3D CHARACTERIZATION OF WAVE-INFLUENCED DELTAIC RESERVOIR OUTCROP ANALOGS: AN EXAMPLE FROM FERRON NOTOM DELTA, UTAH, USA

By

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1. The Problems with Deltaic Reservoir Modeling

In order to perform better reservoir production prediction and management, accurately characterizing reservoir heterogeneities is essential. To characterize deltaic reservoir heterogeneity, the first key step is identifying the right type of delta. The second key step is appropriately characterizing the heterogeneities of identified deltaic reservoir types. The tripartite classification (Galloway, 1975) of deltas is widely used to identify delta type. Different delta types display different morphologies and characteristic internal facies successions, so different types of deltaic reservoirs could have different characteristic heterogeneities that impact fluid flow. Unfortunately, most reservoir modelers from industry often force-fit their particular deltaic reservoir into one of three delta end-members for simplification, even though those deltas are likely to be mixed-energy and plot somewhere within the triangle. From the observation of many modern deltas, fluvial- and wave-mixed deltas show asymmetric feature in both geometry and internal structure (Dominguez, 1996; Bhattacharya and Giosan, 2003). The traditional numerical deltaic reservoir model (also called the tear-drop model) is symmetric both in shape and internal structure. So using the symmetric delta models may not correctly capture the heterogeneities of mixed-energy, asymmetric deltaic reservoirs.

2. Proposed Modeling Work

2.1 Modeling workflow

Current oil industry modeling techniques uses a grid-based approach, typically starting with grid construction at seismic scale and then superimposing higher resolution geologic reservoir architecture. For outcrop modeling, this process evolves surface-based approaches (Denver and Phillips, 1990; Hamilton and Jones, 1992; White and Barton, 1999; Sech et al., 2009). The surface-based approach starts with identifying key geologic surfaces, such as sequence stratigraphic surfaces or other depositional facies boundaries. Those surfaces are then used to construct a 3D grid in modeling software (Petrel, Gocad, Roxar, or GeoModeling). The major steps in modeling workflow are as follows (see Fig. 1 for detail):

1. Find out the plan-view distribution and vertical trends of each major deltaic facies association within or between successions by parasequence.

2. Map out parasequence boundaries (or flooding surfaces) in three dimensions in the modeling software (e.g., Petrel). At this stage, a reference surface is needed. For this proposed modeling area, bentonite layers (or flooding surface) can be selected to reconstruct isochore map of other parasequence surfaces. Each parasequence surface can be generated by interpolation and extrapolation from measured sections.

3. Generate facies architecture for each parasequence. The modeled interval (parasequence) will be filled with a facies association distribution that combines conceptual geological models and existing datasets. Vertical trends and areal trends control facies association gridding in a parasequence space. The grid should be conditioned to the sequence stratigraphic framework and all field conditioning data should be honored.

4. For each parasequence, facies boundaries should be traced in three dimensions. Parts of realized surfaces need to be adjusted by hand to facies maps to honor cross-section

and all available data. Comparing resulting models with measured sections and cliff photomosaics also can check the model quality.

5. Do quantitative architecture analysis based on the realized model. If the grid is populated with petro-physical properties, dynamic flow simulation can be conducted.

In this research, the critical work step is Step 3 - asymmetric delta facies modeling. The next section will discuss the modeling method for asymmetric delta.

2.2 Asymmetric deltaic reservoir modeling

Reservoir facies modeling techniques can be classified into two categories: pixel-based modeling and object-based modeling. Pixel-based modeling algorithms include sequential indicator simulation and multiple point statistic simulation. These algorithms visit all pixels (or cells) from a random starting point and at each location draw a random single value from the local conditional probability distribution (variogram). Pixel-based modeling techniques are very flexible for data conditioning, so they are deployed widely in dense-well subsurface situation. However, filling the facies property pixel by pixel may not capture the overall facies geometry. In other words, pixel-based model techniques cannot capture complex geologic features with defined external shapes such as a delta lobe.

Object-based methods are also referred to as Boolean methods. Object-based techniques were pioneered by Haldorsen and Lake (1984), Haldorsen and Chang (1986) and Stoyan et al. (1987). In object-based modeling, geological heterogeneities, such as sandstone and shale, are defined as a set of geo-objects. Each type of geo-object is defined using limited parameters. Once these objects are defined, the following stochastic simulation simply consists of placing these objects in space, at the same time attempting to honor available data. The object dimension parameters are either specified, based on similar or modern analogs, or drawn from a probability density function. Object-based methods are able to model the connectivity and geometry of complicated reservoir features. However, a long-standing disadvantage with object-based reservoir modeling methods lies in the conditioning to well data, particularly in the presence of many wells. So object-based modeling is usually applied to data-poor reservoirs. For this study, the complexity of asymmetric delta geometry requires an object-based approach. Therefore, the object-based approach will be used for deltaic facies modeling and the pixel-based technique (Sequential Gaussian Simulation) will be used to populate petrophysical properties, such as porosity and permeability within deltaic facies.

