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3D representations of a uranium roll-front deposit

D. Renard* and H. Beucher

This article presents a method to construct a three-dimensional (3D) block within units whose spatial characteristics are similar to those of a uranium roll-front deposit. In order to mimic the particular uranium roll-front deposits, a specific stochastic model has been developed, using some geostatistical simulation concepts. They refer to the well-established PluriGaussian Simulation model which has been rephrased in order to produce the specific ore body shapes.

Keywords: Geostatistics, Simulations, PluriGaussian, Roll front, Uranium

This paper is part of a special issue on uranium deposits and in-situ leaching

Roll-front environment

Among the different geological settings for uranium deposits, the roll fronts hosted within permeable and porous sandstone have a very specific geometry (crescent-shape bodies) due to their particular genesis (Fig. 1). The mechanism responsible is the dissolution of uranium from the nearby formation and the transport of this soluble uranium in the host unit (Dahlkamp, 1993). When this oxidised fluids, circulating within a reduced sedimentary environment, change redox state, generally in contact with carbon-rich organic matter, uranium precipitates to form a front. The current paper presents a new technique developed for stochastic modelling of the roll-type uranium deposits. The proposed approach represents a modification of the conventional Pluri-Gaussian method of conditional simulation developed in 80th for modelling geometry of mineral deposits (Armstrong et al., 2011).

Geostatistical methodology

Geostatistics has been developed as a branch of the spatial statistics since 1965 by Pr Matheron, after the pioneering work from D. Krige. It was initiated in the mining industry for predicting grades in gold mines of South Africa. Then it gained momentum and is now applied extensively to predict probability distributions in diverse disciplines such as the petroleum industry, hydrogeology, hydrology, meteorology, forestry, oceanography and agriculture. All these domains have in common that they make use of quantitative or qualitative variables expressed in a geographical system, referred to as regionalised variables. These random variables are far too complex to be processed using a deterministic approach, and a methodology based on statistics is needed to tackle their evaluation.

A common problem is to interpolate the random variable of interest at a proposed unsampled location,

starting from observations of its value at nearby locations. The geostatistical method, called Kriging, allows the deriving of the best linear estimate of the variable over a given surface or volume (while honouring the sampled information) by reducing the variance of the estimation error to a minimum for all possible linear weighted averaging schemes. The weights assigned to each measurement depend on the spatial characteristics of the variable of interest, calculated from the data through the experimental variogram tool and ultimately fitted using a specific mathematical function called the (variogram) model (Chiles and Delfiner, 2011).

If we wish to deal with issues of variability, Kriging is no more optimal as its minimisation principle leads to estimated results smoother than reality. This may not be a problem for predicting gross grade or tonnage but becomes a real issue when predicting local variability of grade or probability of exceeding a given threshold. The answer is simulation. The simulation technique is a process used for replicating reality using a geostatistical model. It enables the generation of a number of 'equally likely' maps (or outcomes) of the target variable in a Monte-Carlo fashion, sharing the same spatial statistics (i.e. the variogram model) as those measured from the data. Moreover, this procedure becomes 'conditional' if it honours the value measured at data points. It is considered as the optimal tool to reproduce the true variability, to solve problems associated with risk and uncertainty, to address the prediction of non-linear quantities (Lantuejoul, 2002).

Pluri-Gaussian simulation methodology. In the 1980s, the simulations have been extended to categorical variables, such as geological facies. The model relies on truncations of a set of one or two underlying Gaussian random functions (GRFs), hence the name of MonoGaussian or PluriGaussian Simulations (PGSs) (Armstrong et al., 2011). The principal advantage of the PGS method is that it provides a consistent framework for simulating simultaneously a set of facies with a limited number of parameters that can be inferred from the data. Those are the variogram model of each underlying GRF, the proportions of the different facies, and the lithotype rule where each GRF is represented

