Heterogeneity, paleohydrology, and 3D Facies architecture of ancient point bars, Ferron Sandstone, Notom Delta, South-Central Utah

By

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Abstract

Qualitative fluvial facies models have greatly enhanced the understanding of fluvial deposits. The distribution and relationships of architectural elements and depositional environments within a fluvial system are well documented. However, because of the spatial limitation of 2D outcrops, on which most ancient fluvial studies are based, quantitative models with emphasis on 3D distribution of heterogeneity, paleohydrology, and 3D facies architecture still remains undeveloped. Although Willis's model suggests that spatial and temporal bar variations are controlled by orientation of outcrop and condition changing during bar evolution respectively, the interaction between different controls still needs study. This research intends to test the model by studying the ancient point bars from Ferron Notom Delta, Sandstone which present extensive plan view exposures and some vertical cliff faces. Field works, such as collection of paleocurrent data, Gigapan photo mosaics of vertical exposures, documentation of grain size variation, and GPR surveys, will be conducted to calculate paleohydraulic parameters, analyze fluvial bedding styles and heterogeniety, and reconstruct 3D facies architecture of ancient meander belts.

Introduction

Interpretation of hydrocarbon reservoirs or water aquifers based on subsurface data such as cores and well logs have some major drawbacks, including underestimation of reservoir compartmentalization (Li et al., in press, Bhattacharya and Tye, 2004). This interpretation of ancient systems is greatly enhanced by incorporating modern fluvial analogs (Bhattacharya and Tye, 2004) and empirical or theoretical equations for calculating paleo-hydrologic parameters (Bridge and Tye, 2000, Pranter et al., 2007, Bhattacharya and Tye, 2004, Lorenz et al., 1985 and Ethridge and Schumm, 1977). Fluvial analogs can provide knowledge on continuity and connectivity of fluvial sand bodies, distribution and clustering of channels, and width and thickness of channel belts. Therefore, detailed fluvial analog studies with emphasis on three dimensional facies architecture, may be helpful for reservoir characterization, reservoir modeling, and fluid flow simulation.

Fluvial facies models, developed by Galloway and Hobday (1996) (fig.1), Bridge (2003) and Miall (1985) (fig.2), have been focused on individual architectural elements, depositional environments, and the distribution of these elements and environments within a fluvial system. These qualitative models are built with documentation of outcrop data, observation from modern fluvial systems, and understanding of flow characteristics under different hydraulic conditions and in different types of channels (Bridge, 1977). Although it has been recognized that the architecture of fluvial landforms occurs in different scales and are much more complicated than the idealized models, there are not enough case studies or documentation of ancient fluvial deposits with three-dimensional facies architecture, to contribute to the development of a more quantitative model of preserved ancient fluvial systems.

Willis (1993a) reconstructed paleo-hydraulic parameters of ancient channels and estimated channel belt width and the degree of braiding with detailed documentation of outcrop data. The approach by which Willis studied fluvial style is also applied to other fluvial studies (Li et al., 2010). However, most of these studies are based on vertical cliff exposures of either strike or dip orientations, which only show the spatial fluvial style and architecture in two-dimensions (Willis, 1993a). As a consequence, the estimation of the paleohydraulic parameters may contain certain degrees of error when applying empirical or theoretical equations and the three-dimensional architecture of ancient fluvial deposits remains an interpolation based on analogs or models. 3D seismic geomorphology can provide useful information on fluvial facies architecture especially in plan view (Reijenstein, 2011, Wood, 2007), however its vertical resolution is limited (except high resolution seismic reflection surveys with sparker and boomer lines).

To address this issue and test existing facies models, planform geometry and three dimensional facies architecture need to be studied. However, planform studies from modern fluvial systems may not be appropriate for ancient analogs (Brierley, 1989) because (1) planform does not control actual depositional process, (2) the fluvial architecture formed at one temporal stage may not represent the architecture preserved in the rock record, and (3) burial processes such as differential compaction may modify the planform geometry to some extent. Therefore, detailed 3D outcrop studies of ancient analogs are expected to complement 2D cross sectional studies in reconstruction of quantitative 3D facies architecture (Miall, 1988, Pranter, 2007, Bridge, 2003, Bryant and Flint, 1993, Dreyer et al., 1993). However such 3D outcrops are rare in fluvial deposits.

Point bar deposits

Point Bar deposits are probably the most important reservoir sand body associated with meandering river systems. Qualitative models of point bars outline the bar geometry, migration modes, and variation of sedimentary structures along stream (Galloway and Habday, 1996, Bridge, 2003, Miall, 1996). They are generally composed of lateral accretion units. Simple migration modes include translation and expansion. However, combined translation and expansion, rotation, wavelength variation and complex migration modes are common (Willis, 1989) in nature (fig.3). Bar migration by translation will continuously erode the upstream part of point bar and produce a typical fining upward succession (Willis, 1993). Based on Bridge (1977)'s theoretical three dimensional model of open channel bends, Willis (1989) used a computer model to reconstruct paleochannel geometry, grains size variation and paleocurrent orientation (fig.4). His model suggests that spatial bar variations are caused by differences in the orientation of outcrops, while temporal bar variations are induced by changing channel geometry, bend cutoff, and modification of the evolving bar. Willis (1989) also pointed out that paleocurrent deviation is common, in that upper most parts of point bar may not provide proper a paleocurrent indicator, especially when different kinds of macroforms exist on top of the point bar (fig.5) (Bridge, 2006, Bridge and Tye, 2000). Despite the fact that this model can be used to interpret ancient deposits with minor deficiencies (Willis, 1993b), how the interaction of channel geometry, hydraulics, sediment transport, and bank erosion controls the style of bar migration is still largely unknown (Willis, 1989). Three dimensional outcrops with plan view exposure will be able to test Willis's model and thus separate spatial and temporal bar variations.

Heterogeneity of fluvial deposit

Heterogeneity within fluvial deposits may act as main baffles or barriers for fluid flow in hydrocarbon reservoirs (Miall 1988, Pranter et al., 2007). During reservoir simulation, the amount and distribution of heterogeneity significantly affects the result of fluid flow pattern, break through time, sweep volume, and sweep efficiency (fig.6) (Pranter et al., 2007). Thus the characterization of heterogeneity within fluvial deposits is crucial for hydrocarbon production plan design. Heterogeneity exists at different scales, such as the six hierarchy levels of heterogeneity developed by Jordan and Pryor, 1992, while intermediate scale (mesoscopic and macroscopic) heterogeneity is mostly concerned during hydrocarbon production (Miall 1988, Pranter et al., 2007). Such heterogeneity is introduced mainly by juxtaposition of architectural elements or lithofacies (fig.7) (Dreyer et al., 1993), which correspond to third to fifth order bounding surfaces (fig.8) (Miall, 1988, Miall 1996). In reservoir modeling, lithological heterogeneity is closely related to the presence of shale drapes and lithofacies variation, while petrophysical heterogeneity is dependent on grain size variation and sedimentary structures (fig.6) (Pranter et al., 2007). Since actual well spacing in most conventional oil and gas fields is usually greater than the size of intermediate scale heterogeneity, consequently, well data become ineffective in reconstructing intermediate scale heterogeneity, reservoir analogs are used for modeling by providing such lithological and petrophysical information as grain size variation and shale distribution.

