Sediment Trend Modeling Within Stratigraphic Surfaces for Subsurface Characterization

Y. L. Xie, and C. V. Deutsch, University of Alberta
(ylxie@civil.ualberta.ca, cdeutsch@civil.ualberta.ca)

A. Stan Cullick, Mobil Oil Corporation
(A_stan_cullick@mobil.com)

Abstract

Accurate prediction of reservoir prospectivity and performance depends on an accurate estimate of the subsurface structure, lithofacies, associated petrophysical properties, and fluid distribution. Often the reservoir heterogeneities that are controlled by stratigraphic architecture and sedimentological trends are difficult to predict, particularly at subseismic resolution and far from well control. An ongoing challenge in subsurface modeling has been how to utilize analogs of complex geology along with seismic and sparse well data to predict the natural geologic complexity in models of the subsurface, whether generated by deterministic or stochastic techniques. This work presents a hybrid deterministic and stochastic technique to preserve sediment trends in subsurface modeling, honoring analog and well data.

A stochastic surface modeling technique was introduced to model the subseismic surfaces that bound bed-scale sediment units in a companion paper. The surfaces honor both sedimentary analog information and well data, providing a framework for facies and petrophysical properties distribution. The method reported here preserves sediment trends within and across sediment units defined by depositional surfaces. In the method, a trend and its residual are modeled separately and then combined into a final model that preserves the trend. Through a calibration to well data and analog or conceptual geological depositional styles, such as fining or coarsening upward of grain size, progradational stacking pattern, etc, trends are estimated and expressed with parameterized mathematical functions. The trends and their residuals are then generated stochastically for each individual sediment unit. Both systematic and stochastic variations between different sediment units are controlled by user-defined distributions of trend function parameters. The final subsurface model is an assembly of sediment units.

Two examples demonstrate the method. One example consists of a grain size distribution analog generated from a process-response model. The other example uses the interpreted surfaces on an outcrop deposit as analog boundaries for nested vertical and horizontal grain size trends.

Introduction

The reservoir heterogeneities that are controlled by stratigraphic architecture and sedimentological trends are difficult to predict, particularly at subseismic resolution and far from well control. "Subseismic" refers to bedset and lithologic intervals whose thickness is below vertical resolution from seismic. An ongoing challenge in subsurface modeling has been how to utilize geologic knowledge and analogs of complex geology along with seismic and sparse well data to predict the natural geologic complexity in models of the subsurface, whether generated by deterministic or stochastic techniques. This work presents a hybrid deterministic and stochastic method to preserve sediment trends in subsurface modeling, honoring stratigraphic architecture and analog and well data.

Sedimentary formations deposited on continental margins have characteristic stratigraphic surfaces that reflect the changes in depositional events, such as the relative rates of sediment supply, sea level changes and creation of accommodation space. The lithofacies properties of sediments are closely related to the bounding surfaces. In a companion report [10], a stochastic surface modeling approach was reported to generate subseismic stratigraphic surfaces. Surface models generated therein honor both well data and geological stratigraphic information.

Often, multiple sedimentary units or bedsets within stratigraphic layers have defined stacking patterns, nested cyclicity, or trends, such as coarsening upward, fining upward, or some other complex nonstationary trend. Large-scale trends and systematic variations across multiple sediment packages are revealed by the architecture of the sediment units, exhibiting common stacking patterns like *progradational, aggradational, or retrogradational*,

In presence of trends, random function models used in conventional geostatistics are split into a non-stationary trend component and a stationary residual component [3, 4, 6]. Non- stationary algorithms such as *ordinary kriging*, *kriging with a trend* or *kriging with an external drift* are used for estimation. Trend component is specified as a single unknown constant or an analytical function with coefficients to be determined by the kriging system. At well locations, relatively simple trends may be inferred correctly and interpolated between wells. However, complex trends away from well locations are much more difficult.

This report presents early results on an approach accounting for trends of facies and petrophysical properties. The trend is made explicit based on a deterministic understanding of the genesis of the subsurface phenomenon. This rule-based approach enables preservation of more complex geology than the above method. The trend can be as complex as represented by the prior knowledge of the deposition. We express the trend explicitly, subtract the trend attributes to obtain residuals, model residual using a stationary random function model, and add the trend with the residual to get a final simulation.

A FORTRAN 90 program `trend` implements the approach. Two examples are presented. One example consists of grain size distribution from a forward process-response simulation on a continental shelf, and another example is a qualitative interpretation of an outcrop of deepwater origin.

Motivation

Complex sediment trends are often present in geology. These trends can be controlling factors on fluid distribution and fluid flow, but they are difficult to predict at subseismic resolution in areas of sparse well samples. Knowledge of the sediment origin can often lead geologists to conceptualize what trends are present, and new technology of three-dimensional process sediment simulation has the promise of allowing geologists to generate multiple fine-scale conceptual models of paleo-sediment architecture and property distribution that incorporate their best knowledge of paleo-conditions and the correct physics. Heretofore, however, there has not been a means to model these nonstationary complex morphologies very well, while simultaneously honoring field-specific seismic and well data.

The example in Figure 1 illustrates the challenge. The example is a vertical cross-section from a process response simulation of the Wandoo field [7] and will be investigated in more detail later in this report. It represents a transgressive parasequence of small-scale sediment distribution deposited by seven high frequency sea level cycles imposed on a generally rising sea level. The process response model morphology at 23 km downdip compares well with Wandoo well 6 log motif [7]. If this simulation were actually the subsurface sand distribution, the sediment morphology would not be observed by seismic because of the vertical resolution. If the sands were reservoir, it would be somewhat difficult to map between wells in a field, say at 2 km well spacing. And it would not be possible to build a very good prediction of prospective sands several kms away from well control. The variance, or horizontal variogram, shows a typical nonstationary behavior for trends, that is, a sill value is not reached. Figure 2 compares a model built by the surface and trend methods described in this paper [and its companion [10]] and a model generated by a geostatistical sequential Gaussian simulation [3] using the variograms. Model B preserves the underlying trend morphology of the sediment deposit, while Model C does not. So, the motivation for this work is to generate more predictive subsurface models that preserve subseismic geologic architecture and morphology from conceptual and analog models, even far from well control. These more predictive models should assist an increase in drilling and production success.

Uses of Trend Modeling

The trend models are intended to preserve the conceptual or analog depositional style when building models with field seismic. There are a couple of possible approaches to build the models that are also explicitly constrained to the field seismic and well data. Some geostatistical cosimulation options include the use of the trend model in block cokriging with the seismic [2] or treating the seismic as a local mean that imposes onto the trend a mean value for the simulated property [3].

Another approach that offers the extension to integrate even other data types is optimization proposed by Gouveia et al [5]. In that approach, uncertainty and the scale of the individual data are preserved and other information can be combined, for example, a transition probability of facies overprint on the trends. The most straightforward combination is to use the trend residuals' variogram as an objective function component. As an example, assume that the seismic is providing a porosity, ϕ, at a large vertical resolution compared with the trend derived from a process response analog. Then the objective function is a sum of the components for seismic-derived quantile histogram and the variogram of the trend residuals. The seismic-based component is

$$O_1[\phi_r] = \frac{1}{N_{qs}} \sum_{i=1}^{N_{qs}} \| q_\phi(i)_s - frac1N_{qs} \|, \tag{1}$$

where $q\phi_{seis}$ is the quantile histogram for the "seismic"- derived PDFs. And the variogram component is

$$O_2[\phi_t] = \frac{1}{N_{qt}} \sum_{i=1}^{N_{qt}} \|\gamma(i)^{residualmodel} - \gamma^\star\|, \tag{2}$$

where γ is the variogram. Once the objective function is minimized, the residual is added back to the trend. Other data, e.g. the conditional probability of porosity per facies or V_{shale} with respect to facies or facies transitions can be integrated with trends in this framework.

Methodology

Figures 3 and 4 provide a schematic summary of the methodology. First, we assume that a stratigraphic surface model (A in Figure 3) is available and honors a deterministic conceptual model of the stratigraphy and the surface picks at a well location, if available [9]. We also assume a trend, e.g. the fraction sand (Vs) log motif pictured as Figure B. The trend is generally fining upward across all the units, but with some coarsening just above some of the surface intersections. The fining upward trend can be modelled as some parametric function, in this case that is simply a linear function, and then it is mapped into a "stratigraphic" grid interval, see Figure D. That trend is then imposed on each sediment unit one-by-one as a "trend template", simply by a coordinate transform (Figure 4). We see later that more complex trends can be imposed with hybrid stochastic and deterministic rules to form the templates.

The steps are summarized in the schematic flowchart on Figure 5.

- Determine the geologic architecture and morphology based on the depositional analog. The geologic conceptual model, outcrop analog, or process-based simulation will determine the trend morphology and rules that are used to build the trend.

- Establish parameteric function representations of the trends. The functions can be as complex as needed. They should not be too complex, however, since they they are meant to estimate the trend morphology not to replicate an analog exactly.

- If there is systematic trend across multiple sediment units, the simulation follows a specific order of sediment units; otherwise simulation may start from any sediment unit. Draw trend parameters from the user-defined distributions and generate trend parameter distributions.

- Map trends back into the corresponding sediment unit bounded by the surfaces by placing its location stochastically.

- Adjust the trend location for any well data and generate the residual. If one or more wells is present, the residual at the wells is generated as follows:

  1. Take the average of the property value within the sediment unit
  2. Adjust the location and size of the trend template to minimize the difference of the trend's average over the interval at the well location with the well average.
  3. Subtract each trend value corresponding to each well measurement.

If there are no well data, then the residual is a difference between the trend teimplate and the analog, mapped onto the stratigraphic grid.

- Generate a residual model using sequential Gaussian simulation. If well data are available, the simulation is conditional to the residual at the wells.
- Map the residual model back into the corresponding sediment unit grid and add the residual to the trend model, as in C of Figure 4. Each individual sediment unit is a summation of corresponding trend templates and residual models.
- Repeat the same procedure for all sediment units to generate the final trend simulation, as in D of Figure 4.

Trend generation

A critical component of the procedure is the quantification of trends based on well data and geological information. Trends are extracted from the analog information by a deterministic approach. In this work, the shape of trends is parameterized by mathematical functions. For example, the permeability in a fining upward sediment package can be expressed by a function decreasing linearly or exponentially. If the upward fining trend of individual sediment units contained within a general coarsening upward trend across multiple unitss, then the same decreasing function with different value ranges will apply for different sediment units. In other situations, trend may spread out from an original (center) position which may correspond to a river mouth or submarine channel unloading sediment. In such a case, an ellipsoid function might approximate the trend shape. For different sediment units, the position of trend origins change, and the spread of trends may have different orientation and magnitude for different sediment units. Parameters such as central location, angle, width, length are used to model such variations. These must be estimated from a deterministic understanding of the geology and its origin.

Since the sediment units have different irregular shapes in the original stratigraphic coordinate system, it is often better to approximate trends for different sediment units in an unified regular coordinate space. Therefore, trend and residual simulations will be carried out in a three-dimensional cube *template*.

The trend generation starts with making a contour volume (or map in 2-D) for the trend *template* and is followed by assigning trend values in the gridded map or volume based on contour values. The contour takes the shape of the trend and has relative values. Trend locations may be represented by functions such as an ellipsoid. The trend values in real units are then assigned to the gridded cells of the trend *template* based on their contour values. Sometimes, the trend may not be approximated very well by just using a single trend function, so the trend *template* will be a combination of multiple trend functions.

Residuals

Residuals are characterized based on well data and conceptual geological information. Variograms of residuals are evaluated and modeled for their spatial continuity. Since the residuals are spatially stationary data, they can be simulated by conventional geostatistical techniques. In the `trend` program, sequential Gaussian simulation `sgsim` from GSLIB is used to generate residual models.

Trend template

The next step is to map the trend *template* and residual model back into each individual sediment unit. This is merely a coordinate transformation from a regular stratigraphic grid to the irregular sediment unit. For a two-dimensional situation:

$$X = (X_{end} - X_{start}) \frac{X' - X'_{min}}{X'_{max} - X'_{min}} + X_{start}$$

$$Y = (Y_{top} - Y_{bottom}) \frac{Y' - Y'_{min}}{Y'_{max} - Y'_{min}} + Y_{bottom}$$

where X, Y are coordinates of a sediment unit grid cell in the original stratigraphic space, X_{start}, X_{end} are the starting and ending position of the sediment unit along X direction and Y_{top}, Y_{bottom} are the starting and ending position of the sediment unit along Y direction which are defined by the bounding surfaces. X' and Y' are coordinates of a cell in the trend template and X_{min}, X_{max}, Y_{min}, Y_{max} define the dimensions of the trend template.

Well conditioning

Well data are honored in two steps. First, the position of each trend in the sediment unit is adjusted to match the well. Even though the trend template is generated based on parameters calibrated to knowledge about the subsurface system, it may differ with actual data observed at wells. Therefore, after the trend is mapped back into the sediment unit, the average of the trend model along the well interval is calculated and compared with the corresponding log section from the well. If the deviation is larger than a threshold value, the trend position is translated until a small mismatch between trend average and well data average is found.

Trend simulation

The deviations of trend model from well data at well interval are calculated and taken as conditioning data for the residual generation with sequential Gaussian simulation. The trend template and the residual model are then combined to get the final model for the corresponding sediment unit. When this procedure has been completed for all sediment units in the reservoir, a final subsurface model is obtained.

Examples

Two examples will demonstrate the process of building in sediment trends constrained to surface boundaries. The first example is the Wagon Caves rock outcrop where the surface boundaries were generated by `surfsim`. Horizontal and vertical sediment trends are assumed and then used in model construction. The second example is the Wandoo field simulation. Here, a process response model is used as an analog source for the trend template. The model simulation shows that the use of the analog and well data together generate sediment units far from the well that are much better than a conventional modeling approach.