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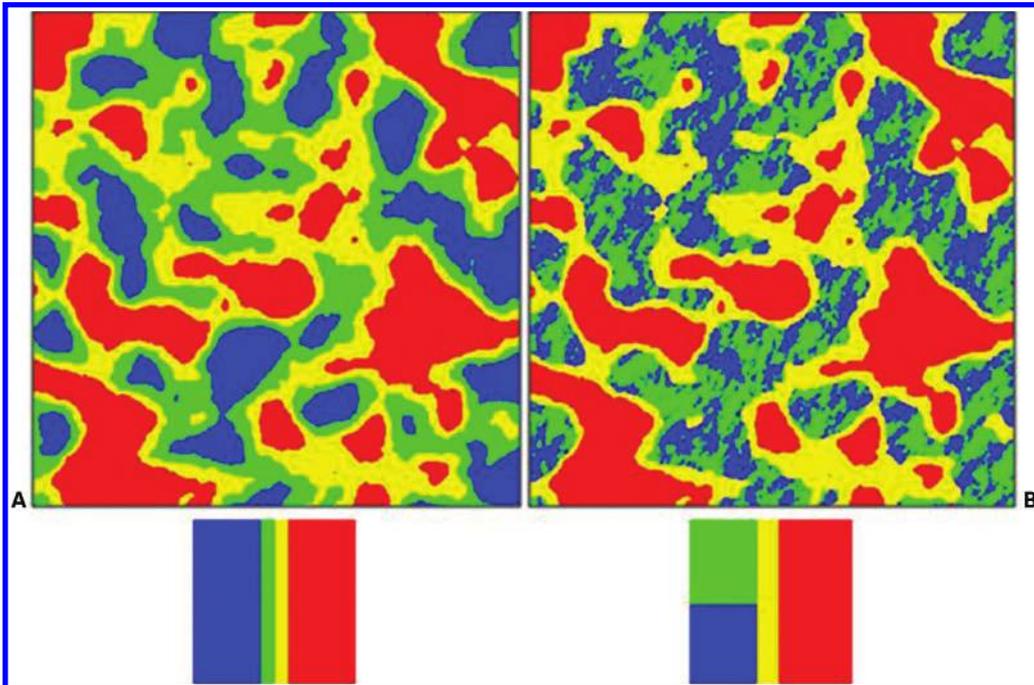
1 A roll front (courtesy from AREVA)

along one axis (non-scaled representation). It describes the vicinity relationships of the different facies usually dictated by the sedimentology environment: for example facies A erodes facies B, facies C and D do not have any contact... (Fig. 2). Finally, these simulations can be conditioned by the knowledge of the lithotype encountered at the conditioning data point.

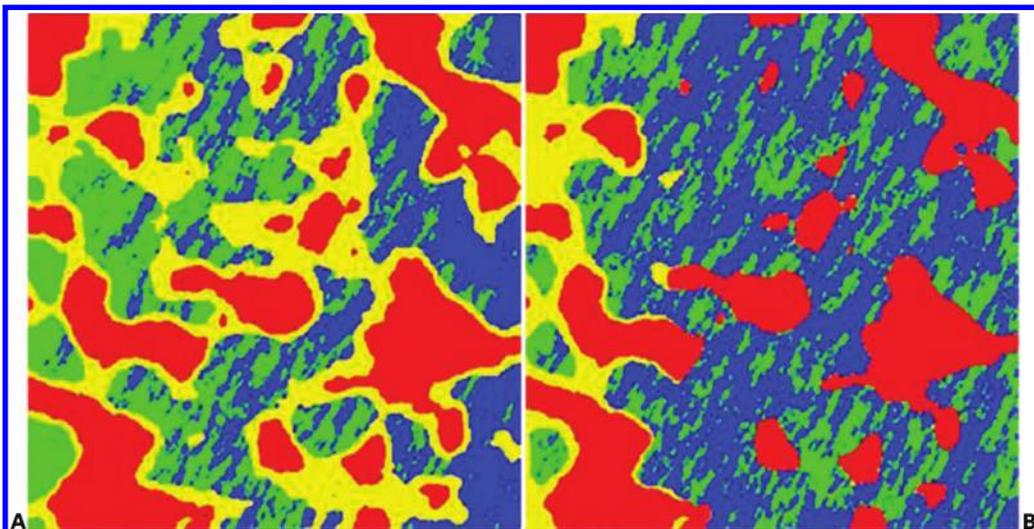
Moreover, an interesting property is that PGS can cope with non-stationarity: this property is simply carried by the proportions which can vary throughout the simulated area (Fig. 3).

