

Increasing Geological Accuracy in Reservoir Models through Process-Oriented Modeling*

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Search and Discovery Article #50215 (2009)

Posted November 10, 2009

*Adapted from oral presentation at AAPG Annual Convention, Denver, Colorado, June 7-10, 2009

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Abstract

An important task in constructing digital reservoir models is the capture of geological detail with sufficient resolution to reduce the uncertainty inherent in interpolation between discrete data points. Even the most sophisticated mathematical or statistical reservoir modeling algorithm, however, remains ignorant of the processes by which reservoir strata are deposited. In a test of process-oriented modeling, which places lithofacies in a reservoir body according to geological rules, we constructed a series of conceptual fluvial models by stochastically placing multiple channel-fill models within the model volume. The desired outcome was a digital fluvial reservoir model incorporating the small-scale, local lithologic variation generated by channel switching and stream aggradation within a broad meander belt.

Process-oriented modeling software was used to generate multiple model realizations ranging from 50% to 70% sandstone by volume. Geometric parameters (channel azimuth, meander wavelength and amplitude, and channel width and depth, etc.) were defined in terms of mean and standard deviation. The software also allows explicit definition of these values. Up to 100 channels were placed in each model volume via random processing. As in the case of geometric parameters, channels may also be deterministically placed by digitization of a channel axis or axes.

Fluvial channels generated by the modeling display geologically accurate internal geometry. The model exhibits cross-cutting relationships between channels and isolated remnants of overbank and abandoned-channel deposits that would form local permeability barriers. The resultant distribution of lithofacies differs from geostatistically-generated models in its preservation of small-scale variations in lithology, and in rule-based lateral and vertical variation and sharp contacts among lithofacies. The use of process-oriented modeling yields facies geometries that honor the distribution of lithologies and sedimentary structures observed in the rock record. This geology-based rock distribution allows improved accuracy in population of a reservoir model, especially where reservoir parameters are facies-dependent.

References

Miall, A.D., 1996, The geology of fluvial deposits: sedimentary facies, basin analysis and petroleum geology: Springer-Verlag Inc., Berlin, 582 p.

Tyler, N., and R.J. Finley, 1991, Architectural controls on the recovery of hydrocarbons from sandstone reservoirs: Concepts in Sedimentology and Paleontology, v. 3; p. 1-5.



Increasing Geological Accuracy in Reservoir Models through Process-Oriented Modeling

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2009 AAPG Annual Meeting
Denver, Colorado

Purpose of Study

- Construct a conceptual geological model using process-oriented modeling (POM)
- Resolve heterogeneity in range of fluvial environments and scales
- Compare POM-based geological and property models to conventional stochastic models



Presenter's Notes: Outgrowth of work performed for a major oil company who preferred that the conceptual models not be published. Models presented here are not those created for the client, and the input parameters have been varied from those of the original project. Our client then compared the results of this modeling, both fluvial facies and reservoir property models, to similar conceptual models created stochastically.

Process-Oriented Modeling: an Overview

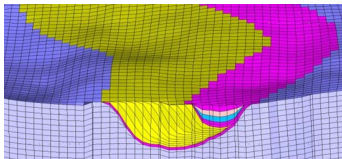
- Distributes lithofacies within stratigraphic sequence as controlled by genetic factors:
 - Geology, *e.g.*, vertical sequence of facies in channel deposits
 - Geometry, *e.g.*, width and height of depositional unit
- Images small-scale lithologic variations within a reservoir's internal structure
- Emplaces non-reservoir intervals to compartmentalize reservoirs naturally
- Allows distribution of reservoir properties on basis of lithofacies, not depositional unit (*e.g.*, "channel lag" instead of "channel")



Presenter's Notes: Process-oriented modeling builds a lithofacies distribution that obeys the geometric and genetic relationships inherent to deposition. Both the position and shape of sediment bodies are defined by the processes that create them, in the case of this study, a range of fluvial environments. POM also allows the distribution of reservoir parameters on the basis of those small-scale lithologic units, such as channel lag and abandoned channel, instead of on the basis of the entire deposition unit – the channel.

