Interpretation of channelized architecture using three-dimensional photo real models, Pennsylvanian deep-water deposits at Big Rock Quarry, Arkansas

M.I. Olariu, C.L.V. Aiken, J.P. Bhattacharya, X. Xu

University of Texas at Austin, Department of Geological Sciences, Austin, TX, USA
University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, USA
University of Houston, 4800 Calhoun Road, Houston, TX 77004, USA
REAL EARTH MODELS, LLC, Dallas, TX, USA

ABSTRACT

Mapping geological details and interpreting three-dimensional geometries in a highly heterogeneous outcrop such as the exposure at Big Rock Quarry has been a continuous challenge especially because high vertical cliffs make access to most of the rocks difficult for direct geological observations. Previous interpretations of facies architecture were derived from gamma-ray files, a core and measurements made on two-dimensional photomosaics. This paper represents the first attempt of three-dimensional interpretation of the geometry and facies pattern of the Jackfork nested channel complex deposited at the base-of-slope.

Examination of the photo real model of the outcrop with assigned lithologies allowed extraction of accurate 3-D qualitative, as well as quantitative (channel dimensions) geometric information. This facilitated interpretation and reconstruction of the submarine channel complex architecture making possible correlations of strata exposed on the two sides of the quarry.

Most of the exposed vertically and laterally stacked channels are large, aggradational with well-defined axial regions overlain by matrix-supported breccia which grades upward into amalgamated sandstones. The thickness of the sandstone decreases toward the southeastern end of the quarry where more shale is present. The channel fill consists of thin-bedded sandstones interlayered with shale which overlie the breccia. The upper part of the quarry is made up of smaller, lateral migrating channels.

Significant channel width and thickness variation can be recognized at outcrop scale. Thirty-eight identified channels are characterized by a relatively low aspect ratio (4:1 to 32:1) with channel dimensions ranging from 25 m to 314 m wide and 2 m to 24 m deep. Bed thickness distributions of various facies show that the sandstone comprises a significant proportion (83%) of the total channel thickness, while shale and breccia represent about 8%, and 17% respectively. This yields a high net-to-gross ratio of more than 80%.

Compared to previous reconstructions our 3-D photo real model is more accurate and it can be used to calibrate simulation of processes in deep-water environments.

1. Introduction

Understanding the depositional processes and lateral geometry of deep-water base of the slope systems is important for predicting the extent and internal architecture of these reservoirs (Bouma et al., 1995; Slatt et al., 2000). Adequate documentation of reservoir properties and flow behavior at reservoir scale requires information about heterogeneity at a sub meter scale in three dimensions. However, it is difficult to include realistic distributions of shale and sandstone bodies in reservoir models because of the wide spacing of wells and limited vertical resolution of seismic surveys. One solution is to characterize shale-sandstone distribution using data from large, continuous three-dimensional outcrops (Coleman et al., 2000; Slatt, 2000). Accurate mapping of the architecture of these reservoirs requires interpretation of erosional and depositional geometries preserved in outcrops.

© 2011 Elsevier Ltd. All rights reserved.

0264-8172/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpetgeo.2010.12.007
Channelized facies of the Mississippian Jackforksandstone exposed at Big Rock Quarry in Arkansas have long been controversial. Originally thought to be fluvial (Taff, 1902) it is now widely agreed to be submarine, although there is still debate about what kind of processes generated it (debris flows, slumps, high vs. low-density turbidity flows) and what submarine settings they should be assigned to (upper canyon slope vs. base-of-slope). Also the geometry of these deposits was difficult to interpret due to high variability of bed thicknesses and lateral discontinuities in three dimensions.

Previous facies interpretation was derived from gamma-ray profiles (Jordan et al., 1993), a core drilled about 15 m behind the outcrop face (Link and Stone, 1986) and from direct geological observations where the outcrop was easily accessible. Measurements on large photographic prints (Cook, 1993; Bouma and Cook, 1994) facilitated statistical characterization of width and thickness dimensions, as well as reconstruction of facies architecture. The three gamma profiles taken at this site illustrated potential problems in well log correlations of laterally discontinuous strata. When comparing information from well logs and cores it was obvious that some of the thinner beds could not be identified on the gamma-ray profiles since they are below the resolution of the logging tools. Cores provide the necessary resolution for distinguishing these features, but unfortunately there is only one core taken at this site. Also two-dimensional photomosaic interpretations are not effective tools in correlation of strata with a complicated three-dimensional geometry.

