Creating three-dimensional channel bodies in LiDAR-integrated outcrop characterization: A new approach for improved stratigraphic analysis

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ABSTRACT

In light detection and ranging (LiDAR)–integrated outcrop characterization, coupled utilization of LiDAR-generated virtual outcrop models and the ArcGIS platform has been rarely pursued. As a consequence, there exists a limited appreciation of this coupled approach in stratigraphic analysis. This study presents a novel approach of three-dimensional (3-D) mapping of fluvial channel sand bodies in the Cretaceous Blackhawk Formation outcrops in Utah by exporting quantitative information from a high-resolution (~10 cm) virtual outcrop model into ArcGIS. The adjoining and near-circular character of six contiguous cliff faces in our virtual outcrop model provided both upstream and downstream data sets, allowing us to gather adequate spatial data points (x, y, and z coordinates for each point) for both basal and top bounding surfaces of individual channel sand bodies. For each sand body, these data points were manipulated in ArcGIS to generate a 3-D geobody, which is a realistic reconstruction of the stratigraphic preservation of that channel sand body in a sedimentary basin. The high resolution of our data set allowed the creation of this 3-D channel body down to individual channel-story level (single-story vs. multilateral). By creating and then populating all channel sand bodies of the entire Blackhawk Formation for our studied outcrop window, this technique generates a robust set of results that is useful for improved understanding of fluvial sand-body organization at a range of spatial scales, over both the short- (single to tens of thousands of years) and long-term (hundreds of thousands to millions of years). Our results are also important for improved reservoir and aquifer exploration and production strategy.

INTRODUCTION

Integration of light detection and ranging (LiDAR) technology into geological studies has been increasingly popular, with applications ranging from lava flow (e.g., Cashman et al., 2013) to fracture characterization (e.g., Olariu et al., 2008; Wilson et al., 2011) to sedimentologic-stratigraphic investigation (e.g., Bellian et al., 2005; Labourdette and Jones, 2007) to human habitat facilities (e.g., fault-scarp characterization beneath human civic facility; Engelkemeir and Khan, 2008). The ease of robust data collection using the LiDAR technology, in either completing field-data acquisition within a short time period or providing an alternative data resource where inaccessible terrain hinders direct field site investigation, has fueled the widespread use of LiDAR technology. This technology can generate digital elevation models or photo-draped virtual outcrop models, either of which retain a wealth of quantitative information (e.g., x, y, and z coordinate values). These LiDAR-generated quantitative data can be exported into various other software platforms for further geological analyses (e.g., Bellian et al., 2005; Enge et al., 2007).

Here, we show that LiDAR-integrated quantitative outcrop data can be manipulated in ArcGIS for complete three-dimensional (3-D) rendering of geobodies useful for improved fluvial stratigraphic analysis. Thus far, use of LiDAR data in fluvial stratigraphic analysis includes: (1) spatial variability of facies in 3-D digital outcrop models (e.g., Bellian et al., 2005), (2) facies analysis and deterministic models for flow simulation (e.g., Labourdette and Jones, 2007), and (3) channel sand-body dimensional attributes (e.g., Fabuel-Perez et al., 2009; Rittersbacher et al., 2013, 2014). The creation of 3-D channel bodies using LiDAR data at a stratigraphic scale yields a spatio-temporal model of channelized sand bodies in a sedimentary basin and contributes significantly toward fluvial stratigraphic analysis on a range of time scales from short- (single to tens of thousands of years) to long-term (hundreds of thousands to millions of years).

GEOLGY AND STUDY AREA

The studied outcrop section is from Cottonwood Creek in the Wasatch Plateau, central Utah (Fig. 1). The Wasatch Plateau is contiguous with, and crops out approximately perpendicular to, the extensively studied Book Cliffs of eastern Utah and western Colorado (e.g., Van Wagoner, 1995; Howell and Flint, 2003; Hampson, 2010). These exposed strata were deposited in the Western Interior Seaway (Fig. 1A), which formed in response to higher sea levels during a Cretaceous greenhouse period as a vast epicontinental sea stretching north-south from Alaska to northern Mexico (e.g., Hampson, 2010). The Western In-
This study deals with the Blackhawk Formation (Fig. 1B), which is an ~300-m-thick coastal-plain, fluvial succession spanning ~4 m.y. of the Late Cretaceous (e.g., Hampson et al., 2012). At the study location, the depositional environment of this formation transitions from a lower marginal-marine section (coal- and mud-prone) to overlying continental-fluvial (e.g., Rittersbacher et al., 2013, 2014; The Blackhawk Formation is underlain by the shallow-marine Star Point Formation and overlain by the continental-fluvial Castlegate Formation. The study area comprises a high-quality outcrop window consisting of a series of clean, vertical, contiguous cliff faces (n = 6) with variable depositional dip and strike orientations (Figs. 1B–1D). Notably, the outcrop window exposes the entire thickness (~300 m) of the Blackhawk Formation with an ~4 m.y. temporal range and encompasses a large spatial extent (~5 × 5 km²). With these spatial and temporal dimensions, the data set is considered large enough to evaluate fluvial sand-body architecture both for stratigraphic analysis and analogous reservoir assessment, because its strike-transect distance (~5 km; Fig. 1D) is much larger (>20 times) than the inferred channel width (~100 m), as described in Rittersbacher et al. (2014). The exposed cliff faces form a near-circular rugose pattern (Figs. 1C and 1D), with minimal structural distortion. These advantages of the outcrop window facilitated a LiDAR-integrated 3-D channel-body mapping approach.

