Advances in Stochastic Surface Modeling: Conditioning, Facies and Non Stationarity

Xingquan Zhang[1] and Michael J. Pyrcz[2]

[1]Department of Civil and Environmental Engineering, University of Alberta
[2]ETC Quantitative Stratigraphy Team, Chevron Energy Technology Company

Reservoirs are formed by a succession of depositional and erosional events, which can be described by sequence stratigraphy. The surfaces used in sequence stratigraphy are not physical surfaces, but time surfaces. These time surfaces can be used as bounding surfaces for hierarchical geostatistical reservoir modeling to explicitly account for stratigraphic trends in element and complex volume, grain size and facies. These trends are commonly observed in reservoirs and form due to well known processes constrained by cycles in climate, tectonic and eustacy.

Surface-based facies models are visually attractive in that they may mimic a high level of geologic realism. The resulting facies and property models reproduce idealized architectural element geometries very well, with a focus on a hierarchy of bounding surfaces. The surface models at a variety of hierarchical orders may be constructed using stochastic surface modeling programs, or interpreted deterministically from seismic volume or by geologic expert judgment based on outcrops and modern analogues. Such models show facies belonging to clean geological shapes with realistic curvilinear continuity, which cannot be modeled with cell-based approaches. In addition, these models are constructed in a forward sense such that evolving bathymetry is modeled; therefore, this method may account for interactions between elements that are not possible with object-based models. Finally this method allows for the natural integration of geological interpretation based on element hierarchy.

There are several stochastic surface modeling programs that have been developed over the past couple of years at the CCG. One such program is known as surfsim. *In this report, limitations in this method are documented and some improvements on* surfsim *program are presented, with a focus on improved trend and infill facies modeling.*

Introduction

As a newly developed approach, the placement of stochastic surface modeling in reservoir characterization has not been established yet [4]. Generations of graduate students at CCG have been working on developing stochastic surface modeling approaches, and several surface-based modeling programs have been developed to meet specific purposes.

- Stochastic turbidite lobe modeling started in 1999 when Deutsch and Tran developed the LOBESIM program. Simulated annealing is used to honor facies proportion. Some important concepts, such as the lobe geometry parameterization, object placement rules for lobes, were established and followed in later surface modeling [3]. A linear shape for long section and cross section is used during lobe modeling, but it can be easily modified to use any curvilinear shape, such as the shape defined by Deutsch and Wang [1].

- The large-scaled surface modeling also started in 1999 [16] by Xie, who developed the `Surfsim` program based on simulated annealing. Lateral accretion is well modeled, and nested vertical trend can also be well honored [17, 18, 19].

- Another fine-scaled surface modeling program, `Turbsim`, was developed by Pyrcz in 2003 [9, 10, 11, 14, 15]. Wells can be well honored; and nested hierarchical trend (short and long scale) can be well honored too based on skeleton transform. It is a versatile program; several types of bounding surfaces can be selected. First, Streamlines are calculated based on topology of base surface; then, lobes are placed at the end of streamlines. In this way no flattening is needed. The surface model is geological realistic. The major limitation is that source positions of turbidite can't be designated explicitly by the end user. No volume trend and stacking pattern can be honored.

- Another large scaled surface modeling program, `Surfsim`, was developed by Pyrcz in 2004 [12, 13]. The boundary surfaces are assumed to be tabular, which is the major limitation of `Surfsim`.

- A versatile fine-scaled surface modeling program, `LE_model`, was developed by Deutsch to model lobe events. Source positions can be designated by the end user. Lobe is placed on a tabular base plane, which makes simulated volume gradually decreased upward. User can specify the source position explicitly, although all source position is assumed to be located on the left side of the research area. Base surface can be flatted to honor proportional strata correlation; or the truncation stratigraphic correlation will be modeled.

The research in this paper is based on the `Surfsim` program for large-scaled surface modeling. The improvements can be summarized as:

- Geological thickness trend of turbidite lobes is analyzed, that is, the volume trends are linked to geometry (size) of elements.

- Piecewise linear trends model is used to capture the reverse to normal grading transition. It is good for large-scaled volume definition.

- Different styles of strata correlation can be honored, not just proportionally.

- Other small changes of `Surfsim` make it more flexible.

In addition to the improvements on large-scaled surface modeling discussed above, a surface-based facies modeling approach is presented. In practice, a local facies trend of a second-order turbidite lobe is derived through multi-disciplined research, although it usually cannot be quantified clearly. Suppose such kind of facies trend exists. So, for a given position, the possible facies proportion at that point will be derived analytically based on its 3D relative coordinates in a specific lobe. The resulting facies model is geological realistic and curvilinear shapes can be well handled. At present, only second-order facies trend information is used, and no hierarchical facies trends are considered. Such kind of facies model can not be put into practice directly, but it is a good start for later conditional facies modeling, and it shows a promising future for the appliance of the surface modeling.

Advances in Surface-based Modeling

Comments on programs used in this report

The stochastic surface modeling approaches can be classified into two classes: large-scaled surface modeling approaches, such as Surfsim developed by Xie and Deutsch (2000) and Surfsim developed by Pyrcz (2004); and small-scaled surface modeling approaches, such as Lobesim developed by Deutsch and Tran (1999), Turbsim developed by Pyrcz (2003), and LE_model developed by Deutsch (2006). In this report, some improvements on large-scaled surface modeling are developed based on Surfsim developed by Pyrcz (2004); but for surface-based facies modeling, the surface model can be built using any fine-scaled surface modeling program.

Summary of improvements on Surfsim program

The Surfsim developed by Pyrcz (2004) is very suitable for large-scaled tabular surface modeling in the sense that all surfaces, including bounding surfaces and generated surfaces, are approximately tabular. Usually, small-scaled surfaces show more curvilinear shape due to the short deposition time. Wells can also be well honored during surface modeling.

The major limitations of original Surfsim program are:

- The boundary surfaces and generated surfaces are nearly tabular. Usually, reservoirs are formed along basin margin; so it is common that surfaces are tilt / bent due to tectonic position / stress. It is difficult to apply Surfsim directly in these circumstances.

- Surfsim can only honor proportional strata correlation during unconditional simulation due to the tabular bounding surfaces, and thickness parameterization method which will be discussed in detail later.

- The thickness is drawn from a given Gaussian distribution, so the thickness is centre around the given mean and thus no vertical trend can be honored.

- The surfaces number is an arbitrary constant number, 20. User cannot control it explicitly. This also reduced the flexibility of Surfsim program.

The character of large-scaled thickness trend

Better understanding of spatial distribution of turbidite lobes is critical for building a realistic turbidite surface model. Usually the reservoir bounding surfaces are sampled from seismic data, so the characteristics of turbidite lobes volume distribution can be forecasted using sequence stratigraphy knowledge. Geological rules can help us to build more geological realistic surface model.

1. **Four types of bounding surfaces**

Due to the resolution of seismic data, the scale of these bounding surfaces should be at least in third-order scale. Fine-scaled sequence boundaries can only be recognized on well logs, well core or outcrops; thus they are not beneficial for large-scaled surface trend definition. Based on sequence stratigraphy, there are four types of bounding surfaces combinations for large-scaled surface modeling, which is shown in Figure 1.

2. **Turbidite lobe volume trend analysis**

The relationship between lithology and turbidite lobe geometry is well known. Deepwater turbidites are usually formed along shelf margins. A sequence is formed within a sea level change cycle. From sequence boundary to adjacent maximum flooding surface (MFS), the grain size becomes

finer upward, which is a well known phenomenon. According to the knowledge of hydrodynamics, we know that coarse deposition usually deposits quickly, which means that the lobe size with coarse grain usually is relatively smaller but thicker; on the contrary, the fine deposition will drift far away, so the lobe size with fine grain should be larger but thinner. This phenomenon is well illustrated in Figure 2. Therefore, from base boundary surface to MFS, the thinner-upward volume trend exists.

Above analysis is based on the assumption that the bounding surfaces are extracted from seismic data and they are at least in third-order scale.

3. Characteristics of lobe volume trends with different boundary surfaces

The characteristics of lobe volume trends with different boundary surfaces can be described using Figure 1:

- Case (a): Both bounding surfaces are MFS's. The grain size of MFS is usually the finest part within a sequence. The coarsest grain is located between two MFS's, at the location of sequence boundary. The grain size has coarsing-upward then fining-upward trends.
  - o For this scenario, the turbidite lobes will have following characteristics according to grain size distribution:

Position	Grain Size	Thickness	Lobe Size
base	fine	thinner	larger
middle	coarse	thicker	smaller
top	fine	thinner	larger
topmost	finest	normal deep sea deposit	

- Case (b): The bottom surface is an unconformity; the top surface is an MFS. This is common in practice. The grain size has simple fining-upward trend because the lower half-sequence is usually very thin. If an unconformity exists, the lower half-sequence is usually missing.
  - o For this scenario, the turbidite lobes will have following characteristics :

Position	Grain Size	Thickness	Lobe Size
bottom	coarse	thicker	smaller
top	fine	thinner	larger
topmost	finest	normal deep sea deposit	

- Case (c): The top surface is an unconformity, and the base surface is an MFS. The top strata will be truncated, but the fining-upward trend still exists.
  - o For this scenario, the distribution of turbidite lobes will have following characteristics:

Position	Grain Size	Thickness	Lobe Size
bottom	fine	thinner	larger
middle	coarse	thicker	smaller
top	fine	thinner	larger
topmost	missing	being truncated	

- Case (d): both the bounding surfaces are unconformities.
  - o For this scenario, the distribution of turbidite lobes will have these characteristics:

Position	Grain Size	Thickness	Lobe Size
bottom	coarse	thicker	smaller
top	fine	thinner	larger
topmost	missing	being truncated	

- There are maybe other types of boundary surface combinations, but the above four scenarios are common ones. The thinning-upward trend is also common within a turbidite lobe. Note that the coarsing-upward section is usually very short, so if a bottom unconformity exists, the coarsing-upward section usually will not be detected on seismic.