The Notom Delta of the Ferron Sandstone preserve the fluvial deposits in rock record and contains not only well exposed cliff faces of both dip and strike orientations but also some plan view exposures of large scale ancient channel belts, which can be readily seen on satellite images (fig.9). Reconstruction of detailed 3D fluvial facies architecture in this area is quite promising with its high quality 3D outcrop exposure. Moreover, correlation of plan view exposure with GPR surveys and the cliff face cross sections will improve the accuracy of prediction fluvial facies architecture. This research intends to reconstruct 3D fluvial facies architecture and compare it with the architecture deduced from 2D cross sections.

Geological Setting

The Ferron Sandstone, member of the Mancos Shale Formation, is the deposit of a series of delta complexes that prograded into the Western Interior Seaway during the Late Cretaceous (Turonian). It overlies the Tununk Shale Member and is topped by the Blue Gate Shale Member. The Notom Delta, located in the central-east Utah, is one of three Ferron wedges (fig.10).

A detailed sequence stratigraphic framework of Notom Delta has been developed by Li (2009) and Zhu et al. (in press). They recognized 6 sequences which comprise 18 parasequence sets and 43 parasequences. Sequence 1 and sequence 2 are non-marine in origin and are interpreted as incised valley deposit while sequences 3 to 4 are fluvial-deltaic in origin (fig.11).

The upper most sequence consists of a compound incised valley system (Li et al., 2009). Li (2010) completed a regional correlation of two incised valleys from outcrops in Neilson Wash. Detailed facies architecture revealed the changes of fluvial style within each valley. Both of the valley fills show a vertical facies transition from fluvial, to tidal, and back to fluvial facies, which is interpreted to be the result of local valley slope increase driven by high-frequency climate change (Li et al. 2010).

The study area of this research lies at the north of Neilson Wash (fig.12) with extensive plan view exposures of ancient meander belts (fig.3). At some locations, bars with relief of 1 to 5 meters and some vertical cliff faces (fig.13) are available for cross sections to be measured and mapped.

Methodology

The outcrop study (both cliff and plan view) will be focused on describing basic sedimentary features from bedding structures to bar forms, to channel wavelength and sinuosity. Fluvial style change can be well interpreted when cliff exposures are available using the methods from Willis (1993) and Li et al. (2010). Paleo-hydraulic parameters of meander belts can be calculated with the empirical equations (table.1) from Bridge and Tye (2000), Bhattacharya and Tye (2004), Pranter (2007), Lorenz et al. (1985) and Ethridge and Schumm (1977). Paleocurrents can be determined from such features as rib and furrow structures and cross bedding (fig.14). The information on paleo-hydology may shed light on the scale of the formative river (Miall, 2006). Besides the paleo-hydrologic reconstruction, the outcrop study will also provide cross section and plan view form for correlation and calibration of GPR data.

The application of GPR surveys in study of ancient deposits are very helpful (Lee et al., 2007, Corbeanu et al., 2004, Lee et al., 2005) although the resolution and maximum detectable depth is limited. I propose to conduct a GPR survey on discernable meander scrolls. A high frequency 3D GPR survey would provide more detailed information about the 3D architecture of the deposits, to be compared and correlated with outcrop data. The GPR data process procedure is outlined by Lee et al. (2007), and the GPR facies analysis and correlation methods are well described by Lee et al. (2007), Corbeanu et al. (2004), and Lee et al. (2005).

Proposed research

The focus of this study will be reconstruction of 3D fluvial facies architecture with emphasis on heterogeneity and paleohydrology of ancient point bars in a meander belt. Longitudinal and transverse variation of different fluvial forms in relationship to channel sinuosity and wavelength will be addressed. The paleohydraulic information of the Notom Delta, obtained from preview studies (Li et al., 2010, Bhattacharya and MacEachern, 2009) will be tested.

The large scale meander scrolls seen on the satellite image may not be confined within valley 1 of Li (2011)'s study, especially when the fluvial styles are apparently different and the location is not close to the valley 1 exposures. Thus, the question is, what would be the possible control of fluvial type change from meandering rivers of valley 2, to braided rivers of valley 1 (Li et al., 2010), and back to meandering rivers in the upper most part of the fluvial succession? Is such a change of fluvial style primarily controlled by river discharge, slope and sediment supply (Bridge, 2003)?

What is climate and high frequency tectonic control on the fluvial style?

During 9th to 15th March 2012, 6 sections along the vertical outcrop have been measured and paleocurrent data have been collected at 40 locations distributed in the study area. Future field work expected during the summer of 2012 will include collection of paleocurrent data, Gigapan photo mosaics of vertical exposures, detailed bedding style analysis along the vertical exposures, documentation and interpretation of grain size variation, and GPR survey.

Thickness and width of bars will be measured to estimate channel depth and channel width respectively. Meander wavelength and sinuosity will be measured and compared to calculated values. The empirical equations for calculating flow depth with set thickness will be tested. Discharge of the formative rivers will be calculated and compared to previous studies. Grain size variation along paleocurrent direction, bar migration direction, and boundary of each individual cross bed will be documented to provide detailed grain size distribution pattern, which will be helpful in developing more precise model of heterogeneity.

The ultimate goal of this study is to provide detailed 3D facies architecture of ancient point bars to supplement existing analog database for reservoir studies. With paleo-hydrology and heterogeneity data acquired in this study, the applicability of ancient analog to subsurface deposit is expected to be improved.

