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The New World of 3D Geologic Mapping

***Terry L. Pavlis** and **Kelsey A. Mason,** Department of Geological Sciences, The University of Texas at El Paso, El Paso, Texas 79968, USA*

ABSTRACT

Digital geologic mapping is now a fully mature technology that dramatically improves field efficiency and problem solving capabilities. Basic digital mapping is just the tip of the iceberg, however, in regard to new and approaching capabilities with true 3D mapping. The key advance is the ability to easily construct high-resolution, photorealistic terrain models as a base surface for 3D mapping using Structure from Motion (SfM) photogrammetry terrain models, particularly through the aid of unmanned aerial systems (UAS). We show how these technologies can aid field visualization and discuss how developing digital field workflows and 3D visualizations will transform field studies, allowing the resolution of problems that were impossibly complex without this technology.

INTRODUCTION

The past 30 years have witnessed a revolution in digital technology that has led to astonishing changes in our lives, from the use of personal devices to advanced computing. Digital technology is also fundamentally changing field geology in ways that will impact all geosciences. Digital geologic mapping has been practical for more than 10 years (e.g., Pavlis et al., 2010), and, although many cling to paper-based workflows, that approach is now outdated and inefficient in comparison. Digital mapping also transforms a geologic map from a static, fixed-scale object to a dynamic, multiscale database complete with the primary data used to construct it.

Digital mapping, however, is only the beginning of an even bigger revolution that is upon us from three-dimensional (3D) mapping and visualization. The geometry of geologic features analyzed in field studies is inherently 3D, and reliance on 2D maps has handicapped advances in our understanding of the earth system. Three-dimensional geophysical imaging of the subsurface revolutionized hydrocarbon exploration and could do the same for field geology, where rich 3D information is available from surface geology when there is significant topographic relief, yet that 3D information is mostly lost in 2D methods. In addition, we continue to teach students flat-map techniques like visualizing Earth's surface through a topographic map, yet this abstraction of Earth's surface is challenging for most students. Digital globes like Google Earth help with this problem, but we now have far better options.

In this paper, we consider the problem of geologic mapping and how 3D visualization can aid that process. We emphasize here the importance of the distinction between 3D geologic mapping and 3D modeling of geologic features. Whole volumes have been written on the latter, but 3D mapping as a data collection technique is still in its infancy (e.g., MacCormack et al., 2015; Buckley et al., 2016). To date the primary work on 3D mapping has been in Europe and Australia, with most applications in engineering geology and geomorphology (e.g., MacCormack et al., 2015; Buckley et al., 2016). This will soon change. We predict that 3D techniques will soon fundamentally reshape all geologic fieldwork in ways we have not even begun to realize. In particular, we emphasize that new technology, Structure from Motion (SfM) photogrammetry in conjunction with unmanned aerial systems (UAS), aka drones, can allow routine construction of inexpensive, high-resolution, photorealistic 3D terrain models. These 3D surface models can serve as a base for high-resolution surface mapping that will allow construction of a new generation of 3D geologic models at scales ranging from hand specimen to tens of kilometers. To support this claim, we begin with a review of the limitations of widely used 3D visualizations of Earth's surface in comparison to capabilities of SfM models. We then use a case study to illustrate how these high-resolution visualizations of Earth can dramatically improve the ability to resolve geometric problems in the field. We then speculate how this technology will reshape field geology in the next 5–10 years.

THE 2D DIGITAL MAPPING OF TODAY AND THE NEW WORLD OF 3D MAPPING

A few years ago, we (Pavlis et al., 2010) reviewed the history of technology that led to the modern generation of field data collection systems for digital mapping, yet seven years is an eternity in this field of rapidly advancing technology. Two-dimensional digital mapping has now become a fully mature practice with numerous applications for field geology (Mookerjee et al., 2015). Software and hardware issues remain, but there is no longer a doubt that paper mapping is outdated due to the inherent efficiency of digital techniques and ability to share data readily (e.g., Whitmeyer, 2012). Moreover, increased mapping accuracy with GPS, routine access to multiple data layers, and the nearly limitless scaling afforded by digital maps allow for the resolution of field problems that was impossible on paper maps. Nonetheless, these systems are only the vanguard to a true revolution that is upon us, 3D mapping.

