IN THE SHADE OF THE TRUNCATED GAUSSIAN SIMULATION

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ABSTRACT

Due to the formation process uranium roll front deposits have very specific geometry. The oxidizing fluids loaded in uranium circulate within a reduced sedimentary environment. When proper oxydo-reduction conditions are met, the uranium precipitates forming the uranium deposit. Three facies types can be interpreted: the oxidized one, upstream of the oxydo-reduction front, the roll itself with high uranium grade and the reduced facies downstream of the oxydo-reduction front. The ore body shape is a meandering ribbon in map view and a croissant shape in cross section. A new method has been developed to model such a deposit. It is based on truncated Gaussian technique. The impact of the different parameters is discussed as well as the specifics of the conditioning and the non stationarity. Finally, the technique is illustrated on a part of a Kazakhstan deposit.

INTRODUCTION

Uranium can be found in very different geological settings. This paper focuses on roll front deposits. Within a reduced sedimentary environment, oxidized fluids transporting uranium are in circulation. When proper oxydo-reduction conditions are met, the uranium precipitates and forms a roll front deposit. The deposit can be divided into three classes of uranium grade: the high grade zone within the roll front itself, the low grade zone within the oxidized zone and the uranium free zone within the reduced facies. The high grade zone has a specific shape: ribbon like in plan view and croissant shaped in cross-section. The orientation is highly dependent on the oxidizing fluids flow direction. The oxidized facies is located upstream while the reduced one is downstream. The main challenge for the modelling is to reproduce an oriented transition zone (the roll) between upstream and downstream.

The shape of the roll front, similar to meandering channels, suggests using existing Boolean techniques (Georgsen and Omre, 1993). It might however be difficult to account for the polarity induced by the oxydo-reduction front.

Moreover when in exploitation, the high number of wells (about a thousand) and their short spacing (about 45m) can be a real difficulty for conditioning.
Regarding a Multi Point Statistics (Strebelle, 2002) approach, a study was conducted in a 2D case (Janot, 2007) using the algorithm Snesim. It shows a real potential. However one of the main challenges for such a method remains the creation of relevant 3D training images.
The two step process that leads to the roll front formation - first the sedimentary phase and then the oxidation-reduction phenomenon- is conducive to the application of truncated Pluri Gaussian techniques (Armstrong *et al.*, 2003; Fontaine and Beucher, 2006; Langlais *et al.*, 2007). One of the main drawbacks of this method is the lack of control on the roll front orientation.
The clear relationship order between the three facies and the strong dependence between their boundaries led to the use of a novel two-step application of the truncated Gaussian technique, called the Shadow Truncated Gaussian Simulation (STGS). First the oxidized facies is obtained by truncation of a Gaussian simulation, its proportion determining the oxidized threshold. This defines the upstream boundary of the roll front facies. Then a "shadow" is defined using the oxidized facies as topography. It indicates the downstream boundary of the roll front. Conditioning by drill hole information requires a specific approach for Roll Front and Reduced facies described in the paper. Finally this technique is applied in 3D to a part of a uranium roll front deposit located in Kazakhstan. The non stationary proportions and the variogram model are derived from the data set. The implementation and the results of the STGS are discussed.

METHODOLOGY

After a description of the technique, the impact of various parameters and their interaction are discussed. Information integration, such as trends and drill hole data, are described.

Description of the Technique

As the Roll Front location and shape are inter- related to the border between the oxidized and the reduced facies, the idea is to use a single Gaussian function and an oriented function to model the three facies (the oxidized facies, the Roll Front and the reduced facies) in order to keep this specific relationship.
First the oxidized facies is generated by classical truncation of the Gaussian field according to its proportions (p_{ox}). The threshold for this truncation is noted t_{ox} (Figure 1-a). The Gaussian values above this threshold are used as topography and its shadow represents the Roll Front facies, the rest being the reduced facies.