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Figures

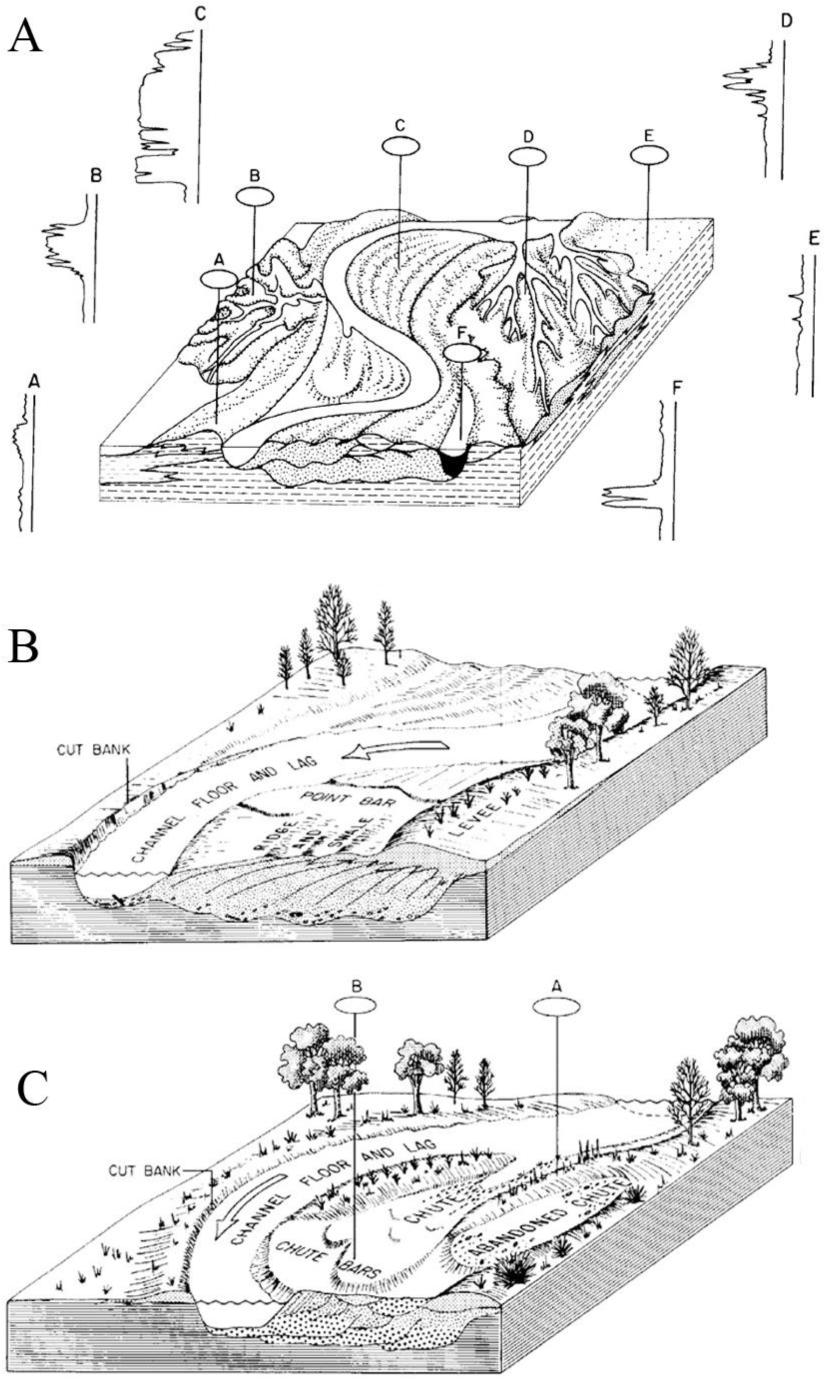

Figure 1-Qualitative fluvial facies model showing relationships between different fluvial deposits and idealized electric logs of different deposits (A). B shows a typical cross section of point bar and C shows that of a chute modified point bar (from Galloway and Hobday, 1996).

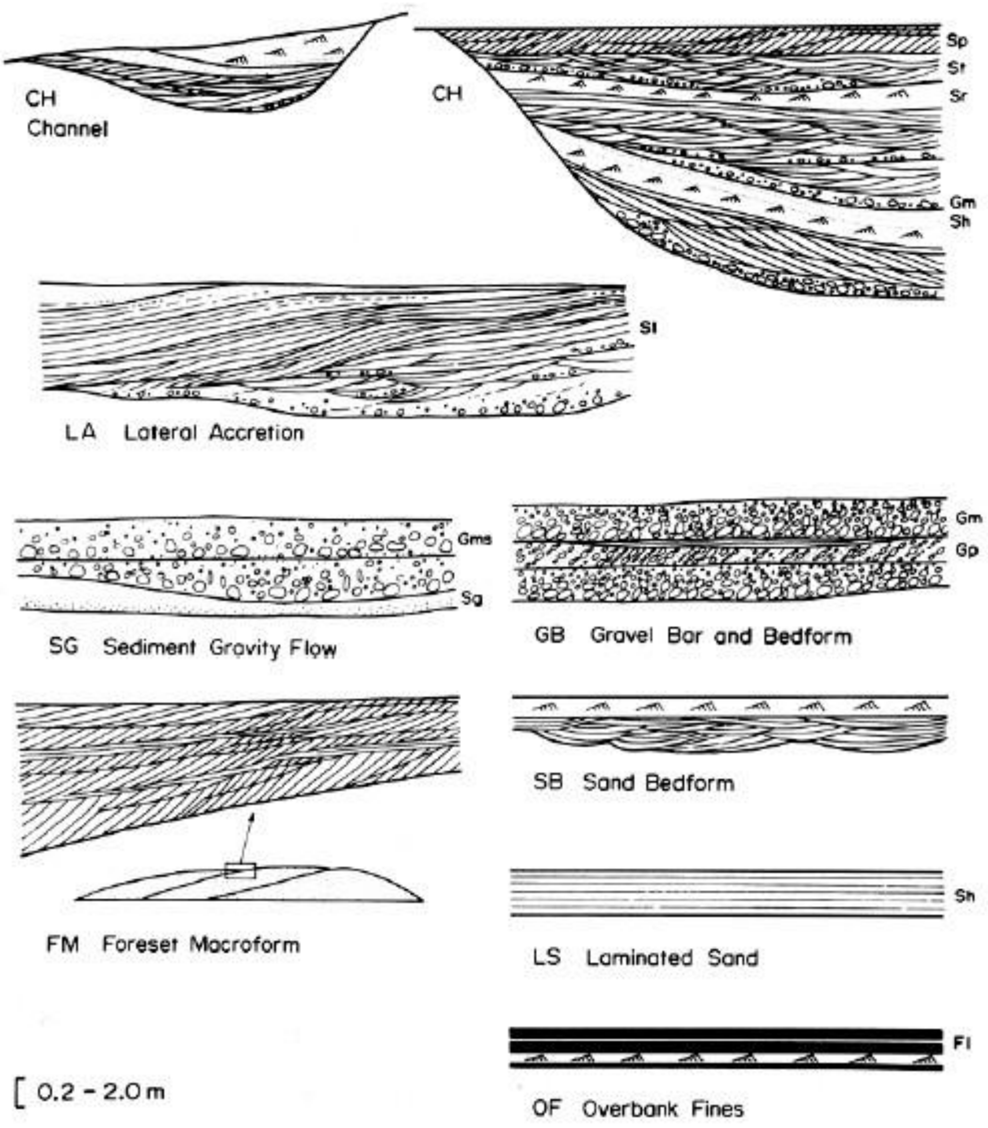

Figure 2-Architectural elements of fluvial deposits developed by Miall (1988).

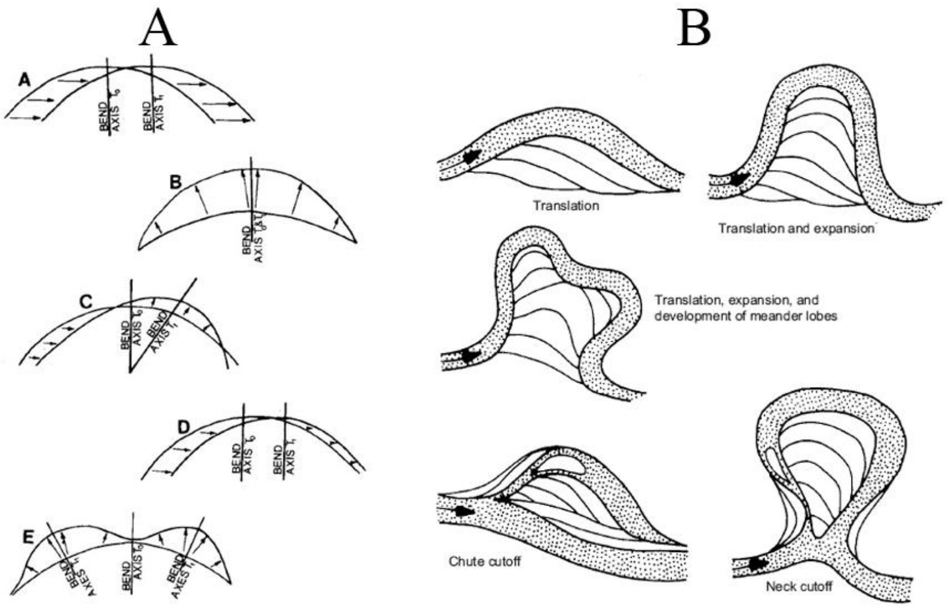

Figure 3-A shows channel migration modes: translation, expansion, rotation, change of wavelength, and complex development (from Willis, 1989). B also shows translation, expansion migration modes, and typical development pattern of a meander channel belt (from Bridge, 2006).

