25–28 Oct. GSA 2020 Annual Meeting

GSA TODAY

THE GEOLOGICAL SOCIETY
OF AMERICA®

VOL. 30, NO. 6 | JUNE 2020

Visualization and Sharing of 3D Digital Outcrop Models to Promote Open Science

Visualization and Sharing of 3D Digital Outcrop Models to Promote Open Science

Paul Ryan Nesbit, Adam D. Boulding, Christopher H. Hugenholtz, *Dept. of Geography, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada;* **Paul R. Durkin,** *Dept. of Geological Sciences, University of Manitoba, 66 Chancellors Circle, Winnipeg, Manitoba, R3T 2N2, Canada; and* **Stephen M. Hubbard,** *Dept. of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada*

ABSTRACT

High-resolution 3D data sets, such as digital outcrop models (DOMs), are increasingly being used by geoscientists to supplement field observations and enable multiscale and repeatable analysis that was previously difficult, if not impossible, to achieve using conventional methods. Despite an increasing archive of DOMs driven by technological advances, the ability to share and visualize these data sets remains a challenge due to large file sizes and the need for specialized software. Together, these issues limit the open exchange of data sets and interpretations. To promote greater data accessibility for a broad audience, we implement three modern platforms for disseminating models and interpretations within an open science framework: Sketchfab, potree, and Unity. Web-based platforms, such as Sketchfab and potree, render interactive 3D models within standard web browsers with limited functionality, whereas game engines, such as Unity, enable development of fully customizable 3D visualizations compatible with multiple operating systems. We review the capabilities of each platform using a DOM of an extensive outcrop exposure of Late Cretaceous fluvial stratigraphy generated from uninhabited aerial vehicle images. Each visualization platform provides end-users with digital access and intuitive controls to interact with large DOM data sets, without the need for specialized software and hardware. We demonstrate a range of features and interface customizability that can be created and suggest potential use cases to share interpretations, reinforce student learning, and enhance scientific communication through unique and accessible visualization experiences.

INTRODUCTION

High-resolution 3D digital models are becoming increasingly common data sets in academic and commercial applications. In the geosciences specifically, digital outcrop models (DOMs), or virtual outcrops, can provide geoscientists with photorealistic models that preserve spatial precision, dimensionality, and geometric relationships between geologic features that are inherently 3D and susceptible to distortion and/or loss of information when rendered in 2D (Bellian et al., 2005; McCaffrey et al., 2005; Jones et al., 2009). Digital 3D mapping approaches using DOMs have enabled geoscientists to perform supplemental measurements, correlations, and interpretations that are difficult or impossible to obtain with traditional methods (Figs. 1–2; Pavlis and Mason, 2017; Nesbit et al., 2018).

Until recently, however, collection and use of digital data sets has been limited to specialists, due to hardware and software limitations. A number of methods are now available for collecting and processing 3D models (Hodgetts, 2013; Carrivick et al., 2016). In particular, structure-from-motion and multi-view stereo (SfM-MVS) photogrammetry software, commonly paired with uninhabited aerial vehicles (UAVs), enables geoscientists to produce photorealistic DOMs through a highly streamlined UAV-SfM workflow (Chesley et al., 2017; Nieminski and Graham, 2017; Pavlis and Mason, 2017; Nesbit and Hugenholtz, 2019).

Related efforts have centered on the development of 3D software solutions with tools for geoscience applications. Custom software packages, such as Virtual Reality Geology Studio (VRGS; Hodgetts et al., 2007) and LIME (Buckley et al., 2019), offer users lightweight executable tools and opportunities to analyze and revisit data at multiple scales. Open source programs, such as Blender and CloudCompare, can be used for data exploration and measurement and have also integrated specific geoscience toolsets (e.g., Brodu and Lague, 2012; Dewez et al., 2016; Thiele et al., 2017).

Although acquiring DOMs has become more straightforward, and various 3D analysis programs are available, dissemination of DOMs, interpretations, and results has remained a challenge due to software and file-size barriers. Specialty 3D programs are often hindered by product licensing and can involve a considerable learning curve to understand controls, file formats, and integrated tools. Furthermore, DOMs can easily exceed multiple gigabytes (GB) in size, which can be taxing on computational resources for rendering, file storage, and data transfer. With the growing collection of high-resolution DOMs and similar 3D data sets, there is a need for dedicated, intuitive, and accessible 3D visualization platforms.

Given the challenges outlined above, we examined existing visualization solutions that could potentially enable sharing of DOMs and support open science through increased data accessibility. To provide a functional introduction to modern visualization platforms, we illustrate the capabilities and functionality of two web-based interfaces (Sketchfab and potree) and a cross-platform videogame engine (Unity) using a geologic case study. A DOM was produced through a UAV-SfM workflow for an extensive outcrop (1 km^2) exposed within the badland landscape of Dinosaur Provincial Park (Alberta, Canada). Each visualization platform provides access to the large DOM through an intuitive lightweight interface without the need for high-end hardware,

GSA Today, v. 30, https://doi.org/10.1130/GSATG425A.1. Copyright 2020, The Geological Society of America. CC-BY-NC.

Figure 1. Geologic interpretations (line drawing on 2D field photograph), a common conventional method to highlight stratigraphic architecture and distribution of related units. Mudstones are gray to light brown; sandstones are light gray to white. This process is often performed on photos or a photomosaic acquired in the field.