The shadow is defined by an oriented virtual light source. This orientation $\vec{t}$ is related to the circulation direction of the oxidizing fluid that generates the Roll Front. The incidence angle (α), the Gaussian field relief and the shadow level (t_{RF}) on which the shadow is projected will define the amount of Roll Front down stream of the oxidized facies (Figure 1-b). The shadow level is counted downwards starting from t_{ox}. The projection level is actually (t_{ox} - t_{RF}). When t_{RF} equals t_{ox} the amount of Roll Front facies is null. Therefore, the amount and shape of Roll Front depends on the Gaussian values of the upstream oxidized facies, the angle and direction of the virtual light and the shadow level.

The virtual light direction controls the polarity between oxidized and reduced zones. It is directly related to the flow direction of the oxidizing fluids and is determined by geological interpretation.

The roll front shape is strongly controlled by the Gaussian field variogram and impacted by the oxidized facies threshold. The local values of the Gaussian field within the oxidized facies have an impact on the shape and amount of Roll Front facies. Extreme Gaussian values will cause elongated shadows leading to a significant amount of Roll Front facies. As the local values cannot be controlled and related to Roll Front proportions, the Gaussian values within the oxidized facies are truncated to t_{ox_max} prior to shadow construction.

To sum up the parameters used in this modeling approach are:

$\vec{t}$, α	Virtual light direction and incidence
γ	Underlying Gaussian field variogram
t_{ox} , t_{ox_max}	Oxidized facies threshold and its maximum
t_{RF}	Shadow level defining the Roll Front facies

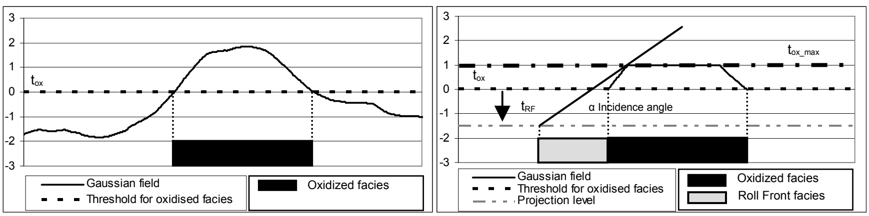

Figure 1: Construction of the three facies in two steps. a) Definition of the oxidized facies (black), b) Construction of the roll front facies (light grey)

These parameters have to be fitted to the characteristics of the studied deposit, which are: oxidizing fluid flow direction, proportions and indicator variograms for all the facies in the field. Their impact on the Roll front shape and proportions as well as their relationship with the input information (drill holes and proportion curve matrix) will be discussed in the following sections.

The Roll Front: Its Shape and Proportion

The Roll Front depends on the upstream oxidized facies; its proportions, variogram and local Gaussian values; the direction and incidence of the virtual light and the shadow level. Parameter impacts are reviewed in a 2D stationary case, only one parameter varies at a time in each test.

The Variogram of the Gaussian Field

The Roll Front shape depends on the oxidized facies boundary. This frontier is related to the Gaussian field variogram. In this study the variogram model is a cubic one to ensure a smooth Roll Front shape.

The shape and Roll Front proportion depend on the variogram range, other parameters being fixed (Figure 2). Roll Front proportion increases when the range decreases (Figure 3).

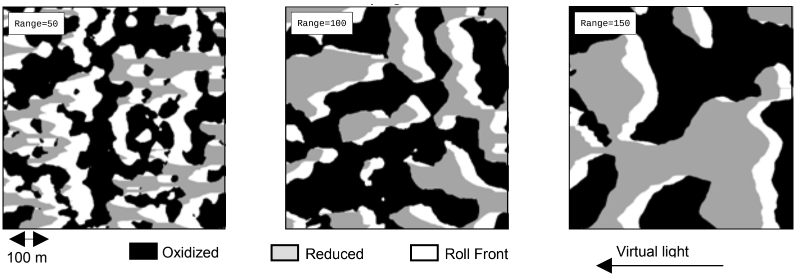

Figure 2 : Roll Front proportion as a function of the variogram range.

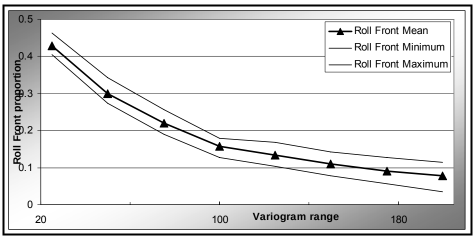

Figure 3: Proportions of Roll Front versus variogram range. The variogram is an isotropic cubic one. Statistics based on 30 simulations.