The Problem of Early 3D Methods

For many of us, geologic mapping through a 3D interface has been a dream since the first 3D computer visualizations appeared on the scene. Two-dimensional digital mapping is largely a data management/collection variant on paper-based field geology, and therefore remains a flat-map–centric approach to a problem that is fundamentally 3D. Geologists first began to experience 3D mapping from digital elevation models (DEMs) using GIS software and digital globes like Google Earth and NASA's Worldwind (DePaor,

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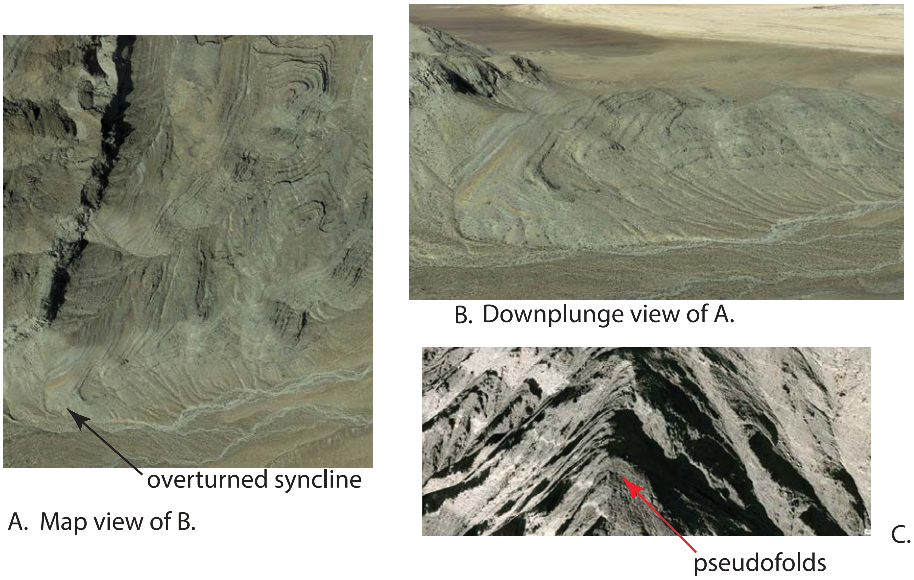

A. Map view of B.

B. Downplunge view of A.

C.

Figure 1. Examples of success and failure of 2.5D techniques for visualization of geologic features. (A) and (B) show a successful visualization of an overturned syncline in the Nopah Range near Pahrump, Nevada, USA, where the visualization is successful due to the large size of the structure (~1 km across) relative to the terrain model. (C) shows a contrasting failure of the method in the same area where pseudofolds are seen in this oblique view due to improper image drape on a narrow ridge line. Oblique view is ~500 m across. All views are from Google Earth.

2016). Digital globes eliminate one problem in flat map approaches by affording an infinite range of views such as down-plunge views of folds (Fig. 1) or down-dip views of dipping beds that eliminates the "law-of-v's" effect. Nonetheless, digital globe visualizations contain errors inherent in the way they are constructed, which is not always appreciated by geoscientists. In particular, any recent GIS textbook describes how surface visualizations like Google Earth are produced by a 2.5D method of draping imagery, typically orthocorrected aircraft imagery or satellite imagery, onto a DEM. When terrain is modest, this approach produces a reasonable rendering of Earth's surface, but in steep terrain this approach produces spatial errors that lead to visualization problems like pixel smear and distortions that introduce spatial errors during 3D mapping (Figs. 1 and 2 and GSA Data Repository supplement 1[1]). This problem has been known for decades in photogrammetry (e.g., Wolf, 1983), but its effects are often misunderstood. For example, consider a vertical or overhanging cliff. In a vertical view, the 3D surface of the cliff is degraded to a line. Alternatively, in an image captured off-nadir, the cliff occupies a 2D area in the photograph, but is distorted due to look angle. In either case, however, orthocorrection, and subsequent draping of the orthophoto onto a terrain model, produces distortions via pixel smear, distorting the image on the terrain model, or both. This effect is particularly significant when the terrain model is low resolution relative to the imagery, which is the case in virtually all visualizations that use a standard 30–90 m DEM (Figs. 1 and 2 and Data Repository supplements 1A–2B [see footnote 1]).