Piecewise linear volume trend definition

The large-scaled thickness trend can be easily visualized and quantified on seismic sections, and it can be defined easily by piecewise linear model. Geologically, the volume trends are usually described as "thinner upward" or "thicker downward", so piecewise linear volume trend definition is good enough for handling this large-scaled volume trend.

The trends are defined in relative scale. It starts from base boundary surface, and top boundary surface has relative total volume 1.0, see Figure 3. The thickness parameter for modeling is then interpolated linearly based on trend definition.

The source code can be easily modified to honor arbitrary trend definition, such as curvilinear trend definition, as long as it can be described as a function for trend data interpolation. Usually, the piecewise linear model is good enough for describing the large-scaled volume trend.

Four types of stratigraphic correlations

There are four common stratigraphic correlation styles:

- **Proportional**: The strata conform to the existing top and base. The strata may vary in thickness because of differential compaction or sedimentation rate and may be structurally deformed and faulted; however, the correlation grids coincide with the existing grids.

- **Truncation**: The strata conform to the existing base but have been eroded at the top. The lower correlation grid coincides with the existing base.

- **Onlap**: The strata conform to the existing up (no erosion) but have "filled" existing topography so that the base correlation grid does not coincide with the existing base.

- **Combination**: The strata neither conform to the existing top nor the existing base. Two additional correlation grids are required [4].

Different boundary surfaces combinations show above four types of stratigraphic correlations. Still use Figure 1 as an example. Case (a) corresponds to the proportional stratigraphic correlation; Case (b) corresponds to the onlap stratigraphic correlation; Case (c) corresponds to the truncation stratigraphic correlation; and Case (d) corresponds to the combination stratigraphic correlation.

With the modified `Surfsim` program, all types of stratigraphic correlations can be honored.

A method to add infill facies

Pyrcz (2003) presented a possible reservoir properties modeling approach by hierarchical (short and long scale) trends modeling [10, 11, 15]. The limitation of this approach is that the exhaustive hierarchical trends definition is nearly impossible in practice, and hierarchical trend definition is also very difficult due to the sparse well data. In this paper, an alternative facies modeling method will be presented based on facies trend template. The facies template can be derived easily and loosely. For example, it can be derived from the local facies model based on multi-disciplinary research, or quantified from seismic inversion results. Then a cell-based SIS program, e.g. Block-

SIS, is used for facies modeling. The facies model is geologic realistic and curvilinear shapes can be well modeled, which is the major limitation of conventional SIS approach. The facies model will be updated later for conditioning all known data. In this paper, the method on unconditionally adding infill facies is presented. The approaches on updating facies model for conditioning purposes will be addressed next year.

Geologic background

Although particle diameters typically span many orders of magnitude for turbidite deposition, the grain size of a well-sorted turbidite fan usually changes gradually, in longitudinal, lateral, and vertical directions. Thus the facies distribution of a classic turbidite system, which is classified by grain size, is divinable by integrating statistical analysis of grain size or facies, geological knowledge database and multi-disciplinary research.

Turbidites were first properly described by Bouma (1976), who studied deepwater sediments and recognized particular fining up intervals within deep water, fine grained shales, which were anomalous because they started at pebble conglomerates and terminated in shales [20]. Now we know that turbidites are sediments which are transported and deposited by density flow, not by tractional or frictional flow. Transportation energy fades with distance and time, so the typical Bouma cycles forms along vertical direction with time. As the result of energy fading, Bouma cycles are formed, which begin with a coarse lower bed of pebble to granule conglomerate in a sandy matrix, and grade up through coarse then medium through cross-bedded sandstone, to cross-bedded shale and finally laminar silt [20]. Typically, a concentric elliptical structure will be formed in planar in a turbidite lobe, see Figure 4. For a given cell, its 3D relative coordinates can be ascertained using its relative longitudinal coordinate x_r, transverse coordinate y_r, and vertical coordinate z_r. All coordinates are calculated based on its distance to the main streamline. A skeleton or medial axis transformation is performed to calculate the main streamline position. Then the facies proportion is calculated based on a given facies template.

Facies proportion calculation

Based on above geological model, see Figure 4, two simplified facies trend models are proposed for the calculation of facies proportion, which is illustrated in Figure 5. A simplified linear facies transition is used here. It can be easily modified to use any arbitrary facies transition definition.

The 3D relative position of a given cell within a turbidite lobe is calculated using skeleton transform; then *Hr*, the horizontal relative position, is calculated based on the x_r and y_r positions. *Hr* is calculated by:

- When *Yr* equals to zero, that is, when the cell locates on the streamline, its horizontal relative position can be uniquely expressed by *Xr*, which is shown on the top panel of Figure 6.

- When *Yr* doesn't equal to zero, an affine scaling transform is performed, see the bottom plot of Figure 6.

The transform is based on the following geological knowledge and assumptions:

- The facies proportion at *Yr* = 0 is the same as the facies proportion at *Xr* = x_r.

- The facies proportion at *Yr = 1* is the same as the facies proportion at *Xr = 1*.

- The facies follows the same transition rate longitudinally and transversely through streamline.

For the two proposed facies trend models, the calculation mechanism is different:

- Model I calculates facies proportions in one step using both *Hr* and *Zr*. For a given cell,
  - Its 3D relative positions *Xr, Yr,* and *Zr* are calculated firstly.
  - Its position *Hr* is then calculated.
  - The facies proportions are calculated according to *Hr* and *Zr*.
  - Examples: Some facies proportions on the left panel of Figure 5.
    - *Hr_1*: %facies1 = 100%
    - *Hr_2*: %facies1 = 50%, %facies2 = 50%
    - *Hr_3*: %facies2 = 100%
    - *Hr_4*: %facies2 = 50%, %facies3 = 50%
    - *Hr_5*: %faices3 = 100%
  - The facies proportion is then standardized to 1.0 or honor the order relationship.

- Model II assumes that the facies follow different trend, horizontally and vertically, and then calculates the prior mean in two steps, using *Hr* and *Zr* separately. Note that the *Z* axis represents facies proportions only and all facies sum up to 1.0. For a given cell,
  - Its 3D relative positions *Xr, Yr,* and *Zr* are calculated firstly.
  - The horizontal relative position *Hr* is then calculated.
  - The horizontal facies proportion at *Hr* position is calculated. This proportion corresponds to the facies proportion on the base of the lobe.
  - The vertical facies proportion at *Zr* position is calculated.
  - The combined facies proportion is calculated by (using the right panel of Figure 5 as example):
    - ```
      If facies1 exists at Hr, then %facies1 = %facies1@Hr × %facies1@Zr; or else
      %facies1 = 0.
      ```
    - ```
      If facies2 exists at Hr, then %facies2 = %facies2@Hr × %facies2@Zr; or else
      %facies2 = 0.
      ```
    - ```
      If facies3 exists at Hr, then %facies3 = %facies3@Hr × %facies3@Zr; or else
      %facies3 = 1.0 - %facies1 - %facies2.
      ```
  - The facies proportion is then standardized to 1.0 to honor the order relationship.

Some comments on facies proportion calculation

Comparing these two methodologies, it's clear that with the same facies trend template, %facies1 accounts for larger proportion with Model I, especially when it is close to the base of a lobe (see Figure 7) so it is suitable for sand-rich turbidite modeling; by contraries, %facies3 accounts for larger proportion with Model II, so it is suitable for mud-rich turbidite modeling. Another difference is that given a cell which is very close to the bottom of a lobe, only one facies can be drawn if Model I is used; but several possible facies can be drawn if Model II is used. That is, Model II shows more variability than Model I, and it will be a little patchier too. As the result, the facies model using Model I will be cleaner than that of Model II.

Facies modeling

After getting the exhaustive facies proportion data, the unconditional facies model can be built with `BlockSIS` program of GSLIB using [2]:

Non-stationary simple kriging using residuals from local mean:

$$i^*_{LVM_1}(\mathbf{u};k) - p_k(\mathbf{u}) = \sum_{\alpha=1}^{n} \lambda_\alpha^{SK}(\mathbf{u};k) \cdot \left[i(\mathbf{u}_\alpha;k) - p_k(\mathbf{u}_\alpha) \right] \tag{1}$$

or, non-stationary simple kriging assigning one minus the sum of the weights to the local mean:

$$i^*_{LVM_2}(\mathbf{u};k) = \sum_{\alpha=1}^{n} \lambda_\alpha^{SK}(\mathbf{u};k) \cdot i(\mathbf{u}_\alpha;k) + \left[1 - \sum_{\alpha=1}^{n} \lambda_\alpha^{SK}(\mathbf{u};k) \right] \cdot p_k(\mathbf{u}) \tag{2}$$

The differences between Formula 1 and 2 are minor when the locally varying mean values are smooth, but the differences are more significant when there is a greater variation in the local probability values, for example, when they come from seismic data. The first local mean option, Equation (1), is the most correct one by theory; however, the simplified option, Equation (2), places slightly more emphasis on the local hard data instead of the local mean values [5].

Limitations of Surface-based Modeling

1. an artifact of volume versus elevation

One conditional `Surfsim` realization is shown in Figure 8. Although several surfaces have extremely large or small volume, the vertical thinning-upward trend is still very obvious. It is clear that the conditioning data control the vertical volume trend. The corresponding unconditional realization is shown in Figure 9. Without conditioning data, four vertical trend cycles are shown. Note that both volume plots show that the generated surfaces are quite large and cover all or at least the majority of the study area, so no surfaces stacking pattern will be honored.

Four unconditional realizations are shown in Figure 10. Note that the vertical volume trend cycles are different for each realization. What is the real volume trend behind these realizations? Is the volume trend analysis based on one realization reliable? The answer is certainly no, because the surface is built sequentially and randomly. Firstly, a horizontal surface is built based on the given mean parameter; then, some random errors are added into this plane. The errors have normal distribution and zero mean. This artifact tells us that the vertical lobe size trend is hard to define using one realization.

2. adequate vertical discretization is required

During surface-based facies modeling, fine-scaled Z grid definition should be used to avoid adjacent surfaces falling into the same grid cell too often. With fine grid definition, more geological details will be captured, but it is also time consuming, see Figure 11 and 12. It is a tradeoff..

