Digital re-evaluation of down-dip channel-fill architecture in deep-water slope deposits: Multi-scale perspectives from UAV-SfM

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Abstract
Recent advances in sea floor measurements and modelling have revealed new insight into submarine channel processes; however, understanding how these short-term perspectives influence long-term evolution of submarine channels has been limited by the difficulty in linking processes to products in the stratigraphic record. Outcrops present opportunities to characterise the detailed internal architecture of deep-water channel fills over a wide range of timescales, but obtaining observations is compounded by challenges in outcrop accessibility and perspective along broad exposures. To demonstrate the potential value of modern remote sensing techniques in supplementing fieldwork, an extensive dip-oriented outcrop exposure of Cretaceous deep-water channel deposits was re-evaluated using a 3D digital outcrop model generated from uninhabited/unmanned aerial vehicle photogrammetry. Results confirmed previous field-based documentation of depositional element-scale stratigraphic architecture, but also revealed nuanced internal detail that was not captured from field-based perspectives alone. Subtle internal channel-fill architecture, including discontinuous sandstone wedges and the interpreted stratigraphic products of upslope-migrating bedforms, are also recognised. This study demonstrates the sedimentary detail that can be uncovered by integrating conventional field-based approaches limited by viewable scale, perspective, and/or accessibility, with emerging remote sensing techniques. The unmanned aerial vehicle photogrammetry approach used here provides valuable supplemental data in the investigation of deep-water channel system deposits and has the potential to overcome inherent challenges in outcrop mapping for numerous applications.

KEYWORDS
channel architecture, deep-water slope deposits, SfM photogrammetry, stratigraphic architecture, UAV, upslope-migrating bedforms
1 | INTRODUCTION

Understanding relationships between depositional processes and their associated products in the rock record has been particularly challenging in deep-water settings due to: (a) their appreciable extent (tens to hundreds of kilometres); (b) a historical lack of metre-scale and sub-metre-scale observations from modern systems; and (c) difficulties comparing across the observational scales and hierarchies provided by different methods of investigation (Cullis et al., 2018; Kane et al., 2008; Mutti & Normark, 1987; Normark et al., 1993; Straub et al., 2008; Talling et al., 2015). Flume experiments (Baas et al., 2004; de Leeuw et al., 2016; Fernandes et al., 2020; Peakall et al., 2007; Sumner et al., 2008) and recent repeat imaging methods of investigation (Cullis et al., 2018; Kane et al., 2008; Talling et al., 2015). Flume experiments (Baas et al., 2004; de Leeuw et al., 2016; Fernandes et al., 2020; Peakall et al., 2007; Sumner et al., 2008) and recent repeat imaging and monitoring of active deep-sea channels (Babonneau et al., 2007; Sumner et al., 2008; Talling et al., 2015). Flume experiments (Baas et al., 2004; de Leeuw et al., 2016; Fernandes et al., 2020; Peakall et al., 2007; Sumner et al., 2008) and recent repeat imaging of active deep-sea channels (Babonneau et al., 2013; Hage et al., 2018; Hughes Clarke, 2016; Paull et al., 2018; Vendettuoli et al., 2019) have offered new insight into sea floor processes; however, these methods have limited spatial resolution and temporally only provide short-term perspectives (i.e., days to years). Therefore, ancient deposits are used as complementary datasets to better understand longer-term system evolution and have historically served as a basis for depositional models (Clark & Pickering, 1996; Mutti & Normark, 1987; Posamentier & Kolla, 2003; Walker, 1978).

Subsurface (e.g., seismic reflection) datasets have been used to distinguish sedimentary units and interpret long-term evolution of these depositional environments at a regional-scale, but are limited to coarse resolutions (tens of metres vertically), limiting interpretation to highly composite architectures (e.g., channel complex, complex sets, complex systems in Figure 1A; Abreu et al., 2005; Deptuck et al., 2007; Mayall et al., 2006). Outcrop analogues provide opportunities to characterise internal characteristics and link observations across multiple spatial and temporal scales (Casciano et al., 2019; Clark & Pickering, 1996; Hodgson et al., 2011; Hubbard et al., 2014; Macauley & Hubbard, 2013). However, outcrops are often non-continuous, variably accessible, and limited to perspectives afforded by exposure orientation relative to depositional dip. Consequently, models of submarine channel evolution have primarily developed from limited views along depositional strike-oriented perspectives (e.g., Figure 1B; Covault et al., 2016), while the variability of facies and stratigraphic architecture along depositional dip is rarely addressed (Bell et al., 2020; Malkowski et al., 2018; Plink-Björklund et al., 2001).

