3-D stratigraphic mapping using a digital outcrop model derived from UAV images and structure-from-motion photogrammetry

Paul Ryan Nesbit¹, Paul R. Durkin², Christopher H. Hugenholtz¹, Stephen M. Hubbard¹, and Maja Kucharczyk¹

¹Department of Geography, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada
²Department of Geological Sciences, University of Manitoba, 66 Chancellors Circle, Winnipeg, Manitoba R3T 2N2, Canada
³Department of Geoscience, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada

ABSTRACT

Fluvial deposits are highly heterogeneous and inherently challenging to map in outcrop due to a combination of lateral and vertical variability along with a lack of continuous exposure. Heavily incised landscapes, such as badlands, reveal continuous three-dimensional (3-D) outcrops that are ideal for constraining the geometry of fluvial deposits and enabling reconstruction of channel morphology through time and space. However, these complex 3-D landscapes also create challenges for conventional field mapping techniques, which offer limited spatial resolution, coverage, and/or lateral contiguity of measurements. To address these limitations, we examined an emerging technique using images acquired from a small unmanned aerial vehicle (UAV) and structure-from-motion (SfM) photogrammetric processing to generate a 3-D digital outcrop model (DOM). We applied the UAV-SfM technique to develop a DOM of an Upper Cretaceous channel-belt sequence exposed within a 0.52 km² area of Dinosaur Provincial Park (southeastern Alberta, Canada). Using the 3-D DOM, we delineated the lower contact of the channel-belt sequence, created digital sedimentary logs, and estimated facies with similar conviction to field-based estimations (±4.9%). Lateral accretion surfaces were also recognized and digitally traced within the DOM, enabling measurements of accretion direction (dip azimuth), which are nearly impossible to obtain accurately in the field. Overall, we found that measurements and observations derived from the UAV-SfM DOM were commensurate with conventional ground-based mapping techniques, but they had the added advantage of lateral continuity, which aided interpretation of stratigraphic surfaces and facies. This study suggests that UAV-SfM DOMs can complement traditional field-based methods by providing detailed 3-D views of topographically complex outcrop exposures spanning intermediate to large spatial extents.

INTRODUCTION

Stratigraphic surfaces resulting from ancient fluvial processes record spatial and temporal changes in river morphology at multiple hierarchical levels and inform our understanding of morphodynamics and paleoenvironments (Jordan and Pryor, 1992; Durkin et al., 2017). Fluvial deposits are highly heterogeneous and challenging to map in outcrop due to lateral and vertical variability, as well as inconsistent exposure (Miall, 1988; Labourdette and Jones, 2007; Pranter et al., 2007; Calvo and Ramos, 2015; Durkin et al., 2015a). Conventional mapping methods commonly include a posteriori correlation (or interpolation) between sedimentary field logs, which can result in subjective interpretations, unquantified uncertainty, and/or oversimplified information between data points (Jones et al., 2004; Bond et al., 2007). Supplemental data sets, such as panoramic photographs, have been used to improve interpretations between isolated sedimentary logs (i.e., Sgavetti, 1992; Arnott et al., 1997); however, this method lacks the geometric and locational accuracy needed for detailed mapping of highly varied fluvial deposits.

Digital outcrop models (DOMs), or virtual outcrops (Trinks et al., 2005), provide a three-dimensional (3-D) scaled replica of outcrops and can supplement field observations with additional quantitative data sets (Xu et al., 2000; Bellian et al., 2005; Enge et al., 2007; Labourdette and Jones, 2007; Pranter et al., 2007; Buckley et al., 2008). Existing techniques used to generate DOMs generally incur a spatial coverage–resolution trade-off. Ground-based photogrammetry and terrestrial laser scanning (TLS) are common techniques for creating DOMs, but they are often hindered by restricted line-of-sight and require multiple viewpoints to eliminate data occlusions. Although there are exceptions (e.g., Rarity et al., 2014), ground-based methods are primarily used for sites smaller than 10⁶ m² and are not practical for mapping extensive outcrop exposures (Hodgetts, 2013; James and Quinton, 2014). Airborne methods, such as aerial photogrammetry and light detection and ranging (LiDAR), are commonly considered for mapping larger areas (>10⁶ m²); however, these methods typically have limited spatial resolution (i.e., >0.3 m/pixel), high costs, and difficulty resolving geologic detail along subvertical slopes (Bellian et al., 2005; Hodgetts, 2013). Despite some unique solutions (e.g., Rittersbacher et al., 2014; James and Quinton, 2014), few techniques have emerged for detailed mapping of sedimentary rocks exposed within laterally extensive (>10⁶ m²), topographically complex, 3-D landscapes.

Small unmanned aerial vehicles (UAVs) paired with structure-from-motion (SfM-MVS) photogrammetry have recently emerged as an alternative, low-cost, remote-sensing approach for generating high-spatial-
resolution data spanning intermediate spatial extents (Hugenholtz et al., 2012; Colomina and Molina, 2014; Whitehead and Hugenholtz, 2014; Whitehead et al., 2014; Toth and Józków, 2016; Chesley et al., 2017; Nieminski and Graham, 2017). In the geosciences, UAV-based SFM-MVS (hereafter UAV-SFM) techniques have primarily been used for generating and analyzing two-dimensional (2-D) and two-and-a-half-dimensional (2.5-D) data sets, such as orthomosaic images and/or digital surface models (DSMs; Carrivick et al., 2016). Although these 2-D and 2.5-D data sets may be suitable for measurement and interpretation of geologic features along planar surfaces, they are susceptible to compression, distortion, and overgeneralization of details exposed along planes nonnormal to image acquisition (Bellian et al., 2005; Pavlis and Mason, 2017; Thiele et al., 2017). Geologic features are commonly exposed along steep slopes and are particularly susceptible to these effects; therefore, further consideration of data collection and visualization is necessary. An alternative approach is to use 3-D data sets generated during intermediate stages of UAV-SFM processing, such as the dense point cloud or textured triangulated mesh, as DOMs for geologic analysis. These “intermediate” data sets contain location (x, y, z) and color information [red-green-blue [RGB]], maintain 3-D topographic integrity, and resemble DOMs created with TLS.

