SPE 68817

Surface-Geometry and Trend Modeling for Integration of Stratigraphic Data in Reservoir Models

YuLong Xie*[1], A. Stan Cullick[2], and Clayton V. Deutsch[1]
[1] University of Alberta, Edmonton, Alberta
[2] Landmark Graphics, Austin, Texas

This paper was prepared for presentation at the SPE Western Regional Meeting held in Bakersfield, California, 26–30 March 2001.

Abstract

Accurate prediction of reservoir 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 the utilization of analogs of complex geology along with seismic and sparse well data to predict the natural geologic complexity in models of the subsurface.

Time surfaces provide very important constraints on the geometric connectivity and continuity of facies and petrophysical properties in reservoirs. Such time surfaces are a suitable framework for facies and petrophysical properties modeling. Instead of modeling each reservoir later as a whole, the elementary sediment units are more easily modeled separately; the final composite model will show realistic heterogeneity patterns consistent with the underlying physics.

This work presents a hybrid deterministic, rule-based, and stochastic technique to generate surface models. These surface models are utilized as a framework to preserve sediment trends and honor analog and well data. Petrophysical properties are modeled for each sediment unit to reproduce trends. Finally, the individual sediment units are assembled into a reservoir model.

The surface model is created stochastically with parameterized surface templates. The shape, extent, height, orientation and regularity of the surfaces are controlled by user-specified distributions. The location of each surface in the reservoir is chosen on the basis of previous events. The addition of each surface is based on sedimentological rules. Conditional Gaussian simulation is used to ensure that the surfaces reflect realistic uncertainty through undulations and that well data intersections are honored.

The surface model divides the reservoir layer into sediment units. From geology and well data, trends are parameterized with mathematical functions as trend templates. Residuals are characterized after removing the trend. For each sediment unit, a trend and a residual model are generated stochastically. The observed well logs serve as conditioning data to guide the deployment of trends and to condition the generation of residuals. The model of each sediment unit combines its trend plus residual. The final reservoir model is obtained by assembling the separate sediment units.

Introduction

Reservoir geometry and continuity provide important controls on the prediction of reservoir performance. The spatial distribution of petrophysical parameters like *porosity* (ϕ) and *permeability* (k) are closely correlated with the facies distribution. Therefore, the general practice of reservoir modeling is to characterize the reservoir facies first, then assign petrophysical properties, and finally transfer the model to flow simulation[2,10]. Notwithstanding the advances in geostatistical techniques in recent years, resulting reservoir models often do not preserve complex geologic architecture and features, such as anisotropic trends, stacking successions, and nested cyclicities.

A reservoir usually consists of several large-scale sediment units corresponding to depositional and erosional events. Each large-scale sediment unit, e.g. a parasequence, may consist of a smaller scale sediment units, or bedsets, which reflect higher frequency depositional events. The time lines separating the high frequency events are boundaries that often reflect some change in the direction or rate of deposition, e.g. a relative sea level rise followed by a fall. The presence of specific facies at specific locations within sediment units can be explicitly accounted for only when the locations of the sediment units are known. Sediment units bounded by time surfaces constitute natural geological units of the reservoir that provide large-scale connectivity and continuity control of facies and petrophysical properties. Considering time

* Currently in Pacific Northwest National Laboratory, Richland, WA, USA and On leave from Xiangtan University, Xiangtan, Hunan, P. R. China

surfaces, and the sediment units constrained therein, as geological units in the modeling process should provide better facies and petrophysical property control.

Some time surfaces are visible with seismic data (usually the large-scale surfaces). Smaller scale time surfaces, e.g. at a bedset scale, while not visible with seismic data, can be observed from core and well-logs. Conventional *object-based*[8,12] and *cell-based*[2,7] modeling techniques have no access to the location of smaller scale sedimentary units except at wells; current numerical modeling techniques focus on the overall distribution of facies and petrophysical properties (ϕ/k) in large reservoir layers and have not utilized models of high-resolution surfaces as constraints. Thus, there is a potential gain in modeling effectiveness by explicitly modeling the sedimentary units as boundary constraints before facies and petrophysical property modeling. There has been little research on this topic[13].

