Surface-Geometry Simulation to Integrate Stratigraphic Surfaces in Subsurface Models

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Abstract

Stratigraphic depositional surfaces, originating from paleo-events such as relative sea level changes, are a fundamental component of subsurface depositional architecture. Reservoir units are often sediment packages bounded by the chronosurfaces. Within each sediment package, facies types and their spatial associations and petrophysical properties are often reasonably correlated on a large scale. Thus, surfaces can provide important constraints on subsurface model facies and property connectivity and continuity .

The source for subsurface major bounding surface maps is usually seismic reflection horizons tied to wells. However, many surfaces observed at wells are subseismic, cannot be traced between wells using seismic, and thus predictions beyond a developed area often poor. Mapping and modeling software packages provide tools to generate interpolated maps automatically between wells for subseismic surface geometric styles, e.g. conformable, proportional, truncated, downlapping, onlapping, etc. With sparse well control, e.g. to extend a model outside a developed area; however, the source for the subseismic surfaces is an analog model. Depositional process modeling, conceptual geologic modeling, and outcrop data can provide reasonably good analogs for the geometric morphology of subseismic surface boundaries. However, these sources for the subseismic morphology are not readily implemented directly into field-area models.

This paper presents an approach to model surfaces stochastically, using a geometry from process-based models, analog or outcrop. Based on the logic of chronological sedimentation, successive surfaces are created. In stochastic simulation, surfaces are generated with parameterized surface template(s); the shape, extent, height, orientation and regularity of surfaces are controlled by user-specified distributions. The location of each surface in the subsurface model is chosen on the basis of the thickness of previous events and depositional style of the unit. Local well data are honored.

A program `surfsim` *for surface-based modeling implements the method, and two examples are presented. One example consists of grain size distribution from a process-response model,* `sedflux`*. Another example uses the geological interpretation of an outcrop section.*

Introduction

The complex spatial arrangement of reservoir facies location, geometry, continuity, and properties are important to reservoir identification, management and economic performance.

It is critical to model the subsurface in sufficient detail to predict the performance accurately. This is especially difficult outside of developed field areas. The ultimate goal of this project is to generate more predictive geologic models by integrating, quantitatively, all available data. Analog data from outcrop or process simulation has not readily been integrated in model generation in the past. Using such data should improve models in developed areas, and should enable significantly more predictive subsurface models in prospective areas outside well control. This report describes the generation of surface-based constraints that can be used to integrate complex geologic analog models, e.g. from outcrop or process simulation. Surface constraints can integrated with field seismic and well data in an optimization modeling framework [9].

Notwithstanding advances in numerical modeling of the subsurface with geostatistics, a continuing challenge has been to generate models that incorporate complex geological architecture, geometry, systematic facies associations, and sediment trends that are observed in geologic data and models. Depositional sequence, parasequence, and bedset surfaces constrain the locations and spatial associations of reservoir facies. The source of maps for the major sequence horizon surfaces for developed field areas are seismic reflections tied to wells. Subseismic parasequence and bedsets are indicated at wells. Geologic software packagessuch as `Stratamodel` and `gOcad` generate maps of the subseismic surfaces tied to well control for specified styles, e.g. proportional, toplap, onlap, or various truncations. In areas outside of well development, however, these surfaces are not readily availble.

This paper reports an initial approach to generate geologic surfaces from conceptual, outcrop, or process models as constraints in an integrated field model. The purpose of the surface modeling is not to get surfaces *per se*, but to provide constraints for modeling facies and petrophysical property trends that control fluid saturation and flow. Geologists have for a long time generated complex conceptual models with their understanding of basin, minibasin, and reservoir systems, and they have measured geometries and associations on outcrops. New technology in process sediment modeling [11] is providing additional detailed models of depositional systems. The challenge for modelers is to integrate conceptual, outcrop, or process model data with field-specific seismic and well data.

As illustrated on Figure 1, there are often multiple sedimentary units of a few 10's of meters within a stratigraphic layer framework bounded by surfaces, which can extend for 100's to 1000's of meters. The presence of specific lithofacies at specific locations within sedimentary packages can be explicitly accounted for only when the locations of the sedimentary packages are known. Conventional object-based [10, 15] and cell-based [3, 8] geostatistical modeling techniques have no access to the location of the sedimentary packages; therefore, such techniques are not always able to correctly position the lithofacies unless the surfaces are mapped. That is, the models do not preserve the true geologic spatial morphology. porosity and permeability within the units often exhibit trends within and across surfaces. Conventional geostatistical techniques for continuous property modeling can account for a trend provided the trend is known deterministically. Two-point statistics of variograms are limited in their ability to preserve non-linear features and the nonstationarity of the distribution of facies and petrophysical properties that are often present in the geology. Oject-based approaches adhere to rules that govern reservoir architecture. However, they are generally limited to conditions for which well-defined geometric objects characterize the geology. Thus, there is a need to explicitly model the sedimentary units before lithofacies and petrophysical property modeling.

Current numerical modeling techniques do not utilize the constraints provided by multiple, subseismic surfaces. Goff [7] has proposed a methodology to model surface architecture, but does not discuss how to model the sediments within the surfaces. MacDonald [12] utilized rules, based on sequence stratigraphy, for surface spatial structure and geostatistics for the sediments in modeling a North Sea reservoir, but did not demonstrate how to model sediment trends bounded by the surfaces.

This paper presents a modeling methodology that uses surface modeling as a first step to modeling sediment units, bounded by the surfaces. The methodology is intended to utilize as input process sediment models, conceptual models, or outcrop data as analogs, governed by rules from sequence stratigraphy. The surfaces are to be utilized as constraints within a subsurface optimization approach [9]. Surface constraints are integrated with field seismic and well data in the optimization modeling framework. A companion paper in this volume presents a methodology for modeling sediment trends within the surfaces.

The surface-based methodology first establishes a parameterized surface template from the seismic, outcrop, or process models. In the simulation, sediment units are assumed to be represented by the volume covered by the surface. Other rules related to the sedimentation process, for example, on the relative location or volume-filling, are applied. Parameters defining the extent, height, orientation, elongation and regularity of the surfaces are stochastically drawn from user-defined distributions. The locations of the successively added surfaces are determined based on the thickness distribution of the reservoir and rules governing the spatial position e.g. whether the system is progading or retrograding. When local well data are available, the surfaces are accepted or rejected that force local well data to be honored, constrained by the rules.

A FORTRN 90 program, `surfsim`, incorporates the approach. Two data sets are used to demonstrate the approach. One data set consists of grain size distribution from a forward process-response model, `sedflux` [11] and another data set is the Wagon Caves outcrop in California [1].

Geological Basis for Surface Modeling

Many sedimentary sequences occur along continental margins where the sedimentation is a result of the interaction of tectonic activity, eustasy, and sediment input [5, 6, 13]. There can be significant changes in the properties of sediment at the boundaries due to the change of geological events, which can result in seismic reflectivity (the bounding surfaces of Figure 1) as sequence or parasequence boundaries. Within low-frequency changes, there are also higher-frequency events, for example from shorter-time scale rises and falls of sea level, which result in features superimposed on the large-scale architecture. Figure 1 shows a schematic cross section where a sedimentary parasequence consists of bedset deposits from higher- frequency events.

Within a sediment bedset unit, the petrophysical properties can have an identifiable trend but not yield an acoustic reflection. The surfaces can provide large-scale connectivity and continuity control of facies and petrophysical properties that is critical for reservoir performance prediction. Considering surfaces in the modeling process will provide better constraints for the modeling of facies and petrophysical properties. The stratigraphic record is generally well behaved at some scale, and thus surface model shapes can be designed to model the limited number of shapes. Time surfaces often are spaced systematically; progradation and transgression are examples. They often have a shape which can be approximated by an analytical function. Natural processes are also stochastic; completely regular surfaces are rarely present.

Methodology and Surface Parameterization

The proposed methodology is designed to provide a surface-based model that is constrained to well data and seismic-reflection horizons while honoring geologic rules on the general spatial trends of the surfaces, truncations, and volume-filling.

The methodology can be outlined as follows:

- Understand the data: for example, what are depositional system's large scale trends. What is the dip? Are the surfaces onlapping, toplapping, or downlapping? What is the size of the basin or minibasin area, that is, what is the model scale? What are the well surface intersections that should be honored? What are the seimically-mappable horizons?
- Obtain analog or proxy data, for example, outcrop data or process simulation (`sedflux`).
- Estimate a parametric function to be used as a surface template that can reproduce the shape of the surfaces.
- Estimate a mean and either standard deviation or limits (to be used with a triangular distribution for example) for the function's parameters.
- Code any rules on the spatial trends, space-filling character of the system, and surface irregularities.
- Simulate a set of surfaces for multiple realizations between the mapped horizons while honoring any well data. Each realization is generated by drawing from the parameter distributions.

"Rules"

Some general principles exist for the stacking pattern. When only depositional processes are considered, surfaces stack upward as sediment units form chronologically; surfaces are relatively smooth, surface shapes have upward curvature, and the surfaces have some location associated with maximum sediment thickness. As an approximation, surfaces are described by a shape with its largest height in a central location and less thickness in positions further from the center. Surface centers may appear anywhere because sediment units could start to form at a different positions due to directional currents, waves, storms, short-cyle rise and fall of sea level, fluvial channel switching, and so on. To approximate the stochastic nature, irregularities are added to each surface using a random undulations.

At the beginning of the simulation, the volume is empty, which provides the maximum accommodation for sediment. Each location has the same probability to accept a generated surface. As depositional events or surfaces are added, the system is gradually filled. Since only deposition is considered, subsequent sedimentation always occurs on top of preceding surfaces. As mentioned, the central location of a newly generated surface is selected based on the distribution of remaining thickness in the volume or rules about the system, e.g. aggradation, retrogradation or progradation.

Suppose now we generated a new surface Z which is an $xmax \times ymax$ matrix. Current overall height of reservoir is $Tsurface$, which is also a $xmax \times ymax$ matrix containing the summation of all previous surfaces. The minimum height of $Tsurface$, min_height is determined. The protion of new surface Z will be added to $Tsurface$ is denoted by Z_adjust which is calculated as:

$$Z\_adjust = (Z + min\_height) - Tsurface, i = 1, \dots, xmax; j = 1, \dots, ymax;$$

$$Z\_adjust(i, j) = 0, if Z\_adjust(i, j) < 0$$

That means the bottom of new surface Z drops to reach the minimum height of current reservoir volume min_height. The portion of Z overlaps with $Tsurface$ will be truncated.

In order to avoid distortion of the surface shapes, the addition of surfaces is based on the following rules. Figure 2 illustrates the dropping or truncation principle of surfaces with a cross-sectional view.

1. Generate first surface with the parametric shape and location from a distribution.

2. Accept first surface without any modification.

3. Modify each subsequent surface before adding it using the overall thickness. The surface elevation is controlled by the smallest thickness of the current volume. Any part of the surface that reaches the previous surface is truncated.

4. The truncation continues until the bottom of the surface reaches current lowest thickness. This process is equivalent to subtracting that part of the system above the current lowest thickness from the height of the generated surface and keeps the difference of the subtraction non- negative. The modified surface contains only the difference of the generated surface and current thickness above the lowest thickness.

5. Add surfaces until the volume has been filled to the maximum thickness.

A flowchart of program `surfsim` is shown in Figure 3. The program was written in FORTRAN 90 and is documented in **Appendix** A.

Illustration

To illustrate the concept, we generate a surface template from a simple parametric surface based on two hemi-circles and a parallepiped, as is shown in Figure 4. This parametric surface is referred to as the "racetrack":

- **X0,Y0:** The central location of the depositional event (generated surface). This location is chosen stochastically based on a current thickness distribution. The lower the current thickness of the position in the system, the higher the probability to accept a new surface (sediment). Initially, there is zero thickness everywhere, that is, all locations have the same probability. After the first event or surface definition, the probability of each location is proportional to the remaining unfilled thickness of the reservoir raised to a power. The central location of each surface is drawn by Monte Carlo simulation from these probabilities.

- **X:** Half the length of the surface with a constant maximum height **H**. Chosen randomly from a triangular distribution with user defined lower limit, mode, and upper limit.

- **Y:** The inner width of the surface (also the radius of the smaller semi-circle at both ends of the rectangle) with a constant maximum height **H**, randomly chosen from a user specified triangular distribution.

- **YY:** The outer width of the surface (also the radius of the larger semi-circle at both ends of the rectangle) with height decreasing to zero, randomly chosen from a user specified triangular distribution.