To evaluate UAV-SFM–generated DOMs as supplemental tools for providing reliable quantitative information, we compared DOM-derived measurements with independently collected field observations of fluvial surfaces and facies exposed within a complex and highly three-dimensional badlands landscape. This research was performed in a section of Dinosaur Provincial Park (southeastern Alberta, Canada; Fig. 1) with extensive exposures of Upper Cretaceous fluvial channel-belt deposits. This paper describes the (1) UAV-SFM workflow; (2) DOM visualization strategies, and (3) a method for digital interpretation of multiscale stratigraphic surfaces and facies estimation. Results exhibit commensurability between geologic measurements and interpretations from field-based observations and the 3-D UAV-SFM DOM, for which the limitations and potential are discussed.

## GEOLOGIC SETTING AND STUDY AREA

Outcrop exposures within Dinosaur Provincial Park include lithologically contrasting layers of siltstone and fine- to medium-grained sandstone of the Dinosaur Park and Oldman Formations (Eberth and Hamblin, 1993; Hamblin and Abrahamson, 1996; Eberth, 2005). Overall, the regional stratigraphy is nearly flat-lying, dipping ~0.05° to the southwest. The Dinosaur Park Formation is the uppermost unit within the Late Cretaceous nonmarine clastic Judith River (Belly River) Group (Fig. 2; Eberth and Hamblin, 1993; Hamblin and Abrahamson, 1996). The Dinosaur Park Formation was deposited at the onset of a regional transgression of the Bearpaw Sea into the subsiding foreland basin, and it interferes with the overlying shallow-marine deposits of the Bearpaw Formation (Eberth, 2005). Deposits of the Dinosaur Park Formation are consistent with meandering channel belts originating from the north-central Canadian Cordillera highlands to the west, with an average paleocurrent direction flowing east-southeast into the shallow Western Interior Seaway (Wood et al., 1988; Wood, 1989; Eberth and Hamblin, 1993; Ryan et al., 2001). There is agreement among investigators that deposition of sediment was from fluvial processes; however, the degree of tidal influence is disputed (Koster and Currie, 1987; Thomas et al., 1987; Wood, 1989; Eberth, 2005).

The study area is in the northeast section of the park, ~1 km east of the present-day Red Deer River (Fig. 1). This area contains exposures of the uppermost Dinosaur Park Formation and evidence of the overlying Bearpaw Formation. Previous work within the area identified an 8–10-m-thick meandering channel-belt deposit with characteristic point-bar and counter-point-bar elements (Smith et al., 2009b; Durkin et al., 2015b; Weleschuk, 2015). The base of the channel-belt sequence is recognizable by the presence of coarser channel scour and bar deposits (fine-medium sandstone and siltstone) sharply overlying finer floodplain deposits (mudstone-siltstone). This contact represents laterally contemporaneous processes (i.e., deposition and erosion) and provides a common datum for identifying higher-order stratigraphic surfaces.

The heavily dissected badland landscape, typified by complex drainage networks, hoodoos, buttes, and mesas of various sizes, is characteristic throughout Dinosaur Provincial Park (Campbell, 1970). This landscape initiated during Wisconsinan deglaciation (~15,000 yr ago) as the Laurentide ice sheet receded and exposed the landscape to contemporary, nonglacial, erosional processes (i.e., piping, overland flow, mass flow) that continue to incise the highly erodible bedrock (Campbell, 1970; Bryan et al., 1987; Rains et al., 1993; Evans, 2000). The combination of naturally varying slope directions, minimal vegetation, and visually distinct lithologies presents excellent opportunities to examine the detailed fluvial stratigraphy in a 3-D (cross-sectional) perspective.

### METHODS

#### Field Data Acquisition

Field observations and measurements were acquired by foot over a 3.5 km² area (Fig. 1), prior to UAV data collection. Point locations along the basal contact of the channel belt were recorded using a Trimble ProXRT2 differential global positioning system (DGPS) and integrated TruPulse 3608 laser range-finder to map features inaccessible by foot. This DGPS has a manufacturer-reported decimeter accuracy following postprocessing (differential correction) with proprietary software; the attached rangefinder degrades precision to 0.30–1.00 m, depending on distance and scan angle (Xu et al., 2000).

Detailed sedimentological observations, including grain size, sedimentary structures, lithologic features, and bedding contacts, were recorded in 10 sedimentary logs within the field area (Fig. 1). Bedding thickness was recorded by tape measure and Jacob staff. The Trimble dGPS system was used to measure the geolocation of the bottom and top of each sedimentary log. Six
distinct facies were determined and associated with sedimentary observations in facies logs (Table 1). Sandstone facies were categorized as massive and cross-stratified (F1) or ripple-laminated (F2). Dominantly sandstone (>50%) intervals with siltstone interbeds (generally <0.10 m thick) were categorized as F3, while dominantly siltstone (>50%) intervals interbedded with sandstone were separately classified as F4. Thicker siltstone intervals without sandstone interbeds were assigned to F5. Organic-rich mudstone layers, generally representing floodplain deposits, were classified as F6.