To perform object-based modeling, the first step is parameterization of the geo-object being simulated. In this work, the lithofacies are simplified as sandstone and mudstone because we are investigating the impact of mudstone distribution. The background will be mudstone and the objects being simulating will be sandstones. Therefore, an asymmetric delta is described using three objects: channel belt object, updrift sandier shoreface object and down drift object (Fig. 2). The parameters defining a channel belt object include: maximum width, maximum thickness, sinuosity, amplitude, and orientation. The parameters describing the updrift shoreface object and the downdrift objects need to be defined as part of dissertation.

Once the geo-object of asymmetrical delta is parameterized, the probability distributions of each parameter will be derived from published modern and measured outcrop data. The derived probability distribution functions then will be used for stochastically simulating individual delta lobe bodies. They can also provide valuable reference in asymmetric deltaic reservoir modeling for reservoir modelers and reservoir engineers.

Since each delta lobe body is bounded by two parasequence surfaces, the lobe bodies should be simulated so that their thickness at any location (*x,y,z*) is equal to or similar to the distance between two related parasequence surfaces at the same location. In this way, the interval between two parasequence surfaces can be completely filled by the delta lobe bodies. This means the facies association modeling needs to not only constrain to the measured cross sections, but also condition to zone or interval thickness. Different optimization methods will be explored for data conditioning purpose.

2.3 Model comparison and sensitivity study

One way to make use of the simulated asymmetric delta geologic models is to compare them to the simulated symmetric ones using the same dataset. This comparison includes static property comparison (such as connectivity, net-to-gross ratio) and dynamic behavior comparison (such as water breakthrough time for water flooding case, sweep efficiency). The comparison will check to see if the geologic models generated using different conceptual models have similar properties. The results can help guide the reservoir modelers to the correct conceptual model selection.

Another way to make use of the asymmetric delta geologic models is to perform a sensitivity study. The sensitivity of five geologic parameters will be investigated: (1) asymmetry index (A) (Bhattacharya and Giosan, 2003); (2) channel dimension; (3) the dimension of updrift shoreface, (4) dimension of downdrift, (5) stacking pattern. Experimental design (White, 2003) will be used to set up different parameter levels. Then asymmetric delta lobe geologic models will be generated using different parameter level combinations. These models will be input into a flow simulator to run flow simulation. The flow responses (such as water breakthrough time, production profile) of different models will be studied and the sensitivity of the geologic parameters will be investigated using response surfaces. The sensitivity study will point out the important geologic parameters controlling the heterogeneity of asymmetric deltaic reservoirs. This will provide meaningful guidance for asymmetric deltaic reservoir modeling.

2.3 Seismic forward modeling

Two-dimensional reservoir modeling results of dip and strike cross-sections can be used to model their seismic responses when grid cells are populated with velocity and density values. For this study, one-dimensional convolution seismic models will be employed. Compares with the interpreted high-resolution outcrop sections, the synthetic seismic images can tell which features of deltaic systems can be observed and which can not be observed on real seismic data. Changing the modeling frequency, how seismic expression of deltaic elements (or features) varies can be modeled. The future modeling work may also include the seismic modeling over production. This seismic modeling work is expected to help seismic interpreters to improve their subsurface seismic interpretation on deltaic reservoirs.

3. Geo-objects of Delta Lobe (Bar Complex)

The three-dimensional geo-objects of a delta lobe are derived from a large amount of observations of modern deltas and studies of ancient deltas. Largely based on observations from modern Wax Lake Delta (Tye, 2004; Wellner, 2005) and ancient Panther Tongue

Sandstone, the generalized tear-drop delta lobe model for fluvial-dominated deltas (symmetric delta) can be considered as a classic delta geo-object. The simplified delta geo-object has a 2-D elliptical plane view from an anchor point (river mouth) and inclined sigmoid shape in dip cross section (Reynolds, 1999, van den Bergh and Garrison, 2004) (Fig. 3). Basically, this is a symmetric model. Three sub-volumes are recognized as three deltaic facies associations, stream mouth bar, proximal delta front and distal delta front, respectively, both on areal view and cross-section view, which also represent decreasing reservoir quality. The teardrop model is utilized widely for reservoir modeling in the oil and gas industry. To deal with wave-reworking effects, the model has been modified (Fig. 4). According to Tye (2004) and Wellner et al.(2005), geomorphic and dimensional parameters of lobes are predictable and statistically similar. They also measured and calculated a large amount of dimensional data, which can be used for deltaic reservoir modeling. With more and more analogue data accumulated both from modern and ancient deltas, more and more accurate reservoir models can be built.