Process-Oriented Modeling with *ReservoirStudio*

- Process-oriented modeling of clastic environments based on facies geometry and fluid dynamics
- Parametrically-controlled by user across multiple levels of detail
- Combines stochastic and deterministic modeling of sedimentary facies
- Property distributions specific to depositional facies instead of overall sedimentary unit



Presenter's Notes: As mentioned, we used Geomodeling's Reservoir Studio software for the project. Reservoir Studio is a process-oriented modeling tool that can be used to build models of clastic environments. The software provides modules for modeling in several environments, including channel-infill, which was used for this project (as shown in the cartoon), channel-levee, and channel plus lobe for turbidites. A finished model typically includes 7-12 different depositional facies of the twenty-five defined facies.

Reservoir Studio's interface allows users to specify channel location and shape, along with many other geometric parameters. Users may alternatively allow stochastic processes to design the channel(s), or combine the two types of specification as desired across a sort of continuum from pure stochastic to mostly deterministic. The software allows for multiple realizations of stochastically-defined values.

Reservoir properties are specified on the basis of the depositional facies, so property distributions reflect the modeled environment's internal stratigraphy. Property modeling can also be performed in multiple realizations

The Varying Resolutions of Geological Models

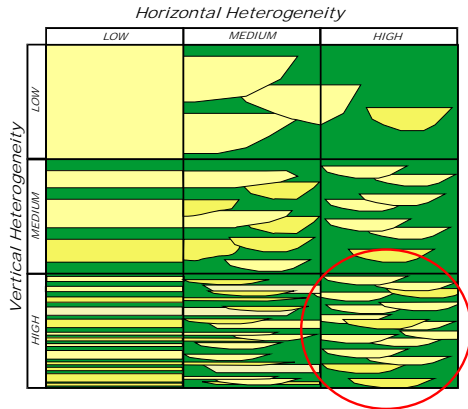
- **Megascopic** scale: “fluvial deposits within an intracratonic basin”
- **Macroscopic** scale: “a meandering channel complex on a coastal plain”
- **Mesosopic** scale: “shale drapes within an upper point-bar facies”
- **Microscopic** scale: “fine sand laminae in a ripple cross-lamination set”



Presenter's Notes: The conceptual model allowed us to evaluate the utility of Process-oriented modeling across two scales of observation, the macroscopic and the mesoscopic scales.

Most geological models are built with what one might term the “macroscopic scale,” which in the context of this study is about the scale of channels or channel complexes. We wanted to test both the validity of models at this common scale, plus evaluate models at the mesoscopic scale, which capture the internal stratigraphy of channels and the cross-cutting relationships between channels within a meander belt. This is a level of heterogeneity at which we can model the facies that create reservoir compartments – facies such as shale drapes and abandoned channels.

Heterogeneity Across Multiple Scales: Macroscopic



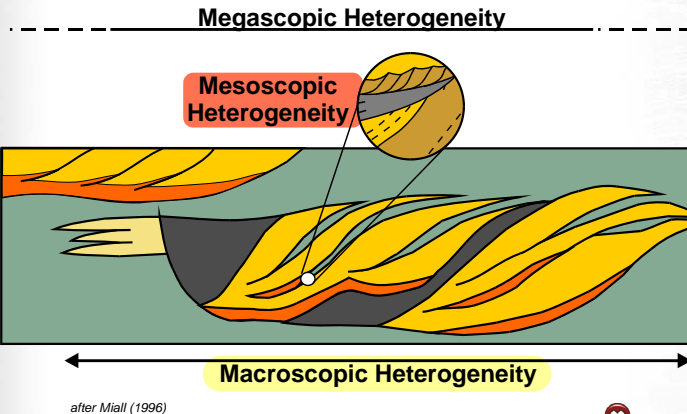
after Tyler and Finley (1991)



Presenter's Notes: At a macroscopic scale, that of channels and channel complexes, reservoir compartments depend on the vertical and lateral extent of a sand body. At this scale, most modeling does little more than a simple differentiation into channel and not channel. In that sense, a compartment becomes only as small as a bedset.

For this study, our client wanted models of the high horizontal-high vertical heterogeneity case in the lower right compartment, what is called the "labyrinth."