Understanding of turbiditic systems has improved with the use of high-resolution shallow 2-D and 3-D seismic data, but the detailed internal architecture of these reservoirs below seismic resolution remains uncertain. Seismic modeling of Big Rock Quarry outcrop indicated that internal sand-body architecture and geometry may not be clearly imageable with conventional seismic profiling (Coleman et al., 2000) mostly due to the cemented nature of the sediments, providing little or no acoustic impedance contrast between sedimentary intervals. These rocks have been subjected to low grade metamorphism (close to green schist) which is responsible for their increased brittleness and cemented nature.

Big Rock Quarry has a horseshoe shape which makes it a good candidate for three-dimensional imaging and interpretation. Facies architecture and dimensions of channel sandstones are highly anisotropic (width/length/depth). As a consequence it is critical to know how outcrops are oriented within depositional strike/dip to make meaningful quantitative analysis of sand-body dimensions. Conventional outcrop analogs are hampered by the 2-D nature of data sets and the inability to overcome or moreover to take advantage of parallax. Compared to previous two-dimensional outcrop photomosaics, the three-dimensional photo real model adds more valuable information for outcrop interpretation (Bhattacharya et al., 2002; Aiken et al., 2004). Photo real models of outcrops are created using a combination of high-resolution terrestrial laser scanners, real-time kinematic global positioning system and digital photos to capture the 3-D topography and spatial geometry of an outcrop in a digital format.

In this study we use innovative 3-D methods to generate accurate dimensional data that represent true dip/strike orientation. These dimensions are compared to those derived from more traditional 2-D methods that have been used to build reservoir analog data bases. The study of bed thickness distributions of various facies can help to identify important reservoir facies within the fill of stacked channels at the base-of-slope where massive, thick sandstone is interbedded with thinner shales.

2. Geologic setting

2.1. Previous interpretations

Big Rock Quarry is located in the southeastern part of the Ouachita Mountains along the north bank of the Arkansas River in North Little Rock, Arkansas (Fig. 1). The cliff faces of the quarry expose a three-dimensional view of the lower part of the upper Jackfork Group (Jordan et al., 1993). The exposure has a horseshoe shape and its total length is about 1250 m with the quarry walls being about 200 m apart. The main face of the quarry has a length of 808 m with a projected length along the y-axis (North–South direction) of 732 m.

In the study area the Jackfork Group is divided into the lower Jackfork (Brushy Knob Fm.) and upper Jackfork (Brushy Knob Fm.). The Jackfork Group was dated as Mississippian (Morrown) (Fig. 2) and it represents the low stand systems tract, associated with a major unconformity on the shelf (Coleman, 2000).
The strata that crop out at this quarry were interpreted as submarine fan channel deposits (Stone and McFarland, 1981), stacked channelized packages of an inner (upper) fan valley (Moiola and Shanmugam, 1983), channel fill and levee deposits in a submarine canyon or upper part of a submarine fan channel system (Link and Stone, 1986; Link and Roberts, 1986) and slope canyon fill generated by retrogressive slope failure (Jordan et al., 1993; Slatt et al., 1997a; b).

Based on these interpretations the channel complex at Big Rock would have been formed on the upper canyon slope. However, Bouma and Cook (1994) and Bouma et al. (1995) considered these rocks as part of a submarine channel complex likely deposited at the base-of-slope based on the limited development of levees and overflow deposits and on the stacked pattern of the channels. Coleman et al. (2000) estimated that this channel complex is at least 9.6 km wide and 16–24 km long and it appears to pinch out about 4 km north of the quarry. Most of the channels have flow indicators oriented west–southwest.

Shanmugam and Moiola (1997) suggested that the Jackfork sandstone was not deposited by high-density turbidity currents and is predominantly of sandy debris flow origin because traction-generated sedimentary structures are not present and the clay matrix content in sandstone is high (5–10%). However this view received much critique (Slatt et al., 1997a; b; Lowe, 1997; Coleman, 1997; Bouma et al., 1997; D’Agostino and Jordan, 1997). The base of the slope is a zone where the gradient of the slope decreases forcing the gravity flows to start deposition. The major fill of the base-of-slope channels consists of somewhat clayey sandstone layers because the high-density currents that transported this fill may have not been able to move their very fine-grained material in suspension toward their upper part and tail and therefore some of the clay remained in the sandstone (Bouma, 2000).

