Simulation of Deepwater Lobe Geometries with Object Based Modelling: LOBESIM

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Abstract

The geometry and continuity of reservoir facies is of great importance in reservoir management decision making. Each depositional setting has particular features that require customized facies modelling algorithms. Sand "lobes" are observed in certain deepwater depositional systems. These lobes occur at different scales and are often created as channelized flow loses energy on less confined topography.

This paper presents equations to parameterize deepwater turbidite lobes. The parameterization can handle lobes of different sizes, shapes, asymmetry, and regularity. These shapes can be linked to common channel-type object based modelling algorithms to provide a practical reservoir modelling tool for certain deepwater depositional systems.

A program, `lobesim`*, is included that will generate channel / levee / lobe facies models for deepwater systems. Local well data and facies proportions, which can be made locally variable to account for seismic data, are honored approximately by an iterative conditioning algorithm. Implementation details and examples are presented.*

KEYWORDS: turbidites, reservoir modelling, facies modelling, Boolean simulation

Introduction

Reservoir performance predictions and decision making depend on the geometry and continuity of the reservoir, that is, the 3-D distribution of porosity and permeability. In many depositional settings, the primary control on porosity / permeability is the depositional facies. In a deepwater depositional setting, the contrast between sandy and shale facies is of critical importance. This paper tackles the task of constructing realistic high-resolution facies models that can be used as a constraint in porosity / permeability, which will be used for reservoir forecasting.

Deepwater depositional systems host important hydrocarbon reserves. Such depositional systems are the result of subaqueous deposition of clay, silt, and sand. The sandy facies are carried away from the shoreline be turbidity currents and debris flows. Such deposition often starts as channelized flow with associated levee deposits, which confine the channel flows. These channel-like flows lose energy and directional focus as the topographic relief becomes flatter. The deposition may then disperse and form more sheet-like flow, which deposits lobe shaped sand bodies. Such lobe-shaped sands are often quite large (kilometers); however, they may also be observed at smaller scales.

The stratigraphy and sedimentology of deepwater depositional systems can become complex. Different sediment suppy, river discharge, sealevel variations, and ocean seafloor topography lead to unique distributions of facies. In general, it will be necessary to tune the sizes, shapes, and relative proportions of channels, levees, and lobes for each reservoir. The reference by Reading and Richards [?] provides much information and references on deepwater systems.

Geostatistical facies modelling techniques may be lumped into cell-based and object-based methods. Cell-based techniques use two-point variogram / covaraince statistics to control the connectivity and relationships between facies. In general, cell-based techniques are appropriate for heterogeneous and poorly connected facies. Object-based methods are used in the case of clearly defined facies geometries and large scale non-linear connectivities. In particular, object based modelling has been used successfully to capture complex non-linear facies geometries in a fluvial setting. The key idea is to place facies objects within a background facies, e.g., sand-filled channels and associated crevasse and levee deposits within a background of floodplain shales.

Object-based modelling became popular in petroleum reservoir modelling in the mid-1980s due to the work of Haldorsen and others [11, 12, 19]. The importance of fluvial reservoirs in the Norwegian North Sea soon prompted the development of these Boolean methods for fluvial facies [3, 4, 8, 10, 14, 17, 18]. The theory and implementation was refined over a number of years [9, 13, 15, 20, 21, 22, 24] with increasing practical application of these methods to Norwegian North Sea reservoirs [2, 23]. Other non-Norwegian oil companies and research institutions also developed object-based modelling capability [1, 7, 16].

Our focus here is to provide detailed object parameters for object based modelling of deepwater facies. In particular, we focus on the geometry of lobe-like sand deposits. These are then coupled with channel modelling methods to yield realistic deepwater facies models.

A flexible and yet straightforward lobe parameterization is presented to handle different shapes, aspect ratios, asymmetry, and irregular geometry. The parameters that define the lobe positioning relative to other facies is discussed. Implementation details and a number of illustrative examples are presented to demonstrate the range of applicablity.

The complexity and diversity of geologic features in deepwater depositional systems make it difficult to devise a general modelling algorithm suited to all cases. The limitations of the present work and some ideas for future development are presented.

Lobe Parameterization

Parameters for a "simple" lobe geometry are illustrated on Figure 1. This set of parameters provides a balance between overly simplistic geometry (too few parameters) and flexibility with the associated difficult inference (too many parameters). The seven parameters illustrated on Figure 1:

sw = **s**tarting **w**idth; typically set to the final channel width. The user, however, could set this arbitrarily.

