STUDY OF CRETAEOUS DELTA FRONT DEPOSITS, INTEGRATING
OUTCROP, GPR AND 3-D PHOTOREALISTIC DATA,
PANTHER TONGUE SANDSTONE, UTAH.

by
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To

My family
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The Spring Canyon / Sow Belly Gulch area in Utah contains the most proximal facies within the Panther Tongue delta represented by terminal distributary channels deposits alternating with mouth bar deposits in the delta front. Ground penetrating radar (GPR) and 3-D photorealistic techniques together with sedimentary section measurements, are used to image the 3-D facies architecture.

The terminal distributary channel facies exposed in the northern cliffs of the canyon die out over less than 100 m on the south side of Spring Canyon where heterolithic deposits representing distal mouth bar facies of the delta front are exposed.

The 3-D photorealistic technique consists of draping oblique, close-range photographic images on 3-D terrain models of outcrops to generate a digital three-dimensional model.
of the outcrop. Using these 3-D photorealistic models in GoCad™, 3-D bedding diagrams of the outcrops are built.

2-D ground penetrating radar (GPR) profiles, collected parallel with cliff faces, are tied with the 3-D outcrop model using a Global Positioning System. GPR lines are correlated with 3-D bedding diagrams to extend mapping of sedimentary features behind the outcrop.

For the first time “terminal” distributary channels and upstream accretion bars were described in ancient delta front deposits.

Three main distinctive facies differentiated in study area were “terminal” distributary channel, upstream accreting bars and distal bars. “Terminal” distributary channels and upstream accretion bars were observed on cliffs oriented perpendicular and respective parallel to the paleoflow direction.

Elongate scours representing the bases of “terminal” distributary channels, were mapped 20 m behind the cliff face. Mapping of 3-D surfaces and bodies show that “terminal” distributary and mouth bar deposits have surfaces with maximum topography of 1-2 meters.
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CHAPTER 1
INTRODUCTION

The study of outcrops remains a primary tool for understanding facies architecture and for reservoir characterization studies.

Delta deposits form major hydrocarbon reservoirs worldwide and represent more than 60% of the sandstone reservoirs in Texas alone (Tyler and Finley, 1991). In places such as Prudhoe Bay, Alaska and the Gulf of Mexico, a great percentage of oil reservoirs are in deltaic or fluvial/deltaic rocks (Tye et al., 1999; Tye and Hickey, 2001). Despite that great hydrocarbon potential, these classes of reservoirs experience significant recovery problems related to depositional heterogeneity (Tyler and Finley 1991; Ainsworth et al., 1999; Tye et al., 1999). A 3-D approach is necessary to build more realistic models of reservoirs associated with delta front deposits.

Facies architectural studies of ancient delta deposits are typically regional and large scale (Bhattacharya, 1991; Bhattacharya and Walker, 1992; Broussard, 1975; Coleman and Wright, 1975; Ori et al., 1991, Reading, 1996, Willis et al., 1999). More accurate, quantitative detailed descriptions of sand body shapes and their relationships are required in the hydrocarbon industry. Small-scale heterogeneity models are required for more effective reservoir engineering and the building of realistic 3-D fluid flow models.

The heterogeneity of deltaic reservoirs is especially complicated because of the great variety of processes operating in deltas, but quantification of this heterogeneity lags behind
the understanding of fluvial and deep-water (Bouma and Stone, 2000) depositional systems (Miall and Tyler, 1991). Studies of the 3-D facies architecture of delta deposits compared to fluvial (e.g. Miall, 1996) or deep water systems (e.g. Bouma and Stone, 2000) have been largely neglected.

This paper focuses on imaging the 3-D facies architecture of “terminal” distributary channel deposits within delta front deposits of the Cretaceous-age Panther-Tongue delta in central Utah, using digital mapping techniques and ground penetrating radar (GPR). There are no 3-D studies that document the architecture of “terminal” distributary channels, despite the abundance of these features in modern deltas (Bhattacharya et al. 2001).

“Terminal” distributary channels form at the distal end of shallow water deltas and form by multiple bifurcation of larger delta plain channels. “Terminal” distributary channels are typically shallow and narrow as the discharge of the “trunk” feeder channel is distributed among many shallow channels (Fig. 1).

Methodologies applied in this paper, GPR and 3-D photorealistic techniques together with classical sedimentary measurements, allows 3-D reconstruction of sedimentary deposits. This study demonstrates an approach that provides quantitative 3-D data, which can be used by reservoir engineers to construct more accurate 3-D volumetric fluid flow models for hydrocarbon reservoirs.