It is easy to show from basic trigonometry that on all steep slopes (>45°) features will be either invisible or hopelessly distorted in conventional map views and 3D visualizations that use a 2.5D image drape approach. Therefore, potentially critical information is mostly lost. Ironically, these same cliff faces are often the most informative rock exposures. Field geologists long have compensated for this limitation by using photographs, field sketches, or both, but these observations contain no quantitative, 3D geographic control. Recognition of this issue was a major driver for the "Virtual Geoscience" initiative in Europe (Buckley et al., 2016), and although the problem can now be resolved, the solution has not yet been widely exploited.

The Solution: A New World of True 3D Terrain Models and 3D Mapping

One solution to this steep-slope/cliff problem has been around for some time through the use of ground-based or airborne LiDAR (light detection and ranging). High-resolution 3D renderings of Earth's surface can be obtained with these methods, including overhanging cliff faces. In addition, photos from any angle can be draped onto the model, or the raw, colored point cloud can be visualized to provide photorealistic scenes.

Although LiDAR is presently the gold standard for terrain modeling, we predict that it will never be used extensively for bedrock field geology except in special cases where very high accuracy is needed. The reason is that a technology has arisen that makes LiDAR overpriced and inefficient. That technology is SfM photogrammetry. SfM has been described elsewhere (e.g., Westoby et al., 2012; Tavani et al., 2104; Furukawa and Hernandez, 2015; DePaor, 2016) and is a fundamental advancement in photogrammetry that eliminates the requirement for near vertical imagery in conventional photogrammetry. Specifically, SfM, or more specifically, multi-view stereo, allows the use of a suite of arbitrary oblique images in the construction of a 3D terrain model (e.g., Westoby et al., 2012; Furukawa and Hernandez, 2015). Most applications of SfM to date have been in geomorphology and engineering geology or in the construction of virtual outcrops (e.g., Buckley et al., 2016; DePaor, 2016). We suggest here, however, that ultimately SfM will have its greatest application at map scales commonly used in bedrock field geology, particularly in areas of extensive rock outcrop. SfM is advantageous at this scale over LiDAR because (a) it only requires equipment already routinely carried by field geologists—a camera, GPS unit, and field computer; and (b) it can be exploited at sites of opportunity via construction of virtual outcrops or at map scales, depending on project needs. Thus, there is no need to carry an expensive extra piece of equipment, and a single individual or small group can produce a photorealistic terrain model at resolutions of centimeters with none of the problems of 2.5D terrain

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[1] GSA Data Repository Item 2017128, four supplementary figures and two animations, is online at http://www.geosociety.org/datarepository/2017/.