The conceptual asymmetrical delta facies 3-D model (Fig. 5) was proposed by Bhattacharya and Gioson (2003) based on a re-evaluation of several modern examples (e.g. Danube-Sf. Geaghe lobe, Brazos, Damietta lobe of the Nile). This conceptual delta model describes the facies and morphologic asymmetries between the updrift and downdrift sides of a delta. Significant prodelta mudstones encasing sand ridges are present at the downdrift portion of delta; the updrift side includes a sandy beach ridge plain and downdip shoreface. As a consequence, this model predicts poor quality reservoir facies in prodelta and downdrift areas and better quality sand in updrift areas. This delta asymmetry has been recognized in ancient systems. For example, according to the paleocurrent and outcrop data in the proposed modeling area (Li et al., 2009), longshore currents reworked deltaic sand bodies that consequently show asymmetrical feature in parasequences of the Ferron Notom Delta (Fig. 6). The arrangement and spatial distribution of mud-dominated lithofacies may have important implications for predicting reservoir heterogeneity because they impact reservoir connectivity and continuity.

The traditional symmetrical teardrop deltaic geo-object cannot explain and predict all the variability observed in both modern and ancient deltas. Therefore, the asymmetric geo-object is an alternative to predict deltaic reservoir heterogeneity. Currently, delta lobes are characterized as symmetrical geo-objects in all commercial reservoir modeling software including Petrel, Gocad, and Roxar. There is a need to develop a new modeling algorithm for asymmetric deltaic reservoirs, in order to investigate the factors that impact the heterogeneity of asymmetric deltaic reservoirs. Comparing and contrasting the symmetrical delta scenario and asymmetric scenarios is also meaningful for the upstream industry.

4. Geologic Setting and Data Availability in the Modeling Area

The Ferron Sandstone is a member of the Cretaceous Mancos Shale Formation, which formed an eastward-progradating clastic wedge in the Western Cordilleran foreland basin during the Turonian-Conacian (Upper-Cretaceous) ages within the western margin of the Interior Seaway (Gardner, 1995, Ryer and Aderson, 2004). Due to its superb exposure, the Ferron Sandstone has long been used as an outcrop analog for subsurface fluvial-deltaic reservoirs (Barton, 1994, 1997; Gardner, 1995; Knox and Barton, 1999, Bhattacharya and Tye, 2004, Anderson and Chidsey et al., 2004).

The Ferron Sandstone is described as comprising three delta lobes (lobe complexes), the Vernal Delta, the Last Chance Delta, and the Notom Delta from north to south respectively in southern Utah (Gardner, 1995; Garrison and Van den Bergh, 2004). According to Garrison and Van den Bergh (2004), the Notom Delta developed first during a widespread regression from the Middle Turonian to Late Santonian. After a river avulsion, deposition shifted northward forming the Last Chance Delta and then the youngest Vernal Delta (Gardner, 1995; Garrison and Van den Bergh, 2004).

The proposed modeling area is a 14km ×14km square located in southern of Utah (Fig. 7). The first high-resolution regional sequence stratigraphy of the Ferron Notom Delta along the dip-oriented east outcrop belt has been documented by Zhu (Fig. 8, 2008). The strike-oriented stratigraphy (Fig. 9) is interpreted by Li (2008). According to Zhu and Li, Sequence 2 consists of five parasequences, 4, 5a, 5b, 6, 7. Parasequence 7 is strongly fluvial- influenced and contains channel deposits. Parasequence 6 is interpreted as an asymmetric delta (Fig. 4) fed by rivers with mouth bars and reworked by longshore currents (Li et al., 2009). Parasequence 5 shows a gradual facies transition from fluvial to bayhead delta, then to shorefaces. Parasequence 4 is more wave-influenced. The reasons for the modeling sequence selection are: sand-rich strata, abundance of data, and complicated deltaic features.

The major dataset used for the modeling are measured sections collected by a number of graduate students over the past 5 years. Here, measured sections can be divided two categories. Category one is used to set up the regional sequence stratigraphic framework. Along the dip direction, more than 40 sections were measured to document dip sequence stratigraphy by Y. Zhu (2007, 2008), 18 sections are included in the proposed modeling area. Along strike, W. Li (2007, 2008) measured 15 sections, 10 of which are in the modeling area. Category two is used to characterize local specific geologic features. W. Li (2008) measured 40 sections across an incised valley in the south of the modeling area. Y. Li (2009) measured 30 sections to document mouth bars in the north of the proposed modeling area. D. Garza (2008) measured 15 sections to document storm-dominated prodelta. S. Ahmed (2009) measured 22 sections in the north of the modeling area to document the transition between delta and shoreface. J. Kelso (2009) measured 7 sections. Each section is positioned using GPS. All those measured sections can thus be used as pseudo-wells (as wells for subsurface reservoir modeling) for modeling purpose.

Photomosaics will be used to trace parasequence boundaries in 3D space, interpret lateral facies changes, examine vertical connectedness of sandbodies, as well as provide quality control. Photomosaics have been taken during section measuring. If I need more measured sections and photomosaics, I shall be able to collect them in the summer of 2010.

