Hierarchical modeling of multi-scale flow barriers in channelized reservoirs

Hongmei Li and Jef Caers
Stanford Center for Reservoir Forecasting
Stanford University

Abstract

Channelized reservoirs often show multi-scale architectures such as large-scale channel belts, middle-scale single channels and small-scale channel infill facies. These architectural elements are defined between bounding surfaces. Along these hierarchical bounding surfaces, thin shale drapes may be present as flow barriers that compartmentalize the reservoirs. Since the distribution of shale drapes are governed by the bounding surfaces of multi-scale architecture elements, they represent multi-scale heterogeneities. Characterizing the distribution of these multi-scale flow barriers calls for a hierarchical modeling approach in which the large-scale reservoir architecture is modeled first, the shale drapes are then simulated within this architecture framework.

The reservoir architecture modeling in this paper involves defining channel deposition fairways (valleys) based on seismic data, modeling long sinuous channels and placing them into defined fairways such that all data are matched. The criteria for choosing a modeling approach include the ability to match hard data, to define object (channel) boundaries (for the purpose of attaching shale drapes), to reproduce a given stacking pattern and to be CPU efficient. This paper adopts a stratigraphic-based modeling approach. In this stratigraphic-based approach, individual channels are simulated using the YACS method (Alapetite et al., 2005). This method is fast and conditions to well data under the assumption that channel sand can be identified in the well data. To put multiple channels together reproducing desirable stacking patterns, the overlap ratio and migration ratio are simulated. The two parameters are typically used by geologists to describe the channel geometry. The overlap ratio provides the information of vertical overlap between channels, while the migration ratio describes the lateral overlap information between channels. Once the large-scale reservoir architecture is modeled, the
corresponding bounding surfaces are recorded; next the shale drapes are simulated along these surfaces using multiple-point statistics techniques.

1 Introduction

Deep-water deposits or fluvial sediments contain architectural elements, defined between bounding surfaces which may be erosional or conformable (Clark & Pickering, 1996). The bounding surfaces often show hierarchy, resulting in multi-scale heterogeneities ranging from seismic-scale (canyons, belts) to sub-seismic scale (channels, within channel structures). In some situations, after an erosional bounding surface forms, a bypass process follows resulting in shale drapes on the surface. Since the geometry and distribution of shale drapes are governed by the eroded surfaces which are at different scales, a multi-scale heterogeneities (Figure 1) is formed.

These thin (in to ft) shale drapes are flow barriers or baffles that compartmentalize the reservoirs, thus may exert strong control on individual well production rates and ultimate recoveries (Begg and King 1985; Jackson and Muggeridge, 2000; Willis and White, 2000; Weimer et al., 2000). Studies have shown that shale drapes have stronger impact on the flow behavior than the shale facies distributed inside channels (Weimer et al., 2000). Characterizing the distribution of these multi-scale flow barriers and understanding their impact on fluid flow behavior are critical to the successful development and management of our reservoirs.

Modeling these multi-scale flow barriers calls for a hierarchical approach in which the large-scale reservoir architecture is modeled first, the shale drapes are then simulated within this architecture framework. The reservoir architecture modeling in this paper involves defining channel deposition fairways (valleys) based on seismic data, modeling long sinuous channels and placing them into defined fairways such that all data are matched. The criteria for choosing a modeling approach include the ability to match hard data, to define object (channel) boundaries (for the purpose of attaching shale drapes), to reproduce a given stacking pattern and to be CPU efficient.

This paper first reviews existing stochastic modeling approaches, then a hierarchical modeling workflow is proposed, and the main components within this workflow are explained in detail.
2 Stochastic simulation of channels: a review

Channels have been an important target for stochastic modeling since they control the fluid flow in the reservoir as conduits. Various channel simulation methods have been developed to capture the geologically realistic channel geometry. This section will review two important stochastic simulation approaches: object-based approach and multiple-point statistic (MPS) approach.
Object-based methods are also referred to as the 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, the geological heterogeneities such as sand and shale are defined as a set of objects. Each type of 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. Object-based methods are able to model the connectivity and geometry of complicated reservoir features. However, with this approach it is difficult, if not impossible, to honor exactly seismic interpreted geobodies. Another long-standing disadvantage with object-based reservoir modeling methods lies in the conditioning to well data, particularly in the presence of many wells. To overcome this problem, Shmaryan and Deutsch developed a rule-based approach (Shmaryan and Deutsch, 1999) for fast conditioning to well data. In the rule-based approach, the speed is achieved through direct conditioning of the undulation channel centerline to the sand intervals by means of 1-D conditional sequential Gaussian simulation. The disadvantage is that this approach is unable to create large channel complexes in the same manner as it creates individual channels within a channel complex.

