Using the Variogram to Establish the Stratigraphic Correlation Structure

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Abstract

Hydrocarbon bearing reservoirs exist as a series of stratigraphic layers that have been structurally deformed since the time of deposition. A significant challenge in geostatistical modeling is to capture the original spatial continuity of petrophysical properties while preserving the stratigraphic layering. Variogaphy is performed within the original layer structure to quantify the original continuity. This note presents a methodology to use the variogram to establish the best transformation to restore an existing layer structure to the original layer structure. Geostatistical modeling is performed within the restored layer architecture and then transformed back to the existing architecture for visualization and post processing.

Introduction

Petroleum reservoirs are made up of a sequence of genetically related strata or layers separated by chrono-stratigraphic surfaces. Each layer corresponds to a particular depositional event that can be correlated between data. The correlation is usually established by a mixture of deterministic and stochastic based methods (Weber, 1990; Abib, 1991). Stochastic calculations such as variogaphy and simulation are performed within each layer separately according to a large-scale reservoir framework model.

Variogram calculation and modeling relies on the assumption of stationarity, which implies the mean is independent from location (Goovaerts, 1997). This assumption is not satisfied for the spatial distribution of petrophysical properties within the reservoir as a whole; however, the assumption improves as petrophysical properties are grouped according to layers. Therefore, layers are defined in a geostatistical study when the nature of geological heterogeneities changes significantly between depositional settings. Typically, reservoirs are partitioned into 5 to 10 layers that are 1 to 50m thick (Deutsch, 2002).

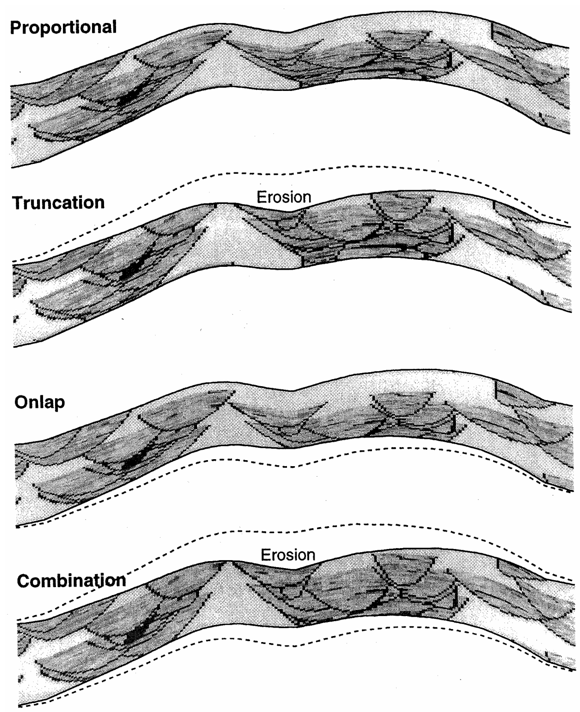
The existing structure of a geological layer is never the same as its original structure. Typically a layer is deposited relatively flat. Over time, the layer surfaces deform according to various structural deformation processes such as differential compaction, differential sedimentation rate, folding, faulting, erosion, and channel filling. As a result, the spatial continuity of petrophysical properties such as facies type, porosity, and permeability changes over time. A significant challenge in geostatistical modeling is capturing original continuity of petrophysical properties and preserving this continuity within the existing layer structure.

Variogram calculations are two-point statistics and are ineffective for capturing curvilinear layer geometry. For this reason, variogram models and subsequent stochastic simulation of the petrophysical properties are performed within a layer structure restored to its original flat form.

Since the reproduction of existing continuity features is vital for accurate reservoir flow response, the geostatistical models are transformed back to be within the existing layer structure.

The first step in a geostatistical reservoir modeling is the establishment of the large-scale reservoir framework. This step should include restoring deformed layer structures to their original form for subsequent geostatistical modeling (Abbaszadeh, 2003). Variogram calculations and geostatistical models are built within the restored layer structures then the models are transferred to the existing layer structure. This approach allows for (1) straightforward calculation and interpretation of two-point statistical variogram models and (2) preservation of the original spatial petrophysical property correlations within the existing layer structure.