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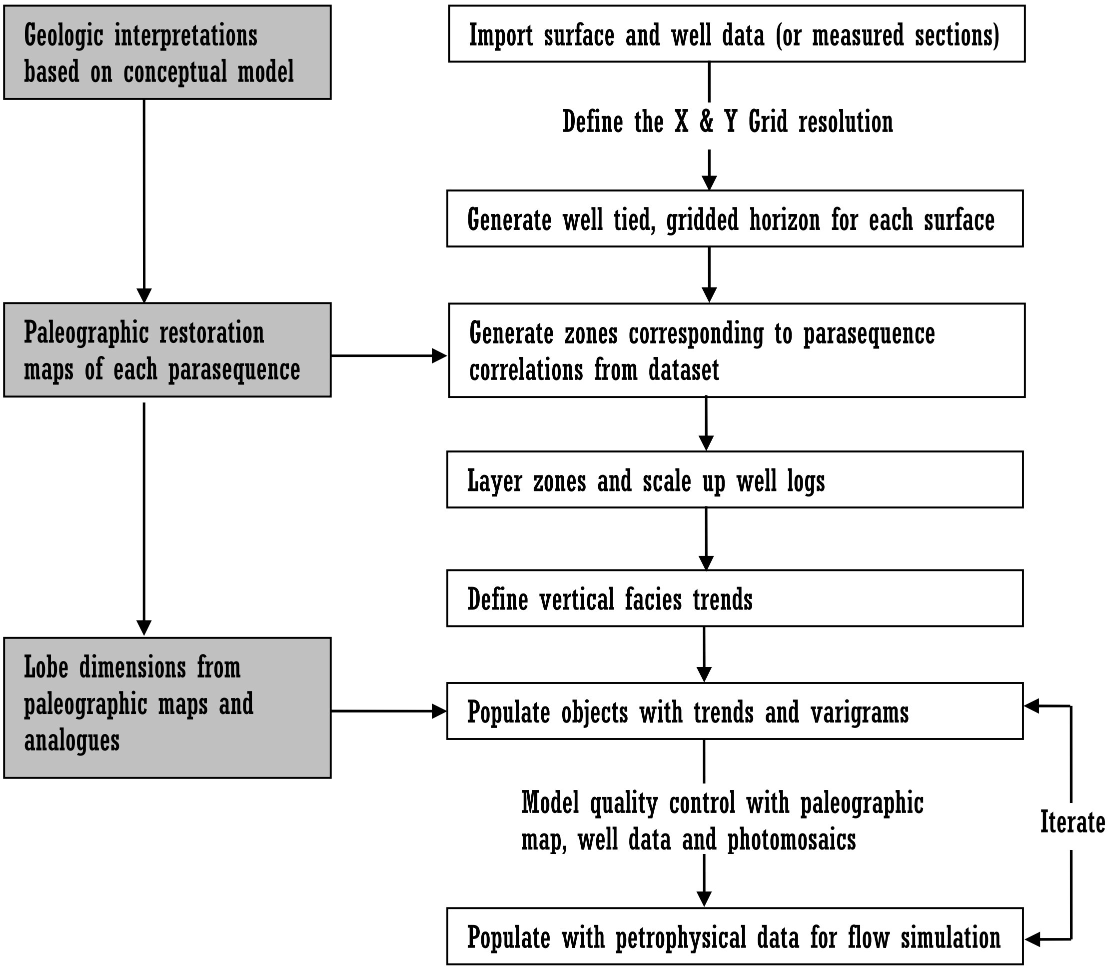

Figure1. Outcrop modeling workflow. The workflow also relates to workflow of reservoir modeling software (e.g. Petrel, Gocad or Roxar).

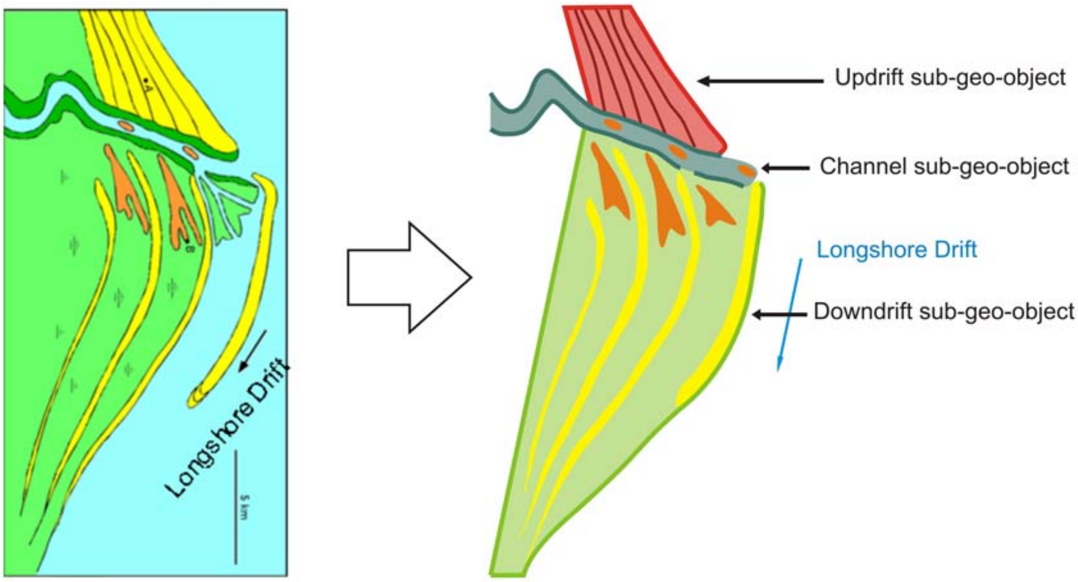

Figure 2. The schematic figure showing three object elements (right) describing an asymmetric lobe body (left)