Compounding issues inherent to outcrop characterisation of deep-water channel strata is a paucity in practical approaches for documenting and measuring outcrop features at multiple scales, specifically linking fine-scale field observations (i.e., grain, laminae, bed) with broad-scale geometry and architecture (i.e., internal body/surface and larger; Figure 1A). For example, sedimentary logs document essential lithologic attributes, but do not provide complete spatial characteristics, such as architecture and geometry. 'Stepping back' often reveals coarse-scale patterns and geometries that can be recorded through sketches and/or photographs (Arnot et al., 1997; Benhallam et al., 2016). This technique is familiar to most field geologists and only requires a field notebook and/or camera; however, it lacks geospatial constraints and scaling required for quantitative characterisation. Additional practical considerations include the need for an unobstructed viewpoint and the inability to quickly switch among perspectives, conceivably restricting the observations perceptible from a given exposure.

Recently, a host of geospatial techniques have been applied in constraining stratigraphic architecture in outcrop studies. Differential global positioning systems (dGPS), sometimes aided by a laser rangefinder, have been used to record points along key bedding surfaces (Alfarhan et al., 2008; Durkin et al., 2015; Pemberton et al., 2016), but also require physical access or an unobstructed view of the outcrop. Digital outcrop models (DOMs), also known as virtual outcrops, collected with ground-based or airborne light detection and ranging (LiDAR), have been used to digitally document 3D outcrops (Bellian et al., 2005; Buckley et al., 2008, 2010; Burnham & Hodgetts, 2019; Hodgetts, 2013; McCaffrey et al., 2005; Rittersbacher et al., 2014). However, LiDAR systems can be challenging in some applications where suitable scanning positions are limited or inaccessible (Chesley et al., 2017; Rittersbacher et al., 2014).

Alternatively, modern photogrammetry using structure-from-motion (SfM) software with uninhabited/unnanned aerial vehicle (UAV) images has recently demonstrated potential for geologic mapping applications. Integration of UAV-SfM workflows into sedimentary studies has proven effective for mapping plan-view exposures (Chesley & Leier, 2018) and documenting localised stratigraphic architecture in vertical to sub-vertical outcrops (Nesbit et al., 2018; Nieminski & Graham, 2017; Pitts et al., 2017). Recent developments in 3D-enabled software provide opportunities to map geologic features, integrate multiple datasets, and make advanced interpretations from DOMs (e.g., Virtual Reality Geology Studio and LIME; Buckley et al., 2019; Hodgetts et al., 2015). Although UAV-SfM workflows and 3D software are emerging in various applications, their full potential in advancing geologic investigations and understanding has yet to be realised.

To demonstrate the additional multi-scale perspectives and quantitative potential provided by a UAV-SfM workflow, an outcrop with depositional-dip-oriented exposures of Cretaceous deep-water channel-fill deposits in the Magallanes-Austral Basin, southern Chile, previously documented with conventional field methods (sedimentary logs, field observations and dGPS surface mapping; Daniels, 2015), was revisited. A well-exposed cliff-face (15–40 m high) reveals 7 km of nearly continuous outcrop roughly parallel to palaeoflow, providing excellent opportunities to investigate longitudinal
(down-system) variations in stratigraphic architecture. This study aims to: (a) document digital methods for performing observation and interpretation of deep-water channel stratigraphic architecture from DOMs; (b) re-evaluate field-based observations of channelised deep-water slope deposits with new digital interpretations that seek to capture previously overlooked sedimentary features due to limitations in data acquisition methods; and (c) characterise subtle down-dip architecture internal to channel-form sedimentary bodies and discuss implications for deep-water depositional models.

2 | GEOLOGIC SETTING AND STUDY AREA

The Magallanes-Austral retroarc foreland basin largely formed and filled in response to uplift, exhumation and denudation of the Patagonian Andes during the Late Cretaceous (Fildani & Hessler, 2005; Fosdick et al., 2014; Wilson, 1991). Deposits of the Magallanes-Austral Basin record the evolution of deep-water to marginal marine depositional systems that transferred detritus from north to south across

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**FIGURE 1** (A) Grain-scale through bed-scale features and commonly considered stratigraphic hierarchical components (e.g., element, complex) for deep-water channel deposits plotted with characteristic horizontal and vertical extents. Note that grey boxes overlap and do not have absolute boundaries—these ranges represent typical extents of features. (B) Idealised strike-oriented cross-section depicting common deep-water channel system architecture (adapted from Covault et al., 2016). Stratigraphic surfaces depicted are highly composite and correspond to the largest-scale features in (A)
Chilean and Argentine Patagonia during this time (Daniels et al., 2018; Malkowski et al., 2016; Moyano Paz et al., 2020; Rivera et al., 2020; Romans et al., 2011; Schwartz & Graham, 2015). Between 50 and 52°S (i.e., the Última Esperanza sector of the basin), the deep-water depositional history of the basin is characterised by three discrete phases of infilling, including deposits of the Punta Barrosa, Cerro Toro and Tres Pasos formations (Figure 2A; Daniels et al., 2019; Katz, 1963; Romans et al., 2011). Together with the shallow-marine Dorotea Formation, the Tres Pasos Formation records the terminal phase of marine sedimentation in this part of the basin (Bauer et al., 2020; Daniels et al., 2018; Hubbard et al., 2010).