2.2. Architecture of the Jackfork channel complex at Big Rock Quarry

The channel complex at Big Rock Quarry consists mostly of laterally and vertically stacked channels and some remnants of channel levees. Massive sandstones comprise a significant proportion of total channel fill and their overall thickness decreases in an easterly direction where more shale is present. This and the fact that the basal upper Jackfork sandstone is thicker at Big Rock than in exposures in the northwest and southeast suggest proximity to the axis of the sandy submarine canyon fill (Jordan et al., 1993) (Fig. 3A).

Jackfork channel complex consists mostly of erosive-based channels that stack up in a nested pattern (Fig. 3B). Because of frequent erosion part of the underlying sandstones and mud drapes are removed as well as levees adjacent to previously formed channels. The aggradational channels have well defined axial regions. Mud clasts, dispersed in a clay matrix, are common in the channel axis. In places, the basal erosional surface is directly overlain by highly amalgamated sandstone beds. In the central part of the exposure, the large aggradational channels are typically filled with amalgamated thick to very thick, fine-grained and massive sandstones interpreted to be deposited from high-concentration turbidity currents (Fig. 4A). The channels display a massive fill with tabular geometry. Toward the southeastern end of the quarry the mud-clast breccias overlie the erosive surface and grade upward into thin-bedded, fine-grained sandstones interlayered with shale which sometime are overlain by massive-to-planar stratified sandstones interpreted to be deposited from high-density flows (Fig. 4B). These channels display a layered fill with convergent geometry. Smaller channels dominate the upper part of the quarry; some of them display lateral accretion surfaces (Fig. 4C).

Sand beds at the channel margin dip in the direction of channel migration, mostly northward. Lateral accretion packages are characterized by interbedded high-concentration turbidites deposited by suspension (massive sandstones) and mud-clast conglomerates deposited by traction as bed load (Abreu et al., 2003). The formation of the smaller, sinuous channels at the top of the aggradational channels can be explained by a reduction in the volume of the turbidity currents that preceded the overall abandonment of this part of the turbidite system (Kneller, 2003; Labouretelle, 2007; Labouretelle and Bez, 2010). Recent research (Sylvester et al., in press) suggested that this type of architecture can be created by incision, migration and aggradation of a single channel form over time. In the upper part of the quarry there are some intervals with thin-bedded sandstone interlayered with shale (or mud-clast conglomerates) which might represent remnants of laterally equivalent levees of the channels (Link and Stone, 1986; Link and Roberts, 1986). The levees are absent at the base of the channel complex.

Figure 2. Correlation chart for Mississippian and Pennsylvanian formations between deep-water Ouachita-Trough and shelfal areas to the north (from Jordan et al., 1993).
2.3. Main facies associations

The sedimentary section at Big Rock consists of four lithofacies: (1) matrix-supported breccia, (2) massive, thick bedded, fine-grained sandstone, (3) thin-bedded, fine-grained sandstone interbedded with siltstone, and (4) finely laminated shale (Link and Stone, 1986; Cook, 1993).

2.3.1. Matrix-supported breccia

This facies association consists of two main groups depending on the nature of the matrix, either shale or sand. The breccia with a sandy matrix occurs in the upper part of the outcrop. Its formation might be related to levee collapse since thin-bedded turbidites are incorporated into the sandy matrix.

The breccia with a muddy matrix is found in the basal part of the individual channel fills just above an erosional surface cutting into the underlying channel. The mud clasts are subangular and range in size from few millimeters to centimeters (Fig. 5A). The shaly-matrix breccia is interpreted to be the product of cohesive debris flow and results mostly from the incorporation of slope to pelagic mudstones eroded during transport.

2.3.2. Massive, thick-bedded, fine-grained sandstone

Channels located in the central part of the quarry which is considered to be the axis of the canyon (Jordan et al., 1993) are typically filled by massive, amalgamated, thick to very thick (6–16 m) tabular to irregular-bedded, fine-grained sandstones deposited from high-concentration turbidity currents (Fig. 5B). Very few sedimentary structures are preserved except for dish and pillar dewatering structures which indicates a turbulent flow; flute cast are rare, load structures are present (Fig. 6). These sandstones represent Bouma Ta divisions and are interpreted to be deposited from high-concentration turbidity currents. The sandstone bodies have flat upper surfaces and undulating lower contacts which are interpreted as channel scours. Massive Ta units are the most common and thickest Bouma divisions in the section. They are interpreted to reflect the fill of mixed erosive-depositional to depositional channels.