In 2005, Alapetite et al. developed Yet Another Channel Simulation (YACS) approach to generate geologically realistic fluvial channels while easily conditioning to multiple wells. The core of this approach lies in the association of a fairway with the channels to be simulated. In this approach, a potential field is first defined within the fairway, then this potential map is mapped into thickness resulting in generating a channel inside the fairway. To add the necessary sinuosity to the channel, a correlated noise is stochastically simulated and added to the potential field. Conditioning to well data is obtained by transforming well observations into channel thicknesses which will constrain the simulation of noise. This method is fast and can perfectly condition to well data and seismic interpreted geobodies under the assumption that the channel sand can be identified in the well data. But as with other Boolean approaches, it cannot reproduce the channel stacking patterns observed from outcrop analog or from training image.

Practical Multiple-point statistics (MPS) techniques have been developed by Strebelle (2002) to simulate geologically realistic models. This approach has been applied to
capture the curvilinear features in the deepwater settings (Strebelle et al., 2003). It allows simulations of 3D facies geometries and distribution using multiple-point statistics and training images and reproduction of the patterns observed from the training images. Training images are non-conditional and purely conceptual depictions of the geological patterns deemed relevant for a particular subsurface. It can be derived from outcrop observation, expert knowledge or geophysics (see an example in Caers et al. 2003). The MPS algorithm extracts geological patterns from the training image and reproduces them in the subsurface models at the same time constraining to seismic and well data. MPS methods make it possible to simulate complex geometries such as channels, meanders and preserve the relations between facies while honoring perfectly well information as well as any other secondary constraints such as seismic derived probabilities. The problems with this method are: (1) the facies patterns are reproduced as a whole hence in the final model one has no knowledge of individual objects. As a result, we can not identify single channels from MPS realizations due to channels cross-cutting with each other (Figure 2). For example, Figure 2a shows one MPS simulated realization with channels (black) coded as 1 and non-channel (white background) as 0. Figure 2b is a part of this realization where two channels cross-out each other. We can notice the cross-cutting in the horizontal direction, however in the vertical direction it would be difficult to identify the channel boundary (Figure 2c) because two channels have the same numerical code (color). One possible solution is to code different channels with different numbers thus boundaries can be identified (Figure 2d). To achieve that, we need to build a large and pattern-rich training image to guarantee enough repetition of different cross-cutting patterns present in the training image. The problem with this solution is that the memory required by the search tree would increase with the number of channels. The algorithm might require several GBs of memory.

These modeling methods can either simulate geologically realistic individual channels or channel patterns as a whole. None of them is capable to simulate channel stacking patterns delineated by bounding surfaces.
Figure 2  Example result from MPS. Where the two channels cross, MPS cannot delineate the fine scale flow barrier that separates the two channels (After Lisa Stright, 2005)

3 Proposed modeling approach: hierarchic modeling workflow

Clark and Pickering (1996) suggested that an appropriate measure of scale of deep-water sedimentary bodies may be obtained from identifying the hierarchy of the bounding surfaces defining the architectural elements. This is true in our study since thin shale drapes are distributed on hierarchical bounding surfaces. Therefore, the modeling of multi-scale shale drapes will start by modeling the reservoir architecture which is delineated by hierarchical bounding surfaces.

To model a multi-scale reservoir architectural geometry, a hierarchical workflow (Figure 3) is adopted which is routinely used in reservoir modeling. Within this workflow, large-scale architectural elements (for example channel belt) are modeled first, their corresponding bounding surfaces are then identified and the shale drapes are
simulated on these surfaces; next the 2nd order hierarchic architecture elements-individual channels within channel belts are simulated, the corresponding bounding surfaces are captured, and shale drapes are modeled; then lithofacies are simulated within each channel, finally continuous petrophysical properties such as porosity and permeability are assigned on a by-facies basis. Within the hierarchical workflow, available or known data must be honored at all times to obtain a reliable geological model, that is, each level of hierarchy model must be consistent with all available data with corresponding scales.

