Visualization of folding in marble outcrops, Connemara, western Ireland: An application of virtual outcrop technology

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ABSTRACT

Virtual outcrops have been generated from terrestrial laser scanner data captured at two marble outcrops in the Dalradian rocks of Connemara, western Ireland. Both locations are popular field study sites in the region, where complex fold structures are visible in the outcrops. The development of virtual outcrops for student instruction is discussed, both in communicating the theories of structural geology in the classroom, and in pre- and post-field study instruction. Supplementary VRML (Virtual Reality Modeling Language) models, Google Earth KML (Keyhole Markup Language) files, and movies are used to communicate the associated geological context for each locality. Virtual outcrops and associated three-dimensional (3D) geological visualizations have the potential to supplement traditional educational content and aid in the improvement of students’ visual literacy.

Keywords: folds, virtual outcrop, laser scan, education, Ireland.

INTRODUCTION

Advances in geospatial surveying technologies have provided new methods for collecting outcrop data, and when supported by digital photogrammetry, can render quantitatively accurate and visually impressive representations of geological outcrops (McCaffrey et al., 2005). This approach produces a data set that has been termed a Virtual Outcrop (Xu et al., 1999; Xu et al., 2000; Pringle et al., 2004a, 2004b; Clegg et al., 2005; Trinks et al., 2006) or Digital Outcrop Model (Bellian et al., 2005). Terrestrial laser scanning (ground-based lidar [light detection and ranging]) is the most commonly used tool to generate these models. A laser pulse is emitted toward the outcrop, and the travel time of the reflected light is used to calculate the distance and three-dimensional (3D) coordinates of the reflecting point. In modern terrestrial laser scanners, this process is repeated up to 12,000 times per second to build a high-resolution topographic model of the outcrop. Georeferencing the data set using a differential global positioning system (GPS) permits the generation of a geospatially accurate virtual outcrop that contains fully integrated supplementary geospatial data such as maps, aerial photographs, and other data sets. Virtual outcrop data sets are increasingly used as a research tool in the earth sciences to investigate problems in geomorphology (Rosser et al., 2005; Wawrzyniec et al., 2007), sedimentology (Bellian et al., 2005; Redfern et al., 2007), structural geology (Trinks et al., 2005; Pearce et al., 2006; Sagy et al., 2007), and hydrocarbon reservoir engineering (Pringle et al., 2004b; Enge et al., 2007). These methods are of significance to archiving sites of geological importance where access to field sites is limited or restricted (e.g., Bates et al., 2008).

The generation and use of virtual outcrops in the analysis and interpretation of geological outcrops can be extended to the classroom, where high-quality 3D visualizations can serve as excellent instruction tools for educators (Trinks et al., 2005). Embedding virtual outcrops within a 3D representation of a landscape, such as a digital elevation model (DEM), enables students to attain an improved perception of the geology in a particular region. These data sets also offer geoscientists the opportunity to collect quantitative data sets and make observations from rock exposures at their convenience, in contrast to collecting data during a time-pressured visit to the outcrop during fieldwork.

In this contribution, we provide two examples to illustrate the role virtual outcrops can play in education for undergraduate students and the general public. From terrestrial laser scanned data, we generated virtual outcrops for two classic exposures of folded Neoproterozoic marbles in Connemara, Ireland. The locations differ significantly in outcrop architecture: one is a marble quarry with cleanly cut vertical walls; the other is a geomorphologically irregular, naturally eroded valley exposing marble. The models generated were used in two training exercises for undergraduate students. A virtual outcrop created for a small marble quarry was used by an undergraduate student who had not visited the outcrops as a basis for a laboratory-based research dissertation. The student carried out a detailed structural analysis of the fold geometries and styles. The other virtual outcrop model was used in an educational resource for students prior to their visit to the site. The laser scan data were integrated with a 3D Virtual Reality Modeling Language (VRML) model depicting the surface cover and bedrock geology. These models allow user-controlled multiperspective viewing of the region’s topography and associated geology at a variety of scales.