### METHODOLOGY

A low-airborne helicopter-based LiDAR scan was conducted on six cliff faces of the near-circular outcrop patch (Figs. 1 and 2). Data were collected perpendicular to the outcrop faces to ensure minimal parallax error in capturing the preserved dimension of the sedimentologic elements exposed on the outcrop faces. The acquisition and processing of these LiDAR data and their integration with digital photographs to build a virtual (3-D) outcrop model were detailed in Rittersbacher et al. (2013).

Mapping of channel sand bodies of the Blackhawk Formation was conducted on this virtual outcrop model (Fig. 3A) by tracing their continuity from one cliff face to the next. The lack of weathered debris and nearly vegetation-free cliff faces were suitable to generate a good contrast between sandstones and mudstones across the entire length of the data set. The high resolution of this model (~10 cm) allowed us to map sand bodies down to individual channel-story level (Fig. 3B). Mapping was done through extracting points on both the basal and top bounding surfaces of all single-story sand bodies, which were laterally either isolated or coalesced (i.e., multilateral) as a part of a channel-belt development.

During 3-D mapping of sand bodies, a combination of geologic controls was applied: (1) The underlying datum surface (i.e., top of the marine Star Point Formation; Fig. 4) is well exposed (characteristic white/dirty-white color) throughout the study area, from which we obtained the altitude of individual sand bodies (i.e., the z value of the sand-body top, after adjusting for the 5°W regional structural dip) when mapping that sand body from one cliff face to the next (Figs. 3B and 4). (2) We took into account the upstream and downstream thicknesses of...
individual sand bodies when verifying the continuity of the same sand body, as thickness of a channel sand body along depositional dip (especially for a limited ~5 km distance) should remain approximately constant. (3) We also considered the stratigraphic positions of regionally extensive, well-defined coal zones (Axel-Anderson, Blind Canyon, and Bear Canyon; Fig. 4) within the data set as reference surfaces while mapping the sand bodies with correct stratigraphic positions. This mapping resulted in creation of a set of data points for each basal and top bounding surface of the channel sand bodies (Fig. 3B), where each data point has $x$, $y$, and $z$ coordinates. Each mapped surface was saved as ASCII files for each basal and top surface.

Guided by the norm that channel sand-body true width is always measured perpendicular to paleoflow direction, we performed channel sand-body width correction in the ArcMap interface. We targeted this dimensional correction to add more interpretation value to our results (e.g., Labourdette and Jones, 2007). Without sand-body width correction, dimensional analyses of channel sand bodies will likely be spurious.

Given the fact that sand bodies produced by channel migration form a sand corridor oriented along the mean flow direction instead of along the localized, variable azimuth of channel mobility, abundant paleoflow data are needed to delineate correct sand-body orientation. We collected ample paleoflow data (from dune and ripple cross-stratifications, and lateral-accretion surfaces) from the Blackhawk Formation ($n = 236$) by physically climbing cliff faces 1 and 6 (Fig. 1), where data were grouped by stratigraphic positions (lower, middle, and upper Blackhawk; Fig. 5). We calculated the vector mean of paleocurrent for the entire data set ($50^\circ$), as well as separately for the lower ($47^\circ$), middle ($57^\circ$), and upper ($45^\circ$) Blackhawk Formation (Fig. 5). As the overall vector mean...
Figure 4. Light detection and ranging (LiDAR) data showing the Star Point, Blackhawk, and Castlegate Formations, along with the three regionally extensive, well-defined coal zones.