Demonstrations of Surface-based Modeling

The parameters of improved `Surfsim` program

A series of new factors are introduced into `surfsim` program to honor stratigraphic correlation and vertical volume trend. The related parameters have been highlighted below.

1) Line3 specifies well conditioning run or not. Under well conditioning run, both vertical trend and conditioning data will be honored; therefore, more surfaces will be rejected during surface modeling. This parameter is added for the convenience of end-user. Originally, if the well data exists, conditional run is performed; or else, unconditional run is performed.

2) Line4 specifies the flattening method. Two stratigraphic flattening methods have been designed at present: a) flatten base surface only; that is, the base surface has proportional strata correlation and the top surface has truncation correlation; b) flattening both top and base surfaces, i.e., the proportional stratigraphic correlation will be honored for both bounding surfaces; and c) no flattening; that is, both bounding surfaces have truncation strata correlation. This parameter has to be used together with the surface number parameter, see Line 11. Some realizations with different flattening options are shown on Figure 13.

3) Line5 through line9 specify the thickness trend template. The trend is defined using relative thickness, see Figure 3.

4) The filling fraction of the model can be specified on Line10. It defines the upper terminus position of turbidite lobes. If it is larger than or equal to 1.0, this means that the top surface is an unconformity and lack of normal sea deposition. It can be used together with surface number and flattening options to define the upper strata correlation.

5) The number of surfaces can be specified on Line11. It also controls the stratigraphic correlation of the top surface. It is useful when the surface number is known through seismic data.

```
START OF PARAMETERS:
well.dat                      - file with data                                Line1
1  2  3  4  5  6  7  8        - well,x1,y1,z1,x2,y2,z3,code,.                  Line2
0                             - well conditioning? (0 - No, 1 - Yes)          Line3
0                             - flatten method (0=no,1=base,2=proportional)   Line4
4                             - number of trend control points                Line5
0.0   3.0   2.0               - relative position, thickness, stdev for 1st point  Line6
0.3   5.0   2.0               - relative position, thickness, stdev for 2nd point  Line7
0.7   5.0   2.0               - relative position, thickness, stdev for 3rn point  Line8
1.0   2.0   2.0               - relative position, thickness, stdev for 4th point  Line9
0.90                          - fraction of the model to fill                 Line10
20                            - Number of surfaces                            Line11
top.out                       - file with top surface                         Line12
bot.out                       - file with bottom surface                      Line13
1                             - number of realizations to generate            Line14
100   0.5   1.0               - nx,xmn,xsiz                                   Line15
50    0.5   1.0               - ny,ymn,ysiz                                   Line16
150   0.5   1.0               - nz,zmn,zsiz                                   Line17
surfsim.out                   - file for simulation output                    Line18
surfsimgrid.out               - file for simulation grid output               Line19
surfvol.out                   - file for surface volume output                Line20
0                             - debugging level: 0,1,2,3                      Line21
surfsim.dbg                   - file for debugging output                     Line22
69069                         - random number seed                           Line23
12                            - number of simulated nodes to use              Line24
1     3                       - multiple grid search (0=no, 1=yes),num        Line25
10.0  10.0                    - maximum search radii (hmax,hmin)              Line26
 0.0                          - angle for search ellipsoid                    Line27
51    51                      - size of covariance lookup table               Line28
1     0.1                     - nst, nugget effect                            Line29
1     0.9  0.0                - it,cc,ang1                                    Line30
          10.0  10.0          - a_hmax, a_hmin                               Line31
```

A synthetic example

A synthetic boundary surfaces are built and illustrated in Figure 14. It is impossible to apply original `Surfsim` program directly on this highly structured bounding surfaces. Both boundary surfaces are flattened to honor the proportional strata correlation; then the surface model is back-transformed to original unit. It also shows that `Surfsim` program can be used to model fine-scaled tabular surface now.

Piecewise linear volume trend modeling

For `Surfsim` program, surface is built sequentially. Originally, a random number is drawn from specified Gaussian distribution, and then it is added onto a constant value as the thickness parameter for simulation. Thus, the thickness is depth unrelated. To explicitly honor the vertical thickness trend, a vertical trend table is used. Firstly, a random number is drawn from specified Gaussian distributions; then, a constant thickness is read from the thickness trend table based on the average elevation of former surface; finally, the two numbers are added up together as the final thickness parameter for simulation. At present, only linear thickness trend is honored, see Figure 3. The source code can be easily modified to honor any trend, as long as it can be expressed as a function for interpolation. But for large-scaled surface modeling, the piecewise linear model will be good enough.

Figure 15 shows the E-type mean surface model of 99 unconditional `Surfsim` realizations. The volume trend is defined on Figure 3. These models were built unconditionally, so no influence of conditioning data is imposed on realizations. The non-equal thickness trend can be visualized clearly. The volume of each layer is calculated and plotted to reveal the volume trend, see Figure 16. The volume trend is well honored. Figure 16 also shows that with different dispersion selection (the standard deviation parameter), the realizations can be totally different.

The workflow of surface-based facies modeling

The workflow of surface-based facies modeling can be summarized as two steps:

1. Facies proportion calculation

A surface-based facies proportion calculation program, `SurFac`, was developed in clean GSLIB code. An example parameter file is shown below:

```
  Line     START OF PARAMETERS:
   1       LE_model.out                    - file with simulated surfaces
   2       1                               - which #simulation want to calculate?
   3        90   25.0   50.0               - nx,xmn,xsiz
   4       140   25.0   50.0               - ny,ymn,ysiz
   5       500   .05     0.1               - nz,zmn,zsiz
   6       debug.out                       - file with debug
   7       lm.out                          - file with prior mean
   8       1                               - prior mean calculation option (1 or 2)
   9       3                               - total number of facies
  10       0.0   0.4   0.4   0.0           - cutoff 1 definition (x1,z1,x2,z2)
  11       0.0   0.7   0.7   0.0           - cugoff 2 definition (x1,z1,x2,z2)
```

The stochastic facies model is specified on Line 1. The surface model used for prior mean calculation is specified on Line 2, so it can deal with surface model with multiple realizations. The grid definition is specified on Lines 3, 4, and 5 where standard GSLIB grid definition is used. The debugging file is specified on Line 6, and no debugging level is specified at present. Prior mean/facies proportion file is specified on Line 7, and the output is written for BlockSIS at pre-

sent. If a user wants to output result for other programs, such as sisim_lm program of GSLIB, the user has to assess to the source code and modify the output part, or simply modify the output file instead. The option to calculate prior mean is specified on Line 8. One-step prior mean calculation algorithm is used in option 1, and two-steps prior mean calculation algorithm is used in option 2. Total facies is specified on Line 9. Next (nfacies-1) lines specify the facies distribution (template) of each facies. At present, only linear interpolation is used; so for each cutoff only 2 extreme points are needed. Curvilinear facies template can be easily fulfilled by modifying the source code.

The meaning of this parameter file is straightforward. At present, only linear facies transition template is used for simplification. User can modify the source code easily to use any curvilinear function. Note that if 3 facies exist, only 2 facies transitions need to be defined.

2. cell-based facies modeling

After calculating facies proportion, conventional cell-based facies modeling program can be used to build the facies model. BlockSIS program of GSLIB is used here to illustrate the effect.

For detailed parameter interpretation, I recomment reader to Deutsch (2005). Some related parameters are: 1) The kriging option should select 2 or 3, and the modeling result should be very similar; 2) the cleaning option is specified on Line 2. Cleaning option 1 is recommended because the order relation is not a serious problem for this approach. The user should choose the level of cleaning carefully. Unnecessary cleaning can impose too much continuity and unreliable distributions of uncertainty and deposition structure will be ruined. Number of categories is specified on Line 3 and it should equal to the total number of facies. User does not need to specify the local conditioning data file, and the file with gridded prior mean values and keyout array should be your prior mean file.

```
Line      START OF PARAMETERS:
  1       2                      -0=SK,1=OK,2=L1,3=L2,4=CC,5=BU,6=PR,7=BK,8=BC
  2       1                       -Clean: 0=none, 1=light, 2=heavy, 3=super
  3       3                       -number of categories
  4       1    2    3         -   categories
  5       .5   .2    .3       -   global proportions
  6       0.5   0.5   0.5     -   correlation coefficients for soft data
  7       nodata                -file with local data
  8       1   2   3   4       -   columns for X,Y,Z, and category
  9       lm.out                -file with gridded prior mean values
 10       2   3   4           -   columns for each category
 11       3                   -   2-D areal map (2) or 3-D cube (3)
 12       lm.out                -file with keyout array
 13       1                   -   column for keyout indicator
 14       0                     -debugging level: 0,1,2,3,4
 15       sisim.dbg             -file for debugging output
 16       sisim.out             -file for simulation output
 17       1                     -number of realizations
 18       90  25.0  50.0        -nx,xmn,xsiz
 19       140 25.0  50.0        -ny,ymn,ysiz
 20       500 0.05   0.1        -nz,zmn,zsiz
 21       69069                 -random number seed
 22       12                    -maximum original data  for each kriging
 23       12                    -maximum previous nodes for each kriging
 24       1                     -assign data to nodes? (0=no,1=yes)
 25       0                     -maximum per octant    (0=not used)
 26        500.   500. 10.      -maximum search radii
 27         0.     0.   0.      -angles for search ellipsoid
 28       201   201   10        -size of covariance lookup table
 29       1 0.01                -Cat 1: nst, nugget effect
 30       1 0.99  0. 0.0 0.0    -       it,cc,ang1,ang2,ang3
 31          500    500   10.   -       a_hmax, a_hmin, a_vert
 32       1 0.01                -Cat 2: nst, nugget effect
 33       1 0.99  0. 0.0 0.0    -       it,cc,ang1,ang2,ang3
 34          500    500   10.   -       a_hmax, a_hmin, a_vert
 35       1 0.01                -Cat 3: nst, nugget effect
 36       1 0.99  0. 0.0 0.0    -       it,cc,ang1,ang2,ang3
 37          500    500   10.   -       a_hmax, a_hmin, a_vert
```

A synthetic surface-based facies modeling example

A synthetic case study was constructed to illustrate the facies modeling effect. The surface model was built with the LE_model program. The base surface is planar, and its maximum height is about 50 meters. Some long (XZ) and cross (YZ) sections are shown on Figure 17 to visualize the surface model. There are 72 surfaces in total, including the top and bottom surfaces. The thickness of some layer is very small, and it is very thick for some layers, so it is a good surface model for facies modeling.