Wagon Caves rock outcrop

The upper plot of Figure 6 is an image of the Wagon Caves outcrop. The lower part of the figure is the surface interpretation by Anderson [1]. The dimension of the outcrop shown is approximately 350 meters long and 70 meters high. There is a fining upward trend for this deep water sediment. `surfsim`, described in detail in [9], was used to generate a series of 3-D surface realizations honoring the intersections of a well sampling location taken as conditioning data.

There is a generally linear vertical fining upward trend and a linear horizontal fining trend rightward across the sediment units. Within each sediment unit, an exponentially decreasing fining trend was assumed. The steps in generating the simulation of the sand distribution in Figure 7 follow those of the previous section.

The range of trend values of the entire model is given as 100 to 0.001 for the fining upward trend. The fining upward trend value for each individual unit is different. These values depend on the position of the unit within the context of the entire model, i.e. on both the vertical and horizontal positions. If the global trend value range is $Overall_{min}$ to $Overall_{max}$, and the range for an individual bed unit is $Local_{min}$ and $Local_{max}$, then.

$$Local_{min} = \frac{(Overall_{max} - Overall_{min})}{(Y_{max} - Y_{min}) \times (Bottom - Y_{min}) + Overall_{min}}$$

$$Local_{max} = \frac{(Overall_{max} - Overall_{min})}{(Y_{max} - Y_{min}) \times (Top - Y_{min}) + Overall_{min}}$$

where Top and $Bottom$ refer to the maximum and minimum values of the bounding surfaces for the unit, and Y_{max} is the maximum height value for the entire model.

The horizontal trend is linear and the vertical has a large-scale linear trend with a short-scale exponential trend within each unit. Weights are calculated for each horizontal position as follows:

$$Weight = \frac{(X - 1)}{(X_{max} - 1)}$$

where x is the horizontal position of the unit,

$$1 \ \leq \ X_{start} \ \leq \ X \ \leq \ X_{ending} \ \leq \ X_{max}$$

and x_{max} is the x-dimension of the entire model. Therefore, the final trend value range for the unit is $[Local_{Min} \times WeighttoLocal_{Max} \times Weight]$, and they will be different along the horizontal direction. The vertical trend within each unit is $e^{-4.6x}$.

The trend model is depicted on the top of Figure 7, and the simulation is the lower figure of Figure 7. The trend is preserved in the simulation model. The modeling of anisotropic, multifunctional trends could not be accomplished with conventional modeling. Figure 8 shows sample well logs at locations A,B,C. The trend model has the distinct fining upward within units with the fining right-ward, larger-scale trend. The simulation model clearly shows a more realistic variability imposed by the Gaussian simulation in the log motifs.

Wandoo

This example generates a 2-D fraction sand, V_s, trend simulation based on a study of the Wandoo field of northwest Australia. Wandoo was deposited on a shallow marine shelf and was the subject of a earlier report on using a process response model to evaluate different paleo- depositional processes that might have led to its particular morphology [7]. The process response model `sedflux` is described in detail elsewhere [8]. O'Grady and Sarg [7] describe the generation of a `sedflux` grain size distribution model from simulated discharge of sediment from a river mouth onto a continental shelf during a period of generally rising sea level, with seven higher frequency cycles of sea level fall and rise. The resulting simulation has characteristics observed in Wandoo well log motifs. We converted the grain size to an estimated fraction sand and will use it as an analog for the Wandoo field area. Figure 9 shows the `sedflux` simulation on a rotated base surface and the seven stratigraphic units associated with seven sea level cycles. Note the aspect ratio of approximately 25 km horizontal vs about 20 meters vertical.

The challenge then is to generate a subsurface model of the Wandoo field area that preserves the essence of the deterministic morphology of this subseismic bedset parasequence and that honors field well data.

Trend template

The first step, as described in previous sections, is to understand the "rules" of the deposit in the analog. The transgressive, backstepping morphology of the bedset units are a consequence of the relative sea level changes. The sediment trends are somewhat systematic between sediment units: from each surface in each unit there is a base of coarse grain deposit in the updip end followed by a fining of a few meters, followed by a ellipse-like coarse deposit that extends downdip some kilometers before losing all the coarse material, and finally fining upward to shale at the next surface. Figure 10 separates the seven units within a single arbitrary grid. The center of the coarse deposits shifts slightly updip from lowest to highest bed in the parasequence and the spread of the coarse sands become larger along the progradational direction. The overall variograms have been shown in Figure 1 to not reach a sill value. Figure 11 shows the skewed distributions of *Vsand* the upper-six sediment units.

The trends observed in the sediment units shown in Figure 13 were "contoured" by using ellipsoid functions to estimate the fraction sand. Each ellipsoid function is characterized by its width, length, anisotropy and azimuth angle. Figure 12 shows examples of the shapes for three such ellipsoid functions with varying azimuth angles, anisotropy, orientation, and asymmetry.

Trend *templates* are built for each of the six sediment units and shown in Figure 13. The residual differences of the trend templates and the original Wandoo Sedflux simulation have a more random distribution than the trend (Figure 14), and the histograms are nearly Gaussian (Figure 15). Comparing Figure 13 and Figure 14 it can been seen that most of the variation comes from the trends. The total variance of *Vsand* in the sediment units is the summation of variance of trend and residual when the trend is assumed to be independent of the residual. Table 1 shows that most of the variation comes from the trend, whereas the variance of the residual represents the remaining variation not captured by the trend

Package	percentage of remaining variance
2	15.33
3	20.58
4	23.74
5	18.63
6	21.93
7	22.52

Table 1: Percentage of variance of remaining residual

model.

The bottom plot of Figure 16 shows the trend model in the original `sedflux` surface model. The main features of the original `sedflux` model are captured compared with Figure 1.

The flexibility of trend *templates* for capturing both the essence of the trend functions and the random or systematic variations comes from the distributions of trend parameters. The ellipsoid trend functions are modeled through drawing from a triangular distribution for each of the following parameters: center location, short axis, long axis, and orientation. There is a systematic spatial location of each bedset trend that can be deterministically estimated from the `sedflux` simulation: both the center of the trend shifts further from the left bottom corner and the spread of the trend becomes larger as the sediment units stack upwards.

Unconditional trend simulations

The first example simulates a trend model within a hybrid deterministic and stochastic unconditional surface model generated by `surfsim` using the skewed Gaussian surface shape [10]. Figure 17 shows three surface model realizations. Recall that `surfsim` generates each surface stochastically but accepts or rejects the surface based on volume-filling rules. In this case there are additional rules that govern the expected transgressive backstepping nature [10]. The trend ellipsoidal triangular distribution respresentations described in the previous section are used to generate the trend templates, constrained by the surfaces, as shown in Figure 18 for the units 2 thru 7. The essential features of the `sedflux` analog are preserved.

Conditional trend simulations

Constraining the simulations to well data should provide much better estimates for the subsurface model. O'Grady [7] interpreted the log motif bedset intersections corresponding with units 1 to 3. The bounding surfaces of the three packages intersect with Wandoo 6 at 606, 611, 615 and 618 meters and Wandoo 3 at 615.8, 621.3, 625 and 630.2 meters, respectively. The gamma logs are scaled into *Vsand* log on an arbitrary scale between 0.2 to 0.7 as shown in Figure 19.

The intersection depth of the surfaces with wells after scaling to relative units between 0 and 1 are used as conditional data for `surfsim`. The surface modeling has incorporated the

variogram model
$\gamma(h)^{Package2} = 0.0 + 0.70\, Sph_{100,42}(h) + 0.30\, Sph_{700,42}(h)$
$\gamma(h)^{Package3} = 0.0 + 0.60\, Sph_{70,38}(h) + 0.40\, Sph_{600,38}(h)$
$\gamma(h)^{Package4} = 0.0 + 0.60\, Sph_{90,30}(h) + 0.40\, Sph_{700,65}(h)$
$\gamma(h)^{Package5} = 0.0 + 0.45\, Sph_{50,20}(h) + 0.55\, Sph_{300,50}(h)$
$\gamma(h)^{Package6} = 0.0 + 0.45\, Sph_{50,20}(h) + 0.55\, Sph_{350,50}(h)$
$\gamma(h)^{Package7} = 0.0 + 0.45\, Sph_{30,20}(h) + 0.55\, Sph_{500,43}(h)$

Table 2: Variogram model of residuals for each sediment package

constraints such as no change and no truncation in the shape of the generated surfaces, and keep successively generated surfaces shifting along the backstepping transgressive direction. For multiple wells, the well intersections are not matched exactly because of the multiple constraints. A *simulated annealing* optimization is used to move the generated surfaces in order to get optimal match between surfaces and well intersections. Figure 20 shows three surface realizations of conditional surface models matching Wandoo 6 and Wandoo 3.

The parameters of trend functions are the same as described above. The center locations of the trends are adjusted by comparing the resulting trend average in the well interval with the average calculated from *Vsand* well log. Figure 21 shows trend models corresponding to the surface models shown in Figure 20. The replacement of the trend matches the trend average with the *Vsand* log average of the well data. The deviations between trend model and well data are then handled by the subsequent residual simulation. The residual at the well is first computed and then for the purpose of simulation of the residual, the spatial continuity of the residual is simulated. The experimental variograms of the residuals of each of six sediment packages were calculated and modeled. The variogram models are tabulated in Table 2.

Based on the residual variogram models for the last three sediment units, the variogram used for residual generation is

$$\gamma(h) = 0.0 + 0.45\, Sph_{50,20}(h) + 0.30\, Sph_{300,50}(h)$$

Sequential Gaussian simulation is used to generate a residual model based on the conditional data and variogram model. Trend simulation realizations after adding the trend and residual models are shown in Figure 22. The well data are honored by this approach.

In the next example, well 6 is placed at a more downdip location relative to the sediment source [7] and a conditional surface simulation generates six surfaces (top Figure 23. A trend simulation generates the lower figure of Figure 23. The sand fraction spatial distribution within the backstepping bedset units is preserved in the model.

Discussion

A methodology has been presented to enable the preservation of complex subseismic stratal unit geometry and sediment trends from analog or outcrop data in subsurface models. The trend residuals can be coded so that they can be utilized directly in an optimization or cosimulation scheme with seismic data. A surface modeling approach provides the framework to do trend simulation. The methodology proposed in this study is a natural extension of surface based modeling.

The critical step of the proposed methodology is the quantification and expression of trends found in analogs for the reservoir sediments. Both repeatable trends within individual sediment units and systematic trend variations across multiple sediment units need to be expressed by parametric functions to form a trend *template*. Such a trend expression must be calibrated with available geologic analog information. The approach incorporates a hybrid of deterministic and stochastic variations. The geological information about the sedimentary formation of reservoir is brought into numerical model in two different stages. First, conceptual geological information has been used in the surface modeling (`surfsim`). The resulting surfaces capture the understanding of the geological architecture. Secondly, in the trend modeling stage, the facies distribution and stacking pattern (like the backstepping pattern in the `sedflux` example) have been taken as constraints in the trend placement. With the inclusion of conceptual geological information and explicitly modeling trend and residual separately, the subsurface model be a better estimate of the subsurface than interpolation methods can provide.

The next phase of this research will further extend the trend to full 3-D and demonstrate the methodology with seismic and other geologic data. An effort is underway to develop data mining technology to assist extraction of causal "rules" and parametric functions from the analog or process simulation analogs that would be utilized in subsurface model building framework.

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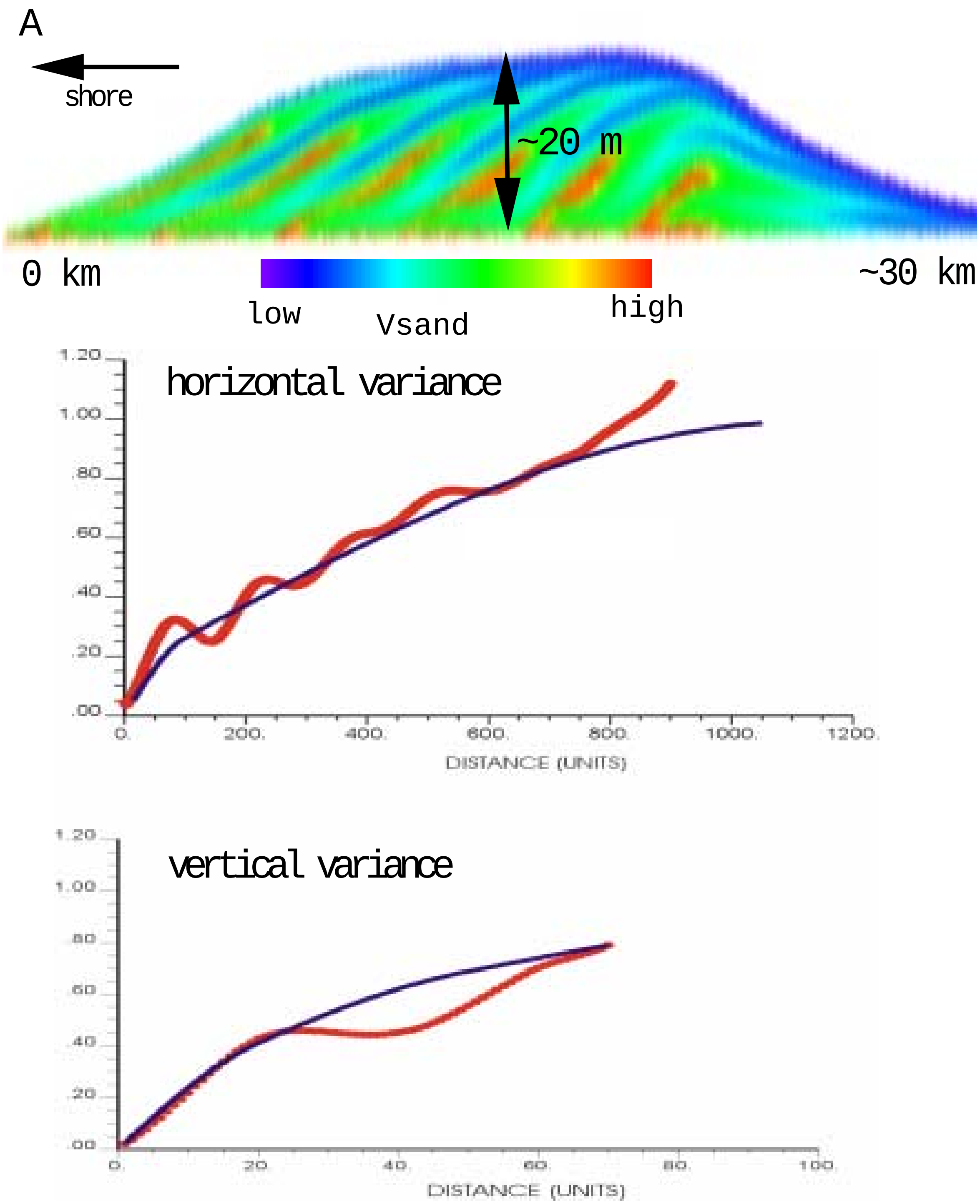

Figure 1: Sedflux "analog" for the Wandoo field and variograms of the fraction sand (red-data; black-model).