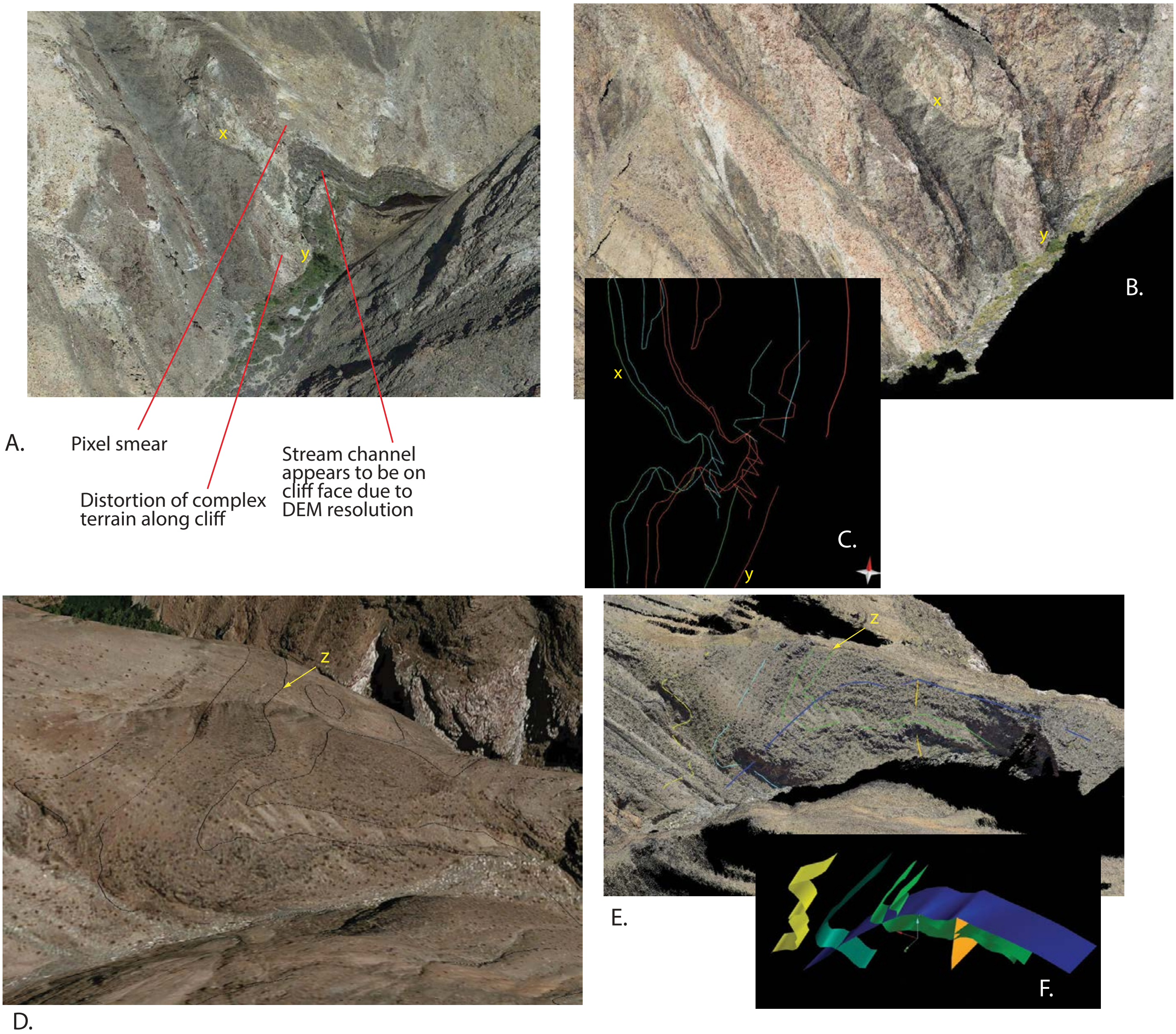

Figure 2. Virtual scenes of the case study area in Surprise Canyon, California, USA (near 36.1133N, 117.1617W), illustrating errors introduced in conventional 2.5D methods (left, perspective views in Google Earth [A] and ArcGIS Pro [D]) versus approximately equivalent perspective views of georeferenced SfM point clouds obtained from oblique, ground-based photography (right). Insets (C) and (F) show local geologic interpretations with (E) and (F) described further in Figure 4. Several errors are apparent in the left scenes. In (A) and (B) (yellow [x] and [y] are equivalent points on the images and [C]) note the distortions and pixel smear in (A) versus true renderings in (B). (C) is a cyan-magenta stereo rendering of the lithologic contact between the dark and light units between (x) and (y) as well as two faults (white lines, rendered blue and red in the view, are from the SfM model and yellow, rendered green and red in the view); note how the 3D model allows 3D rendering of exposed fault faces as a jagged line versus the poor rendering of the faults from map drapes as well as superior 3D resolution of the contact in the SfM model. In scenes (D) and (E) note how errors in the 2.5D method introduce an artifact in D, labeled z, that could produce a major error in a geologic interpretation. In the left scene (D) rock units (outlined in black) clearly appear to dip to the right in this rendering and a three-point analysis of the scene would confirm this, yet the true dip is to the left, which is clear in the right scene (E) and in the field. (F) shows a visualization of structures present in the scene with the dark blue surface, indicating the folded axial surface of early isoclinal folds and the vertical orange plane showing the axial surface of a second generation antiform that warps the older fold system.

visualizations (Figs. 1 and 2 and Data Repository supplement 1 [see footnote 1]). The colored terrain model is still subject to look angle issues such that a model generated entirely by surface observations will be limited by the available views (Fig. 3). Nonetheless, it is straightforward with this technology to combine ground-based photographs and aerial photographs, producing a photorealistic 3D model of Earth's surface (Fig. 3). Best practices still need further research, but we have found that direct mapping on the colored point cloud is straightforward in several software packages (e.g., see workflow suggestions at www.geo.utep.edu/pavlis/digitalmappingwebpages/). In this approach, problems like pixel smear and distortions from image drape are eliminated. In addition, there is no doubt in this method that every point in the point cloud has a proper color for its position in 3D space because the point color is derived directly from the photographs that generated the model. In the following section, we illustrate the power of using these models to solve a field problem, but applications are nearly limitless.