The Panther Tongue sandstones are analogous to other hydrocarbon reservoirs in delta front deposits and as a consequence the results of this study can be used for reservoir characterization in areas where only subsurface data are available.
Figure 1. Terminal distributary channels in modern delta formed by successive bifurcations, Lena delta, Arctic Sea, Russia.
CHAPTER 2
REGIONAL SETTING AND PREVIOUS WORK

Delta front deposits containing “terminal” distributary channels within the Panther Tongue sandstone are superbly exposed in central Utah along Spring Canyon (Fig. 2). Previous work (Howard, 1966b; Newman and Chan, 1991; Morris et al., 1995; Posamentier et al., 1995) show that the Panther Tongue is a river-dominated delta front. The deposits were interpreted as “terminal” distributary channel deposits in Spring Canyon / Sow Belly Gulch outcrops, (Bhattacharya et al., 2001).

The Panther Tongue Sandstone is Campanian in age and represents the lower of two sandy tongues of the Star Point Formation within the Mancos Formation shale. The thickness of the Star Point Formation varies between 7 m and 100 m (Hintze, 1988). The Star Point Formation is overlain by a “Shale Tongue” of the Upper Mancos. Sandstones of the Panther Tongue interfinger to the east (paleo-seaward) with shale of Mancos Formation (Fig. 3) (Young, 1955, Weimer, 1960).

The sedimentary succession has been interpreted as a nearshore depositional environment formed in the Western Interior Seaway (Young, 1955; Howard, 1966a). Young (1955) distinguishes a longshore bar oriented northeast-southwest. The Panther Tongue sandstone was specifically interpreted as deltaic by Howard (1966b) and Newman and Chan (1991). A detailed ichnological study of the Panther Tongue suggested environmental facies intermediate between offshore and nearshore (Frey and Howard, 1985). Morris et al. (1995)
Figure 2. Outcrop belt of Panther Tongue Sandstone and location of data collected in Spring Canyon area. (modified after Howard, 1966a).
Figure 3. Stratigraphic relations of Upper Cretaceous rocks in east-central Utah (modified after Young, 1955; Weimer, 1960).
described the Panther. Tongue deposits from Sow Belly Gulch, north of Helper, Utah, as a top truncated lowstand delta front containing channel deposits alternating with mouth bar deposits. The Panther Tongue contains two distinct types of delta deposits, distal deposits interpreted as bed-load dominated, Gilbert-type delta (Barrell, 1912), and more proximal facies interpreted as a mixed load, turbidite-dominated delta (Morris et al., 1995). The proximal facies are the focus of this study. Prodelta shales bound the sandstone channel and bar deposits (Morris et al., 1995).

Despite the regional stratigraphic studies, no detailed studies of the facies architecture of these deltas have been presented. Adding Panther Tongue deposits on a regional paleogeographic map (Fig. 4), shows that the delta lies landward relative to the published paleoshoreline position. These maps were based on the distribution of marine fauna such as *Baculites sp.* (McGookey et al., 1973), *Haploscaphytes hippocrepis* (Williams and Stelck, 1972) and *Scaphites hippocrepis* (Cobban et al., 1994). The Panther Tongue delta is inland relative to previously mapped shorelines because all authors estimate shoreline position on the basis of distribution of marine fossils. As a consequence, interpretations usually overestimate shorelines basinward, because of lack of marine fossils in more proximal, delta-front environments. Average paleoflow direction is S 271° W (Fig. 4). This value is consistent with previous measurements (Newman and Chan, 1991) but raises questions related to subparallel direction of propagation relative to paleoshoreline (Fig. 4). The southward direction of delta progradation might be controlled by N-S oriented longshore currents or might be structurally controlled.
Figure 4. Paleoflow direction and paleoshoreline during early Campanian (modified after McGookey et al., 1992; Williams and Stelck, 1973; Cobban et al., 1994)
CHAPTER 3

