SURFSIM: A Program for Stochastic Surface-based Simulation for Strataform Sediments

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Abstract

This paper presents a Fortran program for the construction of surface-based strataform models, although the existing code may be easily modified to reproduce any geometry. The surface-based models honor characteristic geometries, erosional and gradational contacts and missing log segments from well. These surface models may be applied to constrain property realizations.
Keywords: Reservoir Characterization; Geostatistics; Facies Modeling

1 Introduction

Xie and Deutsch (2000) addressed methods for stochastically generating surfaces that honor the available data, rules based on volume filling and types of stratal termination and the reproduction of within unit trends. These methods have been shown to generate surfaces that mimic the appearance of actual geologic bounding surfaces in an example outcrop with tabular units.

The surfaces are based on a geometric template determined from the geologic setting. The surfaces are stochastically positioned and then neighbouring conditioning is checked. If the mismatch is below a tolerance the surface is corrected to honor the data and if the mismatch is too large the surface is discarded. Surfaces are generated until the volume of interest is filled.

The application of surface-based models has been extended in this paper to model general tabular stratigraphy with gradational and erosional surfaces and segments of missing log. Research code that `surfsim` is provided research code to demonstrate this procedure and a surface-based model visualization program, `surfcross`, is provided. It is hoped that this code will aid in future research in surface-based models. Additional details on surface-based models and algorithm tailored to model turbidite lobes are available in Pyrcz (2004).

2 Surface-based Models

A surface is denoted as follows:

$$\mho^{\ell}(\mathbf{u}) \forall \mathbf{u} \in A_2 \tag{1}$$

where A_2 is the projection of the area of interest A on to a 1-D plane (commonly the horizontal plane in stratigraphic coordinates). The surfaces proceed from the initial surface $\ell = 0$ to $\ell = L$ the top surface.

Surface-based simulation may be seen as a variation on object-based simulation, although it has some key implementation differences. Surface-based simulation focuses on the surfaces that divide the objects as opposed to the objects themselves.

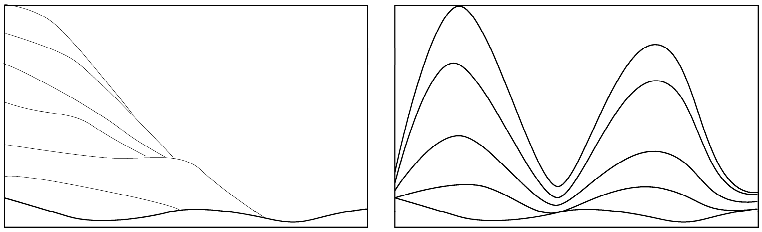

Figure 1: Schematics of two artifacts that may occur in surface-based simulation. The surfaces may be trapped in a subset of the model or features in early surfaces may be amplified.

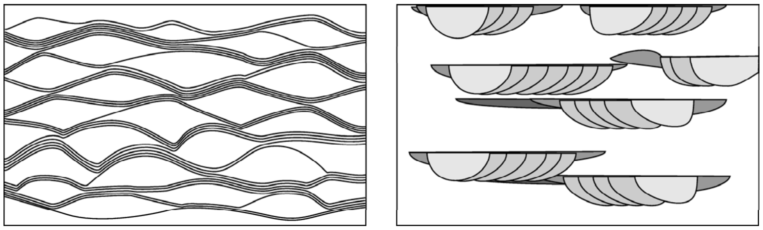

Figure 2: A schematic of surface and object based simulation. The surfaces have been offset vertically to emphasize that the surfaces exist over the entire areal extent of the model area. Note: the object based simulation could not be represented by these surfaces.

This difference renders surface-based simulation well suited to dynamical sequence models in which the current surface is a function of the previous surfaces. The form of the current object is dependent on the form of the previous objects that define the bounding surface on the bottom. Conversely, in object based simulation the current element is superimposed on previous elements.

This dynamical nature may be utilized improve geologic realism by reproducing interrelationships between elements, but this feature makes these models more susceptible to artifacts. These artifacts may include (**1**)previous elements may trap the model and pile up elements in a subset of the model and (**2**) features may be amplified through subsequent elements resulting in unrealistic relief (see Figure 1). Specific placement methodologies are required that utilize the dynamic feature but are robust and resistent to the formation of artifacts.

Surface-based models are not well suited to constructing models with multiple lithofacies with unique geometries. These models are better left to object-based methods. In addition, to avoid computationally expensive surface calculations each surface should exist over the entire model and have an unique solution $\mho^{\ell}(\mathbf{u})$ where $\mathbf{u} \in A_2$. Therefore, surfaces onlap the previous surface where an element pinches out and surfaces do not fold over on themselves. A schematic of a surface-based realization compared to an object based realization is shown in Figure 2.

