Bank Retreat Meandering Fluvial Process-based Model

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Fluvial depositional settings host significant hydrocarbon reserves. The geometries and interrelationships of fluvial architectural elements are important constraints on reservoir performance. In general, process based and deterministic fluvial models are realistic, but cannot be conditioned to the level of data available in most resource studies and may not provide an assessment of uncertainty.

A process based model based on realistic channel streamlines and the bank retreat meandering fluvial model is demonstrated. Some ideas are presented for data conditioning. This model is based on common hydrologic parameters and results in realistic meandering fluvial stochastic models.

Introduction

A variety of approaches have been applied to construct iterative and non-iterative object-based stochastic models of meandering fluvial depositional systems.

The iterative object based methods rely on techniques like simulated annealing to place and perturb objects in a manner that minimizes an objective function that accounts for the mismatch in facies proportions, continuity, vertical and horizontal proportions and the honoring of the available hard and soft data with an algorithm called FLUVSIM (Deutsch and Wang, 1996; Deutsch and Tran, 2002). This technique produces low sinuosity ribbon sand bodies and associated levees and crevasse splays in a matrix of over bank fines. The annealing approach may be computationally inefficient in the presence of significant conditioning and the resulting models may lack the realistic architectural element interrelationships demonstrated in process-based models (Miall, 1996).

The inefficiency of the iterative techniques in the presence of conditioning spurred research in non-iterative object based modeling. Visuer et. al. (1998) and Shmaryan and Deutsch (1999) have developed techniques that honor well log data by construction and then add channels to fill out the unconditioned subsets of the model space. The algorithms segment the well logs into unique channel and nonchannel facies and then fit stream lines through the identified channel segments with simulation. The channels are parameterized by a set sections fit along the streamline (backbone) (Wietzerbin and Mallet, 1993). The Shmaryan method proceeds from the top down and is able to reproduce vertical proportions by adding channels until the layer proportion of channel sand is correct. Horizontal proportions are reproduced by adding artificial channel intervals as required. Visuer (2001) increased the object complexity with the addition of simulated piecewise linear avulsion surfaces which constrain the channel dip and the channel spacing and overlap.

Process based models for the construction of fluvial facies models have been proposed by Howard (1992) and Sun and others (1996). These techniques are based on the bank retreat model. An initial channel is placed and an underlying erosion coefficient grid is initialized. The near bank velocity is calculated from hydraulic parameters such as channel depth and width, curvature, and the average velocity and the rate of channel erosion is set proportional to the near bank velocity.

This model was extended to approximately honor global proportions, vertical and horizontal trends (Lopez, Galli and Cojan, 2001). Global proportions are constrained by hydraulic parameters and the erosion coefficient grid. Vertical trends are honored by aggrading the channel when target facies proportions have been matched. Areal trends are constrained through the erosion coefficient grid.

An advanced process based fluvial model is presented and some potential methods for conditioning are presented.

The Bank Retreat Fluvial Model

The bank retreat model is applied to predict the migration of meandering stream channels based on hydraulic and host material parameters. The algorithm proceeds in the following order (**1**) seed a channel, (**2**) discretized the channel, (**3**) calculate the near bank velocity at discretized nodes, (**4**) calculate the node migration as a function of the near bank velocity and host material erosion coefficient and (**5**) migrate the nodes in a direction normal to the channel.

The equation for the near bank velocity (Sun et al., 1996):

$$\tilde{u}_{sb} = -bu_{s0}\tilde{C} + \frac{bC_f}{u_{s0}}\left[\frac{u_{s0}^2}{gh_0^2} + (A'+2)\cdot\frac{u_{s0}^2}{h_0^2}\right]\cdot\int_0^{\infty}\exp\left(\frac{-2C_f s'}{h_0}\right)\cdot\tilde{C}(s-s')ds' \qquad \mathbf{(1)}$$

where $\tilde{u}_{sb}$ is the near bank velocity, b is the channel half width, u_{s0} is the stream mean velocity, $\tilde{C}$ is the local channel curvature, C_f is the friction coefficient, g is the gravitational constant, h_0 is the average depth of channel, A' is a positive factor describing the scour factor and s is the coordinate along the channel. The integration component accounts for the inertial effects on the near bank velocity.

