Earth prompted enthusiastic responses from the 2008 field course students, especially when they realized that their field data were incorporated into an ongoing, cutting-edge research project. Interactive digital geologic maps with user-viewable metadata are not a new concept (e.g., Condit, 1999), but the ease of use of the Google Earth interface puts the capability to create virtual 3-D geologic maps that incorporate pertinent field data and images into the hands of every geologist, whether computer-savvy or not. We envision that familiarity and acceptance of these modern methods of displaying geologic maps will enable us to present more complex and challenging exercises in the future.

TABLE 1. STUDENT EVALUATION DATA FOR THE DIGITAL MAPPING EXERCISE FROM THE PAST FOUR YEARS OF THE IRELAND FIELD COURSE

	2005 (n = 35)	2006 (n = 25)	2007 (n = 32)	2008 (n = 29)
Students with previous full-semester GIS* class	3%	21%	44%	41%
How much did you learn from this exercise? (1 = nothing, 5 = a lot)	n/a	4.4	3.4	3.1
How valuable was the field component? (1 = not at all, 5 = very)	n/a	4.7	4.0	4.0
How valuable was the laboratory component? (1 = not at all, 5 = very)	n/a	4.8	3.7	3.4
	% agree	% agree		
Background knowledge and skills were appropriate to the level of the course	85%	96%	n/a	n/a
Content of the course would be of value to my own research / career path	91%	88%	n/a	n/a
Would recommend this GIS experience to other geology students	100%	100%	n/a	n/a

Note: Note that the evaluation format changed in 2006 (with a year of overlap).

*GIS—geographic information systems.

DISCUSSION AND CONCLUSIONS

Over the last few years, digital mapping has progressed from being an exciting cutting-edge technology with much potential to being the standard method of recording field data and constructing geologic maps. Whereas, in previous years, students with GIS and digital mapping experience were ahead of the curve, now students must have this experience to keep up with their peers in the competitive job or graduate student market. Word-of-mouth communication to the authors from geoscience professionals in positions within state surveys, environmental consulting firms, and petroleum and mineral exploration companies has stressed the importance of familiarity with GIS and digital mapping techniques. Similarly, feedback from James Madison University field course students that have gone on to graduate programs indicates the value of exposure to digital mapping and visualization techniques. These advantages often extend beyond improved 3-D cognition of geologic features to have application to many disciplines (Butler, 2007).

Our task as geoscience educators is to give the students the skills they need to effectively “do geology” and be competitive in their future academic and workplace environments. Though equipment prices and lack of technological knowledge can still be initial hurdles, we must overcome these issues. We need to expose students to modern equipment and methods, not just to keep up with the competition, but also because these modern methods can facilitate visualization of 3-D structures and time-dependent processes in an unprecedented way. Visualization forms an essential constituent in our cognitive processes, and it is essential that we utilize this for student instruction. As educators, we have long stressed the importance of our students learning to think and see in three dimensions. It is our experience that the integration of 3-D visualizations into field courses and class curricula helps to improve students’ visual-spatial skills, and new digital methods are the latest tool to help us achieve that goal. Our challenge is to devise protocols and lesson plans that make use of these new tools in the most effective learning environments. One of these effective learning environments must be the field, where students assimilate geologic knowledge first-hand. As digital field methods continue to evolve, our ultimate goal is to bring all of the available visualization “firepower” to the student in the natural environment.

Finally, we acknowledge that our “preliminary student feedback” falls far short of a complete assessment of student learning in the field. Effective assessment instruments specifically focused on field education (Hughes and Boyle, 2005; Pyle, this volume) are essential in order to verify that digital visualization tools, such as those advocated in this paper, are accomplishing the transformative leap in students’ comprehension that we desire. Specific learning objects based on digital 3-D visualizations need to be evaluated against the educational methods of traditional field courses. In addition, post-field course surveys that go beyond the anecdotal are needed to more completely assess the value and application of students’ field education in their subsequent careers. We cannot correct the lack of past assessment data for

field education, but as present-day geoscience field educators, we can ensure that our future innovations in field-oriented curricula will be supported by rigorous assessment of student learning.

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APPENDIX 1. LINUX SCRIPT

The following is a snippet of a Linux bash script, written by co-author Daniels, for converting ArcGIS point shapefiles with orientation data (longitude, latitude, strike, dip, dip direction) to KML format for import into Google Earth. The script creates a kml file that then links to a 3-D model of a standard strike and dip symbol (created with Google Sketchup) and orients the model using heading and roll tags. The dollar signs denote variables that are filled at run time with the data retrieved from the ArcGIS attribute table. Model details and attribute table format are specific to our project; however, an experienced programmer might find it useful as a template for creating KML files from ArcGIS data.

```
echo -e "<Placemark>
<name>FID $stess</name>
<visibility>0</visibility>
<Model id=\"042model_ $stess\"042>
<altitudeMode>clampedToGround</altitudeMode>
<Location>
<longitude>${arLONG[$stess]}</longitude>
<latitude>${arLAT[$stess]}</latitude>
<altitude>$ALT</altitude>
</Location>
<Orientation>
<heading>${arSTRIKE[$stess]}</heading>
<tilt>0</tilt>
<roll>-${arDIP[$stess]}</roll>
</Orientation>
<Scale>
<x>$SCALE</x>
<y>$SCALE</y>
<z>$SCALE</z>
</Scale>
<Link><href>./files/$MODEL</href></Link>
</Model>
..."
```

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