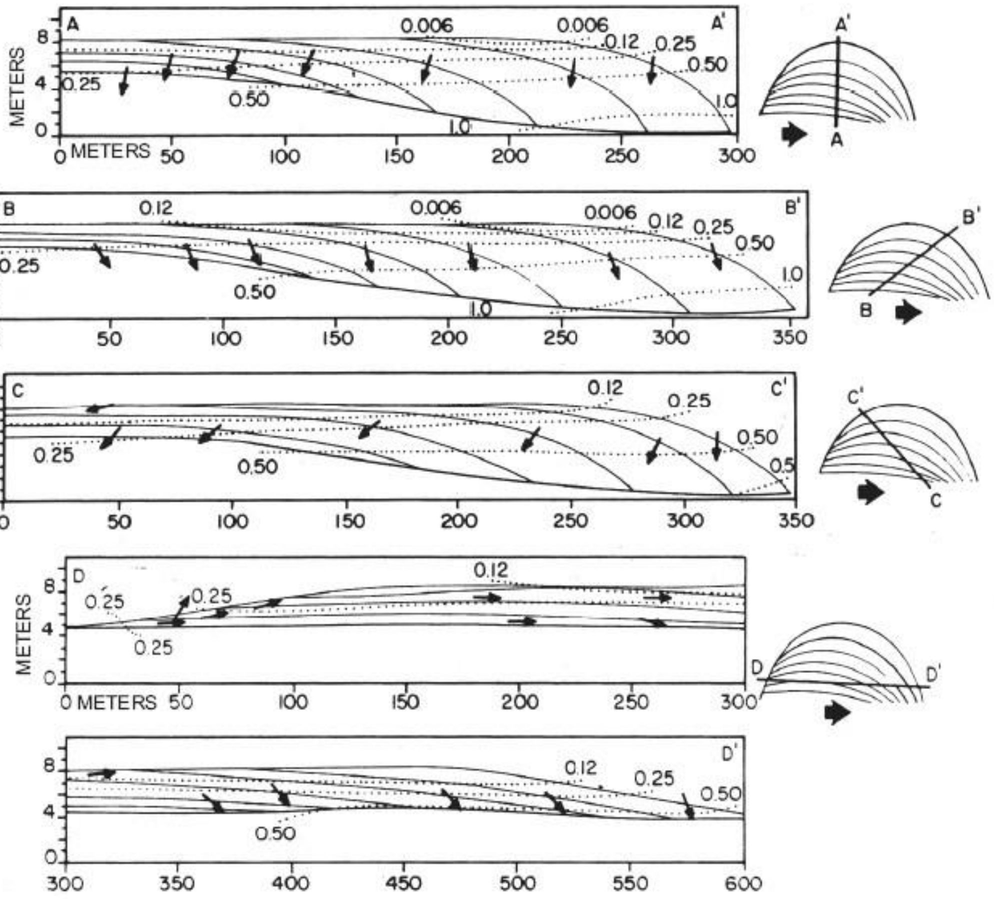

Figure 4-Cross sections with different orientations of a numerically simulated point bar. The spatial variations of geometry, paleocurrent, and grain size are dependent on the orientations of cross sections (from Willis, 1989).

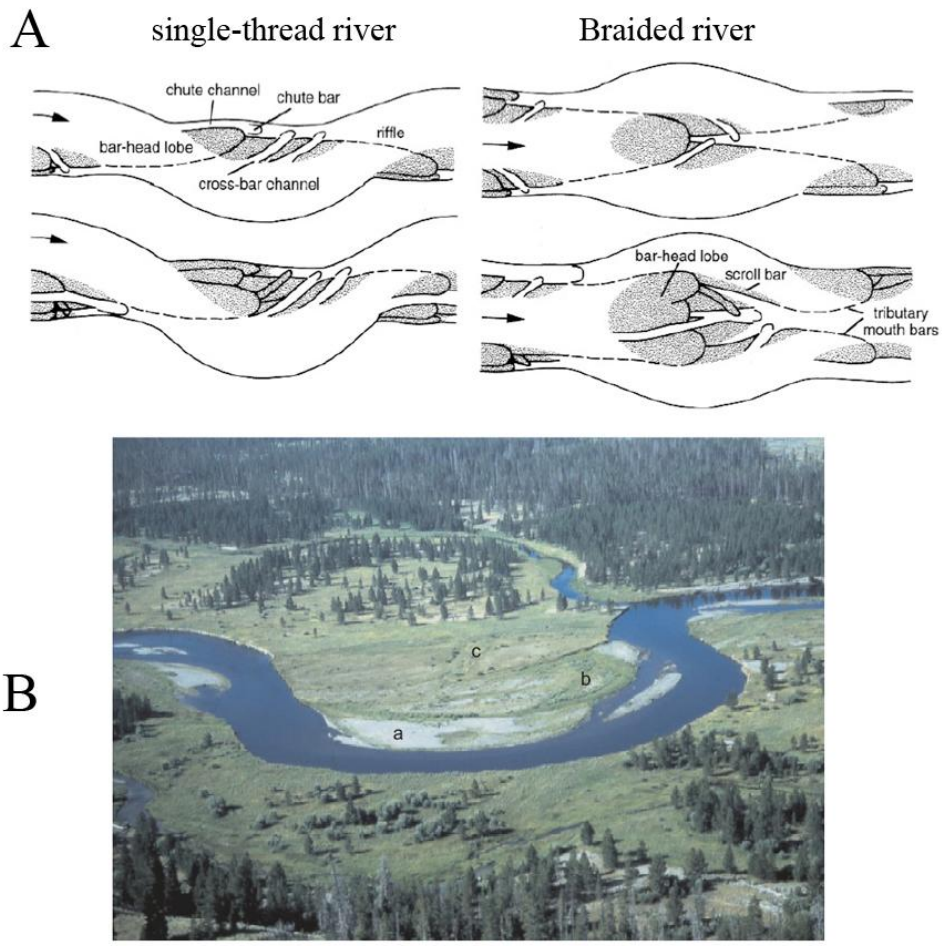

Figure 5- A shows the development of unit bars and cross bar channels (from Bridge and Tye, 2000). B shows unit bar (a), scroll bar (b), and abandoned cross bar channel (c) on a point bar (from Bridge, 2006). Width of channel is about 50 m.