The channel migration is calculated with (Sun et al., 1996):

$$\xi = E\tilde{u}_{sb} \qquad \mathbf{(2)}$$

where ξ is the channel migration distance, E is the local erosion coefficient and $\tilde{u}_{sb}$ is the near bank velocity calculated in Equation 1.

Time steps are applied to model the channel migration. As the channel migrates an underlying facies model is modified with the formation of channel, point bar and abandoned channel architectural elements. The erosion coefficient grid is modified as a function of facies.

Mathematical Models to Generate Meandering Streamlines

Any fluvial model will require the seeding of channel streamlines. For example the FLUVSIM algorithm constructs streamlines as one dimensional Gaussian random functions centered on a linear axis and parameterized by amplitude and correlation length. There are a variety of methods available to generate meandering streamlines. A review of mathematical meandering streamline models is provided by Ferguson (1976, p. 337). Three distinct methods are discussed below.

Regular Wave-Forms Models

The typical regular wave-form model is constructed by oscillating the segment orientation along the streamline:

$$\theta(s) = \omega \cdot \sin\left(\frac{2\pi s}{\lambda}\right) \qquad \textbf{(3)}$$

where θ is the orientation of the segment, λ is the wavelength, ω is the maximum deviation from principle channel direction and s is the length along the streamline. This model is fully determined by wavelength and the maximum deviation terms that may be directly related to sinuosity. While the parameterization is straightforward, the statistical properties of these models do not mimic actual river meanders. While hydraulic morphology does tend towards regularity, nonstationary in the host material topography and properties disrupt this regularity.

Random Walk Models

These methods attempt to capture the irregularity of meandering streamlines by setting the segment orientation as a random variable. The simple random walk model is:

$$\theta_i = \theta_{i-1} + \varepsilon_i \qquad \textbf{(4)}$$

where ε_i, is a disturbance value independently drawn from a distribution, often normally distributed ~ $N(0,\sigma^2)$. This model is not appropriate, since its direction variance increases as length increases and its statistical properties do not mimic actual channels (spectrum is flat) (Ferguson, 1976).

Disturbed Periodic Meanders Models

These models are based on dampened harmonic models that are continuously disturbed (as developed by Ferguson, 1976).

$$\theta + \frac{2h}{k}\frac{d\theta}{ds} + \frac{1}{k^2}\frac{d^2\theta}{ds^2} = \varepsilon(s) \quad \textbf{(5)}$$

where $k = 2\pi / \lambda$, $0 < h < 1$ is the dampening factor and $\varepsilon(s)$ is the disturbance value. The physical analogy for this model is a pendulum dampened by air resistance and continuously hit by rocks. This model may be applied as a discrete approximation and results in streamlines that are based on clear parameters and with statistical properties similar to natural streamlines.

Sinuosity is related to the dampening factor, h, the wavelength through k, and the variance of the disturbance random variable, ε. Decrease in dampening results in more regular and higher sinuosity. Increase in the disturbance variance increases the sinuosity. Given the nominal wavelength a calibration may be performed to find the required dampening factor to get a required sinuosity.

Proposed Process Based Fluvial Model

A FORTRAN program was written to combine (**1**) realistic channel streamlines, (**2**) a variety of architectural elements geometries and interrelationships, (**3**) the bank retreat process model, (**4**) avulsion and aggradation schedule based on system tract and depositional system and (**5**) data and trend conditioning.

Realistic Channel Streamlines

The streamlines are generated with the disturbed periodic model (see Figure 1). This model generates streamlines of a required sinuosity for initial channels after an avulsion event. Avulsion events may occur proximal of the model space or within the model space.

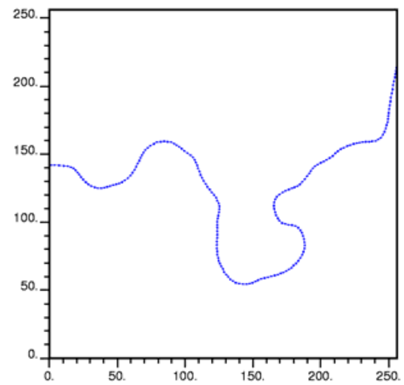

Figure 1 – an example channel streamline calculated with the disturbed periodic model.