2.3.3. Thin-bedded, fine-grained sandstone interbedded with siltstone

Toward the southeastern end of the quarry the channel fill consists mostly of thin bedded, massive-to-planar stratified, fine-grained sandstones...
sandstone deposited from low-density turbidity currents separated by centimeter-scale siltstone and shale (Fig. 5C). They are interpreted to represent Bouma Tb, c, d divisions. Individual sandstone beds have sharp bases and display a lenticular geometry. Ripple cross-lamination and climbing ripples are common in sandstone.

2.3.4. Shale (mudstone)

Finely laminated shale occurs interbedded with sandstone and is more common in the southeastern part of the quarry. Horizontal pascichnial (Helminthoida) and agrichnial (Urohelminthoida, Macrocnus, Neonerites) trails of the Nereites ichnofacies can be seen on the bedding planes. These trace fossils indicate a deep-water setting. This facies is interpreted either as the pelagic background sedimentation or as shale drapes deposited during the waning stage of channel filling (Bouma Te division).

3. Methodology

3.1. Three-dimensional photo real mapping

Three-dimensional photo real mapping techniques have been recently developed (Nielsen et al., 1999; Xu et al., 1999, 2000; Thurmond et al., 2000; Xu, 2000) as effective tools for detailed outcrop studies, but their potential has not been fully exploited. This study makes effective use of the quantitative information incorporated in three-dimensional photo real outcrops and provides new tools for quantitative mapping of sedimentary facies and interpretation.

Using a combination of real-time kinematic global positioning system (Leica RTK-GPS 530), a Topcon total station and laser scanners (Riegl LMS-Z360 and Measurement Devices Ltd-MDL), the surface morphology of the outcrop is captured and can be expressed in a global reference system with centimeter accuracy.

The LMS-Z360 scanner has an accuracy of 6 mm over a distance of 200 m and can capture up to 12,000 data points per second with a resolution of 5 mm. The MDL robotic laser range finding system has a typical accuracy of 10 cm at 600 m and an acquisition rate of about 250 points per second. Coarse-scale (decimeter resolution), low density (less than 15 points per 10² m) capture of the outcrop using the MDL system was adequate for channel interpretation, but facies measurements were done on the high resolution outcrop model generated from LMS-Z360 scanner. Cyber Mapping software (Xu, 2000) allowed for real-time three-dimensional visualization and acquisition of scanner-mapped features. This software is also used to accurately drape photography onto centimeter digital terrain models generated by scanning the outcrop.

Oblique close range photography (18 outcrop pictures) acquired from the ground with a Fuji S1Pro digital camera has been integrated with the terrain data and converted into a three-dimensional digital photo real model of the outcrop (Fig. 7). Image registration is accomplished by converting the two-dimensional image coordinates into pixels which are positioned in three-dimensional world coordinate system and can be re-projected from world space into image space. Position of control points on the outcrop face was acquired with
a reflector less total station with an accuracy of 1–4 mm over a distance of 100 m.

Examination of the photo real model of the outcrop allows for stratigraphic interpretation, since key stratigraphic features such as bed continuity and bed boundaries can be highlighted on the model (Fig. 7). Channels bounding surfaces have been digitized on the 3-D photo real model of the outcrop built in Gocad™, as well.

### 3.2. Statistical analysis of channel dimensions and aspect ratios

Channel width and depth parameters can easily be obtained from outcrops with sufficient exposure, allowing aspect ratios to be calculated. In this study we use dimensional data of individual channels to estimate channel aspect ratios (width:depth) and to evaluate the potential improvements of three-dimensional over classical two-dimensional analysis methods.

Measurements of channel width and thickness were done on the 3-D photo real model of the outcrop built in Gocad™ using a parallel view, also known as an isometric view. The main use of this type of view is to avoid parallax distortions of length, area, volume and angle that are unavoidable in most 2-D photomosaics. It is very useful for comparing the dimensions of objects that are at different distances from the viewer.

As the quarry face is oriented at different angles, generally oblique to the channel axis, channel width and thickness were projected on a vertical plane perpendicular to the mean paleocurrent direction (as estimated from the outcrop) and measured accordingly. This way all widths have been corrected to widths perpendicular to paleocurrent from apparent widths measured at the outcrop. Since successive channels cut into each other removing the upper part of previously filled channels, the maximum preserved thickness of each individual channel has been considered.