The Slope of the Virtual Light and the Shadow Level

The Roll Front proportion decreases as the virtual light incidence increases; as depicted in Figure 4 where the angle α increases from left to right. When the virtual light slope is null, the proportion of roll front is at its maximum; when at its zenith, the proportion of roll front is null (Figure 5, left). The Roll Front proportion grows as the shadow level increases (Figure 5, right).

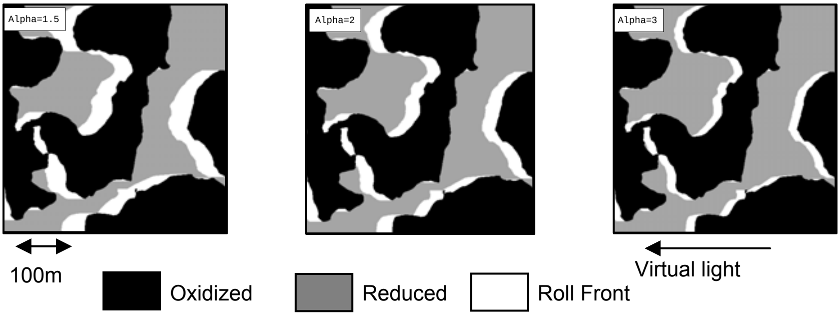

Figure 4: Roll Front proportion as a function of the virtual light angle

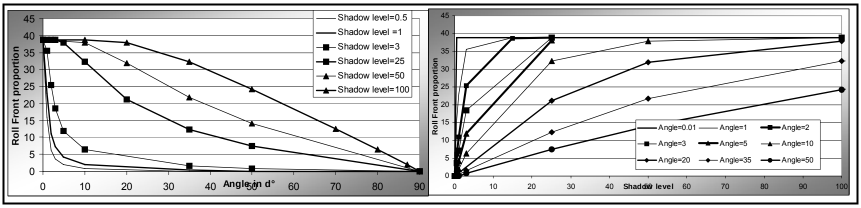

Figure 5: Roll Front proportion versus virtual light incidence angle (left); Roll Front proportion versus shadow level (right). Statistics based on 10 simulations.

Practical Choices

When dealing with a real data set, the parameters of the Gaussian field (γ, t_{ox}) only depend on the oxidized facies; they are determined classically knowing its indicator variogram and proportions (Le Loc'h and Galli, 1997). Consequently the Roll Front proportion is adjusted with two parameters α and t_{RF} . It should be noted that any targeted Roll Front proportion can be obtained for various couples (α, t_{RF}). Therefore it has been decided to keep the incidence angle constant and to vary t_{RF} according to the targeted Roll Front proportion. For the time being t_{ox_max} is set equal to t_{ox} . This leads to an oriented dilation of the oxidized set whose size depends on t_{RF} and incidence angle.

Data Integration

Two types of information are generally available to constrain the model: drill hole information and geological trends. Prior to modeling the geological trends and the drill hole information are combined to elaborate the proportion curve matrix (Beucher and al., 1993).

Drill Hole Facies Conditioning

The facies (oxidized, Roll Front or reduced) known at drill holes locations (x,y,z) are used to perform conditional simulations. In the truncated Gaussian simulation, the first step is to generate Gaussian values at drill holes locations such as after truncation the obtained facies is the conditional one. In this new method, different approaches are necessary depending on the facies type to be honored.

Oxidized Facies Conditioning

As in the classical Truncated Gaussian approach, a location *(x,y,z)* will be affected by the oxidized facies if the Gaussian value at that location is within the correct interval $[t_{ox}, +\infty]$. The threshold t_{ox} is defined by the required proportion of oxidized facies. For this type of facies the conditioning is the classical one.