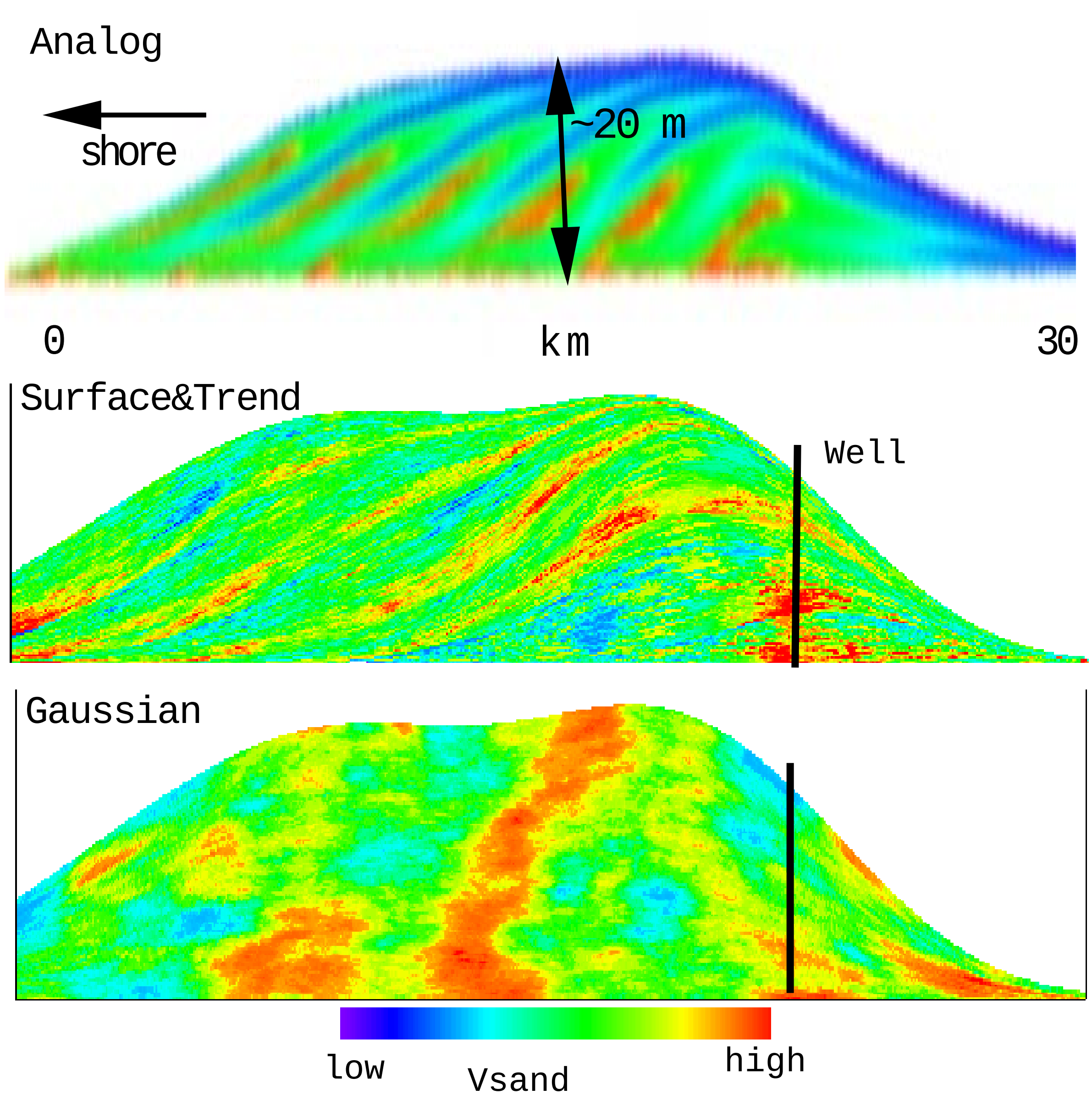

Figure 2: A. Sedflux "analog". B. Sand fraction simulation constrained to the surface-geometry and trends using method presented in this report. C: A "conventional" gaussian simulation using the variogram model from Figure 1.

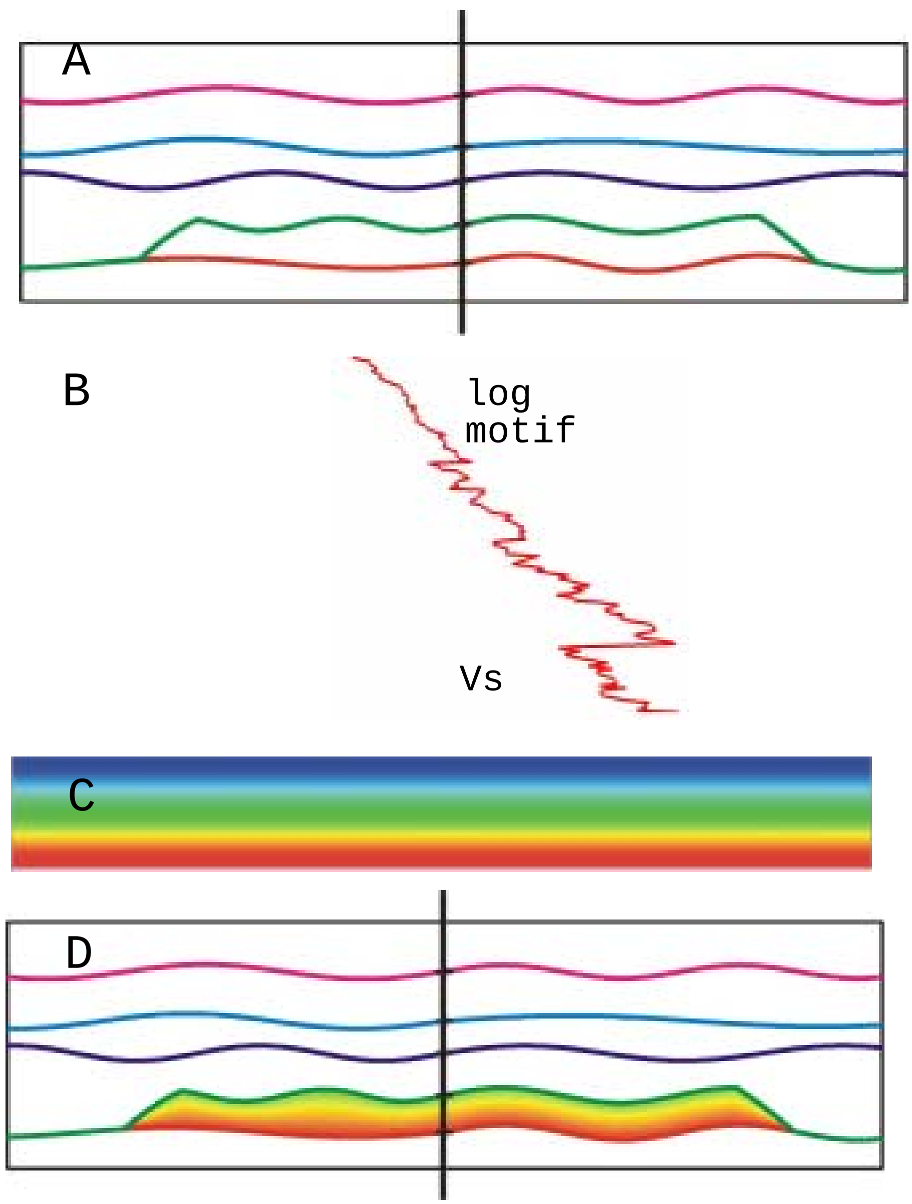

Figure 3: A. A “surface” model, established per [9] B. Log motif at a well sample location, showing a generally fining upward trend, with some internal coarsening within sediment units. C. “Trend template” of a linear trend. D. Trend template within one sediment unit.

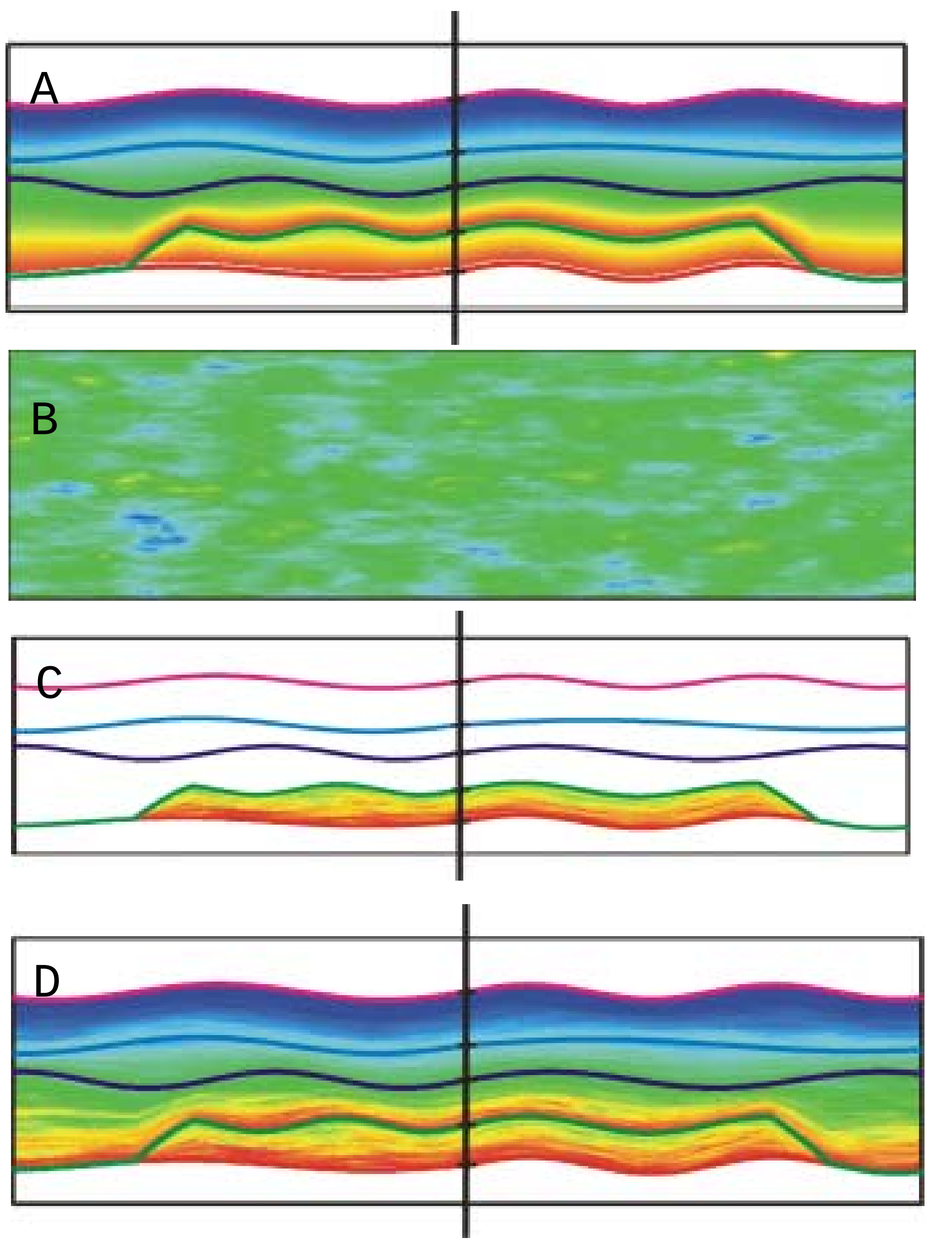

Figure 4: A. Trend templates within all sediment units. B. Residual difference of trend with analog data within one unit. C. Simulated residual plus trend grain size within one sediment unit. D. Simulated grain size for all units.