Porosity, permeability related to grain size and fraction clay often exhibits trends within and across surface intervals. Conventional geostatistical techniques for continuous property modeling can account for a trend provided the trend is known deterministically. Random function (RF) models divide the variability into a trend component and a stationary residual component. Non-stationary algorithms such as *ordinary kriging*, *kriging with a trend* or *kriging with an external drift* are used for estimation. The determination of trends (coefficients) relies on the availability of sufficient well data. Trends away from well locations are incorrectly inferred even if they are known conceptually. This is especially true when trends appear as repeatable local trends within sediment units overlapped with large-scale trends across sediment units.

Instead of implicit trend inference by a kriging system, it is better to make the trend explicit based on the understanding of the genesis of the phenomenon. In the framework of surfaces, the trend can be expressed explicitly, and a residual can be modeled separately using stationary RF models[2,7,9].

Our proposed methodology has two major steps. First, surfaces are stochastically simulated based on rules gathered from natural sedimentation processes. Reservoirs are built upward by sediment units, which are assumed to be represented by the volume covered by the surfaces. A *simple parametric surface* is designed as a surface template. Parameters include the extent, height, orientation, elongation and regularity of the surface, which are stochastically drawn from user-defined distributions. Undulation is added to the generated regular surface. The location of surfaces is determined based on the prior thickness distribution. When well data are available, the surfaces are accepted and rejected according to rules that force surfaces to pass through the observed surface intersections.

Once a surface model is available, trends and residuals in facies and petrophysical properties are characterized based on an understanding of reservoir geology and well data. Trends are parameterized with mathematical functions. Trends and residuals are simulated for each individual sediment unit. The variations of trends between different sediment units are accounted for by distributions of trend parameters. Well log data, when available; serve as conditioning data for guiding the placement of trends and conditioning the generation of residuals.

FORTRAN 90 programs, surfsim and trendsim, are written for the approach. An example using a qualitative interpretation of the Wagon Caves Outcrop in California[1] demonstrates the approach.

Gological/physical Basis

Many sedimentary sequences occur along continental margins, where the sedimentation is a result of the interaction of tectonic activity, eustasy, and sediment input[5,6,11]. There can be significant changes in the properties of sediment at boundaries due to changes in geological events. Within low-frequency changes, there are also higher-frequency events. For example shorter time scale rises and falls of sea level result in features superimposed on the large-scale architecture. Time surfaces are often spaced systematically; *progradation* and *transgression* are examples. Such surfaces are a combination of a predictable shape plus a stochastic component.

Within a sediment bedset unit the petrophysical properties also show identifiable trends. For example, as the sea-level rises, the shoreline *transgresses* across the erosional surface and the locus of deposition shifts inland. Stratigraphic parasequences are built landward and typically coarsen upward trends result in a parasequence. The corresponding trends in the sediments are repeatable due to the periodic changes in the depositional controls. It is important in numerical modeling to quantify and to model such trends.

Methodology

Surface modeling: Surfaces are generated with analytical shapes. As shown in Fig. 1, a *simple parametric surface* is defined by the parameters such as central location (X0, Y0), length X, inner width (also the radius of the smaller semi-circle) Y, which has a maximum height H, outer width (also the radius of the larger semi-circle) YY with height decreasing from maximum to zero, and elongation direction defined by angle α. All parameters except central location (X0, Y0) are drawn from user-defined triangular distributions. Central location (X0, Y0) is chosen based on the distribution of the thickness in the reservoir. Areas with lower thickness will have a higher chance to "deposit" a new surface.

Surface modeling proceeds by adding generated surfaces in the reservoir. To avoid distortion of the surface shapes, the addition of surfaces is based on a classical Boolean formalism. Each surface is dropped in the reservoir until some points reach the lowest height of the system of previous surfaces. Overlapped portions are truncated.

Undulations are added to the regular analytical shape to recognize uncertainty in the shape. The undulations are assumed normally distributed and are generated by sequential

Gaussian simulation. The spatial characteristics and magnitude of undulation are calibrated, as described later.

