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FLUVSIM: a program for object-based stochastic modeling of fluvial depositional systems ☆

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Abstract

This paper presents a FORTRAN program for hierarchical object-based modeling of complex fluvial facies. Unique features of this program include (1) a simple approach to place channel, levee, and crevasse sands within a matrix of floodplain shales, (2) templates for fast rastering of fluvial facies objects, leading to fast CPU times, and (3) the use of simulated annealing and non-random perturbation rules for conditioning to extensive soft facies-proportion data and local well data. Object-based modeling techniques are widely applicable to modeling fluvial depositional systems. Public domain software for such modeling is rare and inflexible with respect to the variety of conditioning data that can be handled. Commercial software is costly and also of limited flexibility. The `fluvsim` program overcomes many of these limitations with an accessible research code. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

From a geostatistical modeling perspective, it is convenient to view fluvial reservoirs with a hierarchical classification scheme. Heterogeneities are described by chronostratigraphic reservoir layers, channel complexes, channels, levees, and crevasses, and on through additional smaller scale features. This genetic hierarchy of heterogeneities may then be quantitatively modeled by successive coordinate transformations and objects representing lithofacies associations. Porosity and permeability models are constructed at the appropriate scale using coordinate systems aligned with depositional continuity.

Fluvial deposits have been studied extensively. The recent book by Miall (1996) provides a well illustrated description of fluvial sedimentary facies, basin analysis, and petroleum geology with more than 500 figures and 1000 references. The literature describing fluvial deposits is rich and varied. The history of quantitative computer models for fluvial systems is also extensive. Allen's early qualitative work in the 1970s (Allen, 1965; Allen, 1974) led to quantitative computer simulations (Allen, 1978). Leeder, at about the same time, was also building quantitative models (Leeder, 1978). Bridge published in this area (Bridge and Leeder, 1979) and also published computer code (Bridge, 1979) that was updated recently (Mackey and Bridge, 1992).

Although not specifically designed for fluvial facies, Boolean (or marked point) models became popular in petroleum reservoir modeling in the mid-1980s due to the work of Haldorsen and others (Haldorsen and Chang, 1986; Haldorsen and Lake, 1984; Stoyan et al., 1987). The importance of fluvial reservoirs in the Norwegian North Sea soon prompted the development of these Boolean methods for fluvial facies (Clemensten et al., 1990; Damsleth et al., 1990; Fælt et al., 1991; Gundesø and Egeland, 1990; Henriquez et al., 1990;

☆ Code available from server at http://www/iamg.org/CGEditor/index.htm

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Omre, 1992; Stanley et al., 1990). The theory and implementation was refined over a number of years (Georgsen and Omre, 1993; Hatløy, 1995; Hove et al., 1992; Tjelmeland and Omre, 1993; Tyler et al., 1992a–c) with increasing practical application of these methods to Norwegian North Sea reservoirs (Bratvold et al., 1994; Tyler et al., 1995). Such applications have set the standard for other oil producing regions of fluvial depositional setting.

There is evidence of other non-Norwegian oil companies developing object-based modeling capability (Alabert and Massonnat, 1990; Jones and Larue, 1997; Khan et al., 1996).

The hierarchical approach documented by the first author (Deutsch and Wang, 1996) has some advantages over conventional object-based fluvial reservoir modeling: (1) an explicit reversible hierarchy of coordinate transformations, (2) geologically intuitive and accessible input data controlling channel sizes and shapes, (3) explicit control over vertically varying and areally varying facies proportions, (4) realistic asymmetric channel geometries, (5) realistic non-undulating channel top surfaces, and (6) integrated porosity and permeability models where the main directions of continuity conform to channel geometries.

This paper describes computer code for such hierarchical object-based modeling with some significant new refinements: (1) introduction of levee and crevasse sands, (2) fast computer code that takes advantage of channel "templates" for establishing raster image of facies objects, and (3) the use of simulated annealing and non-random perturbation rules for conditioning to extensive well data. Each of these developments will be discussed and documented in a GSLIB-style program named `fluvsim`.

2. Conceptual geometric model

Fig. 1 illustrates our conceptual model for fluvial facies modeling adopted in this note. There are four facies types, with the geometric specification of each is chosen to mimic shapes idealized from observation.

The first facies type is background floodplain shale, which is viewed as the matrix within which the