### 3.3. Quantitative facies analysis

Thicknesses of each identified lithofacies have been measured inside individual channels on the 3-D photo real model of the outcrop. Since the rock layers have various geometries (lenticular, tabular, undulating bases) and consequently they do not have a constant thickness across the channel width the maximum thickness for each bed has been considered. Facies percentages of total channel thickness and net to gross ratio for each type of channel have been estimated.

### 4. Results

#### 4.1. 3-D correlations of channels

Paleoflow direction was inferred from direct measurements of longitudinal scours, ripple morphology and cross-lamination. However in most cases it was only possible to tell the direction of the flow and not its sense. Most measured paleocurrents suggest a southwest flow direction; few of them have southeast markers (Fig. 8). These results are in agreement with previous studies (Jordan et al., 1993; Stone and McFarland, 1981) and with the regional paleoflow directions in the Ouachita basin.

Since most of the paleocurrent measurements indicate that the principal direction of transport is southwest the outcrop belt displays a nearly orthogonal cut across the downcurrent direction to the north, a dip-oriented profile into the basin to the northwest.
Figure 7. Three-dimensional photo-real mapping and interpretation of the deep-water succession exposed in the outcrop at the Big Rock Quarry. A) The outcrop belt displays an oblique cut across the downcurrent direction to the southeast and a nearly dip-oriented profile to the north. B) 3-D digital terrain model generated by the laser scanning of the outcrop. C) Surface built in Gocad from terrain data D) Oblique close-in photography acquired from the ground is integrated with terrain data and converted into a 3-D digital photorealistic model of the outcrop E) Bedding diagram superimposed on the 3-D photo real model of the outcrop F) Submarine channel architecture. Bounding surfaces are digitized in Gocad directly from the 3-D photo real model (blue – debris flow; red – thin to medium sandstone interbedded with shale; yellow – fine-grained, structureless, amalgamated sandstones) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Figure 6. Sedimentary structures A) ripple cross-laminated sandstone N72E/S72 W B) groove marks on the base of sandstone bed N54E/S54 W C) cross-bedded sandstone D) climbing ripples N18E/S18 W E) ripple cross-laminated shale N18E/S18 W F) flute cast on the base of sandstone N18E/S18 W.
and an oblique depositional strike section with respect to paleoflow to the southeast (Fig. 8). Bed boundaries were easily followed on the three-dimensional photo real model of the outcrop (Fig. 9, Fig. 10). This way strata exposed in the central part of the quarry were found to appear again on the NW quarry face. In order to correlate beds from one wall to the other attention was paid to the lateral continuity/discontinuity of the strata, to the geometry of the channels and their relative position on the outcrop. Also it has been taken in consideration the fact that the quarry dips about 10° toward the northwest. The lower boundaries of the channels become steeper northward; they incline with about 3° at the southeastern end and reach 10° in the central part of the quarry.

One channel is exposed on both sides of the quarry and is oriented N67E/S67W (Fig. 11). The part of the channel on the northeastern face reveals a strike oriented view whereas the one exposed on the northwestern face is more dip oriented. A debris flow at the base of the channel is about 3 m thick and the sandstone fill is about 12 m. There is a slight difference in thickness between the two parts of the channel. It is assumed that the beds become thicker downcurrent, due to non-uniformity of the flow, reduction in confinement at the base-of-slope, and a downstream decrease in bed shear stress (Kneller, 1995; Kneller and Branney, 1995; Al Ja'Aidi et al., 2004).