METHODS

3.1 Ground penetrating radar (GPR)

Ground penetrating radar is a geophysical technique in which propagation of an electro-magnetic pulse is used to study shallow deposits. Due to heterogeneity of the deposits, the magneto-electrical properties vary with depth. Reflections from variations of electrical impedance are recorded by the system. The system is not expensive, is simple to use and is suitable for fieldwork (Fig. 5). For geological purposes antennas with frequencies between 25 MHz and 500 MHz are typically used. Different frequency bandwidths have different resolutions (Fig. 6) (Davis and Annan, 1989; Smith and Jol, 1992; van Dam, 2001). Therefore, frequencies are chosen based on the goals of survey. Most studies collect data with different frequencies, but the most common 100 MHz represents a good compromise between depth of penetration and vertical resolution for fluvial / deltaic deposits (Corbeanu et al., 2001; Gawthorpe et al., 1993; McMechan et al., 1997; Smith and Jol, 1992; Szerbiak et al., 2001). The logistics of GPR acquisition and processing is similar to seismic, but with some differences. Similar to seismic, depth of penetration increases with decreasing frequency and vertical resolution decreases with decreasing frequency. In contrast to seismic data where velocity increases with depth, velocity decrease with depth in ground penetrating radar (Fisher et al., 1992b). Raw ground penetrating radar data represents a distorted
Figure 5. Block diagram of a typical GPR system (after Davis and Annan, 1989).
Figure 6. The relation between resolution and bandwidth for a 100 MHz radar in rock and wet soil (after Davis and Annan, 1989).
unfocused image of the subsurface (Fisher et al., 1992b). Because of kinematic similarities with seismic data, many commonly used seismic processing principles and steps can be applied to GPR data (Fisher et al., 1992a, 1992b; Zeng, 1998). Also, interpretation of GPR data can be made on the basis of seismic stratigraphic principles (Vail et al., 1977) using the analogous radar facies and radar stratigraphy (Jol and Smith, 1991).

Three-dimensional GPR data have been collected and studied in both modern and ancient deposits (Beres et al., 1995; Corbeanu, 2001; Corbeanu et al. 2001; McMechan et al., 1997; Szerbiak et al., 2001). These datasets were processed and interpreted with seismic software. 3-D GPR data is extremely useful for reservoir analog studies, because GPR attributes can be extrapolated throughout an entire volume and realistic 3-D fluid flow models can be built from them (Corbeanu et al., 2001; Szerbiak et al., 2001).

GPR has been mostly used on recent unconsolidated sediments (Jol and Smith, 1991; Smith and Jol, 1992; Gawthorpe et al., 1993; van Heerden and Roberts, 1998). Studies in unconsolidated sediments are more common because these are more accessible and also GPR has better results because air in the sediment pores gives a high velocity and low attenuation to the signal (van Hetern et al., 1998; Davies and Annan, 1989; Jol and Smith, 1991; Smith and Jol, 1992; Gawthorpe et al., 1993). In addition to GPR data, cores or trenches are used to tie radar reflections with sedimentary facies (Jol and Smith, 1991; van Hetern et al., 1998).

Studies of ancient deposits have been pioneered by McMechan et al. (1997), Corbeanu et al. (2001) and Szerbiak et al. (2001). In studies of ancient deposits, it is rare to find flat topped outcrops with large areas to collect GPR lines. Ancient deposits usually are capped by thick soil which attenuates the signal and limits the depth of acquisition. Outcrop
or cliff face data are used more often than cores to tie GPR data to sedimentary facies in studies on ancient deposits (Corbeanu et al., 2001; McMechan et al., 1997).

3.2. GPR Data collection and processing

We collected 450 m of 2-D GPR along four profiles (Fig. 2). The topography and soil cover of the study area restrains our capability to collect 3-D or more extensive 2-D data. A pulse EKKO IV system with 50 MHz antennas, spaced 3 m apart, and 100 MHz antennas spaced 2 m apart, both with a 1000 V transmitter was used. In this paper only the 50 MHz data will be interpreted because it has a deeper penetration, although resolution was approximately 0.5m. Common mid-point (CMP) data were collected with 50 MHz and 100 MHz antennas and were used for velocity estimation. To process the data we used an average velocity of 0.12 m/ns.

Figure 7 shows the GPR data processing steps. Each step represents an important improvement in imaging primary radar reflections. The first step, signal dewowing, eliminates the low frequency background caused by diffusion of electric current into the ground (Annan, 1999). Time zero alignment, moves the traces so that the direct arrivals occur at the same time. Trace editing, replaces noisy traces (or only a part of a trace) with values from adjacent traces. Air wave average removal is necessary to remove the direct ground and air waves (Annan, 1999). Direct ground and air waves appear because of the high contrast of electro-magnetic properties between air and ground. Topography and migration correction are made for a realistic positioning of radar reflectors in depth. Migration is extremely useful but without a good knowledge of velocity, distortions can be generated (Annan, 1999).
Raw data

Dewowing (Subtract exponential baseline)

Time zero alignment.

Trace editing.

Air wave average removal.