Heterogeneity Across Multiple Scales: Mesoscopic

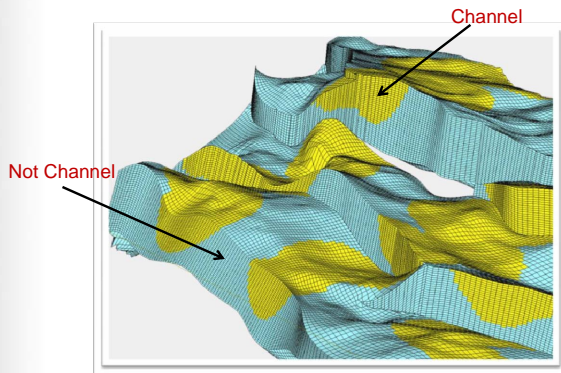


Presenter's Notes: Where conventional modeling appears to fall short is at the mesoscopic scale, shown in this cartoon after *The Geology of Fluvial Systems*

What is shown here is a complex array of channel lag, point bar deposits, and shale drapes, all displaying dipping into the thalweg at an angle. There are also remnants of abandoned channels, where low-permeability fines separate packages of reservoir-quality sands.

A channel reservoir contains all of these sedimentary packages in a complex arrangement of lithologies, each with its own reservoir properties. The interaction of multiple channels results in heterogeneity on the macroscopic scale, which we regularly image. The internal stratification of a channel in response to active depositional processes produces mesoscopic heterogeneity, which we are not quite "getting right."

Accretionary Channel Infill: Conventional Model

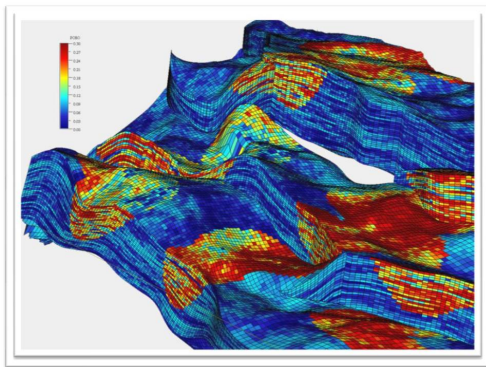


“Binary” facies distribution



Presenter's Notes: By way of illustration, here is a sample of a facies model built by stochastic processes. It reflects a sort of “binary” facies system, in which the reservoir interval is subdivided into “channel” and “not channel” intervals: either you are in the channel or you are not. Most of us have built these, or ternary systems that add in a channel levee facies. In either case, though, statistically-based modeling packages are stochastic and are ignorant of the processes that created the details at the mesoscopic scale.

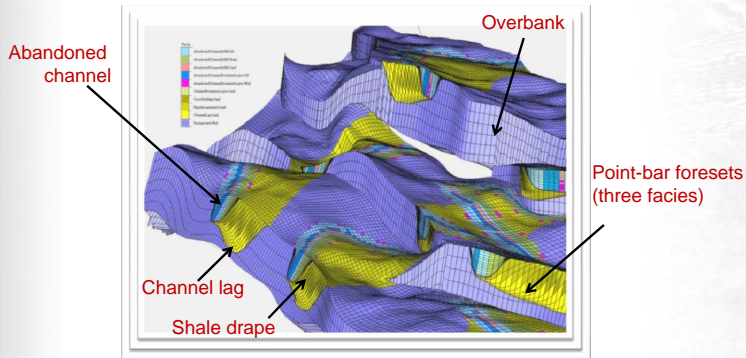
Porosity Distribution, Conventional Model



Presenter's Notes: When we populate a binary facies model, regardless of the algorithm used, the properties end up distributed across the channel interval without respect to the processes by which the sediments were deposited and their inherent geometries.

In this illustration, for instance, rather than an aggradational system in which point-bar foresets build out from the inside of meanders, the properties are distributed as if fluvial sediments are deposited in horizontal layers. There are no abandoned-channel facies and no shale drapes, both of which can be critical to compartmentalization.