Architectural Elements

The architectural elements include (**1**) lateral accretion, (**2**) levees, (**3**) crevasse splays, (**4**) abandoned channel fill and (**5**) over bank fines. An advantage of the process based component of the model is the generation of realistic point bar geometries as the channel migratse. The channel geometry is based on the FLUVSIM parameterization.

Channel Geometry

Channels are parameterized by a streamline, relative thalweg location, stochastic depth and a width to depth ratio. The relative thalweg is calculated as a function of channel curvature. The cross section channel geometry is based on the following equation from Deutsch and Wang (1996).

$$a(y) = \begin{cases} \dfrac{W(y)}{2}\left(1 - \dfrac{|C_v(y)|}{C_v^l}\right) & C_v(y) < 0 \\ \dfrac{W(y)}{2}\left(1 - \dfrac{|C_v(y)|}{C_v^r}\right) & C_v(y) > 0 \\ \dfrac{W(y)}{2} & C_v(y) = 0 \end{cases} \qquad \textbf{(6)}$$

where $a(y)$ is the relative thalweg, C_v^l and C_v^r are the maximum channel curvature in the clockwise and counter clockwise directions, and $C_v(y)$ is the local curvature. The channel cross section geometry is defined by Equation 7 for a thalweg closer to the left bank and Equation 8 for a thalweg closer to the right bank.

$$d(w,y) = 4 \cdot t(y) \cdot \left(\frac{w}{W(y)}\right)^{b(y)} \cdot \left[1 - \left(\frac{w}{W(y)}\right)^{b(y)}\right] \qquad \textbf{(7)}$$

where $b(y) = -\ln(2)/\ln(a(y))$.

$$d(w,y) = 4 \cdot t(y) \cdot \left(1 - \frac{w}{W(y)}\right)^{c(y)} \cdot \left[1 - \left(1 - \frac{w}{W(y)}\right)^{c(y)}\right] \quad \textbf{(8)}$$

where $c(y) = -\ln(2)/\ln(1 - a(y))$.

$d(w,y)$ is a function describing the channel cross section, $t(y)$ is the local channel thickness, $W(y)$ is the local channel width and w and y are the transverse and longitudinal coordinates.

The channel parameters, location, thalweg and depth, are calculated at discrete locations along the streamline. Cubic splines are fit to these properties to allow for a smooth transition along the channel length and interpolation at any channel position.

- Levees: Significant net facies may be represented by levees. They may be more prevalent on the cut bank, and they may extend for large distances (e.g. up to a 100 meters) (Miall, 1996). Levees are thickest adjacent to the channel and thin toward the over bank.

- Crevasse Splays: Crevasse splays are incorporated in a similar fashion to FLUVSIM. The location of crevasse splays are drawn from a distribution of streamline locations, weighted by the curvature; crevasse splays more likely occur at channel bends. Random walkers from the source location, with segment orientation as a one dimensional correlated random function, generate the crevasse splay geometry.

- Lateral Accretion (Point Bars): The lateral accretion deposits are represented as the volume abandoned during bank retreat. The resulting geometries reproduce the complicated inclined heterolithic strata geometries demonstrated in computer models and ancient examples (Diaz-Molina, M., 1993; Willis, B.J., 1993).

- Abandoned Channel Fills: Channels that are abandoned by upstream avulsion or meander neck cutoff are assigned as abandoned channel fill. This architectural element preserves the active channel geometry.

- Over Bank fines: Over bank fines are not modeled directly. The model space is initially set as over bank fines and is modified by the evolution of the process based channels.

Bank Retreat Model

The channel streamlines are migrated by the previously described bank retreat model. An example migrated channel is shown in Figure 2.

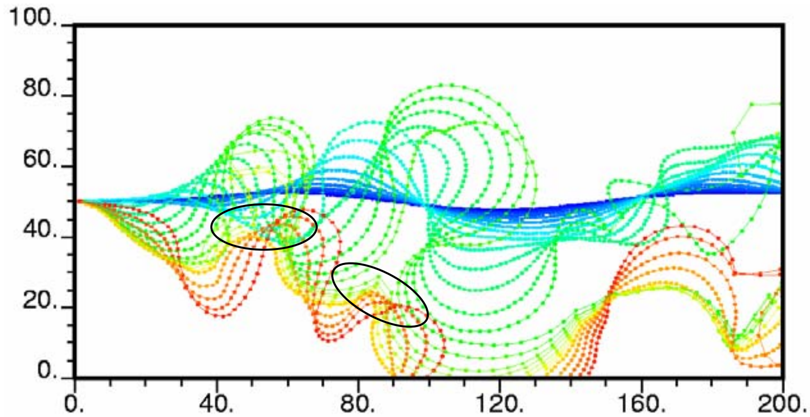

Figure 2 – the migration of a channel streamline over 25 times steps (blue to red). Note the neck cut offs indicated by ellipses.