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Fold visualization using virtual outcrops

Here we introduce the virtual outcrops, outline the methods used in their creation, and discuss their application as an educational resource.

THE DALRADIAN MARBLES OF CONNEMARA

Two distinct marble formations have been described in the Neoproterozoic Dalradian rocks in Connemara (Leake and Tanner, 1994). These are the Lower Dalradian (Appin), Connemara Marble Formation, and the Middle Dalradian (Argyll) Lakes Marble Formation. Correlations between the Connemara Dalradian and Scottish Dalradian have been described in Leake and Tanner (1994). The Connemara Marble Formation consists of green and white marbles, calcareous schists, and tremolitic amphibole-bearing rocks (Leake and Tanner, 1994). The Connemara Marbles have been correlated with the Scottish Appin Islay Limestone Formation (Leake and Tanner, 1994), and the rocks of the Argyll Lakes Marble Formation have been correlated with the Easdale Subgroup of the Scottish Dalradian (Harris and Pitcher, 1975). The Lakes Marble Formation is a thick calcitic limestone, with intermittent sandstone beds and abundant basic sills and lavas, and tuffaceous horizons. The marbles of the Lakes Marble Formation are mineralogically distinguished from those of the Connemara Marble Formation by the lack of ophicalcite and dolomite, and visually by their distinct blue-gray, ribbed appearance. The almost pure-calcite (and slightly graphitic) marbles of the Lakes Marble Formation are generally homogenous but banded on a centimeter scale, displaying thin ribs weathering out on the surface.

GEOLOGICAL SETTING OF THIS STUDY

Two sites were identified as excellent candidates for widely useful virtual outcrops. The sites are located 28 km apart on opposite sides of the ENE-WSW–trending Connemara Antiform (Leake and Tanner, 1994), and the rocks of the Argyll Lakes Marble Formation have been correlated with the Easdale Subgroup of the Scottish Dalradian (Harris and Pitcher, 1975). The Lakes Marble Formation is a thick calcitic limestone, with intermittent sandstone beds and abundant basic sills and lavas, and tuffaceous horizons. The marbles of the Lakes Marble Formation are mineralogically distinguished from those of the Connemara Marble Formation by the lack of ophicalcite and dolomite, and visually by their distinct blue-gray, ribbed appearance. The almost pure-calcite (and slightly graphitic) marbles of the Lakes Marble Formation are generally homogenous but banded on a centimeter scale, displaying thin ribs weathering out on the surface.

GEOLOGICAL SETTING OF THIS STUDY

Two sites were identified as excellent candidates for widely useful virtual outcrops. The sites are located 28 km apart on opposite sides of the ENE-WSW–trending Connemara Antiform (Leake and Tanner, 1994) in the Neoproterozoic-age Dalradian Metamorphic Complex in Connemara, western Ireland (Fig. 1). The Connemara Dalradian, consisting of mainly marbles, schist, and quartzite, is allochthonous (Friedrich et al., 1999; Harris, 1995; Graham et al., 1991; Tanner et al., 1989) and interpreted to have been emplaced from the northwest. The position of the Connemara Metamorphic Complex is anomalous because it lies to the south of the Highland Boundary Fault. Elsewhere in Ireland and Scotland, Dalradian lithologies occur on the northwestern side of this major crustal discontinuity. The Dalradian Supergroup was deposited at the leading edge of Laurentia and is now exposed throughout the northwestern parts of the British Isles. The sequence was deformed and metamorphosed during the Grampian (Taconic) orogeny resulting in the development in the Connemara region of four main fold phases and local attenuation of the stratigraphic package. The metamorphic rocks of Connemara have been subjected to amphibolite facies metamorphism, with grade increasing from north (garnet zone) to south (upper sillimanite zone) through a series of east-west–trending metamorphic zones.