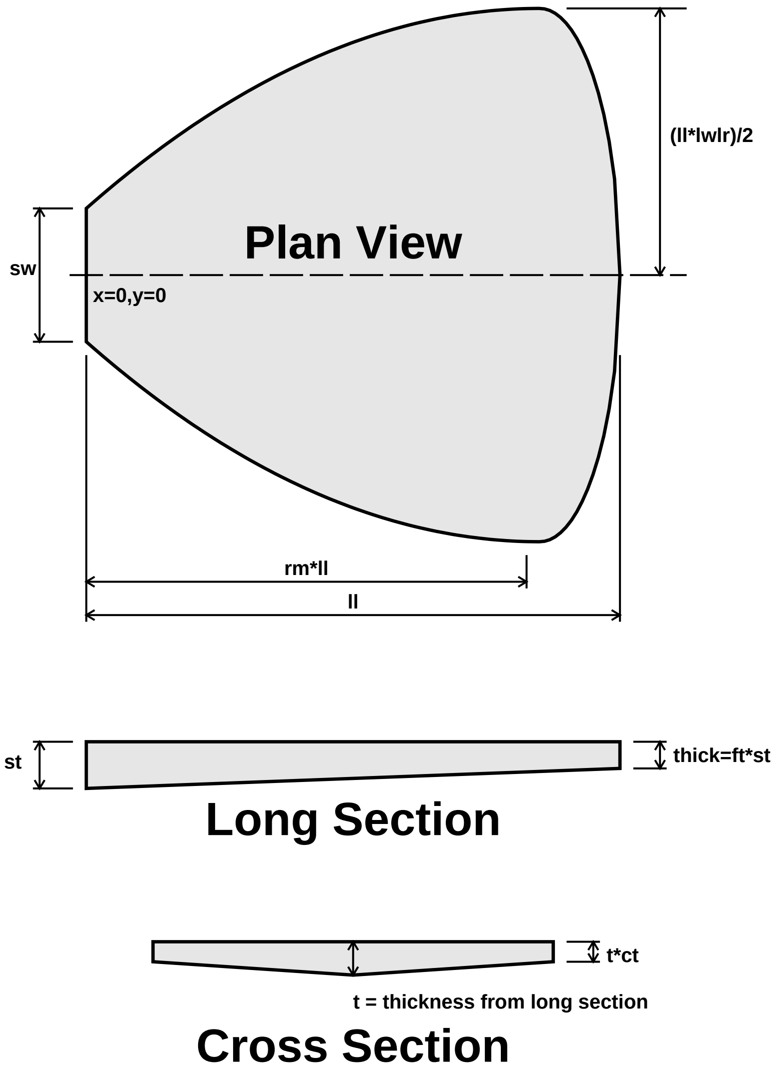

Figure 1: Parameters needed to describe the 3-D lobe geometry.

ll = **l**obe **l**ength; total length of the lobe from the channel to terminus.

rm = **r**elative position of **m**aximum width; the lobe reaches maximum width a distance of $rm \cdot ll$ from the start of the lobe.

lwlr = **l**obe **w**idth / **l**ength **r**atio; maximum width of the lobe is given by $lwlr \cdot ll$ at location specified by relative position rm.

st = **s**tart **t**hickness; start thickness of the lobe next to channel (could be associated to the channel thickness at that point). This is the thickness at the lobe center line.

ft = **f**inal **t**hickness; thickness of the lobe at the terminus (at the lobe center line) relative to starting thickness.

ct = **c**ross section **t**hickness correction; amount that the thickness reduces from the center line to edge of lobe.

The parameterization could easily get more elaborate at the cost of additional parameters that must be inferred from limited observational data. One natural extension is the possibility to keep the base flat for some distance before tapering to zero thickness at the lobe terminus.

In plan view, the constraints on the geometry include: (1) width is equal to starting width at transition point from channel - $y = w$ at $x = 0$, (2) the width is a maximum at relative position l - $y = W$ at $x = l$, (3) the width is zero at maximum lobe length L - $y = 0$ at $x = L$, (4) the tangent to the lobe shape has a zero slope at $x = l$, and (5) the tangent to the lobe shape has an infinite slope at $x = L$. The following equation satisfies these constraints:

$$y = \begin{cases} w + 4 \cdot (W - w) \cdot \left[\frac{x}{2l}\left(1 - \frac{x}{2l}\right)\right], & 0 \le x \le l \\ W \cdot \sqrt{1 - \left(\frac{x-l}{L-l}\right)^2}, & l \le x \le L \end{cases} \tag{1}$$

y is the distance from the center line, x is the distance along the center line, $w = sw/2.0$, $l = rm \cdot ll$, $L = ll$, and $W = (ll \cdot lwlr)/2$. The shape is based on the "$p(1-p)$" shape for the first part (closest to the connection with the channel) and an elliptical shape for the second part. The function and the first derivative are both continuous at all locations around the lobe outline.

Figure 2 shows a series of lobe shapes for different parameters. A combination of the width / length ratio and relative position parameter provides flexibility in the lobe shape.

There are some natural extensions to this areal shape including (1) addition of stochastic variations to the lobe shape for more realism, Figure 3 shows six examples, and (2) consideration of asymmetric lobe geometries, that is, the W, w, and l parameters could be different on the "top/bottom" of the lobe, Figure 4 shows two examples.