Topography correction and prestack migration

Figure 7. Processing steps applied to GPR data.
Historically, most published GPR studies stop with processing after time zero alignment and only a few remove have air waves or correct topography. Migration of GPR data is relatively new, (e.g. Fisher et al., 1992); for our data, migration was done using a prestack Kirchhoff algorithm (Epili and McMechan, 1996).

3.3. Photorealistic technique

Global Positional Systems (GPS) and rangefinder lasers allow more accurate collection of spatial data. There are different approaches to collect digital data to describe the geology of the outcrops. One approach is to measure geological features directly with GPS (Xu, 2000; Xu et al., 2000; Thurmond et al., 2001). Outcrops for such studies must have accessible slopes, because the methodology requires “walking out” features. Another approach is to map geological features on the outcrops remotely, using reflectorless laser guns (Nielsen et al., 1999, 2000; Xu, 2000; Xu et al., 1999, 2002). This approach can be used on steep cliff faces. It uses GPS methodology to locate laser guns with cm accuracy. Laser guns have different ranges from 100 m to 500 m, and decimeters accuracy (Xu, 2000). The pitfall of using laser guns to map geological features is the difficulty of re-interpretation. A wrong interpretation (mapping) of some geological features in the field is difficult to correct in the computer or may require additional fieldwork to collect new data.

A new and better alternative approach (which was used in this project) is to drape close-range color photographic images on a digital terrain model of the outcrop (Xu, 2000). This method allows us to build a realistic 3-D model of the outcrop with cm to dm accuracy with which the geology can then be interpreted interactively on a computer screen instead of
on a 2-D photomosaic. An advantage is the quantitative accuracy of the data and the use of real color images which can be easily interpreted.

3.4. Photorealistic data collection and processing

We collected data from more than 2 km of cliffs in Spring Canyon and Sow Belly Gulch (Fig. 2).

For data collection we used a Leica 500 RTK GPS system in differential mode, two reflectorless robotic MDL Atlanta Laser Systems (ALS) stations, a Topcon GPT-1002 total station with non prism capability and a Fuji Pro digital SLR camera (Table 1). The flow chart of the data collection is shown in Fig. 8. A site for a GPS base station and its radio transmitter is determined by satellite visibility and is accurately located (step 1 in Fig. 8) by being differentially corrected after the location by post-processing with data from Salt Lake City CORS (Continuously Operating Reference Station) (step 2 in Fig. 8) (Parkinson and Spilker, 1996). The “rover” GPS is located by real time differential GPS utilizing the correction from the base station to the satellite signal (step 3.1 in Fig. 8) provided by radio signal in real time received from the base station (step 3.2 in Fig.8) (Parkinson and Spilker, 1996). The rover GPS was used to measure the topography of the area, and to locate the GPR lines (step 4.1 in Fig. 8), the tops of the sedimentary sections on the cliff (step 4.2 in Fig. 8) and the robotic scanners (step 4.3 in Fig. 8) and the reflectorless total station (step 4.4 in Fig. 8). From the known scanner locations, cliff faces were scanned with robotic ALS stations (step 5 in Fig. 8). To scan the outcrop, the robotic scanner was set so that the relative distance between points on the outcrop was ~1 m.
Table 1. Equipment used for photorealistic acquisition and technical characteristics.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leica 500 GPS Systems</td>
<td>Used in Stop and Go in Real Time Kinematic (RTK) mode. Accuracy 1-2 cm.</td>
</tr>
<tr>
<td>MDL Laser ACE System, MDL Laser Atlanta System</td>
<td>Three dimensional robotic laser scanning systems. Acquire relative positions from different surface types without the need of a prism. Range is 300 m and accuracy 5 cm.</td>
</tr>
<tr>
<td>Topcon GPT 1002</td>
<td>Reflectorless total station. In reflectorless mode has a range of 80 meters and 1 cm accuracy.</td>
</tr>
<tr>
<td>Fuji S1 Pro</td>
<td>Professional digital camera with a maximum resolution of 3040 X 2016 pixels. Different Nikon lenses (35 mm, 50 mm, 135 mm) can be attached to the body.</td>
</tr>
</tbody>
</table>
Figure 8. Main steps in collection of data for photorealistic outcrop model.
With a Topcon GPT-1002 electronic tacheometer (total station), control points were postprocessed in the field (step 6 in Fig. 8), using ordinary bicycle reflectors or paint as identifiers of the stations. Digital images of the cliff faces were collected using a digital camera (step 7 in Fig. 8). Images were collected using 35 mm, 50 mm and 135 mm lenses (depending on distance) to increase maximum resolution. Each photographic image had at least eight control points.