**UAV Data Acquisition**

UAVs have demonstrated the ability to capture very high-resolution images in a broad range of geoscience case studies (e.g., Harwin and Lucieer, 2012; James and Robson, 2012; Niethammer et al., 2012; Whitehead et al., 2013; Hugenholtz et al., 2013; Bemis et al., 2014; Johnson et al., 2014; Vollgger and Cruden, 2016; Cawood et al., 2017; Chesley et al., 2017; Nieminski and Graham, 2017; Vasuki et al., 2017), but their application to geologic mapping requires careful consider-
ation, especially where features are exposed in complex landscapes, such as cliff faces or steep slopes (Pavlis and Mason, 2017). For extensive outcrops, fixed-wing UAVs are more suitable because they generally have prolonged flight times compared with multicopter platforms (Colomina and Molina, 2014; Toth and Jóźkowski, 2016). Therefore, in this study, a senseFly eBee fixed-wing UAV equipped with a Sony WX220 18.2 megapixel (MP) consumer-grade digital camera with focal length set constant at 4.6 mm (35 mm equivalent of ~26.2 mm) was selected to record images of the 0.52 km² field area (Fig. 1, UAV area).

Flight parameters were programmed using accompanying flight planning software, eMotion 2. Flights were planned for 70 m above ground level with 90% image overlap and 75% sidelap (Fig. 3). Although minimum overlap requirements for contemporary processing solutions specify that an object point (in the scene) should be clearly visible in three images (Snavely et al., 2008; Carrivick et al., 2016), we selected higher overlap settings to increase point visibility within the complex, highly dissected, 3-D topography. To further increase point visibility along subvertical surfaces, the camera was set to record images at an angle of 10° off-nadir. A second flight with the same parameters was flown over the same footprint with perpendicular flight lines to increase multiviewpoint coverage (Fig. 3). The two UAV flights were conducted on 7 July 2016 during diffuse lighting conditions (cloudy) to reduce shadows on steep outcrop exposures. Data collection resulted in an image block of 728 geotagged images. No additional postprocessing corrections or enhancements were applied to the images.

Prior to UAV surveys, nine ground control points (GCPs) were distributed throughout the field site (Fig. 1), following recommendations made by Harwin et al. (2015). GCP locations were measured at subcentimeter precision with a Trimble R4 real-time kinematic global navigation satellite system (RTK-GNSS). Recorded GCP positions were imported and used for georeferencing during image processing.

**UAV Data Processing**

To process the UAV images into 3-D models, we used structure-from-motion (SfM) software, a recently popularized image-based modeling technique developed in the computer vision community that calculates the 3-D structure of a scene from a series of overlapping 2-D images (Snavely et al., 2006; Szeliski, 2006).

![UAV Data Collection Parameters](image-url)

**Figure 3. Simplified unmanned aerial vehicle data collection parameters programmed into the eBee autopilot: 90% overlap between successive images (blue rectangles to the left), 75% sidelap between flight lines (blue rectangles at the top), and a second flight (gray lines) programmed to fly perpendicular to Flight 1 (black lines).**

<table>
<thead>
<tr>
<th>Field facies</th>
<th>Digital facies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse grained</td>
<td></td>
</tr>
<tr>
<td>F1: massive and cross-stratified sandstone</td>
<td>dF1: sandstone</td>
</tr>
<tr>
<td>F2: ripple-laminated sandstone</td>
<td></td>
</tr>
<tr>
<td>Interbedded</td>
<td></td>
</tr>
<tr>
<td>F3: sandstone with siltstone and organic interbeds</td>
<td>dF2: silty sandstone</td>
</tr>
<tr>
<td>F4: siltstone with sandstone and organic interbeds</td>
<td>dF3: sandy siltstone</td>
</tr>
<tr>
<td>Fine grained</td>
<td></td>
</tr>
<tr>
<td>F5: siltstone</td>
<td>dF4: siltstone and mudstone</td>
</tr>
<tr>
<td>F6: organic-rich mudstone</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Coarse-grained field facies (F1–F2) are considered equivalent to digital facies dF1, and fine-grained field facies (F5–F6) are considered the same as dF4.*
SFM has some similarities with conventional photogrammetric workflows; however, one of the main differences is that SFM does not require any a priori knowledge about the scene, camera location/orientation/settings, or any manual identification of keypoints or tie points (i.e., homologous points occurring in multiple images). Instead, SFM uses automated feature detection and matching algorithms to estimate the location of images relative to one another (Lowe, 2004; Snavely et al., 2008; Westoby et al., 2012; Fondast et al., 2013), making it more suitable for processing images collected with a nonmetric camera and low-flying (close-range) UAV platform (Colomina and Molina, 2014).

SFM processing was completed using Pix4Dmapper commercial software and a high-performance computer (Intel® Core™ i9-7900X central processing unit at 3.30 GHz with 64 GB random-access memory [RAM] and an NVIDIA GeForce GTX 1080 graphics card). Pix4Dmapper is a commercial SFM program with a user-friendly interface and simple workflow that builds on previous Web-based versions and follows similar steps (Kung et al., 2012):

1. Import photos (geotagged photos optional);
2. Conduct initial processing to calculate and match keypoints using feature-matching algorithms similar to the scale invariant feature transform (SIFT; Lowe, 2004), followed by optimization through bundle block adjustment (Triggs et al., 2000);
3. Import GCPs for georeferencing and optimization;
4. Perform point densification using multiview stereo algorithms, similar to Furukawa and Ponce (2010), and mesh interpolation; and
5. Generate DSM and orthomosaic image.