Surface-based methods may be applied to a variety depositional settings. The general methodology is to (**1**) generate a surface geometry, (**2**) place the surface geometry within the model, (**3**) check for agreement with surface intersections observed in well data and regenerate if the surface does not meet an acceptance criteria and (**4**) calculate a stochastic residual to honor well data precisely and to reproduce surface irregularities. This procedure is repeated until all conditioning is honored and the area of interest is filled. The following is an overview of these steps.

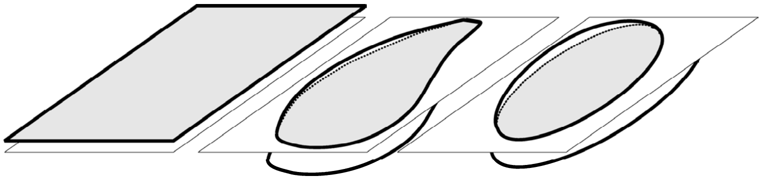

Figure 3: Schematics of three example surface templates. Note the surfaces are shown truncated by a plane. This illustrates the fact that the surface templates are truncated by previous surfaces.

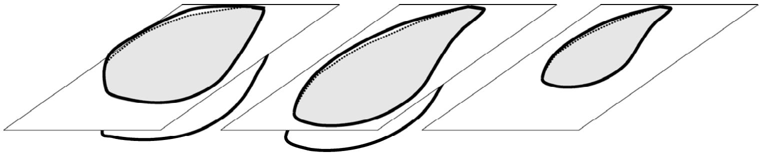

Figure 4: Three example surface templates. Note the surfaces are shown truncated by a plane. This illustrates the fact that the surface templates are truncated by previous surfaces.

2.1 Surface Geometry

Characteristic surface geometries are common in geology. For example, stratiform sediments are expressed in parallel to subparallel surfaces, inclined heterolithic strata sets are composed of onlapping sigmoidal surfaces (Diaz-Molina, M., 1993; Willis, B.J., 1993), channel bedforms may be expressed as down stream accreating bars (Miall, 1996) and turbidites frontal splays often occur as stacked lobes. These characteristic geometries may be characterized in a surface template. Three example surface templates are shown in Figure 3.

From this surface template a surface geometries may be drawn, $v(\mathbf{u})$. A distribution of surface geometry parameters should be constructed prior to modeling. This distribution may be inferred from analog information with regard to the processes related to the formation of these architectural elements. The distributions represents the variability observed in the elements. Possible geometric parameters that may be quantified include length, width, length:width ratio, maximum thickness, thickness:width ratio, sinuosity etc. A schematic is shown in Figure 4 of three surface geometries based on the lobe template from Figure 3.

2.2 Placement of Surface Geometries

The placement algorithm should (**1**) respect geologic information with respect to the interrelationship of the architectural elements described by the surfaces, (**2**) avoid artifacts in the resulting surfaces (see Figure 1), (**3**) result in a reasonable probability of the surface geometry being accepted given the available data and (**4**) be computationally efficient.

Architectural elements may have a variety of stacking relationships. Stacking styles may include aggradation, progradation, retrogradation, shingled, compensational or a variety of combinations of these styles. The style will determine the position and orientation of new elements relative to previous elements.

Placement includes the determination of attitude and location. The areal location may be a function of previous surfaces as is the case in `turbsim` (Pyrcz, 2004) or may be independent of the previous surfaces or may be constant as with the current version of `SURFSIM`. The methodology for determining areal location of the surface geometry should be robust and avoid trapping the future surfaces. For example if a steepest gradient method is applied to position surface geometries from a

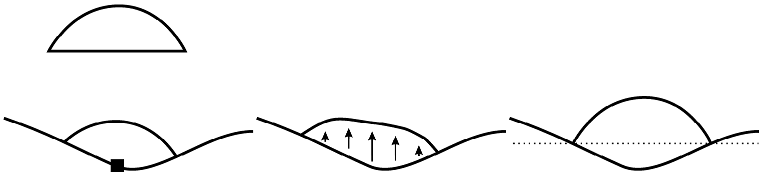

Figure 5: Methods for vertical placement of surface geometries. The surface geometry is shown at the top. The anchor point method is to anchor a specific location on the surface geometry $\upsilon(\mathbf{u})$ onto the previous surface $\mho^{\ell-1}(\mathbf{u})$ (left). The additive method is to add the thickness enclosed by the surface geometry to the previous surface (center). The moving window average is to place the surface geometry with a datum determined as a smooth moving window average of the previous surface.

source location with a thickening distal profile, the algorithm may become trapped (see Figure 1).