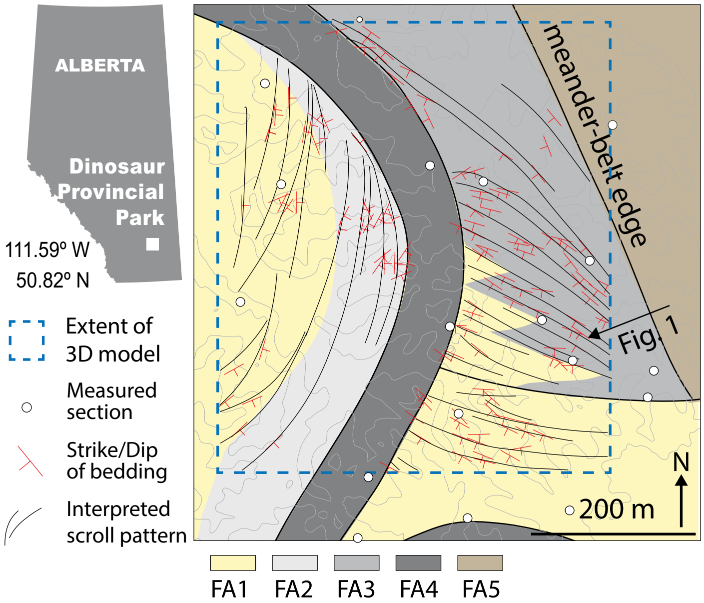


Figure 2. Traditional geologic map used to share field measurements, observations, and interpretations in 2D plan-view. This geologic map was constructed from the integration of traditional fieldwork methods (measured sections as well as paleoflow and bedding measurements) with digital outcrop model mapping to characterize heterolithic channel-belt deposits exposed at Dinosaur Provincial Park, southeastern Alberta, Canada. Field-based Facies Associations (FA)1—sandy point bar; FA2—heterolithic point bar; FA3—Counter-point bar; FA4—abandoned channel; FA5—mudstone. Bedding surfaces, noted in Figure 1 (red), were digitally mapped on the 3D model and yield a more refined and detailed interpretation of accretion surface orientation and stratigraphic architecture. These methods are being widely applied, yet the results are difficult to disseminate and share in 3D.

specialized software, or transfer and storage of large files. This prompts an increased ability to share data sets, interpretations, and results with a wider community, expanding opportunities for scientific communication and open science education.

RELATED WORK

Visualization of digital 3D models has been practical for more than two decades; however, early geoscience applications were typically restricted to dedicated geovisualization labs and required specialized software (e.g., Thurmond et al., 2006; Jones et al., 2009; Bilke et al., 2014). Today, visualization of large 3D data sets is no longer limited to sophisticated labs, but rather an average computer can render 3D models efficiently, due in large part to inexpensive hardware, such as dedicated graphics processing units (GPUs). Despite the capabilities of modern computing hardware, bottlenecks remain, with a lack of accessible visualization software and the need to transfer large files.

Though separate 3D viewers are available to supplement proprietary software (e.g., Trimble RealWorks, FugroViewer), they typically require local storage of large files, learning curves, and have associated licensing restrictions. Alternative applications, such as digital globes (e.g., Google Earth) are a popular method for disseminating spatial and non-spatial data in an interactive, semi-immersive environment, with intuitive controls (Goodchild et al., 2012). Digital globes have been used to create "virtual field trips" (McCaffrey et al., 2010; Simpson and De Paor, 2010; De Paor and Whitmeyer, 2011) and present 3D data sets (Blenkinsop, 2012; De Paor, 2016). Although digital globes provide tremendous benefits, displaying DOMs within digital globes requires a significant reduction of detail and results in overlay issues relative to underlying base layers (Tavani et al., 2014).

Web-based dissemination may be one of the most promising and practical means for rapidly streaming 3D digital data sets without transferring raw data (Turner, 2006; von Reumont et al., 2013). Advances of application programming interfaces (APIs), such as WebGL, allow modern Internet browsers to access the local GPU to improve rendering of 2D and 3D graphics, without the need for plug-ins or extensions (Boutsi et al., 2019). Though not guaranteed, WebGL enables GPU functionality on various operating systems and devices (Schuetz, 2016). Several proprietary web viewers, such as Sketchfab (https://www.sketchfab.com), use WebGL for sharing 3D models. Proprietary web-based viewers have recently been used by geologic databases (e.g., Safari Database, https://www.safaridb.com: Howell et al., 2014; eRock: Cawood et al., 2019).

Web viewers based on open source code, such as potree (Schuetz, 2016), use WebGL API to efficiently render massive point clouds (>10^9 points) in standard Internet browsers. Potree does not require end-users to install software or download large data sets (Schuetz, 2016) and has been adopted by various organizations, including the USGS, for sharing and visualizing national topographic LiDAR data sets (USGS, 2019). Similarly, OpenTopography and Pix4D-cloud provide online viewers, similar to potree, allowing subscribers to share point clouds through standard web browsers.

Alternative methods have incorporated the use of game engines to create customized geovisualizations compatible with various operating systems. Unity and Unreal Engine are two popular game development platforms that are well-documented, have vast online programming communities, and are available for free to developers producing revenue below a defined threshold. Recently, game engines have been used in the geosciences for the gamification and sharing of 3D data sets in immersive virtual reality (VR) (Bilke et al., 2014), translating ArcGIS data into a 3D environment using Unity (Robinson et al., 2015), and presenting virtual archaeological sites (Martinez-Rubi et al., 2016; Boutsi et al., 2019).