Streamstown Marble Quarry

The two locations were chosen due to the contrasting nature of the exposures—one a
natural outcrop surface and the other a quarry exposure. The first location is a small quarry at Streamstown (Irish National Grid 65497 261915) located 3 km northeast of Clifden in Connemara, western Ireland. It was chosen for its excellent exposures of Connemara Marble fold structures (see Fig. 2.26, p. 53, in Stanley, 1999). The quarry is located in a pocket of Connemara Marble, ~1 km east of the Renyle-Clifden-Murvehy Fault, a major NNW-SSE structural feature traversing the western Connemara region (Fig. 2A). Connemara Marble is found in discontinuous outcrops stretching for ~30 km on the southern limb of the regionally significant D4 Connemara Antiform. At Streamstown, the distribution of the Connemara Marble types is controlled by two mésoscála antiforms named the Quarry and Crag antiforms (Fig. 2A). There are three principal marbles in the quarry—a white calcite marble, a green tremolite marble, and a green serpentine marble; hence structures are well defined by the color contrasts. At Streamstown, the stone was extracted by sawing large blocks from the walls and floor resulting in smooth vertical and horizontal surfaces in the main quarry that provide an opportunity to test our ability to extract useful 3D information from a virtual data set (Fig. 5).

**Cur Hill, Maam Valley**

The second site chosen for the study is on the southern slopes of Cur Hill (93117 252856) in a major east-west–trending glacial valley, the Maam Valley (see Yardley and Long, 1983). Cur Hill (310 m) is located on the northern limb of the Connemara Antiform (Fig. 1), and consists of east-west–striking Middle Dalradian marbles, metasediments, and amphibolites. Cur Hill represents an antilinal synform (Yardley, 1974), plunging eastward at a low angle (12°–20°). Scanning was carried out in a small valley in which iconic folds of the Lakes Marble Formation are found (Fig. 2B). The valley is herein referred to as the Green Valley due to the rich vegetation present on the lime-rich bedrock (Fig. 3A). The Green Valley is bisected by a stream, much of which flows below the surface through carbonate caves and cavities. The outcrop surfaces are very irregular varying from near horizontal to near vertical, and it is here that a spectacular exposure of Lakes Marble Formation folds is found (Fig. 3B). The calcite marbles at Cur Hill, comprising the formation’s Upper Marble Member (Badley, 1976), display superb tightly folded mesoscopic (locally D3) folds. The fold geometry is clearly visible due to the alternation of dark graphitic bands with light-gray calcite marble bands. The outcrop shows excellent examples of converging “s” and “z” fold patterns, with two distinct synformal folds present on this west-facing outcrop.

**LIDAR DATA COLLECTION (LASER SCANNING)**

The lidar data sets were collected from tripod positions that were sited for optimum viewshed of the outcrops under study. Point clouds were captured over a two-day period with one day spent at each location. A Riegl LMS Z420i laser scanner with typical acquisition rates up to 12,000 points/s was used (Fig. 3B). A Nikon D100 digital camera with a 14-mm lens was precisely mounted on the scanner and from photographs of the target area, provided individual color (RGB) attributes for the \( x,y,z \) point cloud. A laptop, running RiSCAN Pro version 1.2.1 was used in the field to control the scanner and camera, as well as for data storage and quality control of data gathering during the acquisition process.

Ten scanner reflectors (5-cm cylinder) were distributed around the study sites. The positions of these reflectors were georeferenced using an Ashtech ProMark2 Differential GPS survey system. A base station (Fig. 3C) was set up to record GPS data continuously, while five other reflector locations were captured using a rover GPS unit. Postprocessing the GPS data resulted in horizontal and vertical accuracies in the <2-cm range and enabled the point clouds to be co-registered with one another and georeferenced to the Irish National Grid. The internal precision for the scan co-registration calculated from the reflector positions was less than 2 cm in all three \( x,y,z \) directions.