The Tres Pasos Formation largely records deposition along submarine slopes that were >40 km long and characterised by >1 km of relief (Figure 2B; Bauer et al., 2020). Although the Tres Pasos Formation consists predominantly of siltstone deposits, packages of sandstone up to 300 m thick crop out along the studied transect and are interpreted to represent the products of channelisation along the basin-margin slope (Hubbard et al., 2010, 2014; Macauley & Hubbard, 2013). Here, a 15–40 m thick, near-continuous exposure of
the Tres Pasos Formation was examined along a sub-vertical ridgeline cliff (Figure 2C). The strata were deposited on the palaeo-slope >30 km from the shelf edge (Bauer et al., 2020; Daniels et al., 2018). More than 350 palaeocurrent measurements from sole marks, imbricated mudclasts and cross-stratification indicate that the outcrop is oriented roughly parallel to the principal direction of sediment transfer (north to south; Daniels, 2015).
Recent field-based work in the region by Daniels (2015) documented a system of channelised deep-water slope deposits using a commonly employed stratigraphic hierarchical framework (element, complex, complex set; Figure 1A; McHargue et al., 2011; Sprague et al., 2002). The investigation focussed on stratigraphic correlation of slope channel strata, as well as fine-scale sedimentological characterisation in measured sections. The finest scale features emphasised were channel elements, which were described as mappable bodies recording erosional and depositional processes from a single geomorphic feature (Mutti & Normark, 1987). Twenty distinct channel elements were identified using traditional field data-acquisition techniques and dGPS to constrain stratigraphic architecture (Figure 3A,B). No notable changes of intra-element channel-fill composition or architecture were discerned, but cliff exposures were often inaccessible and idealised perspectives to acquire photomosaics were not available. These limitations of the outcrop at Alvarez Ridge may have prevented the recognition of important sedimentary detail from a conventional field-based approach.

3 | METHODS

A DOM derived from UAV-acquired images was used to digitally record and interpret stratigraphic architecture at multiple scales and compare with previously reported field-based results (Daniels, 2015). A 2 km, depositional-dip-oriented segment of the dataset was investigated, featuring six channel elements (delineated by blue boxes in Figure 3A,B). Field measurements from the original study included eight sedimentary logs (125 m, cumulative), which recorded bed thickness, grain size, sedimentary structures, palaeo-flow indicators (primarily derived from sole marks), and the nature of bedding contacts. In the original study, stratigraphic surfaces were mapped by: (i) walking along unit contacts and recording point locations with a dGPS; (ii) projecting dGPS points onto a 2D plane oriented orthogonal to bedding; and (iii) interpreting a down-dip cross-sectional stratigraphic profile from 2D projected points. The digital method adopted in this analysis followed a similar workflow, replacing field-based dGPS points (step (i) above) with digital observations derived using the workflow described below.

3.1 | Digital data collection and processing

The DOMs were generated from a collection of UAV images processed using structure-from-motion multi-view stereo (SfM-MVS), commonly referred to as SfM photogrammetry. Images were collected with a DJI Phantom 3 Professional quadcopter controlled using the freely available Pix4Dcapture application for iOS. Flights were performed using manual ‘free flight’ mode, which allows user control of lateral movement, altitude and camera pitch angle. In this flight mode, images were captured automatically with changes in UAV location. Primary flights were performed with the camera plane approximately parallel to the outcrop at a distance of 10–15 m in a grid-like pattern along the near-vertical outcrop exposure (Figure 3C,D). Additional flights were performed with a nadir (downward facing) and oblique camera angle of ca 45° along the outcrop ridge in order to: (a) increase coverage of the complex outcrop faces (Nesbit et al., 2018); (b) obtain images of features above the ridgeline to use as ground control points (GCPs); and (c) enhance image network geometry for a higher 3D accuracy in a complex exposure (Nesbit & Hugenholtz, 2019). A total of 50 distinct natural points above, below and on the outcrop were selected as GCPs and recorded with dGPS to constrain the scale and orientation of the model during SfM processing.

More than 2,400 images from all flights were processed together using Pix4Dmapper. Images were divided into a northern and southern half of the model to decrease processing time and to reduce strain on computing hardware and graphics. Processing settings followed those outlined by Nesbit and Hugenholtz (2019), with two modifications. In the Initial Processing (Step 1), ‘free flight’ matching strategy was used instead of ‘Aerial grid or corridor.’ Additionally, during point cloud densification and mesh generation (Step 2), a 3D textured mesh was generated to enhance interpretation.