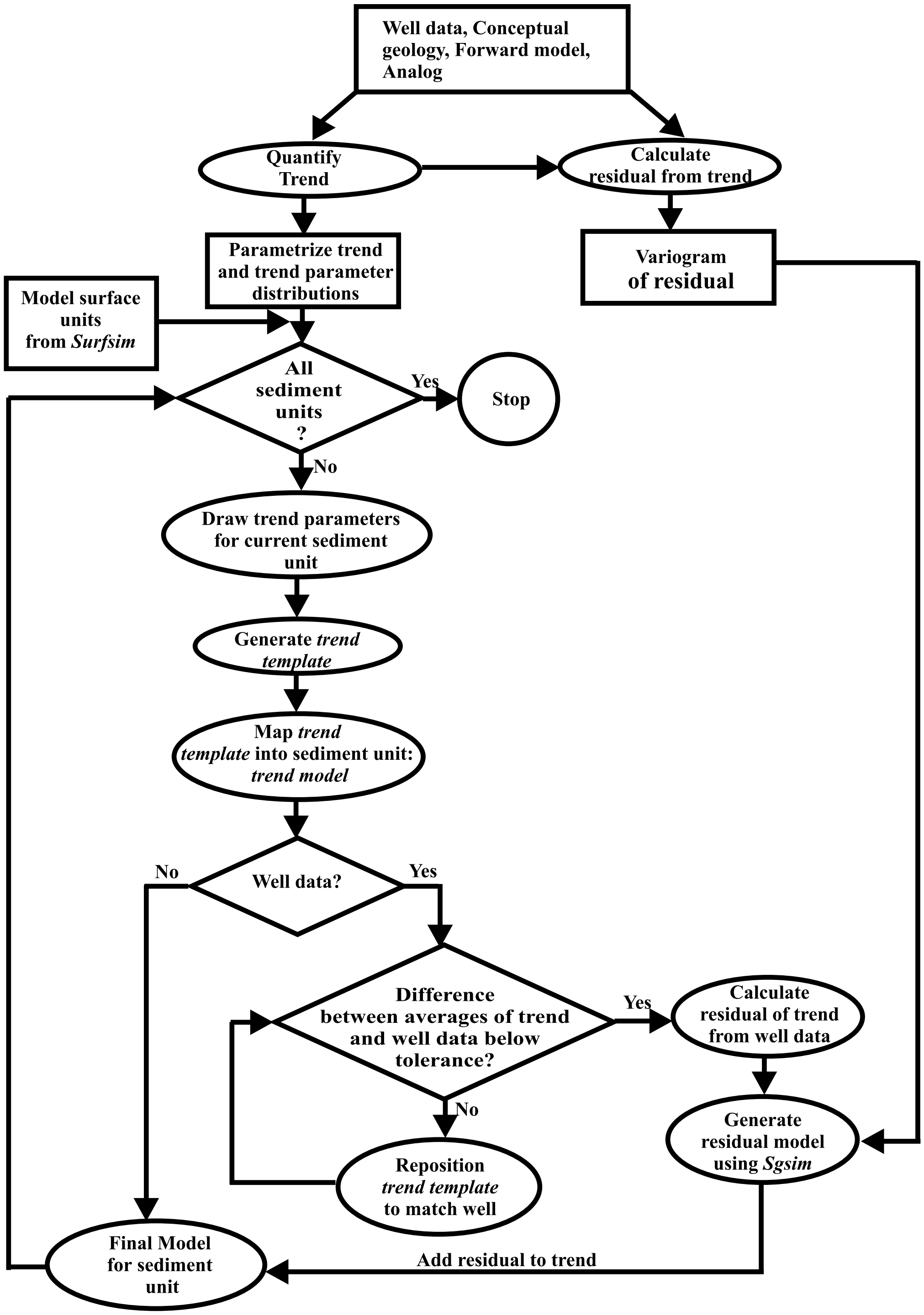

Figure 5: Flow chart of the methodlogy presented in this report and incorporated in program Trend.

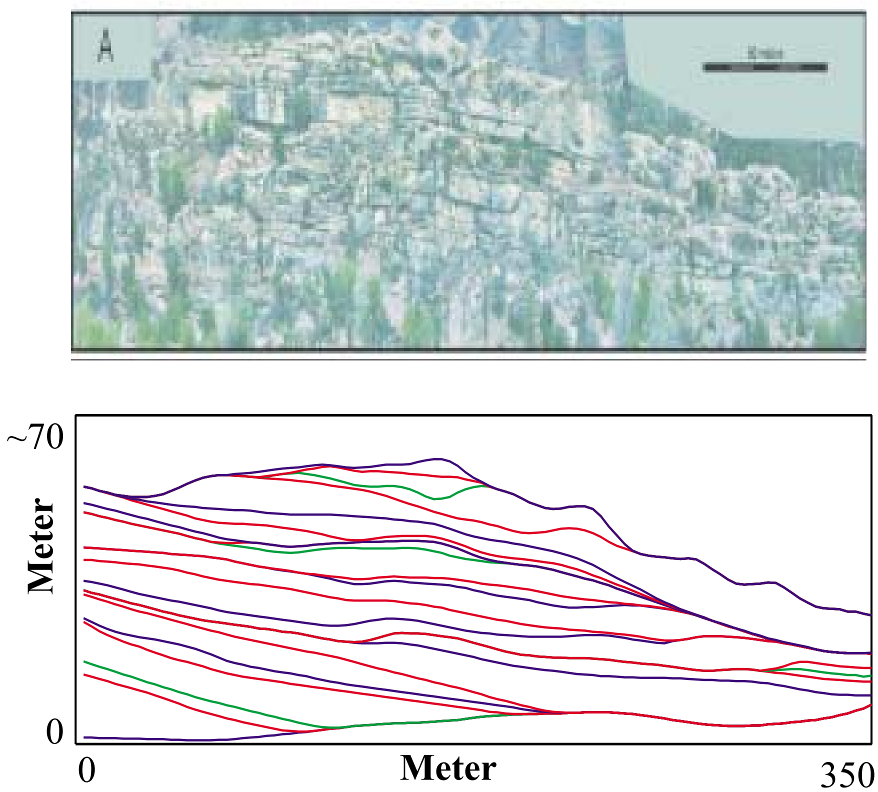

Figure 6: top: Wagon Caves rock outcrop. bottom: interpreted surface stratigraphy

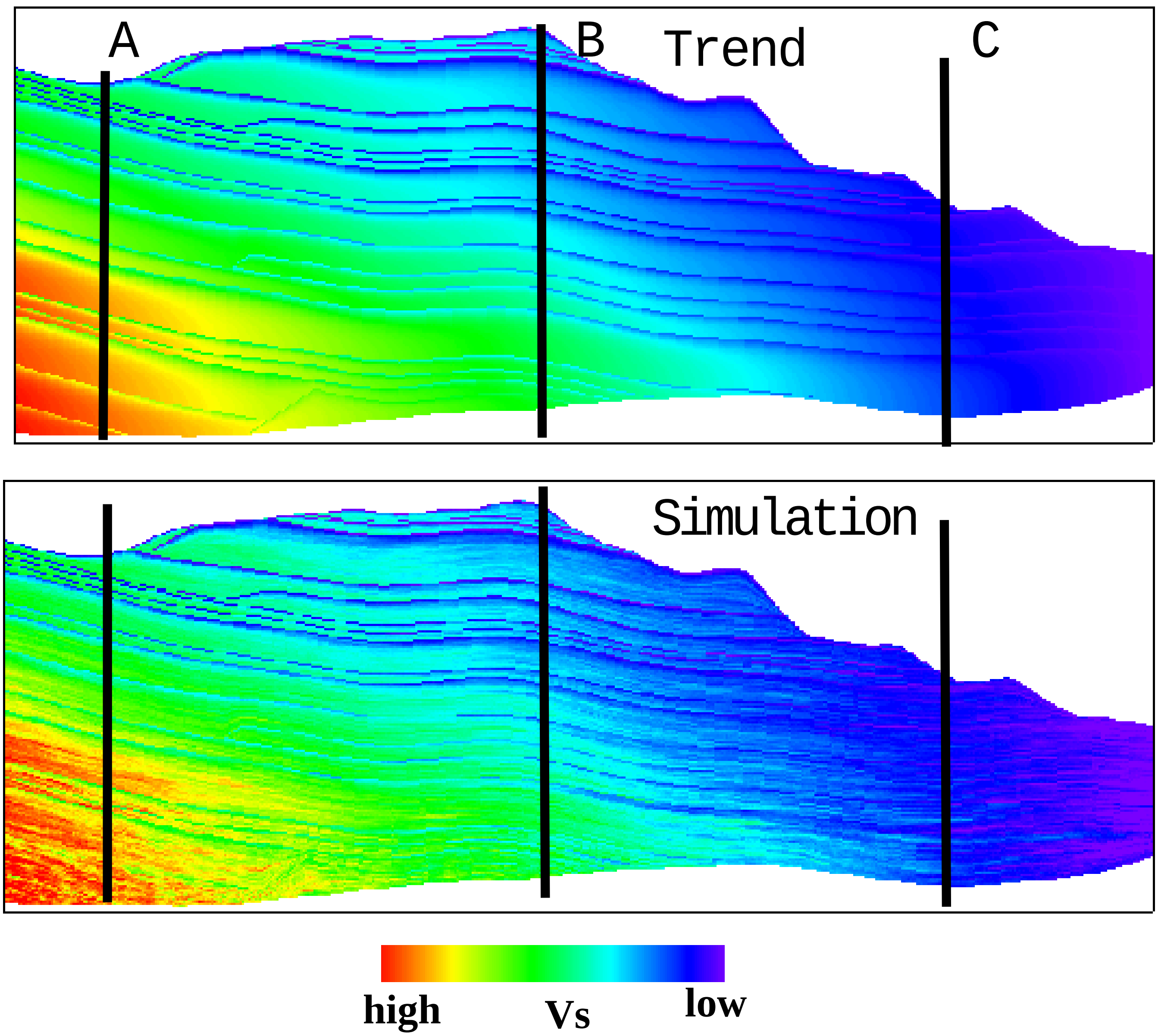

Figure 7: Trend template with nested vertical and horizontal sand distribution compared with trend simulation sand distribution.

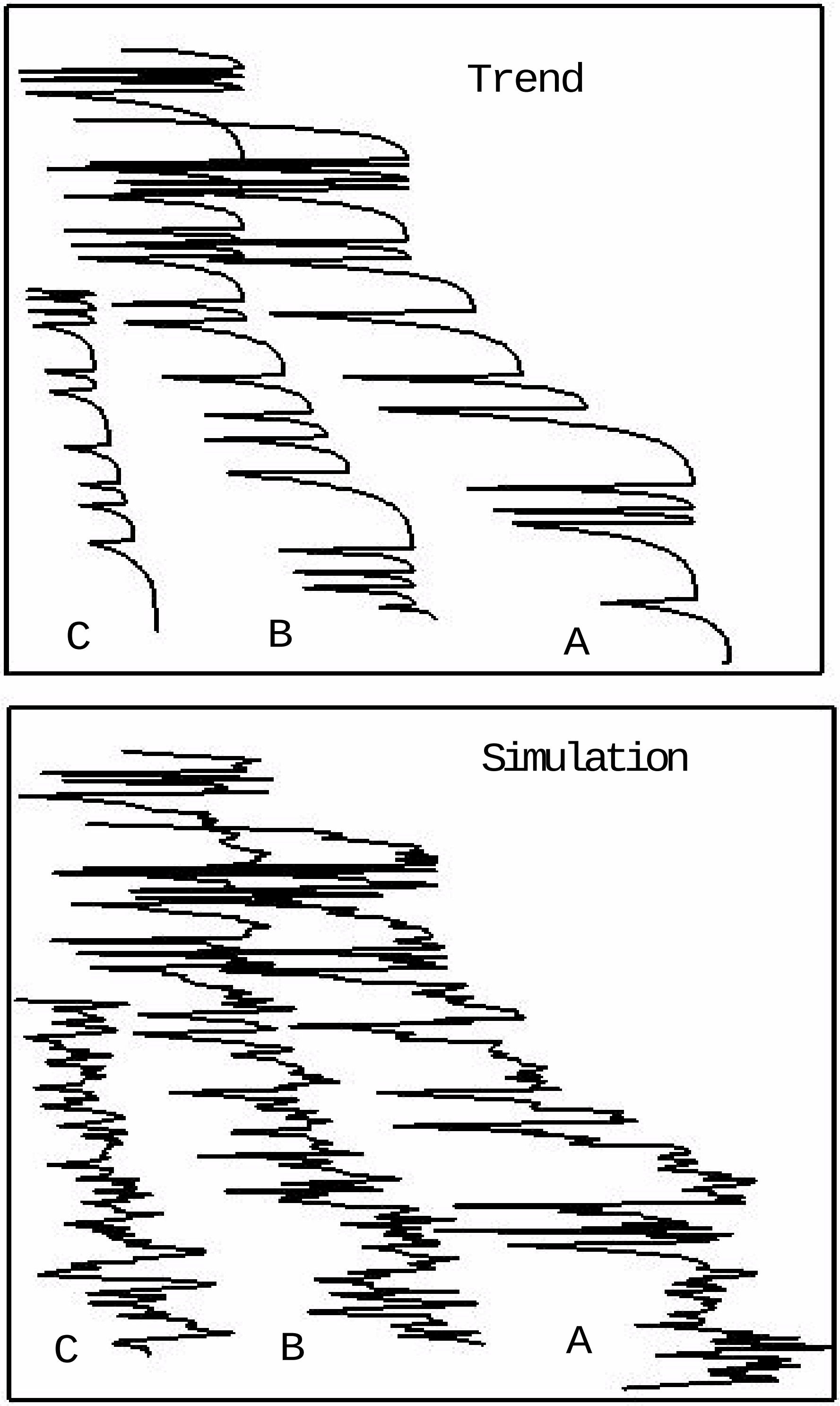

Figure 8: Sample log motifs comparing the sand distributions of trend template with trend simulation from three vertical sample locations (see Figure 7)