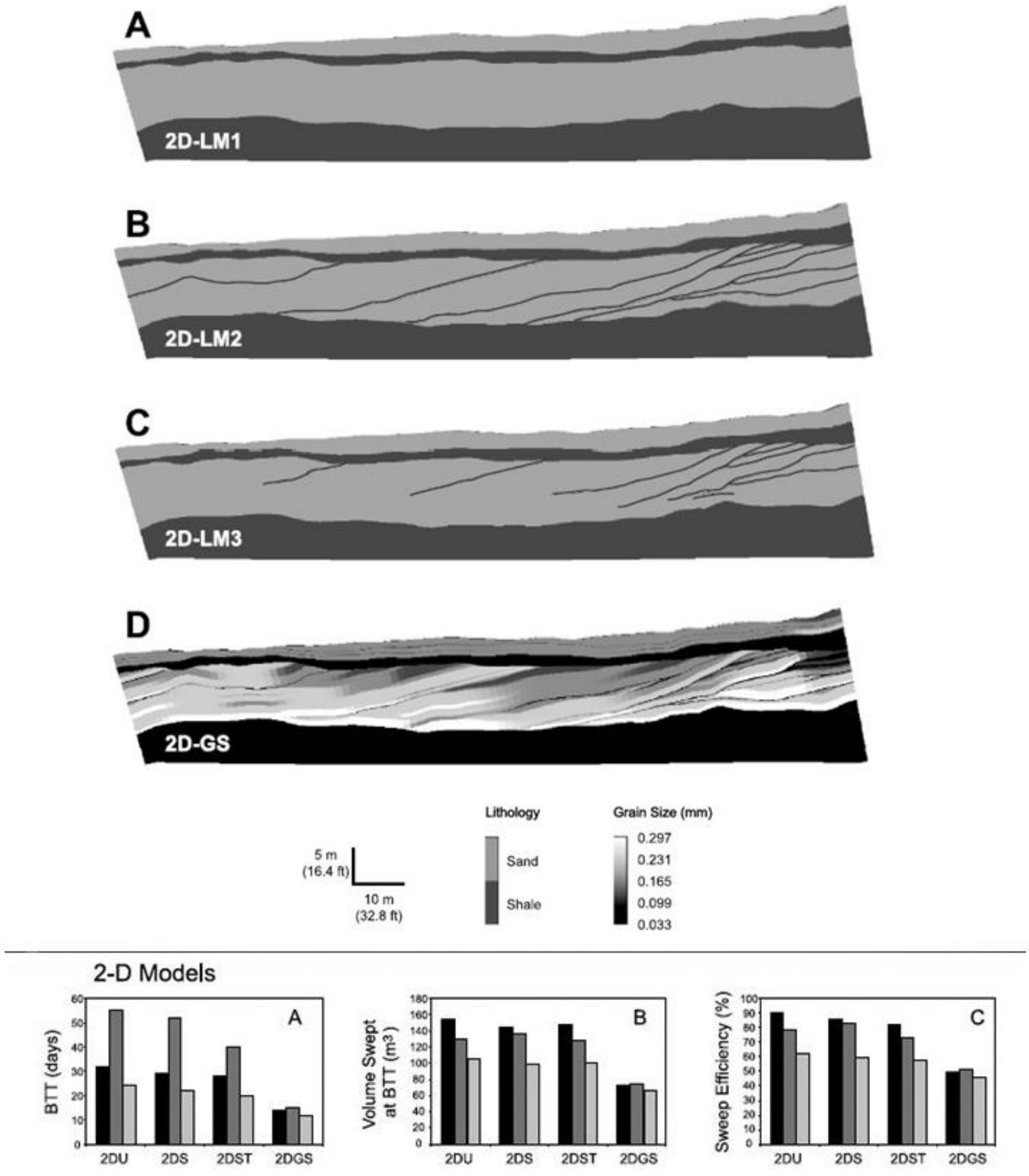

Figure 6-Different 2D reservoir models (with homogeneous lithology, continuous shale drape, discontinuous shale drape, or fining upward trend of both single unit bar and the entire point bar). Break through time, volume swept, and swept efficiency of different models is compared in the histograms (from Pranter, 2007).

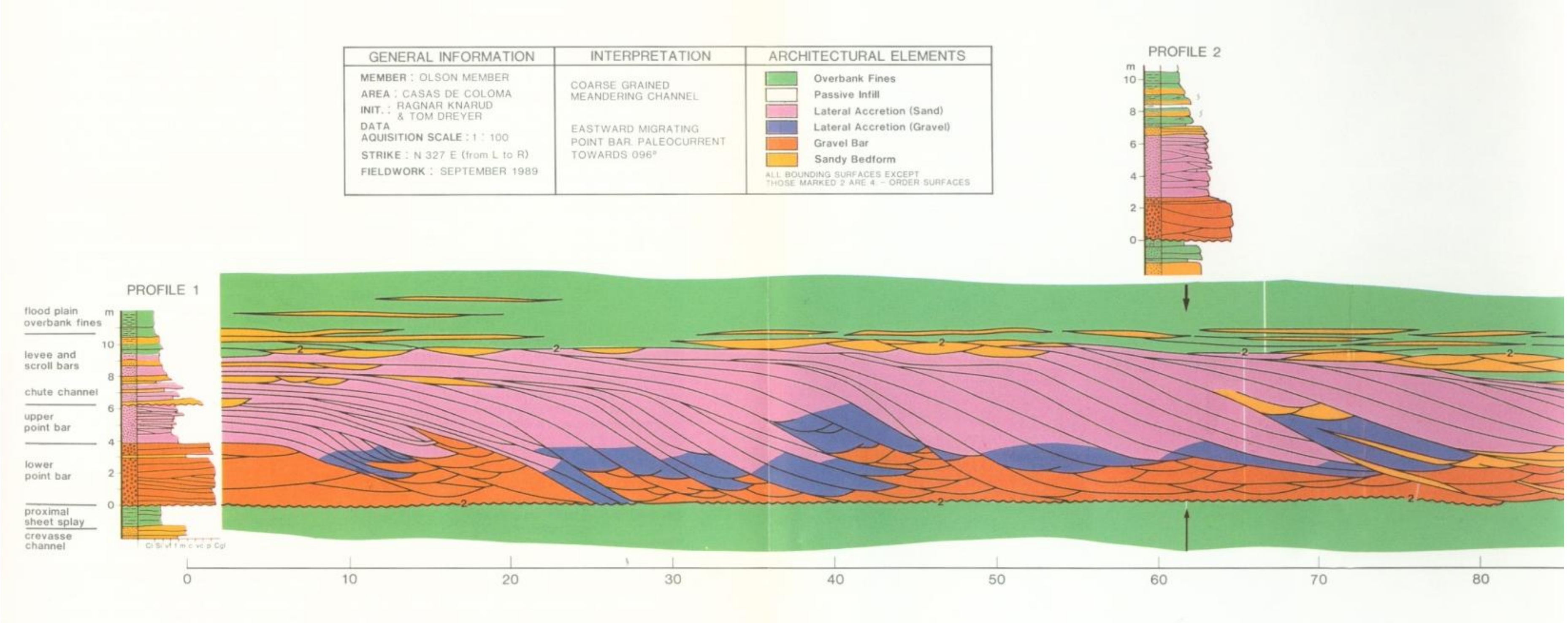

Figure 7-Cross section view of a coarse-grained point bar showing the arrangement of architectural elements from upper part of the Olson Member, Escanilla Foramtion, Spanish Pyrenees (from Dreyer et al., 1993). Grain size and structure variation between different architectural elements induces heterogeneity, which make each architectural element of the channel bodies corresponds to a flow unit.