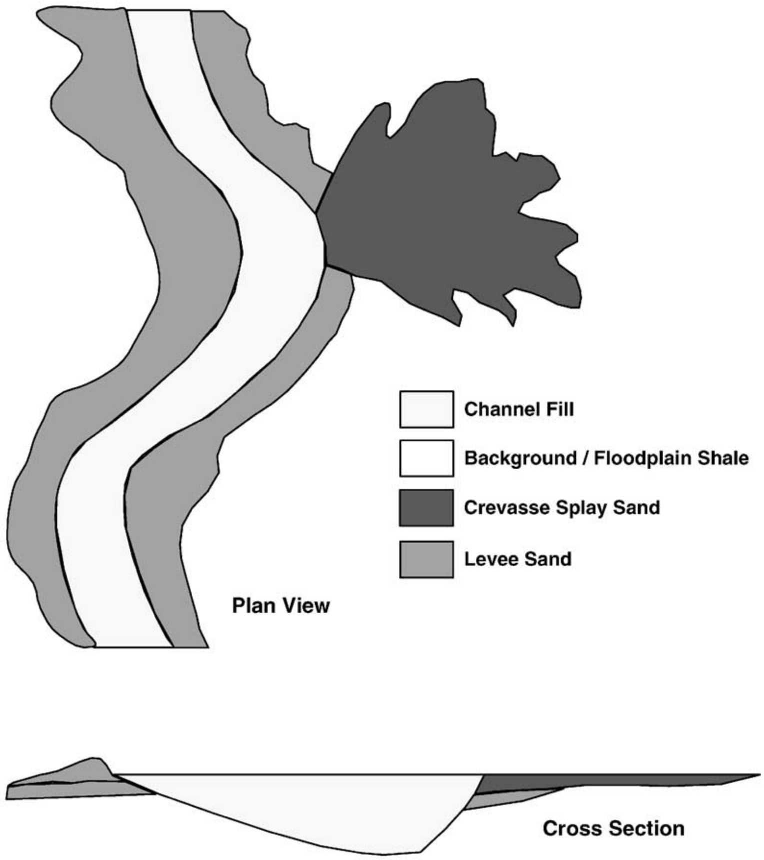

Fig. 1. Plan and section view of conceptual model for fluvial facies: background of floodplain shales, sand-filled abandoned channel, levee border sands, and crevasse splay sands.

reservoir-quality or *sand* objects are embedded. One could consider remnant floodplain shales as objects within a sand matrix if there is less than, say, 10% floodplain shale; `fluvsim` does not model remnant shales as objects.

The second facies type is *channel sand* that fills sinuous abandoned channels. This facies is viewed as the best reservoir quality due to the relatively high energy of deposition and consequent coarser grain size. Special features may be within the channel sands, such as (1) heterogeneous channel fill, perhaps containing some fine-grained non-net material, (2) a channel-lag deposit at the base, and (3) fining-upward trends within the channel fill. The sand-filled channels are geometrically defined by a channel width, maximum thickness, and the relative position of the maximum thickness. The realistic asymmetric channel cross section presented in Deutsch and Wang (1996) is considered.

The third facies type is *levee sand* formed along the channel margins. These sands are considered to be poorer quality than the channel fill. The fourth and final facies type considered in this paper is *crevasse splay sand* formed during flooding when the levee is breached and sand is deposited away from the main channel. These sands are also considered to be poorer quality than the channel fill. As illustrated on Fig. 1, crevasses often form where the channel curvature is high.

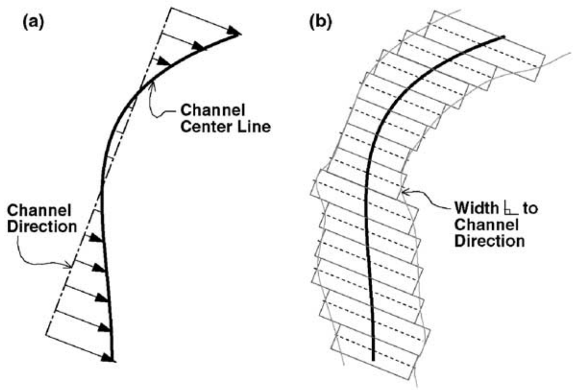

Fig. 2. Areal view of some parameters used to define channel object: (a) angle for channel direction and deviation for actual channel center line, and (b) variable channel width (and thickness) with "blocky" connection between channel cross section slices.

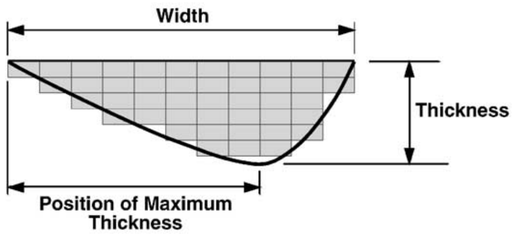

Fig. 3. Cross section view of channel object defined by width, thickness, and relative position of maximum thickness (depends on channel curvature).

3. Object parameterization

An important part of any object-based modeling program is the geometric form and parameters used to represent each facies unit; see Deutsch and Wang (1996) for a more complete discussion. An "object" for `fluvsim` is a channel and all related levee and crevasse sands. The marginal levee and crevasse sands could be treated as the "objects" in a depositional setting with high proportions of those facies types. Each object is a template of cells that would be coded as channel sand (code 1), levee sand (code 2), and crevasse sand (code 3). The template provides significant CPU advantages; however, the connectivity of simulated realizations is sensitive to the choice of an underlying grid size. The grid size must be chosen small enough to preserve the geological shapes represented by the templates.

The parameters used to define an abandoned sand-filled channel are illustrated in Figs. 2 and 3. The channels are defined by an orientation angle, the average departure from the channel direction, the "wavelength" or correlation length of that average departure, thickness, thickness undulation (and correlation length), width/thickness ratio, and width undulation (and correlation length). Each parameter may take a range of possible values according to a triangular probability distribution provided by the user. The channel center line, width, and thickness are 1-D Gaussian fields along the channel direction coordinate. The equation for the asymmetric channel cross section is given in the source code and in reference (Deutsch and Wang, 1996). Note that the width of the channels are measured perpendicular to the straight channel line direction, which makes it impossible to capture meandering channels that cross back on themselves.

Fig. 4 shows the geometric form adopted for the levee sand. The three distance parameters (A) lateral extent of the levee, (B) height above the channel datum elevation, and (C) depth below the channel datum are used to define the size. For simplicity, the geometric shape will remain fixed and only the size will vary. As explained with the program parameters, the levee size parameters depend on the size of the channel; a large channel, in general, has larger levees. The size of the left and right levee may be different.