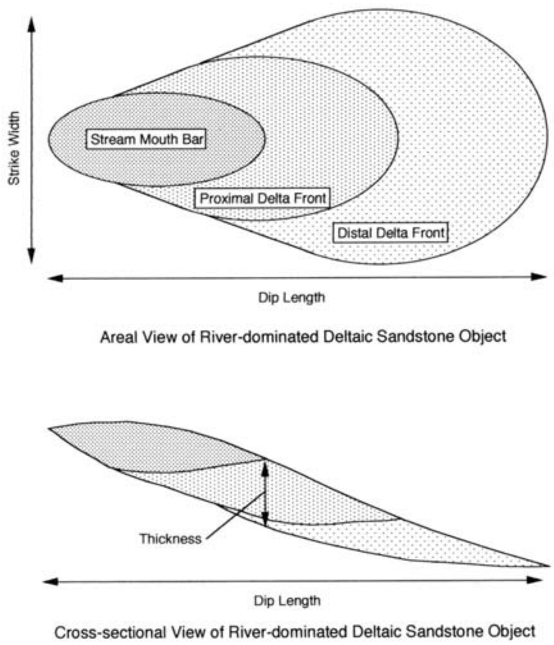

Figure 3. 3-D numerical geo-object for modeling river-dominated deltaic sandstones. The object is internally divided into three sub-volumes representing the stream-mouth bar, the proximal delta-front, and the distal delta-front depositional facies (Reynolds, 1999; Van den Bergh and Carrison, 2004).

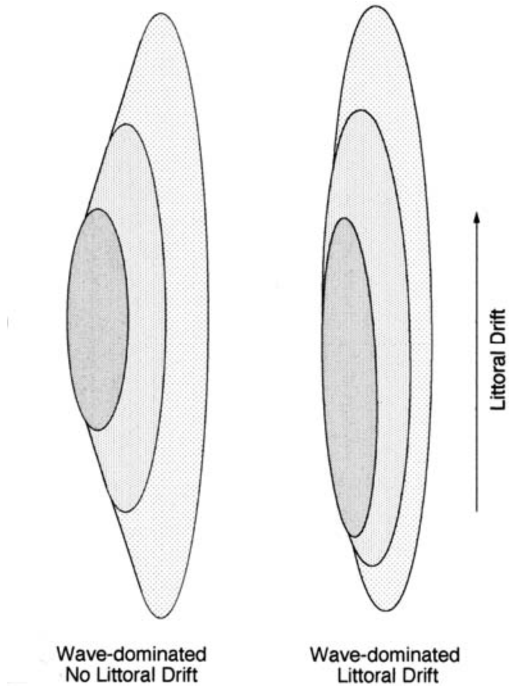

Figure 4. 3-D numerical geo-object for modeling wave-reworked deltaic sandstones (Reynolds, 1999; Van den Bergh and Carrison, 2004).

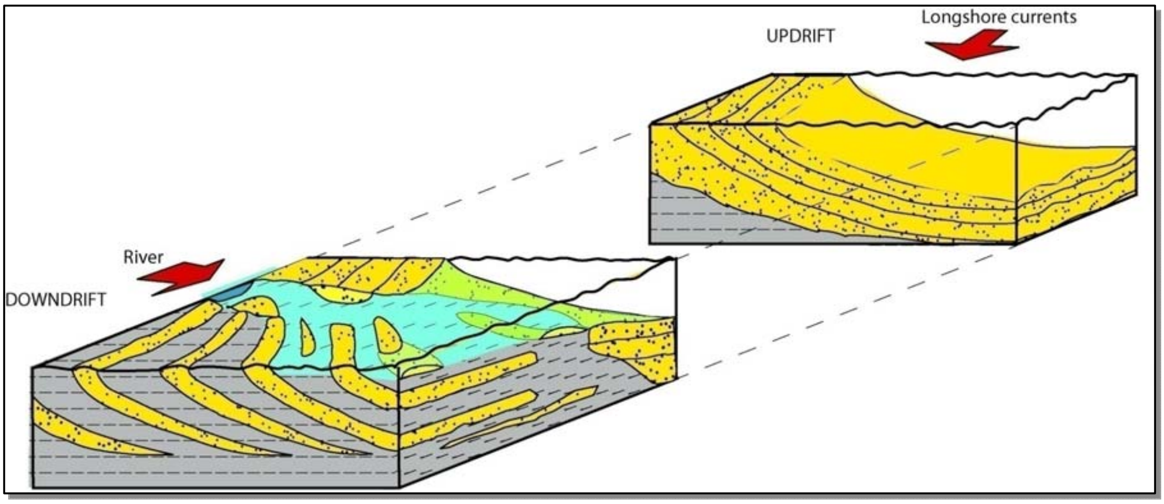

Figure 5. 3-D Conceptual asymmetric delta model (Bhattacharya and Giosan, 2003)