Accretionary Channel Infill: Process-Oriented Model

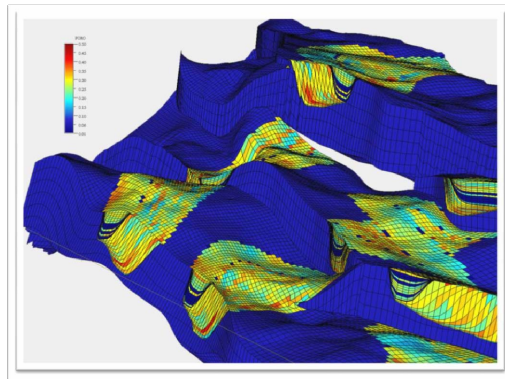


Multiple facies



Presenter's Notes: By using process-oriented algorithms to model our channels, we were able to mimic the fluvial system's inherent mesoscopic heterogeneity. Note the clinoform structure of the point-bar deposits, and the manner in which each is subdivided into three separate facies: channel lag, cross-bedded sand, and ripple-laminated sands. Shale drapes can also be inserted if so desired.

Porosity Distribution, Process-Oriented Model



Presenter's Notes: Taking a look at a property model based on a process-oriented facies model, you can see how the reservoir properties of the individual facies are honored: mixed layering in the abandoned-channel facies captures the presence of low-permeability/porosity baffles. There is a "sweet spot" in the cross-bedded sandstone facies that stands out among the relatively lower porosities at the base of the channel in poorly sorted lag and at the shallow end of the point bar deposits, where lower energy may not have winnowed out fines as well.

Model Specifications

- Two fluvial environments:
 - Low-sinuosity streams with silty-sandy overbank deposits (lower zone)
 - Medium-sinuosity streams with muddy overbank deposits (upper zone)
- Input control parameters:
 - Channel sizes and orientations
 - Meander amplitudes and wavelengths
 - Relative proportions of fluvial facies (channel lag, point bar, abandoned channel fill)
 - Property distributions on facies-by-facies basis (mean and standard deviation)



Presenter's Notes: With that background, let us now talk about the project specifics.

The conceptual model consists of two fluvial systems: a Lower zone that is a low-medium sinuosity meandering system with silty to sandy overbank deposits, and an Upper zone that is medium-sinuosity fluvial deposits with more mud-prone overbank deposits.

Basic controls on the fluvial systems include: (1) Mean and standard deviations of the width and depth of the channels as well as mean azimuth; (2) mean amplitude and wavelength of the meanders, both of an active channel and of the abandoned channel facies following an avulsion event; (3) the relative proportions of the fluvial facies, including channel lag, middle and upper point-bar facies, and abandoned channel fill facies, plus channel-bounding permeability barriers and internal shale drape geometry; (4) properties expressed as mean and standard deviation for each facies in each zone.

Questions to Answer

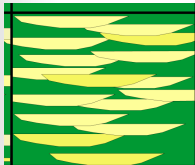
1. Does the use of Process-Oriented Modeling capture reservoir heterogeneity at the macroscopic scale?
2. Does the use of Process-Oriented Modeling improve resolution of the mesoscopic heterogeneity inherent to fluvial reservoirs?
3. Can the use of Process-Oriented Modeling provide “geologically nuanced” realizations of reservoir properties at both macroscopic and mesoscopic scale?



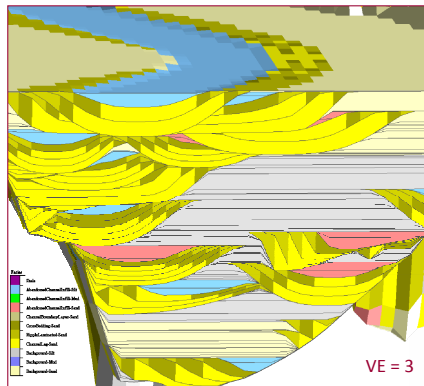
Presenter's Notes: This conceptual-model exercise was intended to answer a number of questions about the differences between POM and conventional stochastic modeling, with special attention to the three you see here.

We shall use some snapshot views of the output models to determine the answers, beginning with the first one.: Does Process-Oriented modeling capture reservoir heterogeneity at the macroscopic scale – remember, that is the scale of channels and channel complexes.