A random-walk procedure is used in this implementation to establish the crevasse geometry, see Fig. 5. The location of a crevasse, along the channel axis, is chosen randomly with the probability increasing in direct

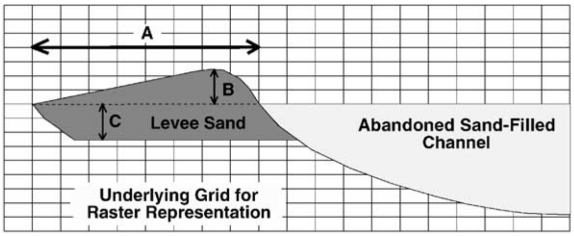

Fig. 4. Cross section through abandoned sand-filled channel and levee sand. Three distance parameters (A), (B), and (C) are used to define size of levee sand.

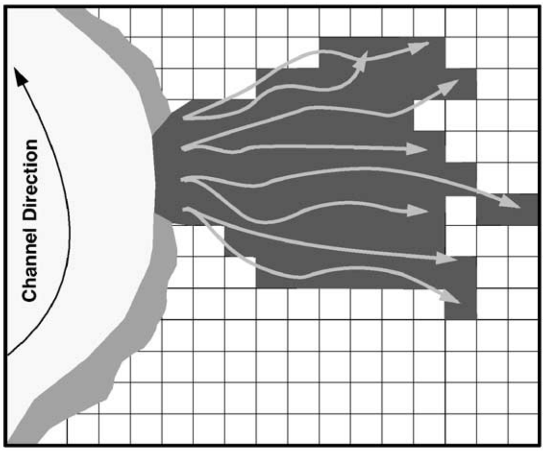

Fig. 5. Areal view of channel and crevasse formed by breaching levee. Number of random walkers are released from breach to establish crevasse geometry. Number, length, and lateral diffusivity control geometry and size of crevasse.

proportion to curvature (see Deutsch and Wang, 1996 for the equation to calculate curvature). A number of random walkers are "released" from the location of the crevasse to establish its areal extent (Fig. 5). The four control parameters are (1) the *average* distance the crevasse sand reaches from the channel bank, (2) the *average* along-channel distance, (3) the irregularity of the crevasse sand or the number of random walkers used; more walkers leads to a smoother outline. The thickness of the crevasse sand decreases linearly from a maximum thickness next to the channel.

The procedure to create a complete facies grid from a set of channel object template is straightforward: (1) initialize the grid to background floodplain shales, (2) sort all channel objects by increasing stratigraphic elevation (the top of all channels is flat), and, starting at the stratigraphic base (3) assign all grid cells within the channel object to channel/levee/crevasse facies, as appropriate.

4. Conditioning data/simulation approach

As described in Deutsch and Wang (1996), the proportions of each facies type (floodplain shale, channel sand, levee sand, and crevasse splay sand) may be specified by vertical proportion curves, areal proportion maps, and reference global proportions. The index $k = 1, 2, 3, 4$ refers to the facies types. Global proportions, P_g^k, $k = 1, 2, 3, 4$, and vertical proportion curves $P_v^k(z)$, $k = 1, 2, 3, 4$, $z = 1, \ldots, N_z$ are derived from declustered well data. We expect areal proportions, $P_a^k(x, y)$, $k = 1, 2, 3, 4$, $x = 1, \ldots, N_x, y = 1, \ldots, N_y$, to be derived from geologic interpretation, seismic data, or historic flow-performance data. In practice, seismic data may not be able to distinguish between the different sand types. The scheme for data conditioning (described below) permits `fluvsim` to use either total sand proportion maps or proportion maps for each facies type. The sum of facies proportions at each location $\sum p_k$ should logically be 1.0; `fluvsim` will enforce this constraint.

The facies are known at well locations. Honoring an abundance of local well data is known to be a challenge for some object-based modeling schemes. The iterative procedure adopted in `fluvsim` handles such well data. The well data are transformed to indicator data:

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

where $k = 1, 2, 3, 4$ for channel sand, levee sand, crevasse sand, and floodplain shale.

Each reservoir layer is modeled independently and then merged with other layers according to appropriate erosion and truncation rules. For a given layer, all data are converted to a "flattened" stratigraphic coordinate system. The object-based facies model is constructed and petrophysical properties are assigned using appropriate channel/levee/crevasse coordinates.

Conditioning to facies proportions and local well data is accomplished via an objective function that measures mismatch from the known proportion data and facies intersections at wells. An iterative procedure is used to perturb the set of geological objects until an acceptably low objective function is obtained. The objective function:

$$\begin{aligned} O = {} & \omega_1 \sum_{k=1}^{K} [P_g^k - P_g^{k*}]^2 + \omega_2 \sum_{k=1}^{K} \sum_{z=1}^{N_z} [P_v^k(z) - P_v^{k*}(z)]^2 \\ & + \omega_3 \sum_{k=1}^{K} \sum_{x=1}^{N_x} \sum_{y=1}^{N_y} [P_a^k(x, y) - P_a^{k*}(x, y)]^2 \\ & + \omega_4 \sum_{i=1}^{n} \sum_{k=1}^{K} [i(\mathbf{u}_i; k) - i^*(\mathbf{u}_i; k)]^2 \end{aligned} \qquad (1)$$

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 Deutsch and Cockerham, 1994), the $*$ identifies quantities from the stochastic realization and the absence of a $*$ identifies reference or target quantities.