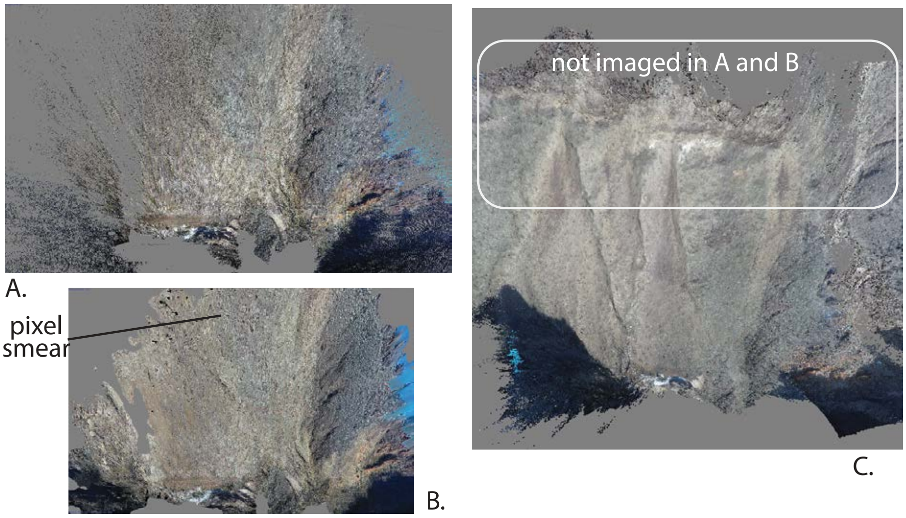

Figure 3. Illustration of the power of using unmanned aerial system (UAS) imagery in Structure from Motion studies. Figure is a comparison of a near-vertical view of the same area developed using the same camera from ground-based images only (A and B) versus ground-level to ~100 m elevation UAS flight images (C). (A) is a visualization of the colored point cloud, whereas (B) is a textured triangulated irregular network model, and (C) is a colored point cloud with all scenes processed at the same resolution using Agisoft PhotoScan. Seventy images were used in (A) and (B) versus 400 in (C), but the increase in resolution is primarily due to greater ranges of look angles in (C).

Case Study: Surprise Canyon, Panamint Mountains, California, USA

Methods

Terrestrial LiDAR survey (TLS) data were acquired in Surprise Canyon in the Panamint Mountains west of Death Valley to conduct an experiment in 3D mapping. Following that survey, we used a handheld, GPS-enabled camera at sites of opportunity and used the photographs to develop SfM models that overlapped with the TLS survey. The SfM data were co-registered with the TLS data using a variety of ground control methods. Data acquisition and error assessment for this study is considered elsewhere (Brush, 2015). The study area was chosen because it contains complex, metamorphic structures, arguably the most challenging 3D visualization problem in field studies, yet the area contains superb bedrock exposures and significant topographic relief. Thus, the site is nearly ideal to test 3D mapping methods. SfM models were generated using Agisoft PhotoScan Professional software; Maptek's I-Site Studio was used to co-register SfM and LiDAR point clouds as well as a 3D