The SIFT algorithm, introduced by Lowe (1999, 2004), detects unique keypoints within each image determined by local pixel variances at a variety of scales. Keypoints are matched in adjacent photos and outliers or incorrect matches are removed. A bundle block adjustment (Triggs et al., 2000) is then iteratively performed to optimize 3-D geometry of keypoint matches and camera parameters (Lourakis and Argyros, 2009). Outputs from this initial SFM process include a “sparse” 3-D point cloud composed of estimated locations $(x, y, z)$ of keypoint matches, camera internal orientation parameters (IOPs; e.g., focal length and radial distortion), and camera external orientation parameters (EOPs; e.g., location, orientation, and scale; Lowe, 2004; Brown and Lowe, 2005).

In a subsequent step, multiview stereo (MVS) algorithms are used to calculate additional point observations, resulting in a “dense” point cloud with point densities similar to typical TLS point clouds (Carrivick et al., 2016). MVS techniques use calculated EOPs and IOPs to limit search areas among overlapping photos and add reliable feature matches (Szeliski, 2010; Remondino et al., 2014). The resulting dense point cloud can have $>10^{8}$ times more points than the initial sparse point cloud (James and Robson, 2012). Dense point clouds are typically interpolated into a continuous 3-D mesh surface visualized as a triangulated irregular network (TIN). Surface interpolation algorithms often apply some adaptation of the Poisson surface reconstruction with texturing from segments of individual images (Furukawa and Ponce, 2010; Carrivick et al., 2016).

Final steps in UAV-SFM workflows include conversion of the 3-D model into a 2-D orthomosaic image and 2.5-D DSM (Figs. 4A and 4B). The latter is calculated from the 3-D dense point cloud using algorithms based on either inverse distance weighting or Delaunay triangulation. The 2-D orthomosaic image is generated by removing perspective distortions from the original images using the 2.5-D DSM to preserve correct geolocation of pixels (Pix4D; https://support.pix4d.com).

Processing Outputs

Stratigraphic features exposed along steep slope faces can be difficult to interpret and are subject to significant distortion within these 2-D data sets. Therefore, we used the dense point cloud and textured mesh from the UAV-SFM workflow as 3-D DOMs for geologic interpretation. The dense point cloud DOM and textured mesh DOM were visualized and navigated directly within Pix4Dmapper. The dense point cloud had $1.35 \times 10^9$ points and an average point spacing of 0.027 m, and it was processed using the highest automated settings (original image size and “high” point density). The 3-D textured mesh had $9.99 \times 10^5$ triangles that resulted from the highest automated processing settings.

Figures 5 and 6 show examples from two field photographs of the outcrop (Figs. 5A and 6A), the corresponding dense point cloud DOM (Figs. 5B and 6B), and the textured mesh DOM (Figs. 5C and 6C). The sharp channel-belt contact is clearly resolved in both the dense point cloud and textured mesh DOMs (Figs. 5B and 5C, light-blue arrows). Smaller features, such as the shallow-dipping, thin-medium beds in Figure 6A, are recognizable in the dense point cloud, but they are noticeably distorted or undetectable in the textured mesh DOM (Figs. 6B and 6C). Although the dense point cloud contained data gaps between points (Fig. 6B, yellow arrows), it could be used to identify fine stratigraphic detail that is noticeably distorted in the textured mesh DOM. Therefore, we used the dense point cloud to make digital measurements and interpretations for evaluation against field observations; see Supplemental Files 1–2.

Digital Interpretation and Measurement

Digital interpretations and measurements of geologic features at multiple scales were made directly on the dense point cloud DOM within Pix4Dmapper by digitizing “manual tie points” in 3-D space. This built-in function was used to trace the basal channel-belt contact (Fig. 7), which is exposed on varying slope faces throughout the field area. Vertical offsets between digital and field measured points were measured by calculating the elevation value difference between the closest points. The length of the identified contact was quantified for comparison of the two methods.
The digitization technique was also employed to identify higher-order surfaces (i.e., individual unit contacts and lateral extent of accretionary surfaces) and define facies for individual units within digital sedimentary logs (Fig. 8). The location of each sedimentary log was determined by GPS coordinates (red arrows) from the corresponding field logs. Unit contacts were digitally identified from spectral contrast (light-blue points), recorded with manual tie points, and exported as \((x, y, z)\) locations. Digital unit thickness was calculated by differencing the elevation \(z\) between the upper and lower contacts of each unit.

Units were given a simple lithofacies descriptor: sandstone, muddy sandstone, sandy mudstone, or mudstone. These facies were determined by distinct coloration discernible in the DOM and guided by field knowledge. Fine sedimentary structures (i.e., ripple-laminated sandstone) could not be reliably distinguished in the DOM. Therefore, the two distinct sandstone facies identified in the field (F1 and F2) were considered matches for the digital sandstone facies \(dF1\) (Table 1). Similarly, the field-identified fine-grained siltstone and mudstone facies (F5 and F6, respectively) were considered \(dF4\) (Table 1).

Lateral accretion surfaces were identified using the same digitization method within Pix4Dmapper to delineate surfaces. Manual tie points were digitized laterally along bedding contacts, creating an interpolated surface fitted to all vertices. Bedding measurements, facies proportions, and observations from both digital- and field-based methods were summarized, and sedimentary logs were qualitatively compared.