Vertical placement is the determination of the vertical position of the surface geometry $\upsilon(\mathbf{u})$ relative to the previous surface $\mho^{\ell-1}(\mathbf{u})$. This placement methodology will determine the thickness and attitude of the element. The placement algorithm should be tailored to the specific application to reproduce features observed in the geology. Some example vertical placement methods are (**1**) anchor point, (**2**) additive and (**3**) moving window average. Figure 5 illustrates these methods with a 2D example of a cross section of a lobe on irregular bathymetry.

The additive method for vertical placement distorts the geometry of the elements and may lead to amplification artifact shown in Figure 1. The anchor point and moving window average methods are more robust but require the setup of parameters such as the location of the anchor and the size of the moving window.

2.3 Surface Acceptance Criteria

The placed surface geometry is compared with the conditioning data for mismatch. Mismatch is difference between the surface contacts from wells $\mho^{wells}(\mathbf{u})$ and the surface geometry $\upsilon^{\ell}(\mathbf{u})$. A threshold of acceptable mismatch should be chosen equivalent to the magnitude of the random residual applied for conditioning. A large threshold will result in the well markers being honored as dimples or cusps.

If a surface geometry has failed the acceptance check it may be corrected or rejected and regenerated. The application of a correction may result in artifacts. A surface geometry may be too high in one well and too low in another. The correction may distort the geometry. Given the speed with which a new surface geometry may be calculated regeneration is applied in the `surfsim` algorithm.

2.4 Conditioning by Stochastic Residual

After a geometric surface has been accepted a conditional stochastic residual $R^{\ell}(\mathbf{u}), \forall \mathbf{u} \in A_2$ is calculated. The stochastic residual; (**1**) may be based on any stochastic model, (**2**) should have a mean of 0.0 so the surface vertical location is not biased and (**3**) should have a correlation and total variance that reflects the short scale fluctuation of the associated surfaces observed in the sedimentological record. The addition of a stochastic residual is denoted below:

$$\mho^{\ell}(\mathbf{u}) = \upsilon^{\ell}(\mathbf{u}) + R(\mathbf{u}) \tag{2}$$

where $\upsilon^{\ell}(\mathbf{u})$ is the surface geometry, $R(\mathbf{u})$ is the stochastic residual and $\mho^{\ell}(\mathbf{u})$ is the conditional surface realization.

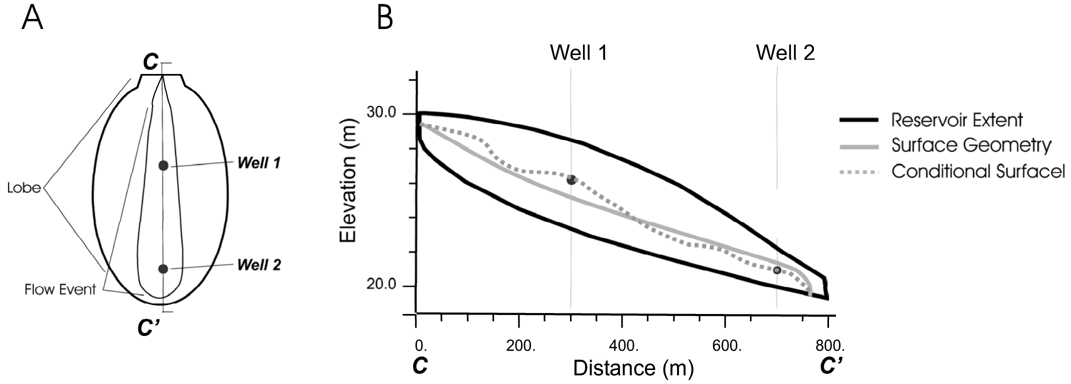

Figure 6: An illustration of the addition of a stochastic residual to characterize fluctuations and to allow for conditioning to well data: A - plan view and B - cross section $C - C'$ with reservoir extents, geometry and the conditional surface realization.

The Gaussian model may be applied to model a conditional stochastic residual. Gaussian simulation is reviewed in Deutsch and Journel (1998). If Gaussian features such as maximum discontinuity of the extremes are deemed inappropriate then indicator or simulated annealing could be applied. The `sgsim` algorithm from GSLIB was modified to simulate a 2-D model to improve efficiency and is applied in the applications as a subroutine. Figure 6 demonstrates the conditioning of a surface geometry with conditional stochastic residual.