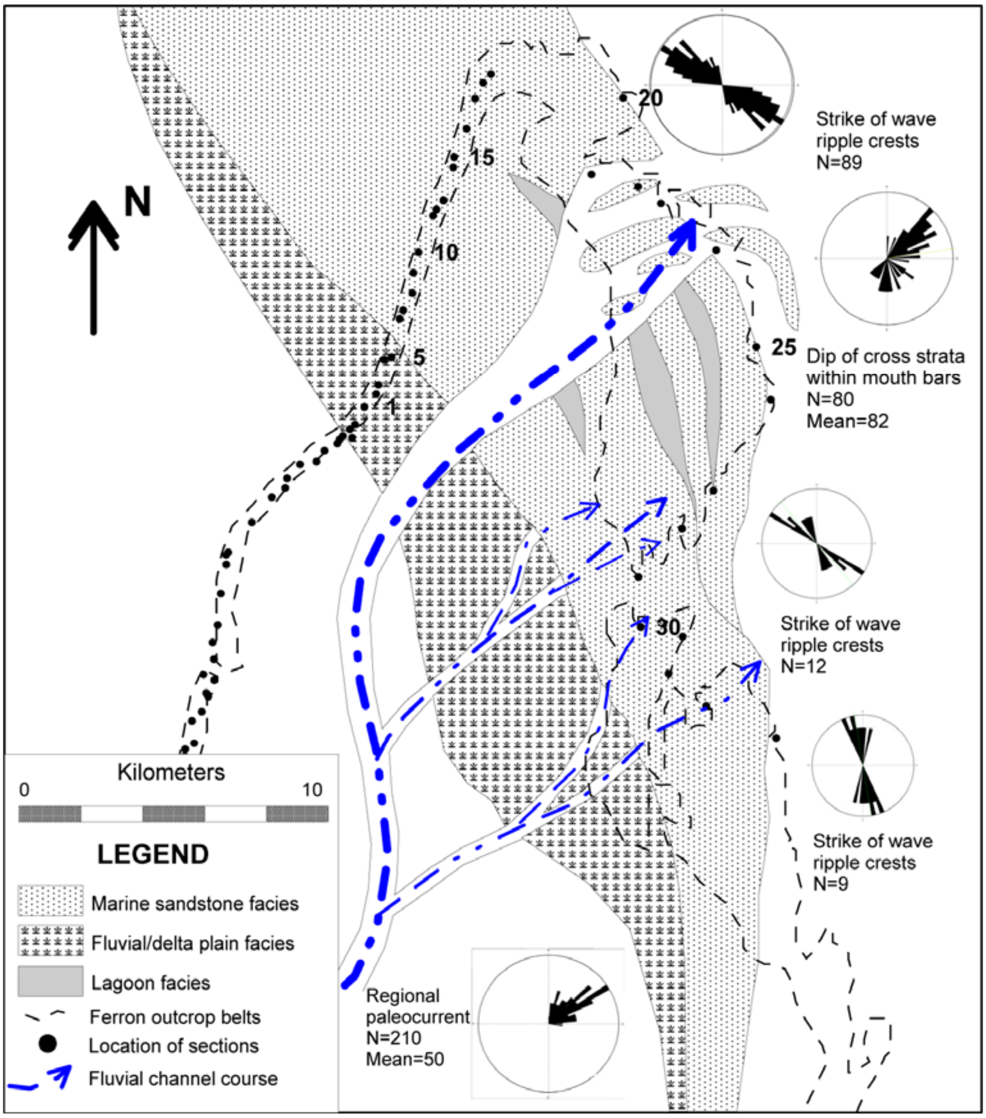

Figure 6. Paleogeographic restoration map of parasequence 6 in the Ferron Notom Delta, showing an asymmetrical wave- influenced delta (Li et al., submitted in 2009).