CASE STUDY: FLUVIAL STRATIGRAPHY, DINOSAUR PROVINCIAL PARK

Geological Overview

Dinosaur Provincial Park is a UNESCO World Heritage Site in southeastern Alberta, Canada, recognized for an abundance of well-preserved dinosaur fossils and characteristic badland topography (Dodson, 1971; Currie and Koppelhus, 2005). This case study presents a 1 km^2 subsection within the northeastern portion of the park containing extensive 3D exposures of the Late Cretaceous Dinosaur Park Formation (Wood et al., 1988; Eberth and Hamblin, 1993). Contrasting layers of siltstone and fine- to medium-grained sandstone along with the stratigraphic architecture are representative of successive meandering channel belts cutting through adjacent floodplain mudstones (Figs. 1–2; Smith et al., 2009; Nesbit et al., 2018; Durkin et al., 2020). Most of the park is a natural preserve accessible only through research permits or guided programs. The digital model provides a viewing window into a small section of the park without disrupting wildlife and the natural landscape.

Data Collection and DOM Processing

Images were collected through eight flights with a sensefly eBee fixed-wing UAV equipped with a Sony WX220 18.2 megapixel camera, resulting in 1760 images. Images were recorded at a pitch angle of 10º off-nadir to increase point visibility along sub-vertical surfaces and increase precision of final models within the high-relief topography (Nesbit and Hugenholtz, 2019). Images were processed using Pix4Dmapper v4.3 following a similar workflow described by previous authors (Küng et al., 2012; Nesbit et al., 2018). Following initial processing, the model was divided into four quadrants and processed into a dense point cloud and 3D textured mesh. Mesh outputs were exported as Autodesk Filmbox (.fbx) format, which generally results in smaller file sizes than commonly used 3D polygon (.ply) and wavefront (.obj) formats.

Visualization Approaches

DOMs are presented in textured mesh and dense point cloud formats, using three different visualization platforms (Sketchfab, potree, and Unity). Although other platforms are available, these were intentionally selected for their ability to provide end-users with access to 3D data sets without specialty software or transfer of large data sets and are representative of the current capabilities of modern viewers.

Web-Based 3D Mesh (Sketchfab)

Using a web-based interface, Sketchfab allows authors to intuitively upload models, define rendering options (e.g., lighting, material properties), and provide supplementary annotations (Fig. 3A). Upload limitations of 200 MB, including all mesh and texture components, prevented rendering of the complete 1 km^2 field area within a single viewer without significant texture distortion. To preserve detail within the field area, we present each quadrant separately. Multiple texture resolutions and VR compatibility are automatically generated during upload to provide end-users with different level of detail (LoD) rendering options based on the capabilities of their viewing device. Location-specific annotations describing geologic features and concepts to end-users were added to models using the upload interface. Additional data sets could not be integrated within 3D model space.

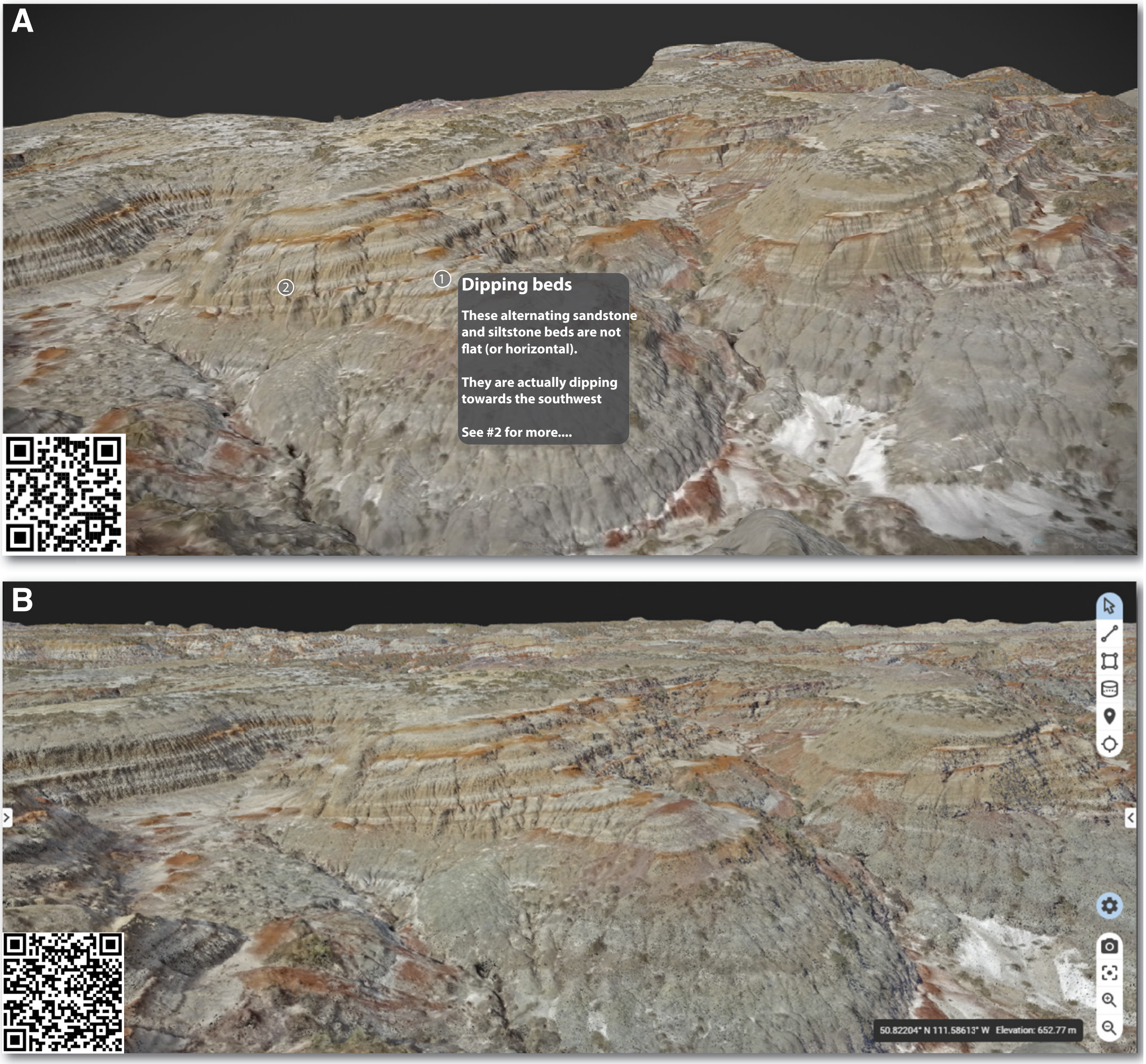
Web-Based 3D Point Cloud (potree)