Shifted PluriGaussian Simulations

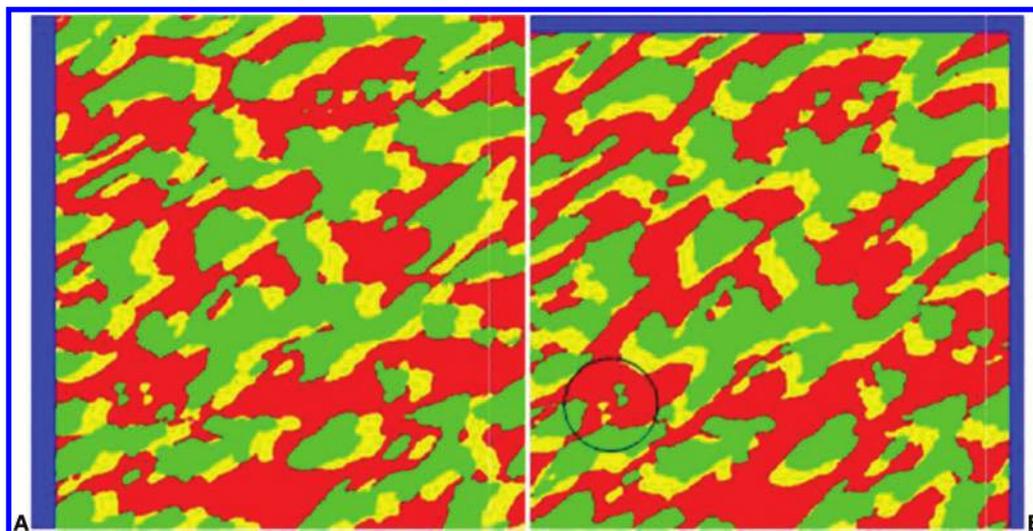
The traditional PGS technique must now be enhanced in order to cope with the particular shape of the uranium roll-front deposit where the three facies (oxidised,



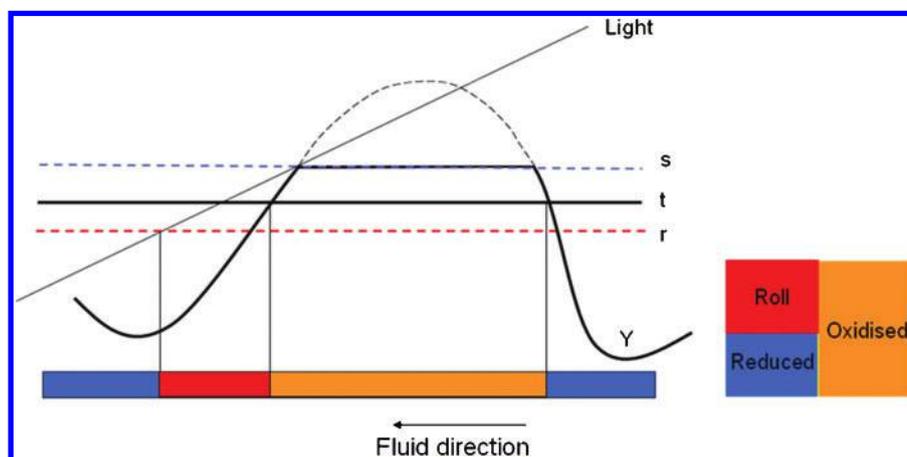
2 Outcomes with four facies (same proportion=25%): MonoGaussian (A) and PluriGaussian (B) – Lithotype rules (second line): contact between blue–green and red facies is forbidden. First GRF: cubic variogram; Second GRF: exponential anisotropic (N30) variogram



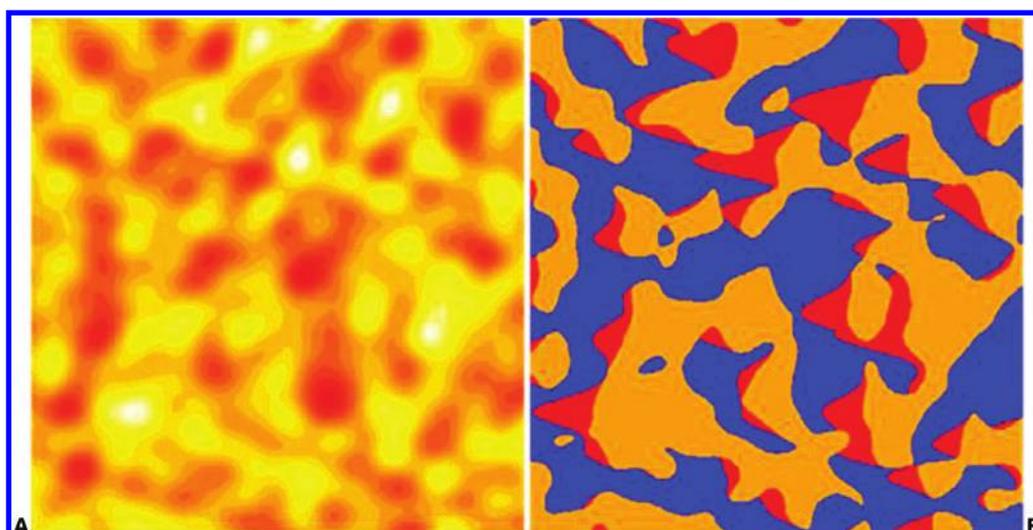
3 Non-stationary PGS: (A) Red and Yellow constant (25%): Blue increases and Green decreases from left to right, (B) Red and Green constant (25%): Blue increases and Yellow decreases from left to right