In 3-D the lobe thickness is greatest along the center line. This maximum thickness decreases linearly from the channel to the lobe terminus. The thickness also decreases linearly in cross section. The lobe cross section could be made rectangular, power-law (see Deutsch and Wang), or half-elliptical. Moreover, the rate at which the thickness thins toward the

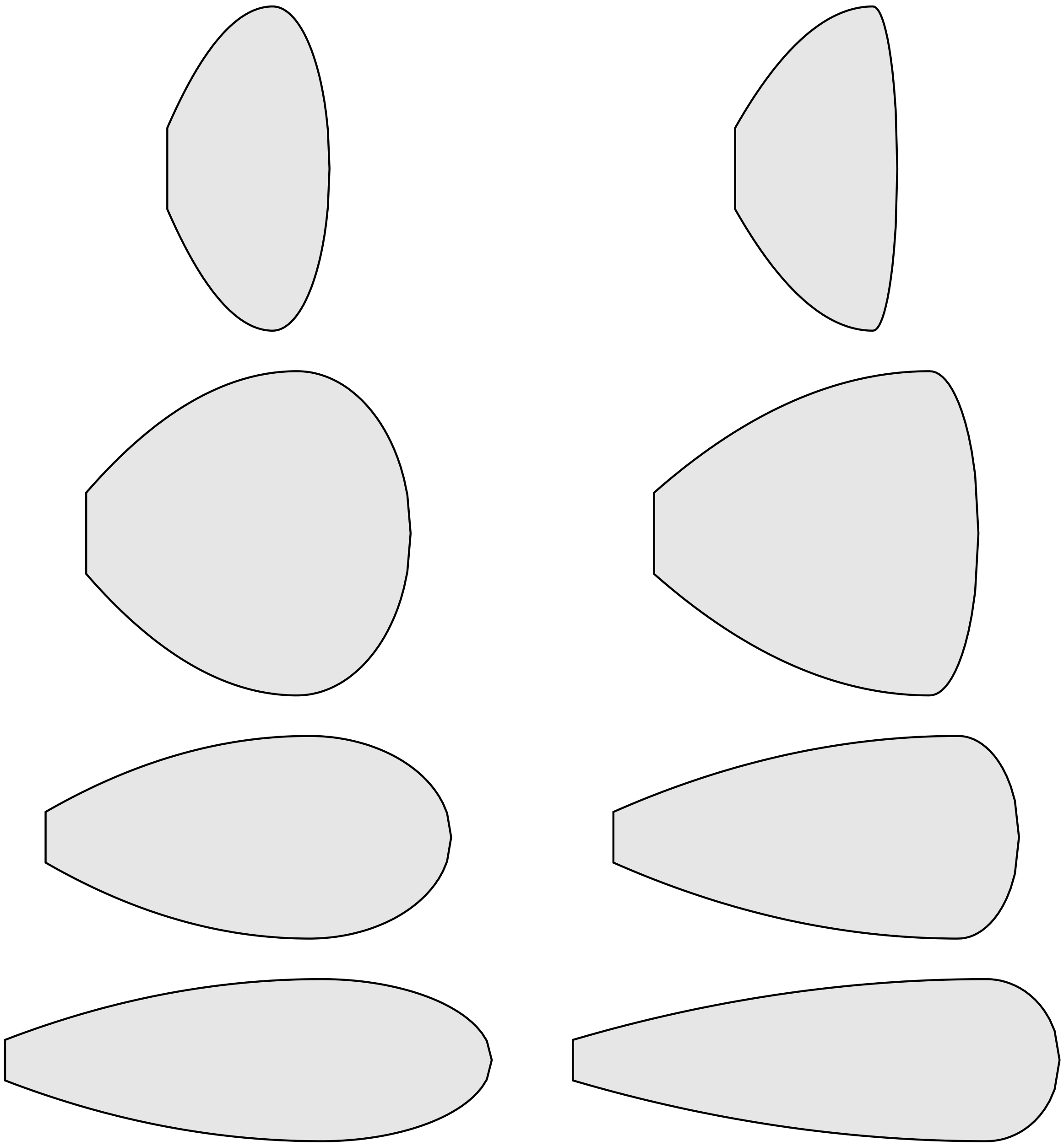

Figure 2: Example lobe geometries for various parameters. From top to bottom the width / length ratio decreases from 2.0:1 to 1:1 to 0.5:1 to 0.33:1. The relative position of the maximum width is 0.65 on the left and 0.85 on the right.