3.2 | Digital outcrop characterisation, projection and interpretation

Digital observations of stratigraphic surfaces were made directly within Pix4Dmapper (Figure 4A,B) following the workflow outlined by Nesbit et al. (2018), because of its capabilities to seamlessly digitise and visualise large 3D point clouds and meshes (Nesbit et al., 2020). Digitised points and lines were created using both the dense point cloud and textured mesh DOMs, with individual observations confirmed in individual UAV images. Digital observations were then exported as ESRI point shapefiles (.shp) and converted into tabular format with identifier (name) and location (x, y, z) attributes. To account for post-depositional tectonic effects on bedding geometry, tabular point data were imported into Petrel (Schlumberger, 2020) and divided into three segments based on variations in structural dip of bedding along the outcrop belt. Data from each segment were then projected onto a 2D plane oriented perpendicular to bedding (striking north-south, dipping east) following methods outlined by Englert et al. (2018), resulting in a structurally restored 2D cross-sectional profile of the outcrop belt parallel to depositional dip (Figure 4C). Data projected in the 2D cross-section were then correlated laterally to reveal related stratigraphic surfaces. Subsequently, strata were...
interpreted further by grouping internal beds or bedding packages of similar lithofacies by cross-referencing the 3D model and/or individual UAV images. To remain consistent with the study of Daniels (2015), channel elements were the focus of mapping along the outcrop belt.

4 | RESULTS

4.1 | Sedimentary facies

The mapping and stratigraphic architecture focus of this study is grounded by a series of sedimentary facies, including: (F1) thick-bedded sandstone and/or conglomerate (with localised pebble-sized to cobble-sized clast accumulations) associated with deposition in channel axes; (F2) thick-bedded to thin-bedded sandstone and mudstone linked to off-axis and proximal margin deposits; (F3) thin-bedded mudstone with sandstone linked to distal margin deposits; and (F4) chaotically-bedded, poorly sorted mudstone and sandstone interpreted as mass transport deposits (MTDs). The main characteristics of these facies are summarised in Figure 5 and Table 1. Sediment gravity flows are interpreted as the dominant mode of sediment transfer recorded in the Tres Pasos Formation, including high-density turbidity currents (e.g., F1, Lowe, 1982), low-density turbidity currents (e.g., F2 and F3, Bouma, 1962), and mass-wasting processes, including debris flows and slumping (e.g., F4, Lowe, 1982; Nardin et al., 1979; Talling et al., 2012). Similar facies have been identified in numerous studies performed on time-equivalent units adjacent to the study area (Hubbard et al., 2014, 2020; Macauley & Hubbard, 2013; Pemberton et al., 2016).

4.2 | Traditional field-based approach

4.2.1 | Description

Traditional field-based mapping approaches resulted in the identification of two packages of sandstone-dominated strata (F1) separated by a surface that is mappable across the entire outcrop transect (red line, Figure 6A). The
Bounding surface is undulous, with up to 10 m of relief (red line, Figure 7A,B). It is commonly overlain by recessive units, including thin-bedded turbidites (F2), concordant siltstone (F3), or mass-transport deposits (F4). The sandstone-dominated packages above and below the widespread bounding surface vary in thickness along the outcrop, from 25 to 40 m (Figure 6A). Each of the sandstone-dominated packages was subdivided into three sedimentary bodies 5–25 m thick, defined by basal surfaces that have concave upward shape. These surfaces are oriented parallel to subparallel to the main bounding surface and are characterised by clearly defined smooth bases and local changes in relief up to 10 m (blue lines, Figure 7B,C). The sedimentary body bases are overlain by mudstone drape (F3) or mudstone rip-up clasts/conglomerate lag (F1) deposits; the bulk of the bodies are composed of thick-bedded sandstone (F1), which sometimes fine upwards due to increased proportions of mudstone interbeds. Internally, the sedimentary bodies commonly contain discontinuous surfaces (<10^2 m extent) characterised by smooth to undulous (<4 m relief) geometries (dashed black lines, Figure 7C). These internal surfaces truncate individual beds and bedsets, and sometimes onlap the bases of sedimentary bodies.

4.2.2 | Interpretation

Identification of a hierarchical arrangement of strata can aid in the interpretation of sedimentary processes that took place during the long-term evolution of slope channel systems (Cullis et al., 2018; Mutti & Normark, 1987; Pickering et al., 1995). Daniels (2015) used regional mapping and context (Figure 3B), as well as sedimentological characterisation to divide the outcrop into a hierarchical framework for submarine channel strata (Figure 1B; Covault et al., 2016; McHargue et al., 2011; Sprague et al., 2002, 2005). The most prevalent stratigraphic surface bounds two sandstone-dominated packages and is interpreted as the boundary between channel complexes (Figure 6A). Channel complexes are thought to record the position of a submarine sediment-routing system over a protracted period and contain two or more stacked channel elements (McHargue et al., 2011).