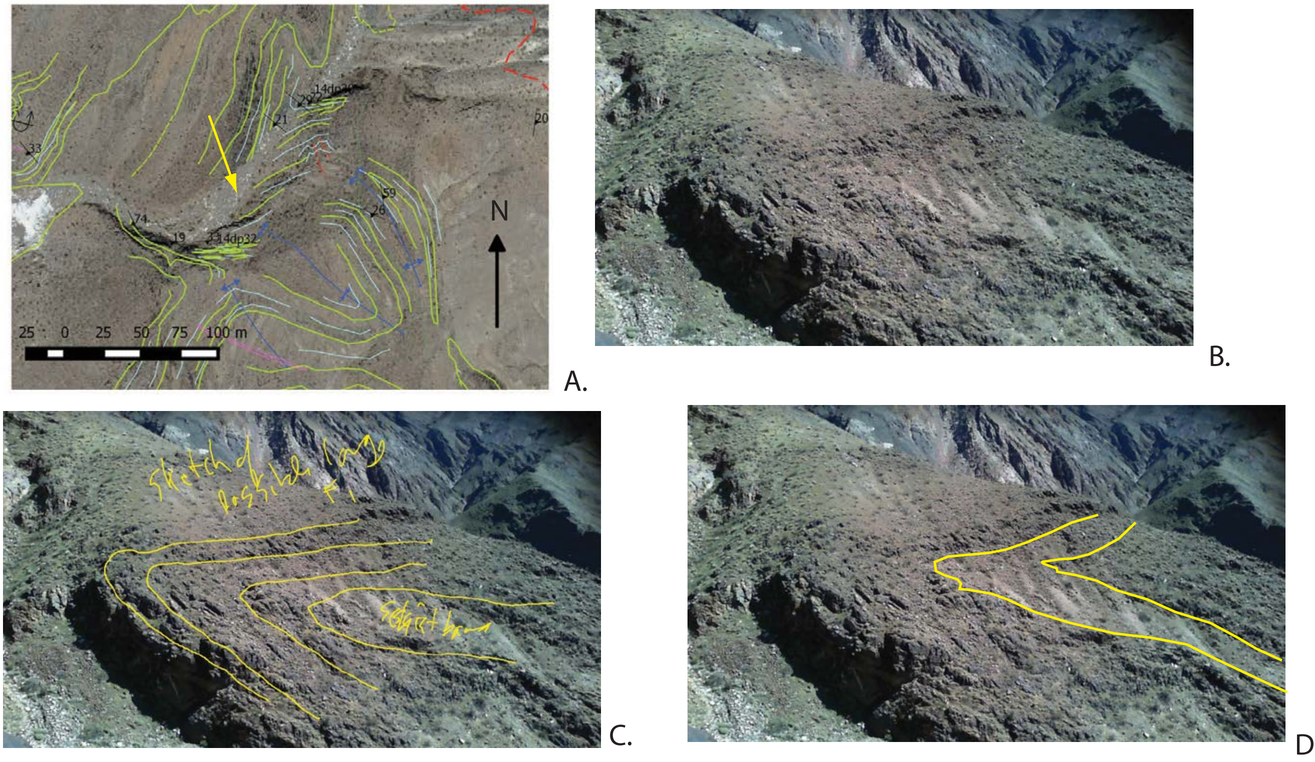

Figure 4. Sequential development of the structural interpretation for the area in Figure 2D–2F. (A) shows field map at the end of the first season (one field day) with contradictory interpretations. Yellow arrow shows view direction in Figure 2 and (B)–(D) in this figure. (B) shows an uninterpreted field image captured on a tablet computer with the same image annotated in (C) showing the field interpretation after the second visit to the site versus the final interpretation (D) developed from model interpretation and a field visit to confirm the interpretation. Linework in (A) shows form lines of layering (green), main foliation (blue), inferred second cleavage (dashed thin red lines), intrusive contacts (magenta), and fault contacts (dashed red line).

mapping interface. We began the study with conventional 2D mapping, albeit aided by 2D digital mapping techniques using the GIS data structure of Pavlis et al. (2010) with QGIS software. Orthocorrected satellite imagery with resolutions of 1–2 m from the USGS and ArcGIS online were used as a base map for our 2D mapping. ArcGIS Pro and Midland Valley's Move software were used for draping 2D map data onto the USGS DEM for the area and for comparison with 3D mapping results (see Brush, 2015, for more details on workflows).

Results

Our 2D geologic map is high resolution by almost any standards due to GPS positioning and the resolution of the orthoimagery (Data Repository supplement 2 [see footnote 1]). Nonetheless, the problems of conventional 2D mapping and 2.5D draping to a terrain model quickly became apparent when we attempted to analyze the data in 3D.

Figure 2 shows a comparison of a 2.5D image and linework drapes (2A) onto a low-resolution elevation model versus mapping directly onto a true 3D view afforded by the SfM models (2D). The principal source of the distortions in Figure 2 include (1) artificial smoothing of the terrain in the low-resolution model leading to errors in elevation positions of image pixels, which transfer to the geologic interpretation; and (2) errors inherited from the orthophoto production process that are transferred to the image drape.