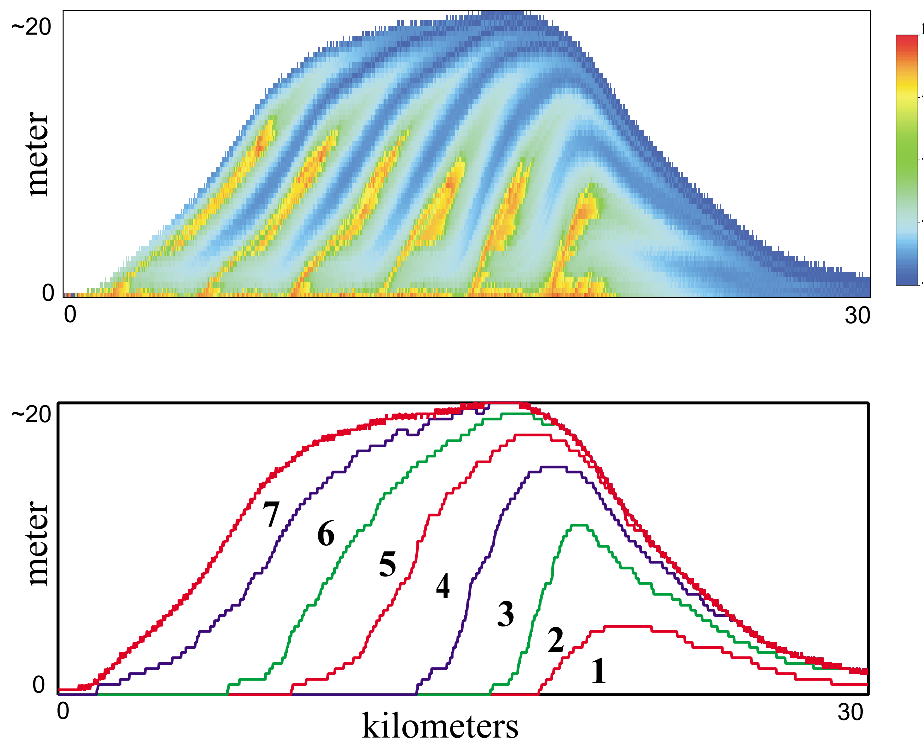

Figure 9: Top: Sand distribution derived from Sedflux "analog" for the Wandoo field and surfaces extracted along the sediment unit boundaries.

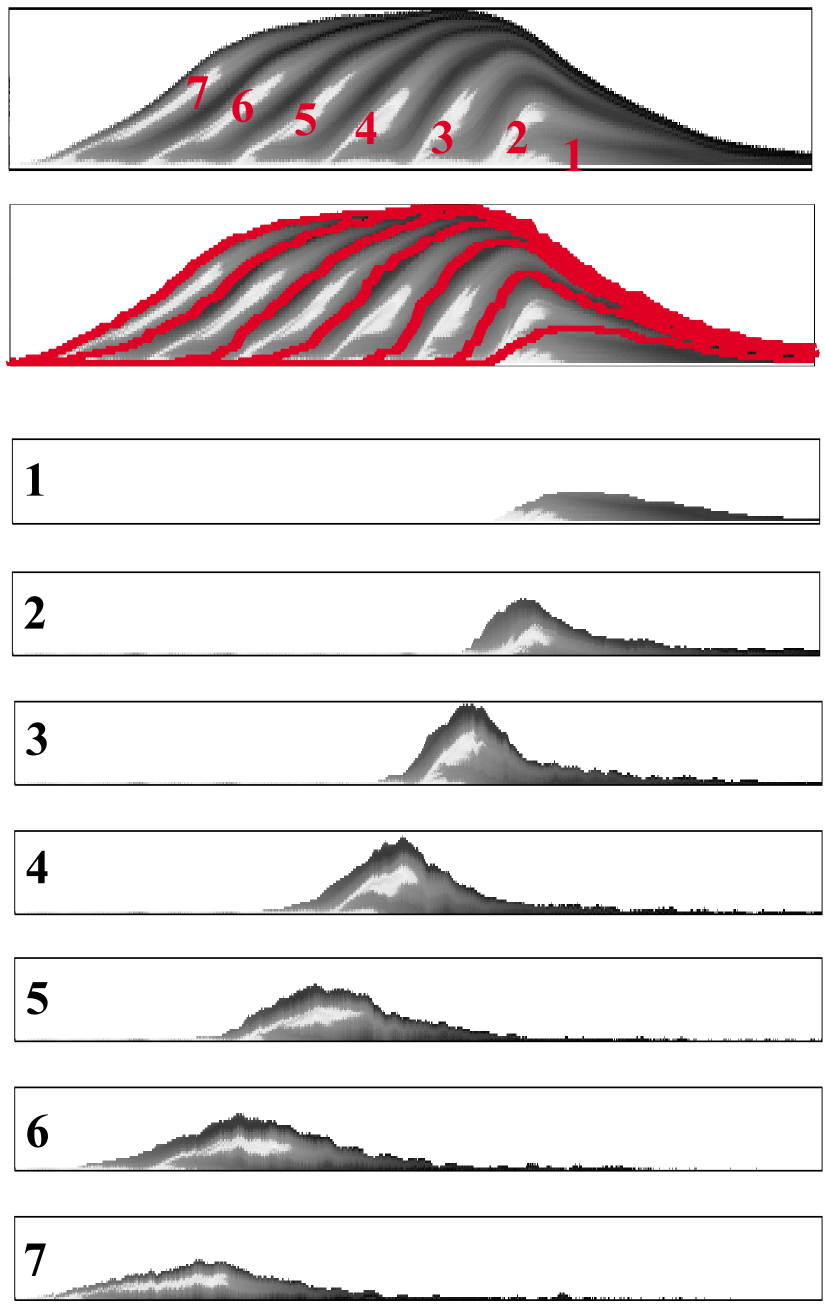

Figure 10: Sand distributions within each sediment unit extracted onto common coordinates.

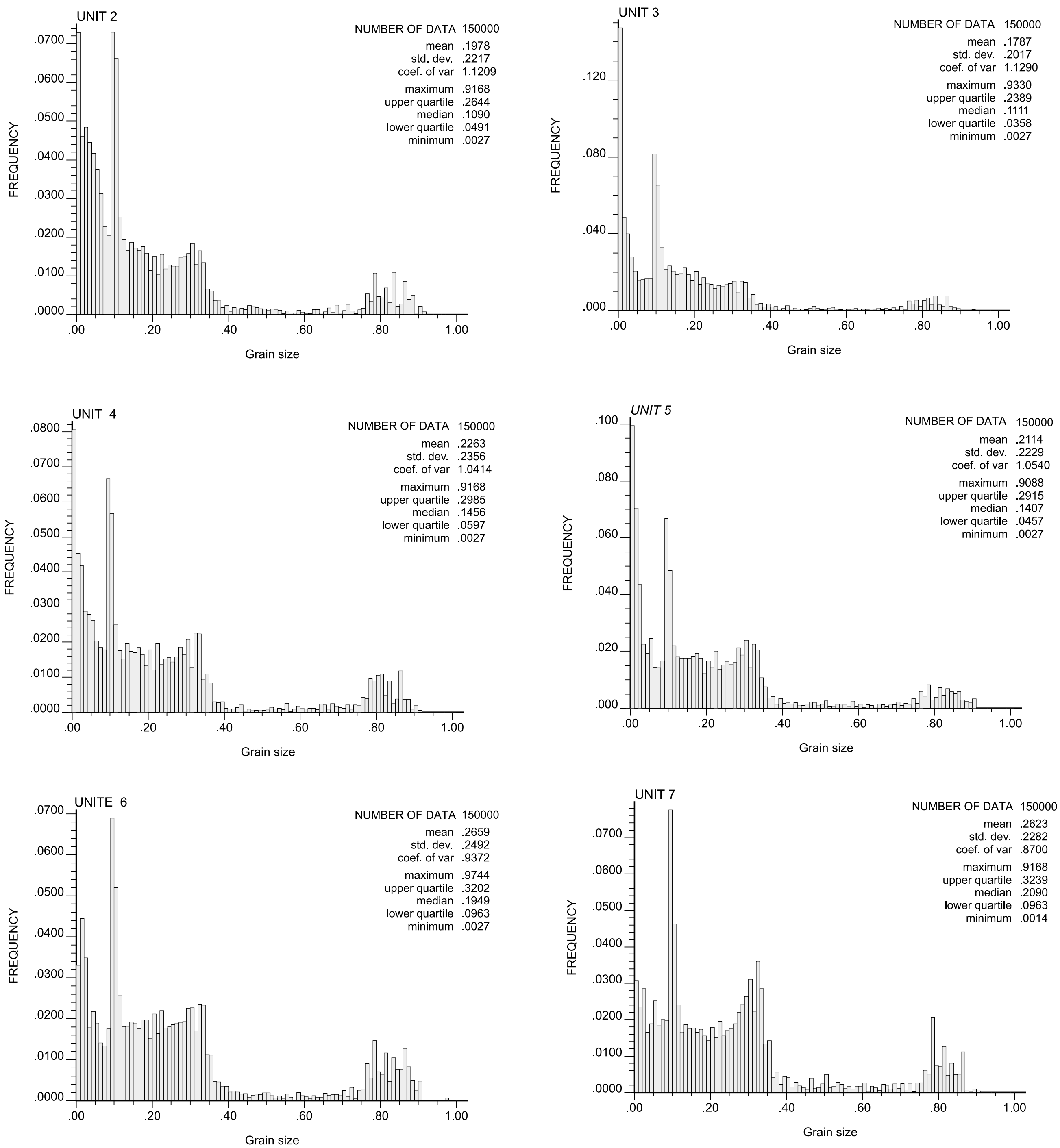

Figure 11: Sand fraction histograms for six of the seven units from the Sedflux analog.

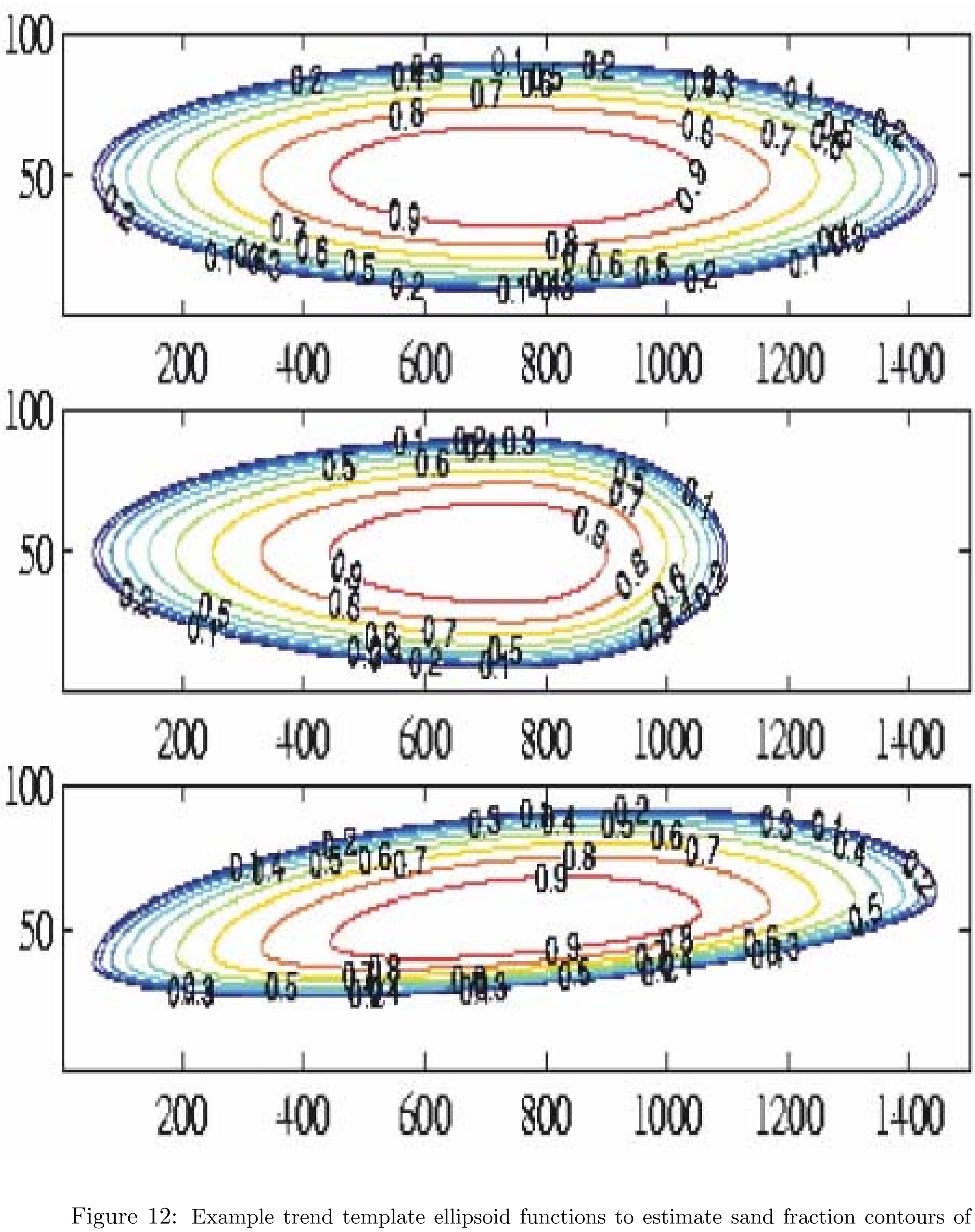

Figure 12: Example trend template ellipsoid functions to estimate sand fraction contours of the Sedflux analog.