**Data Acquisition: Streamtown**

The laser scans were taken from a tripod position on the eastern side of the main quarry (Fig. 2A). For this study we collected a single panorama scan taken with a 360° horizontal sweep and ±40° vertical sweep from the horizontal. A series of seven digital photographs were taken to provide the color information. The digital single-lens reflex (SLR) camera is mounted precisely on top of the laser scanner, which enables the RiSCAN software to calculate the appropriate color for each point in the data cloud. A high-resolution scan set at angular resolutions of 0.02° horizontal and 0.12° vertical was then acquired over the key area of interest (the quarry walls and floor). This took 25 min to acquire ~12 million individual \( x,y,z \) position measurements on the quarry surface. This resulted in point spacing on the quarry walls between 5 and 40 mm depending on distance to the quarry face. Error in the distance estimate is given by the manufacturer as ±5 mm at these scales of observation (<25 m).

**Data Acquisition: Cur Hill**

Four laser scans (three panoramas and one detailed fine scan) were taken at Cur Hill from three positions (Fig. 2B). Scans 1 and 3 were taken in the middle of the Green Valley, while scan 2 was taken approximately 4 m west of the iconic fold outcrop. Each panorama scan took 4 min and 8 s to capture ~2 million measurements at a laser rate of 24,100 Hz. The fine scan (145° horizontal sweep) took 10 min to capture ~3.3 million readings at the same laser rate.

**Point-Cloud Processing**

After data were acquired, a series of standard processing steps including scan co-registration and georeferencing were followed to produce a 3D model. A key challenge in processing and analyzing laser scan data is to reduce file size without losing desired resolution because merged point-cloud files containing tens of millions of points quickly overwhelm most personal computers (PCs). For example, manual filtering can remove extraneous returns from the vegetation in front of the outcrop surface and other data that are peripheral to the main objective.

When viewed from a distance, the colored point cloud provides a reasonable representation of the outcrop surface; however, on closer inspection, as the data are zoomed toward the viewer, the particulate nature of the point cloud means that details of the structures become fuzzy (Fig. 4A). To overcome this effect, the point clouds are meshed and the digital photograph rendered onto the meshed surface to provide a high-resolution color 3D object (Fig. 4B). At this stage the accuracy of the scanner now becomes an issue. In the Streamstown point cloud at 16 m distance the point spacing is ~10 mm, but the distance error is ±5 mm. Triangulation of all the points in a point cloud, when the magnitude of the error approaches the magnitude of the point spacing, produces a very irregular, “spongy” surface that is not an improvement over the original point cloud. It would also require an inordinate amount of central processing unit (CPU) time to mesh such a large data set. The Streamtown quarry faces are flat with a roughness of the order of <2 mm. Given this constraint it was appropriate to filter the point clouds using an octree filter at 50 mm. The octree filter takes center of gravity of all points within a 50-mm cube; however, our data lie within a band of noise that is 15 mm wide. The actual location of the surface within the data is most likely to occur at the center.
Figure 2. (A) Bedrock map of Streamstown Quarry (after Naughton et al., 1992). (B) Bedrock map of Green Valley, Cur Hill.
Figure 3. Data acquisition at Cur. (A) View westward up the Green Valley. Lakes Marble Formation dips ~40° north. The abundance of thistles affected the final point cloud. (B) Riegl LMS Z420i laser scanner used to collect the virtual outcrop data with the spectacular fold exposure behind the scanner. (C) Differential global positioning system (GPS) Base Station collected data to georeference the laser scans to cm-resolution.
of gravity position in each cube. The resulting filtered point clouds contained an order of magnitude less points than the original data set. The filtered point clouds where then triangulated to produce a mesh, and this surface was inspected and where necessary corrected to remove spurious triangles, and some of the more obvious holes were filled in. The appropriate digital photograph was then orthorectified and applied as a texture to the triangulated mesh to create a 3D virtual outcrop (Fig. 4B).