4.2. Channel dimensions and aspect ratios

The mean paleocurrent orientation as determined from direct measurements at the outcrop is N34E/S34W. Therefore the orientation of the main outcrop belt (~N9W) is approximately at 47° to...
Figure 9. Three-dimensional interpretation of channelized features present on the main face of the quarry A) 3-D photo real model of the outcrop made up of 12 images - one picture is missing (y is north) B) Bedding diagram superimposed on the 3-D virtual outcrop (red—channel boundaries) C) Bedding diagram showing the stacked channel pattern. D) Facies architecture of channel complex. Different types of channels are highlighted as follow: yellow—large, aggradational channels with well defined axial regions composed of high relief basal erosional surfaces overlain by matrix-supported breccia which grades upward into amalgamated sandstones; orange—small, laterally migrating channels; red—aggradational channels made out of thin-bedded sandstones interbedded with shale which overlain the basal breccias and skin color—remnants of laterally equivalent levees of channels (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Figure 10. Three-dimensional interpretation of channelized features present on the central and northwest face of the quarry close to the river A) 3-D photo real model of the outcrop made up of 6 images - one picture is missing (y is north) B) Bedding diagram superimposed on the 3-D virtual outcrop (red—channel boundaries, yellow—channel fill) C) Bedding diagram showing the stacked channel pattern. D) Facies architecture of channel complex. Large, aggradational channels are highlighted in yellow — they have well defined axial regions composed of high relief basal erosional surfaces overlain by matrix-supported breccia which grades upward into amalgamated sandstones (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
the transport direction of the turbidite which means that the estimated widths from the main face of the quarry on the 3-D photo real model are overestimated compared to the widths derived from the projected, transverse cross-section. The digitized channel boundaries from the photo real model were projected on a plane oriented N56W/S56E to correspond to the estimated cross-section of the channels and the width measured accordingly. This way all widths have been corrected to widths perpendicular to paleocurrent from apparent widths measured at the outcrop. The other face of the outcrop close to the river is oriented N18E/S18W, almost parallel to the mean paleoflow.

Significant channel width/thickness variation can be recognized at outcrop scale (Fig. 12). Minimum channel thickness observed at the outcrop is 2.1 m and the maximum is 23.7 m with a mean of 8.3 m. The larger, sandstone-rich, aggradational channels at the base of the quarry have widths of about 145 m and thickness of about 10 m. They can reach widths of 300 m, but when corrected they have a maximum width of about 200 m (33% less). Laterally migrating channels within the upper part of the quarry are smaller with thicknesses between 2 m and 6.3 m (mean ~4.3 m) and widths of at least 25 m with an average of 59 m. When corrected with respect to the mean paleocurrent direction they are at least 16 m in width and reach a maximum of 75 m with an average width of 40 m.

Estimated cross-channel width of the channel-shaped unit (perpendicular to the main paleocurrent direction, N34E) and maximum measured thickness of individual channels were plotted on a log–log graph (Fig. 13) and the aspect ratios calculated for each channel. Channel width commonly is one order of magnitude higher than channel depth. Channel bodies have rather flat channel fills (width/thickness ratio 3:1 to 32:1) with a mean aspect ratio of 15:1.

Aggradational channels have a minimum apparent ratio of 4:1, a maximum of 32:1 and a mean value of 16:1. Sinuous channels have a minimum apparent ratio of 9:1, a maximum of 17:1 and a mean value of 14:1. When measured across the estimated cross-channel section all the ratios have lower values compared to those measured from the outcrop. Aggradational channels have a minimum width to thickness ratio of 3:1, a maximum of 20:1 and an average value of 11:1. Sinuous channels have a minimum ratio of 7:1, a maximum of 12:1 and a mean value of 9:1 (Table 1).

4.3. Quantitative facies analysis

Facies thickness and percentages of total channel thickness, as well as net to gross ratios have been estimated for each channel. The sandstone comprises a significant proportion (in average 83.28%) of the total channel thicknesses (Fig. 14), while shale and debris flow deposits make about 17.24% with a range from 3.66% to 59.2% (minimum net/gross = 40.8%).

If only the large, aggradational channels that make up the lower two thirds of the quarry are considered the sandstone will make up at least 41% of the total channel thickness with an average of 83%. Shale and debris flow deposits represent about 18% of the channel thickness.
The smaller channels at the top of the quarry are comprised of about 85% sandstone (range from 68% to 94%). The lateral accretion packages have not been considered, only thickness in the axis of the channel has been measured. Shale and debris flow make up about 16% of the total channel thickness with a range from 6% to 32%. When occurring in amalgamated units the sandstones have a mean thickness of about 60 cm covering a range from 13 cm to 5 m (Fig. 15A). The thickness of the amalgamated units reaches in average 4 m with a maximum thickness of 16 m. Thin-bedded sandstone layers have an average of 34 cm being at least 9 cm thick up to 2 m (Fig. 15B). Shale intraclast breccia has an average thickness of about 1 m (Fig. 15C). Sub-meter thickness usually occurs in the lateral accretion packages of the sinuous channels or in some of the preserved levees while thicker beds occur at the base of aggradational channels. Thin layers of shale have an average thickness of 8 cm covering a range from 2 cm to 30 cm (Fig. 15D).