4 Shifted PGS. The model for the first GRF is an anisotropic cubic structure. The second GRF is a shift of the first one. The shift is equal to [15 m, 0] (A) and [-10 m, -10 m] (B)



5 Explanation scheme for the Shadow PGS

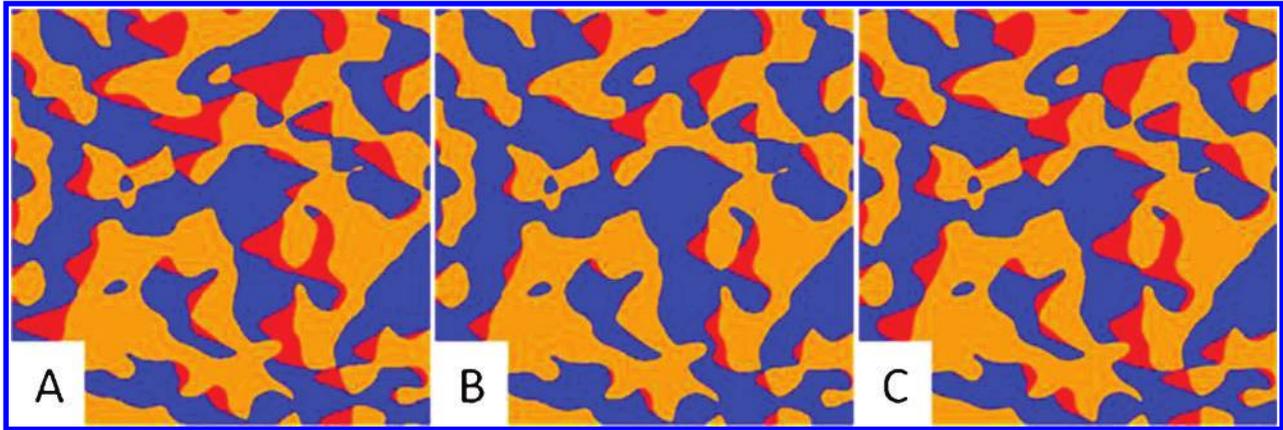


6 Shadow PGS: Gaussian simulation outcome (A) and Shadow PGS (B)

roll-front and reduced facies) must be ordered (non-symmetrical oriented simulation) and where the roll-front must always remain in contact with the oxidised facies.

An interesting extension of the PGS is the shifting technique. The first GRF is standard (characterised by its

model) whereas the second GRF corresponds to the first one shifted by a given fixed vector. Figure 4 represents PGS outcomes over a square field (300 m side) where the first GRF follows an anisotropic cubic model (range is 40 m in N60 direction and 20 m in N150 direction).



7 Shadow PGS: Influence of the parameters. Reference outcome (A); Increased incidence angle (B); Decreased maximum threshold (C)

Obviously, due to the shift, the edge of the field (represented in blue) cannot be simulated.