All data sets from different stations were corrected and tied to global coordinates by GPS. Processing data for a photorealistic outcrop was developed by Xu (2000) and involves several major steps in building the terrain surface of the outcrop and draping images on the terrain surface (Fig. 9). GoCadTm software was used to generate surfaces of the scanned outcrops. GoCadTm has directional constraints to apply on fitted surfaces. Directional constraints are necessary to fit surfaces which are not necessarily vertical (and may even have overhang). GoCadTm software uses the algorithm described by Mallet (1989). It is also relatively easy to fit surfaces defining geological bodies with GoCadTm. With constraints allowed by the software, surfaces are fit to the raw data points (Fig. 10). Surfaces are not required to pass exactly through every raw point; the degree of detail desired in an image depends on the data and the purpose for which it is to be used. To drape images on the terrain surface of the outcrop, corrections for lens distortion has been made. For the approach used a pinhole camera model in which x, y, z, world coordinates are translated into (u, v), image coordinates (Fig. 11) (Xu, 2000). The pinhole camera model is a simplified model which does not include radial and tangential distortions made by camera lenses. Thus, a least squares method is used to minimize the radial and tangential distortion by calibrating the lenses (Xu, 2000).
Figure 9. Data processing steps for building the digital outcrop model.

1. Scanned raw data points in global x, y, z coordinates

2. Terrain surface of the outcrop

3. Draping digital images
Figure 10. Detailed view of raw points and the GoCad terrain surface of the outcrop (the blue dots represent raw datapoints and the line from surface to the points represent the constraint direction).
Figure 11. Pinpoint principle of coordinate translation from \(x, y, z\), to \(u, v\) (modified after Xu, 2000).
3.5. Sedimentology

Thirty-six vertical stratigraphic sections were measured along the cliff face using technical climbing devices. GPS (Global Positioning System) measurements allow accurate location of measured sections at the top of cliffs (Fig.2). In this paper, the only sections measured on cliffs close to GPR data are used to build 3-D geometries of the deposits. The other sections are used in a detailed analysis of the sedimentology, which will appear elsewhere.

Three areas were mapped in detail. The first area (Fig. 2) shows terminal distributary channels in cliff faces oriented perpendicular to paleoflow. The 2-D bedding diagram shows shallow channels alternating with tabular beds (Fig. 12). Channel deposits reach 4 m thick and 20 m wide, with lateral transition to tabular, submeter thick beds which extend tens to hundreds of meters laterally. Measured sections show overall coarsening-upward facies successions within which occur meter scale fining upward beds. Beds associated with the channels are structureless but locally show trough cross stratification or hummocky cross stratification (HCS).

We interpret these channel deposits as storm-flood deposits related to times of high discharge in the feeding trunk streams. Channel deposits with trough cross stratification and structureless sandstone show a gradual transition to mouth bar deposits with tabular beds consisting of structureless to planar laminated sandstone interbeded with highly bioturbated very fine sandstone. Transition between these deposits was observed in vertical and lateral facies associations. Massive sandstones are capped by bioturbated fine sandstone. These beds are submeter scale; bioturbation ranges from low to very intense. Trace fossils consist of Skolithos, Paleophycos and Ophiomorpha, an association which defines a Skolithos
Figure 12. 2-D photomosaic of terminal distributary channels, located in Fig. 2, Area 1.
ichnofacies. Asymmetric ripples are observed within these beds. Very rare, centimeter thick organic rich beds are associated with highly bioturbated beds. Based on facies description a facies bedding diagram was built using the 2-D photomosaic diagram and measured sections (Fig. 13).

The second cliff is oriented subparallel to parallel relative to the paleoflow direction (Fig. 2). Lithology as well as ichnofacies assemblages are similar to those at the previous location. Beds are meters thick, fine to medium massive sandstone alternating with sub-meter highly bioturbated, rippled sandstone. This cliff is particularly interesting because the beds are inclined in an upstream direction, relative to paleocurrents. These beds were therefore interpreted as upstream accreting mouth bars in channel cuts (Fig.12). Upstream accretion of bars was observed in flume experiments (Ashworth et al., 2001) as well as in ancient deposits (Corbeanu et al., 2001) in fluvial environments, and on modern deltaic deposits (Van Heerden and Roberts, 1988).