Roll Front Facies Conditioning

In order to get Roll Front facies at a given location *(x,y,z)* two conditions are required. First the Gaussian value at *(x,y,z)* location should not be within the interval defining the oxidized facies; it should be within the interval $]-\infty, t_{ox}[$. Secondly, there should be a point upstream that will shade the location *(x,y,z)*. The furthest point ($x_{\lim}$) that can shade location *(x,y,z)* is located at $x_{\lim} = x + \frac{|t_{\max} - t_{RF}|}{tg(\alpha)}$ and the associated Gaussian value should be greater than $t_{\max}$. Any point above this ultimate ray and within the oxidized facies will shade point (x,y,z) (grey area in Figure 6). Therefore the conditioning is performed as follows: a point location called a replica is drawn at random within the interval $[x, x_{\lim}]$ and an interval is assigned to the associated Gaussian value to ensure that it lies within the grey zone. For each Roll Front point one replica is generated, doubling the number of conditioning points for this facies.

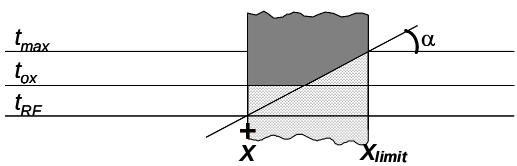

Figure 6: Roll Front Facies conditioning.

Reduced Facies Conditioning

When reduced facies information is encountered, it implies that it is not oxidized and that there is no point upstream that can shade this location. Therefore, it means that there is no point within the dark grey area depicted in Figure 6. All points along the segment $[x, x_{\lim}]$ should be below the maximum of t_{ox} or the ray (dotted area). A reduced facies point in x indicates constraint on a whole segment $[x, x_{\lim}]$. In practice the segment is discretized into a finite number of additional conditioning points (replicas). The discretization lag depends on the segment length and the variogram range. The shorter the range; the larger the number of replicas.

Facies Proportions Conditioning

Stationary Case

Starting from the construction of the Roll Front, in a stationary case and for constant t_{ox}, t_{RF}, the roll front probability at a given point x_0 can be written as:

$$\{x_0 \in (\text{Roll Front})\} \Leftrightarrow \{x_0 \notin (\text{oxidised}); \exists x_1\ x_1 \subset [x_0 + L] \text{such as } x_1 \in (\text{oxidised})\}$$

with Z the stationary Gaussian Random Function (GRF) and $L = t_{RF}/tg(\alpha)$.
After discretization on a regular grid of cell size d (L=nd), the probability of this event is:

$$P[x_0 \in (\text{Roll Front})] \Leftrightarrow P[(Z(x_0) < t_{ox}) \text{and } \exists i, 1 \le i \le n\ Z(x_0 + id) < t_{ox}]$$

Then

$$P[x_0 \in (\text{Roll Front})] \Leftrightarrow P[(Z(x_0) < t_{ox})] - P[\forall i\ 1 \le i \le n\ Z(x_0 + id) < t_{ox}]$$

The second term of this formula corresponds to a (n+1) multi-Gaussian variables, however, it cannot be computed literally; thus this probability is estimated by simulations. For further applications, the interest is to find a relationship between Roll Front probability and t_{RF} knowing t_{ox}.

Non Stationarity

For Roll Front deposits where the relative location of the three facies is very specific, the stationarity hypothesis is not valid. Non stationarity is taken into account in the model by means of proportion curve matrix. Oxidized facies proportions are honored using a location dependent t_{ox} derived for the non stationary oxidized facies proportions as in the non stationary Truncated Gaussian Technique. For the Roll Front facies, the proportion transformation in 3D values of t_{RF} is an approximation, deduced from the previous computations. As a first approximation, considering the linear dependence of these two variables for a given t_{ox}, a multiplying coefficient has been used in the following illustration.