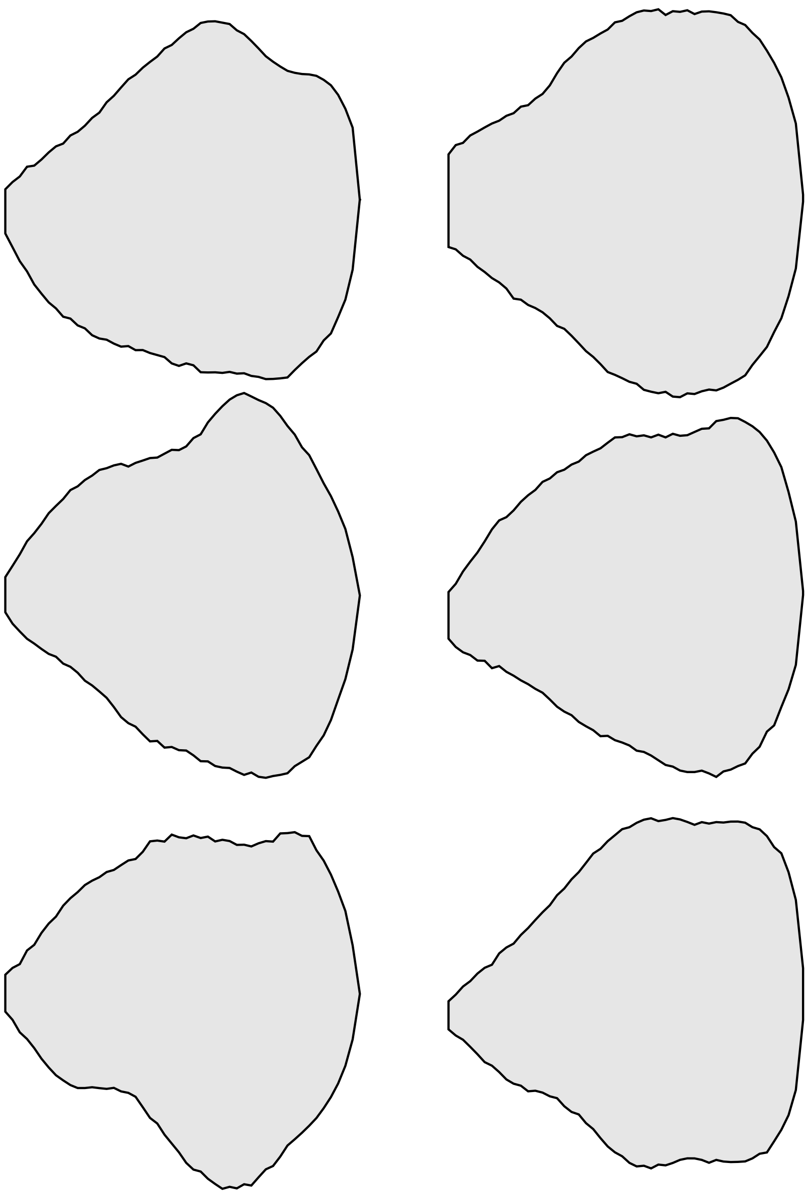

Figure 3: The same basic geometry ($W = 0.5, w = 0.01, L = 1.0$, and $l = 0.6$) with six different Gaussian simulations added.

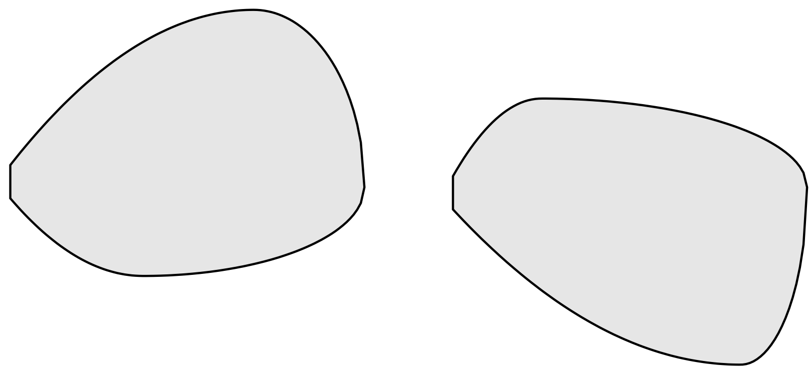

Figure 4: Two asymmetric lobe geometries. The lobe shape and first derivative are continuous around the lobe.

end and sides of the lobe could be made more elaborate. The channel cross section equation shown in [7] could be considered, that is, a cross section defined by a channel width $W(y)$, maximum thickness $t(y)$, and the relative position $a(y)$ of the maximum thickness. The equation for the depth of the channel base below the channel top when $a(y) \leq 0.5$ (maximum thickness closer to the left bank) is:

$$d(w,y) = 4 \cdot t(y) \cdot \left(\frac{w}{W(y)}\right)^{b(y)} \cdot \left[1 - \left(\frac{w}{W(y)}\right)^{b(y)}\right] \tag{2}$$

where $b(y) = -Ln(2)/Ln(a(y))$, and $w \in [0, W(y)]$. When $a(y) > 0.5$ the depth of the channel base below the channel top is given by:

$$d(w,y) = 4 \cdot t(y) \cdot \left(1 - \frac{w}{W(y)}\right)^{c(y)} \cdot \left[1 - \left(1 - \frac{w}{W(y)}\right)^{c(y)}\right] \tag{3}$$

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

Lobe Positioning

The lobes are positioned at the end of channels. Figure 5 illustrates the parameters needed to specify the positioning of lobes within a model. The distance from the model boundary is the only parameter needed when the lobe is positioned with the same orientation as the associated channel. This distance parameter is not constant; it will follow a specified probability distribution.

The final configuration of channels and lobes in any model will ultimately be determined by the simulation algorithm and conditioning data. Areally varying facies proportions and well data could lead to lobes in preferred locations.