Figure 3  A hierarchic workflow to simulate multi-scale flow barriers

In this paper, the channel infill facies will only take into account sand which means channels are fully filled with sand facies. Properties such as porosity and permeability are modeled using traditional sequential Gaussian simulation. The shale drapes along the bounding surfaces will be simulated using MPS. For reservoir architectural modeling, this involves defining channel deposition fairways (valleys) based on seismic data, modeling long sinuous channels and placing them into defined fairways such that all data are matched. Since we assume that channel valleys (belts) can often be identified from
seismic data (with some associated uncertainty), the 2\textsuperscript{nd} order hierarchic architecture modeling- individual channel geometry and stacking pattern modeling are the challenging part in this workflow. Next, we will first present the 2\textsuperscript{nd} order hierarchic architecture modeling workflow, then the shale drapes modeling approach will be described.

4 2\textsuperscript{nd} order reservoir architecture modeling

The 2\textsuperscript{nd} order reservoir architectural modeling consists of two components: individual channel modeling and channel stacking pattern modeling. The criteria for choosing a modeling approach include the ability to match hard data, to define object (channel) boundaries (for the purpose of attaching shale drapes), to reproduce a given stacking pattern and to be CPU efficient. This paper adopts a stratigraphic-based modeling approach. In this stratigraphic-based approach, individual channels are simulated using the YACS method (Alapetite et al., 2005) since this method allows the simulated channels to be continuous throughout the modeling area, to have defined boundaries and to stay within an observed fairway (valley). The method is a stochastic technique, not a geological or process technique; it only attempts to mimic the latter. But this method is fast and conditions to well data under the assumption that the channel sand bodies can be identified from well data. To put multiple channels together reproducing desirable stacking patterns, stacking pattern parameters such as overlap ratio and migration ratio are simulated.

4.1 Individual channel modeling

To perform the YACS approach, the following parameters are required to specify channel geometry (Figure 4):

- Channel orientation(\(\alpha\)): the direction that channel extends
- Channel wavelength (\(\lambda\)): the distance between adjacent peaks or troughs
- Channel amplitude(\(A\)): the distance between adjacent trough and peak
- Channel width(\(W\)): the maximum width of the channel; it is located at the center of the channel
- Channel thickness(\(H\)): the maximum thickness of the channel; it is located at the center of channel
Channel cross-section geometry is defined by a parabola:  
\[ h(x) = H \left( 1 - \left( \frac{2(x - x_0)}{W} \right)^2 \right) \]
where \( x_0 \) is the location of channel center point and \( x \) is the position on the cross-section to be computed.

Figure 4  Definition of the parameters used to describe the channel geometry

The core of YACS method lies in the association of a fairway with the channels to be simulated. In this method, a single channel simulation starts by selecting a particular depositional surface. On this surface, a channel belt is defined and a so called “potential field” is computed within this belt. In order to create sinuosity and realistic channel geometry, a stochastic perturbation is applied to this original potential field. The perturbed potential field is then mapped to channel thickness using a transform function. Placing the thickness underneath the selected depositional surface results in a generating a channel inside the channel belt. The main steps for single channel modeling are:

1. Select a deposition surface and define the channel belt boundaries on this surface (Figure 5a);
2. Compute the original potential values between two boundaries by interpolation (Figure5b). One boundary is set to negative and the other one is positive. The
absolute number of these two extremes corresponds to the bottom of the channel belt at which the channel is located;

(3) A correlated noise is simulated using Sequential Gaussian simulation (SGSim) (Figure 5c);

(4) A perturbed potential map (Figure 5d) is obtained by adding the simulated noise to the original potential map; Keep the positive potential values in Figure 5d and flip the negative potential values into positive, the 0-isopotential line is the channel centerline (Figure 5e);

(5) Once the channel centerline is located, the channel region is defined (Figure 5f) since we know the channel width;

(6) Apply a transfer function \( h(d) = H(1 - \left(\frac{2d}{W}\right)^2) \) on the channel region to obtain channel thickness map (Figure 5g); At the 0-potential point on Figure 5f, \( d \) is 0, and \( d \) increases towards the channel boundary along the potential gradient direction.