### RESULTS

#### Channel-Belt Contact

DOM interpretation resulted in 3.50 km of channel-belt contact delineated throughout the 0.52 km² study area (Fig. 7A; Table 2). Field observations identified and mapped 1.36 km of the contact within the focused UAV area (Fig. 7A), although a 4.26 km length was identified and mapped throughout the larger 3.50 km² field area (Fig. 1; Table 2). Digital points had an average point-to-point spacing of 1.69 m, whereas field-acquired points were much sparser, averaging one every 7.45 m (Table 2). Points were commonly analogous between the two methods, with mean elevation offset of 0.32 m and a maximum offset of 1.44 m (Figs. 7B and 7C).

#### Sedimentary Logs

Ten sedimentary logs measured in the field, totaling 78.0 m vertically, were collocated in the DOM data set (Figs. 9A–9J). Field observations identified more than 250 unique beds, while 109 digital units were identified from the DOM. The average bed thickness from field measurements was 0.31 m, with a median of 0.19 m, while digital units averaged 0.71 m, with a median of 0.51 m. Individual beds <0.11 m could not be distinguished in the DOM, yet they constituted more than 30% of unique beds identified in the field.

Figure 4. Typical outputs from the full unmanned aerial vehicle structure-from-motion multiview stereo process: (A) two-dimensional orthomosaic image; and (B) two-and-a-half-dimensional digital surface model. The resolution of these outputs is 0.02 m/pixel, but details along steep slopes are distorted or omitted.
Figure 5. Profile view of channel-belt basal contact (yellow arrows), with shallow-dipping counter-point-bar deposits (sandstone and siltstone) overlying flat-lying floodplain mudstone: (A) field photograph; (B) unmanned aerial vehicle-structure-from-motion (UAV-SfM) dense point cloud (see Supplemental Files 1–2 [text footnote 1]); and (C) UAV-SfM triangulated mesh. Light-blue arrows in B and C represent the interpreted contact from the digital outcrop model (DOM); pink bars represent ~3 m on the ground.
Figure 6. Profile view of thin-bedded, shallow-dipping, counter-point-bar deposits: (A) field photograph; (B) unmanned aerial vehicle–structure-from-motion (UAV-SfM) dense point cloud; and (C) UAV-SfM triangulated mesh. Note the “gaps” in the dense point cloud (B, yellow arrows) and the loss of fine detail due to interpolation in the triangulated mesh (C). Pink bar represents ~3 m.
The total thickness of individual sedimentary logs varied by an average of 0.27 m, with a maximum difference of 1.04 m (Fig. 9F) and a minimum difference of 0.00 m (Fig. 9H) between field and digital methods. Disparities could be attributed to inconsistencies between individual units in field and DOM logs. For example, log 07 (Fig. 9G) denotes a grouping of thick-bedded sandstone from 0.2 to 2.6 m, which appears to correspond to a similar DOM unit that measured 0.25 m thinner. If this 0.25 m difference is accounted for, the DOM and field logs would have similar overall measurement and comparable composition. Similarly, large disagreements were found between the mudstone layers (2.7–4.3 m) and groupings of mudstone/sandstone beds (4.6–7 m) in log 06 (Fig. 9F), which measured 0.37 m and 0.53 m thicker than corresponding units measured from the DOM.

Thin beds distinguished as unique units in the field were commonly omitted in DOM logs. For example, the 0.2-m-thick sandy mudstone bed (3.7–3.9 m) in log 01 was misclassified and/or not visible in its digital equivalent (Fig. 9A). Similarly, the 0.1-m-thick sandstone unit at the 3.8 m mark in log 04 was not observed in the digital counterpart (Fig. 9D). More commonly, however, groupings of thin beds identified in the field corresponded to a larger generalized unit in the DOM, consistent with facies-level detail rather than bedding-level detail.
For example, in log 05, the muddy sandstone unit at 5.0–6.0 m appears to correspond to the 10 alternating sandstone and mudstone beds (<0.1 m thick) within the same interval of the field log (Fig. 9E). Disagreements between field and digital logs also included misclassification of units (i.e., log 03, 2.8–3.1 m; Fig. 9C). However, these misclassifications were commonly minor, because the primary composition was maintained (i.e., muddy sandstone classified as a sandstone) or the proportion of sandstone:mudstone in a mixed-composition unit was characterized differently (i.e., sandy mudstone classified as muddy sandstone in digital data).

The 250 unique beds identified in the 10 field logs were categorized into one of the six facies from Table 1, resulting in 160 unique facies units that could then be compared with the 109 digital stratigraphic units (facies) derived from the DOM. The mean thickness of the field-derived facies was 0.49 m, with a median of 0.22 m. Table 3 summarizes the facies proportions determined for each field log and digital log based on the four digital facies categories in Table 1. Digital units (df1–df4) had an average absolute difference from field facies (f1–f6) of ±4.9% and a standard deviation of 0.06. The maximum discrepancy between field and digital facies proportions was 13.6% for the sandy

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**Figure 8.** Digital sedimentary log interpretation (log 08; Fig. 9H). (A) Bedding contacts (light blue) on the dense point cloud were determined by spectral changes on the dense point cloud digital outcrop model, digitized within Pix4Dmapper. The bottom and top of sedimentary logs were determined from differential global positioning system locations (red arrows) collected in the field. (B) Digital sedimentary log (log 08) resulting from digital identification of changing lithology (symbology is consistent with Fig. 9). Pink bars in A represent ~3 m. Grain-size abbreviations: si—silt; vfs—very fine sand; fs—fine sand; ms—medium sand; cs—coarse sand.