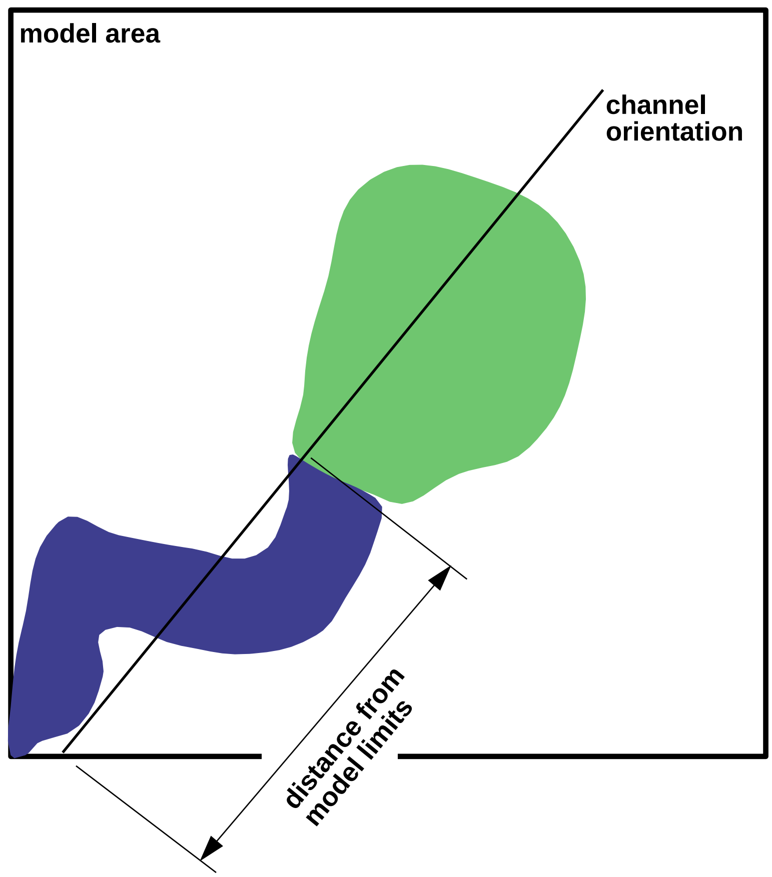

Figure 5: Lobes could be positioned with the same orientation as the associated channel. The only positioning parameter is then the distance from the model boundary.

Implementation Details / Simulation Algorithm

The simulation algorithm implemented in `fluvsim` [7, 6] was modified to include the lobe geometry and positioning described above. Details of the iterative algorithm adopted in `fluvsim` will not be repeated here; significant changes and modifications will be described. The revised program is referred to as `lobesim`.

Five facies can be simulated in `lobesim`. A classical indicator transform of the facies data is considered:

$$i(\mathbf{u};k) = \begin{cases} 1, & \text{if } \mathbf{u} \text{ is within facies } k \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

where $k = 1, 2, 3, 4, 5$ for channel sand, levee sand, crevasse sand, lobe sand, and floodplain shale. Crevasse and lobe sands are usually related to quite different depositional settings; therefore, it is unlikely that a user would generate a model with both. Flexibility is maintained for terriginous fluvial simulation.

Local well data and, perhaps, locally varing proportion data are accounted for with same iterative procedure as `fluvsim`. An objective function of the following form is minimized:

$$O_C = \omega_1 \cdot \sum_{k=1}^{K} \left[P_g^k - P_g^{k*}\right]^2 + \omega_2 \cdot \sum_{k=1}^{K}\sum_{z=1}^{N_z} \left[P_v^k(z) - P_v^{k*}(z)\right]^2 \quad (5)$$

$$+\omega_3 \cdot \sum_{k=1}^{K}\sum_{x=1}^{N_x}\sum_{y=1}^{N_y} \left[P_a^k(x,y) - P_a^{k*}(x,y)\right]^2$$

$$+\omega_4 \cdot \sum_{i=1}^{n} \left[i_w(\mathbf{u}_i) - i_c(\mathbf{u}_i)\right]^2$$

where ω_i is the weight applied to objective function component i. These weights are automatically determined such that each component has, approximately, equal importance; see [5]. The global, vertical, and areal oproportions P_g^{k*}, $P_v^{k*}(z)$, and $P_a^{k*}(x,y)$ are input by the user and calculated from the reslting model. The indicator variables $i_w(\mathbf{u})$ and $i_c(\mathbf{u})$ are calculated from the well data and model respectively. The facies objects are randomly perturbed until this objective function is reduced close to zero.

This conditioning is very brute force, that is, no empirical rules are used to position channel / lobe entities according to observations. A logical extension of this brute force approach would be to scan through the well data and determine a preliminary positioning prior to iterating for complex conditioning data.

Each lobe object is described parametrically by its parent channel, a positioning distance, and the seven lobe parameters presented above. The lobe is also represented as a template of cells that would be coded as lobe sand (code 4). In this case, the template consists of a three dimensional array:

$$lobethick(ic, ix, iy) \quad (6)$$

where ic is the channel number (each lobe is associated to a channel), ix is the block index in the direction perpendicular to the channel direction, and iy is the block index along the axis of the channel. Such templates provide significant CPU advantages because a raster image is quickly obtained after a perturbation to the model parameters. The penalty for representing geological objects as raster images is a sensitivity due to the choice of an underlying grid size. The grid size must be chosen small enough to preserve the geological shapes.