Viewers using potree code can render raw point clouds and integrate multiple data sets into a single viewer with customizable options. The dense point cloud for the 1 km^2 field area is ~25.5 GB and contains more than 805 million points (Fig. 3B). Point cloud data sets can be compressed (from .las to .laz format) to reduce file size and converted into a potree file and folder structure for efficient tile-based rendering using the potree converter (Schuetz, 2016), with a final size of 3.5 GB. By default, the potree code includes an interactive overview map that displays the viewer's location and view direction, various navigation options and settings, and several measurement tools allowing end-users to record simple measurements, including distances, areas, volumes, and topographic cross sections. Following conversion, the files and folder structure can be added to a web host and dispersed through a standard web domain. Information on getting started can be found on the potree GitHub page or homepage (http://www.potree.org). An example is presented in Figure 3B using the Pix4Dcloud viewer, which implements the potree library.

Videogame Engine (Unity)

Videogame engines allow the production of unique end-user experiences through customized data visualization and presentation (Fig. 4). Unity provides a platform to design and develop videogames and is well documented through user manuals, community forums, and online tutorials (e.g., https://unity.com/learn/get-started). The program interface contains simple "drag and drop" functions for creation of simple scenes, but also allows fully customizable objects and interaction through scripting. Unity supports various formats, including point clouds, meshes, and 2.5D digital elevation models (DEMs). However, point cloud rendering through Unity can be challenging (Fraiss, 2017), and DEM interpolations are susceptible to distortion along slopes (Bellian et al., 2005; Pavlis and Mason, 2017). Therefore, we used 3D meshes (.fbx files) and associated textures (.jpg), which made up much of the final videogame file size (~1 GB).

Navigation within the scene was programmed through a first-person movement script, in which the camera is controlled by directional keys on the keyboard and orientation based on the mouse. Camera movement was restricted within the scene boundaries by enabling the "mesh collider" option



Dipping beds

These alternating sandstone and siltstone beds are not flat (or horizontal).

They are actually dipping towards the southwest

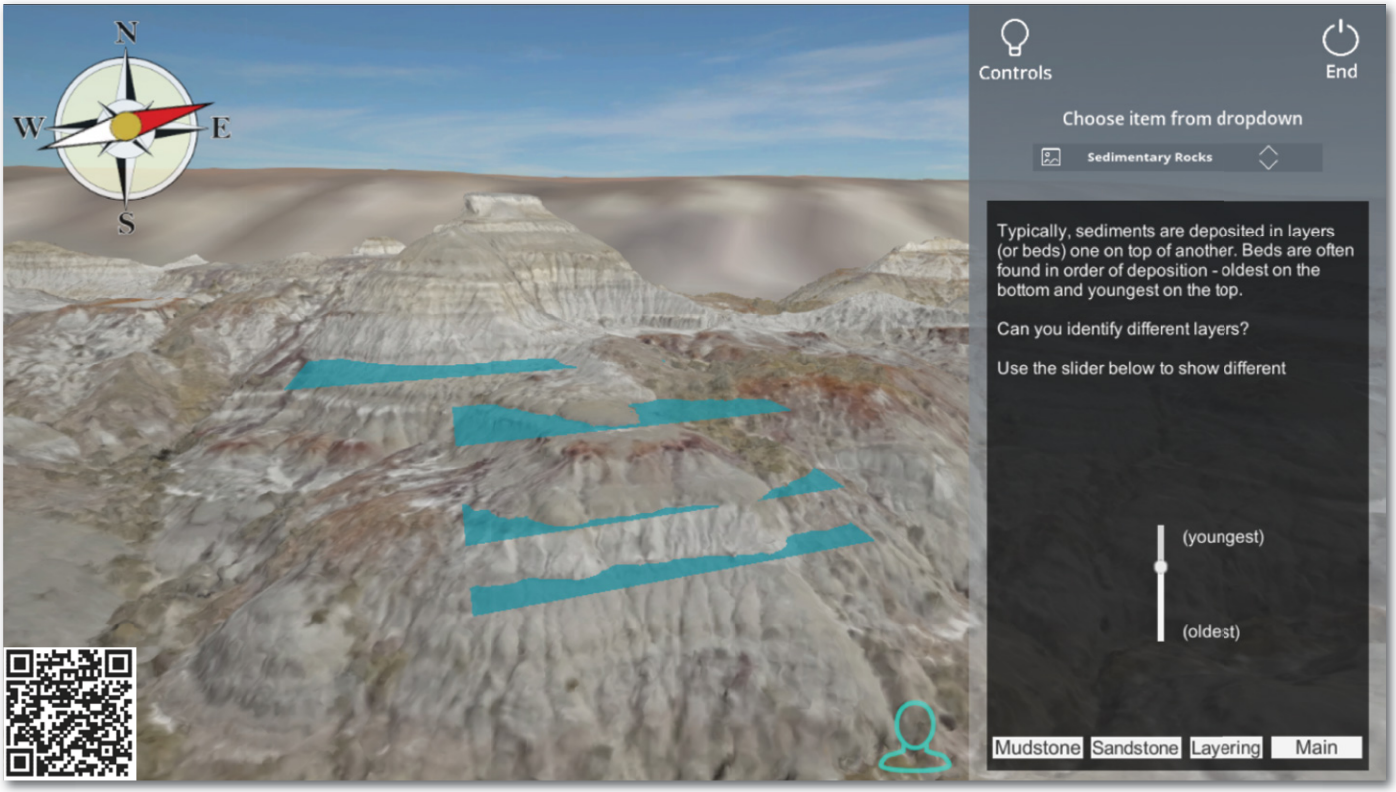
See #2 for more....