- **H:** The maximum height of the surface, randomly chosen from a user specified triangular distribution

- α**:** The angle of the elongation direction of the surface from X axis, randomly chosen from a user specified triangular distribution

Plots in the left part of Figure 5 show 3-D view, plan view and cross section view of the racetrack. The parameters used were $\mathbf{X} = 35$, $\mathbf{Y} = 5$, $\mathbf{YY} = 20$, $\mathbf{H} = 3$, and $\alpha = 45\ C^o$. A natural surface does not follow such a regular shape; there is variability in the surface. In order to make surfaces more realistic, undulation is added to the parametric form. The undulation surface is generated by a conditional Gaussian simulation, and the conditioning data are those data points located on the edge of the surface which remain unchanged. Sequential Gaussian simulation using (`sgsim`) is described in detail in [3]. Plots at the right of Figure 5 show views of the surface after adding undulation.

Undulation

It is assumed that undulations are normally distributed, therefore, undulations are generated with sequential Gaussian simulation. There are conditioning data at the edges of the surface to ensure that the undulation goes to zero. For only a single conditioning datum, the undulation surface is generated with that single conditioning datum. The conditioning points for `sgsim` all have a value of zero. For surfaces honoring more than one conditioning datum, conditioning points for `sgsim` consist of data located at the edge of the surface and conditioning data at all well locations. The values of the conditioning points for `sgsim` are zero for data at the surface edge and the modified distances from the surface to the conditioning data. A Gaussian variogram model is used, for which the range is chosen from calibration with analog surface data. Since `sgsim` generates values obeying a standard normal distribution, the magnitude of the undulation needs to be scaled properly before being added to the analytical surface shapes. The variation of surface lines are calibrated;

the standard deviation of the variation is used as the scaling factor to the standard normal distribution values.

Conditioning to Well Data

Two methods are used match the surface intersections with stratigraphic layers observed in wells: a set of rules, based on volume-filling, and a simulated annealing optimization.

Figure 6 shows the flow of the code of the rule-based conditioning part of `surfsim`. The method generates a suite of realizations, each with differing undulations in the surfaces, but now constrained to match surface intersections at wells. In practice, major time surfaces are visible as seismic reflection horizons. The well observations are conditioning data that should be honored for the subseismic surfaces. When major time surfaces are available, the system can be divided into subsystems that are modeled independently. A surface should pass through the intersections observed in the well logs and core, and there should be no other surface intersections appearing between surface intersections observed in the well logs and core (see Figure 7).

Each new surface may be accepted, rejected, or modified. The first step is to check if there are any conditioning data in the area of a generated surface. If there are no conditioning data in the area, the surface will be accepted and undulation added. The surface will not violate any existing surface intersections observed along the wells. For the situation of one conditioning well existing in the area, the vertical distance of the generated surface at the well location to the conditioning data point is calculated. If the distance is negative, the generated surface is below the conditioning data, and the surface will be rejected. If the distance is non-negative, the generated surface will be moved down to the conditioning data to honor it. Any negative value of the surface resulting from such a subtraction will be rounded to zero.

A conditioning situation with only a single conditioning data location or well is depicted in Figure 8. The situation with more than one conditioning well is more complex. First, the vertical distances of the generated surface at the well locations to the conditioning data are calculated. If all distances are negative and the surface is below all the conditioning data, the surface is rejected. If any of the distances is positive, that means the surface either passes through the conditioning data or above the conditioning data. The median of the distance is calculated. If the median distance is negative, the surface is rejected. Otherwise, if the median is non- negative, the surface is moved down by subtracting the median of the distance. Correspondingly, the distances of the surface from the conditioning data points are modified by subtracting the median of the distances. If any distance exceeds a preset tolerance limit, the surface is rejected. If all the modified distances are smaller than the tolerance limit, the conditioning data points within the surface area will be honored by generating an undulation surface passing through them. Figure 9 shows the acceptance and rejection rules for situations with more than one conditioning data location.

Simulated annealing is an alternate method available in `surfsim` to match well data and was found to be effective for some multiple-well problems. Simulated annealing is a stochastic optimization [2, 3, 9] algorithm which minimizes the mismatch between the well surface intersections and the generated surfaces.

Examples

Two examples are presented. The first is from a forward response model and has seven surfaces related to deposition on a continental shelf over a relatively short time. The second is an outcrop of a deepwater deposit that has many surfaces with truncations. Both examples are 2-D models, but all simulations are conducted in 3-D. In order to simulate the surfaces in 2-D for the first example, the central locations of the generated surfaces have the same Y coordinate. The simulated realizations shown in the figures are actually the $X-Z$ cross-sections at that particular Y coordinate. For the 2-D outcrop, the synthesized wells are assumed to be located along a line parallel with X-axis having the same Y values. Only the corresponding $X-Z$ cross sections are shown in the figures.

`sedflux` Model

The first example is a grain size distribution from forward modeling `Sedflux` [11, 14]. `Sedflux` is a forward response model that deposits sediment using fundamental governing fluid mechanics and sediment transport equations. The resulting models can provide detailed spatial distributions of sand and other major depositional facies.

Figure 10 shows the grain size distribution from a `sedflux` simulation. This dip cross-section model is a simulation related to a petroleum reservoir, with the sediment source (shoreline) toward the left [14]. The sediment was deposited on a sea floor slope of approximately 0.25 degrees with a generally rising sea level, but with seven short cycles of relative sea level fall. Thus, the deposit is seven backstepping units, with a generally fining upward of sediment across the surface boudaries. Within each sediment unit there is a coarsening upward trend. After coordinate rotation, the data are shown on top plot of Figure 11. From the top plot of Figure 11, seven distinct sediment units have been interpreted, which are separated approximately by red surface lines shown on the second plot of Figure 11. These surfaces correspond to the high-frequency sea level drops, imposed on the low-frequency sea level rise. The grain sizes for each distinct sediment unit was then extracted individually and plotted onto a translated coordinate, as displayed in the lower part of Figure 11. The sediment boundary surfaces have a fairly systematic shape, appearing to maintain the shape with superposition of each sediment unit on the previous sediment. A positive skewed Gaussian shape defined as follows has been used as the surface template:

$$y = \begin{cases} \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{1}{2\sigma^2}\left(x^k - x_0^k\right)^2} & k < 1 \text{ if } x > x_0 \\ \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{1}{2\sigma^2}(x-x_0)^2} & \text{if } x \leq x_0 \end{cases}$$

Figure 12 displays analytical shapes generated by using such an equation. The k values are $1, 0.9, 0.85$ and 0.8 from left to right, respectively. A 3-D surface is the product of such a skewed Gaussian shape along the elongation direction and a Gaussian shape in the orthogonal direction.

There is an obvious backstepping of the surfaces moving from right to left; the backstepping, transgressive nature is imposed as a "rule" on the surface location parameter in `surfsim`. Therefore, the surface simulation begins from a starting point on the right side of the axis and the central location of new sediment shifts toward the left by a distance drawn from a triangular distribution. And the simulation stops when the central location of new sediment is beyond the limit of the axis. Figure 13 shows the simulated surfaces from `surfsim`. The top plot is the original synthesized surface lines from the sediment grain size distribution.

Figure 14 shows the surfaces generated by conditioning to one of the wells, assumed to be downdip, by the method described in the previous section. Figure 15 shows the uppermost of the three surfaces in 3D. Further updip, outside the well control, additional unconditional surfaces must be generated to honor the backstepping "rule" or constraint which is shown in Figure 16. Figure 17 illustrates the surfaces generated, when constrained to match interpreted surface intersections at two wells. The wells are near the center of the system with about 1.5 km separating them. The conditioning was done with simulated annealing in this case. The surface intersections do not match the wells exactly because of the multiple constraints imposed by both surface geometry and the backstepping rule.

Wagon Caves outcrop

The second example is on surface boundaries observed at the Wagon Caves rock outcrop. The upper plot of Figure 18 is an image of the Wagon Caves outcrop section and the lower plot of Figure 18 contains surface lines interpreted by Anderson [1]. The surface lines in the lower part of Figure 18 were digitized and are shown in the upper plot of Figure 19. The digitized lines contain 100 equidistant points each. Downlap stratigraphic layers exist, but there are many truncations. In order to follow the stratigraphy a vertical transformation to stratigraphic coordinates was performed [4]. First, restored base, z_{rb}, and top, z_{rt}, of stratigraphic layers are estimated, which are shown as thick dark lines in upper plot of Figure 19. The stratigraphic coordinates are then calculated based on the restored base/top as following:

$$z_2 = \frac{z_1 - z_{rb}}{z_{rt} - z_{rb}}$$

where (z_1) is the height of the data location on the Cartesian coordinate system and (z_2) is the stratigraphic vertical coordinate. The coordinate (z_2) is zero and one at the stratigraphic base and top, respectively, and represents a relative coordinate. This transform is reversible:

$$z_1 = z_{rb} + z_2 \left(z_{rt} - z_{rb} \right)$$

The existing top and base are used for constraining the values after back transformation. All backtransformed (z_1) values outside of the interval $[(z_{eb}, z_{et})]$ are not kept in the final model. The surface lines of Wagon Caves Outcrop after such a coordinate transform are shown in lower plot of Figure 19.

The magnitude of undulation (scaling factor) and the variability of the surface (*range* in generating the undulations with `sgsim`) must be calibrated. For this purpose, the residuals of some surface lines are calculated after the original surface is fit by a *simple parameter surface*, which is used in the surface modeling. The histogram and variogram of the residuals can also be calculated, using a Gaussian model. Figure 20 shows the calculation for surface line 13. The spread and the spatial continuity of the residual provide an indication of the variability and the magnitude of undulation that should be superimposed on the analytical shape.

No. of lines	Std	Range
4	0.024	40
5	0.031	60
6	0.061	90
7	0.018	60
8	0.004	8
9	0.007	35
10	0.004	8
11	0.029	70
12	0.018	42
13	0.012	25
14	0.008	13
15	0.012	20
16	0.016	33
17	0.011	18
18	0.011	20
19	0.018	25
20	0.040	28
mean	0.019	35

Table 1: Range and standard deviation of the fitted residual

Table 1 lists the standard deviations of the residuals for fitting surface lines 4 to 20 and the *range* of the corresponding variogram models. The calculated standard deviation spreads from 0.004 to 0.06 and the *range* of the variogram has value between 8 to 90. The means of the standard deviation and *range* are 0.019 and 35, respectively.

The calculated *range*s are used as a guide to set the *range* parameter when generating undulation surfaces. We found that a *range* parameter of 35 leads to greater variability than the actual surfaces. This is partially attributable to the excellent fit of the residual from which the *range* is derived; the actual *range* would be larger with poorer fit. Figure 21 compares two examples of the dependence of *range* with the goodness of fit.

Figure 22 presents unconditional simulation results with two sets of *range* parameters. Simulation *I* use 40, 60 and 70 as the lower limit, mode and upper limit for the triangular distribution of *range*, and simulation *II* use 20, 35 and 50 accordingly. Three realizations are generated for each simulation. Larger *range* parameters yield more realistic surface lines compared to the outcrop, as shown on the top of the figure.

Conditioning data are taken from the outcrop from vertical sampling locations. The intersections of the vertical wells with the surface lines are regarded as conditioning data. When conditioning data exist, the undulation surfaces generated by `sgsim` honor both the data points at the edge of the surface and the conditioning data within the surface area. The magnitude of undulation for the rest of the surface is also scaled since `sgsim` gives values from a standard normal distribution. It is assumed that the variability of each surface is normal with a different standard deviation. Therefore, the values of the conditioning points for `sgsim` are divided by the standard deviation, then the undulation surface generated from `sgsim` is multiplied by the standard deviation. The calculated standard deviations of the fitted residual of the surface lines are used for determining the standard deviation to be used. The standard deviation for such a scaling is drawn from a triangular distribution and the parameters of the triangular distribution used in the simulation are 0.015, 0.020, and 0.025 for lower limit, mode and upper limit, respectively. The simulated results with one and four conditioning wells are shown in Figures 23 and Figure 24, respectively.

Note on CPU Effort

The CPU time is dependent on the size of the model, the number of surfaces, and the number of conditioning data. Table 2 shows the numbers of finally accepted surfaces and totally generated surfaces for each realization of the simulations for the Wagon Caves example. The corresponding CPU time in seconds for the three realizations of the simulations are tabulated (Pentium II, 300 MHz).

Discussion

In the two examples, the simulated surfaces are good approximations to the real surface lines. This is precisely our goal. Even with advances in geostatistical modeling, numerical models often do not reproduce complex geological features that are consistent with geological boundaries or are not able to preserve complex morphology of analog models. The surface modeling approach developed in this report is a step in this direction.

Each realization looks close to the target image, however, it is difficult to quantitatively judge how good the realizations are, that is, what is the real advantage of surface modelling? Some quantitative criterion is required for evaluating the quality of surface modeling. As mentioned, the purpose of surface modeling is not to get surfaces *per se*, but to provide constraints for further modeling facies and petrophysical properties. That modeling is the subject of a companion paper [16].