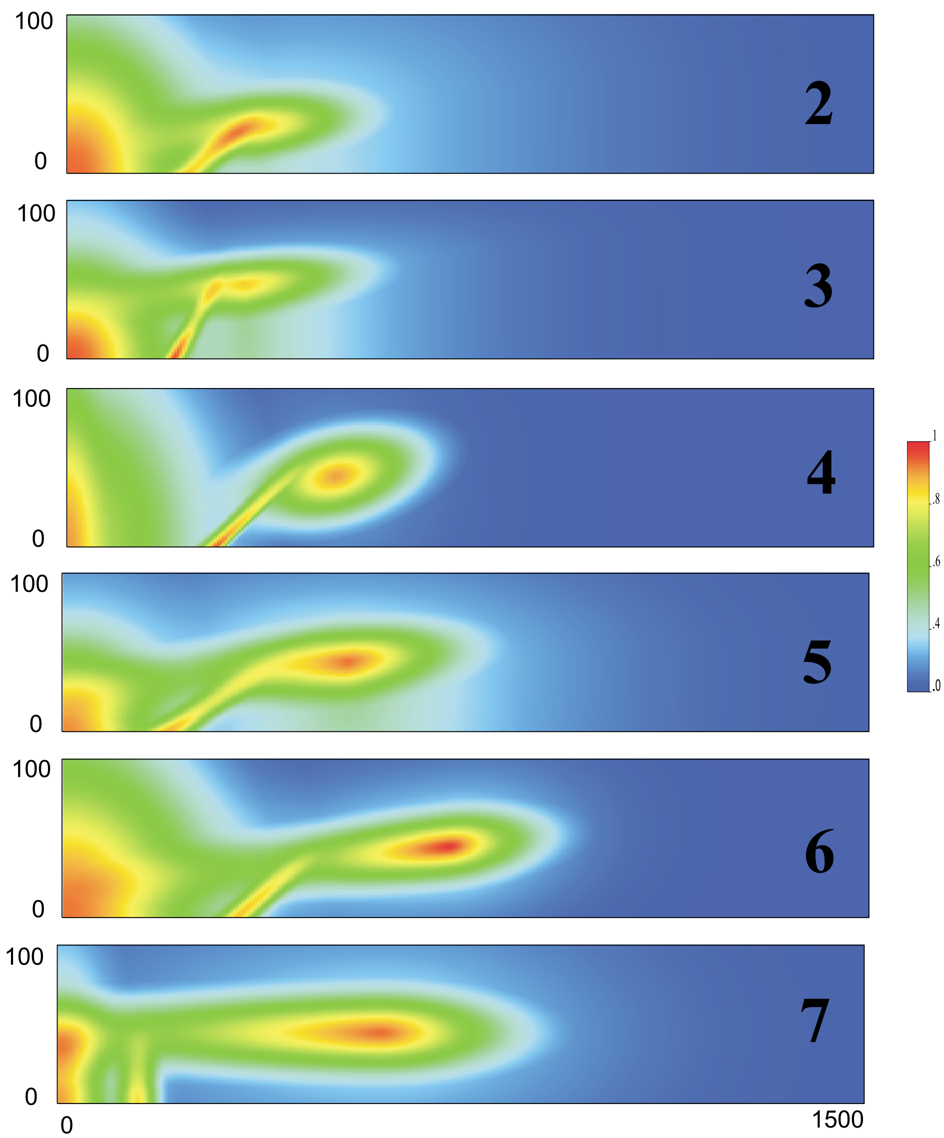

Figure 13: Trend templates of Vsand for sediment packages 2 to 7 of Sedflux analog.

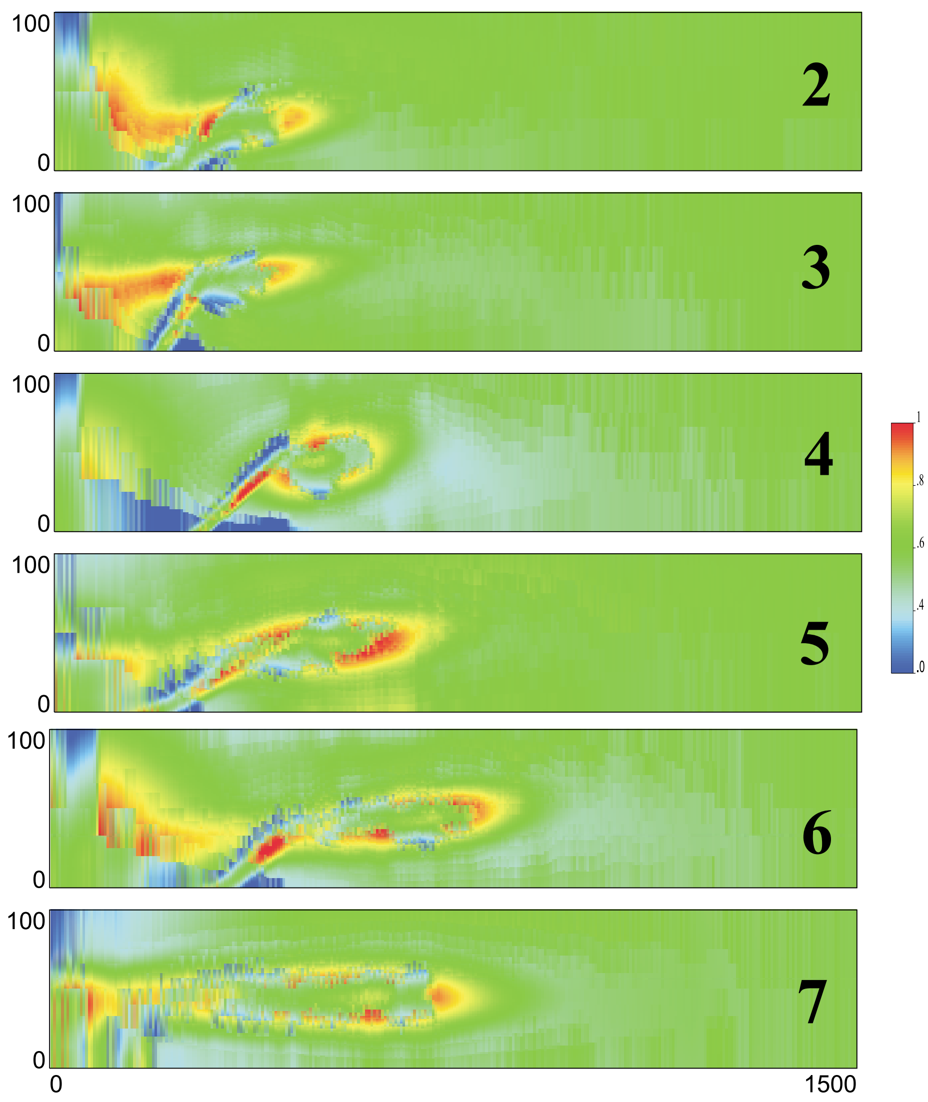

Figure 14: Residuals of Vsand after trends removed from sediment packages 2 to 7 of Sedflux analog

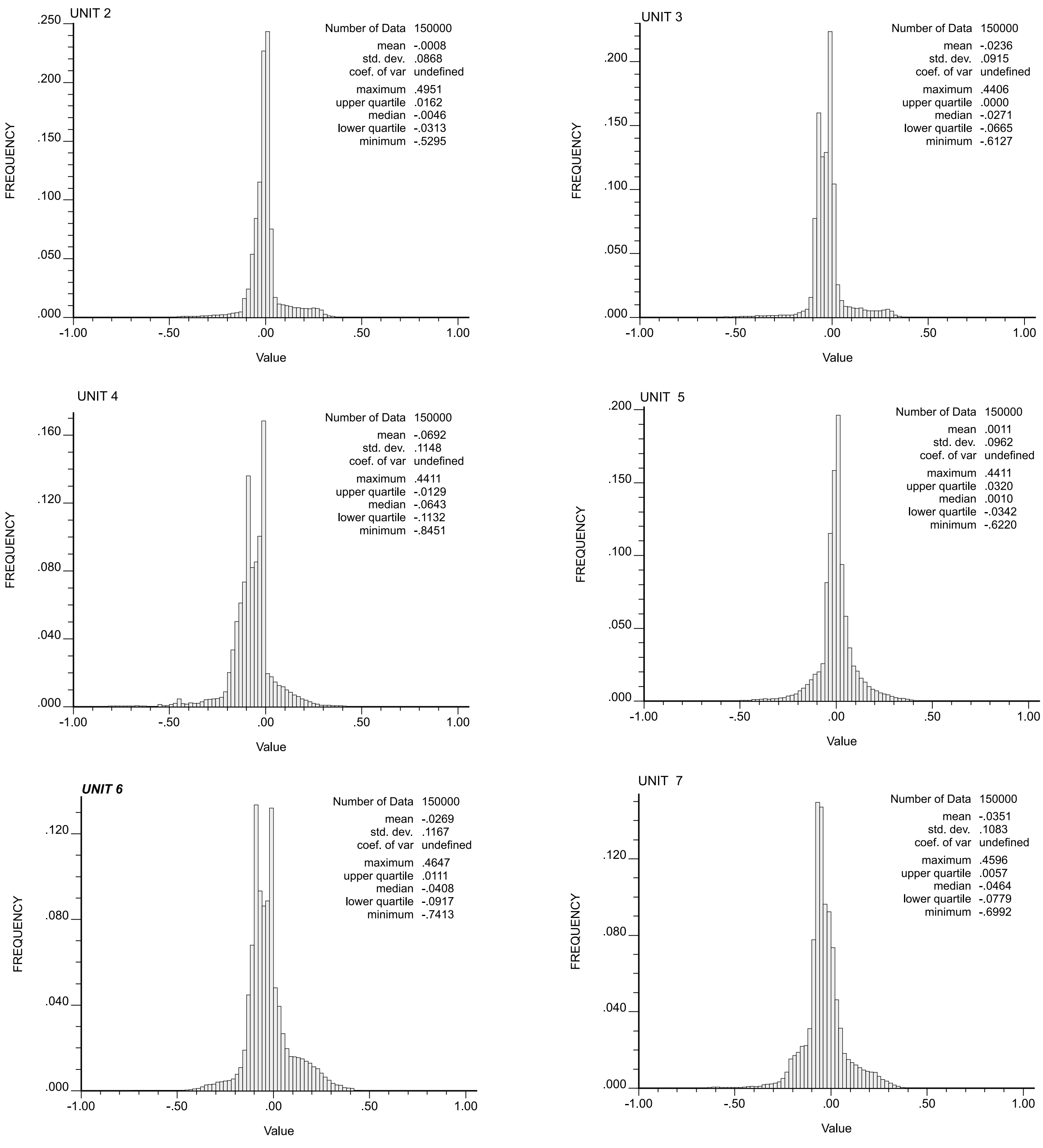

Figure 15: Histograms of Vsand residuals of the sediment packages 2 to 7 of Sedflux analog

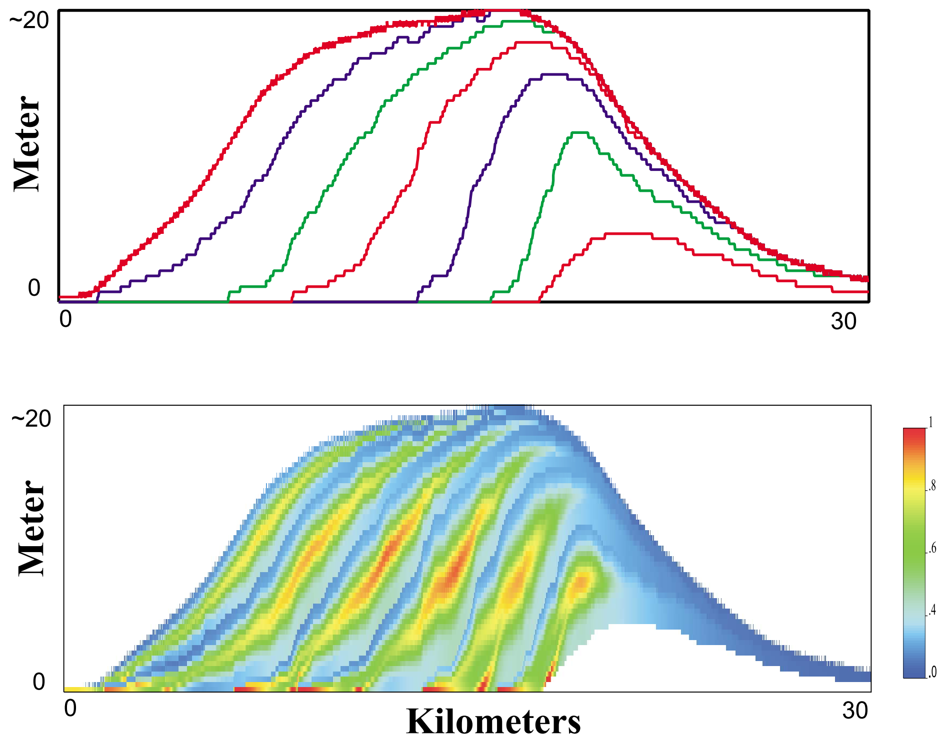

Figure 16: Trend model imposed within Sedflux sediment units from the trend templates.