Avulsion and Aggradation Schedule

The avulsion and aggradation schedules determine the rate of avulsion and aggradation over the time steps. This schedule may be set a priori, or dynamically to reproduce specific vertical trends. The impact of rate of avulsion (and meander migration) and aggradation on the architectural element model is demonstrated in Figure 3.

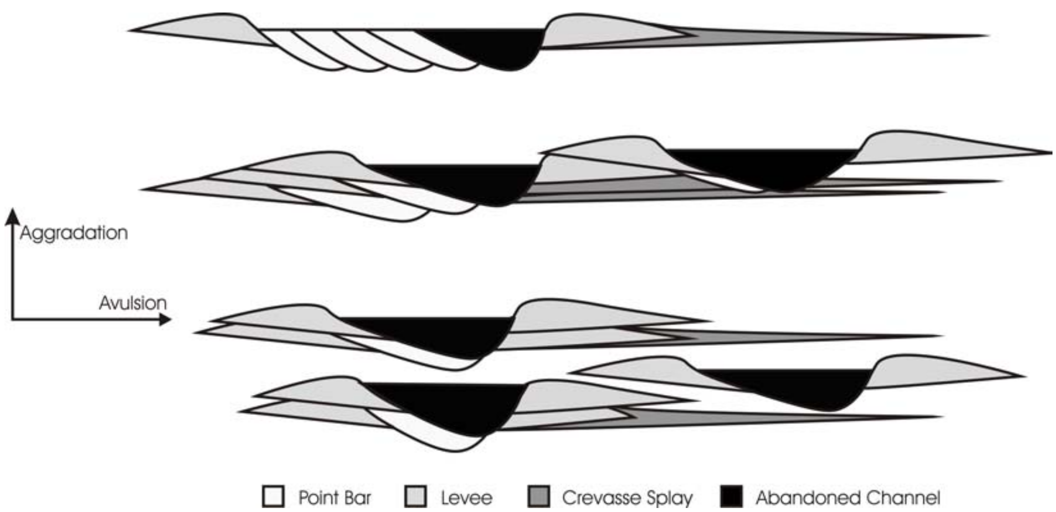

Figure 3 – the effect of rate of avulsion and rate of aggradation on the evolution of architectural elements. Top – low rate of aggradation and avulsion allow for the development of extensive later accretion elements, Middle – higher rate of aggradation with increased avulsion and Bottom – high rate of aggradation results in isolated sand bodies.

Example Model

The current code was applied to generate a hybrid stochastic process based fluvial model. The initial channel parameters are shown in Table 1. The average flow velocity and channel depth were calculated based on hydraulic relationships.

Parameter	Description	Value
b	Channel half width	3.0 m
C_f	Friction coefficient	0.0036
A	Scour factor	10.0
Q	Average flow	3.256 m^3/s

Table 1 – the hydraulic parameters applied in this demonstration.

A 2D image demonstrates the meandering of a channel and the modification of the underlying architectural element model (see Figure 4). While channel migration increases sinuosity, periodic neck cutoffs reduce the sinuosity. Visualizations of a 3D process based model are shown in Figure 5, Figure 6 and Figure 7.