The simulation procedure amounts to establishing the number of channels, their geometric specification, and the geometric specification of all related levee and crevasse sands. This is done with an iterative simulated annealing technique:

1. Randomly place enough (N_c) channels to match the global proportions of each facies. The number of crevasses attached to each channel depends on the relative size of channels and crevasses and the target proportions. The sizes of the levees are scaled to achieve the correct proportion of levee sand. Calculate an initial objective function O.
2. Define an array of operations: (1) replace a channel object, (2) add a channel object, (3) remove a channel object, and (4) correct a particular well interval. Choose one operation from this array by random drawing and perform the operation. The channels to be removed are picked at random. The location for a new channel is also picked at random and the parameters of the new channel (and associated sands) are picked from the size and orientation distributions specified by the user.
3. Update the objective function O' and decide the acceptance or rejection of that operation according to the decision rule (a simulated annealing schedule [Deutsch and Cockerham, 1994] is used). If needed, update the list of channels.
4. Return to step 2 until O is deemed low enough.

When the simulation is finished `fluvsim` reports the list of channel objects and associated parameters, a raster image of facies, and summaries of data conditioning.

The fourth perturbation mechanism, *fix a well interval*, requires clarification. The purpose for this option is to make it faster and easier to honor well data. The CPU time requirements would be significantly greater if we relied solely on the objective function to guide the placement of the channel objects to honor the well data. So, when this perturbation mechanism is chosen, a well interval is picked at random from the set of input wells and a change is proposed to improve the reproduction of this interval. That is, if necessary, channel objects that violate a shale interval are moved and new channel objects are added to honor channel facies.

5. Program parameters

The `fluvsim` program is research code and suitable for experimenting with the ideas presented in this paper; the program has not been optimized for speed and with the support system of commercial software. Nevertheless, it may prove useful for testing and research in this area.

The `fluvsim` program follows GSLIB conventions. The parameters required for the program are listed below and a parameter file is shown in Fig. 6:

- `line 1`: input file containing the well data. The standard GSLIB/GeoEAS format is expected.
- `line 2`: columns in the well data file for the X-, Y-, and Z-coordinates, the well number (used to identify different well intersections), and the facies code.
- `line 3`: trimming limits used to flag missing values; well data with a facies code less than the lower limit or greater than the upper limit are discarded.
- `line 4`: debugging level. The higher the debug level, the more output reported to the debug file (next parameter).
- `line 5`: output file for debugging messages.
- `line 6`: output file for the geometric specification of all facies objects. This file could be used by a post-processing program to add petrophysical properties that follow appropriate facies object coordinate systems.
- `line 7`: output file containing the output gridded facies realization. The realizations are written from the lower left corner and then realization-by-realization (X cycles fastest, then Y, Z, and realization number).
- `line 8`: output file for the input and realization vertical facies proportion curves (facilitates checking proportion reproduction).
- `line 9`: output file for the input and realization areal facies proportion maps (facilitates checking proportion reproduction).
- `line 10`: output file for the input and realization facies at each well data location (facilitates checking well data reproduction).
- `line 11`: number of realizations to generate.
- `line 12`: the size of the model in the X-direction.
- `line 13`: the size of the model in the Y-direction.
- `line 14`: the number of stratigraphic slices in the layer and the average layer thickness in "real" distance units (feet or meters).
- `line 15`: the random number seed (large odd integer).
- `line 16`: integer flags specifying the components in the objective function: global facies proportions, vertical proportion curves, areal proportion maps, and well data.
- `line 17`: the program automatically determines weights for each component to allow convergence of all constraints; however, these multiplicative weights modify the automatically determined weights to place more importance on selected components.

```
                   Parameters for FLUVSIM
                   *********************

START OF PARAMETERS:
tmp/well01.dat               -file with well conditioning data        - line  1
1  2  3  4  5                -  columns for X, Y, Z, well #, facies   - line  2
-1.0      1.0e21             -  trimming limits                       - line  3
1                            -debugging level: 0,1,2,3                - line  4
tmp/fluvsim.dbg              -file for debugging output               - line  5
tmp/fluvsim.geo              -file for geometric specification        - line  6
fluvsim.out                  -file for simulation output              - line  7
tmp/fluvsim.vp               -file for vertical prop curve output     - line  8
tmp/fluvsim.ap               -file for areal prop map output          - line  9
tmp/fluvsim.wd               -file for well data output               - line 10
1                            -number of realizations to generate      - line 11
100   0.0   40.0             -nx,xmn,xsiz - geological coordinates    - line 12
100   0.0   40.0             -ny,ymn,ysiz - geological coordinates    - line 13
50          50.0             -nz, average thickness in physical units - line 14
69069                        -random number seed                      - line 15
1   0   0   1                -1=on,0=off: global, vert, areal, wells  - line 16
1.  1.  1.  1.               -weighting : global, vert, areal, wells  - line 17
100   50   0.05              -maximum iter, max no change, min. obj.  - line 18
0.0   0.10   3  1  8         -annealing schedule: t0,redfac,ka,k,num  - line 19
0.1 0.1 0.1 1.0              -Pert prob: 1on+1off, 1on, 1off, fix well - line 20
   1    0    0               -Facies(on): channel, levee, crevasse    - line 21
0.30 0.10 0.10               -Proportion: channel, levee, crevasse    - line 22
pcurve.dat                   -  vertical proportion curves            - line 23
0                            -     0=net-to-gross, 1=all facies       - line 24
1  7  8                      -     column numbers                     - line 25
arealprop.dat                -  areal proportion map                  - line 26
1                            -     0=net-to-gross, 1=all facies       - line 27
2  3  4                      -     column numbers                     - line 28
150                          -maximum number of channels              - line 29
-30.0    0.0    30.0         -channel:  orientation (degrees)         - line 30
200.0  200.0   200.0         -channel:  sinuosity: average departure  - line 31
800.0  800.0   800.0         -channel:  sinuosity: length scale       - line 32
  1.0    4.0     7.0         -channel:  thickness                     - line 33
  1.0    1.0     1.0         -channel:  thickness undulation          - line 34
250.0  400.0   450.0         -channel:  thickness undul. length scale - line 35
100.0  150.0   300.0         -channel:  width/thickness ratio         - line 36
  1.0    1.0     1.0         -channel:  width: undulation             - line 37
250.0  250.0   250.0         -channel:  width: undulation length scale - line 38
160.0  240.0   320.0         -levee:    average width                 - line 39
  0.1    0.1     0.1         -levee:    average height                - line 40
  0.2    0.3     0.4         -levee:    depth below top               - line 41
 80.0   80.0    80.0         -crevasse: attachment length             - line 42
  0.25   0.5     0.75        -crevasse: relative thickness by channel - line 43
500.0  500.0   500.0         -crevasse: areal size (diameter)         - line 44
```