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**TABLE 2. CHANNEL-BELT BASAL CONTACT INTERPRETATION**

<table>
<thead>
<tr>
<th>Method*</th>
<th>Interpreted points</th>
<th>Length of contact identified (km)</th>
<th>Average point-to-point distance (m)</th>
<th>Field area (km²)</th>
<th>Time (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field (dGPS)</td>
<td>654</td>
<td>4.26</td>
<td>7.45</td>
<td>3.50</td>
<td>~20</td>
</tr>
<tr>
<td>Digital (DOM)</td>
<td>2178</td>
<td>3.50</td>
<td>1.69</td>
<td>0.52</td>
<td>15.5†</td>
</tr>
</tbody>
</table>

*GPS—differential global positioning system; DOM—digital outcrop model.
†Digital unmanned aerial vehicle—structure from motion (UAV-SfM) DOM interpretation required 1.5 h to collect data, 13 h to process at high resolution, and 1.0 h to interpret.
mudstone (dF3) classification in log 03 (Fig. 9C), and the smallest difference was 0.3% in the muddy sandstone (dF2) in log 04 (Fig. 9D).

Digitization of higher-order surfaces resulted in the identification of several meander-belt elements throughout the DOM. Most notable features were aligned sequences of shallow-dipping planes characteristic of lateral accretion surfaces from a migrating point bar (e.g., Thomas et al., 1987; Fig. 10; see also Supplemental Files 3–4 [footnote 1]). Similar surfaces were also identified within relatively finer-grained facies, indicative of counter-point-bar surfaces (Smith et al., 2009a; Fig. 11; see also Supplemental Files 5–6 [footnote 2]). Shallow-dipping (<12°) surfaces of heterolithic strata correspond to the original depositional surface and are indicative of channel metrics (i.e., migration direction). Digital measurements of the point-bar surfaces had a mean dip azimuth of 90° to the east, while counter-point-bar deposits had a mean dip azimuth of 190° toward the south-southwest.

**DISCUSSION**

UAV-SfM applications in geology have primarily used 2-D and 2.5-D methods for analysis (e.g., Bemis et al., 2014; Johnson et al., 2014; Vasuki et al., 2014; Chen et al., 2015; Zahm et al., 2016; Chesley et al., 2017; Thiele et al., 2017).

Although UAV-SfM–derived orthomosaic images and DSMs have very high spatial resolution and have been used to identify fluvial stratigraphic surfaces in plan view (i.e., Chesley et al., 2017), they are not always suitable for mapping laterally extensive exposures along steep slopes (cross-sectional view). Nieminski and Graham (2017) used UAV-SfM–derived digital terrain models (DTMs), referred to here and elsewhere as DOMs, to map thin-bedded (0.1–0.7 m thick) turbidites and deformation features along an extensive vertical cliff. The authors suggested that more complex outcrop geometries would require additional photographs to limit distortion and obtain complete coverage in a DOM.

The Dinosaur Provincial Park badlands are an excellent example of a geometrically complex landscape with well-preserved, extensive exposures of fluvial channel-belt and floodplain deposits. To obtain complete coverage of the complex exposures, we acquired a highly redundant block of images, with high overlap, perpendicular flight lines, and oblique (off-nadir) image angles. It has been suggested that similar imaging networks would increase outcrop coverage (Bemis et al., 2014; Vollgger and Cruden, 2016; Cawood et al., 2017) and could also improve photogrammetric camera calibration and overall accuracy of model reconstruction (Wolf and Dewitt, 2000; Luhmann and Robson, 2006; James and Robson, 2014; Carbonneau and Dietrich, 2016; Luhmann et al., 2016; James et al., 2017). We found that the data collection...
strategy captured sufficient geologic detail along steep slopes; however, data sets required further consideration of visualization strategies (i.e., use of the 3-D dense point cloud) in order to retain geologic detail during analysis.

### DOMs

We examined alternative UAV-SfM data sets as DOMs for mapping multiscale fluvial channel-belt features and facies exposed within a topographically complex outcrop. Although the UAV-SfM dense point cloud functioned as a DOM for digital analysis and interpretation of fluvial features, other data sets can also be used to create a DOM. For example, both dense point cloud and textured mesh DOMs represent a scaled, georeferenced, and colorized representation of the field area. The main distinction between the two DOMs is use of interpolation and texturing. Point clouds resemble raw data sets collected with TLS and include a color (RGB) attribute calculated from corresponding image pixels. Textured meshes are interpolated into a continuous triangulated surface from the point cloud and are textured directly from corresponding images (Carrivick et al., 2016). Point clouds contain gaps between points (i.e., Fig. 6B) that can lead to difficulties in analysis. Geologic applications, in particular, commonly process TLS point clouds into a triangulated mesh for interpretation and measurement (Enge et al., 2007; Buckley et al., 2008).

We found that, although the triangulated mesh provided a continuous view of the outcrop, a high-resolution textured mesh could not be processed for the 0.52 km² study site due to computational limitations in processing a large data set. Mesh triangulation for the entire study area required a limitation of triangles, resulting in more generalized topography, distortion of photo texture, and loss of bedding-level detail. Although gaps between points may complicate analysis, we found geologic features were more clearly resolved in the dense point cloud than in the textured mesh.