Realization of Lower Zone (flattened on top surface)



after Tyler and Finley (1991)

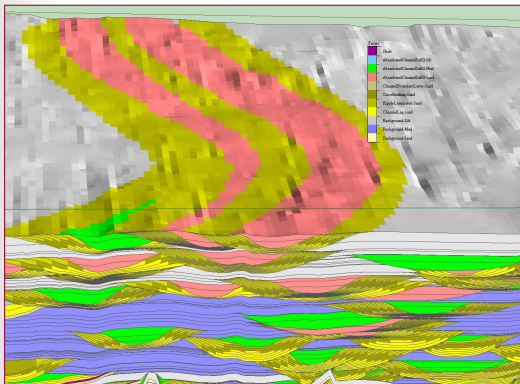


Presenter's Notes: Our first look at the output models is one realization of the lower zone – the low-medium sinuosity meandering channel. Here, the model is flattened on the top of the lower zone for viewing clarity. Vertical exaggeration is 3:1

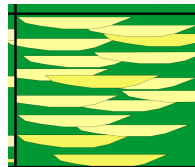
The lower zone contains multi-story stacked channels, shown here in cross-section. Per input specifications; channel lag (light yellow) deposits in this zone are thick relative to the cross-bedded sandstones and ripple laminated sandstones higher in the point bars (darker yellow), and the abandoned channel deposits are sandy (pink) or silty (cyan). The overbank deposits are dominantly silt (gray) with some sand (beige).

I have shown the “labyrinth” (high vertical-high horizontal heterogeneity) case from the Tyler and Finley (1991) classification alongside.

Realization of Upper Zone



VE = 3

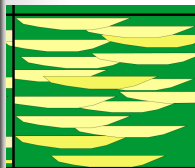


after Tyler and Finley (1991)

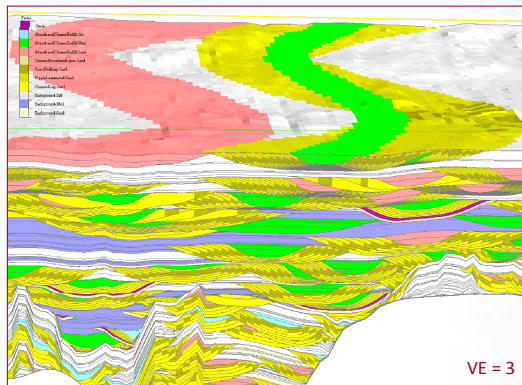


Presenter's Notes: Here is a view of the upper zone, the medium-sinuosity meandering system. This view also has a vertical exaggeration of 3:1. This zone has more muddy sediment in the overbank deposits (blue), as well as the abandoned channel deposits (green). Three channels can be seen on the upper surface, two of which rework older channel deposits. Note the presence of additional permeability baffles in the form of subtle shale drapes (purple) that occur in selected channels marked here by arrows. These show more clearly in the next slide. Again, the Tyler and Finley labyrinth is shown for comparison.

Selected Realization of Completed Model



after Tyler and Finley (1991)



Presenter's Notes: And finally, a section of an entire model realization showing both zones. Vertical exaggeration = 3. Tyler and Finley labyrinth displayed for comparison.

Question #1 asks if POM captures heterogeneity at the macroscopic scale. Based on visual comparison to our "go-by," the labyrinth case, the answer is yes. As the modeled system aggrades, POM stacks channels and channel complexes to achieve vertical heterogeneity. Within channel complexes, relatively young channels run sub-parallel to and sometimes cross-cut older channel courses, cannibalizing existing deposits to increase lateral heterogeneity.