Following the processing and generation of the virtual outcrops, animated “fly-throughs” of the outcrops were generated using RiSCAN’s animation function. A series of user-specified viewpoints provide the key frames for the animations in RiSCAN, with a seamless transition between viewpoints creating the camera path. The animations were saved in Microsoft Audio Video Interleave (.avi) multimedia format and serve as an excellent dynamic visualization of the study locations (see Animation 1).

VIRTUAL OUTCROPS: VISUALIZATION AND ANALYSIS

Having created the basic virtual outcrops, they can be used in a variety of ways depending on the desired application. Here we highlight two different uses that are relevant to geoscience training and education. In the first application, an undergraduate, who was not able to visit the Streamstown quarry during the data acquisition, made a structural interpretation using the laser scanner software as part of a laboratory-based dissertation. The objective was to attempt to extract meaningful 3D geometrical data from the marble folds from the virtual outcrop, a task that would not be possible from a standard photograph. In the second application, the Cur virtual outcrop was integrated with Google Earth and geographic information system (GIS) models to illustrate the geomorphology and geology of Cur Hill and its overall context in the larger-scale structure of Connemara. These models were used in teaching classes for groups of students before and after they carried out a field visit to the site.

Picking of Structural Elements in Virtual Outcrop Data Sets

The RiSCAN software has the capability of producing planes through 3D objects from one, two, or three points that the user has defined in Figure 4. Virtual outcrop data from Streamstown Quarry. (A) The color-rendered point cloud shows geology from a distance, but close up, the particulate nature of the data means detail is poor. (B) A meshed surface with a draped photo provides much more detail of the marble layering in the quarry. Height of face 8.84 m.
the data. Here, we used the three-point method as it is most similar to the “three-point problem” known to geologists. We selected three points on a prominent marble layer on at least two quarry faces (Fig. 5). A plane is drawn through the three points to the boundaries of the data volume. Each plane was then inspected by moving the view to different positions to see how well it represented the corresponding layer. If the overall fit is not acceptable, the plane is either deleted and a new one drawn from three different points, or the plane can be rotated to a better visual fit. If the plane is acceptable, then its orientation is given by the direction vector (the pole to the plane) making sure to record plunge and trend values downward, i.e., a lower hemisphere projection. Several planes are fitted to different parts of the layer to define an error estimate and also to capture any nonplanar behavior.

Results from Quarry Virtual Outcrop Structural Analysis

North Wall

The north wall is clearly the best for structural analysis as it contains a right-angle corner where the wall steps back to the north, giving good 3D control (Fig. 5). Due to a shadow region in the scan, there is a small (5-cm) gap in the rendering that coincides with a ledge about two-thirds distance down the wall. By rotating the view it is possible to link layers above and below the gap. Each clearly defined layer on the north wall was estimated using the three-point method at a minimum of five times per layer. Figure 6A shows a stereonet of poles to planes fitted to marble layers in the north wall. The planes dip moderately to steeply to the north (Fig. 6B) in a uniform fashion and define a small part of a girdle distribution with a pole (β axis) plunging gently to the west.

South Wall

Structures on the south wall aligned at very low angles to cut faces (Figs. 6C and 6D) and are therefore not as well constrained as the north wall; however, there is some 3D control where folds can be traced around a step in the quarry face. The layers in this part of the quarry show a range of orientations (Figs. 6C and 6D) and on average dip more gently than those in the north wall. Calculated fold hinge orientations are varied, perhaps reflecting the unfavorable orientation of the left wall relative to the scanner. In general, these β axes plunge gently to the west. A prominent fault that can be traced across the south wall shows a clear hanging wall-up (thrust) displacement. Its orientation could not be determined on this face but is likely to be parallel to a similar structure observed in the floor (see below).