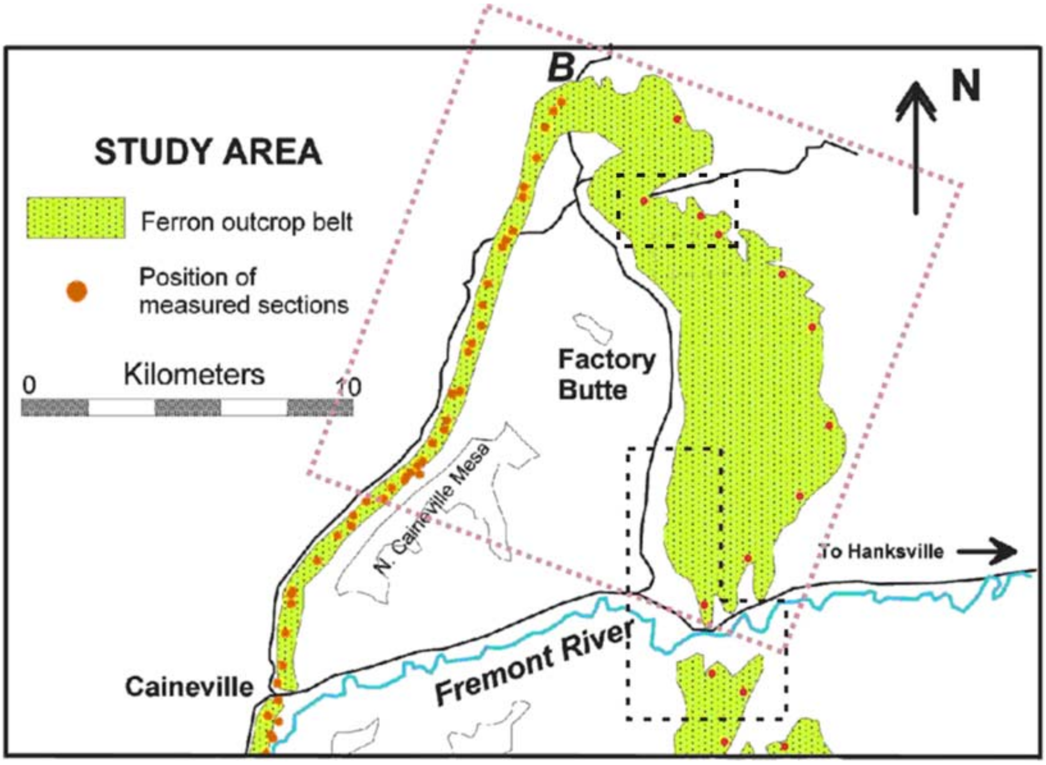

Fig.7 Data availability of modeling area. 28 regional sections measured by Y. Zhu and W. Li (2007, 2008) are in proposed modeling area. In the upper black dashed-line box, 30 local sections measured by Y. Li (2009), 22 local section measured by S. Ahmed (2009), 15 local sections measured by D. Garza (2008, 2009) and 7 sections measured by J. Kelso (2009). 40 local sections measured by W. Li (2008) in the lower black dash-line box.