(7) Paint the thickness underneath the depositional surface, a channel in 3D space forms (Figure 5h).

**Figure 5** The workflow for single channel modeling
4.2 Simulation parameters

In this modeling method, the channel geometry is controlled by the simulated noise (step3) which is generated using Sequential Gaussian Simulation. To obtain a desirable channel geometry, the simulation parameters such as variogram ranges and histogram variance of the noise distribution determine the channel geometry parameters such as channel wavelength, amplitude and sinuosity. Figure 6 shows the perturbed channel potential maps with different noise histogram variances. As the noise variance increases, channel amplitude and sinuosity increases. The channel wavelength is related to the noise variogram range along the channel orientation direction. From Figure 7 top row we observe that the channel wavelength increases with noise variogram ranges along the channel orientation direction. Figures 7 bottom row shows channel geometries with different noise ranges perpendicular to the channel orientation direction. The channel amplitude decreases with an increase in the variogram range perpendicular to the channel orientation.

![Figure 6 Channel potential maps with different noise histogram variances](image)

Besides geostatistical parameter related to noise simulation, the potential gradient in the original potential map also affects the final channel geometry (Figure 8). Figure 8 top
row are the original potential maps generated using different potential gradients. The 0-isopotential line is located at the same position on these maps. The bottom row shows the perturbed potential maps depicting channel center line geometry after adding the same noise. It shows that with potential gradient increase, channel amplitude decreases.

![Channel potential maps](image)

**Figure 7** Channel potential maps with different noise variogram ranges: top row is for ranges along channel orientation direction, bottom row is for ranges perpendicular to this direction

4.3 Well data conditioning

This modeling approach is easy to condition to well data because the only stochastic engine is pixel-based Sequential Gaussian Simulation. The basic idea of conditioning well data is that the simulated noise at the well locations must be such that the resulting potential, consisting of a noise component and the original potential (which maps back into channel thickness) is close to zero (i.e. close to channel centerline). Based on this idea, the interpreted channel thicknesses at the well locations are first converted into potential values, then transformed to noise values. These noise values are used to condition the Sequential Gaussian Simulation (Alapetite, 2005). Unlike the Boolean simulation “move-until-fit” process, this approach directly places the generated object to
the locations corresponding to the well data. In other words, the channels in this approach
are generated directly, not through McMC type perturbation, to match the well data; this
makes the conditioning fast. However, the method of conditioning is not as general as
traditional sequential simulation. Certain assumptions need to be made. Most
importantly, the well data needs to be interpreted in terms of architectural elements. Such
interpretation is subject to uncertainty (not considered in this paper), as further detailed in
the next section.

4.3.1 Well data Interpretation

Well data in this case are facies values known along the well path. The first step in the
well data interpretation is to separate channel and non-channel facies from well data.
Next, the channel facies are assigned to different channel sections (Figure 9). This
assignment is essentially a process of geological interpretation that takes into account all
the geological information available about the stacking patterns (this paper assumes
channel has determined and constant dimensions). Incorporating the channel stacking pattern information into well data interpretation is necessary because the stacking architecture of channel sand bodies has a strong control on the interconnectivity between channels. Similar as Viseur’s method (Viseur et al., 1998), this paper uses two parameters to define the stacking pattern, i.e. the overlap ratio and the migration ratio. The reason to choose these two parameters is that the channel stacking architecture is controlled by the interaction between a lateral and vertical amalgamation process (Clark & Pickering, 1996).

![Figure 9 Schematic graph showing the well facies data and its interpreted channel sections](image)

The overlap ratio (Figure 10) is the ratio of vertical overlap thickness \((h)\) between two channels and the channel maximum thickness. It constrains the interpreted sections to overlap vertically with each other by a defined number. The migration ratio is the ratio of horizontal distance \((x)\) between two adjacent channel section center points and the channel amplitude. It constrains the interpreted channel sections overlap horizontally by the defined amount. We assume that the probability distribution functions of these two parameters can be obtained either from outcrop study, training images or process-based models. As a result, the interpretation of the well data is stochastic. For each interpretation, we draw pattern parameters from their distribution functions and then
convert them into a channel section center position relative to the adjacent channel section. In other word, for the same well data set, we can obtain multiple channel sections with different stacking patterns. All of their pattern parameters follow the same given distributions.