Figure 5. Distribution of paleocurrent data for various stratigraphic levels of the Blackhawk Formation of the studied data set. Paleocurrent data were collected during field work from dune and ripple cross-stratification, and lateral-accretion surfaces.
(50°) is reasonably consistent with the individual vector mean values of the lower, middle, and upper Blackhawk Formation, we considered the overall vector mean (50°) as the representative paleocurrent value for the entire data set. Moreover, we found that this overall mean value (50°) is also broadly consistent with the regional paleoflow direction of the Blackhawk Formation (Hampson et al., 2012; Rittersbacher et al., 2013). We pursued the width correction of mapped channel sand bodies perpendicular to the paleoflow vector mean in ArcMap by reorienting them perpendicular to the paleoflow (i.e., by populating additional points perpendicular to the paleoflow; Fig. 6). This correction technique is similar to that used in other LiDAR-based studies (e.g., Jennette et al., 2004; Fabuel-Perez et al., 2009; Rittersbacher et al., 2013).

After width correction (for both the mapped basal and top surfaces of individual channel stories; Fig. 7A), we applied the “natural neighbor” interpolation method in ArcMap on the basal data points to generate the basal bounding surface of the respective sand body (Fig. 7B), and on the top data points to generate the top bounding surface of the same sand body (Fig. 7B). These two surfaces appear to be topographically consistent with the basal and top surfaces of a channel sand body, respectively (Fig. 7B). The “natural neighbor” method operates on the weighted-average algorithm, generates a subset of input samples, and assigns weights to them based on proportionate areas for interpolation (cf. Sibson, 1981). The interpolated values are always well within the range of input samples. We chose this interpolation method for its ability in rendering a realistic view of topographic surfaces sculpted by channel scouring and depositional processes.

Finally, by extruding between the top and basal bounding surfaces, a 3-D volume of each sand body (i.e., geobody) was generated, yielding a realistic stratigraphic manifestation of a preserved channel body (Fig. 7C). This “extrusion” method, when applied between two surfaces (e.g., upper and lower) in ArcGIS, generates a bounding volume for these two surfaces. The lateral dimension of this volume is constrained by an area of a polygon, the coverage of which is common within the areal extent of both the upper and lower surface. The vertical extent of the volume is determined by the vertical distance between these two surfaces. In total, 124 3-D channel bodies were populated for the entire Blackhawk Formation (Fig. 8). As the length of the 3-D outcrop patch is only ~5 km along depositional dip, it is reasonable to assume that the channel bodies are linear and have uniform width across our outcrop data set along depositional dip (Fig. 6A). These assumptions are based on longitudinal characterization of fluvial sand bodies in literature (e.g., Holbrook et al., 2006) and are supported by the appearance of channel belt extent of the Gilbert-Einasleigh River in a coastal-plain landscape in Australia, which is likely a modern analog for the Blackhawk Formation (cf. Rittersbacher et al., 2013).

### APPLICATION AND DISCUSSION

By applying a novel approach to the study of the fluvial channel sand bodies of the Blackhawk Formation, we generated 3-D geobodies for the entire formation that are realistic, stratigraphic manifestations of these sand bodies (Fig. 8). This full 3-D representation of fluvial channel bodies in the outcrop has significant potential for improved understanding of various fluvial aspects in alluvial basins in a range of spatial and temporal scales, as described next.
A Mapped channel-story base (pink line) and top (blue line).

B Generating basal and top bounding surfaces of the channel sand body in ArcGIS after sand-body width-correction (Fig. 6).

C Generating a 3D geobody of the channel sand body by extruding between top and basal bounding surfaces in ArcGIS.

Figure 7. Light detection and ranging (LiDAR) data integrated with ArcGIS platform to generate a three-dimensional (3-D) geobody for each individual channel-story sand body.

Figure 8. Three-dimensional (3-D) perspective view of all channel bodies of the entire Blackhawk Formation. Single-story sand bodies are presented in different colors. Background black color represents floodplain deposits. V.E.—vertical exaggeration.
Figure 9. Outcrop and light detection and ranging (LiDAR) expressions of fluvial sand-body organizations as well as their three-dimensional (3-D) rendering achieved through coupled LiDAR and ArcGIS analysis. The background black color in each 3-D geobody-bearing image represents floodplain deposits. (A) Single-story sand body encased within floodplain fines; (left) outcrop data, (right) 3-D geobody creation approach. (B) Multilateral sand body (i.e., coalescence of single-story sand bodies at the same stratigraphic level); (left) LiDAR data, (right) 3-D geobody creation approach. (C) Localized channel incision producing higher relief for that associated sand body compared to its surrounding sand bodies, which show regular channel erosion; (top) LiDAR data, (bottom) 3-D geobody creation approach. (D) Stratigraphic ordering of channel bodies, from older (1) to younger (13). This contributes to improved sand-body organization analysis in both time and space linked to avulsion dynamics.
Channel Sand-Body Mapping Down to Story Level