The facies proportion is calculated using both Models I and II for comparison; then the same BlockSIS parameters are used for cell-based facies modeling. The cleaning option of Block-SIS is set to 1 (slight clean) to clean the facies models.

Facies proportion calculated using Model I

The prior mean is calculated with both *Hr* and *Zr* using Model I. Geological interpretation results can be integrated easily.

The facies trend template is shown on Figure 18. Only three facies are defined in this case. The corresponding 3D facies model was visualized with `Petrel`, see Figure 19. The curvilinear shape is well modeled, which is the major limitation of traditional SIS approaches. The facies model is cut and some modeled surfaces are shown to check the facies distribution in lobes, see Figure 20. The facies distribution is geologically realistic and reasonable. Some facies cross sections are shown on Figure 21. The sections positions are the same as those in Figure 17. The order relation is well honored, and the facies change in thin layer is also well modeled, see Figure 21. The NTG map and vertical facies proportion map are shown in Figure 22. Both facies 1 and facies 2 are treated as the net facies in this case. The shape of streamlines can be visualized clearly. No clear vertical facies proportion exists. The facies proportion changes due to the upward decrease of surface volume, see Figure 17.

Facies proportion calculated using Model II

In this example, the facies proportion is calculated using Model II, see Figure 23. At present, the same facies template is used for both horizontal and vertical facies proportion calculation. User can modify the source code easily to use different facies template for *Hr* and *Zr* separately.

The fence view of the simulated facies model is shown on Figure 24. The simulated facies has great variability in vertical direction, but the facies model is also very clean. From the cut view of the facies model, the facies distribution in lobes is geologically realistic and reasonable, see Figure 25. Some cross sections are shown in Figure 26. The curvilinear shape of the lobes can be visualized clearly, and the facies model is also very clean. Because of the mechanism, the facies has great variability in vertical direction, it is a little patchy than the result of Model I. The NTG map is shown in Figure 27. It shows that facies 2 has larger range than that of Model I, but the lobe shape is still very clear. No clear vertical facies proportion trend exists. The facies proportion changes due to the upward decrease of surface volume .

Comparing the results of the facies trend templates, Model I is easy to control. Model II shows great variability and it is suitable for the situation that horizontal facies trend and vertical facies trend come from different ways. No clear 3D facies trend need to be known for Model II.

Some comments

The main purpose of modeling a categorical variable such as facies and rock type before continuous petrophysical properties is to permit a more reasonable decision of stationarity, that is, to provide subdivisions that are more geologically and statistically homogeneous. Interestingly, however, it is common for the categories themselves to have trends and regions of higher and lower proportion. Geological trends are mapped as facies proportions or probabilities. This paper presents a surface-based facies approach through integration of geological interpretations, the facies trend template.

- Because the intrinsic characteristic of sequential indicator modeling, the resulting facies model is a little patchy, more or less, so the `MAPS` program of GSLIB or the cleaning option of `BlockSIS` should be used to clean the facies model. User should be careful

when using image cleaning approach/option. The deposition structure shouldn't be damaged.

- The surface model can be built stochastically with `LE_model` or `Turbsim` program developed at CCG, or extracted deterministically from seismic volume, as long as the facies trend model is defined properly. The major assumption of this approach is that the facies change gradually with time, so the third order architectural elements are suitable for better facies modeling result. Therefore, the surface model built with `Surfsim` program is not suitable for this approach for the nearly tabular strata correlation. The lobe geometries can be well honored which is the major limitation of SIS.

- Facies proportion is calculated based on the 3D relative position of a given cell in a second-order lobe, so no hierarchical facies trend definition is needed.

Future work

In general, unconditional turbidite lobe modeling and surface-based facies simulation is straightforward. Lobes are built based on geometry template and placed randomly until the volume is filled up. Facies trend template is used for facies proportion calculation, and then facies model is built by conventional SIS algorithms. Because of the randomness of lobes size and position, the surface model has a large uncertainty. The facies distribution is simplified and idealized since only the main streamline is considered for facies proportion calculation. Branch channel will be added in the future for more geological realistic facies modeling and for simplifying the well conditioning. The simulation results are interesting, but it is still far away from practicality.

In petroleum industry, wells are usually drilled preferentially and sparsely because of the expensive drilling cost; 3D seismic techniques are widely applied but the resolution is the major limitation for fine-scaled reservoir modeling. Fine-scaled turbidite lobe surfaces usually cannot be visualized clearly on seismic sections even after special processing. So seismic data can only provide large scale trend information on lobe geometry. In spite of above limitation, seismic data can be accessed any where, and some seismic attributes have good relation with large-scaled facies changes. Therefore, methods to better utilize the seismic data efficiently becomes a very interesting topic.

The improved construction of geological realistic and reasonable surface-based facies model with limited information will be addressed in future work. The data can be accessed and should be honored include:

- Seismic trends in net-to-gross ratio. Some seismic attributes have very good relation with facies, so large-scaled net-to-gross map can be derived using seismic data.

- Fine-scaled facies can be identified at well locations with well log data as well as core data. Careful examination of core data permits identification of many facies; however, it is also a big challenge to honor the wells data because during surface modeling, the lobe is placed randomly. So during surface modeling, the facies proportion should be considered to reduce the difficulty of conditional facies modeling. This will also be a great challenge.

- Large-scaled surfaces, such as the bounding surface for lobe events modeling, should also be honored. Large-scaled surfaces can be extracted form seismic data or be modeled with

some surface modeling programs, such as the `Surfsim` program. There is a huge uncertainty for large-scaled surface themselves.

- Geological interpretation results, well test and production data should provide constraints on the model.

Conclusions

- The relationship between lobe geometry and grain size is established to reveal the volume trend with time.

- `Surfsim` program is improved with the ability to predict piecewise linear trend, and it can be easily modified to honor any functional trend.

- Some volume trend artifacts are demonstrated, and the solution is proposed.

- `Surfsim` program is improved to work with different strata correlations styles.

- A surface-based facies modeling approach is proposed. The result is geologically realistic and reasonable, and the nonlinear shape can be well modeled which is the major limitation of SIS. This approach can be applied to any third-order fan-shaped depositional system.

    o Two facies proportion calculation methods are proposed.

    o All sand-rich and mud-rich turbidite facies can be well modeled.

    o It works well with 3D or 2D facies trend information.