Each channel complex is characterised by three sedimentary bodies 5–25 m thick, interpreted as channel elements (see also, Hubbard et al., 2014; McHargue et al., 2011; Mutti & Normark, 1987), and are numbered successively from the base of section (Figure 6A). Channel elements provide a record of inception through final infill of a single submarine
TABLE 1 Facies characteristics for the Tres Pasos Formation at Alvarez Ridge

| Facies                  | Grain size                        | Sedimentary features                  | Bed geometry                      | Thickness range           | Lower/upper contact                  | Process interpretations                  |
|-------------------------|-----------------------------------|---------------------------------------|-----------------------------------|---------------------------|----------------------------------------|------------------------------------------|
| F1: Thick-bedded sandstone and/or conglomerate | V. coarse grained sandstone at base—fines upwards; conglomerate consists of matrix supported pebbled to cobble clasts | Massive amalgamated to non-amalgamated beds | Lenticular to tabular          | 0.2–2.5 m thick; amalgamated packages <6 m | Sharp base with undulations caused by scours containing extrabasinal or mudstone clast accumulations; gradational top | Erosion and deposition from high-density turbidity currents |
| F2: Thick- to thin-bedded sandstone and mudstone | Fine-grained sandstone and siltstone | Incomplete Bouma sequences (Tb to Td); ripple and planar laminations common | Tabular to lenticular            | 0.02–0.2 m thick; packages <5 m thick | Typically sharp and sometimes undulatory | Low-density turbidity currents associated with traction sedimentation; some scouring |
| F3: Thin-bedded mudstone with sandstone | Siltstone and fine-grained sandstone | Incomplete Bouma sequences (Tc to Te); some ripple and planar laminations | Chaotic bedding and poorly sorted | Sandstone <0.2 m thick; siltstone <3.0 m thick with accumulations 0.2–15 m thick | Variable, typically sharp and undulous | Deposition following mass wasting; mass transport deposits (MTD) |
| F4: Chaotically bedded, poorly sorted mudstone and sandstone | Siltstone with sandstone | Chaotic bedding and poorly sorted | Chaotic                           | Sandstone <0.2 m thick; siltstone <3.0 m thick with accumulations 0.2–15 m thick | Variable, typically sharp and undulous | Deposition following mass wasting; mass transport deposits (MTD) |

Conduit on the sea floor and include evidence for numerous phases of erosion and infill to form composite channel-form deposits (Hubbard et al., 2020). Channel element bases are interpreted to record periods of erosion and sediment bypass (e.g., lag deposits and drapes; Hubbard et al., 2014; Stevenson et al., 2015). Channel fills are products of lower energy, depositional, turbidity currents or due to channel abandonment (Mutti & Normark, 1987). Internal surfaces within channel elements were only locally mapped and are interpreted to have been sculpted by multiple phases of cut and fill oriented sub-parallel to the channel element base erosion surface (Hubbard et al., 2014).

4.3 | Digital DOM approach

4.3.1 | Description

Digital mapping approaches revealed two sandstone-dominated stratigraphic packages (F1) separated by a distinct interval (1–8 m thick) characterised by recessive units (F2, F3 and F4) that extends throughout the digital model (Figure 6B). The base of this recessive interval is undulous with up to 12 m change in local relief, commonly truncating underlying strata (Figure 7D). As with the field-based approach, sandstone-dominated packages above and below the bounding surface are 20–40 m thick and are each subdivided into three sedimentary bodies (5–20 m thick) with mappable basal surfaces marked by a sharp change in lithology. The bases of these bodies are typically marked by a 0.4–2 m thick recessive mudstone (F3 or F2) overlain by sandstone (F1), which is often highly amalgamated and structureless (Figure 8). The surfaces that define the base of sedimentary bodies are identifiable along the extent of the outcrop (10^2–10^3 m) and commonly oriented nearly parallel to the bounding surface that separates the two sandstone-dominated packages (local variations in relief up to 4 m; Figure 6B).

Within each sedimentary body, numerous internal surfaces (10^1–10^2 m in length) are identified throughout the outcrop. These surfaces can be flat-lying to undulous, with vertical relief up to 6 m (Figure 7F). Surfaces typically truncate strata within sedimentary bodies, although they onlap other surfaces locally (Figure 7D). Internal surfaces commonly bound lenticular or wedge-shaped units with asymmetric geometries that are steeper in the upslope direction. Surfaces can appear discontinuous (e.g., Figure 8), or may bound 0.5–3 m thick beds and form a backset stacking pattern with beds sequentially offset and dipping gently in the upslope direction (Figures 8 and 9).
**FIGURE 6** Down-dip cross-sectional profile of interpreted stratigraphic architecture. (A) Cross-section based on observations using traditional field methods (modified from Daniels, 2015); (B) Cross-section based on observations using digital UAV-SfM DOM methods.