Fig. 6. Parameter file for `fluvsim` program. Conventions from second edition of GSLIB are followed, that is, line number after "START" matters but not the column position.

- `line 18`: the maximum number of iterations, the maximum number of iterations without a change to the objective function, and the minimum objective function (stopping criteria).
- `line 19`: the annealing schedule: initial temperature, the reduction factor, the maximum number of perturbations at any one given temperature, and the target number of acceptable perturbations at a given temperature, and the stopping number (maximum number of times that the **ka** is reached). These parameters are described in detail in *Numerical Recipes* (Press et al., 1986).
- `line 20`: the probability of each perturbation mechanism at each perturbation (1) turn a channel

entity on and one off, (2) just turn one on, (3) just turn one off, and (4) pick a well interval at random attempt to fix conditioning.

- `line 21`: integer flags specifying the facies objects: channel sands (must be on), levee sands, and crevasse sands.
- `line 22`: global proportions of channel sands, levee sands, and crevasse sands; the shale proportion is 1.0 minus the sum of sand proportions.
- `line 23`: the input file for vertical facies proportion curves. The standard GSLIB/GeoEAS format is expected; however, the first column must be the proportion of channel sand, the second levee sand (if present), and the third crevasse sand (if present).
- `line 24`: an integer flag that specifies whether the vertical proportion curves correspond to the net-to-gross ratio (lumped proportion of all sand facies) or to each facies proportion.
- `line 25`: column numbers for the lumped facies proportion or each sand facies proportion (channel, levee, and then crevasse).
- `line 26`: the input file for areal facies proportion maps. The standard GSLIB/GeoEAS format is expected; however, the first column must be the proportion of channel sand, the second levee sand (if present), and the third crevasse sand (if present).
- `line 27`: an integer flag that specifies whether the areal proportion curves correspond to the net-to-gross or to each facies proportion.
- `line 28`: column numbers for the lumped facies proportion or each sand facies proportion (channel, levee, and then crevasse).
- `line 29`: maximum number of channel objects.All remaining parameters are set with triangular distributions, that is, defined by a minimum, mode, and maximum.
- `line 30`: channel orientation (angle in degrees measured clockwise from North/Y-axis). The angles can be negative or positive (e.g., -10.0, 0.0, -10.0 would orient the channels parallel to the Y-axis with a 10 degree deviation in the channel direction).
- `line 31`: average departure from channel center line (horizontal distance units) representing the half width of the meander.
- `line 32`: horizontal correlation length for sinusoidal departure from channel center line (horizontal distance units).
- `line 33`: channel thickness (vertical distance units)
- `line 34`: average magnitude of channel thickness undulation (fraction relative to channel thickness). The channels will have a constant thickness if this parameter is set to either 0.0 or 1.0. The channels will vary between 0.8 and 1.2 times the average thickness when this parameter is set to 0.2.
- `line 35`: horizontal correlation length for channel thickness undulation (horizontal distance units). The channel thickness undulation (line 34) follows a Gaussian histogram; the correlation length is the distance range of correlation along the axis of the channel.
- `line 36`: channel width to thickness ratio (horizontal to vertical distance units).
- `line 37`: channel width undulation (fraction relative to channel width). See explanation for thickness undulation (line 34) for more details.
- `line 38`: horizontal correlation length for channel width undulation (horizontal distance units).
- `line 39`: levee width (horizontal distance units).
- `line 40`: levee height (relative to thickness of channel).
- `line 41`: levee depth below channel top (relative to thickness of channel).
- `line 42`: crevasse attachment length (horizontal distance units).
- `line 43`: crevasse thickness next to channel (relative to channel thickness).
- `line 44`: areal size of crevasse (diameter in horizontal distance units).

6. Some examples

A number of examples will be presented to show the main abilities of the `fluvsim` program. We could not hope to present the complete range of flexibility. Fig. 7 shows isometric views of four unconditional realizations created by `fluvsim`: (a) base-case channel model, (b) decreased channel sinuosity, (c) increased channel sinuosity, and (d) model with crevasse splay sands (dark blue) and levee sands (light blue). Note the realism of the models (with respect to the conceptual model) and the lack of edge effects. Fig. 8 shows two sensitivity realizations, both unconditional, with different channel widths: (a) base-case channel model, and (b) much wider channels.