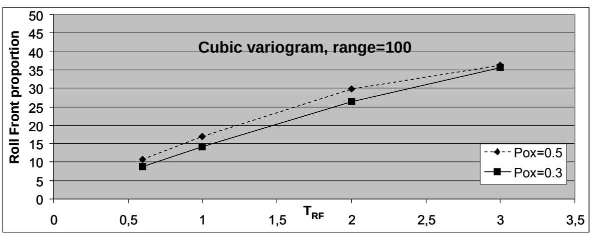

Figure 7: Roll front proportion versus T_{RF} for two Tox values

A CASE STUDY: MUYUMKUM ORE

Geological Context

The Muyumkum uranium deposit is located in Kazakhstan in the southern part of the Tchou-Sarysou basin. The southern parcel of Muyumkum is limited by the Souzak fault to the south and in the north by the Muyumkum fault. The main mineralized horizon, named Uyuk, is from the Lower Eocene. It is represented by a facies deposited in a sedimentary margin littoral environment. It can be split into two parts: the lower Uyuk (the sandy productive horizon) and the upper Uyuk (shaly sand, impermeable). Within Uyuk, shaly sands are present as well as shale lenses with thickness varying from 0.2m to 4m. The mineralized horizons are isolated by shale layers (about 10% of shales).

Data Analysis

Two hundred and forty one drill holes are available in the zone of interest. The drill holes spacing varies in the NW-SE direction from 12m to 200m leading to an average of 44m. The drill holes lines are spaced by 38m to 68m with an average of about 49m. Along the drill holes within the mineralized horizon the logs have been interpreted into three classes: Oxidized facies, Roll Front facies and Reduced facies. Prior to any analysis the data has been flattened in relation to a paleo-horizontal surface. As the oxidizing fluid flow can be considered as horizontal and EW oriented at the working scale of this deposit, the virtual light direction has been taken constant for the whole domain.

The Uyuk thickness varies from 22m to 40m. The global proportions are 40% of oxidized facies, 36% of reduced and 24% of Roll Front. As expected the proportions are clearly non stationary. Therefore, a 3D matrix of proportion curves is constructed to introduce a realistic constraint in the model. Figure 8 shows the vertical proportion curves calculated from groups of similar drill holes and used for the matrix construction.

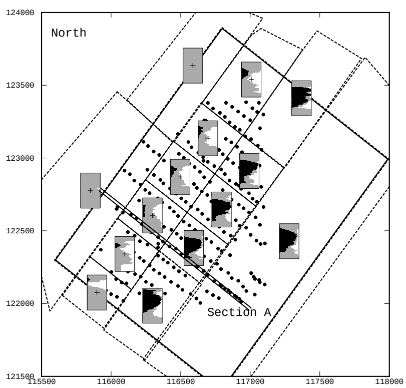

Figure 8: Drill hole locations and vertical proportion curves (VPCs).

Figure 9 shows the roll front proportion along section A extracted from the 3D matrix built from all available drill holes.

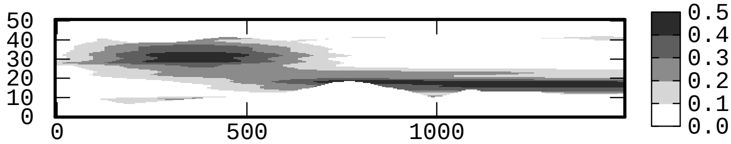

Figure 9 : Roll Front proportion along section A.

Non Conditional Simulations and Data Conditioning Results

Fifty non conditional facies simulations were performed in a 3D block around section A. Figure 11 shows the corresponding roll front probability of occurrences. This figure looks like Figure 9 but shows some differences. The shadow level t_{RF} needs a more accurate tuning to better satisfy the input proportions.

Figure 11 shows one conditional simulation with only two drill holes in the area, (as the moving neighborhood is not yet implemented). Figure 12 shows the roll front probability of occurrences on 50 simulations. The impact of conditioning is quite clear when comparing with the unconditioned one Figure 10. The leftmost well has a clear effect of simulating roll front upstream.

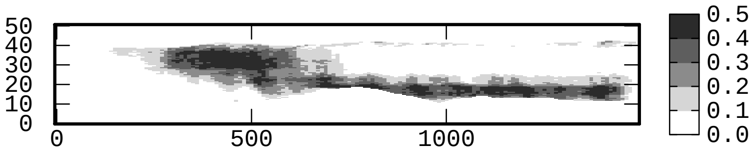

Figure 10: Section A. Probability map of Roll Front occurrences based on 50 non conditional simulations.