5. Discussions

5.1. Uncertainty of 2-D vs. 3-D measurements

Significant variations exist among channel dimensions (width and thickness) and aspect ratios in turbidite systems as they are measured from modern and ancient records especially because of the difference in scale. Our data (channel width and thickness) when compared to data published by Clark and Pickering (1996) falls in the lower aspect ratio area of the data scatter (Fig. 13). Their data comes from modern, ancient and subsurface data sets with channels, canyons and channel-shaped elements of deep-water depositional systems plotted together which explains the wide range covered by the data.

Jackfork stacked channel sequences deposited at the base-of-slope have low aspect ratios (4:1 to 32:1). When compared with outcrop data from similar deep-water settings such as the outcrop example, from Fan#3 Tanqua Karoo basin, in South Africa (Bouma et al., 1995), Mt. Messenger Formation, in New Zealand (Browne and Slatt, 2002), Zerrissene Formation, in Namibia and Marnoso Arenaceae Formation, in Italy (Cossey, 1994) our results show similar values for the width/thickness ratio. The channel complex at Tanqua Karoo is characterized by high sandstone/shale ratio and rather flat channel fills (aspect ratios from 30:1 to 50:1). Mt. Messenger channels have aspect ratios that average 23:1 (range from 13:1 to 47:1). The Zerrisene turbidite of Namibia and Marnoso Arenacea of Italy have width to thickness ratios of 19:1 and between 10:1 and 30:1 respectively. Jackfork channels at Big Rock Quarry have somewhat smaller aspect ratios which might be explained by the different methods used to measure the channel dimensions (3-D vs. 2-D measurements). Outcrop data from Magallanes Basin, Chile indicates a mean width for slope channels of 307 m and mean thickness of 13 m (McHargue et al., 2010).

<table>
<thead>
<tr>
<th>Channel type</th>
<th>Width (m)</th>
<th>Apparent width (m)</th>
<th>Thickness (m)</th>
<th>Ratio (w:t)</th>
<th>Apparent ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laterally migrating</td>
<td>16.27–75.15</td>
<td>25.33–102.74</td>
<td>2–6.3</td>
<td>7:1–12:1</td>
<td>9:1–17:1</td>
</tr>
<tr>
<td></td>
<td>40.39</td>
<td>58.63</td>
<td>4.3</td>
<td>9:1</td>
<td>14:1</td>
</tr>
<tr>
<td></td>
<td>102.07</td>
<td>144.86</td>
<td>9.71</td>
<td>11:1</td>
<td>16:1</td>
</tr>
</tbody>
</table>

Table 1
Channel dimensions and aspects ratios.
Bouma and Cook, 1994 estimated from 2-D photomosaics a total length of the main face of the quarry projected along North-South direction of 838.2 m (2750 feet) which is overestimated by 100 m (13.5%).

Since the maximum channel width measured on the digital outcrop is 314 m (mean width 122 m) the layers that make up the channel infill should have at a maximum this length. Therefore at least some of the layers measured by Bouma and Cook (1994) are overestimated since their maximum measured length for sand is 448 m, 347 m for thin beds and 381 m for muds, which is well over 300 m. Based on these values 2-D outcrop data overestimated the extent of sand layers by 43%, thin beds by 10.5%, and mud by 21%. It is mentioned in their paper that the actual layer length is not the distance between both ends of one layer, but the distance along the y-axis of the projected length. Since the projected length is shorter than the actual length of the outcrop the length of the layers in outcrop would have been even bigger. Also their layer thicknesses have higher mean values when compared with ours. Their amalgamated sandstones have mean thickness values of about 1.77 m while ours have in average 64 cm; their thin beds have mean values of 4.3 m, ours only 34 cm; they found that debris flow deposits are about 1.52 m thick while we found mean values of 72 cm; and finally their shale is 1.27 m thick while the shale we measured is about 8 cm thick. We assume that this depends on the resolution and various scales and different angles of view of the pictures used in the photomosaic. For each of the four identified lithologies they have at least 4 times more layers. This may happen because they measure vertical sections equally spaced (about 30 m) along the outcrop which means that some of the layers are considered twice or more in the calculations.