There are some simple stratigraphic vertical coordinate transformations that can facilitate the restoration of existing layer structures to their original structures. Typically, the layer structure can be characterized by four basic types of coordinates: (1) elevation, (2) proportional, (3) truncation, and (4) onlap (Deutsch, 2002). Figure 1 illustrates schematic facies formations within a reservoir layer for each of the latter three coordinate systems. The original and existing surfaces, shown as broken and solid lines, respectively, illustrate the type of structural deformation that occurred. Proportional structures occur when the original and existing top and bottom surfaces coincide, but the thickness varies due to differential compaction or sedimentation rate. Truncated coordinates are used when the original and existing bottom surfaces coincide, but the original top surface was eroded down to a lower existing top surface. Onlap structures occur when the original and existing top surfaces coincide, but the original bottom surface was filled to a higher existing bottom surface. And elevation coordinates apply when minimal structural deformation has occurred. These coordinate transformations account for various by-layer structural deformation processes and can easily be revered.



Source: Deutsch (2002)

Figure 1 – Proportional, truncation, onlap, and combination stratigraphic coordinate system transformations. Original and existing surface are represented with broken and solid lines, respectively.

A methodology is proposed to calculate proportional, truncated, and onlap stratigraphic coordinate systems based on elevation. The horizontal variogram is calculated within each coordinate system and compared. The most accurate representation of the original reservoir stratigraphy is based on maximum horizontal spatial correlation; therefore, the coordinate system that yields the lowest variogram values is the best representation of the original structure. An application using real data is presented to illustrate the process.

Geostatistical modeling and horizontal variography calculations are performed on petrophysical variables located at the restored stratigraphic locations. The coordinates can be easily mapped back to the existing stratigraphic elevations.

Experimental variogram calculations within the restored coordinate systems are appropriate two-point statistics and the true (original) continuity is preserved within the existing structure. The process is straightforward and can easily be implemented with minimal time requirements.

Proposed Approach

The hydrocarbon bearing formation is segmented into multiple geological layers according to all available data. The data within the top and bottom chrono-stratigraphic surfaces of each layer are extracted for the coordinate transformation. Figure 2a shows a schematic reservoir with five geological layers. The shaded portion of WELL I and WELL II are extracted within layer 3 of the reservoir.

The data are taken as equal length intervals. The centroid of each data location corresponds to the 3D location of a petrophysical property variable. Figure 2b illustrates WELL I and WELL II. There are a total of seven and four petrophysical property values in WELL I and WELL II, respectively. They are numbered starting at 1 for the highest elevation sample.

Proportional, truncated, and onlap stratigraphic coordinates are then calculated using the elevations. The existing structure of the layer is characterized by the existing top and existing bottom surface elevations. Proportional coordinates Z_{PROP} are calculated as the relative distance between the existing top and bottom elevations; truncated coordinates Z_{TRUNC} are the elevations from the existing bottom; and onlap coordinates Z_{ONLAP} are the depths from the existing top surface:

$$\begin{aligned} Z_{PROP}(\mathbf{u}_i) &= \frac{z_s(\mathbf{u}_i) - B(\mathbf{u}_i)}{T(\mathbf{u}_i) - B(\mathbf{u}_i)} \cdot T_{avg} \\ Z_{TRUNC}(\mathbf{u}_i) &= z_z(\mathbf{u}_i) - B(\mathbf{u}_i) \qquad\qquad i = 1,\ldots,I \qquad (1) \\ Z_{ONLAP}(\mathbf{u}_i) &= T(\mathbf{u}_i) - z_s(\mathbf{u}_i) \end{aligned}$$

where $\mathbf{u}_i$, $i = 1,\ldots, I$ represent the aerial locations of the data, T and B are the existing top and bottom layer surfaces, respectively, and z is the data elevation. The Z_{PROP} coordinates are standardized according to the average thickness T_{avg} of the layer. The coordinate transformations in equation (1) are calculated using WELL I and WELL II in elevation coordinates. The restored stratigraphic coordinates at the wells are shown in proportional, truncated and onlap coordinate systems in Figure 2b.

Consider now the calculation of a horizontal variogram between WELL I and WELL II within each coordinate system. For each stratigraphic coordinate system in Figure 2b, the composites that are paired to calculate the horizontal variogram are shaded. For the proportional system, all composites are shaded; however, for the other coordinates systems, different data pairings are used. Depending on the stratigraphic coordinate system, the horizontal variogram value will be different due to different stratigraphic offset between the wells.

During the formation of reservoir layers, petrophysical properties are deposited with high horizontal correlation. This is manifested in low horizontal variogram values for petrophysical properties. The horizontal variogram values calculated within each stratigraphic coordinate system can be compared on one plot to determine the lowest variogram structure. The lowest variogram values correspond to the stratigraphic transformation that yields the most continuous structure for an accurate prediction of the original stratigraphic layer structure. This is the chosen transform and all subsequent geostatistical modeling is performed within this coordinate system. The coordinate transformations in equation (1) are easily reversed so that the geostatistical models can be transferred to within the existing layer structures.