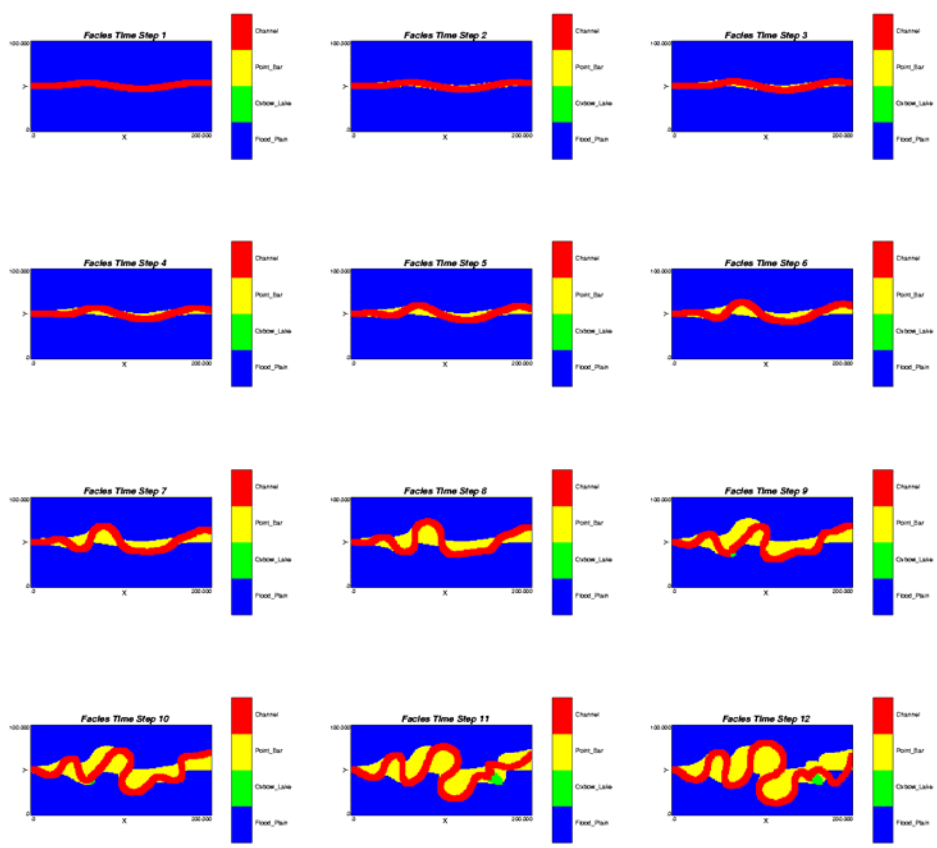

Figure 4 – the facies model evolution over 12 times steps.

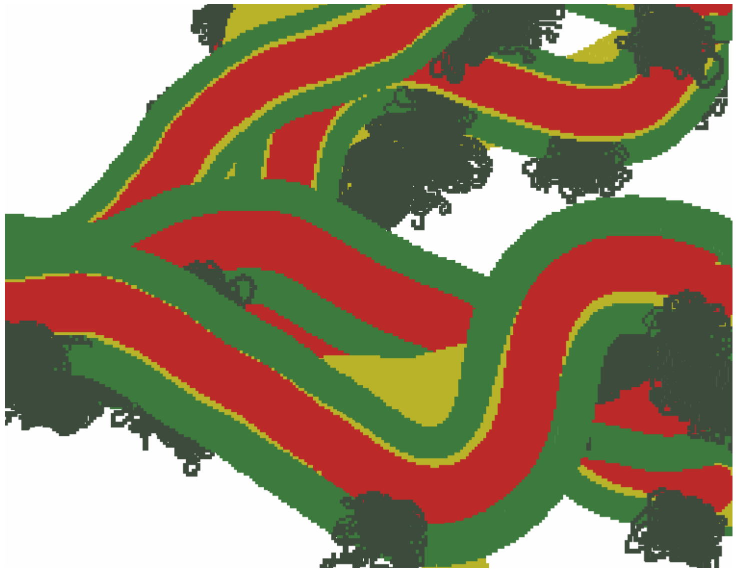

Figure 5 – plan view of a realization of the process based model.

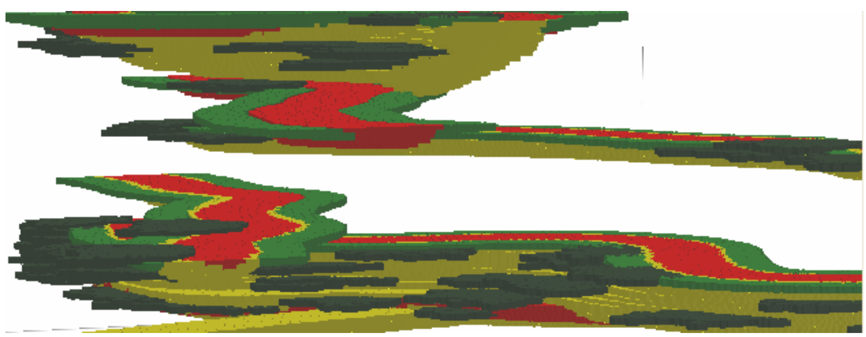

Figure 6 – cross section of a realization of the process based model.