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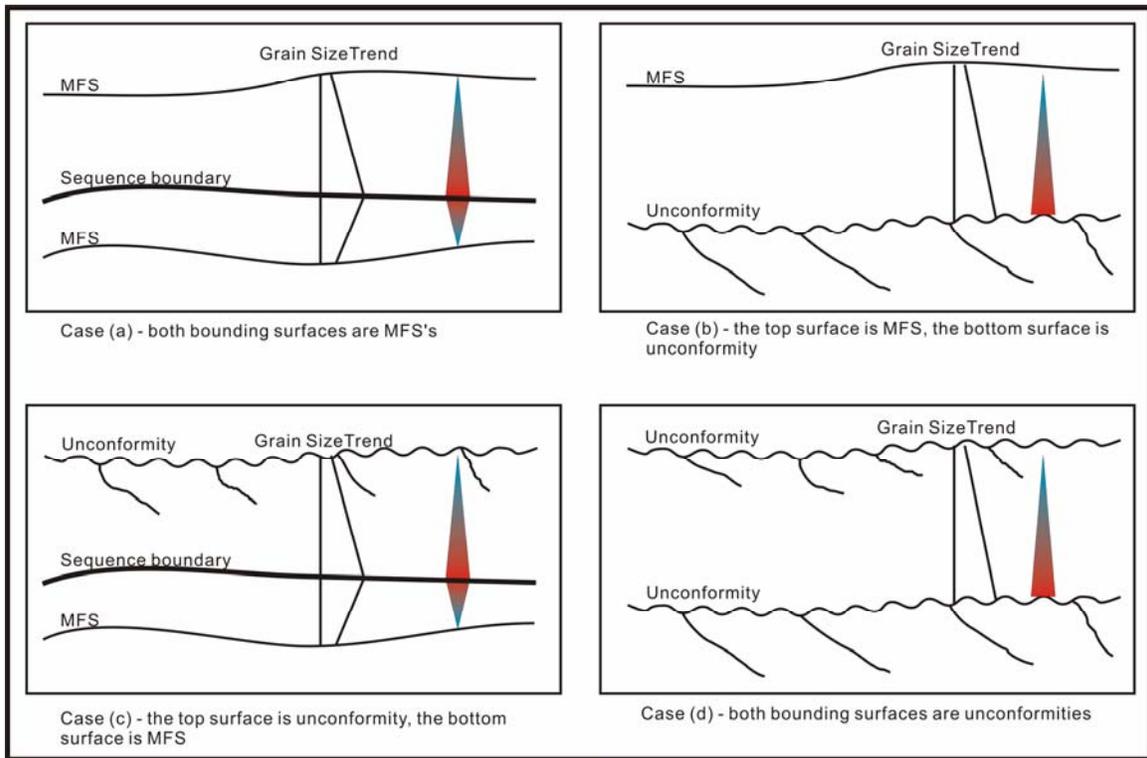
Figure 1: Examples of different bounding surface combinations; Case (a) shows that both bounding surfaces are Maximum Flooding Surface (MFS), the finer grain size part of a sequence; it can be easily recognized on seismic because it is a clear lithology interface. Case (b) shows that the upper surface is an MFS, but the bottom surface is an unconformity, which can also be easily recognized on seismic according to stratigraphic correlation. Case (c) is the reverse case of Case (b).Case (d) shows an extreme example that both bounding surfaces are unconformities. In Case (b), (c), and (d), the sequence boundary may or may not exist depending on the position of unconformity.
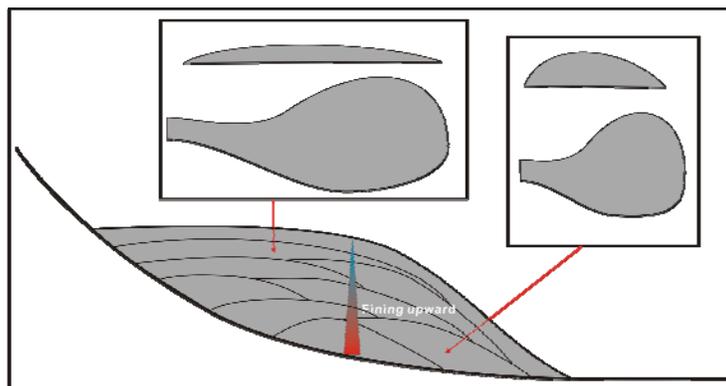
Figure 2: Schematic plot shows the shapes changing in a deep sea turbidite. The base surface is a sequence boundary with coarse grain size; the top surface is an MFS with fine grain size
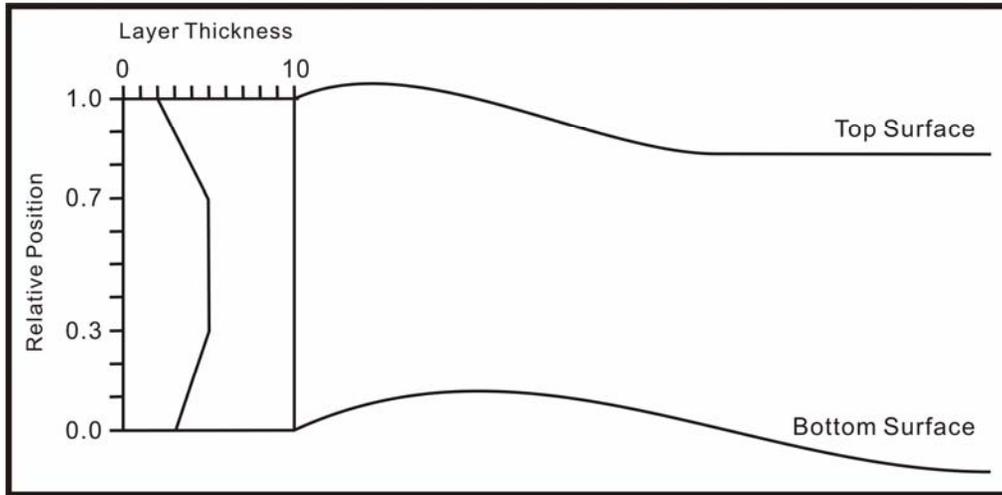
Figure 3: A schematic plot shows the trend definition.
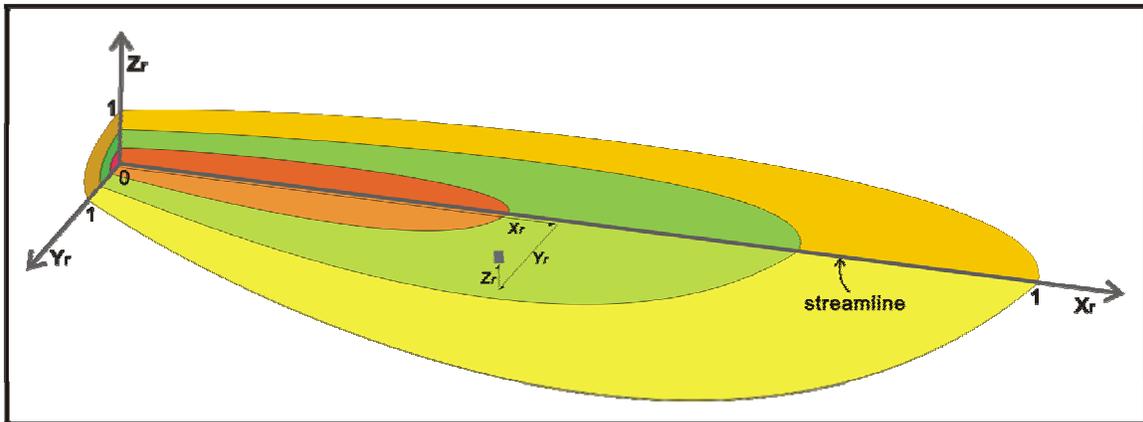
Figure 4: Idealized facies distribution of a turbidite lobe. This plot also shows how to locate the 3D relative position of a given cell within a turbidite lobe (after M.J. Pyrcz, 2003). The scale of this lobe is equivalent to the 2nd order turbidite lobe defined by M.J. Pyrcz (2003).
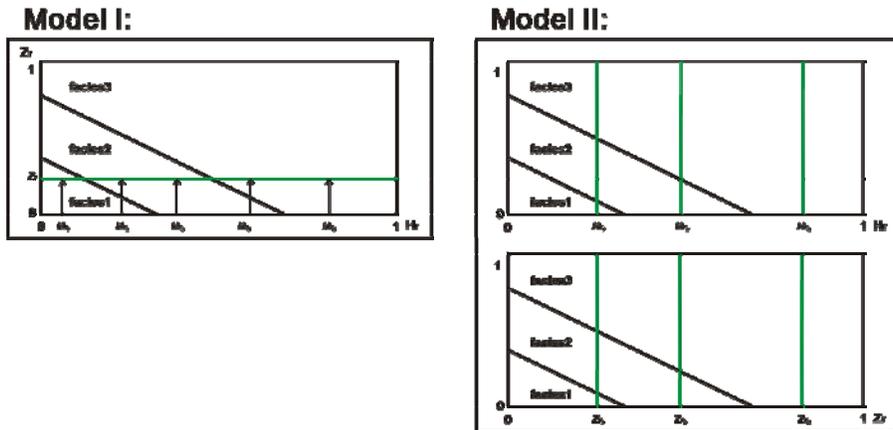
Figure 5: The simplified facies trend models based on above geological model
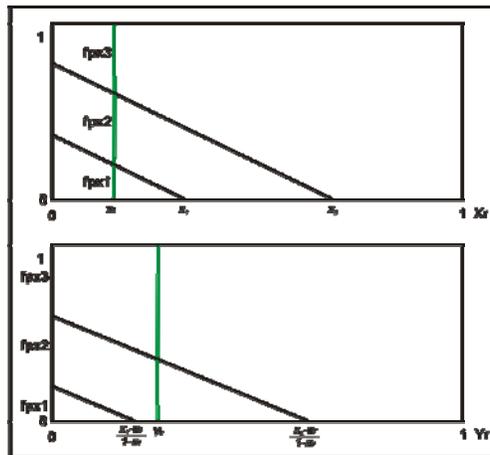
Figure 6: The affine transformation approach.
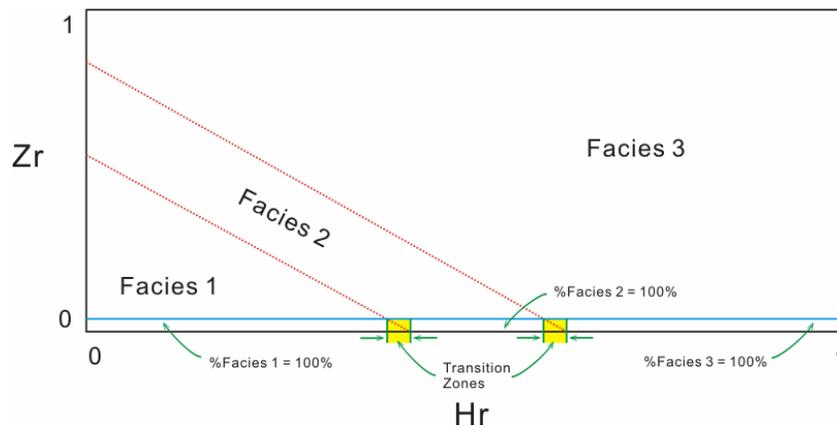
Figure 7: The facies transition zones of Model I. It is clear that the transitions are very narrow for any facies model using Model I, which means that the facies realizations will be very similar on the base surface for a given lobe.