It is very important (and sometimes difficult) to honor the sand/shale intersections at well locations. Fig. 9 shows an example of a model constrained to four wells: (a) isometric view of final channel model, (b) decrease of total objective function versus the number of iterations, and (c)–(e) cross sections through the wells showing how the sand/shale intersections are honored.

Figs. 10 and 11 show models constrained to locally varying channel proportions. Fig. 10 shows an example considering an input areal proportion map: (a) isometric view of final model with well locations and input areal proportion map, (b) input areal proportion map (derived from seismic, historical production data, or geological interpretation), and (c) reproduction of areal proportions in final model—the large scale features are reproduced quite well. Fig. 11 shows an example with a vertical proportion curve: (a) isometric view of final

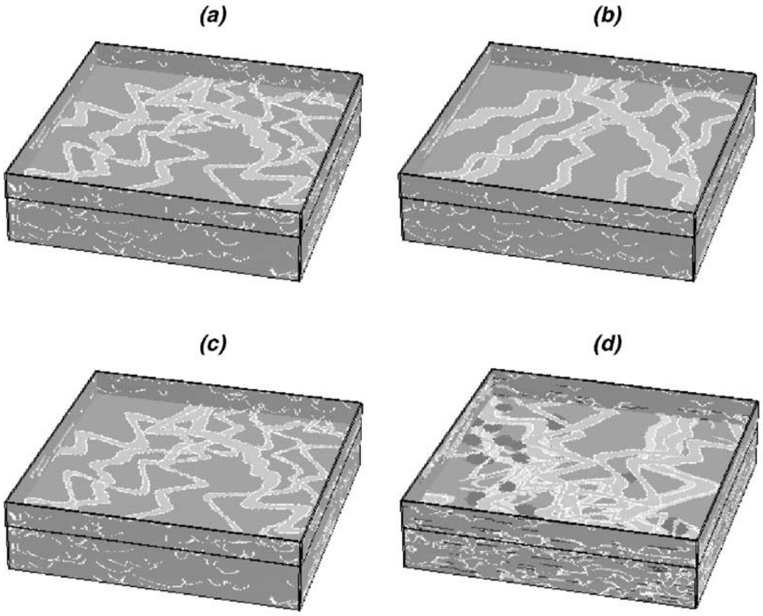

Fig. 7. Isometric views of some models created by `fluvsim` program (a) base case channel model, (b) decreased channel sinuosity, (c) increased channel sinuosity, and (d) model with crevasse splay sands (dark grey) and levee sands (light grey).

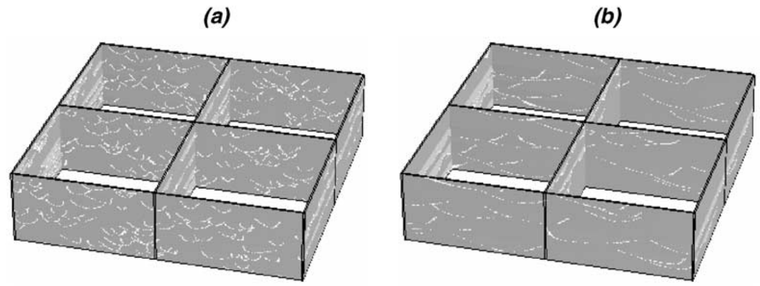

Fig. 8. Fence diagram through two models showing different channel width parameters (a) base case channel model, and (b) relatively wide channels.

model with well locations, (b) input vertical proportion curve (derived from well data or geological interpretation), and (c) reproduction of vertical proportions in final model—this is a cross section view in the Y direction (looking to the top left of page).

7. Conclusions

Reservoir modeling proceeds sequentially. One reservoir model is built at a time to create a family of multiple equiprobable stochastic reservoir models. Each major reservoir layer bounded by chronostratigraphic surfaces is modeled independently and then combined in a final reservoir model. Within a layer, the distribution of channel complexes is modeled to honor well data and perhaps locally varying facies proportions. Channel, levee, and crevasse sand objects are then positioned within each channel complex to honor well data and a more detailed representation of the facies proportions. Finally, in object-specific coordinate systems, porosity and permeability are modeled.

A simple approach to add levee and crevasse sands was described. The levees are added stochastically to the right and left bank of the channel sands. A number of parameters are required to specify the size. The levees may be breached in times of flooding causing the deposition of crevasse splay sands. These objects are modeled with random-walker-based templates. An objective function can be written to enforce reproduction of facies proportions and local well data.