The approach generates parmetric-based surfaces stochatiscally, and these are accepted or rejected by rules. Goff [7] also reports a surface architecture modeling approach. Goff's surfaces are built conformable to the bathymetry, with stochastic undulations, using a coherence methodology. His method can also be constrained to well data but since the succeeding surfaces are conformable, the method will not produce truncations as observed on the Wagon Caves outcrop. He also does not mention preserving a spatial trend to the surfaces. MacDonald [12] defines azimuth and inclincation angles relative to the paleo sea floor to estimate the location of retrograding parasequence boundaries using geostatistical simulation. The method provides for extension to other "rules" and would be a good complement to the method presented in this paper.

Future work

Methodology to develop more representative surface templates is needed, e.g. the Goff approach of using Fourier transforms is one approach. Additional capability to locate surfaces based on sequence stratigraphy, e.g. the azimuth and inclination approach of MacDonald

Simulation (no. well)	Accepted/total surfaces of realization 1	Accepted/total surfaces of realization 2	Accepted/total surfaces of realization 3	CPU time for all three realizations
0 well(I)	18/18	22/22	18/18	35
0 well(II)	20/20	24/24	20/20	49
1 well	21/25	22/26	26/32	46
2 wells	23/134	21/37	22/33	45
3 wells	25/163	25/262	28/122	86
4 wells	35/2785	29/2174	36/1062	587
5 wells	30/652	35/765	30/547	217

Table 2: CPU time (in seconds) on a 300 MHz Intel PC processor

should also be incoporated. More complex geologic rule and surface morphologies need to be included. Research on data mining technology has been initiated in that area. Using surfaces as constraints in an optimization-based modeling scheme and flow simulation within models generated using the surface and trend constraints are ongoing.

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[16] YuLong Xie, A. S. Cullick, and C. V. Deutsch. Sediment trend models within subseismic stratigraphic surfaces for subsurface characterization. *CCG Annual Report*, 2000.

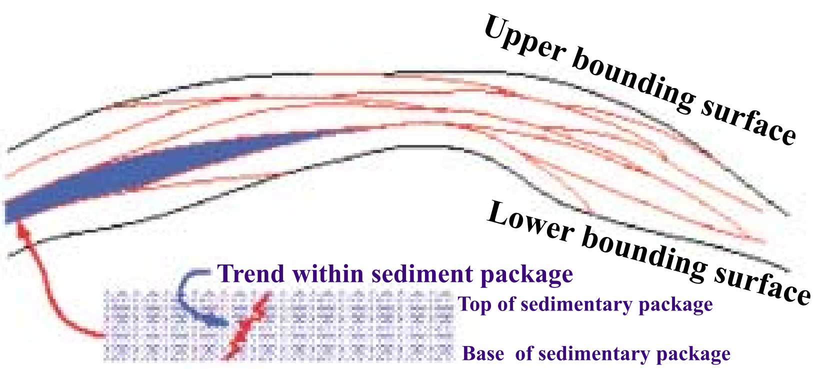

Figure 1: Sediment units bounded by major horizon surfaces and subseismic bedset surfaces. Sediment grain size or facies trends can be present within units.

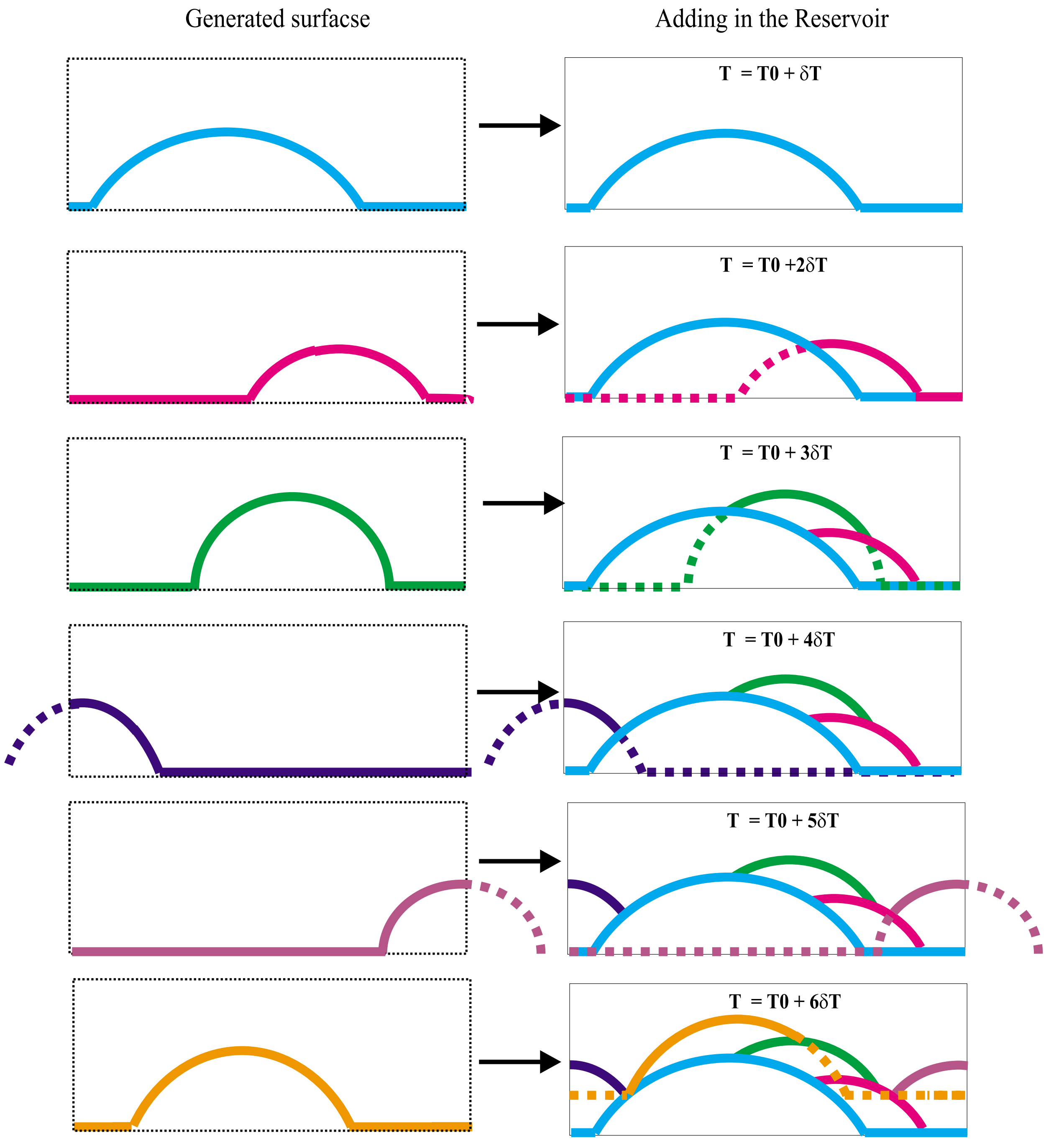

Figure 2: Example of "filling" with six surfaces. Surfaces are generated stochastically with proscribed shape, then truncated on earlier surfaces.