The third area lies about 100 m seaward of the first area and is oriented oblique to the paleoflow (Fig. 2). The photomosaic shows sub-meter tabular beds of fine to very fine sandstones (Fig. 14). Beds thicker than 1 m are rare. For the most part, beds are laterally continuous across the outcrop, or show low angle pinchouts. Measured sections show a higher wave /storm influence with wave ripples and HCS. Highly bioturbated beds with undistinguished trace fossils are common. Organic rich beds extend tens of meters laterally and are usually associated with highly bioturbated beds. These beds were interpreted to form in the distal mouth bar environment within the delta front.

Based on previous environmental descriptions, the Panther Tongue deposits from Spring Canyon / Sow Belly Gulch area were interpreted as a river influenced delta lobe.
Figure 13. 2-D photomosaic of upstream aggradation of mouth bar deposits, located in Fig. 2, Area 2, legend is the same as in Fig. 11.
Figure 14. 2-D photomosaic of distal bars, located in Fig. 2, Area 3, legend is the same as in Fig. 12.
No evidence for subaerial exposure was observed. HCS and Skolithos ichnofacies are indicators of shallow water with depths less than 10 m. Existence of storm wave influence structures were formed because water depth was low. Little fair-weather wave structures can be explained through river dominance during fair-weather or was a relative protected basin where wave energy was low. Thick massive sandstone alternating with highly bioturbated facies are interpreted to be caused by highly seasonal river discharge. Periods of high river discharge caused by floods are interpreted to produce the massive sandstone beds. Times of lower discharge are associated with finer grained deposits and invasion of organisms.
CHAPTER 4
3-D INTERPRETATION

GPR data was collected parallel to cliff faces in two areas. The first area represents cliffs oriented perpendicular to the paleoflow direction of the Panther Tongue delta and the second area represents cliffs oriented parallel to paleoflow (Fig. 2).

The location of the first data collection area is shown in Fig. 2. The GPR data shows channel type features similar to those observed on the outcrop (Figs. 15, 16). The 2-D photomosaic of the outcrop (Fig. 12) shows channels filled with trough cross stratified sandstone or structureless sandstone.

Measured sections were correlated based on bedding diagram and facies types are distinguished.

Using the 3-D model of the outcrop and ground-penetrating radar in global coordinates bedding surfaces are build in 3-D. Surfaces were constrained by points digitized from the outcrop and by a ground-penetrating radar line behind the outcrop for the two areas where GPR data was available (Figs. 17, 18). Between these surfaces, sedimentary bodies were built and each was assigned a sedimentary facies (Fig. 19). Resolution of surfaces in global coordinates is at decimeter scale, due to GPR resolution and to uncertainties in fitting of the outcrop surfaces.

Channel deposits described on cliff faces (Figs. 12, 13, 14) are up to 6 meters thick and less than 100 m in width. Channel deposits can laterally pass into mouth bar deposits.
Figure 15. GPR line (GPR1) collected parallel to cliff face, located on Fig. 2, Area1.
Figure 16. GPR line (GPR4) collected parallel to cliff face, located on Fig. 2, Area2
Mouth bar deposits are less than 1 meter thick and can extend hundreds of meters (Figs. 12, 13, 14). Channel and mouth bar deposits were extended in 3-D, behind the outcrop using the GPR images. 3-D surfaces and bodies show that “terminal” distributary form swell linear features. “Terminal” distributary channels and mouth bar deposits have surfaces with maximum topography of 1-2 meters. The difference between 3-D surfaces and the outcrop observation is given by the fact that GPR penetrate only the upper half of the outcrop. In upper half of the outcrop, no channel with significant topography was identified (Fig. 12).

The resulting 3-D surfaces show same characteristic of deposits observed on the correspondent part of the outcrop, with slight lateral variation of channel deposits (Fig. 17).
Figure 17. 3-D view of Gocad surfaces built based on digital outcrop and GPR data, Area 1 in Figure 2.
Figure 18. 3-D view of Gocad surfaces built based on digital outcrop and GPR data, Area 1 in Figure 2.
Figure 19. 3-D sedimentary bodies built based on 3-D Gocad surfaces and sedimentological data, Area 1 in Figure 2.
Geologists agree that digital acquisition of outcrops will improve interpretation made on outcrop data. Also, geological models based on digital outcrop models provide more data than classical 2-D photomosaics. Additional approaches have been used to build 3-D models of the outcrops. One approach is to use LIDAR (Light Detection and Ranging) systems, (Bellian et al., 2002). With this approach, the result is a highly accurate 3-D image of the outcrop. Using the intensity of the reflected beams, a 3-D black and white digital image based on very dense data points is created. The advantage of this approach is the rapidity of the system and high accuracy of the data. The weaknesses are the high cost of the equipment and that the final image, based on reflection intensity, needs to be linked to geology. Some geological features, such as faults or sedimentary structures, can be misinterpreted or missed. Lithology can not be seen and beds can not be differentiated on the outcrop model, especially without color information.