Figure 3. Digital outcrop models (DOMs) of the heterolithic channel-belt deposits in Figure 1, presented in two different viewers. (A) Sketchfab viewer contains 3D textured mesh DOM, but is limited by resolution and only supports text annotations to provide supplemental information; note the limited field area loaded to preserve detail in texture and topography—additional interactive models of the field area are online at https://sketchfab.com/paulnesbit or by following the QR code. Additional proprietary web viewers include Euclidean Vault (https://www.euclideon.com/vaultinfo/), and voxxlr (https://www.voxxlr.com/). (B) Visualization of the 3D dense point cloud DOM of the entire 1 km² field area (>805 million points) in a standard web browser using potree code applied in customized web viewer from Pix4D. QR code provides digital access to the fully interactive viewer, also available at http://tiny.cc/Pix4DpotreeViewer.

within the mesh options panel. Various components were added to the scene, such as the sky background, surrounding topography, and interactive features. Sky textures were adapted from the Unity Asset Store (assetstore.unity.com). Surrounding topography was added by creating a terrain object within Unity, defining height values by importing a 10 m DEM (AltaLIS, 2017), textured with a 10-m true-color satellite image (Copernicus, 2018). Interactive features were added to a dropdown menu within the user interface (UI) and included several "points of interest" that automatically transport end-users to areas with educational information within the scene. The UI menu allows users to navigate between integrated data sets and associated information panels within the scene and can be exited at any time to return to free fly mode.

DISCUSSION

Sharing of large 3D data sets without specialist software is possible through modern viewers; however, a host of challenges remain with current solutions before the full potential can be realized. Data acquisition technologies continue to offer higher resolutions and larger file sizes. Contrastingly, visualization platforms commonly limit file sizes, forcing a compromise between field area extent and detail. As demand increases for sharing larger 3D data sets, more advanced multi-resolution rendering solutions, such as LoD in Sketchfab and LIME or tiled approaches similar to potree, will be essential. Options for end-



Typically, sediments are deposited in layers (or beds) one on top of another. Beds are often found in order of deposition - oldest on the bottom and youngest on the top.

Can you identify different layers?

Use the slider below to show different

Figure 4. Videogame viewer (executable application) of the entire 1 km^2 field area rendered as a textured mesh and created with Unity. Note the dynamic orientation arrow in the upper left corner of the game, the options menu to the right of the screen, and interpretations of geologic surfaces turned "on." Drop-down menu in the side panel provides end-users with options to navigate to predefined "points of interest" throughout the field area, simulating virtual field-trip stops. Note the resolution difference between the foreground (uninhabited aerial vehicle [UAV]) model and the peripheral topography and landscape, created with a digital elevation model draped with a 10 m satellite image. End-users can also select "free fly" mode in order to navigate throughout the field site on their own. A fully interactive viewer is available in GSA's Data Repository[1] (also accessible from the QR code). Both data repository supplemental files are interactive videogame visualizations presenting a "virtual field trip" that introduces basic geology concepts using a UAV–Structure from Motion textured mesh model within Dinosaur Provincial Park (Alberta, Canada). One is a standalone application (.exe file) for machines running Windows (no software required). The other is a standalone application (.app file) for machines running macOS (no software required). Note the README.txt file after unzipping prior to running.

users to select display quality based on the capabilities of their machine provides additional avenues to smoothly render large data sets; for example, the Unity UI offers *Quality* and *Screen Resolution* settings upon startup, and potree code provides adjustable options for *Point Budget* and *Quality*.

Capabilities of 3D viewers can be expanded through incorporation of basic interpretation tools, the ability to integrate multiple data sets, and customizable interfaces. There are various levels of customizability in modern platforms. Sketchfab, for example, currently permits addition of text and web-linked photo annotations, but does not support integration of additional 3D objects, shapefiles, or drawings. Open source platforms (e.g., potree and Unity) contain support to integrate meshes, shapefiles, and custom objects within a scene (Fig. 4) but require additional coding to convert and render data properly. The default potree code supports basic measurement tools (see Fig. 3B), but further customization within potree or Unity requires significant upfront programming efforts.

Compatibility and design considerations may also emerge as issues for visualization platforms. Although potree code is currently compatible with standard web browsers, future updates to browsers may impede performance. Similarly, users who rely on third-party applications are subject to decisions made by suppliers. On the other hand, formats supported by Unity (e.g., Windows [.exe], Apple [.app], mobile device [iOS, Android], Sony PlayStation 4, Microsoft Xbox, and WebGL) have been standard for their respective platforms and are likely to maintain functionality through updates, as backward compatibility is often built into new versions.