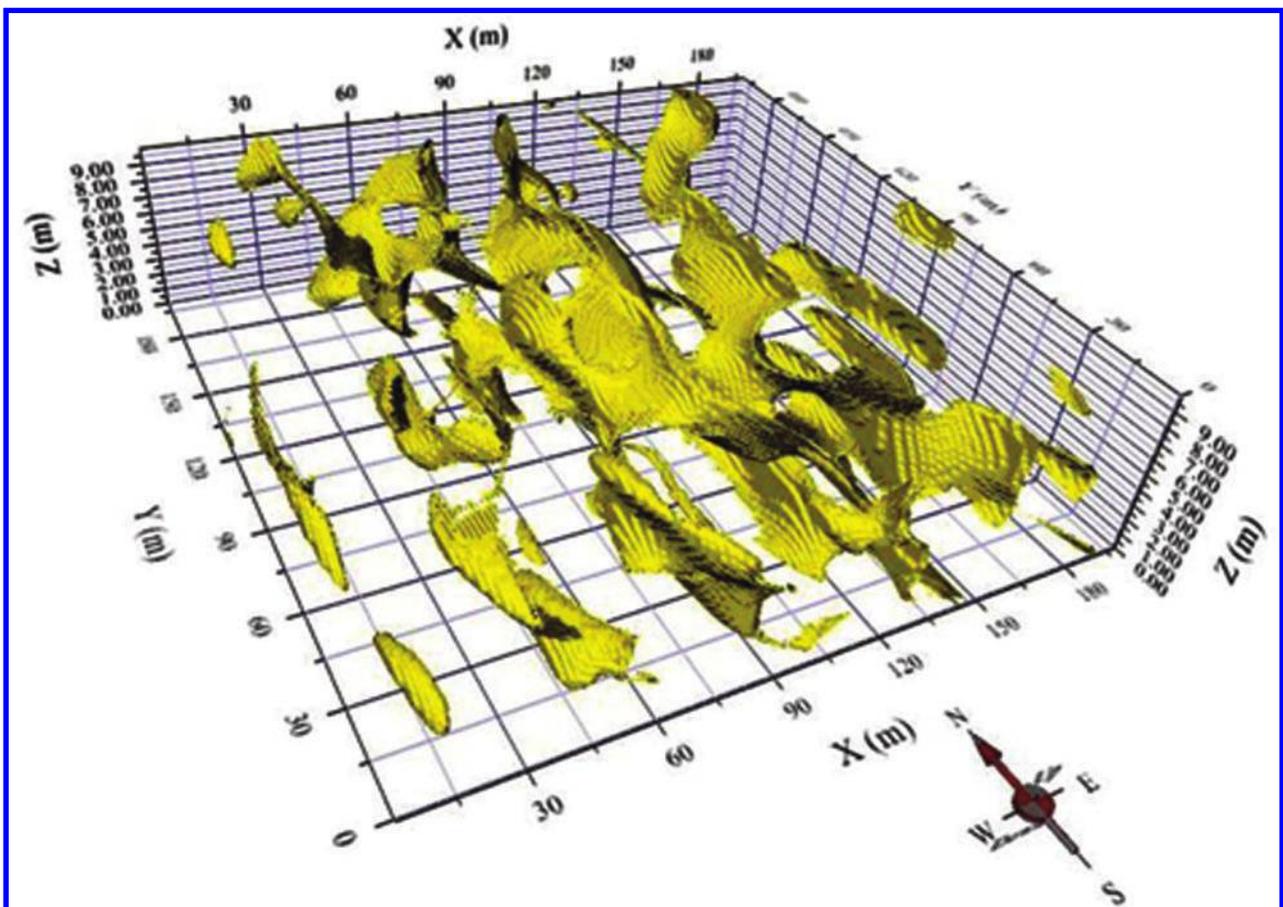
Obviously the shifted PGS correctly represents the specific relationship between the oxidised area (green), the reduced area (red) and the roll front (yellow). However, it is still not perfectly suited as the roll front can be disconnected from the oxidised area (as shown in the circle). This inconsistency is more visible if the shift is larger.

Shadow PGS

The Shadow PGS is a specific extension of the PGS. One Gaussian random function (Y), characterised by its

model, is simulated and considered as topography (in Gaussian scale). Then we consider a virtual light source whose orientation α corresponds to the circulation direction of the oxidising fluid. When the topography is above a threshold t (which is linked to the proportion of the oxidised facies), the simulated facies is oxidised. The shadow of the relief on a reference plane r represents the roll front, the rest being the reduced facies. In order to avoid extreme Gaussian values creating an elongated shadow, the relief may be truncated below a maximum threshold s (Figs. 5–7).

The shadow PGS can also be non-stationary by simply considering proportions that vary over the field:



8 Roll front simulated using shadow PGS

this will induce a variable threshold t . Note that the thresholds r and s could also vary over the field.

The shape and quantity of roll-front facies depend upon the spatial model of the GRF as well as the three thresholds. The first one (t) is directly linked to the proportion of oxidised facies. The other two thresholds (r and s) are more difficult to define: they are related to the proportion of roll-front but also depend on the length of the boundary of the oxidised facies.

Case study: uranium roll-type deposit in Central Asia
Example of a Shadow Pluri-Gaussian simulation of the uranium roll-type deposit is shown in Figure 8. The model of the GRF is an anisotropic Gaussian with the shortest range in the fluid direction. The proportion decreases from East to West and is stationary along the vertical axis. For better legibility, we only represented the roll front facies.

Conclusions

The Shadow PGS is a new method developed to generate a picture of a uranium roll-front deposit. It is constructed as an extension of the traditional PGSs which ensures the possibility to generate several outcomes using a model based on a limited set of parameters while honouring a set

of facies data. It takes advantage of the usual tools such as the proportion matrix for the oxidised facies, but also introduces a few additional parameters such as the light incidence and the different thresholds.

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