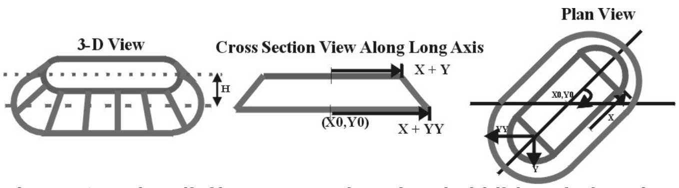

Fig. 1 - 3-D view (*left*), cross-section view (*middle*) and plan view (*right*) of a *simple parametric surface.*

Well data intersections are honored. A surface should pass through the intersections observed at the wells, and there should be no other surface intersections appearing between known intersections observed in the well data. Empirical rules are used to decide if a newly generated surface should be accepted or rejected. The honoring of well data is aided by the generation of the surface undulations by conditional Gaussian simulation.

Trend modeling: Fig. 2 provides a schematic illustration of the methodology for trend modeling. First, we assume that a surface model is available (Fig. 2-A) from surface modeling. Also, assume there is a trend that can be quantified with parameterized mathematical functions, *e.g*. the fraction sand (Vs) log motif pictured as Fig. 2-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 is modeled simply by a linear function. In other situations, trend may spread out from an original (center) position, which may correspond to a paleo river mouth unloading sediments. In such a case, an ellipsoid function may be chosen to approximate the trend shape. Since the sediment units have different irregular shapes in the original stratigraphic coordinate system, trend modeling and residual simulation are carried out in a unified regular Cartesian coordinate space (Fig. 2-C and D) and then mapped back into a "stratigraphic" grid interval, see Fig. 2-E.

Residuals can be characterized based on well data and conceptual geological information. Variograms of residuals are evaluated and modeled. Residuals are then simulated by conventional geostatistical techniques.

Trends are imposed on every sediment unit one-by-one as a "*trend template*" as well as the residual, simply by a coordinate transform (Fig. 2-F). Trend modeling can start from any sediment unit in the reservoir, but if there is a larger scale trend across sediment units, the trend simulation must be done in the context of its location within the larger scale trend.

Wagon Caves Outcrop Example

This example is a qualitative interpretation of Wagon Caves Outcrop in California. In Fig. 3 the left plot is an image of the Wagon Caves Outcrop and the right one contains major surface lines interpreted by Anderson[1]. The dimension of the outcrop is approximate 500 meters long and 50 meters high.

Downlap stratigraphic layers exist in the outcrop shown in Fig. 3. The outcrop surface interpretation is first transformed to stratigraphic coordinates[3,4]. Restored base and top of stratigraphic layers are estimated and the stratigraphic coordinates are then calculated based on the restored base and top. The surface lines in original *depth* space with real units are thus transformed into relative units in stratigraphic space. When surface modeling is complete, surface models are then back transformed to *depth* space. The existing base and top lines are used to guide the back transformation by truncating all back-transformed values outside the interval defined by the existing base and top.