At the fundamental level, channel dynamics undergo a series of erosional-depositional cycles, including scouring of the floodplain and filling of the channel with bars. The end product is the development of a channel sand body in the stratigraphic record. The degrees of erosion and deposition that occur during the life cycle of a channel vary spatially and can be extracted from the stratigraphic record of preserved sand bodies. By meticulously reconstructing both the basal and top bounding surfaces of a single channel unit, we were able to portray sand bodies down to individual story level (Fig. 9A). Furthermore, our LiDAR data have sufficient resolution (~10 cm) to capture successive erosional-depositional cycles that occurred during the course of channel-belt (i.e., multilateral sand-body) development (Fig. 9B). Multiple basal erosional surfaces, characterized as internal truncations within a multilateral sand body, are demonstrative of successive “wing-cannibalization” that occurs when erosion modifies single-story sand bodies during channel-belt development at the same stratigraphic level (Fig. 9B). Our detailed mapping significantly revealed that the channel sand-body stacking pattern is linked with story-level history: Single-story sand bodies tend to develop vertical stacking, whereas multilateral sand bodies are prone to generate compensational stacking.

Channel Erosion versus Incision

In fluvial sedimentology, we commonly attribute channel erosional behavior to two types: (1) regular channel erosion, which produces scouring depths equivalent to the normalized thickness of the resultant channel sand body, and (2) channel incision, which renders the relief of the resultant sand body abnormally higher than its normalized thickness, commonly associated with extrinsic modulation (e.g., formation of incised valley). Our study results illustrate that the majority of sand bodies show regular (i.e., unincised) channel erosion. However, a few localized channel incisions exist, the reliefs of which are an order of magnitude greater than the erosional reliefs of the surrounding channels (Fig. 9C). Unlike incised valleys, these incised channels are largely single-story, and their erosional bases are not traceable laterally as sequence boundaries; hence, they are intriguing and worth exploring further.

Large-Scale 3-D Stratigraphic Architecture of Channel Sand Bodies

The population of all \( n = 124 \) 3-D channel bodies provides a high-resolution stratigraphic manifestation encompassing a large spatial scale (~300 m thickness, 5 × 5 km² area), and a long temporal scale (~4 m.y.) organization of sand bodies in an alluvial basin. This complete 3-D rendering of individual channel bodies cannot be constrained from conventional outcrop data, vertical-bearing data (e.g., core and well-log data), and/or two-dimensional (2-D) or 3-D seismic data (even high-resolution 3-D seismic data cannot resolve channel-story anatomy).

With a full 3-D mapping of all \( n = 124 \) channel bodies of the Blackhawk Formation, we were able to determine their complete stratigraphic ordering (Fig. 9D). This enables us to explore further, for example, the avulsion frequency of fluvial channels in the rock record, which is currently ongoing. The 3-D stratigraphic organization of fluvial channel bodies can bring a new dimension in fluvial avulsion analysis, particularly for selecting, validating, and/or modifying current avulsion models (e.g., Hajek and Wolinsky, 2012).

Application in Petroleum Industry

Our study interval (~300 m thick, 5 × 5 km² spatial scale) is commensurate with a reservoir-scale volume. Thus, a range of sand-body organizations at various spatio-temporal scales (e.g., clustering with or without amalgamation, compensational stacking), as revealed by our results, brings the analogy of reservoir complexity that can be conditioned with our data. Moreover, volumetric calculation of our 3-D channel bodies can aid in quantifying sand-body proportion during analogous, 3-D characterization of a reservoir body (e.g., Pranter et al., 2013).

At this reservoir scale, study results can guide in optimizing production well layout. For example, 3-D channel bodies when connected laterally and/or vertically demonstrate a degree of static connectivity (proportion of connected sand bodies; sensu Larue and Hovadik, 2006; Pranter and Sommer, 2011). In this regard, we are particularly investigating the importance of differentiating 2-D versus 3-D connectivity of sand bodies.

CONCLUSION

The novelty of integrating LiDAR data with the ArcGIS platform in reconstructing fluvial channel bodies in true 3-D in a large outcrop data set brings intriguing new perspectives in fluvial stratigraphic analysis. The approach undertaken in this study produces significant results, which are not possible to generate with conventional outcrops, cores, wireline logs, and even 3-D seismic data. These results are a step toward improved understanding of high-resolution (spatio-temporal) stratigraphic organization of fluvial channel bodies in sedimentary basins, as well as of subsurface aquifer and hydrocarbon reservoir development. Our method of creating 3-D channel bodies by coupled utilization of LiDAR and ArcGIS can be used for creating other types of geobodies for improved stratigraphic analyses.

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