Beyond these issues of spatial errors from the 2.5D method, we suggest that the greatest strength of SfM 3D surface models is the increased geologic insight that can be gained from using these distortion-free, 3D visualizations as a mapping base during and after fieldwork. Probably every field geologist has wanted the ability to "fly like a bird" to view features from different perspectives. Indeed, this is one reason helicopters are used in field studies and is the most obvious reason UAS are beginning to see widespread use in fieldwork (e.g., Jordan, 2015; Hackney and Clayton, 2015). SfM models +/– UAS flight video provide a virtual experience close to this capability at a tiny fraction of the cost of a helicopter and allow limitless virtual views of the scene that is impossible from a live aircraft flight. As an illustration of the power of this capability, Figure 4 shows the evolution of our understanding of the structure shown in Figures 2D and 2E. In the 2D field map from the initial visit to the site (Fig. 4A), the field interpretation was relatively simplistic and contradictory. Field-note sketches considered several alternative fold geometries, but the initial work was inconclusive. In a second visit to the site, more orientation data were obtained and photographs were acquired for the SfM model shown in Figure 2. Like the first visit, however, multiple hypotheses were considered for this structure, and a field sketch (Fig. 4C) at the end of the field day was the working hypothesis. After later analysis manipulating 3D visualizations and mapping onto the SfM model, we realized that the structure was a large, refolded recumbent fold (Fig. 2F). This hypothesis was confirmed by a third field visit to the site.

Clearly this was not a controlled experiment and arguably we would have recognized the structure anyway, either with more field time or through traditional methods like serial section construction. Moreover, the approach was inefficient relative to our present workflow model because we were developing techniques at the time. Nonetheless, the ease of the analysis from the 3D visualization made recognition of the feature easier and led to greater confidence in the interpretation.

Similarly, 3D analysis of the broader area in this study answered several questions (e.g., Data Repository supplement 2 [see footnote 1]) but, perhaps more importantly, led to hypotheses that probably would not have arisen without the 3D mapping. For example, directly along structural trend from Figure 2, outcrop-scale, plunging, type 3 (coaxial) refolded folds (terminology of Ramsay, 1967) like those in Figure 2 are common. However, the orientation of the most prominent isoclinal folds is grossly different along strike—approximately recumbent to the north and upright to the south. In the absence of a 3D model, this observation is difficult to evaluate, but using the 3D model to visualize geometry across the area, our working hypothesis is that there is a large-scale west-vergent recumbent fold that was refolded by upright folds associated with the second cleavage (Pavlis et al., 2016). More work is needed to test that hypothesis and will be the subject of future fieldwork. Nonetheless, the important point is that in the absence of the 3D visualization we probably couldn't have even raised this question without much more fieldwork, the ability to climb across the steep terrain, or both. Thus, how many other unresolved geologic problems or missed issues lie hidden in steep terrain that could be resolved with these methods?

3D Mapping and its Importance to 3D Modeling

This case study gives a partial illustration of the potential of using SfM for solving geologic problems, but it is a limited example in the broad range of potential applications. The key features in this case were (1) the dramatic increase in accuracy of the 3D view, which aided confidence in geometric interpretations as real, not artifacts of mapping imprecision; and (2) the ability to view 3D features from a variety of viewpoints, and revisit these views repeatedly, allowing fast evaluation of geometry, something impossible with conventional mapping. This ability is a cognitive breakthrough for field geology because it allows geologists to break from the traditional paradigm (e.g., Compton, 1985) that key features should always be recognized the first time around due to the economics and logistics of fieldwork—i.e., this paradigm may still hold for the field visit, but a key site can now be captured as a 3D visualization that can be viewed ad infinitum to help resolve problems.

For those inexperienced with field geology in areas of complex structure, particularly in steep terrain, it may not be obvious how important these abilities can be. From our experience, the 2.5D method can be used for construction of 3D geologic models of complex structure (e.g., Pavlis et al., 2012), but the distortions and imprecision in the underlying terrain model make geologic model construction inefficient as well as potentially wrong due to uncertainties in the sources of spatial error. In a true 3D model based on SfM, none of those spatial uncertainties exist in the raw data, and the only uncertainties arise from potential interpretation errors—a problem much more easily evaluated through an iterative mapping approach. Note also that for those who have only used 2D methods (maps and cross sections) for geologic analysis, it is easy to underestimate the difficulty of constructing a true 3D geologic model from 2D sources. It is largely for this reason, and the spatial error issues in the 2.5D method, that most 3D geologic modeling to date has been limited to the relatively simple visualizations of flat-lying to nearly flat-lying strata or simply deformed rocks (e.g., MacCormack et al., 2015).

At present, workflows for both 3D mapping and 3D model construction are dependent on software that is neither customized for the field environment nor readily amendable to the limitations of field computers. Nonetheless, given the speed of development of software and hardware, this limitation will be trivial within the next two to three years, suggesting that all of these capabilities will be readily available for field geology, if we choose to embrace them.

