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Stochastic Surface Modeling in Mud Rich, Fine-grained Turbidite Lobes

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Mud rich, fine-grained turbidite fan deposits are significant exploration targets in the off shore Gulf of Mexico, West Africa and North Sea. Recent outcrop studies have indicated a potential for compartmentalization at a variety of scales due to the lateral continuity of shale facies within the lower fan environment. Well test, seismic data and well log provide excellent structural and stratigraphic information, but do not adequately resolve small scale features such as thin shale units that may have a significant impact on oil and gas production.

Analog outcrop studies often provide a wealth of information with respect to the continuity of these shale units. Distributions characterizing these units may be extracted and applied to a reservoir model through the application of stochastic surface techniques to assess the impact of shale baffles and barriers on producibility and the associated uncertainty.

A novel approach with stochastic surface simulation is introduced that honors the geometries and interrelationships between the surfaces, while honoring a realistic level of conditioning data.

Introduction

The inaccessibility of the subsurface generally results in a high degree of uncertainty. Stochastic models are required to quantify this uncertainty. These models provide a measure of uncertainty in reservoir response through the construction of multiple equally likely to be drawn realizations of reservoir properties such as porosity, permeability and lithofacies. Stochastic models are often cell-based; the model is calculated on a by-cell basis. These models are generally limited to two point statistics, the variogram, and do not efficiently reproduce complicated spatial structures. The motivation to construct more geologically realistic stochastic models has lead to research in object based and surface based models (Deutsch, C.V., Xie, Y., and Cullick, A.S., 2001). These models are able to reproduce a wide variety of geologic morphologies, such as those found in deep sea clastics.

Turbidites are unique since they are the result of discrete, short-lived events and their products are rarely reworked by other process after deposition. Turbidity flows may occur in any stage of relative sea level and may be caused by rivers in flood, earthquakes and sediment failures along rapidly deposited delta front. Turbidites are readily recognized in outcrops as thousands of thin alternating beds of graded sandstone and shales although they may result a variety of facies associations. Their extent may be large, for example the Black Shell Turbidite in the Western North Atlantic Ocean has some single beds extending beyond 500 km with a thickness of up to 4m (Walker, 1992, p. 240).

This work introduces and demonstrates a possible application of surface-based simulation to a specific setting observed in turbidite reservoirs. The procedures and algorithm presented here will be further developed to model a variety of deep sea clastic settings and to further honor geologic information.

Fine Grained Turbidite Lobes

Mud rich, low permeability turbidite fans commonly exhibit a hierarchy of compartmentalization in the lower fan lobes (see Figure 1). Individual lobes with thicknesses of 10’s of meters and lateral extents of kilometers are separated by thick shale units (often on the order of meters to 10’s of meters) (Dudley, Rehmer and Bouma, 2000, p. 318). These 3rd order architectural elements (Ghosh and Lowe, 1996) may be well defined by seismic and may be well correlated by well logs up to distances of kilometers.

Within these lobes, there may be higher frequency individual flow events. These 2nd order architectural elements (Ghosh and Lowe, 1996) represent individual flow events. Basin ward the turbidity flow events lose strength and may not significantly scour into previous lobes; therefore, the preservation potential of the shale divisions may be high. An outcrop study based on the fine-grained sheet sandstones in the Tanqua Karoo Subbasin, South Africa identified sections with only 65% of sandstone sheets connected over exposures up to a couple of kilometers (Dudley, R.C., Rehmer, D.E. and Bouma, A.H., 2000, p. 334).

These 2nd order architectural elements may have a significant impact of reservoir connectivity, but they are generally sub seismic and are poorly characterized. Surface-based stochastic models may be applied to characterize the shale units that are often present along the bounding surfaces of these sub seismic features and their potential influence on reservoir response.

Discussion on Data

Well test, seismic data and well log provide excellent structural and stratigraphic information. Multichannel lines reveal deep internal structure at a coarse scale, while 3.5 kHz reveals shallow structure (up to 10's of meters) with high resolution (Slatt, R.M. et al., 1998, p. 845).