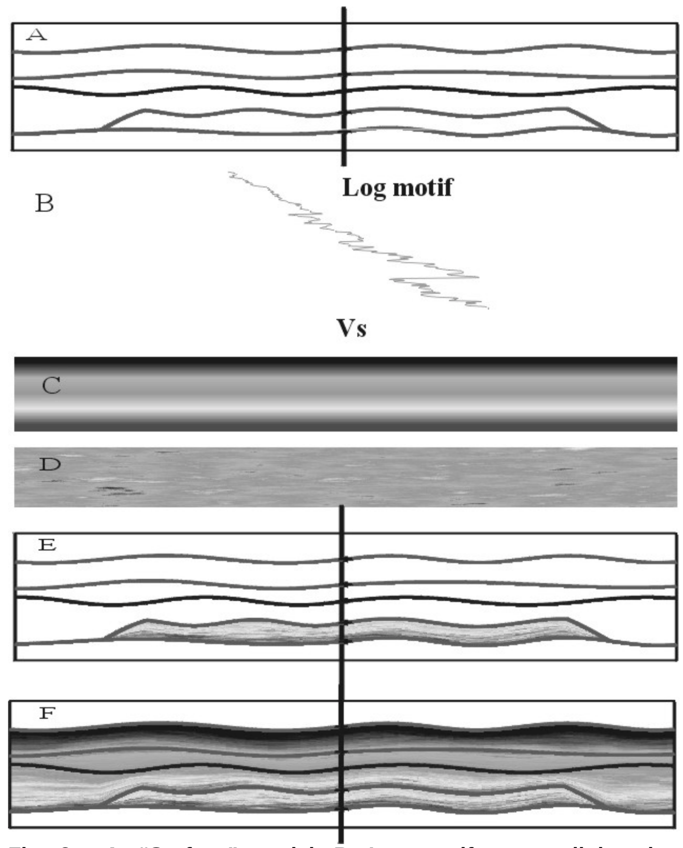

Fig. 2 - A. "Surface" model, B. Log motif at a well location showing a generally fining upward trend, with some internal coarsening within sediment units, C. "Trend template" of a linear trend, D. Residual, E. Trend template plus residual within one sediment unit, F. Simulated values for all units.

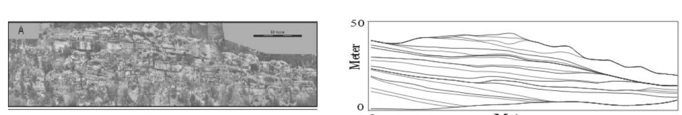

Fig. 3 - *Left*: image of Wagon Caves Outcrop. *Right*: interpreted surface lines[1].

The magnitude of undulation *i.e., scaling factor* and the spatial variability of the surface *i.e., range* are calibrated. Fig. 4 shows the calibration process. Representative surface lines are fitted by *simple parameter surface* and residuals are obtained (left plot of Fig. 4). The histograms (middle plot of Fig. 4) and variograms (right plot of Fig. 4) of the residuals are calculated. A Gaussian type model is used to model the variograms. The *range* used for geometry undulation is related to the range obtained from the variogram models of residuals, and the magnitude is related to the standard deviation of residuals.

Pseudo well sampling locations are placed in the reference model and on the outcrop. The intersections of the vertical wells with the surface lines are regarded as well data. A realization conditioned with a single well is shown at the top of Fig. 5. All simulations are conducted in three-dimensions.

Trends were assumed for the purpose of demonstrating the method with this example. There is a generally linear vertical fining upward trend and a linear horizontal fining rightward trend across the sediment units. Within each sediment unit, an exponentially decreasing fining upward trend was assumed. The fining upward trend value range 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.

The trend model is depicted on the left of Fig. 5, and the simulation is on the right of Fig. 5. The trend is preserved in the simulation model. Fig. 6 shows sample well logs at locations A, B, C. The trend model has the distinct fining upward within units with the fining rightward, larger scale trend. The simulation model clearly shows a more realistic variability imposed by the Gaussian simulation in the log motifs.

Conclusion and Discussion

The distribution of facies and petrophysical properties in real reservoirs are not random. Usually, repeatable trends and systematic variation exists in the sediment units bounded by time surfaces. Time surfaces reflect the depositional events when reservoir formed and they can provide important constraints to heterogeneity modeling. General understanding and conceptual knowledge about reservoirs are usually based on time surfaces; thus they provide important constraints to numerical simulation.

The approach developed in this paper attempts to take advantage of the constraints provided by time surfaces. First, surface models are created stochastically based on acceptance and rejection rules derived from chronological sedimentology. Well data are honored at exact depth of the observed intersections.

Subsequent trend modeling is done for each sediment unit or set of units. Often, trends account for a majority of reservoir variation, and it is proper to split the trends from random factors and model them *separately*. The quantification and expression of trends observed in the reservoir sediments is very important. Both repeatable trends within individual sediment units and systematic trend variations across multiple sediment units are expressed by a set of parameters in a trend *template*. Such a trend expression is calibrated with available geological information and well data.