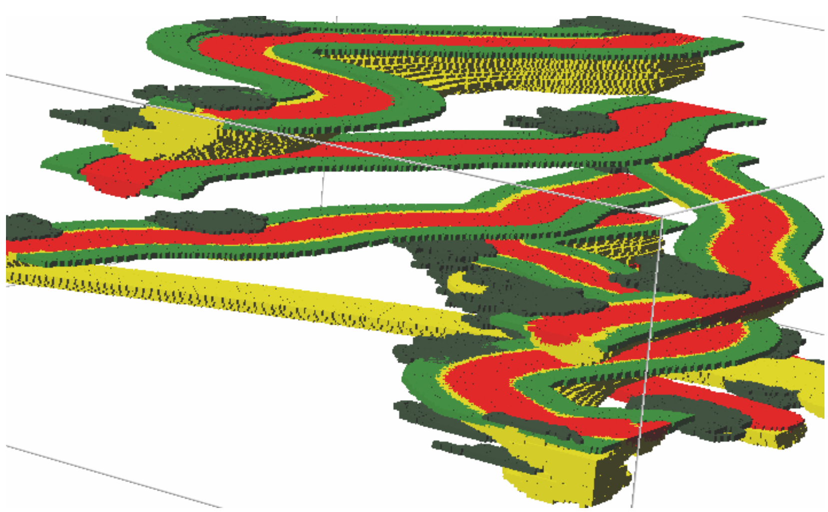

Figure 7 – oblique view of a realization of the process based model.

Future Work

The current model is unconditional at this time. Future research will address data conditioning. There are a variety of methods that may be applied; (**1**) attempting to solve the inverse problem, (**2**) kriging for conditioning, (**3**) pseudo-reverse modeling and (4) apply as a training image for multiple-point geostatistics.

Inverse Problem

Other researchers, working with the bank retreat model, are attempting to solve the inverse problem of determining the required input parameters to constrain a model to specific conditioning (Lopez, Galli and Cojan, 2001). The erosion coefficients are adjusted to force channels to honor areal trends and the rate of aggradation is adjusted to honor vertical trends.

Traditional Method of Conditioning

The traditional method of conditioning is applied a posteriori to condition realizations produced by methods that calculate unconditional realizations, such as turning bands. A recent idea from Deutsch (2003) considers the application of traditional kriging to condition object based models a posteriori. The procedure proceeds by (**1**) logical coding of the categorical model as a continuous model, (**2**) introduction of categorical conditioning, (**3**) application of the traditional method of conditioning and (**4**) truncation of the continuous distribution to return to the categorical case.

The logical coding to a continuous variable should be based on ordering relationships. This step requires further development. Traditional conditioning requires a kriging of the difference between the conditioning data and the collocated values in the unconditional model. This kriged difference is then added to the unconditional model.

$$z_{sc}(x) = z_k^*(x) + [z_s(x) - z_{sk}^*(x)] \quad \textbf{(9)}$$

where $z_{sc}(x)$ is the conditional realization, $z_k^*(x)$ is the kriged estimate from conditioning data, $z_s(x)$ is the unconditional simulation and $z_{sk}^*(x)$ is the kriging with the values from the unconditional realization at the conditioning locations.

This technique has shown potential in a binary channel / over bank fine object based model.

Pseudo-reverse Modeling

Reverse modeling is not directly possible with process based models. A recent idea from Pyrcz (2003) is based on approximate reverse modeling. The proposed algorithm will (**1**) generated realistic channel streamlines, (**2**) correct the streamlines to fit conditioning (as demonstrated by Oliver, 2002), (**3**) apply an approximate reverse bank retreat model until the appropriate vertical proportions are reproduced.

Training Image for Multiple-Point Geostatistics

This proposed model may be conditioned with the application of multiple-point statistics. Unconditional models with the appropriate features and proportions may be calculated and then applied as training images. These training images may be used to infer multiple-point statistics for conditional simulation (Strebelle, 2002).

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