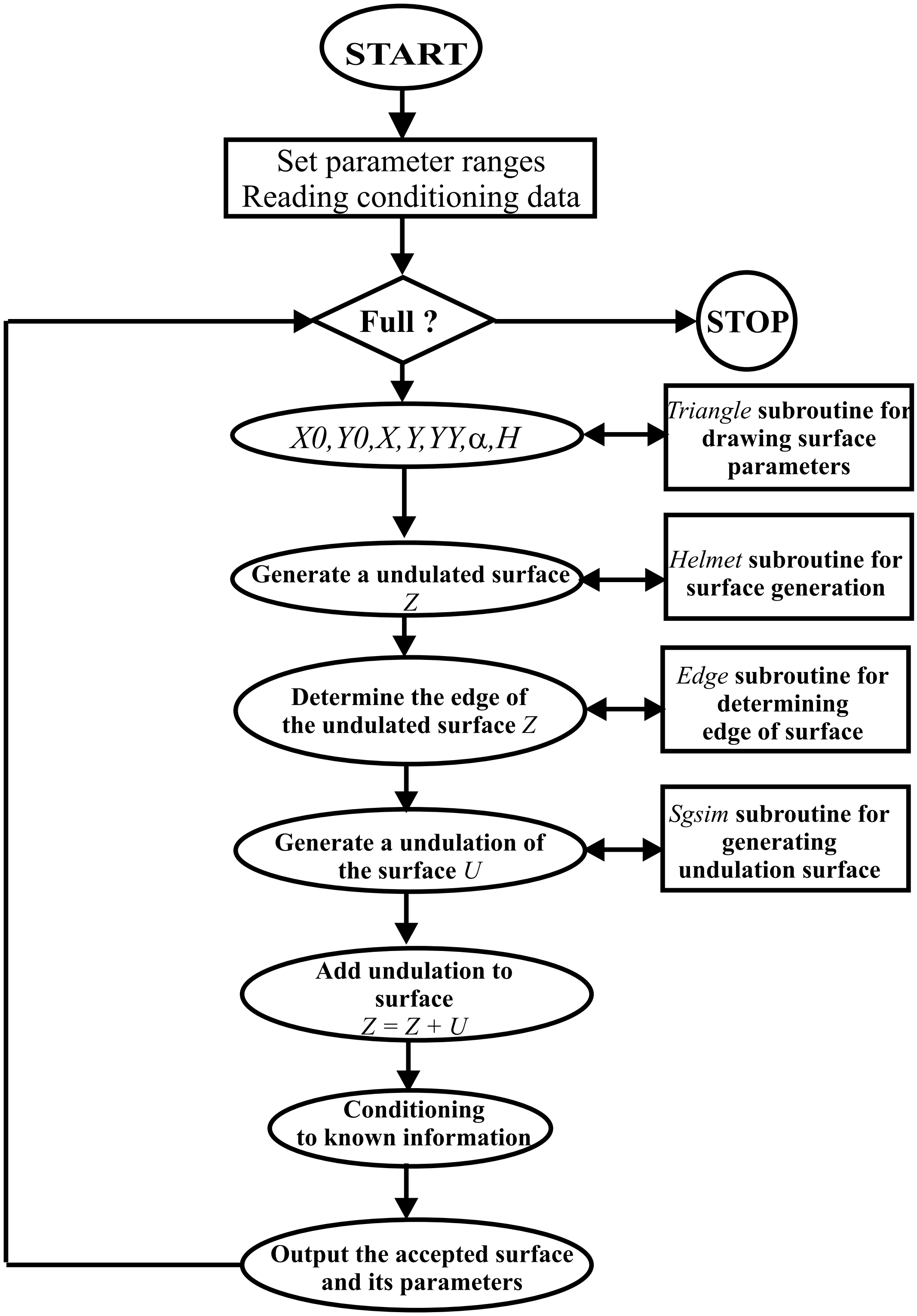

Figure 3: Flowchart of program `surfsim`

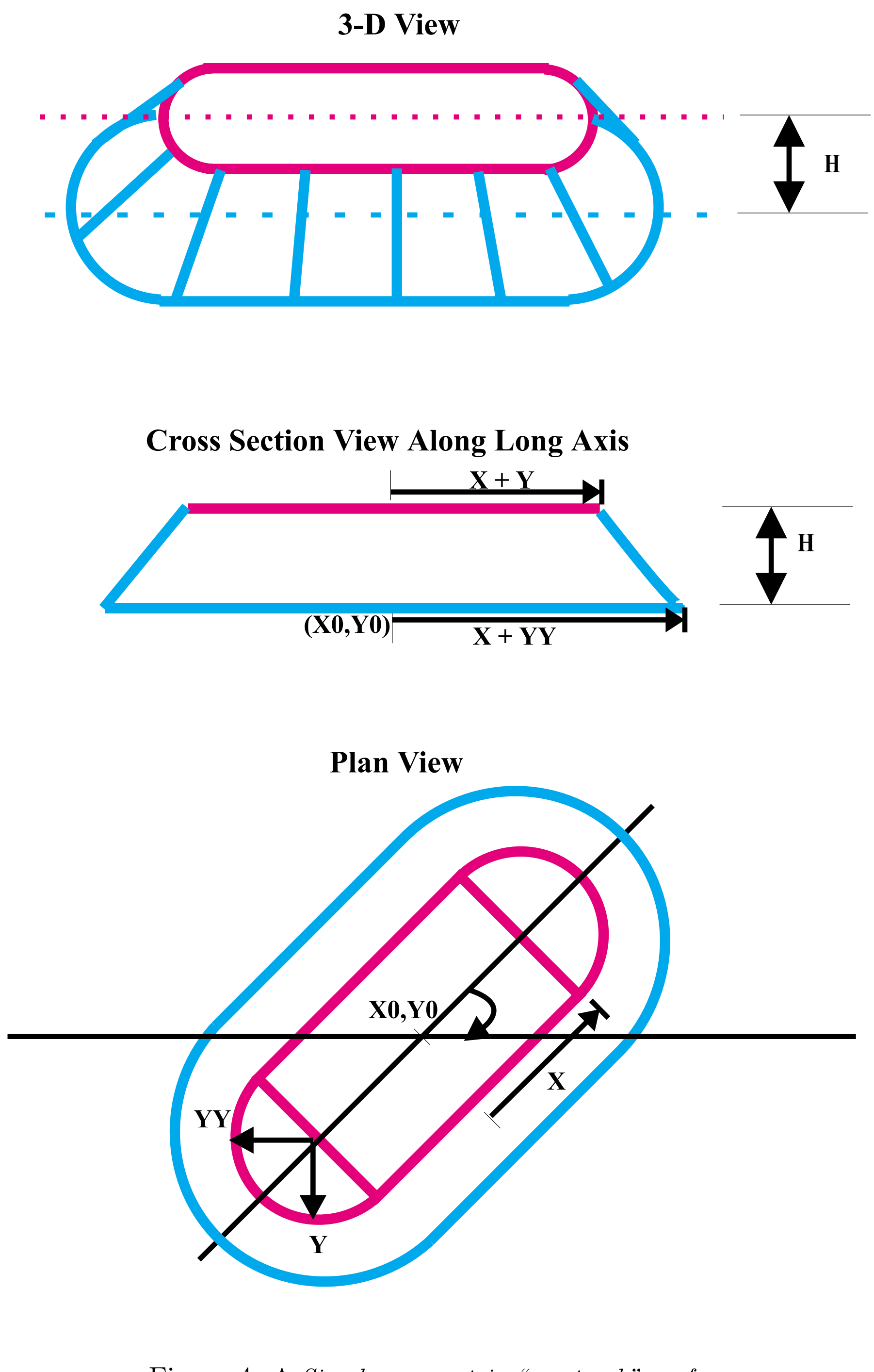

Figure 4: A *Simple parametric "racetrack" surface*

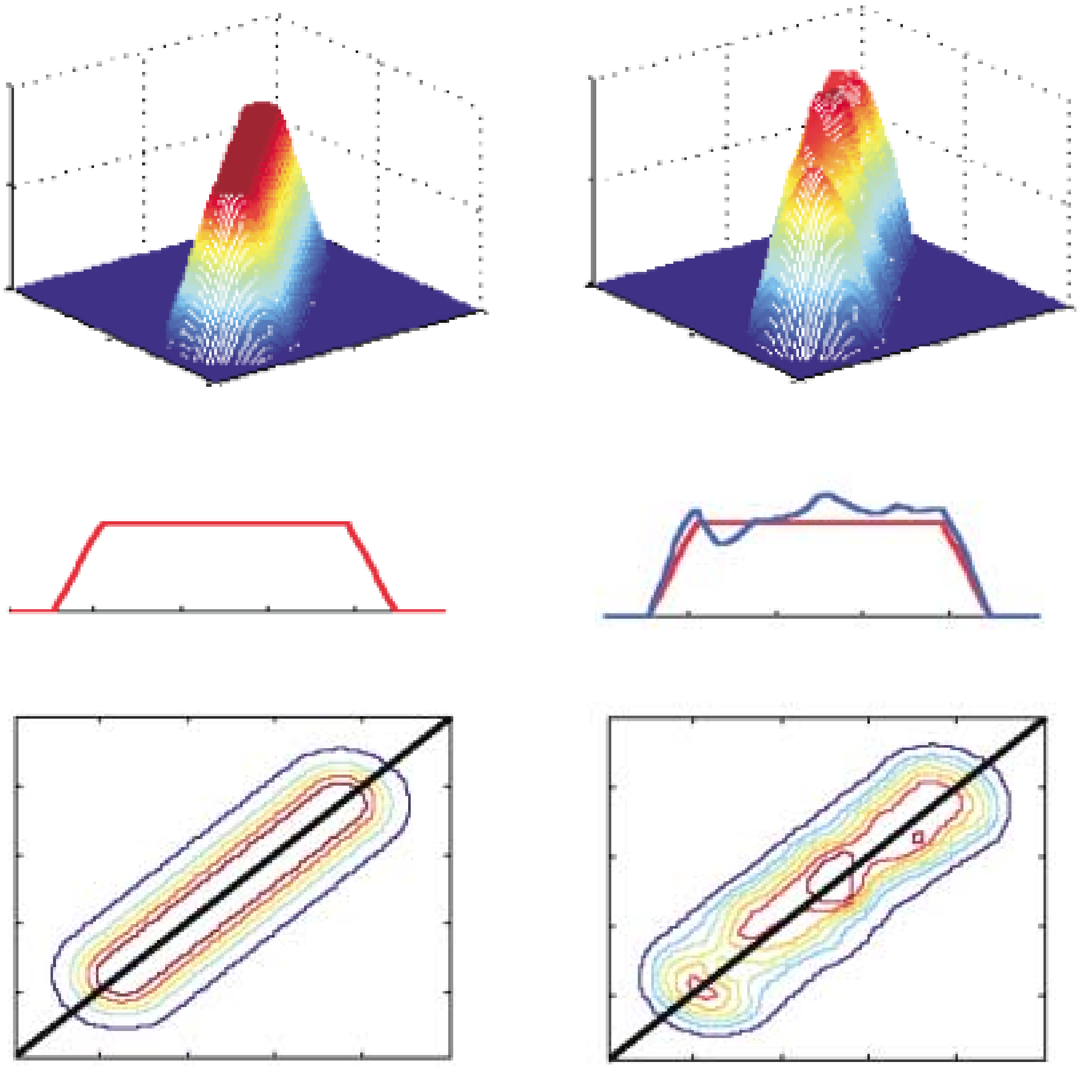

Figure 5: 3-D view, cross-section view from the elongation direction and plan view of *the racetrack surface* before and after adding undulation

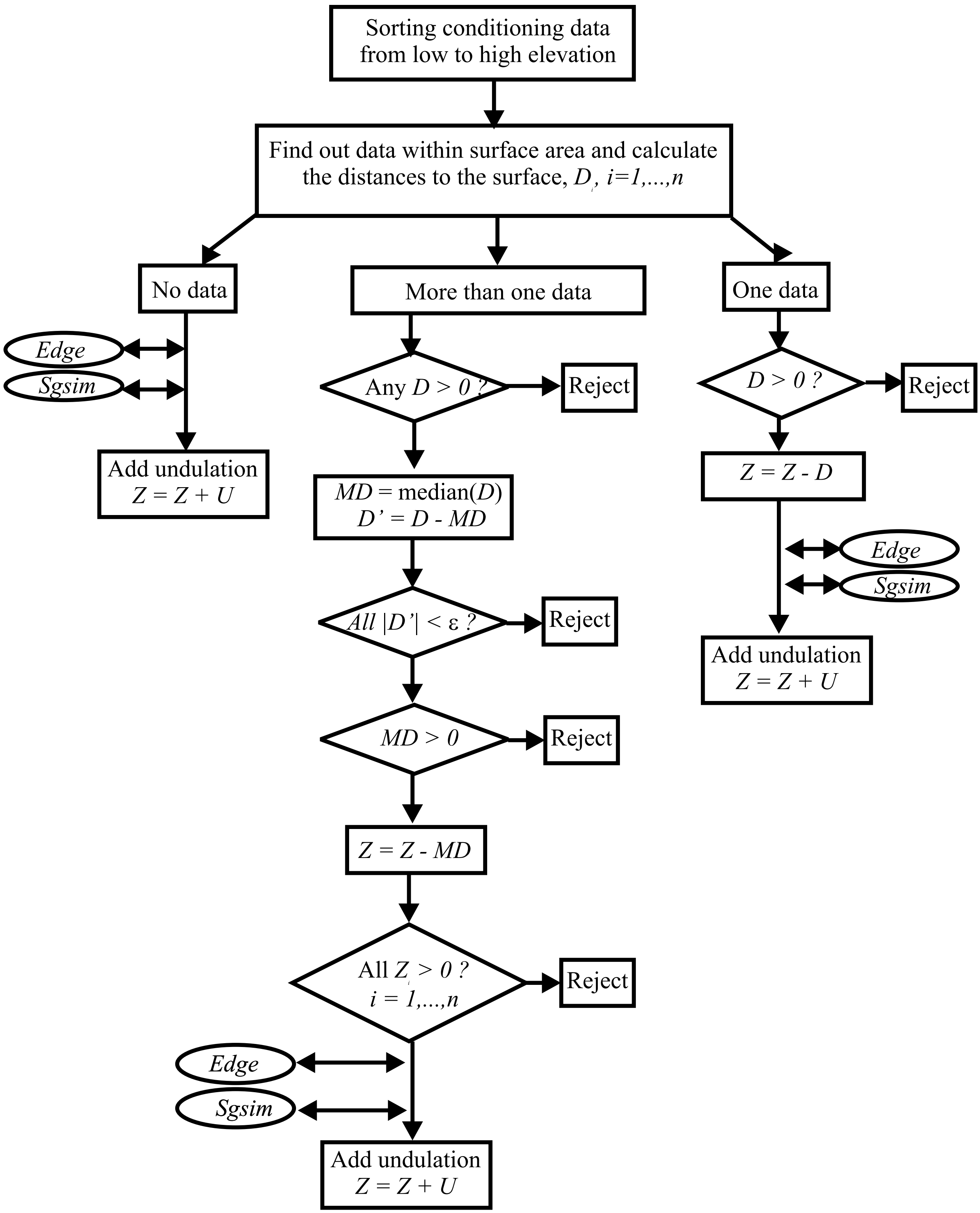

Figure 6: Flowchart for conditioning to well data.

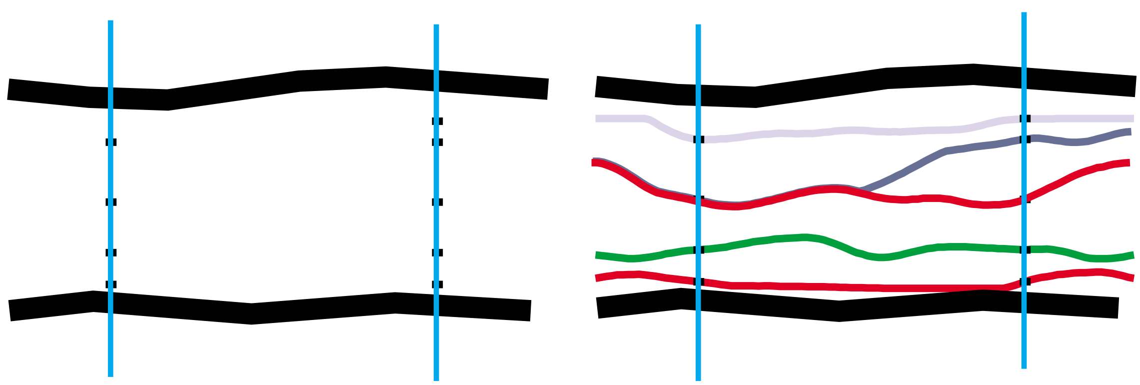

Figure 7: Conditioning to well data. Right well has one more surface intersection than left well, so that surface truncates between the two wells.