2.5 Termination of Surface-based Simulation

The algorithm terminates when the last surface $\mho^{\ell}(\mathbf{u})$ exceeds the top surface $\mho^{L}(\mathbf{u})$. The last surface is truncated by the top surface. Due to the dynamic nature of the surface-based approach it is not possible to constrain the algorithm to honor a top surface. This may lead to artifacts; although, this problem should be minimized by careful selection of the model methodology and input parameters. Also the resulting realizations may be screened to remove surface-based realizations with poor agreement with the top surface.

2.6 Erosional Rules

Erosional and conformable contacts are honored through constraints provided by erosional rules. For the conditioning the rules are:

1. a single surface may only honor erosional or conformable contacts
2. if an erosional surface does not have a erosional contacts available at a well then the surface is conditioned to a intersect a random location above the well
3. if a conformable surface does not have an available conformable contact at a well then the surface is conditioned to a random location below the well.

For surface postprocessing the rules are:

1. an erosional surface truncates all previous surfaces
2. a conformable surface onlaps all previous surfaces

3 Parameter File

The parameters include well data, grid definition and simulation parameters (search and semivariogram) for the 2-D simulation of the residual. An example parameter file is included below and an explanation for each parameter is provided in Table 1.

```
Parameters for SURFSIM
1.  well.dat            -file with data
2.  1 2 3 4 5 6 7 8     - well,x1,y1,z1,x2,y2,z3,code
3.  5.0 2.0             -layer thickness:mean,st.dev.
4.  top.out             -file with top surface
5.  bot.out             -file with bottom surface
6.  1                   -number of realizations to calculate
7.  100 0.5 1.0         -nx,xmn,xsiz
8.  50 0.5 1.0          -ny,ymn,ysiz
9.  150 0.5 1.0         -nz,zmn,zsiz
10. surfsim.out         -file for simulation output (surfaces)
11. surfsimgrid.out     -file for simulation output (grid)
12. 1                   -debugging level:0,1,2,3
13. surfsim.dbg         -file for debugging output
14. 69069               -random number seed
15. 12                  -number of simulated nodes to use
16. 1 3                 -multiple grid search(0=no, 1=yes),num
17. 10.0 10.0           -maximum search radii (hmax,hmin)
18. 0.0                 -angle for search ellipsoid
19. 51 51               -size of covariance lookup table
20. 0.0                 -nst, nugget effect
21. 1 5.0 0.0           -it,cc,ang1
22.   10.0 10.0         -a_hmax, a_hmin
```

4 `surfcross` Program

The `surfcross` program reads in a surface based model, well data (optional) and a property grid model (optional) and produces a cross section. The program uses large parts of the `pixelplt` program from GSLIB (Deutsch and Journel, 1998). The code is not very well tested and its design is ad hoc, but it serves the purpose of visualizing surface-based models.

The parameters include well data, grid definition and simulation parameters (search and semivariogram) for the 2-D simulation of the residual. An example parameter file is included below and an explanation for each parameter is provided in Table 2.

```
Parameters for SURFCROSS
 1.  surfsim.out                     -file with surfaces
 2.  well.dat                        -file with the well data (optional)
 3.  1 2 3 4 5 6 7 8                 -iwell,ix1,iy1,iz1,ix2,iy2,iz2,infocode*
 4.  grid.dat                        -file with grid (optional)
 5.  1 1 0.0 40.0 5.0 0.0 100.0      -lcol,icolor,cmin,cmax,cinc,tmin,tmax
 6.  50 0.5 1.0                      -nx,xmn,xsiz
```

Line	Description
1	input file with well data.
2	column numbers for the well, x, y, z location and marker code. The x2, y2, z2 are used for no information intervals. The codes are 0-erosional, 1-gradational and 2-no information.
3	the mean and standard deviation of the parallel beds.
4-5	the files with the top and bottom surfaces in GEOEAS format and GSLIB grid convention.
6	the number of surface realizations to calculate. Realizations stacked in the same output file.
7-9	the regular grid parameters. The z parameters are required for the pixel-based output for visualization.
10	the surfaces output. The surfaces output is regular grid in x and y with elevation for the z coordinate.
11	the gridded output. Each grid node is assigned a layer number.
12	the debugging level
13	the file for debugging information
14	the random number seed
15-22	simulation search and semivariogram parameters