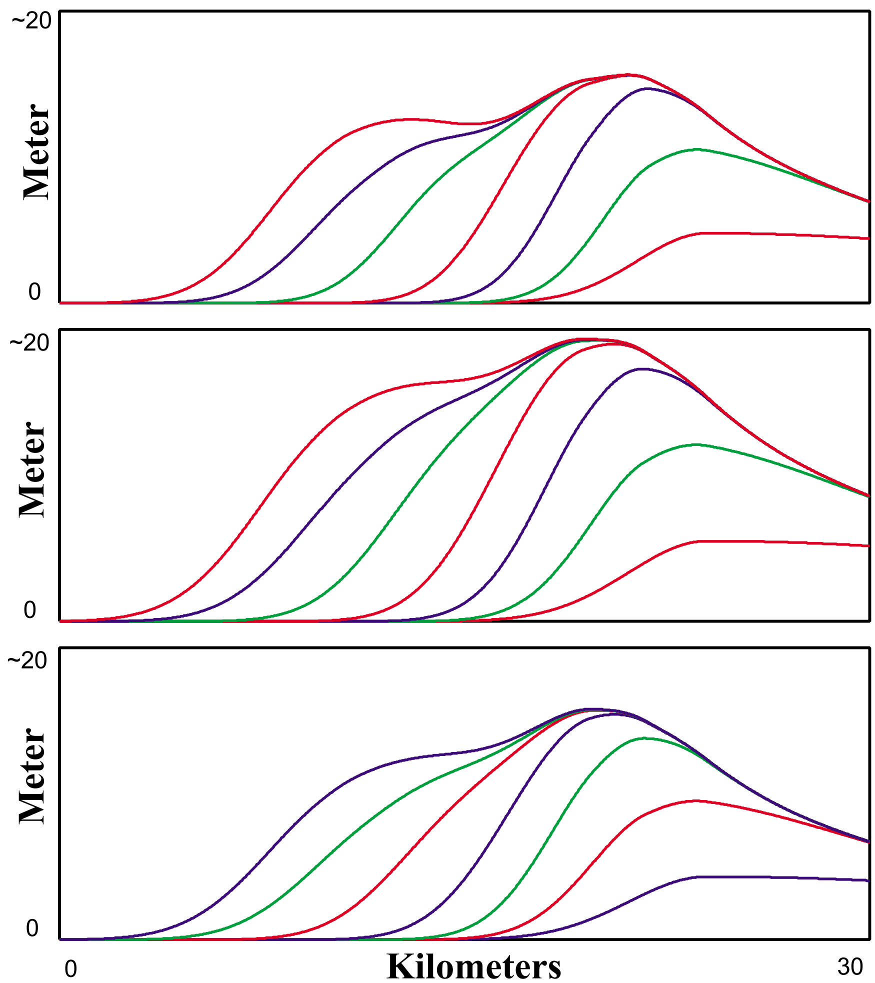

Figure 17: Three realizations of unconditional surface models using the Sedflux analog-derived skewed Gaussian shape.

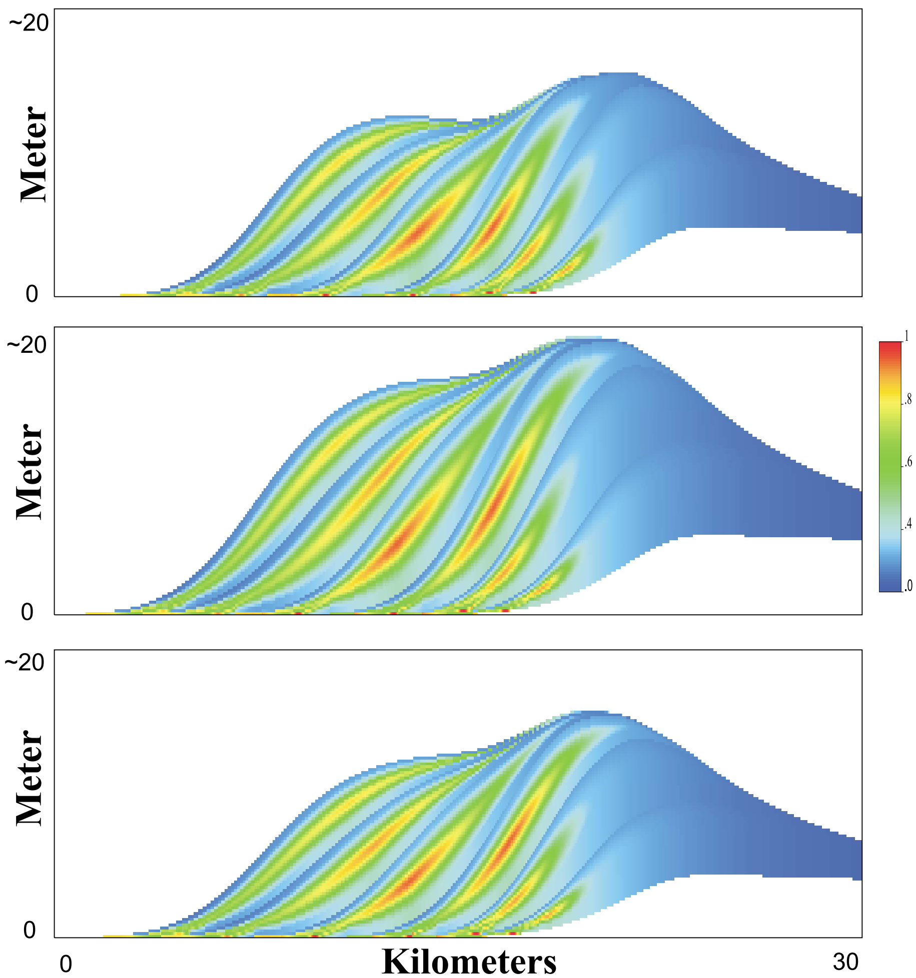

Figure 18: Trend models after building in the trend *templates* into the sediment units of unconditional surface models.

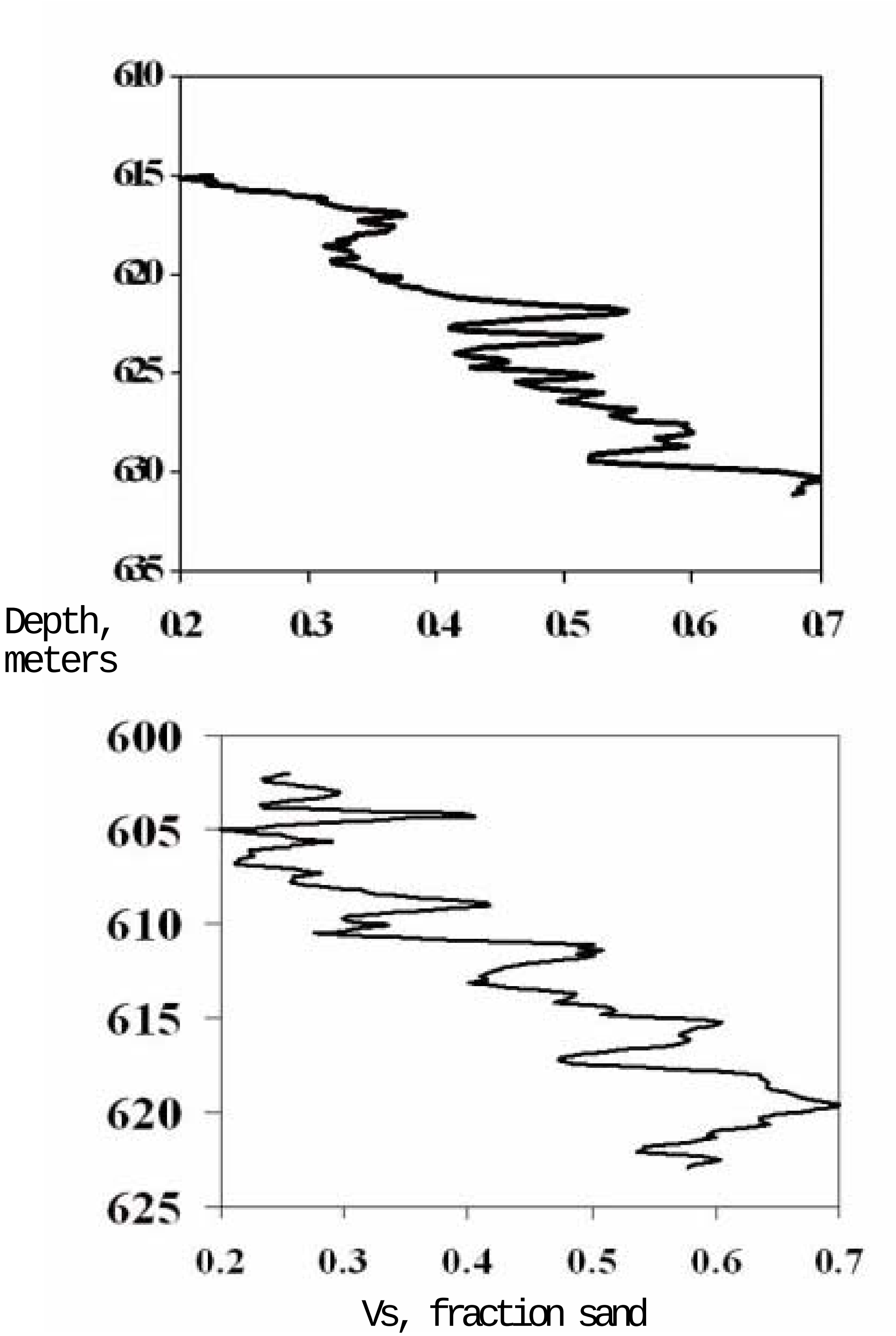

Figure 19: Log motifs for Wandoo Wells 6 and 3 (fraction sand derived from gamma ray). (See [7] for formation interval picks.)

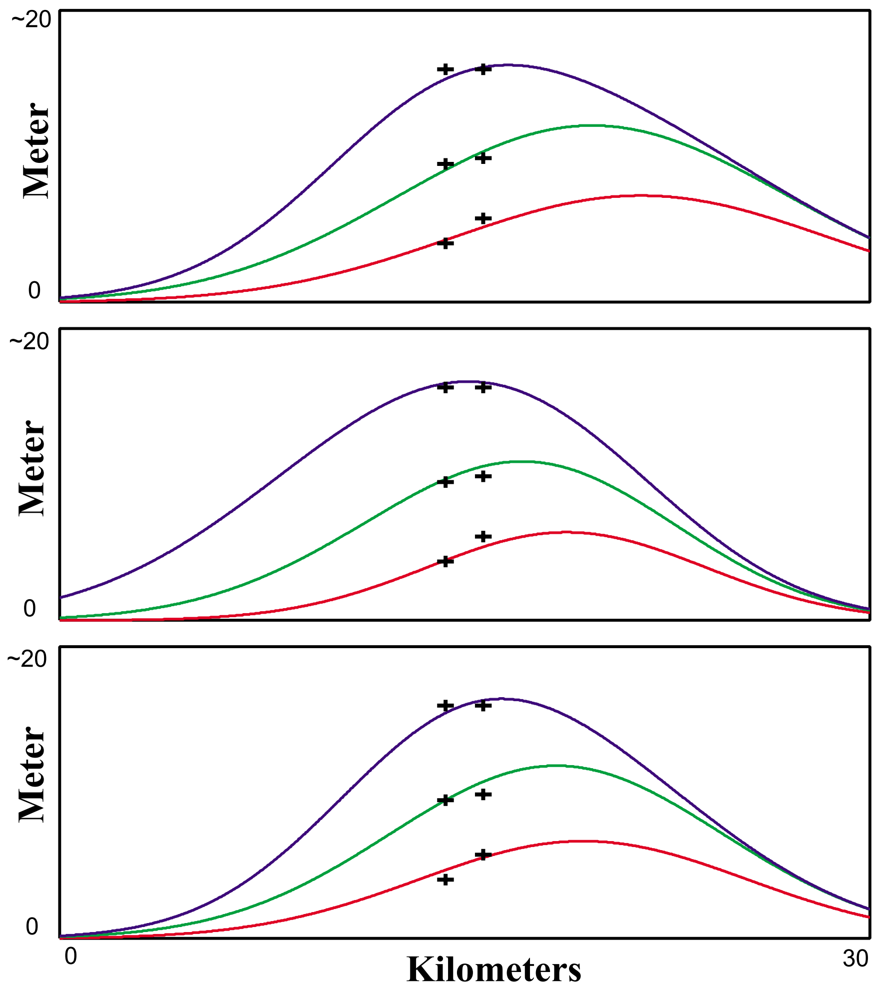

Figure 20: Three realizations of surface models from `Surfsim` conditioned to Wandoo well 6 and Wandoo well 3 (Well 3 is downdip).