Floor

The floor of the quarry provides good 3D exposures through layered marble, a discordance, presumed to be a fault, that cuts through the layering and some patches of brecciated marble. The marble layers below the fault (in footwall) are clearly discordant to the layers above (Figs. 6E and 6F). These layers have similar orientations to those in the south wall (Figs. 6E and 6F), whereas those above the fault in the hanging wall are similar in orientation to those in the north wall. The floor fault orientation is constrained as being 104/55°N—kinematics have not been established but it is likely to be a thrust fault (prominent thrusts are visible on the south wall).

Back Wall

The back wall contains the most impressive range of fold structures, most of which are above the floor fault and are continuous with the north wall (Figs. 6G and 6H). Unfortunately, the degree of 3D control is poor as there are no major steps in the face and there is only a small ledge toward the bottom which provides limited information on the geometry of the structures (Fig. 6H). The approach adopted was to use the small ledge to provide some 3D constraint on fold hinge orientations and based on information already collected from the north wall (the β axis set as a viewing direction for the RiSCAN camera). This makes the assumption that fold plunges in the north wall and back wall are collinear. This is supported by the continuous nature of the structures across both walls in the hanging wall to the floor fault. In RiSCAN, if a viewing direction is defined, then only two points picked on a layer will define a plane. Data produced in this way allowed some further fold properties to be established, e.g., limb dips and interlimb angles. Given the variability in fold orientation determined in the other surfaces, assuming that all the folds are collinear may not be reasonable.

Geology Surrounding Quarry

Detailed mapping at the 1:600 scale shows that mesoscale folds surrounding the quarry have similar geometric properties to those in the quarry. The marble layering dips moderately to steeply NNW and SSE with a calculated fold axis plunging gently WSW (Fig. 6I). Measured fold axes plunge slightly (~10°–15°) more steeply, but the direction is the same as those determined in the quarry.

Compiling Multiscale Visualizations of Cur

The virtual outcrop generated from the Cur Hill data set was used to complement a series of visualizations of the topography and geology of the Cur Hill region. The visualizations were used to introduce undergraduate students from both Ireland and the United States to the outcrop using Google Earth. The site is an important location for geological field courses in the Connemara Dalradian.

Google Earth KML Content

Regional geological maps of Connemara were displayed in the 3D Earth viewer using
Figure 6. Structural interpretation of the Streamstown quarry. (A) Structural data from the north wall plotted on stereonet. (B) Planes shown in (A) in the virtual outcrop (VO). (C) Data from the south wall. (D) Marble layers (green lines) traced on the south wall surface. (E) Data from floor region. (F) Colored point cloud of floor region. (G) Back wall structural data. (H) Marble layers traced in the footwall and floor region. (I) Structural data from detailed map surrounding the quarry.
the KML (Keyhole Markup Language) Image Overlay function. The relationship between the topography and underlying geology is clearly demonstrated using this application. Students were familiar with the use of Google Earth for this purpose and hence were sufficiently “visually literate” in the context of viewing 3D landscapes. However, as the spatial resolution for the Cur area in Google Earth is poor (in contrast to the high-resolution QuickBird imagery at the Streamstown locality), it was necessary to use the virtual outcrop data to gain an improved resolution.

**Google Maps Content**

The locations for both virtual outcrops are displayed in a customized Google Map, using the Google Maps API (Application Programming Interface). JavaScript functionality enables placemarks to be positioned at specific locations and may be configured to have pop-up information windows (Fig. 7). A tabbed window was used for the Cur Hill virtual outcrop. Three types of media were presented: a QuickTime virtual reality (VR) panorama of the site; a QuickTime movie of the scanner in operation at Cur; and a photograph of the folds outcrop. This method of presenting multimedia geoscientific content provides an easy-to-use interactive interface through which users can access a variety of information “snippets.” Through the Google Maps interface, users can gain insight into the geology of a location and choose to explore further, or quickly move to a different location.