**FIGURE 7** Examples of surface characteristics as seen in the field (A through C) and in the digital outcrop model (D through F). Note channel complex boundaries in (A) and (D) highlighted in red; channel element boundaries in (B) and (E) in blue, and internal element surfaces highlighted in (C) and (F) in black.
4.3.2 | Interpretation

Interpretations from the digital methods are primarily dependent on the architectural characteristics and surface expression of facies described in Table 1. In the model, thick sandstone is distinguished from finer-grained units by outcrop colour (i.e., light-coloured tan or grey sandstone) and is typically more resistant to weathering than recessive, and often vegetated, fine-grained lithologies. In some instances, a dark and mottled appearance of the outcrop is associated with mass-transport deposits (F4). As interpreted from traditional outcrop field data, the base of the prominent recessive interval that separates the two sandstone-dominated packages is interpreted as the bounding surface between two channel complexes and is traceable throughout the study area. Likewise, sedimentary bodies (5–20 m thick) within channel complexes are distinguished by sharp changes in lithology at their base, with a thin recessive layer overlain by sandstone-dominated deposits. These bodies are interpreted as channel elements and are numbered chronologically in Figure 6B.

**FIGURE 8** Example of stratigraphic surfaces within channel elements that are difficult to detect in amalgamated sandstone, but easily recognised in UAV datasets. (A) Contextual overview (see Figure 6B for broader context). Blue box specifies location in (B) and (C). (B) UAV image of inaccessible amalgamated sandstone. (C) Line drawing trace of photograph in (B) highlighting base of overlying channel element (blue) and discontinuous internal element surfaces (black).
Internal surfaces within channel elements document a more composite history of channel development, as described by previous strike-oriented investigations (Hubbard et al., 2014, 2020). Although some of these surfaces terminate or become undetectable over distances of tens of metres down-dip, particularly in amalgamated sandstone (Figure 8), some reveal lenticular wedges of sediment that were not interpreted from initial field observations. These intra-channel-element wedges could be the deposits or erosional remnants of bedform or barform features within submarine channels, as recently described in modern and shallow subsurface studies (Conway et al., 2012; Heijnen et al., 2020; Heiniö & Davies, 2007; Nakajima et al., 2009; Paull et al., 2011).

Although the lenticular wedges are largely characterised by apparently structureless sandstone (F1), in several instances the DOM reveals a series of inclined bedding surfaces (Figure 9). Field calibration reveals these lenticular beds dip shallowly upslope, forming backsets tens of metres long. The scale and architecture of these beds is comparable to the depositional products of upslope-migrating bedforms documented from both the modern sea floor and the stratigraphic record (Englert et al., 2020; Hage et al., 2018; West et al., 2019). These bedforms are commonly interpreted as cyclic bedforms.

**FIGURE 9**  Example of internal surfaces revealing nuanced detail of a sequence of low-angle inclined surfaces. (A) Oblique view of UAV-SfM DOM. (B) Line drawing trace of image in (A) highlighting the underlying channel complex boundary (red), overlying channel element boundary (blue), and internal element surfaces (black). Low-angle inclined surfaces that dip in the upslope direction bound lenticular wedge-shaped bodies, forming a backset stacking pattern. These features are similar in scale and geometry to upslope-migrating bedform deposits (Englert et al., 2020), however, they were overlooked when mapping the outcrop using conventional field-based approaches. (C) Field logs collected following digital DOM analysis to lithologically calibrate digital interpretations of stratigraphic architecture.
steps or antidunes, in which lee-slope erosion and stoss-slope deposition result in upslope bedform migration that produces backstepping beds over time (Englert et al., 2020; Sloatman & Cartigny, 2020; Vendettuoli et al., 2019).

5 | DISCUSSION

5.1 | Comparison of results from field and digital approaches

Stratigraphic surfaces interpreted using both field and digital methods (Figure 6A,B, respectively) produced similar results in broad-scale architecture, but notable differences at finer scales. Both methods identified two channel complexes composed of three distinct channel elements bound by a well-defined, relatively thin, interval of recessive material (F2, F3 or F4). In general, digital methods resulted in interpretation of more-undulous surfaces, which can be expected with more observation points and reduced interpolation. The bounding surfaces of channel elements and the channel complex (base of channel element 4) have similar general form between the two methods with two exceptions. First, there is a sharp change in relief (>5 m) associated with an MTD that was recognised at the northern end of the DOM (200 m mark in Figure 6B) truncating channel element 3, which was not depicted in interpretations based on conventional methods. Second, the basal surface of channel element 4 was originally interpreted to truncate to the base of channel element 2 (1,500 m mark in Figure 6A), whereas the digital interpretations demonstrate remnants of channel element 2 sandstone are preserved (Figure 6B).

Differences between interpretations of element-scale channel-form surfaces from conventional (field-based) and digital (UAV-SfM DOM) techniques may be explained by shortcomings in either method. For example, differences may result from the inability to correlate an unexposed contact laterally in the field or the inability to obtain ground data in digital methods. Geometric differences can also be explained by similar challenges; field-based interpretations were commonly based on interpolation between scarcely distributed points, resulting in generally smoother surfaces, while digital observations were often laterally continuous following exposed geometries. In both approaches, interpreted surfaces were strongly influenced by outcrop exposure quality and continuity in addition to stratal geometry. Regardless, differences in overall delineation of channel elements were negligible and produced similar interpretations of channel element stacking patterns.