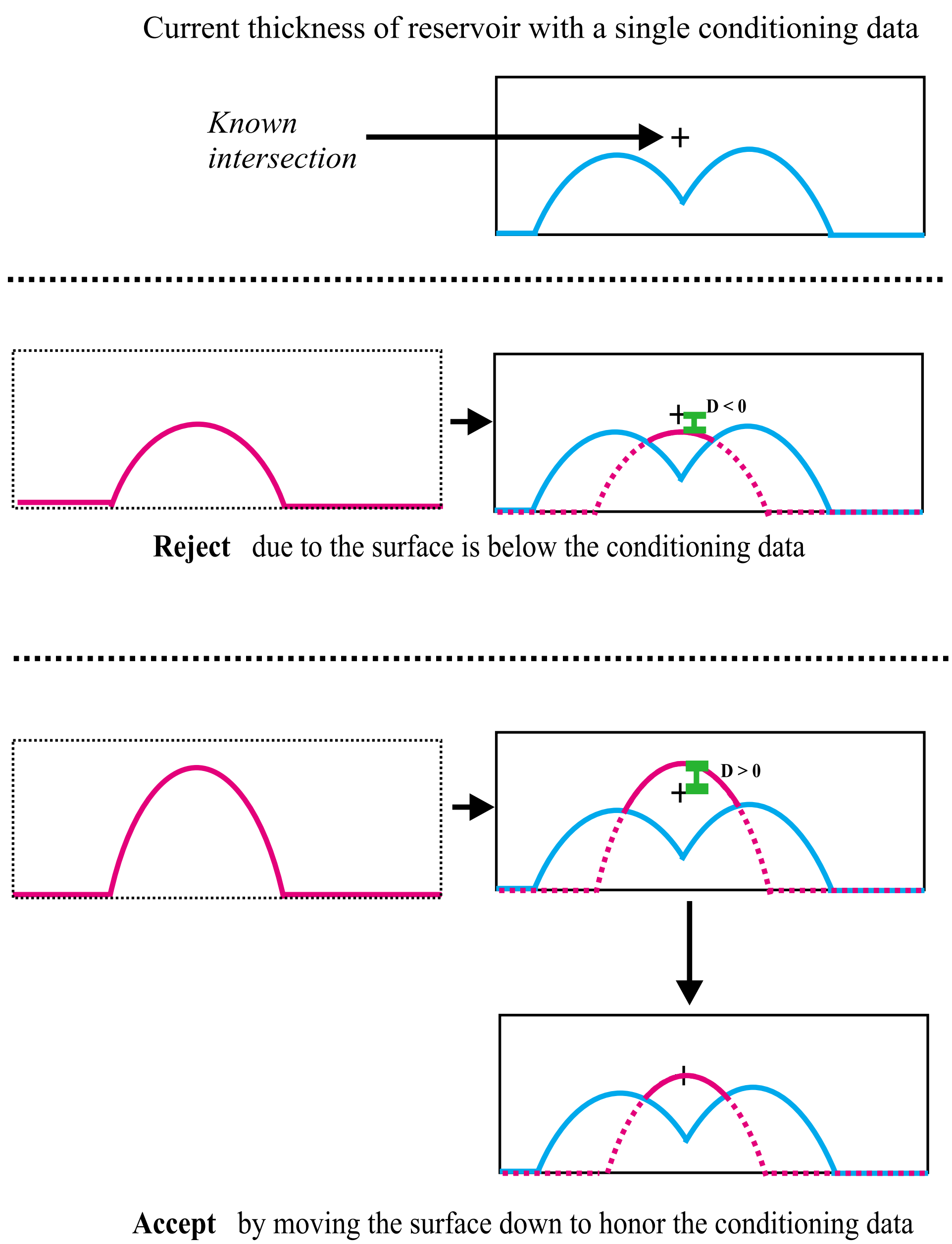

Figure 8: Acceptance and rejection of surfaces with a single conditioning data location. (*epsilon* is a small tolerance.)

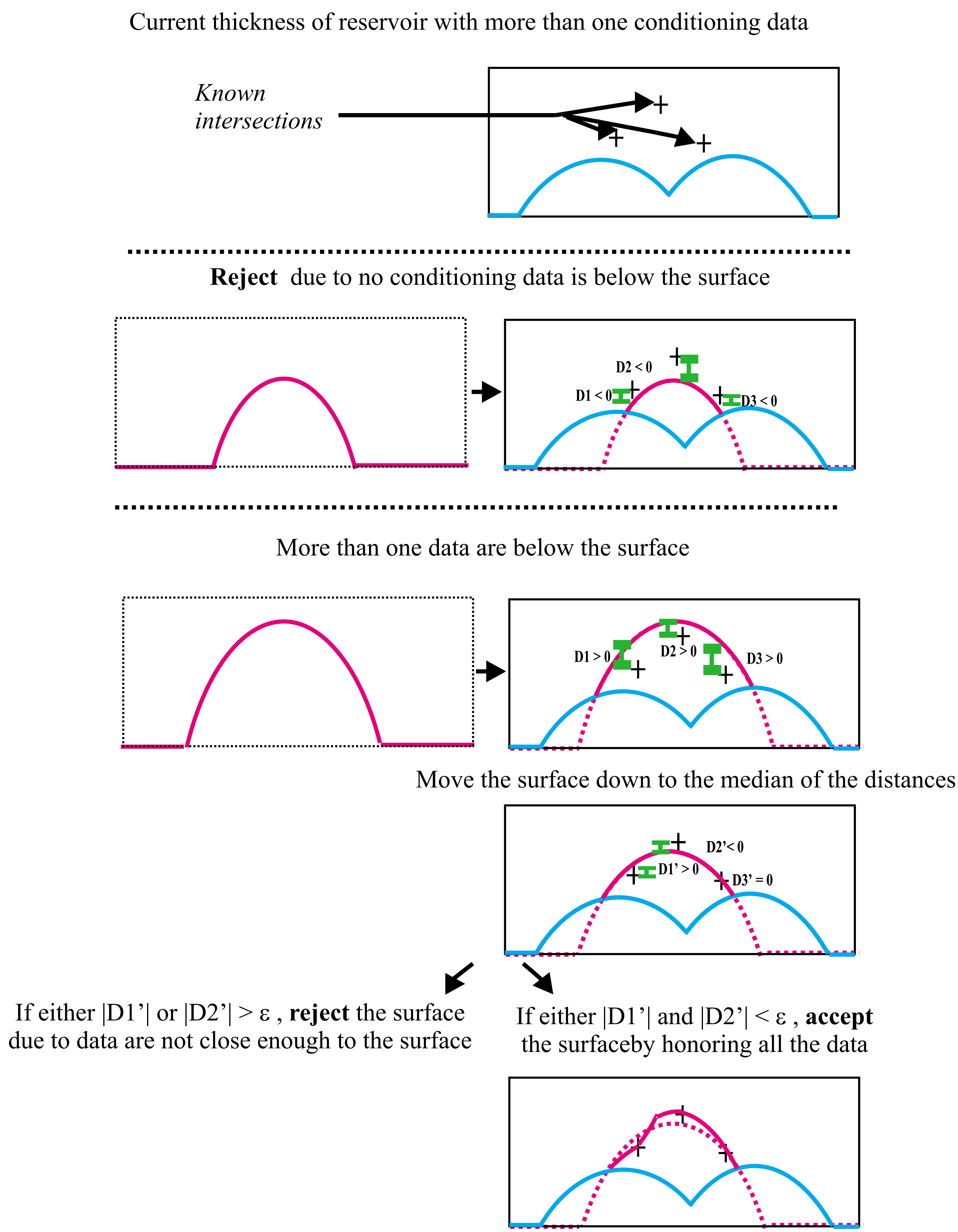

Figure 9: Acceptance and rejection of surfaces for more than one conditioning data locations.

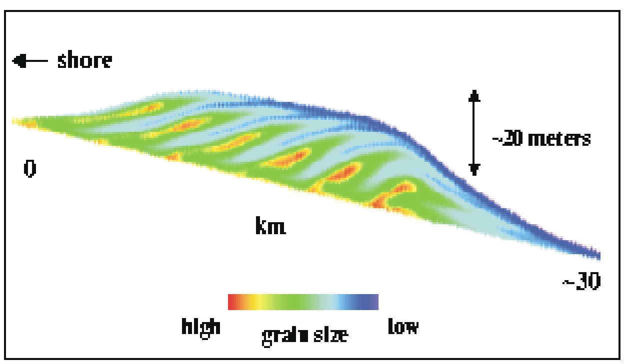

Figure 10: Grain size distribution from Sedflux model for the Wandoo-base sediment deposit simulation [14]

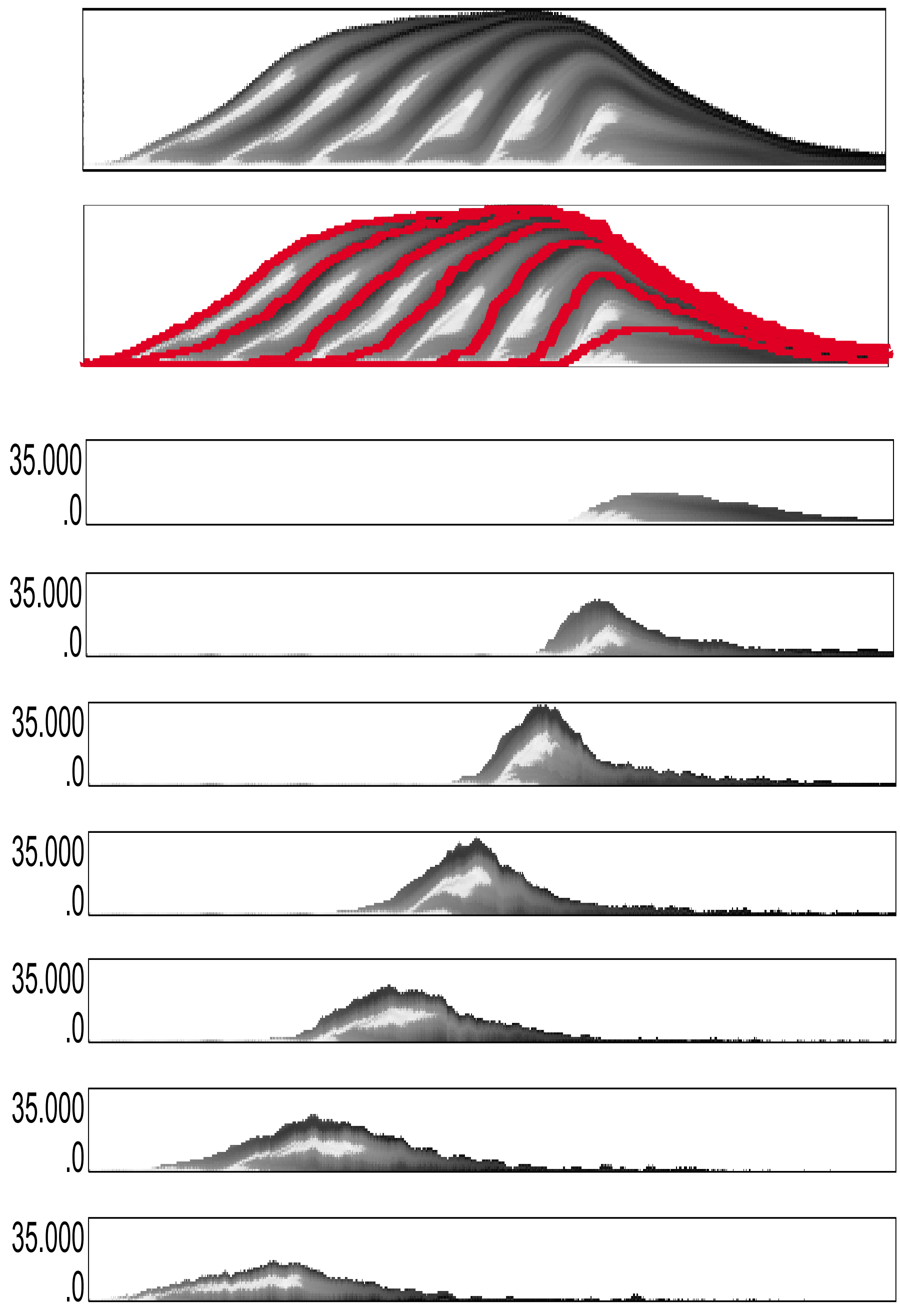

Figure 11: *Top*: Grain size distribution from Sedflux model after rotation. *Next*: Red surface lines separate the sediment units *Next seven*: Seven distinct sediment units, extracted onto flat coordinates