Some Examples

Figure 8 shows six hrizontal slices through a `lobesim` model. Note that the lobes are attached to the channels and oriented in the same direction. Figure 9 shows two vertical cross sections. The attachment is more difficult to see in cross section since the channels undulate in and out of the section plane.

Figure 10 shows horizontal slices through a `lobesim` where the channels have associated levee sands.

Future Work / Conclusions

There is always a need to fine tune "object" geometries to reflect details of each geological modelling exercise. There may be associated facies such as levee sands at the lobe margins. The lobes may be stacked in a particular fashion with a predictable thickness of shale between sand deposition.

The iterative approach to well conditioning does not, in general, permit exact reproduction of well data. Determinisitic approaches to position objects at the correct location have been used successfully with "small" objects that do not interact with many wells. Implementation is more complex with the large scale complex facies associations presented here.

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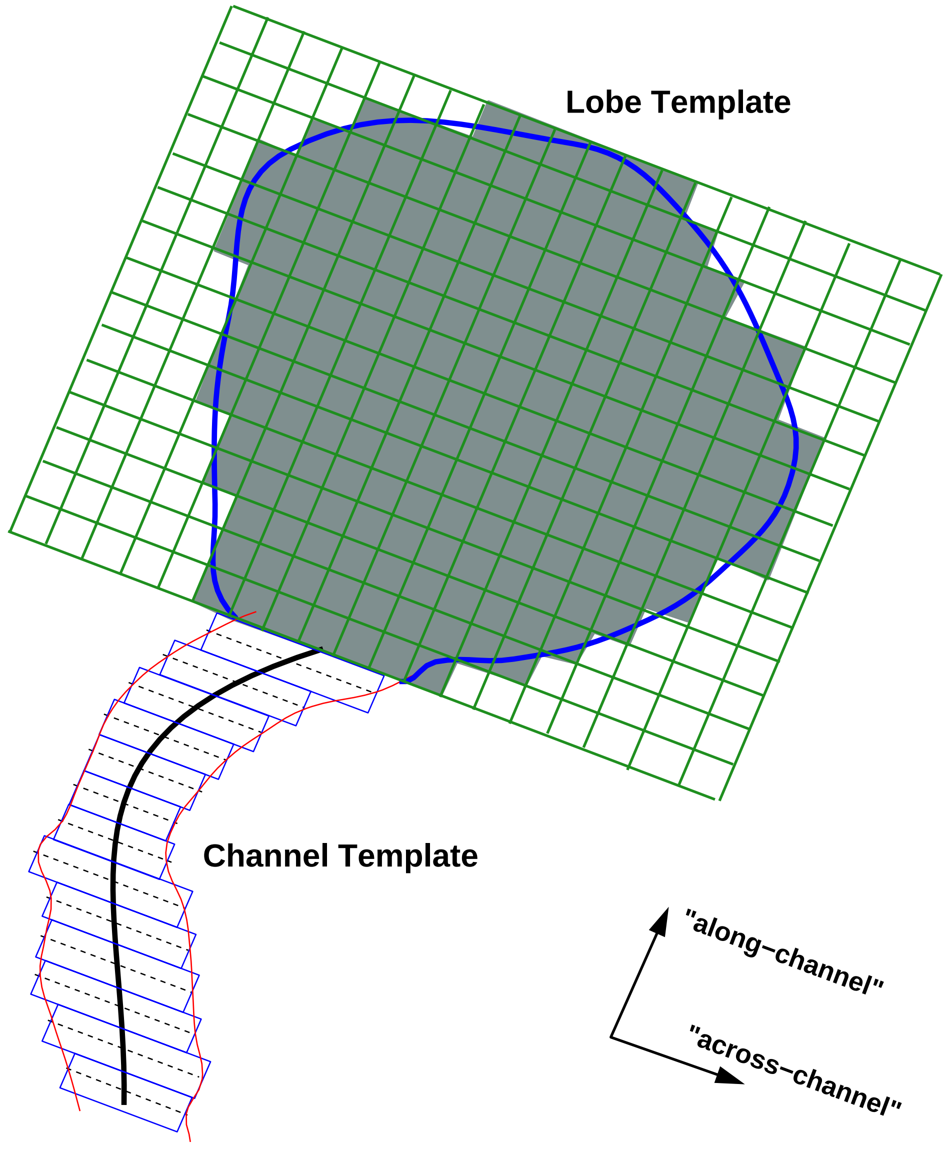

Figure 6: Channels and lobes are represented by templates. In the case of lobes, the gray shaded area is kept in memory together with the depth under each cell.