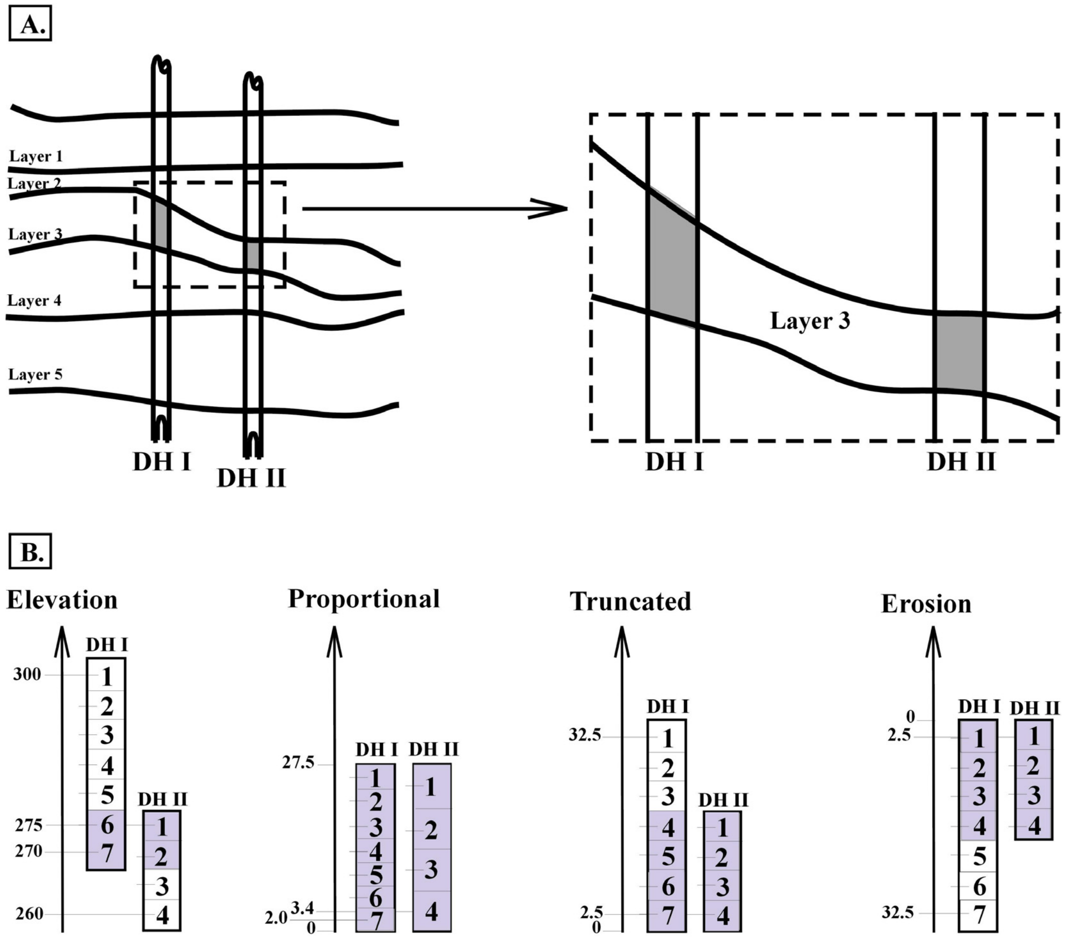


Figure 2 - (a) A schematic five-layer reservoir; the shaded portion of WELL I and WELL II are extracted within the layer 3. (b) proportional, truncated, and onlap coordinates are calculated and shown. The shaded composites represent horizontal variogram calculation pairs. All units are in meters.

Application

The data in this example is a subset of coreholes within the Athabasca oil sands located in northern Alberta, Canada. There are three layers: marine, estuary, and fluvial, in order of descending elevation (Leuangthong, 2003). The data for this example is from the estuary layer. There are a total of 174 vertical wells and 6,533 bitumen data values. The wells are composited into regular 3m intervals. For each composite, northing – Y, easting – X, elevation – Z, and bitumen – *BIT* (%) values are available. The study area is a square 2000m in plan and the average well depth is 90m. Figure 3 shows a plan view of the area.