**VRML Surface Models**

A higher-resolution visualization of Cur Hill than that available in Google Earth is provided by a 3D VRML surface model of Cur Hill and the surrounding landscape (~3 km²) generated using a 50-m digital elevation model (DEM). The DEM consisted of 3721 points (61 × 61). The VRML model was generated using Pavan software, which is a VRML compiler and project management system for the MapInfo GIS software. Navigable 3D VRML models were generated from geospatial data in MapInfo format. The VRML surface model was reproduced with a variety of textures, such as OSI (Ordinance Survey of Ireland) color aerial photography; Geological Survey of Ireland 1:100,000 bedrock geology; and a georeferenced, digitized reproduction of a structural geology map (Yardley, 1974). Georeferenced embedded links were positioned throughout the surface model using the VRML Anchor node (see Thurmond et al., 2005). The links provided access to photographs, animations, QuickTime VR panoramas, text files, Web pages, Google Earth KML files, and other VRML models. To view the .kml and vrml files, see http://geoscene.ie/geosphere/index.htm.

**Virtual Outcrops**

Finally, after providing a background to the Dalradian geology of Connemara and putting the location of the Lakes Marble Formation outcrop in the context of the locality, students were shown animations generated in RiSCAN from the Cur data set (Figs. 8 and 9). The focus was primarily on the iconic folds outcrop. Photographs and QuickTime panoramas were used to reinforce the communicative efficiency of 3D animations. This enabled students to visualize the outcrop from a variety of perspectives. Animations showing the location and nature of the fold outcrop were used to communicate the geological architecture of the valley. For example,
Figure 8. Virtual outcrop data from the Green Valley at Cur Hill. View toward northwest. Faulting in the amphibolite clearly visible. Field of view ca. 20 m at front of model.

Figure 9. Virtual outcrop data from the Green Valley at Cur Hill. The iconic D3 folds in the Upper Marble Member. Outcrop width 2.5m.
faulting in the amphibolites in the northern cliff faces is clearly visible in the virtual outcrop.

**DISCUSSION**

**Geometrical Interpretation**

Variations between the map data and the virtual outcrop–derived data are mostly a result of the different scales of observation. Structure in the vicinity of Streamstown is dominated by upright, gently WSW-plunging, mesoscale folds. Within the quarry, folds have a similar geometry to the regional data sets with calculated fold axes that are gently WSW plunging in all cases. Different parts of the quarry are dominated by different average dips ranging from moderately NNW dipping to steeply SSE dipping, but this depends on which part of the larger mesoscale folds that part of the quarry is exposing and also location relative to the fault exposed in the quarry floor. The Streamstown example shows that it is clearly feasible to extract 3D structural information from the virtual outcrop; however, due to access reasons it has not been possible to verify the virtual data against a data set measured in the quarry. The quarry is somewhat unique in that the smooth, flat walls cut in different orientations help interpretation in some cases where there was a corner available to pick on two surfaces. In other places, such as the back wall, this causes a problem because there was no edge available to give a required 3D component.

The virtual outcrop of the Green Valley at Cur clearly shows folding in the upper marble member. This iconic outcrop is often reproduced in photographs (see cover of Leake and Tanner, 1994; Yardley, 1989, p. 26). The virtual outcrop provides useful information on the 3D geometry of the outcrop, for example. The plunge direction can be determined from the model either qualitatively by rotating the view or quantitatively using the same method as we used in the quarry. The virtual outcrops are used as a resource for students to access prior to visiting the location and provide visual content for post-fieldwork discussions and revision in the context of the regional structure. The structural geology of Connemara is complex because of the presence of major refolded fold structures. However, the use of Google Earth and Google Maps to communicate the regional geological context enables instructors to create effective visual content for classroom and field-study-related teaching. Because Google Earth and Google Maps are freely available, they are excellent tools for displaying custom maps and data, as well as enabling students to have remote access (via intranet or Internet) to course content.