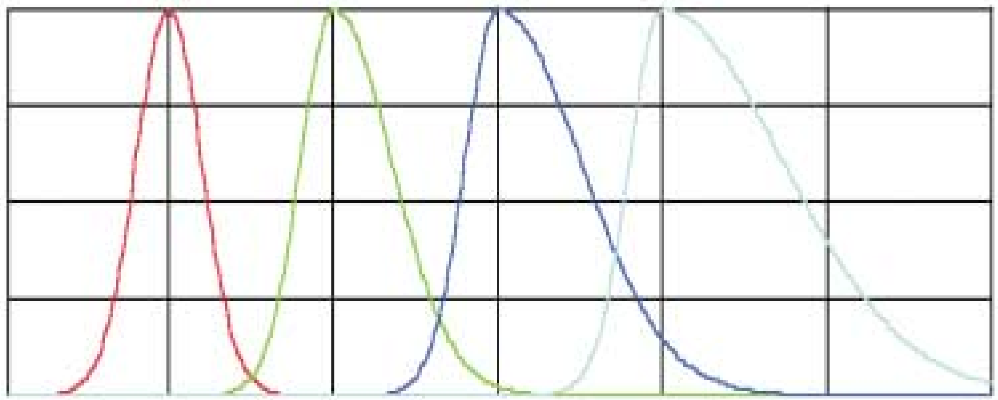

Figure 12: Skewed Gaussian shape used as template from the Sedflux model

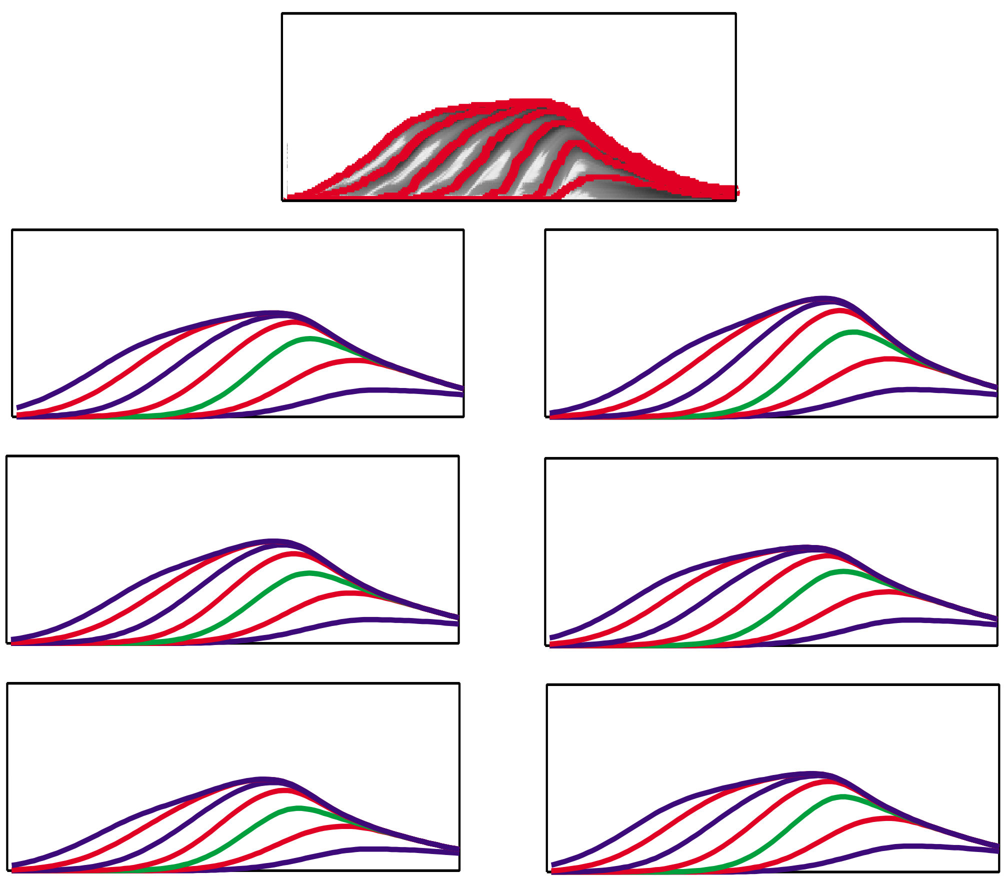

Figure 13: Six realizations of surfaces using the Sedflux-derived skewed Gaussian shape.

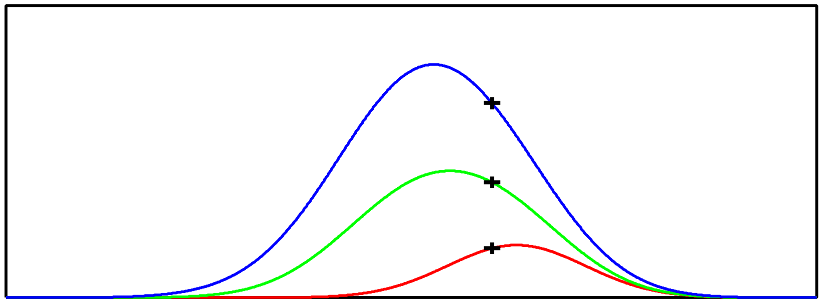

Figure 14: Dip cross-section for the Wandoo surfaces with one conditioning well.

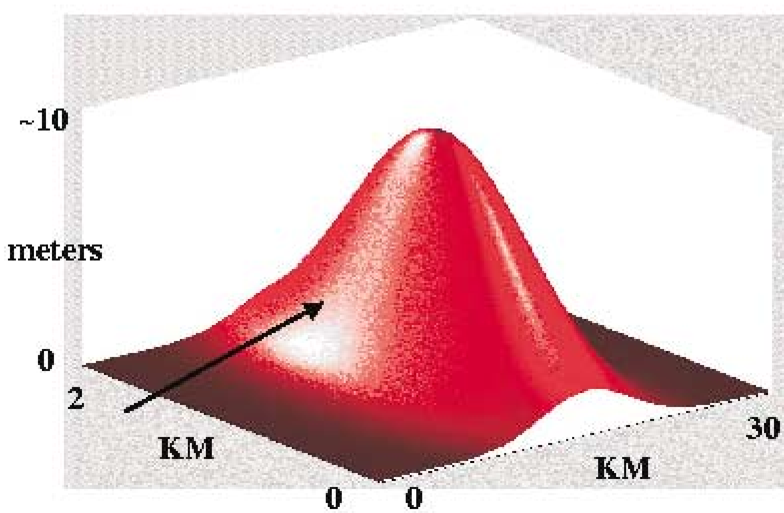

Figure 15: Wandoo model top surface in 3D with a single conditioning well.

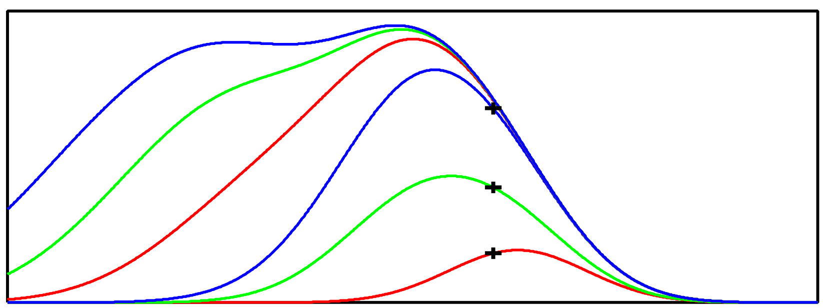

Figure 16: Dip cross-section for the Wandoo surfaces with one conditioning well. Surfaces show updip unconditional surfaces generated using the backstepping transgressive constraint.

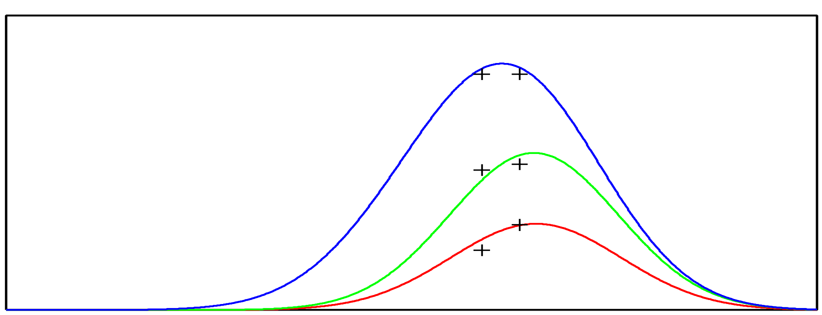

Figure 17: Dip cross-section for the Wandoo conditioned to two wells, using simulated annealing for the conditioning.

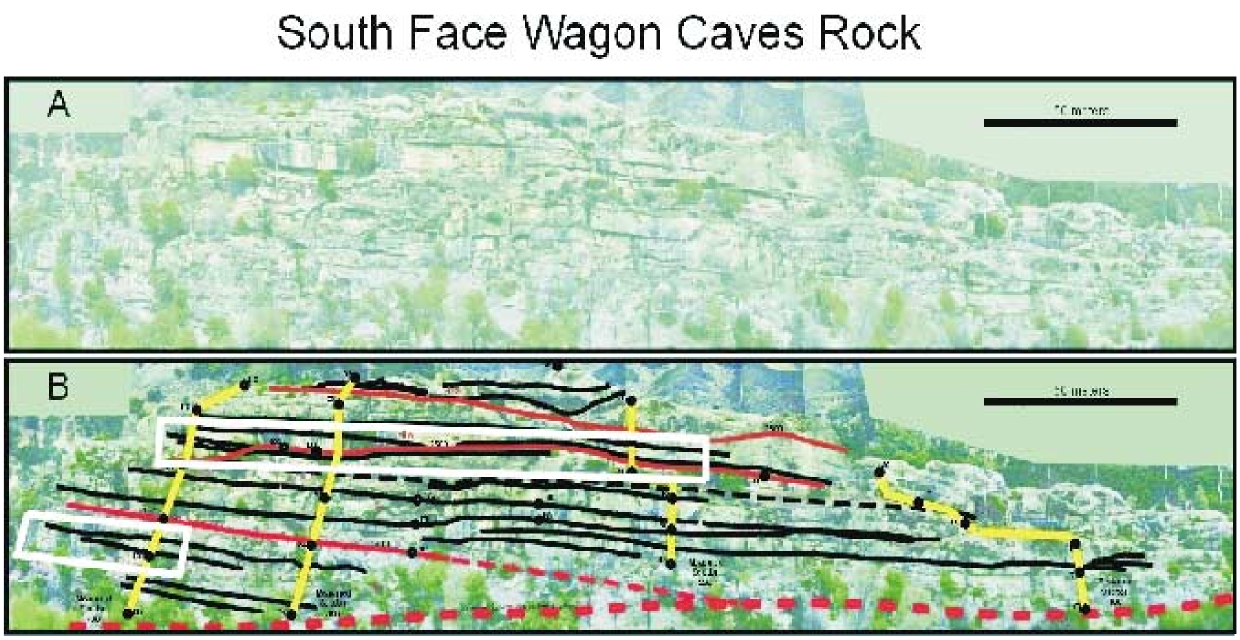

Figure 18: A. Wagon Caves rock outcrop. B. Depositional surfaces interpreted by Anderson.

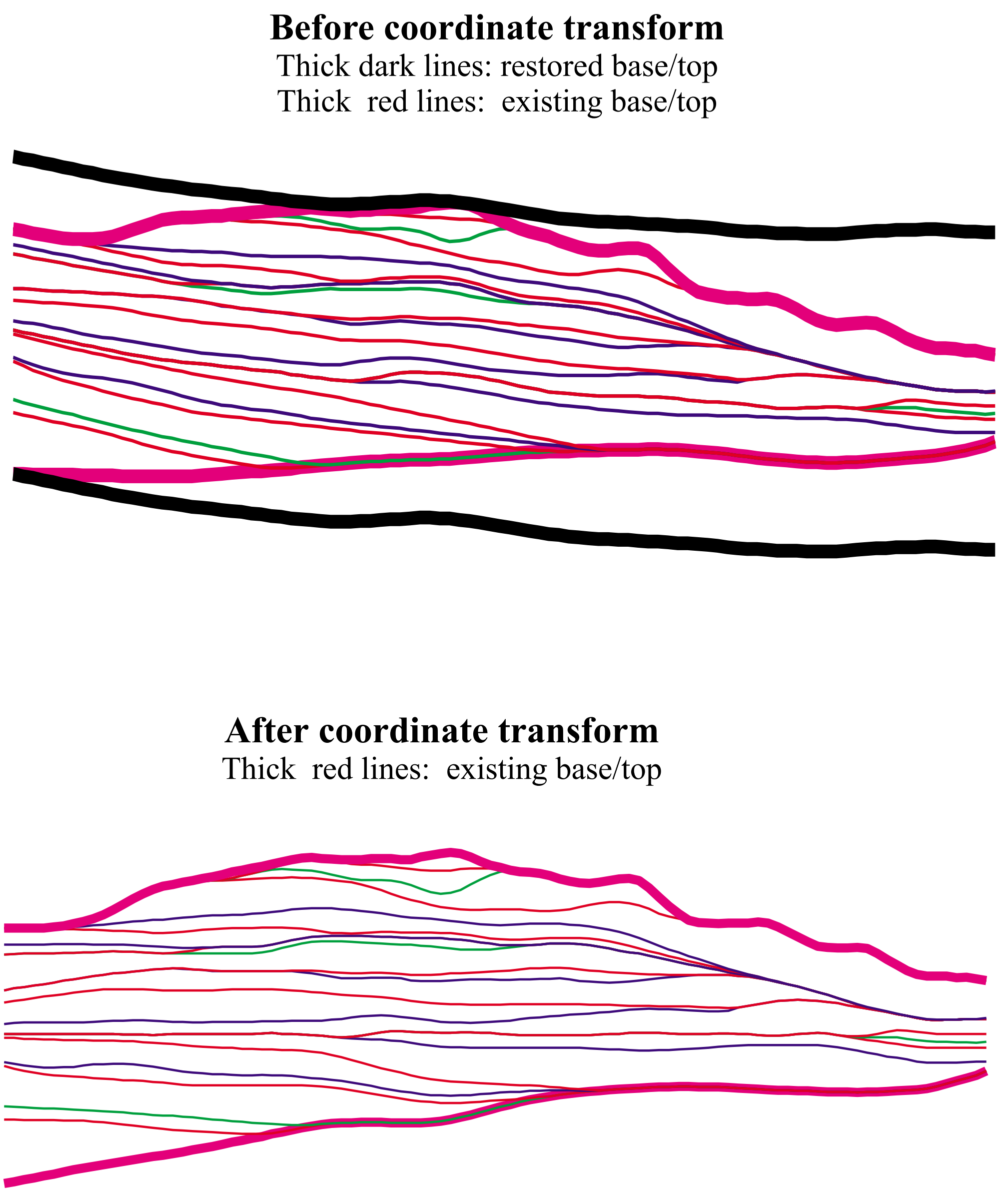

Figure 19: Interpreted surfaces of Wagon Caves outcrop in the original and transformed coordinates.