### 3-D Interpretation

Macroscale features, such as the channel-belt basal contact, were clearly visible throughout the field site in both the textured mesh and dense point cloud (Fig. 5). Recognition of this feature throughout the field site provided constraints on interpretation of finer-scale fluvial features. Specifically, the channel-belt contact provided a common datum that served as a reference surface for aligning detailed measurements (e.g., sedimentary logs; Calvo and Ramos, 2015). Mapping extensive surfaces in the field can be time-consuming and problematic when traversing difficult terrain, with exposures on slopes facing different azimuths and crossing drainages. Although field campaigns commonly employ GPS or DGPS units that can be used to record points along surface contacts, it remains difficult to keep track of the specific

### Table 3. Results of Facies Comparison: Field versus Digital

<table>
<thead>
<tr>
<th>Sedimentary log ID</th>
<th>Method</th>
<th>Sandstone df1 (%)</th>
<th>Silty sandstone df2 (%)</th>
<th>Sandy siltstone df3 (%)</th>
<th>Siltstone and mudstone df4 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Field</td>
<td>62</td>
<td>10</td>
<td>20</td>
<td>08</td>
</tr>
<tr>
<td>02</td>
<td>Digital</td>
<td>60</td>
<td>17</td>
<td>07</td>
<td>17</td>
</tr>
<tr>
<td>03</td>
<td>Field</td>
<td>39</td>
<td>02</td>
<td>22</td>
<td>38</td>
</tr>
<tr>
<td>04</td>
<td>Digital</td>
<td>31</td>
<td>06</td>
<td>16</td>
<td>48</td>
</tr>
<tr>
<td>05</td>
<td>Field</td>
<td>22</td>
<td>06</td>
<td>64</td>
<td>08</td>
</tr>
<tr>
<td>06</td>
<td>Digital</td>
<td>25</td>
<td>05</td>
<td>55</td>
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<tr>
<td>07</td>
<td>Field</td>
<td>07</td>
<td>09</td>
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</tr>
<tr>
<td>08</td>
<td>Digital</td>
<td>13</td>
<td>09</td>
<td>39</td>
<td>38</td>
</tr>
<tr>
<td>09</td>
<td>Field</td>
<td>62</td>
<td>08</td>
<td>09</td>
<td>21</td>
</tr>
<tr>
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<td>Digital</td>
<td>57</td>
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<tr>
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<tr>
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<td>04</td>
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</tr>
<tr>
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<td>34</td>
<td>09</td>
<td>17</td>
<td>40</td>
</tr>
<tr>
<td>05</td>
<td>Field</td>
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<td>21</td>
<td>52</td>
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<td>Digital</td>
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<td>Digital</td>
<td>26</td>
<td>21</td>
<td>29</td>
<td>23</td>
</tr>
</tbody>
</table>

Note: df1 is equivalent to coarse-grained field facies, F1–F2, and df4 is equivalent to fine-grained field facies, F5–F6 (see Table 1).
contact of interest, especially in fluvial environments with multiple channel belts exposed.

Identification of the channel-belt basal contact using the DOM, however, is an efficient and straightforward exercise. Digitally tracing a contact around intricate topography, across drainages, and through vegetation is possible by way of flexible visualization and navigation throughout the 3-D model. Identification of the lower channel-belt contact for the interval exposed within the field site was completed within 1.0 h (15.5 h if including image collection and processing), as compared to 20 h required to map the contact in the field (Table 2). Digital (red points) and field (blue points) locations of the contact were not always in agreement, with vertical offsets up to 1.44 m (i.e., Fig. 7B). These offsets could be explained by a combination of factors, including reduced accuracy of field dGPS and laser rangefinder (i.e., satellite coverage obstruction, laser scan angle, or multipath error) or inaccurate reconstruction and georeferencing (location and orientation) of the UAV-SfM model. Based on the recent vetting of UAV-SIM models produced from a similar methodology (i.e., similar UAV platform, SfM software, and RTK-GNSS of GCPs; Whitehead and Hugenholtz, 2015; Hugenholtz et al., 2016), we strongly believe that the former factors were more likely the cause for the discrepancies.

Figure 10. Profile view of sedimentary log 01 [Fig. 9A]: (A) within the digital outcrop model, where light-blue points separate digitally identified units within a one-dimensional sedimentary log; (B) lateral interpretation of bedding surfaces (purple polygons), which allows three-dimensional quantification and interpretation of geologic deposits; and (C) overview showing the same surfaces in the context of the surrounding geology indicative of a point bar migrating 90° east (left in the image). Pink bars in A–C represent ~3 m. For interactive model, see Supplemental Files 3–4 (text footnote 1).
Furthermore, these inconsistencies signify errors in absolute location on Earth with respect to a geographic reference system (i.e., latitude, longitude, and/or elevation). Degraded absolute accuracy may complicate the ability to locate a particular feature or compare across data sets; however, UAV-SfM DOMs preserve relative spatial relationships (i.e., distance and direction) among points within the model. With appropriately defined scale and orientation from GCPs and/or ground measurements, UAV-SfM DOMs maintain high relative accuracies and can be used to record quantitative geologic measurements (i.e., bed thickness, lengths, and angular measurements of architectural features), although the DOM may not be accurately located in absolute space (Chesley et al., 2017).