Table 1: The description of the `surfsim` parameter file.

```
 7.  50 0.5 1.0                    -ny,ymn,ysiz
 8.  50 0.5 1.0                    -nz,zmn,zsiz (profile)
 9.  Profile.out                   -output profile for pixelplt only
 10. 100                           -horizontal resolution (nu)
 11. 0 0 50 50                     -x1, y1, x2, y2
 12. Profile.ps                    -profile post script output
 13. Cross Section                 -plot title
 14. 100.0 1 1 1.0 0.0 0.0         -thresh,iscale,ilegend,lsc,xltr,yltr

*0 - erosional, 1 - gradational and 2 - missing information
```

4.1 Example Surface-based Model

For demonstration of the `surfsim` program synthetic data set was constructed with two wells with erosional and conformable contacts and intervals with no information. Surfaces were simulated with a layer thickness distribution $N\{5, 3\}$, a residual semivariogram consisting of a single spherical structure with a range of 500 m. A cross section of the surface realization is shown in Figure 7.

5 Comments on the Code

This version assumes near parallel bedding; therefore, the surface template is a plane (see left of Figure 3), although any geometry may be applied by modifying the code. The areal location is drawn from a uniform distribution of the entire area of interest. The vertical location such that an average thickness (drawn from a Gaussian distribution with a user defined average and standard deviation) is honored.

Line	Description
1	input file with the surfaces.
2	input file with well data.
3	column numbers for the well, x, y, z location and marker code. The x2, y2, z2 are used for no information intervals. The codes are 0-erosional, 1-gradational and 2-no information.
4	input file with property grid.
5	the column with the property, color (1=yes,0no), property min, max and increment, trimming limits.
6-8	the regular grid parameters. The z parameters are required for the pixel-based output for visualization.
9	output file with a 2-D grid of the property along the cross section.
10	the horizontal resolution of the surfaces. nu is the number of bins along the cross section.
11	the start and end location of the cross section.
12	the output post script file.
13	the plot title.
14	the maximum distance to project a well onto the cross section, include scale (1=yes,0=no), include legend (1=yes, 0=no), legend scale, legend offset.

Table 2: The description of the `surfcross` parameter file.

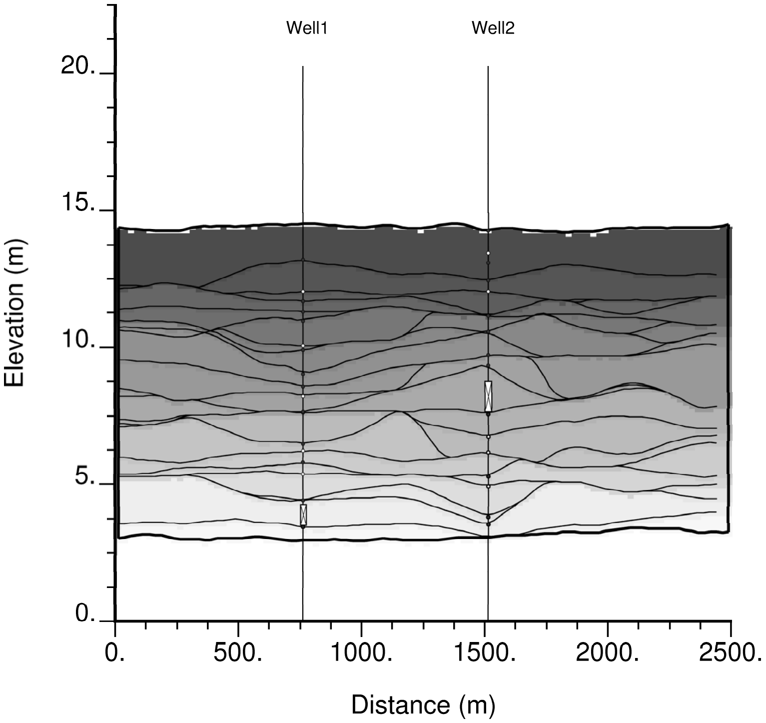

Figure 7: A realization of stochastic surfaces that honor surface geometry and erosional (solid dots) and conformable (circles) surface contacts and segments with no information.

6 Conclusion

The `surfsim` algorithm and general surface-based approach have been presented in this paper. This algorithm and associated methodologies may form the foundation for further development in surface-based simulation.

7 Future Work

The `surfsim` algorithm may be augmented with a suite of characteristic surface templates, such as lobes and bars. These templates may be scaled with geometric parameter distributions and placed with stochastic processes that account for interrelationships between surfaces. For example, lobes may be preferential placed in topographic lows to reproduce compensational stacking of detached lobes.

8 Acknowledgements

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