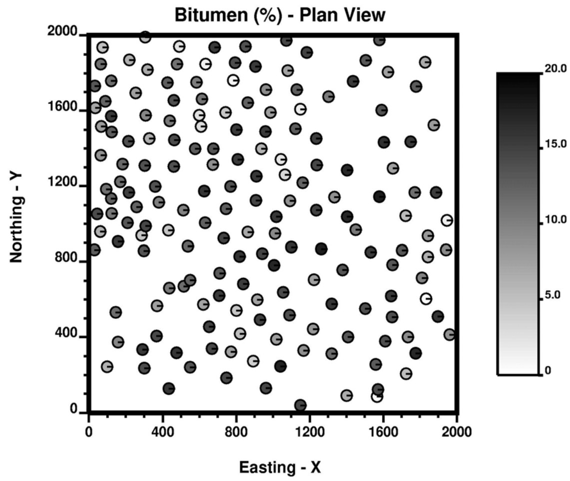


Figure 3 – Plan view of the corehole locations.

Restorative proportional, erosional, and onlap coordinate transformations are performed using equation (1). A horizontal variogram is calculated within each of the coordinate system with the following parameters:

azimuth = 0^o	**horizontal bandwidth = ∞**
azimuth tolerance = 90^o	**vertical bandwidth = 20m**
dip = 0^o	**lag separation distance = 150m**
dip tolerance = 10^o	**lag separation distance tolerance = 100m**

The calculated variogram values are shown in Figure 4. The proportional coordinate system yields the lowest variogram values over all distances indicating that it is the most accurate depiction of the original structure of the estuary layer. The results suggest that the most significant structural deformation on the estuary layer is differential compaction. All geostatistical calculations and modeling would be performed within proportional stratigraphic coordinates and then transformed to the existing elevation coordinates in the final numerical model.

Discussion and Conclusion

The Athabasca oil Sands are often gridded using elevation as the stratigraphic vertical coordinate since minimal structural deformation is assumed to have occurred since the time of deposition. The results of the application, however, suggest that a proportional stratigraphic coordinate system better represents the original structure of the estuary layer. A similar analysis on additional reservoir volumes within marine and fluvial layers could be performed to establish the appropriate restored coordinate system for these layers.

Reservoir frameworks are structurally unique and may require coordinate transformations different than the stratigraphic ones presented here (Deutsch, 2002). For example, fluvial hydrocarbon bearing formations are often aerially sinuous; here, a straightening function could be used in this case to restore the alignment of the formation before it formed meanders. Faults commonly compartmentalize deposits laterally and vertically in which case flattening, shrinking,

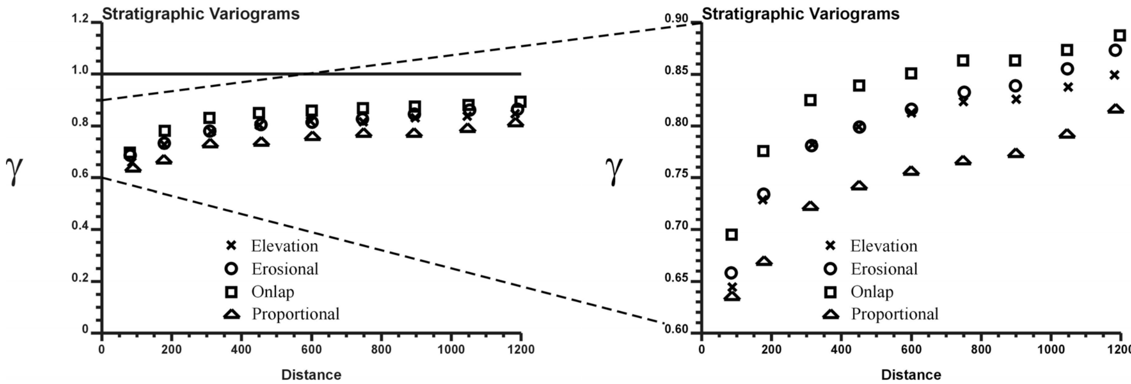


Figure 4 – Horizontal variogram values calculated within elevation, proportional, truncated, and onlap stratigraphic coordinate systems. The right variogram expands the 60% to 90% variance contribution area. All distance is in m.

or extension coordinate transformations could be considered to restore the original structure (Melichar, 2003).

Existing reservoir layer structure is restored to original layer architecture for geostatistical modeling for two reasons: (1) variogaphy is a two-point statistic and is invalid for curvilinear structures, and (2) we want to capture the original spatial correlation of petrophysical variables within the existing reservoir layer architecture.

Proportional, truncated, and onlap stratigraphic transformations account for various structural deformation processes, are straightforward, and reversible. The transformed coordinates provide an appropriate stratigraphic domain for two-point statistical calculations such as the variogram and allow for the true continuity of petrophysical properties to be accounted for in the final reservoir model.

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