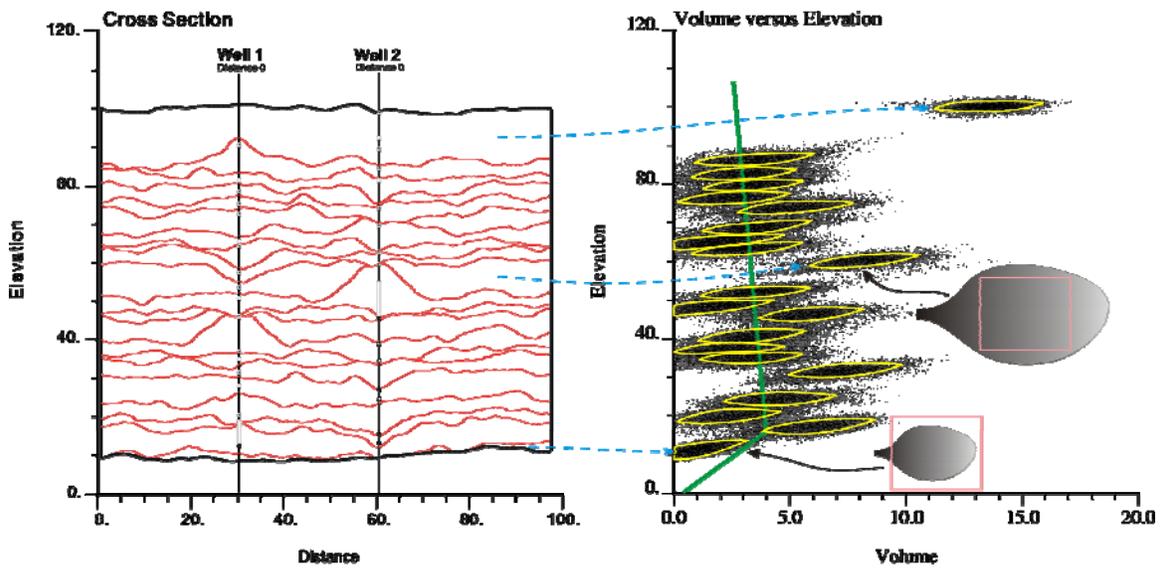
Figure 8: Vertical trend analysis of one `surfsim` realization of conditional run. The `surfsim` program used here is the original version. Note that the well conditioning data control the vertical volume trend distribution. Also note that the generated surface geometry is very large, so no surfaces stacking pattern will be honored.
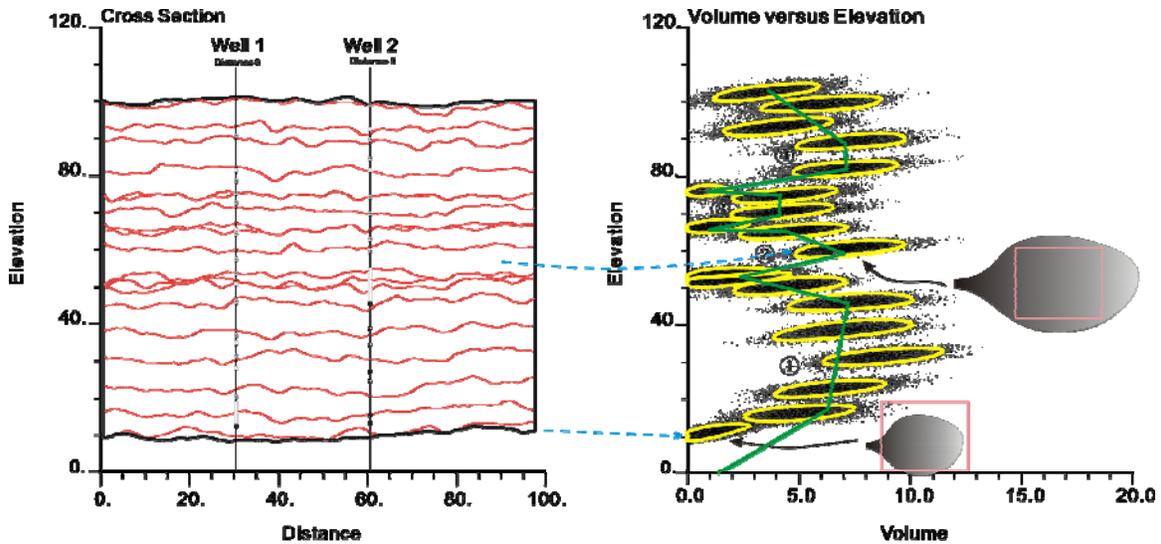
Figure 9: Vertical trend analysis of one surfsim realization of unconditional run. The surfsim program used here is also the original version. Note the four vertical volume trend cycles. Also note that the generated surface geometry is very large, so no surfaces stacking pattern will be honored.
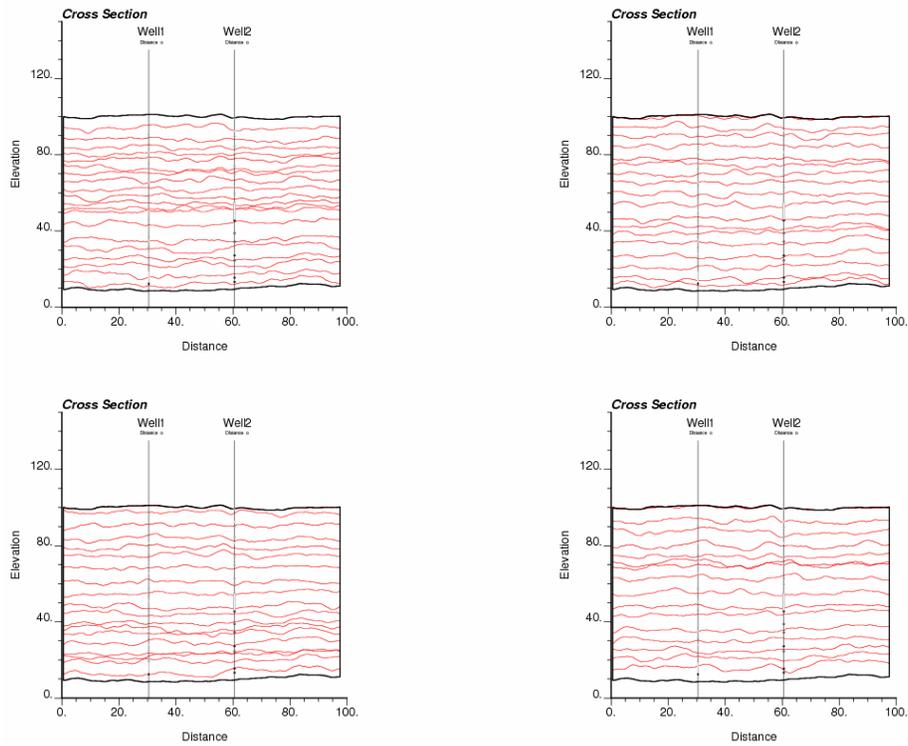
Figure 10: Four surfsim realizations of unconditional run. Note that the vertical volume trend cycles are different for each realization
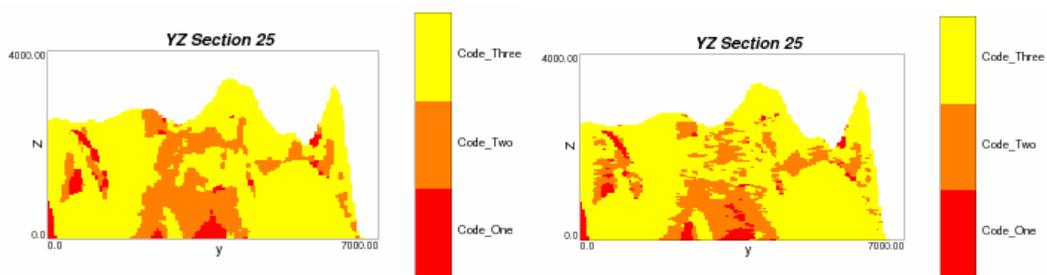
Figure 11: The facies models with different Z grid definitions. The left facies model is built with 100 Z grids; the right facies model is built with 500 Z grids. More geological details can be revealed with fine grid definition, and the facies continuity is better too.
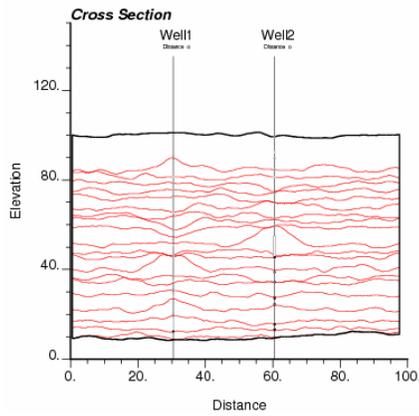
(a) conditioning run without flattening any bounding surface
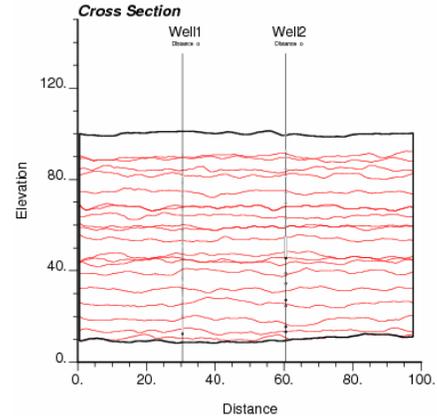
(b) unconditioning run without flattening any bounding surface
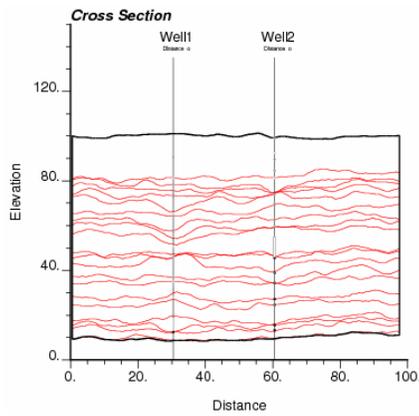
(c) conditioning run with flattening the base surface
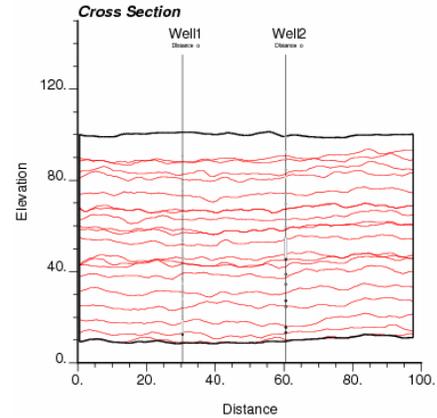
(d) unconditioning run with flattening the base surface
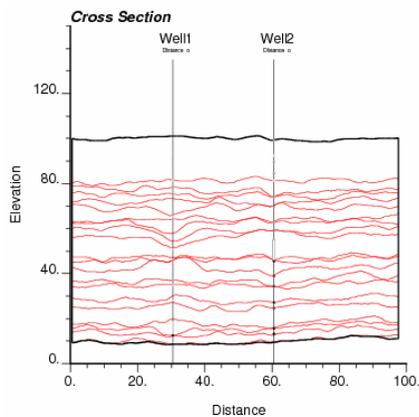
(e) conditioning run with flattening both bounding surfaces
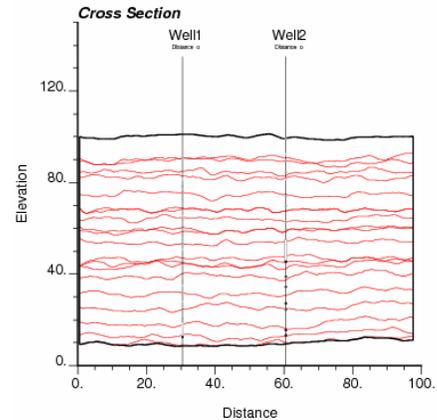
(f) unconditioning run with flattening both bounding surfaces