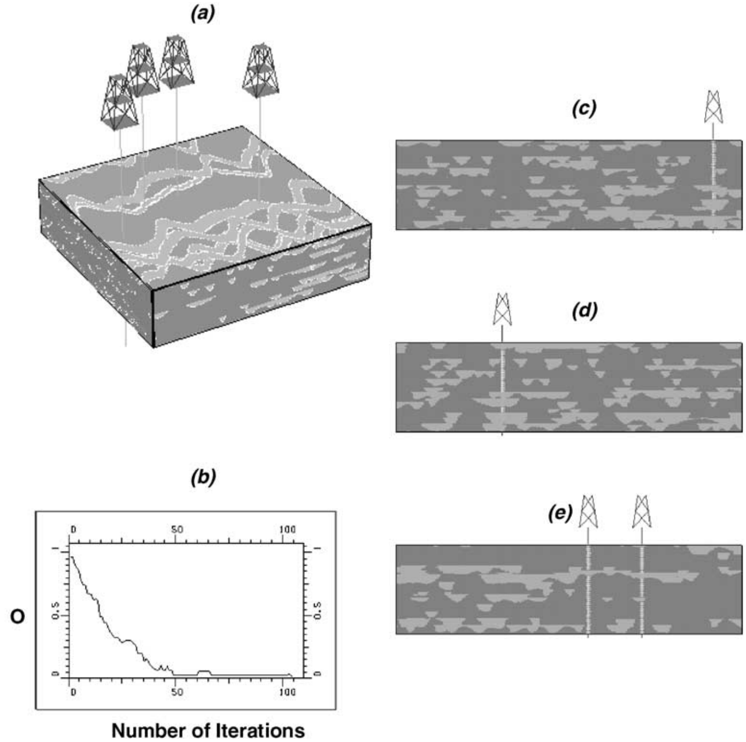

Fig. 9. Example showing channel model constrained to four wells (a) isometric view of final channel model, (b) decrease of total objective function versus the number of iterations, and (c), (d), and (e) cross sections through wells showing how sand/shale intersections are honored.

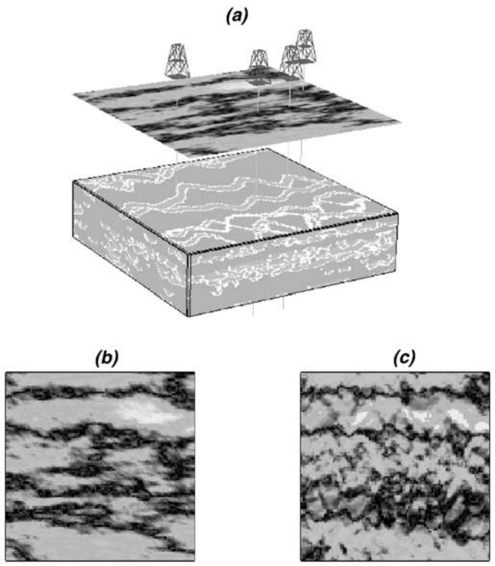

Fig. 10. Example showing reproduction of input areal proportion map, (a) isometric view of final model with well locations and input areal proportion map, (b) input areal proportion map (derived from seismic, historical production data, or geological interpretation), and (c) reproduction of areal proportions in final model—large scale features are reproduced well.

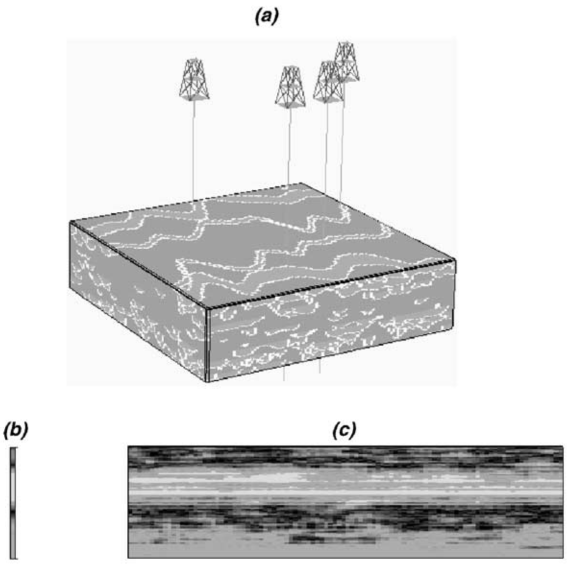

Fig. 11. Example showing reproduction of input vertical proportion curve, (a) isometric view of final model with well locations, (b) input vertical proportion curve (derived from well data or geological interpretation), and (c) reproduction of vertical proportions in final model—this is cross section view in Y-direction (looking to top left of page).

Practical implementation of the iterative simulation depends on fast updating of intermediate raster models. An approach, based on facies-object templates, allows fast updating. This, in turn, allows the implementation of true simulated annealing for the optimization procedure instead of steepest-descent algorithms. Realizations with very low objective function values can be generated.

The research program `fluvsim` provides a useful starting point for geologic modelers considering object-based facies modeling.

References

Alabert, F.G., Massonnat, G.J., 1990. Heterogeneity in a complex turbiditic reservoir: Stochastic modelling of facies and petrophysical variability. SPE Paper Number 20604. 65th Annual Technical Conference and Exhibition, September, pp. 775–790.

Allen, J.R.L., 1965. A review of the origin and characteristics of recent alluvial sediments. Sedimentology 5, 89–191.

Allen, J.R.L., 1974. Studies in fluviatile sedimentation: implications of pedogenic carbonate units, lower old red sandstone, Anglo-Welsh outcrop. Geology Journal 9, 181–208.

Allen, J.R.L., 1978. Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion—controlled alluviate suites. Sedimentary Geology 21, 129–147.

Bratvold, R.B., Holden, L., Svanes, T., Tyler, K., 1994. STORM: integrated 3D stochastic reservoir modeling tool for geologists and reservoir engineers. SPE Paper Number 27563, pp. 242–261.

Bridge, J.S., 1979. A FORTRAN IV program to simulate alluvial stratigraphy. Computers & Geosciences 5, 335–348.

Bridge, J.S., Leeder, M.R., 1979. A simulation model of alluvial stratigraphy. Sedimentology 26, 617–644.

Clemensten, R., Hurst, A.R., Knarud, R., Omre, H., 1990. A computer program for evaluation of fluvial reservoirs. In: Buller et al. (Eds.), North Sea Oil and Gas Reservoirs II. Graham and Trotman, London, UK, pp. 372–385.

Damsleth, E., Tjolsen, C.B., Omre, K.H., Haldorsen, H.H., 1990. A two-stage stochastic model applied to a north sea reservoir. In 65th Annual Technical Conference and Exhibition, pp. 791–802.