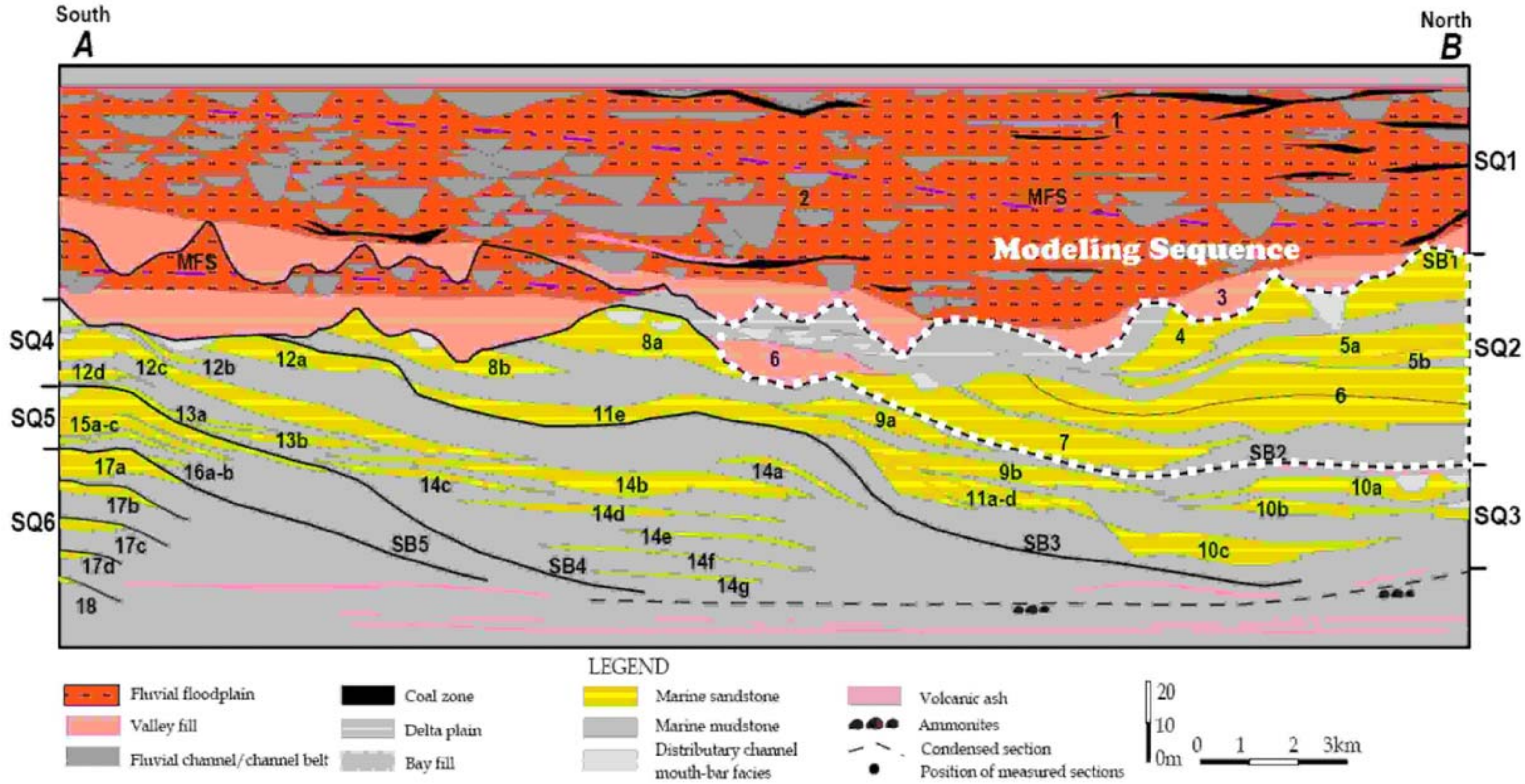

Fig.8 The fluvial-deltaic complex dip sequence stratigraphy, consisting of 6 depositional sequences, 18 parasequence sets, and 43 parasequences (from Zhu and Li, 2008). This modeling work will focus on Sequence 2, the white dotted line circled area.

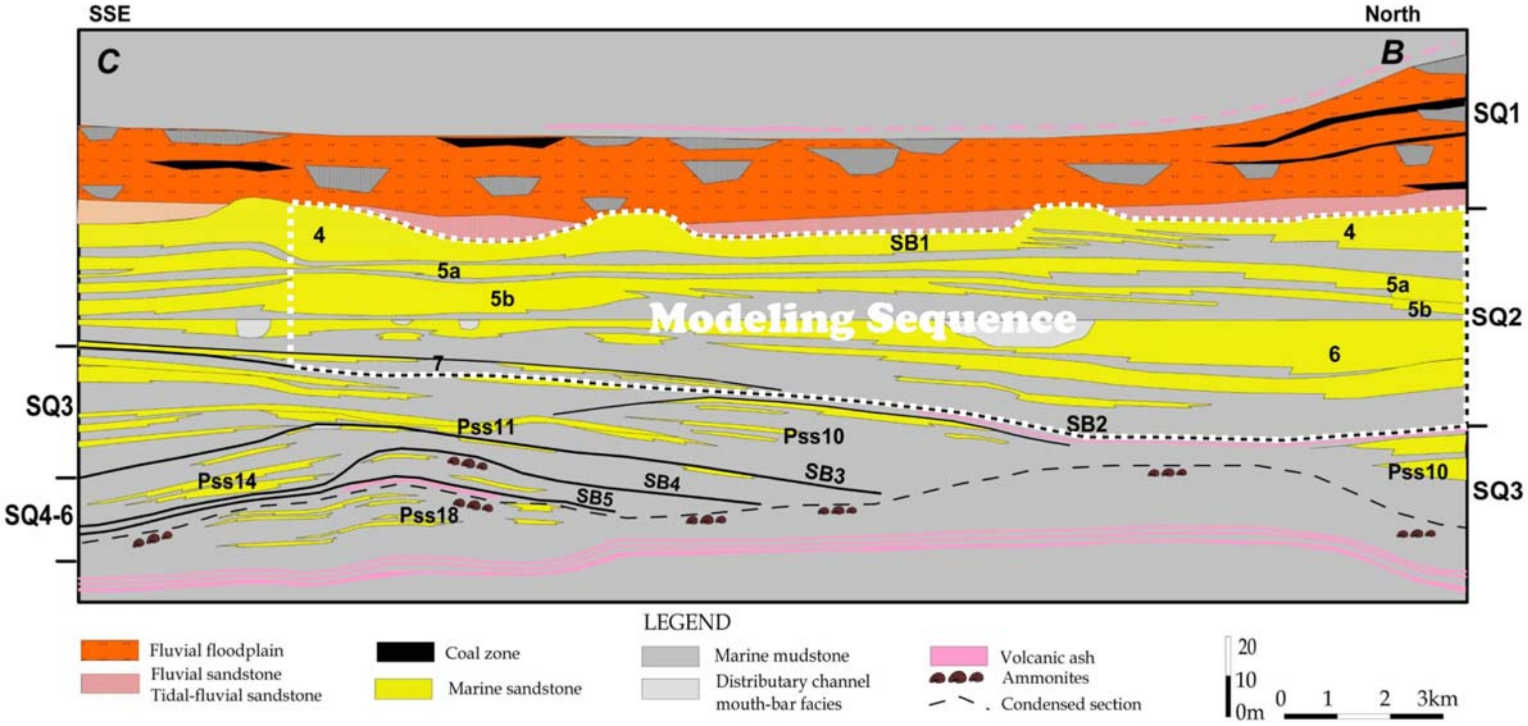

Fig.9 The fluvial-deltaic complex stike sequence stratigraphy, consisting of 6 depositional sequences, 18 parasequence sets, and 43 parasequences (from Li and Zhu, 2008). This modeling work will focus on sequence 2, the white dotted line circled area.