Figure 12: Some `Surfsim` realizations with different flattening options. The surface number is set to 20, so not all volume is filled up.
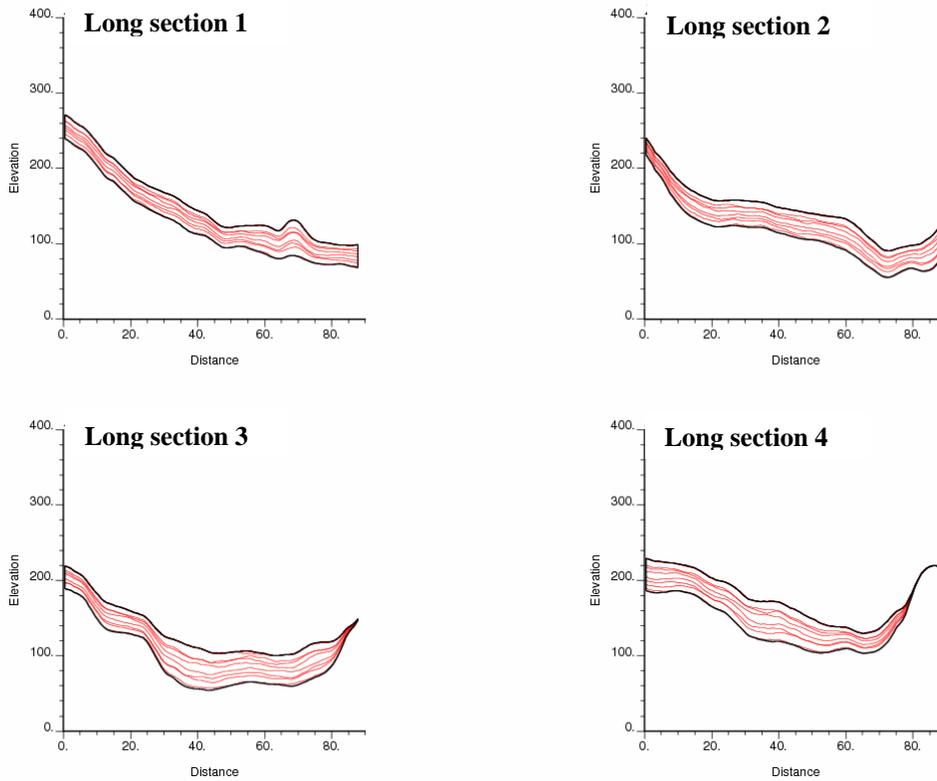
Figure 13: Some long sections of the synthetic boundary surfaces example. Both bounding surfaces are flattened to honor proportional stratigraphic correlation, and the number of surfaces is well selected to meet this need.
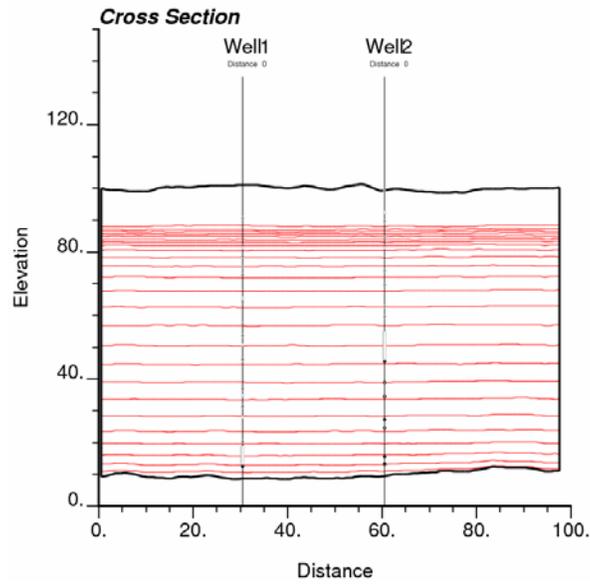
Figure 14: The E-type mean surface model of 99 unconditional Surfsim realizations. The total surface number is 20 and the volume to fill is set to 0.90.
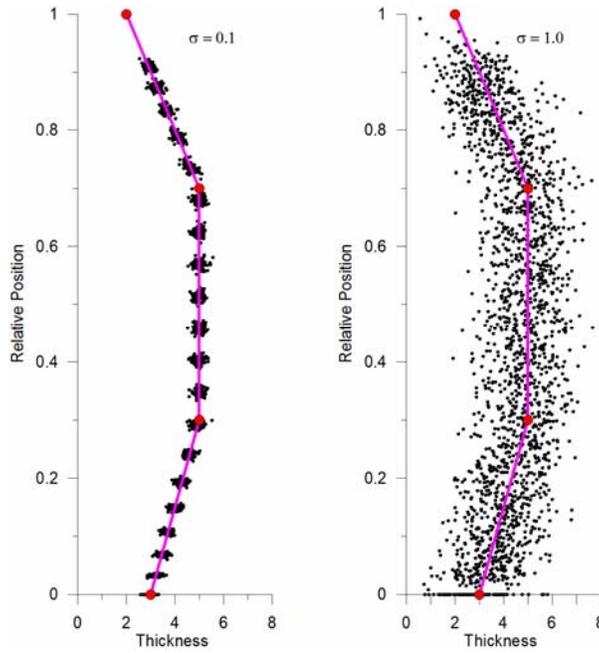
Figure 15: Comparing the layer thickness of 99 realizations with the trend definition. The standard deviation for each layer is set to 0.1 on the left plot, and it is set to 1.0 on the right plot
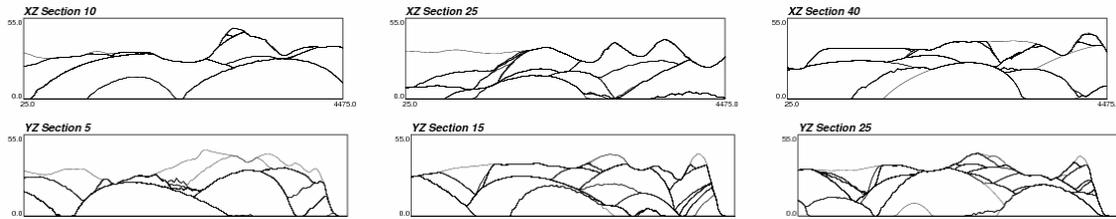
Figure 16. Some XZ and YZ section of the surface model. The curvilinear lobe geometry is very clear on these sections.
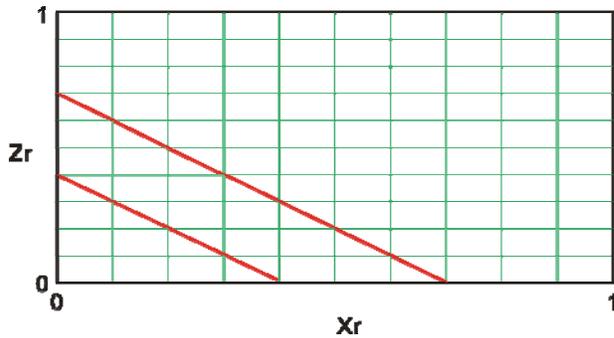
Figure 17: The facies trend template used for example I.
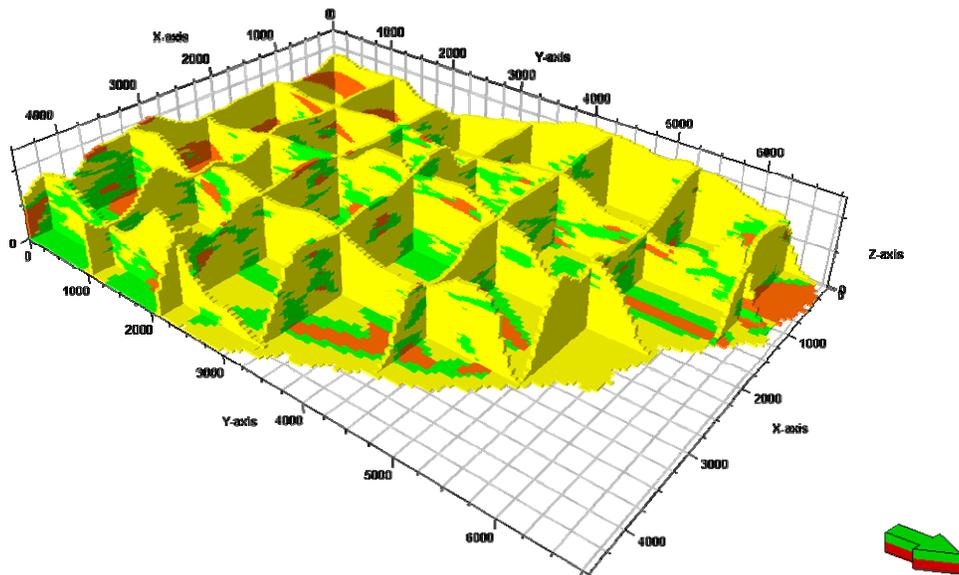
Figure 18: The fence view of the facies model from Petrel^{TM}. The curvilinear shape can be visualized clearly, and the facies model is very clean.