Figure 10  Schematic graph explaining the definition of pattern parameters

Next we will use a synthetic example to explain this interpretation process. Suppose we know the channel stacking pattern parameter probability distribution functions for our reservoir (Figure 11) and we also know individual channel geometry parameters: wavelength $\lambda = 25$ feet, amplitude $A=12$ feet, orientation $\alpha=0^\circ$, thickness $H=9$ feet and width $W=15$ feet. All the channels have constant geometry parameters.

Figure 11  Synthetic uniform distributions of two pattern parameters

For the facies section of a well shown in Figure 12, the sand thickness is 20 feet which is much larger than an individual channel thickness $H$ (9 feet in this case). This indicates
that the well passes through multiple channels. Therefore an interpretation is required to assign multiple channel sections to fill the sand facies at the well location. A pair of stacking pattern parameter values is drawn using their respective probability distribution functions shown in Figure 11. This pair of values is used to obtain the location of a channel section centerline relative to its adjacent one. Once we have simulated channel section centerline position, a channel section is added into the well sand facies with this simulated centerline position. We repeat the random drawing of pattern parameter ratios and the channel section generation process until the sand facies are fully filled by channel sections at the well location. The final result is one stochastic interpretation (eg. Figure12, Case1). If we repeat the above process several times, we can obtain multiple interpretation results (Figure 12). Note that in this case we assume no knowledge of the channel boundaries in the well data. If such information were available, the uncertainty in the interpretation could be further reduced.

Figure 12  Synthetic example demonstrating the stochastic interpretation of well facies data.

The same well data can result in multiple channel section stacking pattern realizations.
For a case with multiple wells, the individual well facies data interpretation follows the previously stated interpretation process. In addition, the interpretation should consider well correlation data and channel geometry parameters such as sinuosity and amplitude. This will ensure that the interpreted multiple well data are compatible. In other words, if two wells are close to each other (distance less than the channel amplitude) and have sand facies at the same interval, the interpreted channel sections from these two wells should not conflict with the channel sinuosity information if they are on the same depositional surface. For example, in Figure 12, the blue dash line represents a predefined channel geometry in map view. Well A and B are within the channel amplitude region in the x direction and very close to each other in the y direction. If these two wells have interpreted channel sections on the same depositional surface (such as purple channel section for well A and the green section for well B), then these two channel sections are candidates to belong to the same channel. However, in the left interpretation the channel section centerline locations are not consistent with the channel sinuosity information thus is incompatible data, while the right one is compatible. In practice, it may not be trivial to generate “compatible data”, especially when many wells are present. In this paper we assume the interpreted channel sections are compatible when multiple wells occur.

Figure 13 Schematic example showing the compatible/incompatible interpretation when multiple wells present
4.3.2 Hard noise data computation

Having the interpreted channel sections along the well path, the tops and center points as well as channel thicknesses at the well locations for these channel sections are recorded. Next the hard noise data will be computed based on these interpreted results. The computed hard noise data will be honored during noise simulation using SGsim in order to fit a channel object to the interpreted channel section. The main steps are explained using an example in Figure 14:

1) Calculate the distance \(d\) between the well location (point A in Figure 11) and the channel center line (point C in Figure 11) using

\[
d = \frac{W}{2} \sqrt{1 - \frac{h}{H}},\ 
\]

so for data in Figure 11

\[
d = \frac{20}{2} \sqrt{1 - \frac{8}{15}} = 6.8
\]

2) Generate the original potential map with predefined potential gradient \(dP\) (=0.75). The 0-isopotential line (original channel centerline) passes through the interpreted channel center point (point C). Read the original potential value \(P_{org}\) (=10.5) at the well location A;

3) Calculate the potential value at the well location A: \(P_w = dP \times d = 0.75 \times 6.8 = 5.1\)

4) Calculate the noise at the well location: \(N_w = P_w - P_{org} = 5.1 - 10.5 = -5.5\)

The result in step 4 is hard noise data for noise simulation. For shale interval at well location, simply assign large \(P_w\) to avoid the shales falling close to the 0-potential line (the channel centerline) on the perturbed potential map.