Internal surfaces within channel elements and the discontinuous bodies they define were less similar between the two methods. The DOM observations produced interconnected internal surfaces that were characterised into 75 unique sandstone bodies (Figure 6B), while the original interpretations distinguished 24 bodies (Figure 6A) in the study area. Fewer discrete bodies can be attributed to inaccessible (e.g., steep cliffs), apparently structureless sandstone that could not be directly observed or captured in the field. It is important to note that many of the surfaces that define intra-channel element sedimentary units were not confidently characterised using digital methods due to poor contextual exposure or lack of validating field data where surfaces were indistinct with more subtle variations in colour or weathering on the DOM (e.g., Figure 8).

5.2 | Implications of new digital observations

Surfaces internal to channel elements identified using digital methods resulted in the recognition of numerous subtle sedimentary geometries that were not documented by conventional field-based techniques. These surfaces are the products of numerous flows, which deposited, eroded and reworked sediments throughout channel evolution (Hubbard et al., 2020). Complementary observations have been noted in numerous outcrop studies of submarine channel fills but are challenging to document and have not been characterised extensively down-dip. For example, Hubbard et al. (2014) and Li et al. (2016) presented the poly-phase history of slope channels in predominantly 2D strike-oriented perspectives, emphasising that submarine channels evolve through innumerable cut-and-fill events.

The observations made along dip in this study complement these findings, enabling a more continuous, and perhaps complete, perspective of internal surface geometry that could provide key criteria in the interpretation of formative channel maintenance processes (i.e., erosion, bypass, deposition). Additionally, the prevalence of features attributed to upslope bedform migration and supercritical-flow conditions were locally identified, complementing recent studies that have documented similar features in 3D over much shorter dip-oriented outcrop profiles in a variety of deep-water depositional settings (Cornard & Pickering, 2019; Hage et al., 2018; Lang et al., 2017; Ono & Pink-Björklund, 2018; Postma et al., 2020).

The prevalence of upslope-migrating bedforms on sea floor slopes from prodelta channels to submarine fan lobes is now widely appreciated based on numerous high-resolution sea floor surveys from around the world (Babonneau et al., 2013; Carvajal et al., 2017; Fildani et al., 2020; Hughes Clarke, 2016; Normandeau et al., 2019; Paull et al., 2011; Smith et al., 2005; Zhong et al., 2015). Although these bedforms are commonly identified on steep slopes in locations with a distinct change in flow confinement, there is uncertainty regarding their prevalence and preservation in different
segments along submarine sediment-routing systems (Covault et al., 2017). Nonetheless, such features, including cyclic steps and antidunes, are perhaps underrepresented in descriptions of deep-water channel deposits, as comparatively fewer examples have been identified in outcrop.

Factors influencing the positive identification of upslope-migrating bedform deposits possibly include the low preservation potential of full-relief or near full-relief bedforms, a lack of recognition criteria for their deposits, and a previous under appreciation of their prevalence (Engler et al., 2020; Hage et al., 2018; Piper & Kontopoulos, 1994; Symons et al., 2016). Recent work using repeat bathymetry surveys has revealed that depositional geometries resulting from upslope bedform migration are characteristically discontinuous along slope, primarily consisting of the eroded remnants of bedform deposits (Hage et al., 2018; Vendettuoli et al., 2019). Internal channel element surfaces identified from UAV-SfM mapping in this study exhibit similar discontinuous geometries and some of these surfaces may derive from bedform migration at the Alvarez Ridge outcrop belt.

5.3 Future considerations for UAV-SfM DOM mapping

Geologic systems are complicated and require multiple sources and scales of observation to understand their evolution. Long-established geologic methods are often hindered by an ‘observational gap’ (realised or unknown), which may result in incomplete data and partial understanding. For example, fine-scale field observations (e.g., sedimentary logs) are essential for characterisation of lithology and depositional processes, but can be unsuitable for capturing spatial characteristics (i.e., architecture and geometry; Figure 10A). Such limitations can be overcome by taking photographs or LiDAR from a nearby vantage point, or by correlating several sedimentary logs to reveal larger-scale architecture. However, these approaches require an unobstructed viewpoint, or outcrops that are generally accessible and correlatable. In either case, the documented architectures and relationships may not be resolvable (from distance or through correlation) and are susceptible to overlooking important stratigraphic detail, as demonstrated in this study.