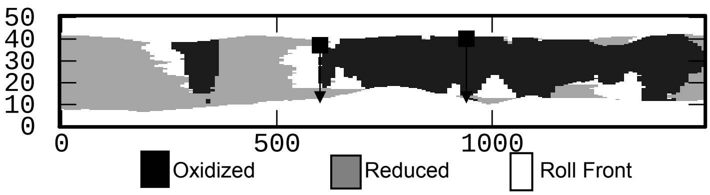

Figure 11 : Section A. One conditional simulation going through the two conditioning wells.

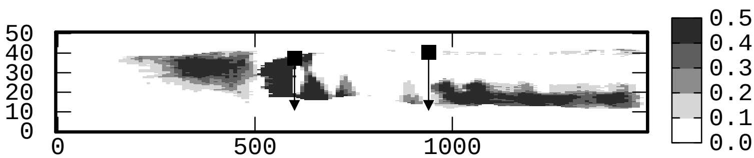

Figure 12 : Section A. Probability map of Roll Front occurrences based on50 conditional simulations.

CONCLUSIONS AND PERSPECTIVES

This new method developed to generate oriented sequences of facies is very promising. Starting with the truncated Gaussian approach, it takes advantage of the existing tools such as the construction of 3D proportions. A few additional parameters are necessary to reproduce this particular shape; orientation of the deposit, incidence of the virtual light and level t_{RF}. The first parameter is given by geological knowledge whilst the others have been combined in a first approach and estimated from the roll front proportions. Due to the particular relationship between the facies, the conditional simulations require specific treatment of the dataset. Conditional simulations have been applied successfully to a real dataset.
At this time improvements are still in progress: in particular the estimation of the t_{RF} from Roll Front proportions in a non stationary case.

In this paper, the choice that has been made for generating the Roll Front corresponds to a dilation of the oxidized facies whose size is constant for a given t_{RF}. The variability from one simulation to another is mainly due to the variability on the location of the oxidized facies. The randomization of the dilation size and the variability of the dilation orientation is still under study. But we should keep in mind that there is a lack of knowledge and data about the orientation and its variation. Only general tendancy is accessible.

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REFERENCES

Armstrong, M., Galli, A., Le Loc'h, G., Geffroy, F. and Eschard, R. (2003).*Plurigaussian Simulations in Geosciences*, Springer-Verlag Berlin, 149p.
Beucher, H., Galli, A., Le Loc'h, G. and Ravenne C., Heresim Group. (1993). *Including a Regional Trend in Reservoir Modeling using the Truncated Gaussian Method,* In Soares ed., *Geostatistics Tróia '92*. Vol. 1. Dordrecht : Kluwer. pp.555-566.
Fontaine, L. and Beucher, H. (2006) *Simulation of the Muyumkum Uranium Roll Front Deposit by Using Truncated Pluri-Gaussian Method,* AusIMM 2006, Darwin, Australia, August 2006.
Georgsen, F. and More, H. (1993). *Combining Fiber Processes and Gaussian Random Functions for Modeling Fluvial Reservoirs,* In Geostatistics Tróia'92, A. Soares, ed. Kluver, Dordrecht, Netherlands, Vol. 1 pp. 425-439.
Janot, N. (2007), *Modélisation des Gisements d'Uranium de Type Roll Fronts par Statistiques Multi-points.* Areva NC, Stage de fin d'études ENSGN.
Langlais, V., Ourir, A., Goblet, P. and Beucher, H. (2007) *A 3D Methodology for ISL Modeling and Uncertainty Quantification from Geology to Recovery Process,* in APCOM 2007 Proceedings, E. Magri, ed.
Le Loc'h, G., Galli, A. (1997). *Truncated Plurigaussian Method: Theoretical and Practical Points of View*, In Baafi et al. eds., Geostatistics Wollongong '96. Vol. 1. Dordrecht : Kluwer. pp. 211-222.
Strebelle, S. (2002) *Conditional Simulation of Complex Geological Structures using Multipoint Statistic*, Mathematical geology vol.34,N°1, January 2002.