Cartographic principles will become increasingly important as 3D visualizations are used to disseminate spatial data layers with 3D DOMs. This technique has the potential to extend models beyond simple visuals into scientific visualizations designed to aid the understanding of data, provide new perspectives, and provoke individual knowledge construction (MacEachren and Kraak, 1997). Delivering data in this way requires consideration of cartographic design as it relates to the purpose of a model, intended audience, and how to best present data. For example, use of these platforms as geospatial data viewers still requires basic map components (e.g., scale, orientation, legend, metadata, etc.), which are not currently available in some 3D viewers, but are essential for extending these 3D models to spatially meaningful 3D geovisualizations.

---

[1] GSA Data Repository item 2020176, supplemental file 1—virtual field trip videogame for Windows (.exe—no software required); supplemental file 2—virtual field trip videogame for MacOS (.app—no software required), is available online at https://www.geosociety.org/datarepository/2020.

CONCLUSIONS AND RECOMMENDED USE

Tools for collecting high-resolution 3D data sets have recently become commonplace in both commercial and academic fields; however, sharing 3D data sets typically requires end-users to have specialty software, high-end processing computers, and/or locally store large files. Through the presentation of a large UAV-SfM derived DOM, we introduce three representative visualization platforms that harness potential to advance 3D data dissemination and promote open science communication to end-users without the need for specialized software and hardware.

Web-based viewers, such as Sketchfab and potree, provide practical options for sharing data sets with end-users without cumbersome transfer and storage of large files. Web-based viewers typically provide an easy solution to share 3D visualizations without the need for programming, though customizability and file sizes are limited. The default potree code has extended capabilities, such as measurement tools, display options, and the ability to integrate multiple file types within a single viewer. Open-source code allows capable programmers to customize the potree viewer and could potentially be used as a raw data viewer or educational supplement. A web domain and web storage are required to host potree visualizations, which may limit uptake for educational purposes, but it remains promising for sharing raw data sets with collaborators or commercial partners.

Game engines require more significant coding knowledge for customized visualizations and measurement tools and may therefore be less practical as raw data viewers. However, videogames create opportunities to broaden scientific communication and education beyond conventional 2D maps and photo-based line drawings (e.g., Figs. 1–2) by contextualizing 3D information within a 3D, immersive, and realistic environment (Fig. 4). Videogame visualization could be used for engaging museum displays, presentation of course material, or virtual field experiences, in which “participants” can follow guided prompts or explore the scene freely in self-navigation mode.

Although virtual platforms provide exciting potential for enhanced student learning and improved scientific communication to the broader public, their efficacy as a learning tool necessitates future research. Regardless, emerging visualization platforms provide access to 3D data sets without the need for advanced software and hardware. Though often limited by logistical constraints, we encourage authors to share high-resolution DOM data sets whenever possible. Methods of 3D data dissemination and visualization are still in their infancy behind the relatively recent rise in 3D mapping applications and acquisition techniques; as the latter continue to grow, we expect the former to develop in new and unique ways to facilitate open science initiatives through communication and democratization of photorealistic 3D models.

ACKNOWLEDGMENTS

We thank the *GSA Today* editorial team and two anonymous reviewers for recommendations that greatly improved this manuscript, and thanks for research permission from Dinosaur Provincial Park (Research Permit #17-146) and land access from J.G. and L.X.

REFERENCES CITED

AltaLIS, 2017, Alberta 20K Digital Elevation Model (DEM).

Bellian, J.A., Kerans, C., and Jennette, D.C., 2005, Digital outcrop models: Applications of terrestrial scanning lidar technology in stratigraphic modeling: Journal of Sedimentary Research, v. 75, p. 166–176, https://doi.org/10.2110/jsr.2005.013.

Bilke, L., Fischer, T., Helbig, C., Krawczyk, C., Nagel, T., Naumov, D., Paulick, S., Rink, K., Sachse, A., Schelenz, S., Walther, M., Watanabe, N., Zehner, B., Ziesch, J., and Kolditz, O., 2014, TESSIN VISLab—Laboratory for scientific visualization: Environmental Earth Sciences, v. 72, p. 3881–3899, https://doi.org/10.1007/s12665-014-3785-5.

Blenkinsop, T.G., 2012, Visualizing structural geology: From Excel to Google Earth: Computers & Geosciences, v. 45, p. 52–56, https://doi.org/10.1016/j.cageo.2012.03.007.

Boutsi, A., Ioannidis, C., and Soile, S., 2019, Interactive online visualization of complex 3D geometries: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, v. XLII-2, W9, p. 173–180, https://doi.org/10.5194/isprs-archives-XLII-2-W9-173-2019.

Brodu, N., and Lague, D., 2012, 3D terrestrial lidar data classification of complex natural scenes using a multi-scale dimensionality criterion: Applications in geomorphology: ISPRS Journal of Photogrammetry and Remote Sensing, v. 68, p. 121–134, https://doi.org/10.1016/j.isprsjprs.2012.01.006.

Buckley, S.J., Ringdal, K., Naumann, N., Dolva, B., Kurz, T.H., Howell, J.A., and Dewez, T.J.B., 2019, LIME: Software for 3-D visualization, interpretation, and communication of virtual geoscience models: Geosphere, v. 15, p. 1–14, https://doi.org/10.1130/GES02002.1.