Figure 14 Well channel section data (left) and its original potential map (right). The channel section geometry-maximum width and thickness- should be the same as the defined channel cross section geometry.
4.3.3 Fitting a channel object to the interpreted channel sections

For the multiple-well case one first identifies all channel sections whose top fall within the same depositional surface (or layer). These channel sections potentially belong to the same channel object. To check if these channel sections belong to the same channel, one calculates the centerline distances between channel sections in the direction perpendicular to the channel orientation direction. If channel sections are within a channel amplitude range, they belong to one channel (Figure 15 left). However, the same channel section (such as the section of well 3 in Figure 15) could belong to a different channel (Figure 15 right). In this case we need to make a decision to deterministically set the channel section to a channel. This means that two interpretations are possible leading to two different interpreted hard data sets (hard data uncertainty).

Figure 15  Well conditioning for interpreted channel sections. Well 1,2,3 could be connected with one channel (left); However, well 3,4,5 can be connected within another channel (right). Hence two interpretations are possible.

Once we know the conditioning data points for one channel, the actual channel centerline is equated to the average value of channel sections’ center point locations. Then the previous single channel simulation approach is applied to generate a channel passing through these channel sections by means of conditional sequential Gaussian simulation of the noise. Figure 16 shows the case where 10 channel sections interpreted from 10 wells belong to one channel (on the same depositional surface). In the top row plot, 10 points
indicate well locations and their color represent channel section thicknesses at the well locations. The bottom figures are three realizations conditioned to the top well thickness data. We observe that the larger thickness the point has, the closer it is located to the 0-potential line which represents the channel centerline. Figure 17 shows the 20-well case, the well data are perfectly honored and multiple realizations can be obtained. Figure 18 shows the case where one well vertically passes through different layers, and there are three interpreted channel sections overlapping one another. Based on the interpreted thickness information, three channels are simulated and the interpreted channel stacking patterns at the well location is reproduced.

As we mentioned before, the YACS method can easily condition to well data under the assumption that channel sand for each individual channel can be properly identified in the well data. This means that the conditioning process requires much more interpretation than traditional sequential simulation (snesim). Such interpretations are based on geological knowledge hence subject to uncertainty. Given the interpreted well data, the conditioning process in this method is much faster than Boolean methods because it mitigates the problem of the data conditioning to pixel-based noise simulation (by using SGsim). The YACS method provides better channel geometry reproduction than traditional pixel-based approach (snesim) which is one of the main concerns in this geological modeling work, in particular considering the attachment of shale barriers as an important modeling goal.
Figure 16  Three realizations (bottom) of channel potential conditioned to 10 wells (top)

Figure 17  Three realizations (bottom) of channel potential conditioned to 20 wells (top)
4.4 Modeling reservoir architecture

Reservoir architectural geometry is reflected in the channel stacking pattern. As stated in the well interpretation section, the channel stacking pattern is described by two parameters: overlap ratio and migration ratio. Instead of using migration ratio to locate the channel section center point in the well data interpretation (Figure 10), the migration ratio information in this section is used to determine the location of the channel object center line relative to an adjacent channel (Figure 19). We assume the distribution functions of these two parameters are available from certain sources, and the uniform distribution is used in the following synthetic cases for demonstration purpose. We also assume the net:gross ratio for each channel belt can be obtained. Based on the natural deposition rule, the younger channel (deposited on upper surface) erodes the older one (deposited on lower surface) if they are in contact with each other. For the channels deposited on the same surface (roughly deposited at the same time), the previously
simulated channel erodes the later simulated one. Given the assumptions and erosion rules, the architecture modeling is performed as follows:

1) In a channel belt (Figure 20), if there is no well data to be conditioned to, first simulate a single channel at the channel belt top center using the simulation method stated in section 4.1 (Figure 21a); if there are wells passing through this belt, then first generate channels fitting all the interpreted well channel sections;

2) Draw a value for the migration ratio and overlap ratio from their corresponding distribution functions, and use these ratios to obtain the location relative to the previously simulated channel; simulate a new channel centered at this location (Figure 21 b).