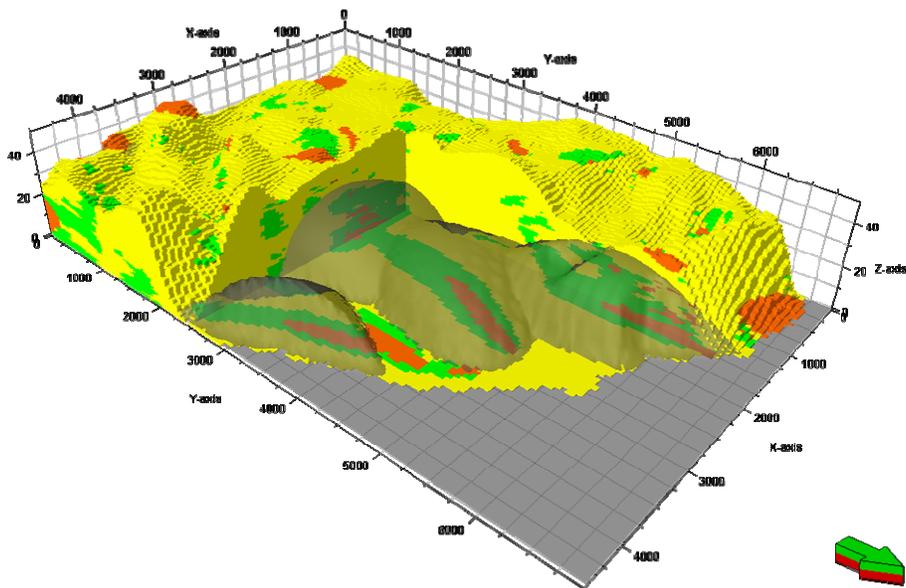
Figure 19: The cut view of the facies model from Petrel^{TM}. Some modeled surfaces are also plotted to check the facies distribution in lobes.
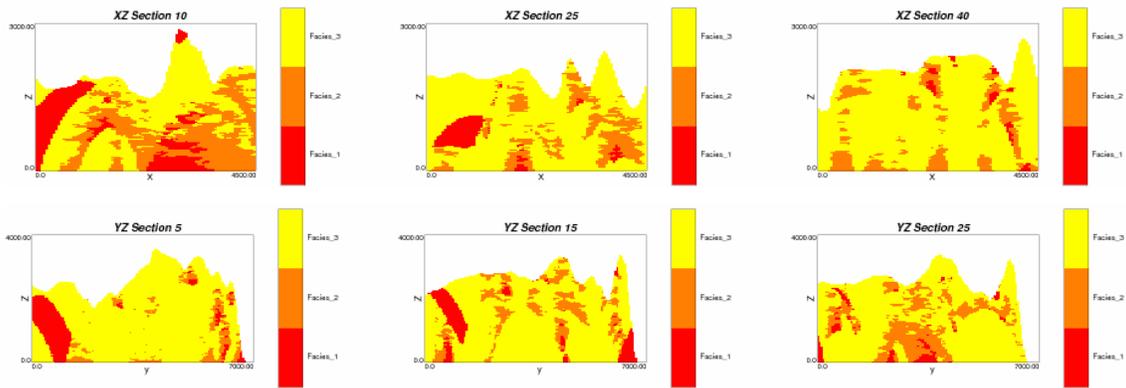
Figure 20: Some facies cross sections. The curvilinear shape of the lobes is well honored.
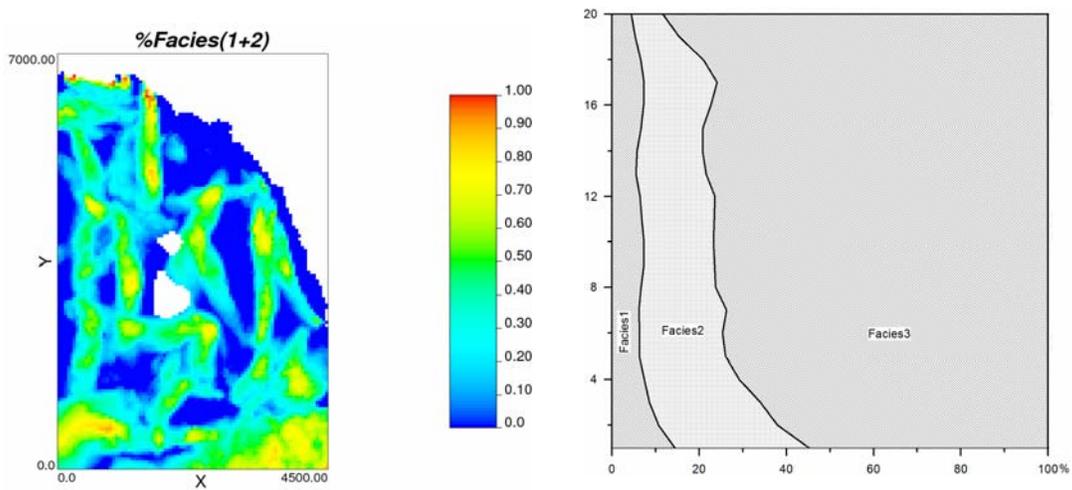
Figure 21: The NTG map of the facies model and vertical facies proportion. Facies 1 and 2 are treated as net facies in this case.
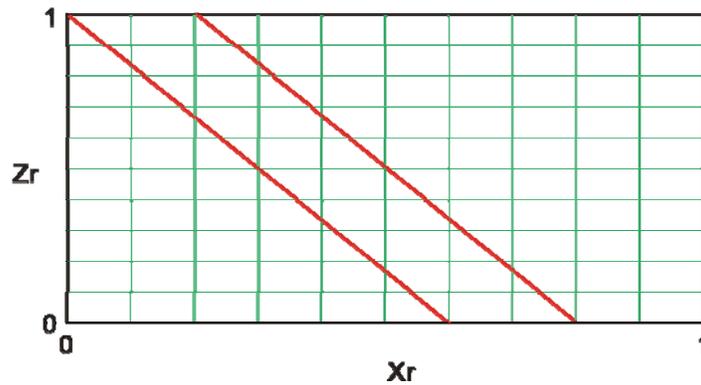
Figure 22: The facies trend template used for example II.
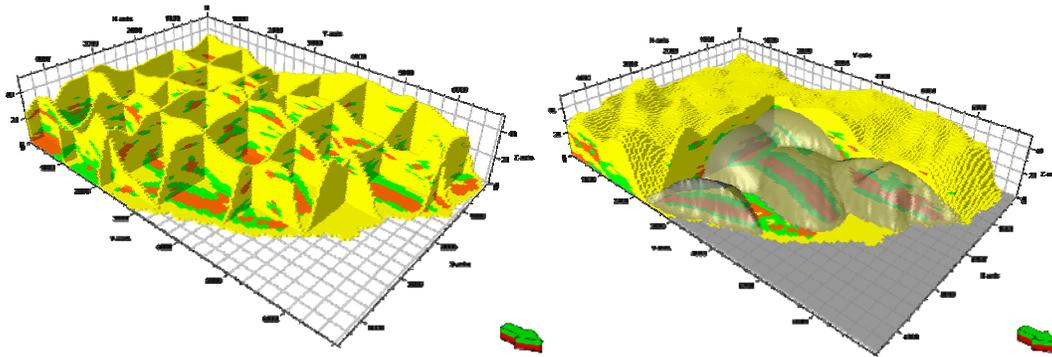
Figure 23: The fence view of the facies model from Petrel^{TM}.   **Figure 24:** The cut view of the facies model from Petrel^{TM}. Some surfaces are plotted to check the facies distribution in lobes.
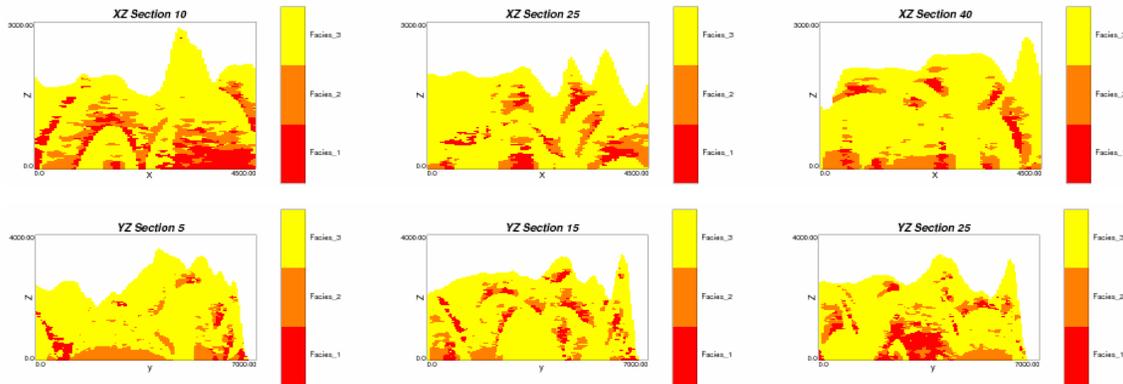
Figure 25: Some cross section of the facies model. The curvilinear shape of the lobes can be visualized clearly. The facies model is a little patchy than that of Model I.
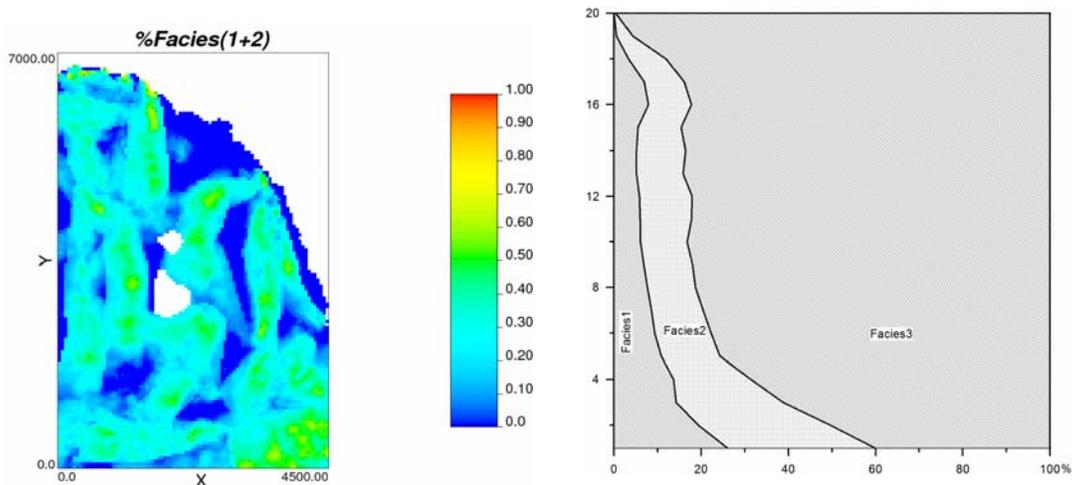
Figure 26: The NTG map and vertical facies proportion map of above facies model. Facies 1 and 2 are treated as the net facies.