Carrivick, J.L., Smith, M.W., and Quincey, D.J., 2016, Structure from Motion in the Geosciences: Oxford, UK, Wiley-Blackwell, https://doi.org/10.1002/9781118895818.

Cawood, A.J., and Bond, C.E., 2019, eRock: An open-access repository of virtual outcrops for geoscience education: GSA Today, v. 29, p. 36–37, https://doi.org/10.1130/GSATG373GW.1.

Chesley, J., Leier, A., White, S., and Torres, R., 2017, Using unmanned aerial vehicles and structure-from-motion photogrammetry to characterize sedimentary outcrops: An example from the Morrison Formation, Utah, USA: Sedimentary Geology, v. 354, p. 1–8, https://doi.org/10.1016/j.sedgeo.2017.03.013.

CloudCompare, 2019, Version 2.9. GPL Software. Available online: http://www.cloudcompare.org (accessed 7 Feb. 2020).

Copernicus, 2018, Sentinal data: Retrieved from USGS, Earth Explorer 15 August 2019, processed by ESA.

Currie, P.J., and Koppelhus, E.B., editors, 2005, Dinosaur Provincial Park: A Spectacular Ancient Ecosystem Revealed: Bloomington, Indiana, Indiana University Press, 648 p.

De Paor, D.G., 2016, Virtual rocks: GSA Today, v. 26, p. 4–11, https://doi.org/10.1130/GSATG257A.1.

De Paor, D.G., and Whitmeyer, S.J., 2011, Geological and geophysical modeling on virtual globes using KML, COLLADA, and Javascript: Computers & Geosciences, v. 37, p. 100–110, https://doi.org/10.1016/j.cageo.2010.05.003.

Dewez, T.J.B., Girardeau-Montaut, D., Allanic, C., and Rohmer, J., 2016, Facets : A CloudCompare plugin to extract geological planes from unstructured 3D point clouds: International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives, v. 41, p. 799–804, https://doi.org/10.5194/isprsarchives-XLI-B5-799-2016.

Dodson, P., 1971, Sedimentology and taphonomy of the Oldman Formation (Campanian), Dinosaur Provincial Park, Alberta (Canada): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 10, p. 21–74, https://doi.org/10.1016/0031-0182(71)90044-7.

Durkin, P.R., Hubbard, S.M., Holbrook, J.M., Weleschuk, Z., Nesbit, P.R., Hugenholtz, C.H., Lyons, T., and Smith, D.G., 2020, Recognizing the product of concave-bank sedimentary processes in fluvial meander-belt strata: Sedimentology (in press).

Eberth, D.A., and Hamblin, A.P., 1993, Tectonic, stratigraphic, and sedimentologic significance of a regional discontinuity in the upper Judith River Group (Belly River wedge) of southern Alberta, Saskatchewan, and northern Montana: Canadian Journal of Earth Sciences, v. 30, p. 174–200, https://doi.org/10.1139/e93-016.

Fraiss, S.M., 2017, Rendering Large Point Clouds in Unity [B.S. thesis]: Vienna, University of Technology (TU Wien), 38 p.

Goodchild, M.F., Guo, H., Annoni, A., Bian, L., de Bie, K., Campbell, F., Craglia, M., Ehlers, M., van Genderen, J., Jackson, D., Lewis, A.J., Pesaresi, M., Remetey-Fülöpp, G., Simpson, R., Skidmore, A., Wang, C., and Woodgate, P., 2012, Next-generation Digital Earth: Proceedings of the National Academy of Sciences of the United States of America, v. 109, p. 11,088–11,094, https://doi.org/10.1073/pnas.1202383109.

Hodgetts, D., 2013, Laser scanning and digital outcrop geology in the petroleum industry: A review: Marine and Petroleum Geology, v. 46, p. 335–354, https://doi.org/10.1016/j.marpetgeo.2013.02.014.

Hodgetts, D.L., Gawthorpe, R., Wilson, P., and Rarity, F., 2007, Integrating Digital and Traditional Field Techniques Using Virtual Reality Geological Studio (VRGS): 69th EAGE Conference and Exhibition incorporating SPE EUROPEC 2007, p. 11–14, https://doi.org/10.3997/2214-4609.201401718.

Howell, J.A., Martinius, A.W., and Good, T.R., 2014, The application of outcrop analogues in geological modelling: A review, present status and future outlook, *in* Martinius, A.W., Howell, J.A., and Good, T.R., eds., Sediment-Body Geometry and Heterogeneity: Analogue Studies for Modelling the Subsurface: Geological Society, London, Special Publication 387, p. 1–25, https://doi.org/10.1144/SP387.12.

Jones, R.R., McCaffrey, K.J., Clegg, P., Wilson, R.W., Holliman, N.S., Holdsworth, R.E., Imber, J., and Waggott, S., 2009, Integration of regional to outcrop digital data: 3D visualisation of multi-scale geological models: Computers & Geosciences, v. 35, p. 4–18, https://doi.org/10.1016/j.cageo.2007.09.007.

Küng, O., Strecha, C., Fua, P., Gurdan, D., Achtelik, M., Doth, K.-M., and Stumpf, J., 2012, Simplified building models extraction from ultra-light UAV imagery: ISPRS—International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, v. XXXVIII-1, p. 217–222, https://doi.org/10.5194/isprsarchives-XXXVIII-1-C22-217-2011.

MacEachren, A.M., and Kraak, M.J., 1997, Guest editorial exploratory cartographic visualization: Advancing the agenda: Computers & Geosciences, v. 23, p. 335–343, https://doi.org/10.1016/S0098-3004(97)00018-6.