Photorealistic acquisition and digital mapping provide a "virtual outcrop". The photorealistic technique used with GPR is a new quantitative approach to reservoir analog studies; quantitative results are extracted directly from 3-D digital model of the outcrop.

The resolution and accuracy of geologic features interpreted on the "virtual outcrop" (clinoforms, channels, cross bed dip, sole marks orientation) depend on the photo resolution, the laser scanning density and the accuracy of scanners used to scan the outcrop.
The rapid increase in computer capabilities will enhance the development of these techniques, allowing higher resolution images to be draped on densely scanned terrain models of the outcrop.

GPR technology was previously used for analog reservoir studies (McMechan et al., 1997), tied with GPS-laser technology (Corbeanu et al., 2001). Acquisition and processing of GPR data was improved, 3-D GPR data is now used for reservoir analog studies (Corbeanu et al., 2001). The methodology described in this paper shows that combination of GPR with digital mapping technique could be used for 3-D study of bed geometry in areas where 3-D GPR data can not be collected.

Numerous studies on Panther Tongue sandstone were made at large scale (Young, 1955; Howard 1966a, 1966b; Newman and Chan, 1991; Morris et al., 1995; Posamentier et al., 1995), (Fig. 2) in contrast to this study, which is focused on 3-D facies architecture of specific depositional elements within the delta front (Fig. 2).

For the first time, “terminal” distributary channels were identified in an ancient delta deposits (Figs. 2, 12). “Terminal” distibutary channels are common features in modern deltas (Bhattacharya et al., 2001), but have been previously referred to as “secondary” or “tertiary” channels, since they sometimes represent the second or third order of branching within a multiple-bifurcating delta system, such as the modern-day Atchafalaya delta (van Heerden and Roberts, 1988) or the Lena delta (Fig. 1). In ancient deposits it is more appropriate to use the term “terminal” distributary channel, because information about branching order can not be readily or easily determined from an outcrop.

“Terminal” distributary channel deposits are relatively small features that lie at the transition from delta-plain fluvial - distributary channel deposits to mouth bar – marine
deposits. Because of this transitory position, “terminal” distributary channel deposits have often been misinterpreted and attributed to be fluvial channels or mouth bar deposits. In cores or subsurface, they can easily be missed, especially because they are contained completely within the delta front, and do not cut down into underlying pro-delta facies. Many subsurface examples of “distributary channel deposits” (e.g. Busch, 1971; Cleaves et al., 1988; Rasmussen et al., 1985) actually refer to far larger features, many of which are probably better interpreted as incised valleys rather than as distributary channels (Willis, 1997; Bhattacharya et al., 2001). In general, “terminal” distributary channel deposits are contained within the delta front and are intimately associated with mouth bar deposits. Not all “terminal” distributary channels deposits have trough cross stratification, rip up mud clasts or show obvious cut banks. This is especially true where the channels are filled with mouth bar deposits, such as we interpret much of the structureless sandstone within otherwise clearly shallowly-incised features. Evidence of unidirectional flows (trough cross beds) are found within some of the Panther Tongue “terminal” distributary channels (Fig. 12).

“Terminal” distributary channel deposits are potentially important in defining heterogeneities in delta front deposits because they are formed mainly from clean sands like mouth bar deposits but have a more or less channel-shaped geometry.

Upstream accretion was also observed on Panther Tongue deposits on a cliff parallel with the paleoflow (Figs. 2, 13). In flume experiments, upstream accretion has been related to channel avulsion and migration (Ashworth et al., 2001). Upstream accretion of bars has also been observed in the modern Atchafalaya delta using successive aerial photos (van Heerden and Roberts, 1988).
In ancient deposits, the only descriptions of upstream accretion of bars is described by Corbeanu (2001) in delta plain channels in the Cretaceous Ferron sandstone in Utah and in distributary mouth bars of the Ferron within synsedimentary growth faults (Bhattacharya and Davies 2001). In the growth faulted example, there was some question as to whether the upstream accretion was related to infilling of sand as a consequence of hangingwall rotation or as a consequence of loss of discharge at the terminus of the distributary channel. Although not well documented, the modern examples suggest that upstream accretion should be quite common in the delta front, and especially within “terminal” distributary channels. Flume and modern examples of upstream accretion were made on subaerially exposed deposits but the particularity of Panther Tongue upstream accretion is that mouth bar deposits were formed in shallow water.