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                   Parameters for LOBESIM
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START OF PARAMETERS:
nodata                        -file with well conditioning data
1  2  3  4  5                 -  columns for X, Y, Z, well #, facies
-1.0       1.0e21             -  trimming limits
1                             -debugging level: 0,1,2,3
lobesim.dbg                   -file for debugging output
lobesim.geo                   -file for geometric specification
lobesim.out                   -file for simulation output
lobesim.vp                    -file for vertical prop curve output
lobesim.ap                    -file for areal prop map output
lobesim.wd                    -file for well data output
1                             -number of realizations to generate
100   0.0   40.0              -nx,xmn,xsiz - geological coordinates
100   0.0   40.0              -ny,ymn,ysiz - geological coordinates
50          50.0              -nz, average thickness in physical units
69069                         -random number seed
1   0   0   1                 -1=on,0=off: global, vert, areal, wells
1.  1.  1.  1.                -weighting : global, vert, areal, wells
100   10   0.05               -maximum iter, max no change, min. obj.
0.0   0.10   3  1  8          -annealing schedule: t0,redfac,ka,k,num
0.1 0.1 0.1 1.0               -Pert prob: 1on+1off, 1on, 1off, fix well
   1    0    0    0           -Facies(on): channel, levee, crev, lobe
0.20 0.10 0.10 0.20           -Proportion: channel, levee, crev, lobe
pcurve.dat                    -  vertical proportion curves
0                             -     0=net-to-gross, 1=all facies
1  7  8  9                    -     column numbers
arealprop.dat                 -  areal proportion map
1                             -     0=net-to-gross, 1=all facies
2  3  4  5                    -     column numbers
150                           -maximum number of channels
-30.0    0.0    30.0          -channel:  orientation (degrees)
200.0  200.0   200.0          -channel:  sinuosity: average departure
800.0  800.0   800.0          -channel:  sinuosity: length scale
  1.0    3.0     5.0          -channel:  thickness
  1.0    1.0     1.0          -channel:  thickness undulation
250.0  400.0   450.0          -channel:  thickness undul. length scale
150.0  200.0   250.0          -channel:  width/thickness ratio
  1.0    1.0     1.0          -channel:  width: undulation
250.0  250.0   250.0          -channel:  width: undulation length scale
160.0  240.0   320.0          -levee:    average width
  0.1    0.1     0.1          -levee:    average height
  0.2    0.3     0.4          -levee:    depth below top
 80.0   80.0    80.0          -crevasse: attachment length
  0.25   0.5     0.75         -crevasse: relative thickness by channel
500.0  500.0   500.0          -crevasse: areal size (diameter)
2000. 2250.   2500.           -lobe:     distance from model boundary
 300.  400.     -1.           -lobe:     starting width (-1 => auto)
1000. 1000.   1000.           -lobe:     lobe length
   0.5   0.5     0.5          -lobe:     relative pos of max width
   1.0   1.0     1.0          -lobe:     width/length ratio
   1.0   3.0    -1.           -lobe:     starting thick (-1 => auto)
   0.5   0.5     0.5          -lobe:     final thick (rel.)
   0.5   0.5     0.5          -lobe:     cross section thick. (rel.)
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Figure 7: Parameter file for `lobesim`. The "Facies(on)" flag, proportion of lobe facies, and the final 8 parameters specify the presence of lobes, the positioning and size.