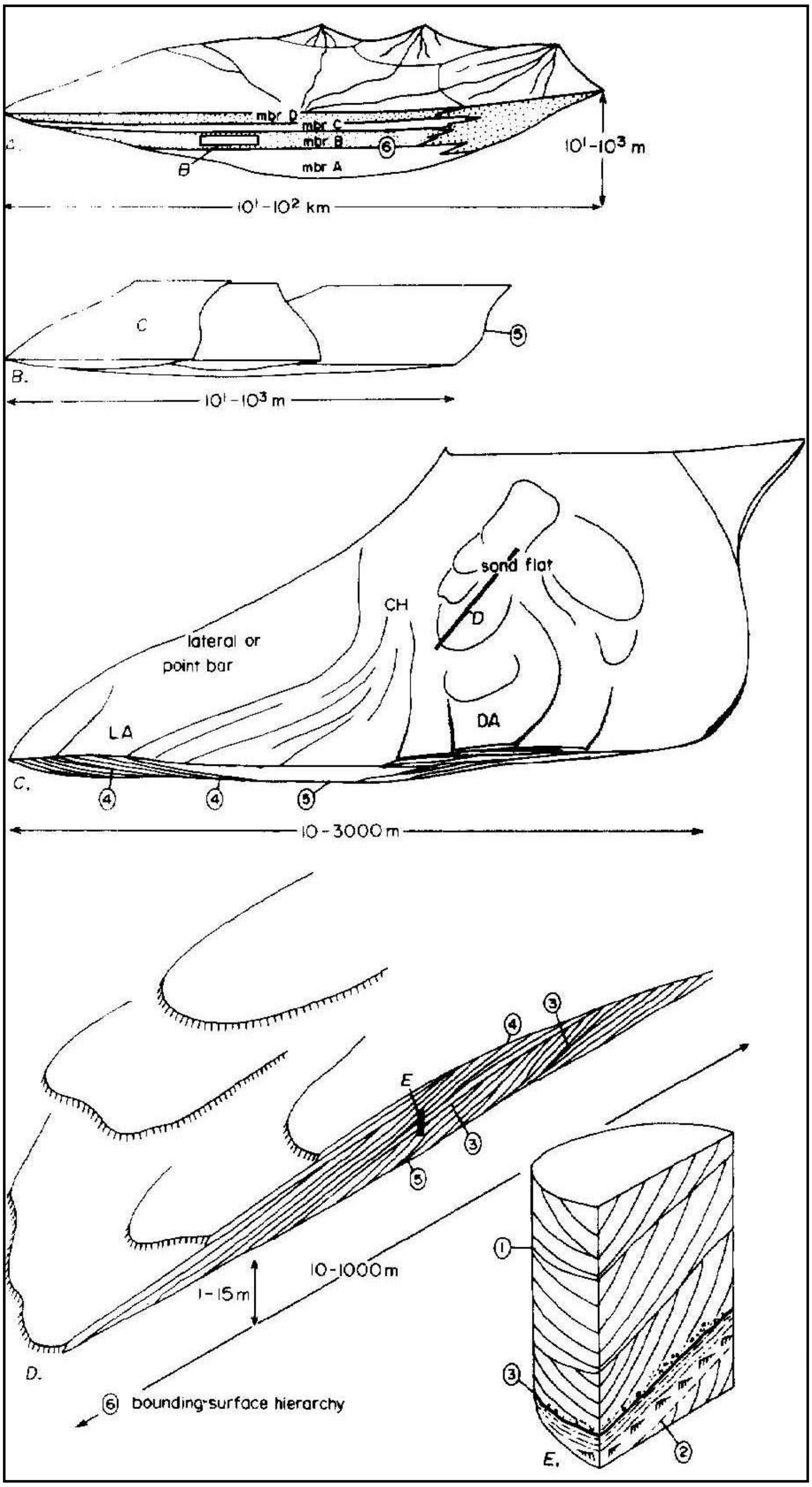

Figure 8-Hierachy of bounding surfaces (from Miall, 1988).

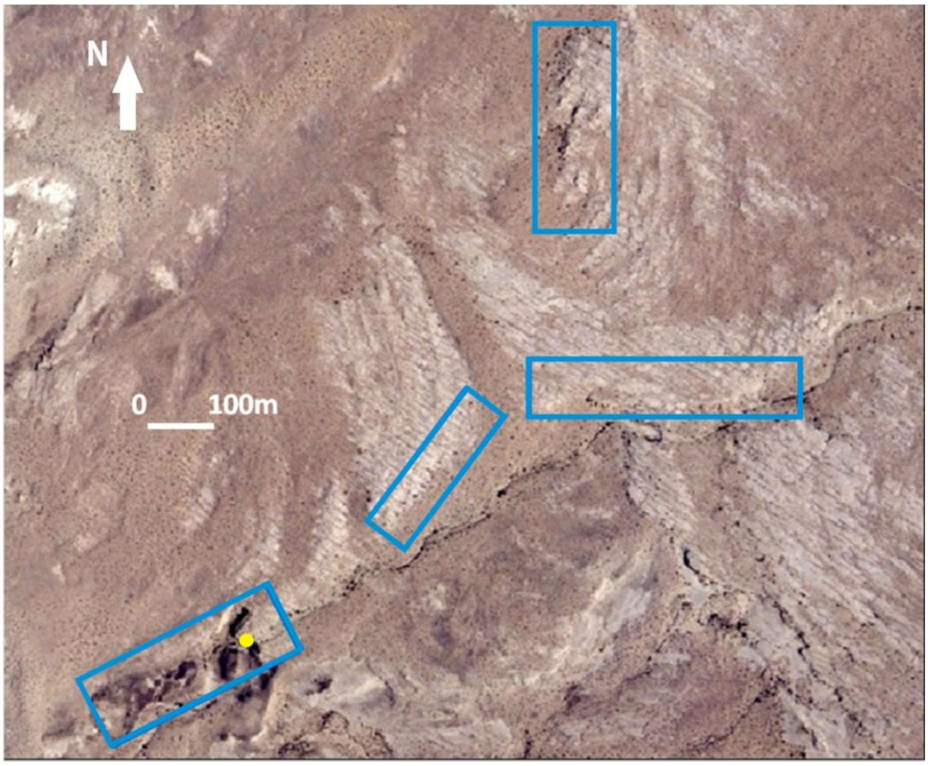

Figure 9-Satellite image of the study area. Several point bars can be identified by the migration pattern. The blue rectangles mark the area with vertical cliff faces. The yellow spot mark the location of measured section in fig.13. The location of the study area is indicated in fig.12.