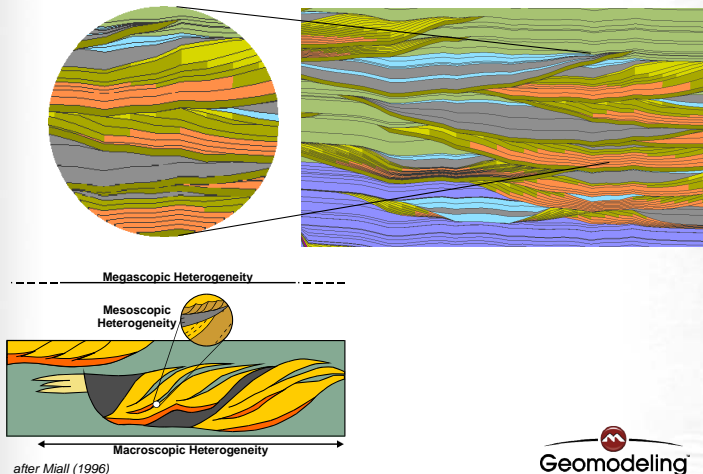
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Presenter's Notes: That brings us to question # 2, in which we turn to the smaller-scale sub-seismic heterogeneities that depend on position in a stream's cross-section. Does POM capture this mesoscopic heterogeneity?

Mesoscopic Heterogeneity in Facies Modeling



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Presenter's Notes: The "go-by" here is that schematic cartoon we saw before, in the lower left (geology of fluvial systems). Let us compare that schematic representation of multiple channels with included shale drapes and abandoned-channel deposits to a section of a facies model from the upper zone. The depositional facies appearing within the model have been colored to approximate those of the schematic: Orange--channel lag; yellow and gold--point bar deposits; dark gray--abandoned channels (in the model, the abandoned channel consists of interbedded mud (gray) and silt (cyan)); greenish--overbank fines, mainly mud.

Compare the circular detailed insets, which show both mesoscopic heterogeneity caused by the interbedded facies and potential reservoir compartmentalization resulting from angular contacts between deposits of different channel generations.

So the answer to question # 2 – capture of mesoscopic heterogeneity – is again yes.

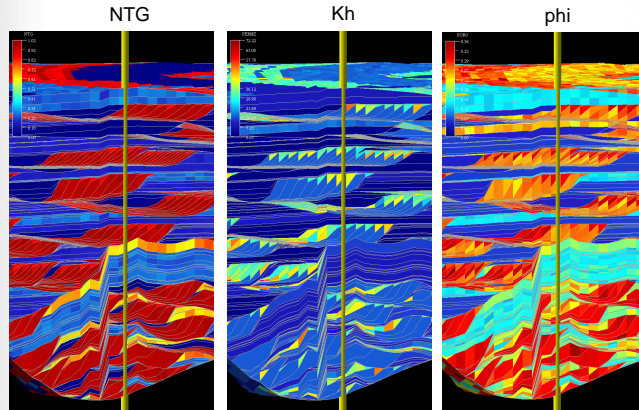
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Presenter's Notes: Which brings us to question #3: will using POM assist in building a property model that takes into account the mesoscopic variations in geology, instead of concentrating on features the size of a channel or channel complex? More pictures:

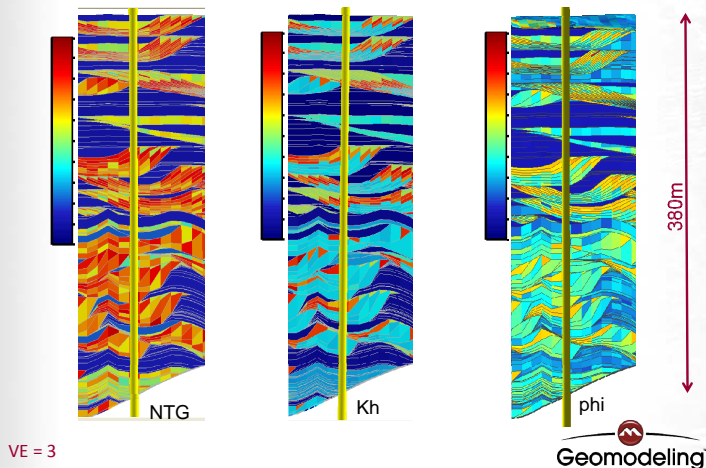
Reservoir Properties, Well 11-08



Presenter's Notes: We assigned three different reservoir properties to each one of the dozen or so different facies, in the model using mean and standard deviation of the property. Reservoir Studio uses Gaussian simulation to distribute the properties within a model cell based on its facies. In this example you can see the effects of assigning different reservoir properties to the four different processes that deposit sand in the model – channel lag, cross-bedded point-bar sands, ripple-laminated point bar sands, abandoned channel sands – and to the silty bodies in the overbank and abandoned channel. Abandoned channel fill stands out as non-reservoir sections of the model, even immediately adjacent to good-quality sands.