Without data there would not be a difficulty in reproducing the complicated geometries within a depositional setting. Quantitative dynamic stratigraphy (QDS) models based on initial and boundary conditions and on a continuum of relationships spanning well established fundamental laws, first order approximations, empirical relationships to poorly defined gross empirical relationships are available (Cross and Harbaugh, 1989). These models are able to reproduce the wealth of geometries and relationships observed in the sedimentological record. While these models are useful for refining conceptual models, their chaotic nature renders them unable to be conditional to a realistic level of data.

Methodology

Large scale 3rd order architectural element lobe geometries are first established from the available data. A measurement of error is assigned to the interpolation between wells. Uncertainty due to this error is injected as simulated fluctuations in the large scale surfaces. Realizations of the 3rd order architectural element are retained to define the original bathymetry and the container.

The algorithm steps forward by generating flow events characterized by bounding surfaces. It is assumed that flow events are low energy and do not significantly scour the previous flow events; therefore, they do not change the geometry of previous flows. Also, allogenic controls, such as tectonics are not considered.

The creation of stochastic bounding surfaces to characterize the individual flow events requires two steps. First, the geometry is generated and then a stochastic residual is added with 2D sequential Gaussian simulation. The geometric construction considers factors such as; (**1**) source location, (**2**) bathymetry, (**3**) flow path and (**4**) characteristics lobe geometry. The stochastic residual accounts for fluctuations within the bounding surfaces and is conditioned to well data.

The source location represents the entry location of a flow event into the lobe. The source is stochastically located along the proximal margin of the lobe prior to each flow event. The source location is drawn from a probability distribution with the probability inversely proportional to the elevation of the margin; therefore, flow events are more likely to enter in the lowest parts of the proximal margin of the lobe.

The bathymetry is initialized as the base of the lobe. Subsequent flow events modify this bathymetry. Bathymetry directly effects path of subsequent flow events. Flow paths are set to follow the path of steepest gradient. The length of the flow path is based on a stochastically drawn energy, and energy consume per unit distance is inverse proportional to gradient. Thus the energy measure has a direct influence on extent and volume of flow events.

Distributions characterizing the thickness and width of the flow events are determined from analog and are scaled by the gradient and distance along the flow path. As the gradient decreases the lobes widen, and the flow event thins towards the distal. See Figure 2 for a schematic illustrating the construction of geometry of individual flow events.

The stochastic residual is characterized by nominal amplitude and a variogram model. The variogram model defines the smoothness of this residual. The residual is simulated by a 2D version of SGSIM from GSLIB (Deutsch and Journel, 1998).

Application

This algorithm was applied to construct stochastic flow event surfaces within approximate lobe geometry, conditioned to contacts at four vertical wells (see Figure 4).

The average energy is set so that most flow events would reach the distal edge of the lobe and the average width of the flow events was set to a quarter of the width of the lobe. The 2D variogram applied for the simulation of the residual was set with a long range. Two equally likely to be drawn realizations are shown in Figure 5.

Conclusions

- Stochastic surface reproducing the complicated inter-relationship of sequential flow events within a turbidite lobe and conditional to well data have been demonstrated.
- Future work will include involve the application of this technique to an actual reservoir setting and further refinement of surface geometries.
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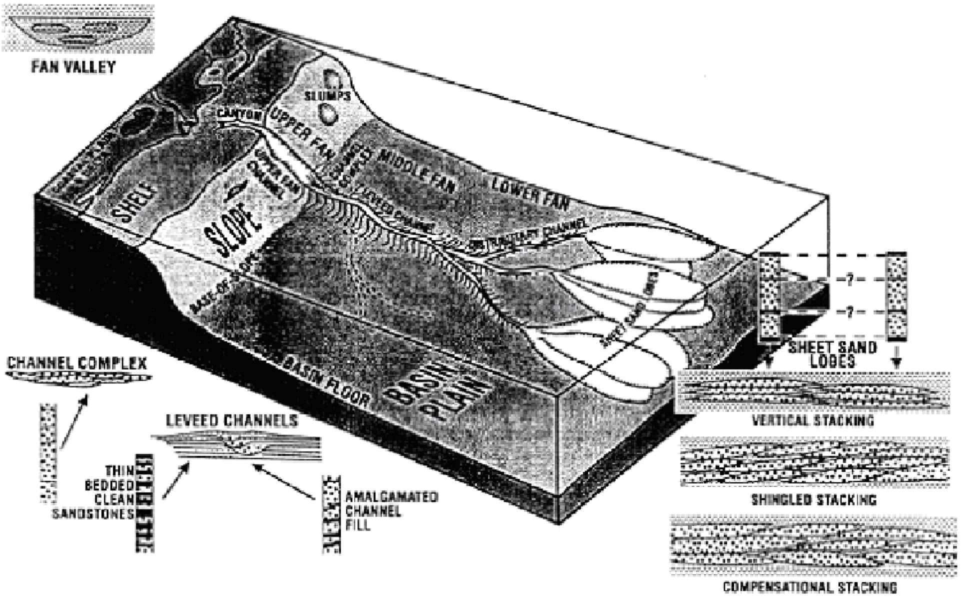