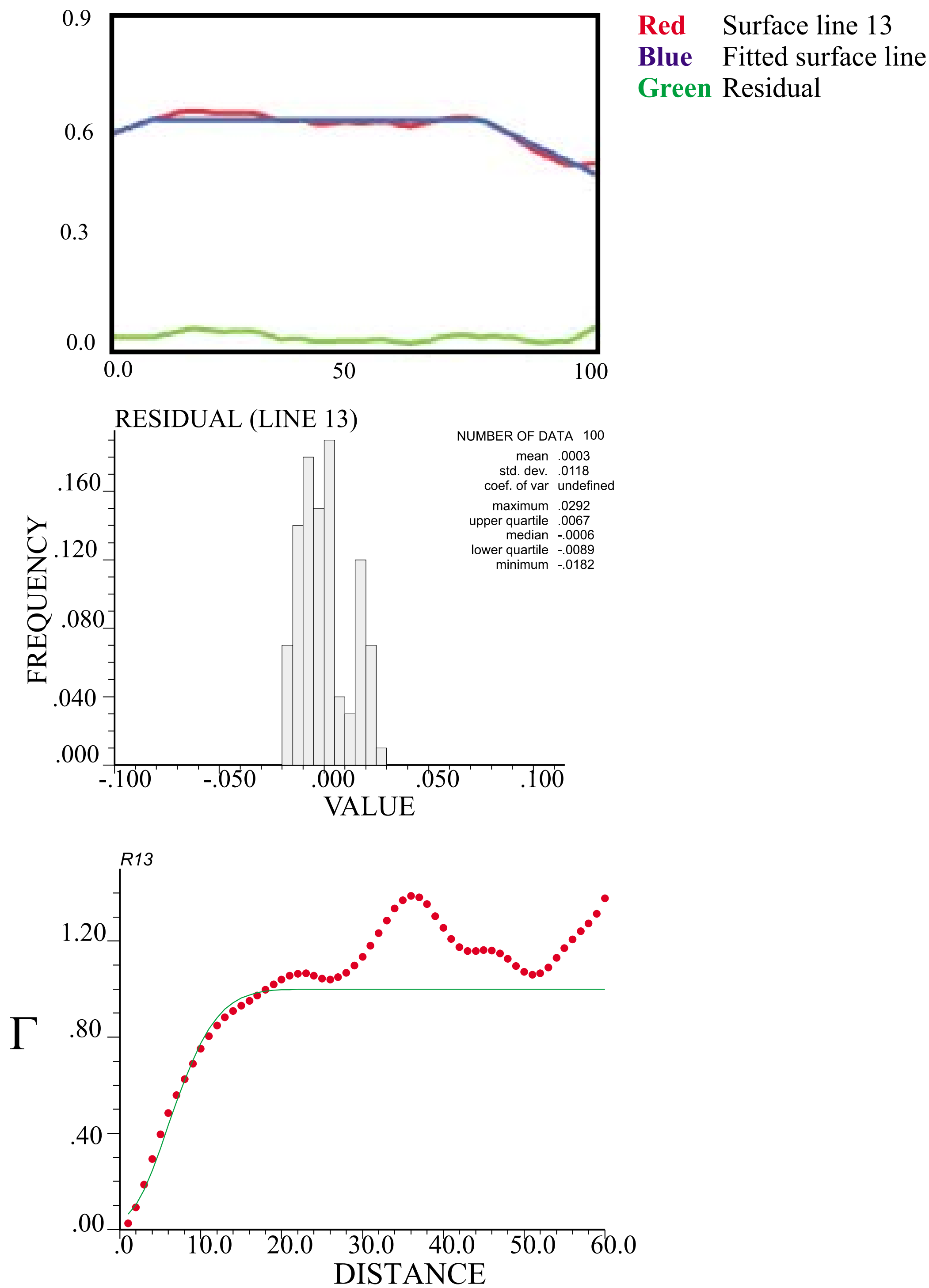

Figure 20: Surface line 13 of Wagon Caves outcrop. *Top*: fitted residual *Middle*: histogram of the fitted residual *Bottom*: experimental (dotted line) and model variogram (solid line) of the residual

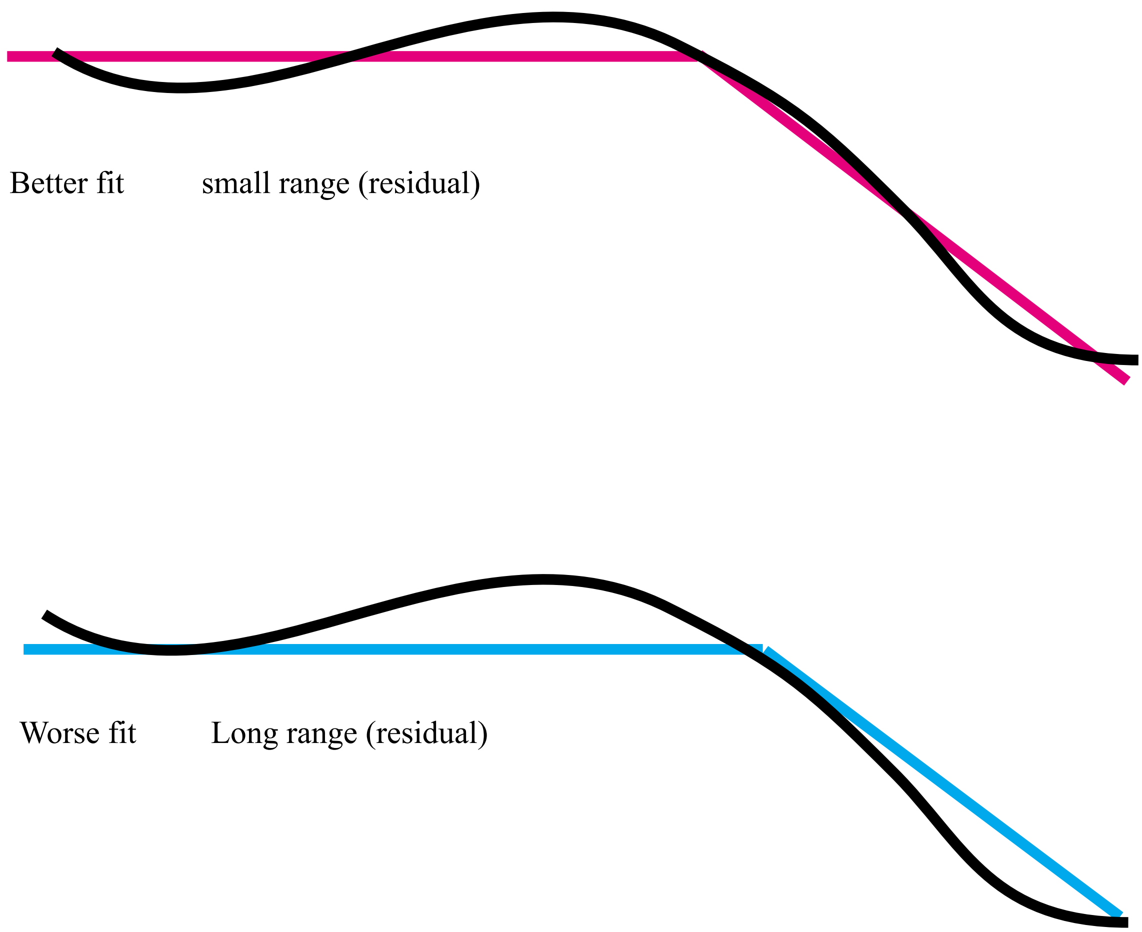

Figure 21: Comparison of goodness of fit and range assigned to residual

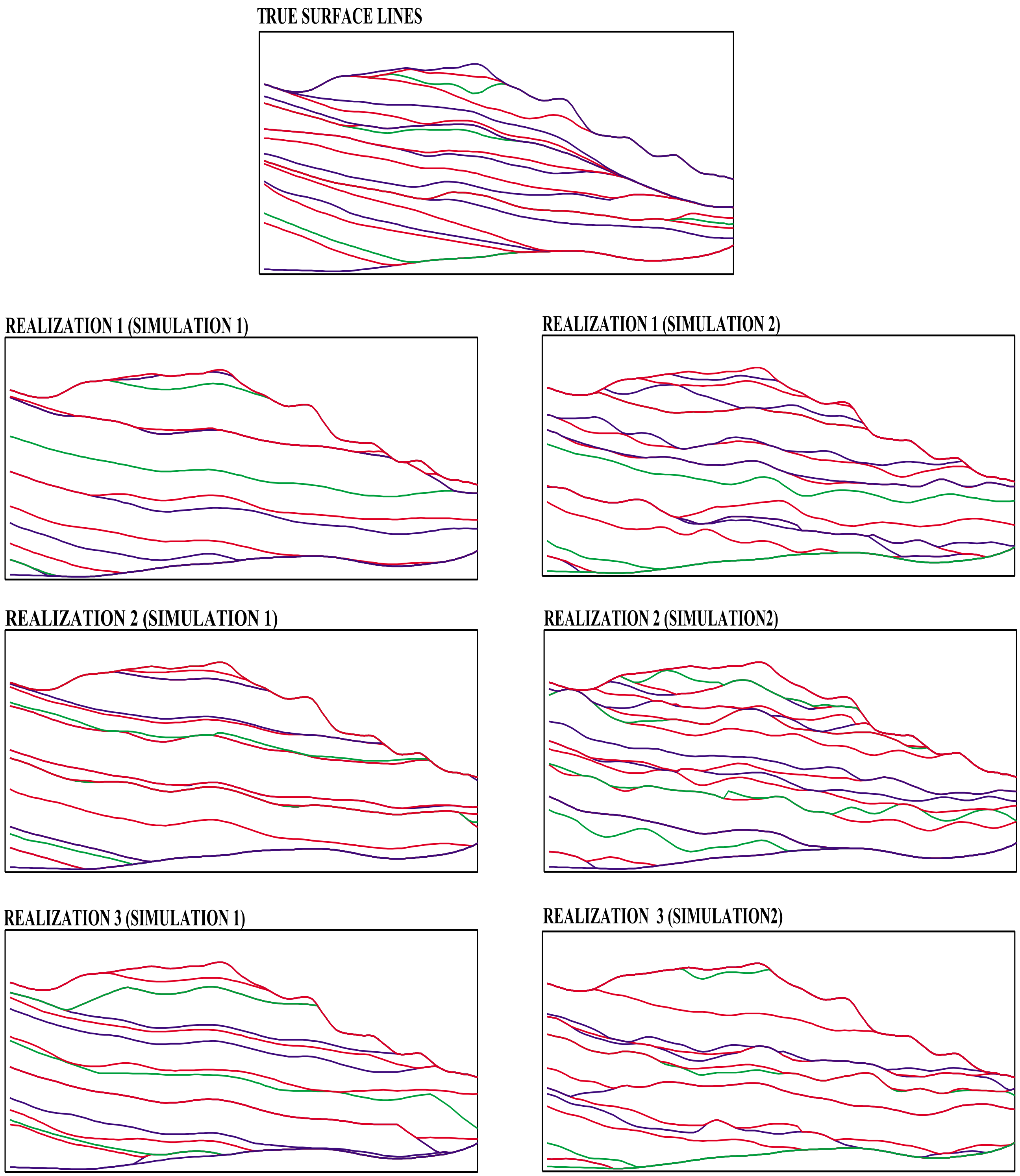

Figure 22: Wagon Caves unconditional surface simulation. I. triangular distribution for the range is 40,60,70. II. triangular distribution for the range is 20,35,50.