Figure 14. Facies percentages of total channel thickness. The four identified lithofacies are color coded and plotted as percentages of total channel thickness. The small laterally migrating channels located at the top of the quarry are circled, (for position of channels on the quarry walls look at Figures 9 and 10). Sandstone comprises a high proportion (more than 80%) of the channel fill.

Bouma and Cook, 1994 estimated from 2-D photomosaics a total length of the main face of the quarry projected along North-South direction of 838.2 m (2750 feet) which is overestimated by 100 m (13.5%).

Since the maximum channel width measured on the digital outcrop is 314 m (mean width 122 m) the layers that make up the channel infill should have at a maximum this length. Therefore at least some of the layers measured by Bouma and Cook (1994) are overestimated since their maximum measured length for sand is 448 m, 347 m for thin beds and 381 m for muds, which is well over 300 m. Based on these values 2-D outcrop data overestimated the extent of sand layers by 43%, thin beds by 10.5%, and mud by 21%. It is mentioned in their paper that the actual layer length is not the distance between both ends of one layer, but the distance along the y-axis of the projected length. Since the projected length is shorter than the actual length of the outcrop the length of the layers in outcrop would have been even bigger. Also their layer thicknesses have higher mean values when compared with ours. Their amalgamated sandstones have mean thickness values of about 1.77 m while ours have in average 64 cm; their thin beds have mean values of 4.3 m, ours only 34 cm; they found that debris flow deposits are about 1.52 m thick while we found mean values of 72 cm; and finally their shale is 1.27 m thick while the shale we measured is about 8 cm thick. We assume that this depends on the resolution and various scales and different angles of view of the pictures used in the photomosaic. For each of the four identified lithologies they have at least 4 times more layers. This may happen because they measure vertical sections equally spaced (about 30 m) along the outcrop which means that some of the layers are considered twice or more in the calculations.

Figure 14. Facies percentages of total channel thickness. The four identified lithofacies are color coded and plotted as percentages of total channel thickness. The small laterally migrating channels located at the top of the quarry are circled, (for position of channels on the quarry walls look at Figures 9 and 10). Sandstone comprises a high proportion (more than 80%) of the channel fill.

**Figure 15.** Histogram frequency and statistics of bed dimensions. Facies thickness measurements have been obtained from channels identified on the 3-D photo real model. A) amalgamated sandstone. B) thin beds. C) debris flow deposits. D) shale layers.
6. Conclusions

The primary purpose of studying this outcrop was to determine its viability as an analog input for deep-water hydrocarbon reservoir models. The geometry and facies pattern of nested channel complex at the base-of-slope may provide models of heterogeneity distribution. This paper described the geometry and the internal architecture of the channels within the channel complex of the Jackfork Group.

This study represents the first attempt of three-dimensional interpretation of the deposits exposed at Big Rock based on correlation of channels from both sides of the quarry, a difficult exercise without a three-dimensional data set. Despite limited exposure relative to channel dimensions, the photo real model provides quantitative and spatial data suitable for three-dimensional facies architecture studies.

Reconstruction of body geometry was accurate in areas where lithologies were highly distinct and where surfaces/bodies could be correlated on the two sides of the quarry. Channel bounding surfaces were mapped on the three-dimensional photo real model, as well as the internal architecture of the channel fill. Channel dimensions and morphology, stacking pattern, limited development of levees and overbank wedges and a high sandstone/shale ratio (5:1) suggest deposition at the base-of-slope.

Our analysis shows that the widths of the channels as they are measured in outcrop are overestimated by 30% compared to the widths measured perpendicular to the paleoflow direction. Most of the channels have low aspect ratio (width: thickness = 15:1) and high net to gross (more than 80%). Faces percentages of total channel thickness shows that the sandstone comprises a significant proportion (about 83%) of the channel fill, whereas shale and matrix-supported breccia make up only 8% and 17% respectively.

Since some of the beds measured on 2-D photo panels are wider than the actual channels as they are measured on the 3-D photo real model of the outcrop we suggest that the 2-D data set overestimates the channel width by at least 10%. High resolution 3-D outcrop data sets help in reducing uncertainty in the geologic interpretation of sparse and lower resolution well log and subsurface data.

Acknowledgements

This study benefited from a GCSEPM Ed Picou Fellowship Grant for Graduate Studies in the Earth Sciences. The authors would like to thank Charlie Stone for lively discussions and input.

References

Lowe, D.R., 1997a. Oil and Gas Journal 95 (33), 67.