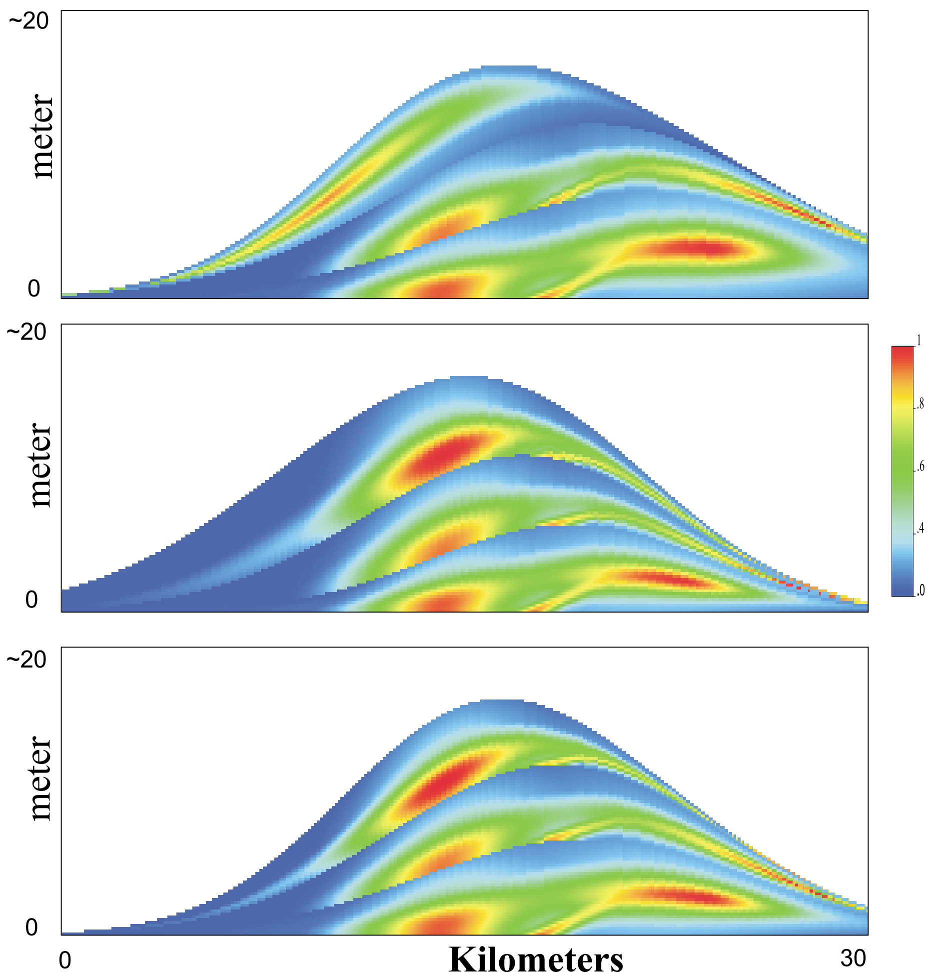

Figure 21: Trend models generated within the three realizations of surface models shown in Figure 20

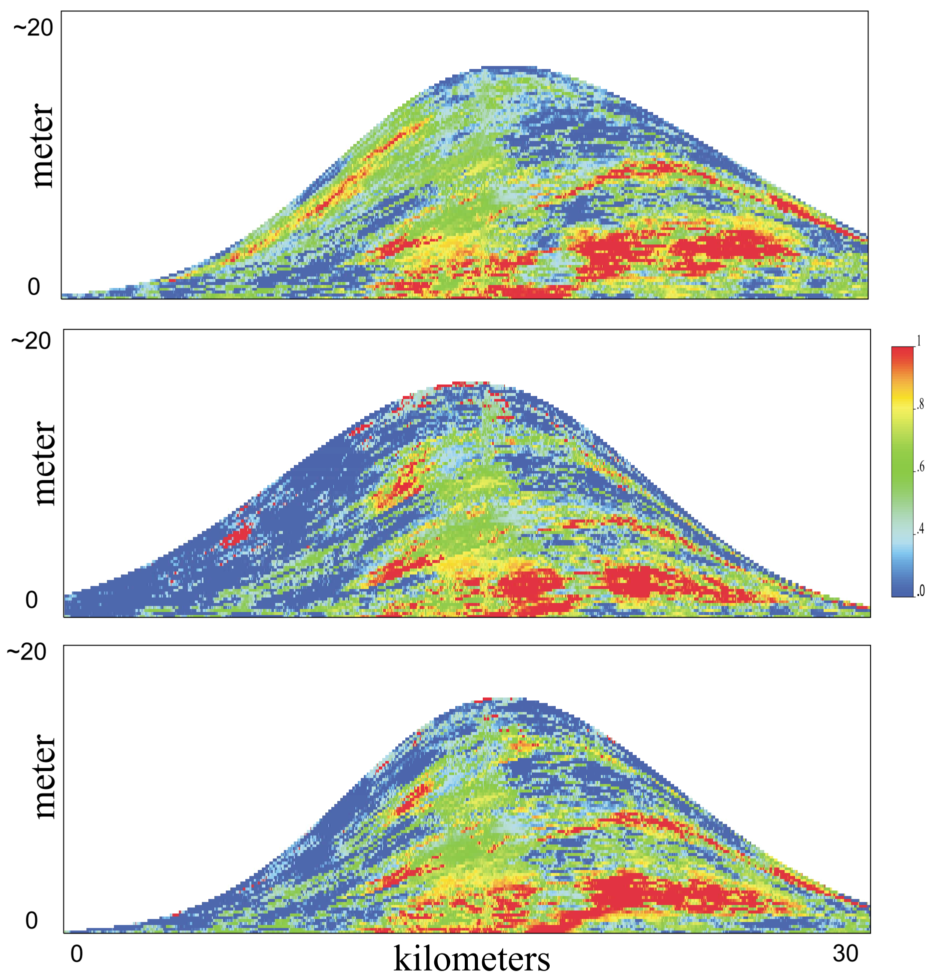

Figure 22: Trend simulation realizations within surface models shown in Figure 20 by combining trends and residuals.

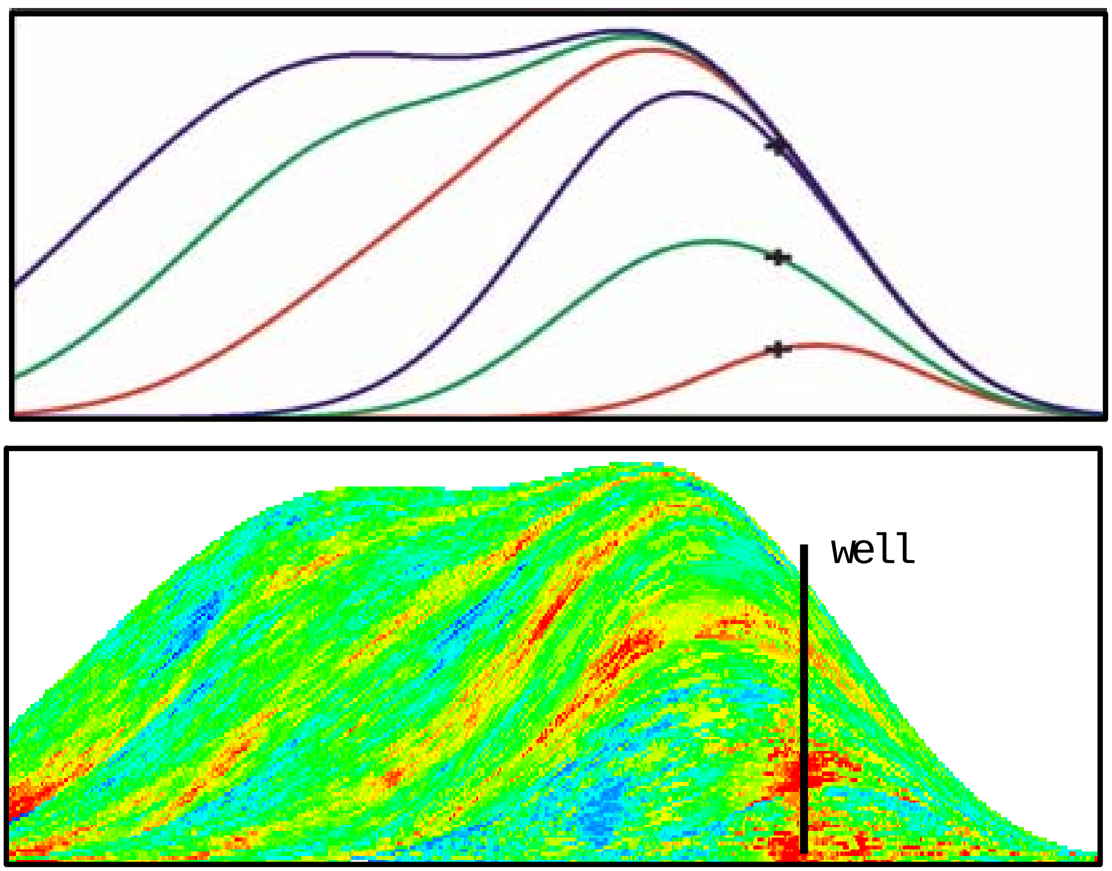

Figure 23: Simulation of the Wandoo. Top: Surfaces generated with “backstepping” rule, but constrained to three intersections in Well 6. Bottom: Trend simulation constrained by sediment units and well log.

Appendix A Parameters for `trend`

An example parameter file for `trend` is shown in Figure 24 and the parameters are documented below.

The parameters contain four parts, the first part consists of parameters defining dimension and number of trends used for trend *template*.

- **nx, ny:** dimension of trend *template*
- **thickness:** total thickness to be filled
- **seed:** random number seed (a large odd integer)
- **no_trn:** number of trend functions
- **minV,maxV:** minimum and maximum values of trends in real units

The second part contains parameters defining each individual trend function and their evolution along sediment packages.

- **contour:** type of function for trend shape. 0: linear, 1: ellipsoid
- **RminV,RmaxV:** realtive contour value for current trend function
- **minX0, modeX0, maxX0, flagX0:** lower limit, mode, upper limit for triangular distribution of X0 for trend center, and flag (=1) for systematical change at X0 (if **contour** = 1)
- **minY0, modeY0, maxY0, flagY0:** lower limit, mode, upper limit for triangular distribution of Y0 for trend center, and flag (=1) for systematical change at Y0 (if **contour** = 1)
- **α_min, α_mode, α_max, flagα:** lower limit, mode, upper limit for triangular distribution of azimuth angle, and flag (=1) for systematical change at α (if **contour** = 1)
- **minX, modeX, maxX, flagX:** lower limit, mode, upper limit for triangular distribution of length of ellipsoid, and flag (=1) for systematical change at X (if **contour** = 1)
- **minY, modeY, maxY, flagY:** lower limit, mode, upper limit for triangular distribution of width of ellipsoid, and flag (=1) for systematical change at Y (if **contour** = 1)
- **minAX, modeAX, maxAX:** lower limit, mode, upper limit for triangular distribution of asymmetry factor (**AX**) along X axis, (if **contour** = 1)
- **minAY, modeAY, maxAY:** lower limit, mode, upper limit for triangular distribution of asymmetry factor (**AY**) along Y axis, (if **contour** = 1)
- **type:** function type for assigning trend values. 0: linear, 1: exponential, 2: ...

The third part contains parameters for defining surface model, well data, and mapping back purpose.

- **surfl:** input file with surface models
- **col_no,col_v:** no. of column and col no for attribute
- **nnx,nny:** dimension of surface model
- **thick:** maximum height of surface
- **surf0,surf_no:** starting surface and no. of surface for current realization of surface model in **surfl**
- **flag_dim:** dimension flag, 0: 2-dimensional surface lines, 1: 3-dimensional surfaces
- **flag_xy, fix_xy:** section flag, 1: XZ section, 2: YZ section, **fix_xy** is the corresponding Y or X coordinate specified the section (if **flag_dim** = 0)
- **well_flag, well_loc:** well data flag, without well data: 0, with well data: no. of wells; if **well_flag** is not equal to 0, **well_loc** contains the well locations
- **datafl:** well data file
- **welllogfl:** output file for well logs at well locations
- **imagefl:** output file of the final reservoir model
- **logfl:** output file of log of computation

The last part consists of parameter related to residual simulation

- **itrans:** distribution of residual, 0: normal Gaussian, 1: distribution defined by conditional data
- **flag_res, flag_cond:** residual is or is not added if **flag_res** = 1 or 0, respectively. condition data is honored or not honored if **flag_cond** = 1 or 0, respectively, when **flag_res** = 1
- **nst, c0:** number of variogram structures and the isotropic nugget constant
- **it, cc, ang1, ang2, ang3:** For each of the **nst** nested structure, **it** defines the type of the structure, **cc** the variance contribution of the nested structure, and three angles defining the geometric anisotropy.
- **aa_hmax, aa_hmin, aa_vert:** The range parameters in three principal directions

```
Parameters for Trend (trend.PAR)
***************************

START OF PARAMETERS:

1500, 100                   -nx,ny
 69069                      -random number seed
 1                          -number of trends
100, 0.01                   -overall min, overall max
 ----------------------------------------------------------
 0                          -contour type
 0.0, 1                     -minvalue, maxvalue
 330, 345, 360, 1           -min,mode, max of X01,     Varyflag
  45,  50,  55, 0           -min,mode, max of Y01,     Varyflag
  -4,  -2,   0, 0           -min,mode, max of alpha1,  Varyflag
 250, 260, 270, 1           -min,mode, max of X1,      Varyflag
  30,  40,  50, 0           -min,mode, max of Y1,      Varyflag
 0.3, 0.7, 1.0              -min,mode, max of anisoX
 1.0, 1.0, 1.0              -min,mode, max of anisoY
 1                          -function type
 ----------------------------------------------------------
..\surface\surf1scl.dat     -input file of surface model
1   1                       -no. of col, var. col
1500 20                     -nx,ny (size of surface model)
250                         -max height of surface (training image)
53,23                       -start surface, no of surface
0                           -dim_flag, 1: 3D, 0: 2D
1,10                        -xy_flag, 1: XZ, 2:YZ, fixxy
0, 750                      -wellflag, well location,
truelog.txt                 -input well log data file
OutEc.wel                   -output file of the trend
OutEc.img                   -output training image model
OutEc.log                   -log file
-------------------------------------------
1                           -itrans
1,0                         -ResidualFlag, Condflag conditional/unconditional
1    0.01                   -nst, nugget effect
1    0.99 0.0   0.0   0.0   -it,cc,ang1,ang2,ang3
         10.0 300.0  10.0   -ahmax, ahmin, avert
```

Figure 24: Example Parameter file for `trend`