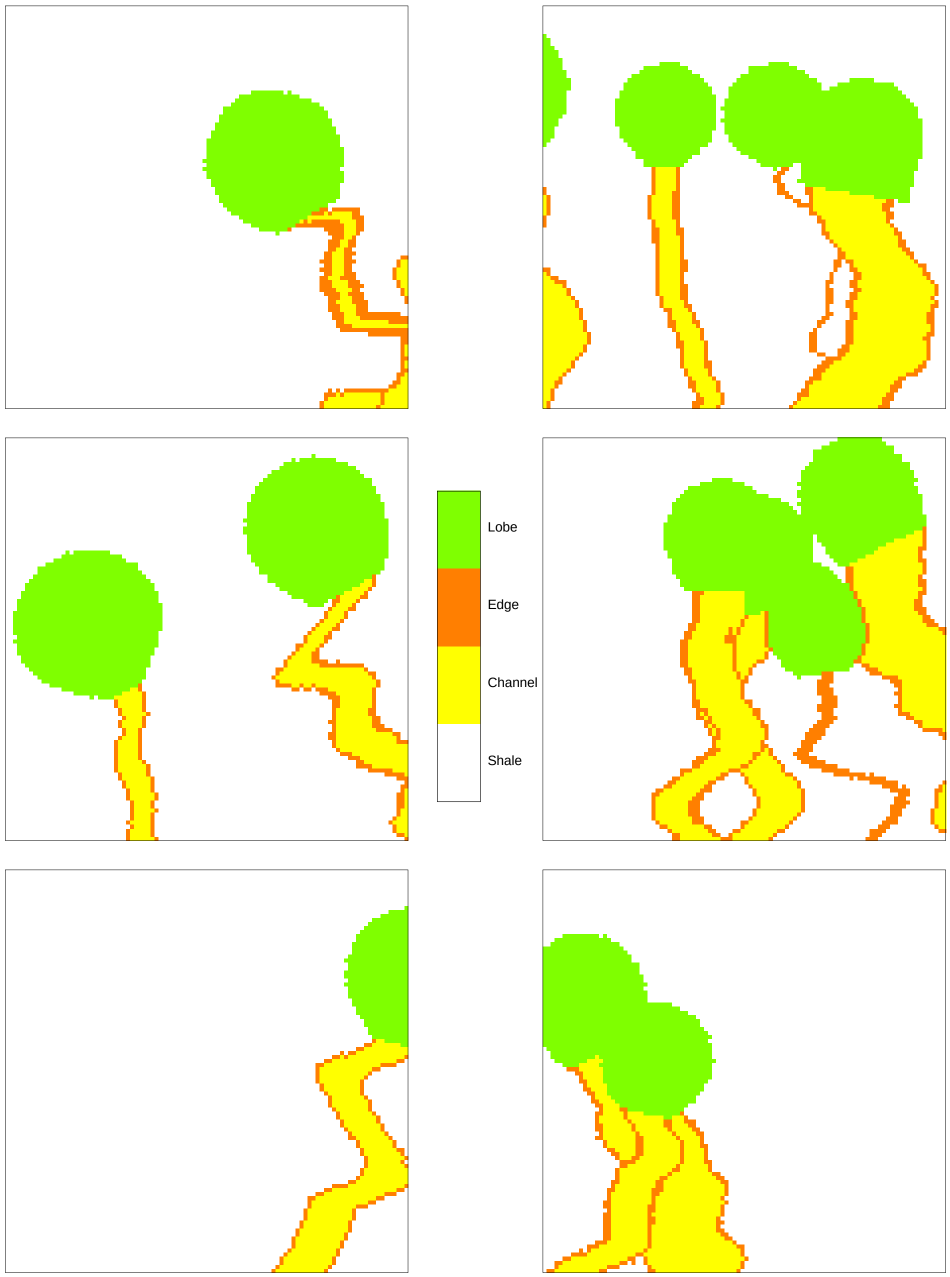

Figure 8: Horizontal slices through a `lobesim` model with lobes of constant size. The target proportions of channel and lobe sand are both 0.1.

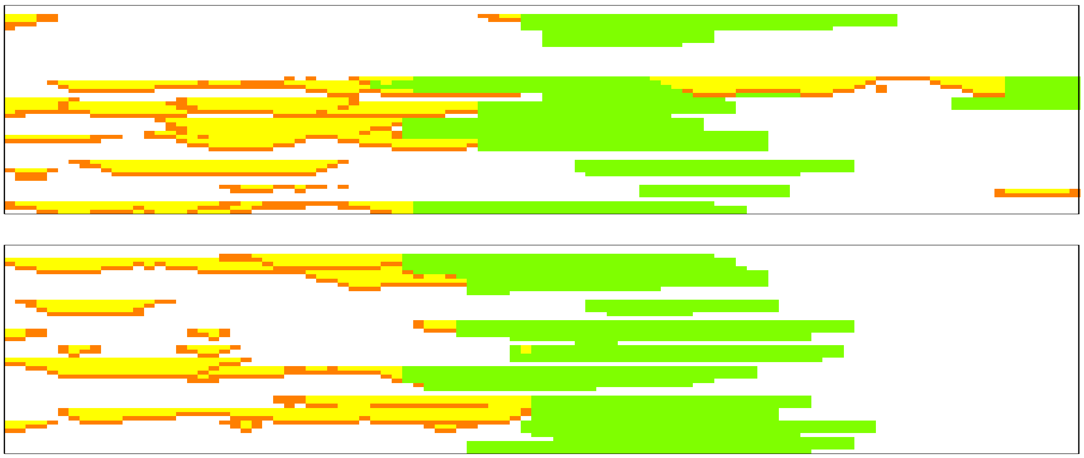

Figure 9: Vertical slices through a `lobesim` model with lobes of constant size. The target proportions of channel and lobe sand are both 0.2 in this case.

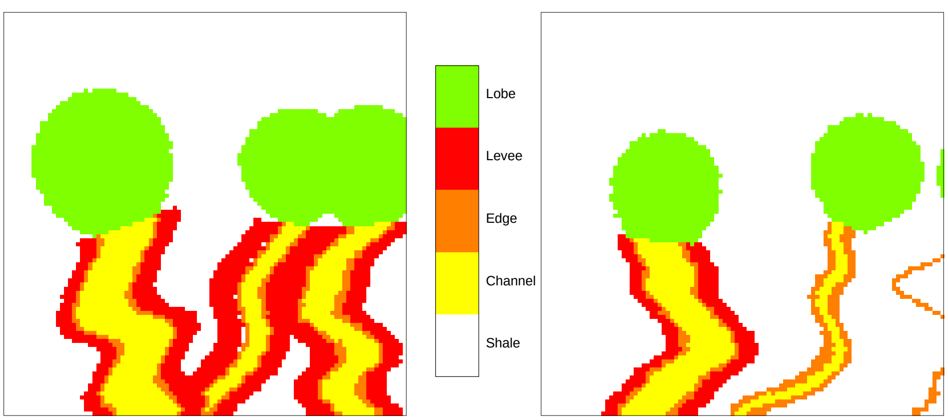

Figure 10: Horizontal slices through a `lobesim` model with lobes of constant size and levee sands associated to the channels. The proportions of channel, lobe, and levee sand were 0.1, 0.1, and 0.05, respectively.

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