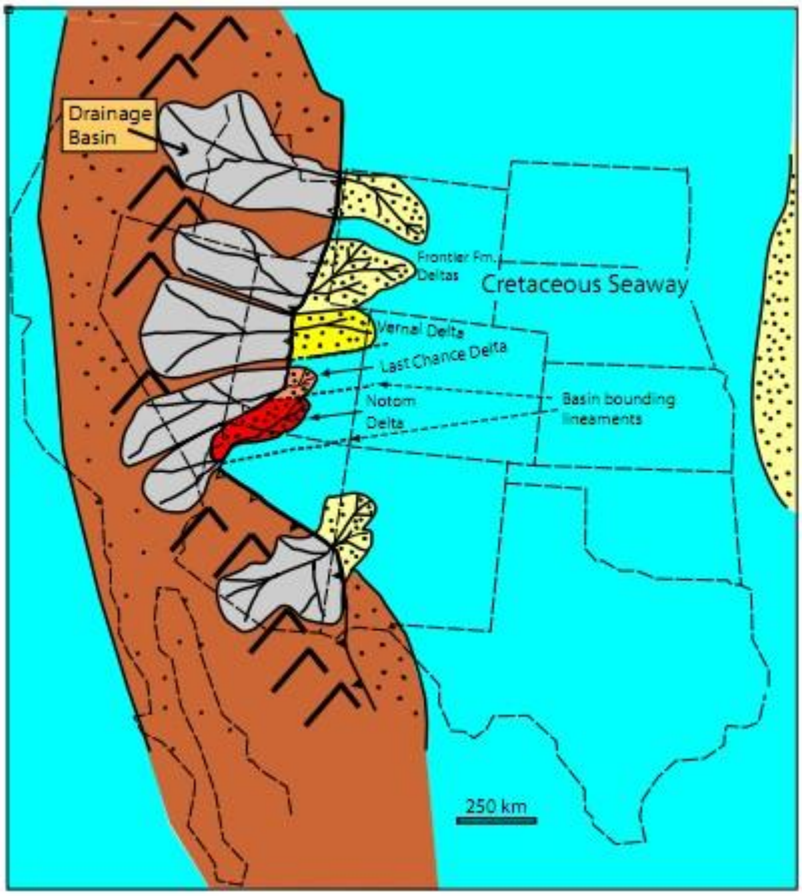

Figure 10-Cretaceous Interior Seaway during Turonian time (From Bhattacharya and Typ, 2004).

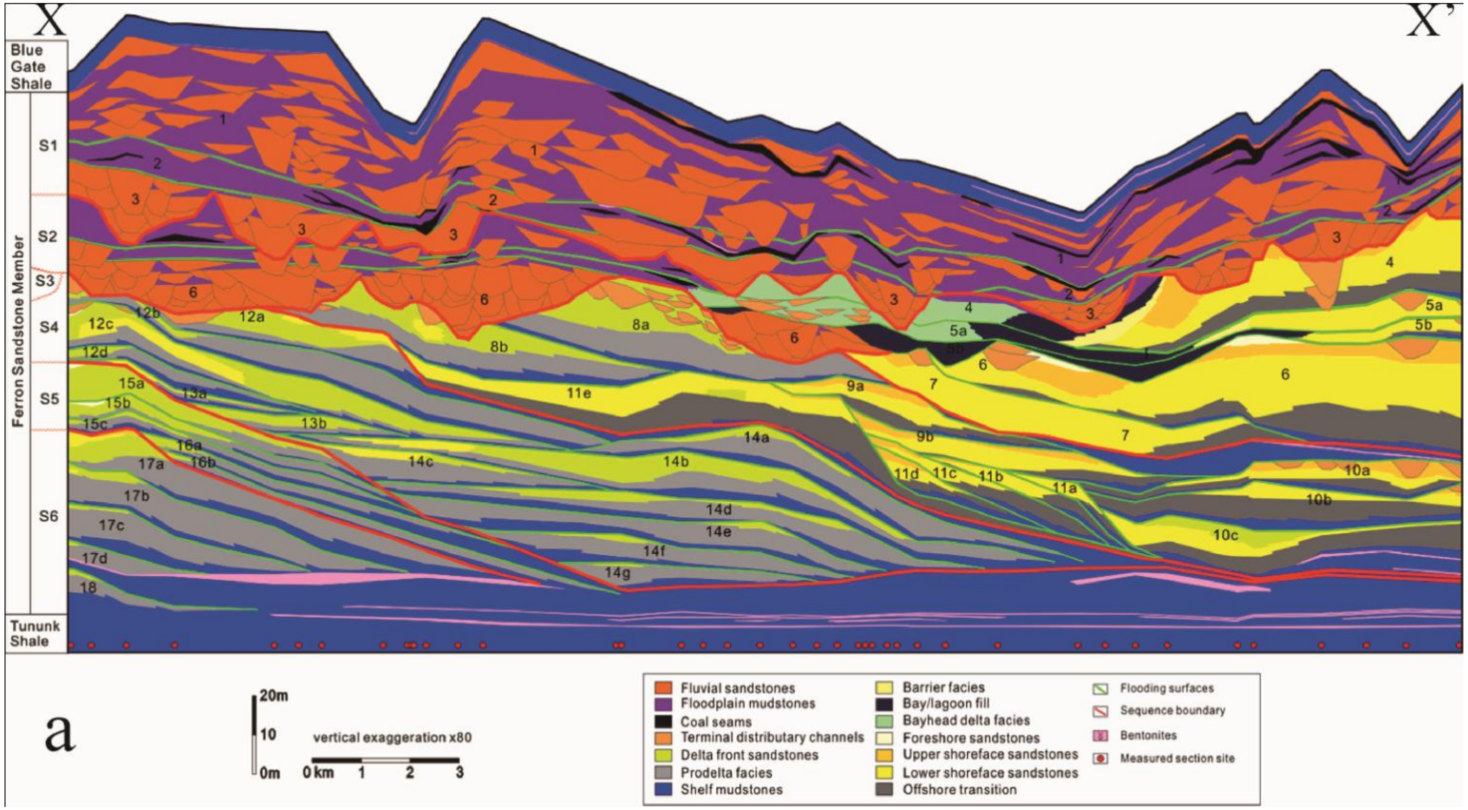

Figure 11-Regional stratigraphic cross section of the Notom delta (from Zhu, 2011).