Figure 1 - a facies model for fine-grained, mud rich submarine fan systems (taken from Dudley, Rehmer and Bouma, 2000, p. 328)

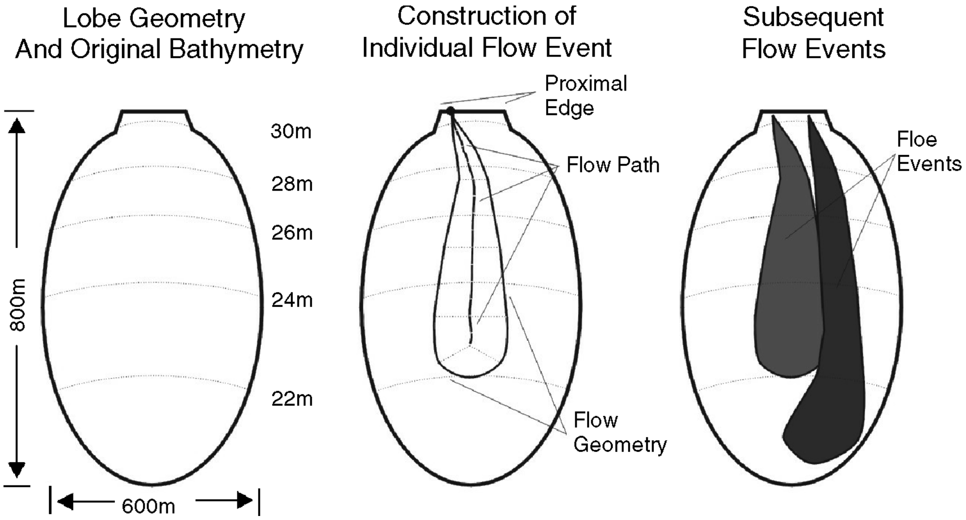

Figure 2 – the construction of individual flow events within a lobe. An example lobe geometry and bathymetry are defined. In a stepwise manner stochastic flow events are generated, characterized by flow path and flow geometry around the flow path.

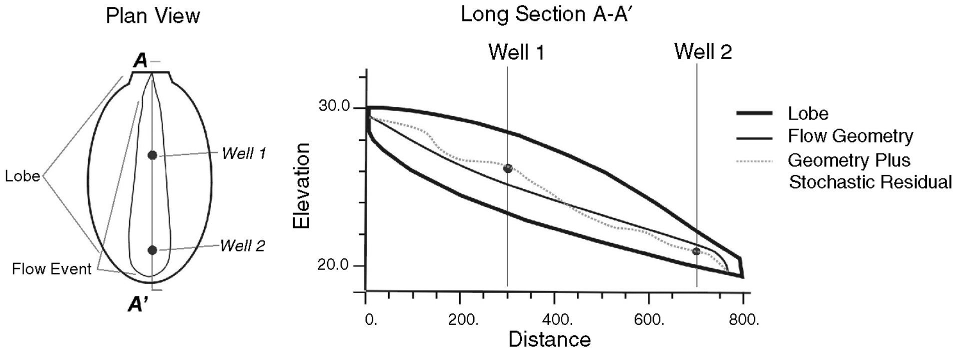

Figure 3 – the the addition of a sctochastic residual to characterize fluctuations and to allow for conditioning to well data.