Advances in UAV-based remote sensing provide an opportunity to reveal outcrop details within this observational gap that have been difficult or impossible to capture with established techniques. Utilising UAV-SfM has demonstrated effectiveness in supplementing field data with additional perspectives (Chesley & Leier, 2018; Chesley et al., 2017; Durkin et al., 2020; Nesbit et al., 2018; Nieminski & Graham, 2017). This study further demonstrates that UAV-SfM can be used to identify previously unobserved intermediate-scale features and link fine-scale observations with quantifiable geometric and architectural measurements over wide spatial extents (Figure 10A, red dashed box). The UAV-SfM DOM in this study was essential in recognising intermediate-scale features that were not identified, or accessible, using conventional field techniques. In the case of Alvarez Ridge, the added observations significantly impacted the ultimate interpretation of channel evolutionary processes. Although this study presents a single example from deep-water channel deposits, it is conceivable, if not probable, that a UAV-SfM approach could reveal new perspectives of outcrops that characterise nearly any depositional and/or structural setting (Burnham et al., 2020).

Emerging methods, such as UAV-SfM, offer comparable advantages to LiDAR and terrestrial laser scanning methods described more than a decade ago (Bellian et al., 2005; Buckley et al., 2008, 2010), with added benefits of portability, relatively low-cost, flexible imaging vantage points and practicality for covering larger areas (Figure 10). Digital 3D datasets generated from UAV-SfM methods are ideal for multi-scale analysis of inaccessible areas allowing users to seamlessly change perspectives, view locations on individual images, and switch between views to zoom out (or ‘step back’) and zoom in to the outcrop. This enables geologists to concurrently identify and re-interpret finer features (e.g., Figure 10B through D) within the context of the broader architecture (e.g., Figure 10E through G). Although geologic calibration (i.e., ‘ground-truthing’) with conventional field-based observations should be carried out whenever possible, such best practices are not always feasible.

FIGURE 10 (A) Common data collection techniques and their typical coverages and resolutions relative to the breadth of scales considered for deep-water channel deposits in Figure 1. UAV-SfM photogrammetry (dashed red box) provides an ideal opportunity to identify intermediate-scale features, which link commonly employed large-scale (e.g., seismic) and fine-scale (e.g., core/logs). Data collection techniques represent common coverages and resolutions (noted in brackets), although these are largely dependent on sensor and collection strategy (i.e., imaging distance from outcrop; autonomous underwater vehicle [AUV] or remotely operated vehicle [ROV] distance from sea floor) and a number of exceptions exist. Data collection method, coverage and resolution depiction inspired by Piper and Normark (2001), with data from Maier et al. (2011); Wynn et al. (2014); Jones et al. (2009); Hodgetts (2013); Carrivick et al. (2016). (B–G) Multi-scale observations of features in Figure 10A from UAV-SfM DOM analysis; (B) grain (mudstone clasts); (C) laminae; (D) bed; (E) internal body/surface; (F) element (blue lines); and (G) complex (red line). (H) Complex set-scale detail identifiable in satellite imagery. Base map imagery: Google, Maxar Technologies, collected 1 March 2011, obtained 1 October 2020
Although UAV-SfM DOMs can provide spatially constrained perspectives and quantitative constraints, they require careful photogrammetric consideration (e.g., imaging geometry, processing and georeferencing strategies). Researchers often emphasise the importance of relative accuracy in lieu of absolute accuracy (and GCPs) when using SfM photogrammetry workflows, but must recognise that both are susceptible to systematic and random errors propagating
from unconstrained input data (e.g., poor imaging geometry or lack of control points). In other words, practitioners should be aware that high relative accuracy cannot be assumed in SfM datasets, as geometric errors can propagate with poor consideration of photogrammetric principles (James & Robson, 2014; Luhmann et al., 2016; Nesbit & Hugenholtz, 2019). Future research should investigate the effects of imaging, processing and georeferencing strategies on accuracy of UAV-SfM DOMs in challenging 3D geometries commonly associated with outcrop exposures (e.g., sub-vertical cliffs).

6 | CONCLUSIONS

Outcrops provide opportunities to characterise sedimentological detail within depositional systems across geologic timescales, but outcrop geometry and accessibility may not always allow for complete characterisation. Emerging remote sensing techniques, such as UAV-SfM, can supplement field-studies with additional perspectives and reveal nuanced detail that is imperceptible in the field. This case study reports on UAV-SfM mapping methods used to confirm and enhance previous field-based documentation of coarse-scale stratigraphic architecture in deep-water channel deposits by revealing subtle internal details (including the deposits from up-slope-migrating bedforms) that were largely overlooked using a conventional field-based approach. These results expose the complexity of channel-filling processes evidenced by numerous wedge-shaped sedimentary bodies internal to channel elements and demonstrate that UAV-SfM workflows can support multi-scale analyses and geological characterisations that have been elusive in some outcrop settings. These supplemental perspectives can provide new geological insight and enable a key opportunity to link morphodynamic processes with their associated deposits in the rock record. Although this is one case study, similar strategies could be used to produce comparable outcomes (i.e., reveal new perspectives and subtle geological detail) from challenging outcrop exposures in various depositional and/or structural settings.

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DATA AVAILABILITY STATEMENT

Data supporting the findings within this study are available from the corresponding author upon reasonable request.

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