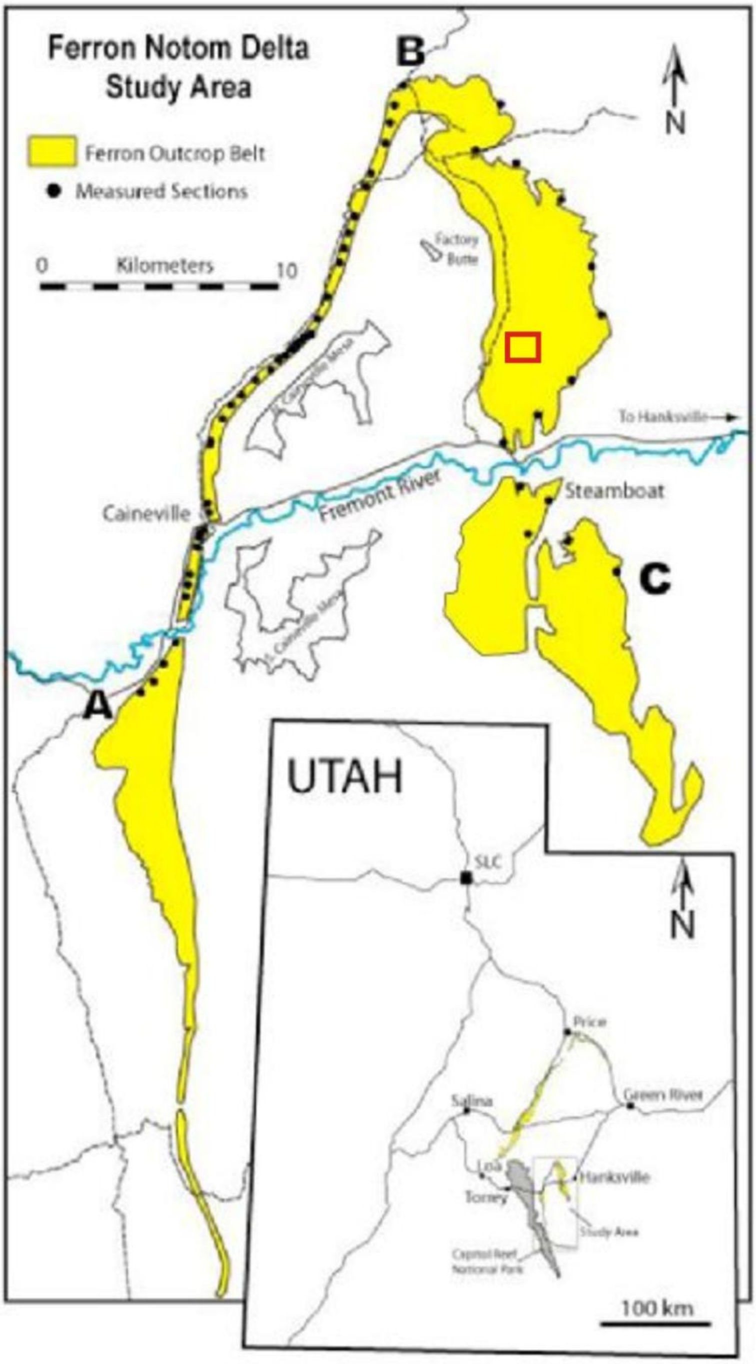

Figure 12-Location of the study area (marked by red rectangle) (modified from Zhu, 2010).

Figure 13-Uninterpreted (upper) and interpreted (lower) cross section. The dashed line separates the point bar and the unit bar on top of it. White lines within the point bar represent the boundaries of large scale cross bedding or lateral accretion units. The vertical section measured shows a fining upward trend on the scale of both single lateral accretion unit and the whole point bar.

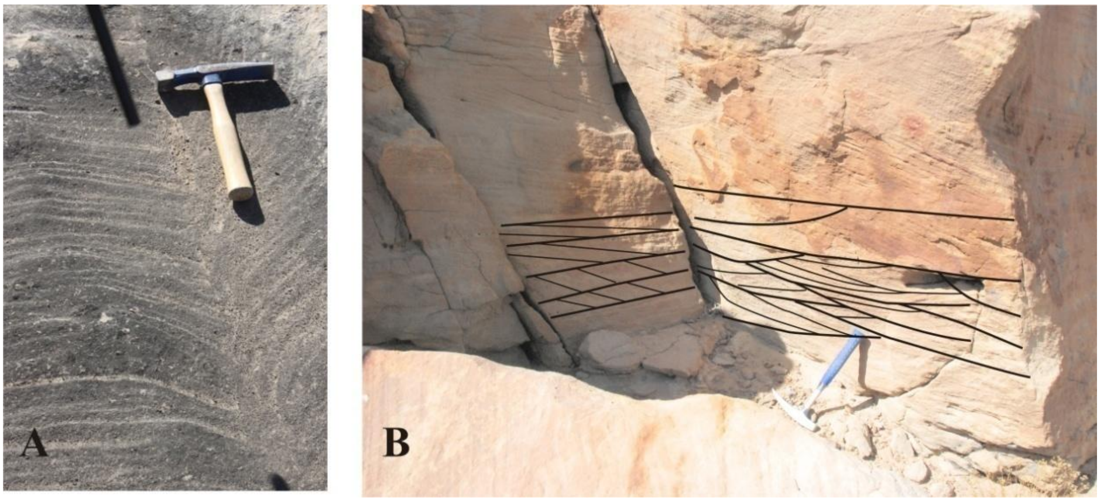

Figure 14-Rib and furrow structure (A) and cross bedding (B) are used as paleocurrent indicator. The cross bedding shown in B has exposures of both dip and strike orientations which makes the measurement of paleocurrent more accurate.

Table 1-Enpirical equations for calculating different paleohydraulic parameters

Empirical equation	Parameters	Conditions for using	References
$h_m = \alpha\beta$ (1) $\beta \cong s_m/1.8$ (2) $\alpha = 4 - 8$ (3) $h_m = 2.22\beta^{1.32}$ (4) $d/h_m = 6$ (5) $d = 11.6h_m^{0.84}$ (d=flow depth) (6)	h_m= mean dune height d=flow depth	s_{sd} (standard deviation)/s_m (mean) should approximately equal 0.88 (±0.3). Dunes may not be in equilibrium with flow condition. Thickness data should be collected as much as possible	S. F. Leclair, 2000
$cbw = 59.9d_m^{1.8}$ (6) $cbw = 192d_m^{1.37}$ (7) d_m=0.57d (13)	cwb=channel belt width d=maximum channel depth d_m=mean channel depth	(7) is most applicable for a high-sinuosity channel. (Bhattacharya and Tye 2004)	Bridge and Mackey (1993)
$LogQ_{flood} = -0.07(LogA^2) + 0.865logA + 2.084$ (8)	A=drainage area (units=km^2) Q=peak flood (units=m^3/sec)		Matthai (1990)
Q=A*U (9)	Q = discharge, U = average velocity A = cross-sectional area of the channel (width x depth)		Bhattacharya and Tye, 2004
$w_c = 8.88d_m^{1.82}$ (10)	w_c=channel width, d_m=mean channel depth		Bridge and Tye. 2000
$w = 64.6d_m^{1.54}$ (11) $w = 65.6d^{1.57}$ (12)	d_m=mean channel depth d=max channel depth	These two equations can provide range of channel or channel belt	Fielding and Crane (1987) Collinson (1978)
D=0.585D*/0.9 (14) W=1.5*W (15) $W = 6.8D^{1.54}$ (16) $\lambda_m = 10.9W^{1.01}$ (units=m) (17) $\lambda_m = 18(F^{0.53}W^{0.69})$ (F=W/D) (18)	D=bankfull channel depth D*=average thickness of the sand body W=bankfull channel width W*=average horizontal width of the lateral –accretion surfaces as exposed in outcrop.	For high simuosity rivers	Ethridge and Schumm, 1977 Allen, 1965 Leader, 1973 Leopold and Wolman,1960 Schumm 1972