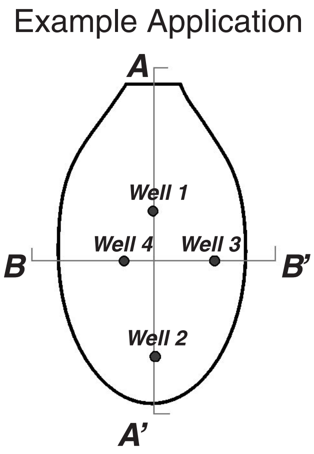

Figure 4 – the layout of the example application. All wells are vertical.

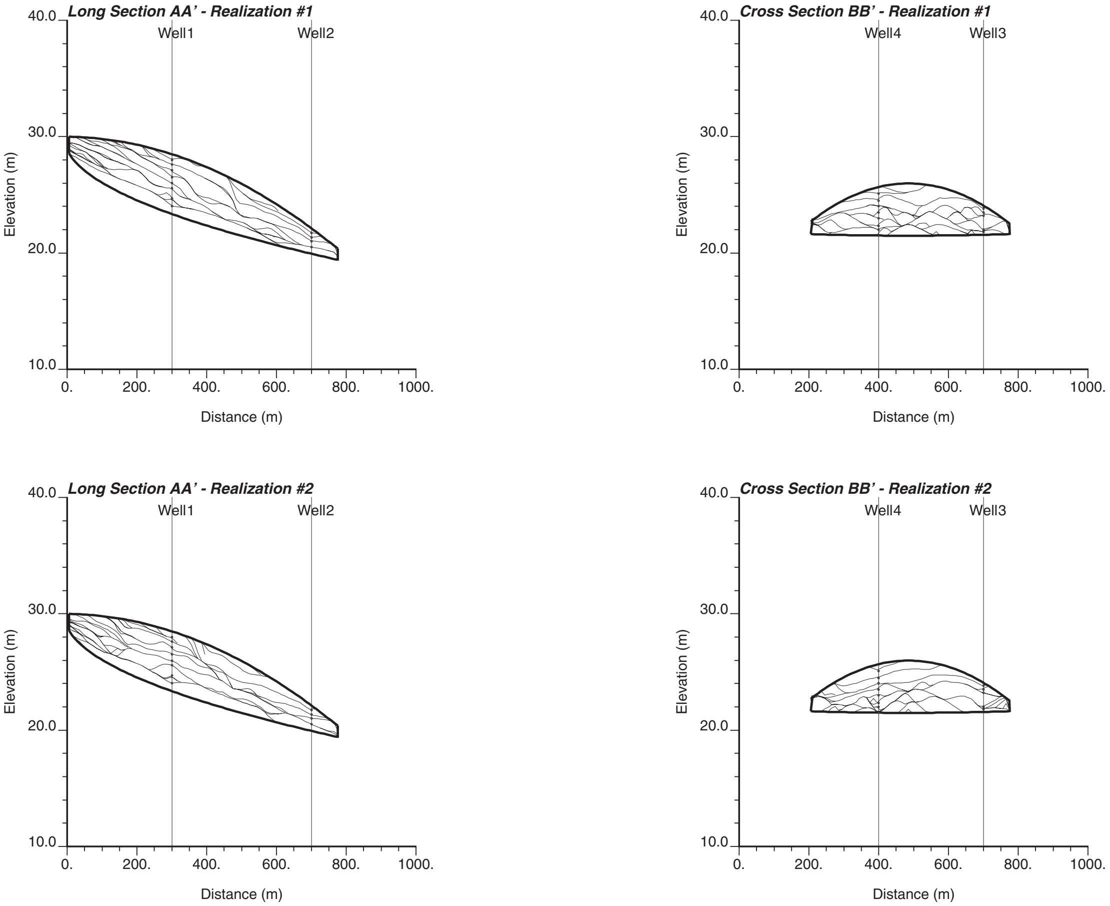

Figure 5 – two equally likely to be drawn realizations of within lobe flow event surfaces conditioned to contacts identified at the four wells.