3) If the simulated channel does not fully stay within the channel belt, then it is rejected and step 2 is repeated until the new channel is completely within channel belt;

4) Repeat step 2-3 to generate a new channel within the channel belt until the given net:gross ratio is approximately reached (Figure 21 c-h);

5) Repeat step 1-4 for each channel belt in the reservoir (Figure 22);

The architecture modeling is performed from top to bottom which appears to contradict the sequence of deposition. There is no doubt that the channels can be generated from base to top following the deposition rule. However, the proposed modeling sequence is more favorable when a vertical proportion curve needs to be taken into account. The vertical proportion curve obtained through well and seismic data specifies the proportion of all sand as a function of vertical elevation (or depth). This information will provide a constraint on the number of channel to be simulated for each layer. Since channel thickness simulated in the upper layer of the grid will contribute to the sand proportion for current layer of the grid, it is reasonable to generate channels from top to bottom in order to honor the vertical proportion curve.

We should notice that all the individual channels are continuous throughout the simulation domain if they are not eroded. These channels stay within the predefined belts as expected. Once these channel complexes are generated, their bounding surfaces can be traced for shale drapes modeling (Figure 23).
Figure 19  Plan view of two channels overlapping each other. The migration ratio will be used to determine the value of x - the distance between two channel center lines.

Figure 20  A channel belt body (left) and its bounding surface (right). Channels will be filled into the space within the channel belt limit.
Figure 21  The architecture modeling process showing how channel is filled into belt (continue to next page)
Figure 21  The architecture modeling process showing how channel is filled into belt. Left column is the architecture model, middle column are the realizations for migration ratio, and right column are the realizations for overlap ratio.
Figure 22  Three channel belts case. Individual channels are filled into each belt until its net-to-gross reached. All the channels are confined by channel belt limits.

Figure 23  Channel bounding surfaces extracted from Figure 22
5 Shale drapes modeling

As previously stated, shale drapes are associated with erosional bounding surfaces. Although shale drapes may exhibit a varying degree of coverage, they are often very thin (inches to few feet) compared to sand bodies. Therefore, ignoring their volume effects, shale drapes will be simulated on their associated bounding surfaces in 2D space. The simulated 2D shale drapes can be easily converted into transmissibility multipliers in flow simulation model for shale drapes effects study (Stright, 2005). In this work, multiple-point statistic (MPS) program \textit{snesim} will be used for shale drapes modeling. To perform MPS, a shale drape training image representing the reservoir conceptual shale drape distribution model is required. Figure 24 is one example of the shale drape training image. The red color indicates scour holes and the background represents shale drapes covered on the bounding surface. In fact, if shale drapes only cover a small portion of the bounding surfaces (<40% areally), the reservoir connectivity is not affected by these shale drapes. On the contrary, if bounding surfaces are fully draped by shales, and only a small portion of scour holes are present among the shale drapes, the location and proportion of scour holes will have significant impact on reservoir connectivity (Li, 2003, Stright and Li, 2006). This is because the holes may connect two channels if they contact with each other. Therefore, instead of simulating shale drapes, we will simulate holes distribution on the bounding surfaces. The modeling process is as follows (Figure 25):

1) Extract the bounding surfaces of the architecture elements (such as belts and channels) from simulated architectural model

2) Flatten these bounding surfaces into multiple 2D surfaces

3) Apply \textit{snesim} on these 2D surfaces to generate holes

4) Fold back 2D surfaces with simulated holes into their original 3D space

This process is applied for each hierarchy. Finally a multi-scale shale drapes model can be generated.
Figure 24 One example of shale drape training image. Red color represents holes, and blue color indicates shales.

Figure 25 The workflow of shale drape modeling
6 Summary
This paper presented a hierarchical modeling workflow to capture multi-scale shale drapes associated with bounding surfaces in a channelized reservoir. In this workflow, the large-scale reservoir architecture is modeled first, the shale drapes are then simulated within this architecture framework. The architecture modeling approach adopted in this paper is essentially a stratigraphic-based modeling approach. It is fast and can easily condition to well data, at the same time the channel stacking patterns can be reproduced. However, as we mentioned before this modeling process works under some assumptions. The first assumption is that the probability distribution functions of pattern parameters are available or can be derived from some sources. We also assume that the net-to-gross ratio of each channel belt is known. As a result, the number of channels within channel belts is determined based on this net-to-gross ratio input. In practice, obtaining the pattern parameter distribution functions that reflect the geological pattern features is not an easy job; and finding the net-to-gross ratio for each channel belt is also a challenge.

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