3-D Measurements

Attempts to identify individual beds from the UAV-SfM DOM had mixed results. In general, thicker units were more consistently plotted than thinner units, while beds <0.11 m were not discernible in the DOM. This is similar to results found by Nieminski and Graham (2017), who were able to dependably identify beds ranging from 0.1 to 0.7 m thick. It is likely that increased resolution (from lower flight altitude, longer focal length, or higher camera resolution) could result in identification of thinner beds. However, this would also reduce spatial coverage and provide excessive detail in some applications. Regardless, comparison of units identified from the DOM with field facies logs

Figure 11. Profile view of sedimentary log 09 (Fig. 9I): (A) within the digital outcrop model, where light-blue points separate digitally identified units within a one-dimensional sedimentary log; (B) lateral interpretation of bedding surfaces (purple polygons), which allows three-dimensional quantification and interpretation of geologic deposits; and (C) overview showing the same surfaces in the context of the surrounding geology indicative of a counter point bar migrating 190° south-southwest (right in the image). Pink bars in A–C represent ~3 m. For interactive model, see Supplemental Files 5–6 (text footnote 1).
suggestion that DOMs can reliably resolve facies-level detail. Digitally identified facies averaged ±4.9% within proportions of facies identified in the field. Differences in unit thickness may be due to errors in UAV-SfM DOM or errors in field measurements, which are not uncommon (Groshong, 2006). Facies proportions reported from field logs are typically one-dimensional (1-D) and, at best, can be estimated between sedimentary logs through interpolation. UAV-SfM DOMs present the opportunity to extend facies estimations laterally and contiguously throughout extensive outcrop exposures, with similar conviction as 1-D field interpretations.

Extending bedding measurements laterally from 1-D sedimentary logs can provide additional geometric information about inherently 3-D geologic features that is often difficult, if not impossible, to quantify using traditional field methods (McCaffrey et al., 2005). Using the digitization method in Pix4Dmapper, we were able to identify abundant inclined and aligned accretion surfaces characteristic of point-bar (Fig. 10) and counter-point-bar (Fig. 11) elements (Thomas et al., 1987; Smith et al., 2009a). Figures 10A and 11A show the (1-D) digital sedimentary log (black line) with light-blue points separating distinct lithologic units that were compared to field sedimentary and facies logs. Figures 10B and 11B show the same views with bedding surfaces extended laterally from the sedimentary logs. Similar to the channel-belt basal contact, these interpretations can be easily followed to corresponding units around outcrop bends and across drainages to form 3-D surfaces representing interpreted depositional surfaces (purple polygons; see Supplemental Files 3-6 for interactive models [footnote 1]). An alternative approach could be to export manual tie points from Pix4Dmapper into an external software program that permits more complex surface interpolation options (i.e., Petrel, ArcGIS; e.g., Durkin et al., 2015a); however, this was not considered necessary in this demonstration.

Lateral accretion surfaces have been recognized in plan view using similar UAV-SfM methods to interpret a 2-D orthomosaic image (Chesley et al., 2017). We extended these methods into 3-D analysis through identification of accretionary bedding planes in multiple cross-section views, facilitating the detailed quantification and reconstruction of channel metrics. In particular, by measuring the attitude of a series of accretion surfaces, point-bar migration directions could be reconstructed from the UAV-SfM data sets. These data are critical for detailed stratigraphic correlations and paleoenvironmental reconstructions (e.g., Durkin et al., 2015a; Chesley et al., 2017). Additionally, digital observations using DOMs can be shared, reevaluated, and reinterpreted based on new information.

Digital identification of stratigraphic surfaces and lithologic units is reliant upon distinct surface coloration calibrated by extensive field knowledge of the facies within the local field area. Sandstone (dF1) and mudstone (dF4) were primarily identified by dominant surface coloration in the DOM (dF1 = light tan to white; dF4 = dark gray to brown). Muddy sandstone (dF2) and sandy mudstone (dF3) facies typically had colors ranging between the two end members. Correspondence between field and digital facies is attributed in large part to the marked contrast between fine- and coarse-grained members. Without the contrasting weathered color of different lithofacies, digital interpretation may not be possible to the extent demonstrated here.

DOMs, whether derived from TLS, ground-based photogrammetry, or UAV-SfM, are not presented as a replacement for field observations. However, DOMs are well suited to provide supplemental quantitative measurements and interpretations that are difficult, or impossible, to acquire in the field. In this study, we demonstrated that multiple orders of fluvial stratigraphic surfaces and lithofacies could be independently interpreted from the DOM alone with similar results to field interpretations. Integration of detailed field measurements (i.e., sedimentary logs, paleocurrent measurements, and strike and dip measurements) with DOMs in a digital database yields potential for highly detailed vertical and lateral reconstruction of fluvial deposits and the processes that formed them through time.

CONCLUSIONS

We examined UAV-SfM data sets for mapping multiscale stratigraphic surfaces and facies of a heterogeneous fluvial channel-belt deposit exposed within a topographically complex outcrop. We evaluated the commensurability of digital measurements made from a 3-D DOM derived from UAV-SfM and the independently collected field observations. Building upon recent geologic mapping applications using UAV-SfM, the data acquisition, processing, and visualization methods proposed here preserved the 3-D topographic integrity and geologic detail, even in a geometrically complex landscape. Results indicate that UAV-SfM methods can produce visually representative DOMs that can be used to derive unaided interpretations and measurements comparable to field methods in myriad geologic applications. UAV-SfM DOMs are not a replacement for field observations; however, they can efficiently provide supplemental measurements and enable guided interpretation between sparsely distributed 1-D and 2-D field data (i.e., sedimentary logs, cross-section sketches). Integration of multiple data sets can result in highly constrained geologic models that, for fluvial environments, can potentially result in more complete stratigraphic models. Future research will take on such challenges by using integrated data sets and UAV-SfM DOMs to better understand the temporal evolution and preservation of channel-belt deposits.

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