The presence of “terminal” distributary channels and upstream accretion bars in delta front deposits suggest that delta formation is more complicated than a simple seaward prograding of bars, as is most commonly assumed in subsurface studies of delta front deposits (e.g. Ainsworth et al., 1999; Tye et al., 1999). This study suggests that facies architecture of delta fronts can be quite complicated and that bedding surfaces may dip both downstream and upstream, especially within the proximal delta front. These needs to incorporated into 3D facies architectural models of delta front deposits and may have important implications for how and where sediment is sequestered in deltaic sedimentary sinks.

The new data set of this study is represented by a digital model of the outcrop, which allows an accurate construction of 3-D architecture of deposits. The 3-D shape and
relationships between “terminal “distributaries and associated mouth bar deposits was used to build a 3-D sedimentary model (facies architecture) of delta front deposits.

3-D sedimentary bodies of Panther Tongue deposits built based on data collected show that aggradation and lateral migration are related processes. Aggradation of delta front deposits has a lateral migration component as well. As it is expected surfaces and deposits do not have exact the same geometry as outcrop data behind the outcrop. “Terminal” distributary bodies are thinning laterally (Fig. 18), away from channel axis. This approach shows that most 3-D fluid flow models extrapolate from 2-D outcrop studies, assume that deposits have little variation in the third dimension.

The 3-D outcrop studies documented here also may be used to extract quantitative data for understanding the relative proportion of processes occurring in delta front areas as either aggradation, lateral migration, switching of the “terminal” distributary channel location, upstream accretion, or erosion. Quantitative outcrop data is required not only by the oil industry but also by the sedimentary modeling system community, (Paola, 2000). Computer models need to be tested on real 3-D data sets such as that presented in this paper.
CHAPTER 6

CONCLUSIONS

1. GPR used with photorealistic techniques is a powerful tool for the study of reservoir analogs.

2. 3-D digital photorealistic models of the outcrops allow extraction of quantitative geometric data about the deposits.

3. The study was focused on the 3-D geometry of “terminal” distributary channels in delta front deposits, so that the 3-D sedimentary bodies which are modeled can be associated with the facies distribution in delta front deposits.

4. For the first time “terminal” distributary channels and upstream accretion bars in ancient delta front deposits are described.

5. In the study area three main distinctive facies were differentiated; these are a “terminal” distributary channel, upstream accreting bars, and distal bars.

6. 3-D surfaces of GoCad and bodies show that “terminal” distributary and mouth bar deposits have surfaces with maximum topography of 1-2 meters.

7. Delta front deposits contain upstream (landward) inclined beds and channelized beds not only seaward dipping clinoforms.
Map with location of measured section (triangle for this particular section).

**LEGEND**

- **Cross Stratification**
- **Hummokey Cross Stratification**
- **Parallel Stratification**
- **Assymetric ripples**
- **Paleo current** - $S^{18}W$
- **Bioturbation** - scarce $\exists$, medium $\exists\exists$, abundant $\exists\exists\exists$
- **Scour**
- **Iron concretion**
- **Organic matter**
- **Skolithos**
- **Ophiomorpha**
- **Paleophycos**
- **Scanned outcrop**
- **GPR line**
- **Measured section**
- **Road**
Sections 2 to 5. For location and scale please refer to first section or Figs. 2 and 12.
Sections 6 to 9. For location and scale please refer to first section or Figs. 2 and 12.
Sections 10 to 13. For location and scale please refer to first section or Figs. 2 and 12.
Sections 3r to 6r. For location and scale please refer to first section or Figs. 2 and 12.
Sections 18, 19, 1i, 2i. For location and scale please refer to first section or Figs. 2 and 12.
Sections 3i to 6i. For location and scale please refer to first section or Figs. 2 and 12.
Sections 1ii, 2ii, 1r, 2r. For location and scale please refer to first section or Figs. 2 and 12.
Sections 14 to 17. For location and scale please refer to first section or Figs. 2 and 12.
Sections 7r to 9r. For location and scale please refer to first section or Figs. 2 and 12.
APPENDIX B

RADAR PROFILES
Map with location of GPR profile (triangle for this particular profile).

Scanned outcrop
GPR line
Measured section
Road

100 MHz

Profile GPR 1

50 MHz
Map with location of GPR profile (triangle for this particular profile).

Profile GPR 3
Map with location of GPR profile (triangle for this particular profile).

Profile GPR 2
Map with location of GPR profile (triangle for this particular profile).

50 MHz

Profile GPR 4
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VITA

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