Martinez-Rubi, O., de Kleijn, M., Verhoeven, S., Drost, N., Attema, J., van Meersbergen, M., van Nieuwpoort, R., de Hond, R., Dias, E., and Svetachov, P., 2016, Using modular 3D digital earth applications based on point clouds for the study of complex sites: International Journal of Digital Earth, v. 9, p. 1135–1152, https://doi.org/10.1080/17538947.2016.1205673.

McCaffrey, K.J.W., Jones, R.R., Holdsworth, R.E., Wilson, R.W., Clegg, P., Imber, J., Holliman, N.S., and Trinks, I., 2005, Unlocking the spatial dimension: Digital technologies and the future of geoscience fieldwork: Journal of the Geological Society, v. 162, p. 927–938, https://doi.org/10.1144/0016-764905-017.

McCaffrey, K.J.W., Hodgetts, D., Howell, J.A., Hunt, D., Imber, J., Jones, R.R., Tomasso, M., Thurmond, J., and Viseur, S., 2010, Virtual fieldtrips for petroleum geoscientists: Geological Society, London, Petroleum Geology Conference Series, v. 7, p. 19–26, https://doi.org/10.1144/0070019.

Nesbit, P.R., and Hugenholtz, C.H., 2019, Enhancing UAV-SfM 3D model accuracy in high-relief landscapes by incorporating oblique images: Remote Sensing, v. 11, https://doi.org/10.3390/rs11030239.

Nesbit, P.R., Durkin, P.R., Hugenholtz, C.H., Hubbard, S.M., and Kucharczyk, M., 2018, 3-D stratigraphic mapping using a digital outcrop model derived from UAV images and structure-from-motion photogrammetry: Geosphere, v. 14, p. 1–18, https://doi.org/10.1130/GES01688.1.

Nieminski, N.M., and Graham, S.A., 2017, Modeling stratigraphic architecture using small unmanned aerial vehicles and photogrammetry: Examples from the Miocene east coast basin, New Zealand: Journal of Sedimentary Research, v. 87, p. 126–132, https://doi.org/10.2110/jsr.2017.5.

Pavlis, T.L., and Mason, K.A., 2017, The new world of 3D geologic mapping: GSA Today, v. 27, p. 4–10, https://doi.org/10.1130/GSATG313A.1.

Robinson, A., Gordon, C.E., Houghton, J., Lloyd, G.E., and Morgan, D.J., 2015, ArcGIS to Unity: A design pipeline for creation of 3D terrain in serious egames for geology: Geology Today, v. 31, p. 237–240, https://doi.org/10.1111/gto.12121.

Schuetz, M., 2016, Potree [Thesis]: Rendering Large Point Clouds in Web Browsers: Vienna University of Technology, 84 p.

Simpson, C., and De Paor, D.G., 2010, Restoring maps and memoirs to four-dimensional space using virtual globe technology: A case study from the Scottish Highlands: Geological Society, London, Special Publication 335, p. 429–441, https://doi.org/10.1144/SP335.20.

Smith, D.G., Hubbard, S.M., Leckie, D.A., and Fustic, M., 2009, Counter point bar deposits: Lithofacies and reservoir significance in the meandering modern Peace River and ancient McMurray Formation, Alberta, Canada: Sedimentology, v. 56, p. 1655–1669, https://doi.org/10.1111/j.1365-3091.2009.01050.x.

Tavani, S., Granado, P., Corradetti, A., Girundo, M., Iannace, A., Arbués, P., Muñoz, J.A., and Mazzoli, S., 2014, Building a virtual outcrop, extracting geological information from it, and sharing the results in Google Earth via OpenPlot and Photoscan: An example from the Khaviz Anticline (Iran): Computers & Geosciences, v. 63, p. 44–53, https://doi.org/10.1016/j.cageo.2013.10.013.

Thiele, S.T., Grose, L., Samsu, A., Micklethwaite, S., Vollgger, S.A., and Cruden, A.R., 2017, Rapid, semi-automatic fracture and contact mapping for point clouds, images and geophysical data: Solid Earth, v. 8, p. 1241–1253, https://doi.org/10.5194/se-8-1241-2017.

Thurmond, J.B., Løseth, T.M., Rivenæs, J.C., Martinsen, O.J., and Aiken, C.L.V., 2006, Using outcrop data in the 21st century—New methods and applications, with example from the Ainsa Turbidite System: Deep-Water Outcrops of the World Atlas, CD-ROM.

Turner, A.K., 2006, Challenges and trends for geological modelling and visualisation: Bulletin of Engineering Geology and the Environment, v. 65, p. 109–127, https://doi.org/10.1007/s10064-005-0015-0.

USGS, 2019, 3D Elevation Program (3DEP): https://www.usgs.gov/news/usgs-3dep-lidar-point-cloud-now-available-amazon-public-dataset (accessed 11 Feb. 2020).

von Reumont, F., Arsanjani, J.J., and Riedl, A., 2013, Visualization of geologic geospatial datasets through X3D in the frame of WebGIS: International Journal of Digital Earth, v. 6, p. 483–503, https://doi.org/10.1080/17538947.2011.627471.

Wood, J.M., Thomas, R.G., and Visser, J., 1988, Fluvial processes and vertebrate taphonomy: The upper cretaceous Judith River formation, South-Central Dinosaur Provincial Park, Alberta, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 66, p. 127–143, https://doi.org/10.1016/0031-0182(88)90085-5.

Manuscript received 5 Nov. 2019
Revised Manuscript received 12 Feb. 2020
Manuscript accepted 26 Feb. 2020