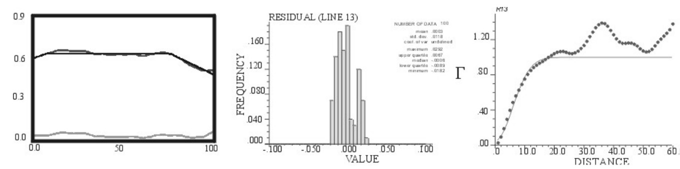

Fig. 4 - *Left*: A representative surface line of Wagon Caves Outcrop, the fitted line by a *simple parametric surface* and the fitted residual. *Middle*: histogram of the fitted residual. *Right*: experimental (dotted) and model variogram (solid line) of the residual.

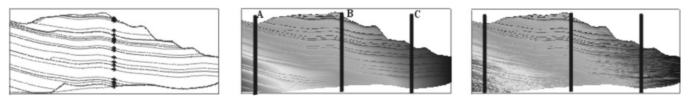

Fig. 5 - *Left*: One realization of surface model from surfsim conditional to a single well. *Middle*: Trend template with nested vertical and horizontal sand distribution. *Right*: Simulated trend plus residual

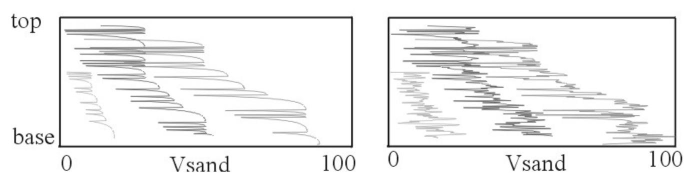

Fig. 6 - Sample log motifs comparing the sand distributions of trend template with trend simulation from three vertical sample locations (see Fig. 5)

The results of the example show the resemblance of the simulated surface and trend model with the reference model, which is actually consistent with our goal to bring more geology into numerical models. The geological information is incorporated in the model in two stages. First, the resulting surfaces capture the understanding of the geological architecture. The choice of surface *template* considers the shape of the surfaces. Observed surface intersections with wells are honored.

The proposed approach is a hybrid deterministic, rule-based, and stochastic method. Conceptual knowledge is used deterministically. Incomplete information is revealed by the variations in the surface and trend parameters, which lead to different models honoring the same well data. The difference between the models is a measure of uncertainty due to incomplete information.

With the inclusion of conceptual geological information and explicit trend modeling, the final reservoir model should better preserve complex geology than conventional geostatistical models. The surface and trend models are three-dimensional.

References

1 K. Anderson, *Wagon Caves Rock Outcrop Study*. Ph.D. thesis, Stanford University, Stanford, CA, 1998.

2 C. V. Deutsch and A. G. Journel, *GSLIB: Geostatistical software library and user's guide.* Oxford University Press, New York, 2nd edition, 1998.

3 C. V. Deutsch and T. T. Tran, *Fluvsim: A program for object-based stochastic modeling of fluvial depositional systems*, submitted to Computers & Geosciences, 1998.

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

5 D. Emery and K. J. Mayers, *Sequence stratigraphy*, Blackwell Science, London, 1996.

6 W. E. Galloway, *Clastic depositional systems and sequences: Applications to reservoir prediction, delineation, and characterization*, The Leading Edge, pp. 173-180, 1998.

7 P. Goovaerts, *Geostatistics for natural resources evaluation*, Oxford University Press, New York, 1997.

8 H. H. Haldorsen, P. J. Brand, and C. J. Macdonald, *Review of the stochastic nature of reservoirs*, in. S. Edwards and P. R. King, editors, *Mathematics in oil production*, pp. 109-209, Clarendon Press, Oxford, 1988.

9 E. H. Isaaks and R. M. Srivastava, *An introduction to applied geostatistics*, Oxford University Press, New York, 1989.

10 A. G. Journel and J. J. Gómez-Hernández, *Stochastic imaging of the Wilmington clastic sequence*, SPE paper # 19857, 1989.

11 J. W. Mulholland, *Sequence stratigraphy: basic elements, concepts, and terminology*, The Leading Edge, pp. 37-40, 1998.

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

13 V. Suro-Pérez, L. Ramos Martinez, and A. Villavicencio Pino, *An algorithm for the stochastic simulation of sand bodies*. In III Latin American/Carribbean Petroleum Engineering Conference, pp 1171-1178, Buenos Aires, Argentina, April 27-29, 1994, Society of Petroleum Engineers, SPE paper # 27024.