Deutsch, C.V., Cockerham, P.W., 1994. Practical considerations in the application of simulated annealing to stochastic simulation. Mathematical Geology 26 (1), 67–82.

Deutsch, C.V., Wang, L., 1996. Hierarchical object-based stochastic modeling of fluvial reservoirs. Mathematical Geology 28 (7), 857–880.

Fælt, L.M., Henriquez, A., Holden, L., Tjelmeland, H., 1991. MOHERES, a program system for simulation of reservoir architecture and properties. European Symposium on Improved Oil Recovery, pp. 27–39.

Georgsen, F., Omre, H., 1993. Combining fibre processes and Gaussian random functions for modeling fluvial reservoirs. In: Soares, A. (Ed.), Geostatistics Troia 1992, Vol. 2. Kluwer, Dordrecht, pp. 425–440.

Gundesø, R., Egeland, O., 1990. SESIMIRA—a new geologic tool for 3-d modeling of heterogeneous reservoirs. In: Buller et al. (Eds.), North Sea Oil and Gas Reservoirs II. Graham and Trotman, London, UK, pp. 360–371.

Haldorsen, H.H., Chang, D.M., 1986. Notes on stochastic shales: from outcrop to simulation model. In: Lake, L.W., Caroll, H.B. (Eds.), Reservoir Characterization. Academic Press, London, pp. 445–485.

Haldorsen, H.H., Lake, L.W., 1984. A new approach to shale management in field-scale models. SPE Journal, April, pp. 447–457.

Hatløy, A.S., 1995. Numerical facies modeling combining deterministic and stochastic method. In: Yarus, J.M., Chambers, R.L. (Eds.), Stochastic Modeling and Geostatistics: Principles, Methods, and Case Studies, AAPG Computer Applications in Geology, 3, 109–120.

Henriquez, A., Tyler, K., Hurst, A., 1990. Characterization of fluvial sedimentology for reservoir simulation modeling. SPE Formation Evaluation, September, pp. 211–216.

Hove, K., Olsen, G., Nilsson, S., Tonnesen, M., Hatloy, A., 1992. From stochastic geological description to production forecasting in heterogeneous layered reservoirs. In SPE Annual Conference and Exhibition, Washington, DC, October 1992. SPE Paper Number 24890, pp. 311–325.

Jones, T.A., Larue, D.K., 1997. Object-based modeling and deepwater depositional systems. In: Pawlowsky-Glahn, V. (Ed.), Proceedings of IAMG'97, Vol. 1, pp. 438–443.

Khan, A., Horowitz, D., Liesch, A., Schepel, K., 1996. Semi-amalgamated thinly-bedded deepwater gom turbidite reservoir performance modeling using object-based technology and bouma lithofacies. In 1996 SPE Annual Technical Conference and Exhibition, Denver, CO, October 1996. SPE Paper Number 36724, pp. 443–455.

Leeder, M.R., 1978. A quantitative stratigraphic model for alluvium with special reference to channel deposit density and interconnectedness. In: Miall, A.D. (Ed.), Fluvial Sedimentology, pp. 587–596.

Mackey, S.D., Bridge, J.S., 1992. A revised FORTRAN program to simulate alluvial stratigraphy. Computers & Geosciences 18 (2), 119–181.

Miall, A.D., 1996. The Geology of Fluvial Deposits. Springer, New York, 582pp.

Omre, H., 1992. Heterogeneity models. In SPOR Monograph: Recent Advances in Improved Oil Recovery Methods for North Sea Sandstone Reservoirs, Norway. Norwegian Petroleum Directorate, pp. 141–153.

Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., 1986. Numerical Recipes. Cambridge University Press, New York, 963pp.

Stanley, K.O., Jorde, K., Raestad, N., Stockbridge, C.P., 1990. Stochastic modeling of reservoir sand bodies for input to reservoir simulation, Snorre Field, northern North Sea. In: Buller et al. (Eds.), North Sea Oil and Gas Reservoirs II. Graham and Trotman, London, UK, pp. 91–103.

Stoyan, D., Kendall, W.S., Mecke, J., 1987. Stochastic Geometry and its Applications. Wiley, New York, 283pp.

Tjelmeland, H., Omre, H., 1993. Semi-Markov random fields. In: Soares, A. (Ed.), Geostatistics Troia 1992, Vol. 2. Kluwer, Dordrecht, pp. 493–504.

Tyler, K., Henriquez, A., Georgsen, F., Holden, L., Tjelmeland, H., 1992a. A program for 3d modeling of heterogeneities in a fluvial reservoir. In 3rd European Conference on the Mathematics of Oil Recovery, Delft, June, pp. 31–40.

Tyler, K., Henriquez, A., MacDonald, A., Svanes, T., Hektoen, A.L., 1992b. MOHERES—a collection of stochastic models for describing heterogeneities in clastic reservoirs. In 3rd International Conference on North Sea Oil and Gas Reservoirs III, pp. 213–221.

Tyler, K., Henriquez, A., Svanes, T., 1995. Modeling heterogeneities in fluvial domains: a review on the influence on production profile. In: Yarus, J.M., Chambers, R.L. (Eds.), Stochastic Modeling and Geostatistics: Principles, Methods, and Case Studies, AAPG Computer Applications in Geology, 3, 77–89.

Tyler, K., Svanes, T., Henriquez, A., 1992c. Heterogeneity modelling used for production simulation or fluvial reservoir. SPE Formation Evaluation, June, pp. 85–92.