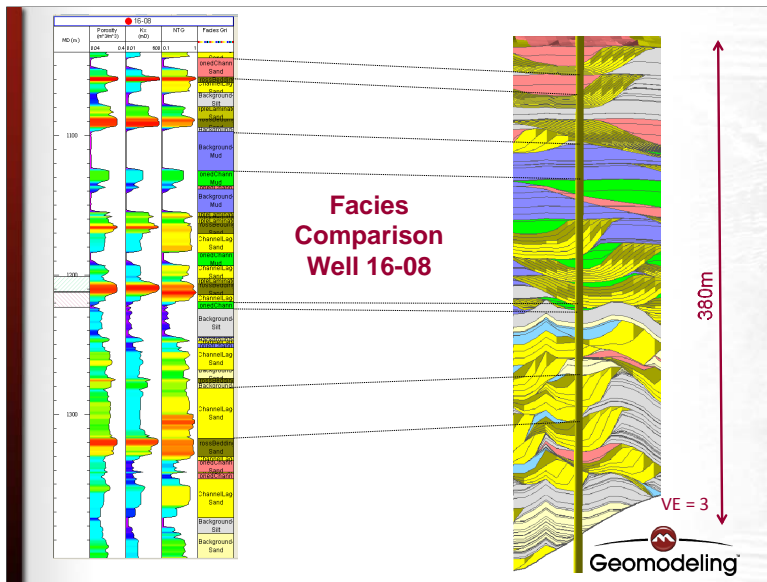
Vertical exaggeration = 3

Reservoir Properties, Well 16-08



Presenter's Notes: Here is a second montage showing hypothetical well 16-08. Again, note the variations in reservoir properties resulting from the mesoscopic-scale heterogeneity based on the depositional processes. The occurrence of abandoned-channel deposit baffles is particularly well shown just above the middle of the section.

VE = 3



Presenter's Notes: Another well montage comparing the reservoir properties (left) occurring in this hypothetical well to a slice through the facies model (right). This well actually sits in the middle of the cell immediately in front of the slice; this causes slight variations in thickness and position of facies in the two views. The tracks in the montage are, from left to right, porosity, horizontal permeability, net:gross, and fluvial facies.

Again, note the high-quality reservoir intervals corresponding to the "sweet spot" cross-bedded point-bar sands, which display the most favorable properties. These two montages suggest that the answer to question 3, does POM capture property heterogeneity attributable to the depositional environment, is also yes.

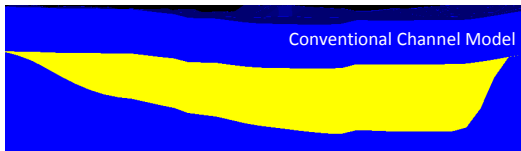
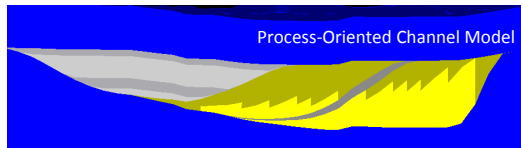
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Presenter's Notes: Our conceptual-model exercise was intended to answer a number of questions about the differences between POM and conventional stochastic modeling, especially these three. Let us look at the answers.

Choose Your Channel



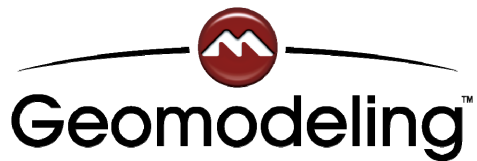
Acknowledgments

Thanks to my colleagues at Geomodeling Houston (John Sherman, Jerry Mazzaferro, Jeff Donnellan, Paul Casey) and at Geomodeling Calgary (Renjun Wen, David Segonds, Peter Phillips, Fred Peterson, Les Dabek, Jeanne Gonnason, and Scott Mitchell) for your input and suggestions.

Thank you also to the anonymous company who commissioned this study: you know who you are.



Questions?



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Maximized revenues