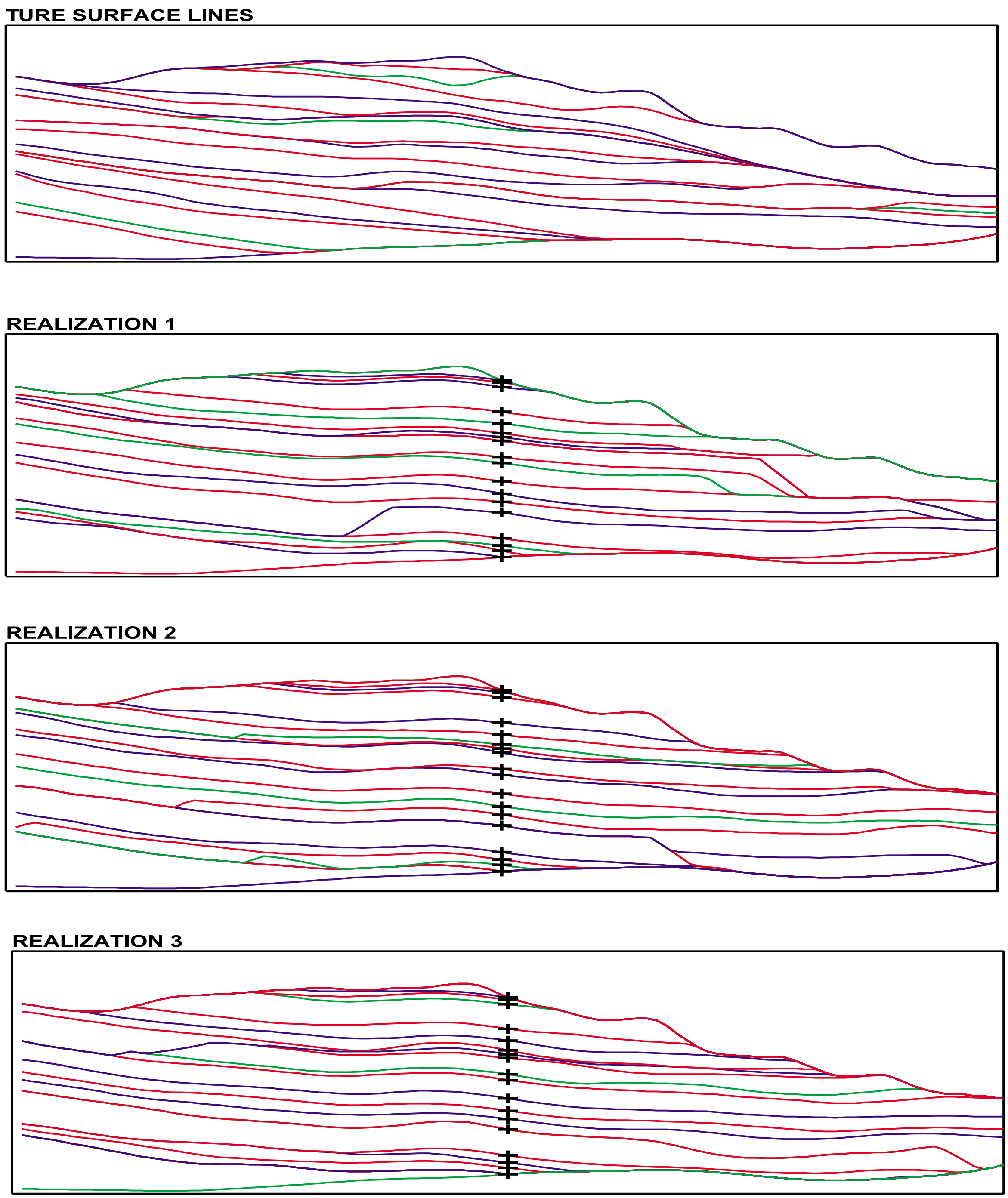

Figure 23: Wagon Caves simulation conditioned to one well

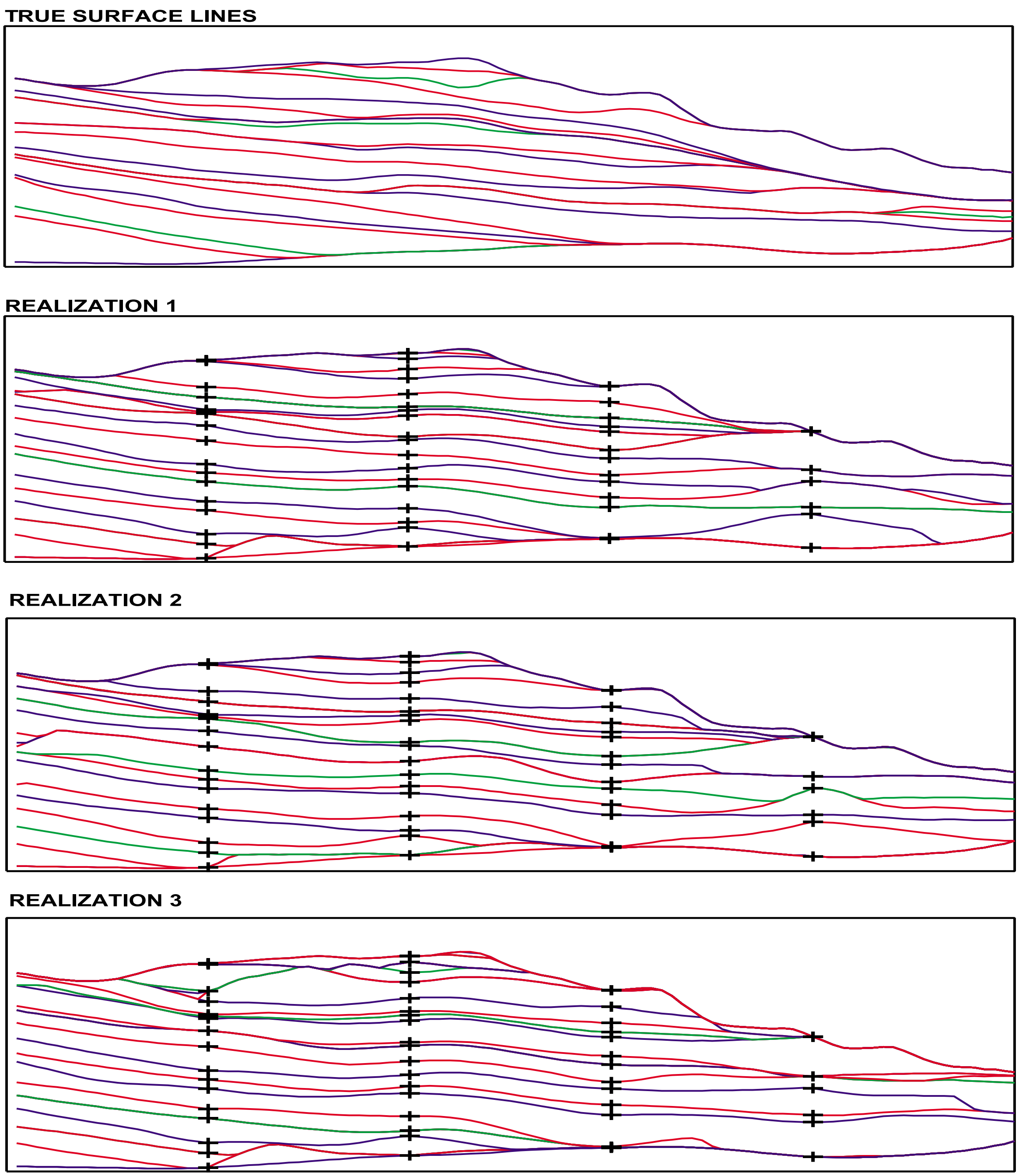

Figure 24: Wagon Caves surface simulation conditioned to four wells

Appendix A:

Parameters for `surfsim`, `Backtran`, and `Line_plt` programs

- **nsim:** number of realizations to consider
- **condfl:** input file with local well data for conditioning
- **thickfl:** output file of thickness of the surfaces in each grid
- **paramf:** output file of parameters for generating the surfaces
- **nx, xmn, xsiz:** definition of the grid system (x axis)
- **ny, ymn, ysiz:** definition of the grid system (y axis)
- **nz, zmn, zsiz:** definition of the grid system (z axis)
- **maxsurf:** maximum number of surfaces to be accepted
- **thickness:** total thickness to be filled
- **seed:** random number seed (a large odd integer)
- **type:** the surface template type (1 = simple parametric surface, 2 = ellipsoid, 3 = Gaussian type)
- **h_min, h_mode, h_max:** lower limit, mode, upper limit for triangular distribution of surface height
- **x_min, x_mode, x_max:** lower limit, mode, upper limit for triangular distribution of length (elongation direction) of the surface
- **y_min, y_mode, y_max:** lower limit, mode, upper limit for triangular distribution of the width (inner width for simple parametric surface) of the surface
- **yy_min, yy_mode, yy_max:** lower limit, mode, upper limit for triangular distribution of outer width of the simple parametric surface
- **α_min, α_mode, α_max:** lower limit, mode, upper limit for triangular distribution of the angle of the elongation direction from X axis
- **σ_min, σ_mode, σ_max:** : lower limit, mode, upper limit for triangular distribution of the residual standard deviation(for scaling of undulation surface)
- **nst and c0:** the number of semivariogram structures and the isotropic nugget constant
- **it, cc, ang1, ang2, ang3:** for each of the nst nested structures one must define **it**, the type of structure; **cc**, the c parameter; **ang1, ang2, ang3**, the angles defining the geometric anistropy;

- a_{hmax}, a_{hmin}, a_{hvert}: range parameters of the three principal directions;

If there was a coordinate system transform along stratigraphic layer before simulation, the simulation results are back-transformed with program `backtran`. The program needs the restored base/top on which the transformation was based and the existing base/top for truncating the values beyond the range defined by the existing base/top. The parameter file is shown on Figure and documented below:

- **infl:** input file containing surface lines in a specific slice of a realization (output from `extract`)
- **base_top:** input file containing the existing base/top
- **outfl:** output file of the surface lines after coordinate system transformation
- **no:** number of the data points of the surface lines

The simulated result is viewed as slice in cross section of the 3-D reservoir. The surface line extracted from a specific slice of a realization (before or after coordinate system transform) is viewed through plots generated by program `Line_plt`. Any local well data appeared in the section will be plotted as a black cross. The parameter file is shown on Figure and documented below:

- **infl:** input file containing surface model
- **ncol,icol** number of column and index of the attribute column
- **condfl:** input file with local well data for conditioning
- **outfl:** output PS file
- For 3D surfaces, **dim** = 1, or = 0 if surface is 2D
- **xmin, xmax:** the minimum and maximum data in X dimension
- **ymin, ymax:** the minimum and maximum data in Y direction
- **zmin, zmax:** the minimum and maximum data in Z direction
- **iview:** slice orientation $1 = XZ, 2 = YZ$
- **islice:** slice number
- **startS,noS:** index of starting surface and no. of surfaces

Example parameters for surfsim
****

```
START OF PARAMETERS:
3                              -number of simulation
Cnd00well.txt                  -input file of conditioning data
surf00thk.dat                  -output file of the thickness
surf00par.dat                  -output of the parameters
100   0.5    1.0               -nx,xmn,xsiz
 20   0.5    1.0               -ny,ymn,ysiz
 1    0.5    1.                -nz,zmn,zsiz
100                            -Maximum number of surface
1                              -total thickness to be filled
69069                          -seed of random number
1                              -surface type (1-helmet 2-ellipse 3-Gauss)
0.002,0.10,.15                 -min,mode,max height of surface
40.0,50,80.0                   -min,mode,max length: (helmet);
                                              long-axis: (ellipsoid), SigmaX (Gauss)
10.0,15,20.0                   -min,mode,max width: (Helmet);
                                              short axis: (ellipsoid), SigmaY (Gauss)
10.0,12,15.                    -min,mode,max width 2: (helmet) (not for ellipsoid & Gauss)
0.0,90,180.                    -min,mode,max angle
1                              -flag for truncation. 1: allow truncation; 0: no truncation
0                              -distribution of residual.  0: Gaussian;
                                                            1: Conditional data
0.0150,0.020,0.025             -min,mode,max sigma of residual
1    0.0001                    -nst, nugget effect
3    0.9999  0.0   0.0   0.0   -it,cc,ang1,ang2,ang3
            60.0  40.0   1.0   -range parameters in three principal directions
```

Example parameters for backtran
****

```
START OF PARAMETERS:
surf02bk2.dat           -input file of surface lines
base_top.txt            -input file of existing base and top
surf02bb2.dat           -output file of surface lines after back transformation
100                     -number of points in each line
```

Example parameters for Line_plt
****

```
START OF PARAMETERS
../surfsim/surf0scl.dat                         \line data file
1,1                                             \no of col & var col
--------.scl                                    \condition data file
surf0Line.ps                                    \output file name
0                                               \0:2D, 1:3D
0.0 1500.0                                      \min and max X data dimension
0.0   20.0                                      \min and max Y data dimension
0.0  250.0                                      \min,and max Z data dimension
1                                               \slice orientation 1-XZ, 2-YZ
10                                              \slice number
1,8                                             \no. of starting line, no. of lines
```