The generation of a virtual outcrop from the Cur Hill data set proved to be a labor-intensive task owing to the geometry of the point cloud captured at the location (Animation 2). The primary difficulty concerned vegetation cover at the site on the day of the scanning. Figure 3A demonstrates the abundance of thistles at the outcrop. The resultant point cloud contained a significant amount of data that did not reflect the topography of the outcrop. Meshing the raw point cloud created a very irregular and erroneous surface model. While a significant amount of time was spent cleaning up the point cloud to remove vegetation profiles at specific locations, it was not possible to remove all the vegetation. As scanning was carried out at the height of summer, we suggest that scanning at similar locations be carried out in winter or early spring when vegetation cover is minimal.

**The Benefits of Virtual Outcrop Technology**

Virtual outcrops offer students the possibility to study outcrops from localities they are not able to visit. In our Streamstown example, data collection took place in the summer when the students were not available, yet they still generated a useful structural data set and made a good attempt at interpreting the outcrop. This exercise shows how virtual outcrop technology could provide good structural geology training and supplement traditional field classes. For example, Figures 4, 5, and 6 were generated by the students as part of their laboratory dissertation and illustrate the type of analysis possible from virtual outcrop technology. During the project, the students had to reexamine the fundamental concepts of structural geology (dip, strike, plunge, and azimuth) to ensure that they were collecting valid data. This training is normally only available during relatively short field trips, and students are likely to benefit from being able to practice these measurements during a longer-term laboratory project.

The generation of VRML models, using high-resolution aerial photography and DEMs, exposes students to the concept of spatial multidimensionality, when used in conjunction with Google Earth content and virtual outcrop data. Students can be shown how the topography and surface cover can sometimes reflect the underlying geology. This is particularly true with the VRML aerial photography model of Cur Hill, whereby the surface signature over the Lakes Marble Formation shows rich green vegetation, while the surface signature over the amphibolites indicates poorly drained ground, with clearly visible, east-west–trending lineaments following the strike.

The effectiveness of the animations in communicating information about the two geological outcrops cannot always be assumed to have a positive outcome. In consideration of the Principle of Apprehension (Tversky et al., 2002), animations can often fail to communicate familiar visual content to the observers, and can overwhelm the viewer with abstract graphic illustrations of imperceptible features and scales. To overcome this potential miscommunication, the virtual outcrops (VOs) are supplemented by photography and QuickTime panoramas to give the observer an alternative method of visualizing the outcrops. These additional media are retrievable through embedded links in the regional VRML models and through customized Google Maps. Using the information pop-up window in Google Maps, QuickTime VR content and QuickTime movies can be embedded in the Google Maps interface. However, no known support for QuickTime content is available in Google Earth at present.

Virtual outcrops technology can bring the most spectacular outcrops worldwide direct to the student no matter where they are based as long as they have an Internet connection. These models have great potential for introducing geology to a wide sector of the public who would not, for whatever reason normally visit such sites, for example, students with disabilities, middle and high school students, or interested amateurs. As the technology becomes cheaper and more data sets become available, we suggest that interpretation of virtual outcrops will become an important part of the earth science curriculum. They will provide supplementary learning methods that are not always feasible with traditional outcrop studies.
resources for existing field classes and help to further broaden students’ knowledge base by providing examples from worldwide databases. A final point is relevant to the ongoing debate regarding public access rights to land in Ireland and other countries, and the concerns geoscientists have about the future of field visits to geologically important sites. Through the use of virtual outcrops for student instruction, some of these concerns can be overcome. However, we emphasize that geological visualizations such as terrestrial scanner–generated virtual outcrops and 3D surface models cannot substitute for “real-world” experiences of field geology. Nevertheless, visualizations can serve as aids in the learning process and provide valuable tools for “bringing” remote or inaccessible outcrops to students.

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