Near Future Capabilities and the Importance of UAS

Another technology, unmanned aircraft systems (UAS), promises to expand 3D mapping further in ways we undoubtedly do not yet fully grasp. UAS have become a prominent topic across society, and their proliferation offers huge opportunities for field geologists (e.g., Hugenholtz et al., 2013; Bemis et al., 2014; Jordan, 2015; Hackney and Clayton, 2015). They already serve as aerial platforms to enhance construction of SfM models. However, there are many opportunities beyond this application. Some examples include

1. A low-cost, lightweight drone that could become every geologist's "field assistant," with tasks ranging from safety to planning (e.g., applications as simple as route planning to as complex as geologic recon or hazard assessment).
2. A drone with a remote video feed equipped with a suitable magnetometer-accelerometer system and an ability to orient the device remotely could gather remote orientation measurements from cliff faces or inaccessible terrain. To our knowledge no such device yet exists, but is possible with modern technology.
3. A major advance in geomorphology arose with bare-ground models obtained by filtering airborne LiDAR data (e.g., Haugerud et al., 2003). A drone equipped with an object-avoidance system, such as an optical proximity measurement tool, could be developed to fly through a forested area below treetop level carrying a LiDAR system and cameras for SfM work. The resultant data could be used to obtain a true bare-ground model with no questions on potential filtering artifacts that can arise from conventional airborne LiDAR. Alternatively, this application could be used as a simple outcrop finder tool in areas of poor exposure.
4. The expansion of cheaper and lighter-weight multi- and hyperspectral sensors for UAS and the improvement of commercially available UAS to more easily integrate with these sensors (e.g., see Buckley et al., 2016) will potentially lead to a geologist's ability to develop 3D lithological classification maps in the field—essentially giving field geologists live, multispectral eyes. As of yet, studies with multi- or hyperspectral cameras on UAS have been limited, with few applications to bedrock geology (e.g., Buckley et al., 2016). In the United States this is likely due to the previously strict Federal Aviation Administration UAS regulations as well as the high cost of these sensors, but experiments of this type clearly are ongoing in Europe (Buckley et al., 2016). In addition, the current commercially available sensors for UAS only provide visible and near infrared (VNIR) imagery/data designed for agricultural purposes (Link et al., 2013; Herrero-Huerta et al., 2014; Rasmussen et al., 2016) or thermal infrared (TIR) for disaster management, monitoring geothermal environments, etc. (Nishar et al., 2016; Yahyanejad and Rinner, 2014), while lithology is best distinguished with shortwave infrared (SWIR).

Beyond these drone-based applications, perhaps the biggest advances will come from full 3D visualization and mapping capabilities in software in the field environment. Virtual reality (VR) headsets are becoming more readily available and could be used in a field scenario to produce a 3D representation of a scene in front of the geologist, potentially complete with multispectral 3D renderings, providing an augmented reality interface that would allow resolution of features undreamed of, even now. Perhaps most important, however, is the potential of this technology to teach concepts to the next generation of students at all levels. Freed from the confines of flat maps, there is a potential for accelerated learning of 3D concepts using this technology. Nonetheless, research is needed on how these techniques can aid learning rather than hinder it.

Finally, many have lamented the decline of field geology, yet at the same time blame high-tech for this decline (e.g., Callan, 2016). Our experience is the opposite. Specifically, paper-based field geology using nineteenth-century technology is viewed by most modern students as "old school," and many shy away from field studies as a result. Incorporation of digital mapping and these 3D techniques, however, excites modern students and has the potential to attract a whole new generation of tech-savvy field geologists who could solve problems previously considered impossibly complex.

CONCLUSIONS

Three-dimensional terrain models derived from SfM, particularly when augmented with aerial photography from UAS, provide an inexpensive base for the next generation of geologic mapping using a 3D interface. Visualization of these models frees geologists from the confines of flat maps and allows high-precision mapping of steep slopes and cliffs, which are virtually invisible in conventional maps. The ability to easily examine multiple view angles of Earth's 3D surface outside the time limitations and logistical constraints of fieldwork is a cognitive breakthrough that frees field geology from the one-site–one-visit paradigm. Many geologists have lamented the decline of field geology, but the rise of these 3D technologies has a potential to revitalize field geology and launch a new generation of studies. Research is desperately needed, however, on ideal workflows that employ this technology across a range of applications and the range of field sites, and perhaps most importantly, how this technology can aid 3D learning rather than hinder it.

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