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The 10th International Geostatistical Congress took place in Valencia on September 2016 following the traditional quadrennial gathering of theoreticians, engineers and practitioners on geostatistics. From September 5th until September 9th, more than 200 experts discussed the latest developments on the many fields in which geostatistics have found application. This book contains the abstracts for the papers of those people who also submitted a full paper to the book of proceedings. The abstracts are arranged in six parts: Theory, Mining, Petroleum, Hydro(geo)logy, Environmental, and Big Data, corresponding to theoretical and applied communications on the subjects of matter. In addition, there is a special part with the abstracts of the communications presented at the special session in honor of professor Danie Krige, the person who gives name to the technique on which geostatistics is built upon, who passed away on March of 2013.

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Special session in honor of professor Danie Krige

Professor Danie Krige's first memorial lecture: A summary of the basic tenets of evaluating the mineral resource assets of mining companies, as observed in Professor Danie Krige's pioneering work over half a century

Winfred Assibey-Bonsu[1]

[1] *Gold Fields Ltd.*

Keywords: Professor Danie Krige, tribute, tenets, mineral resources

Abstract This paper provides a write up of the first Professor Danie Krige memorial lecture in 2014, which was organised by the University of the Witwatersrand in collaboration with the Southern African Institute of Mining and Metallurgy (SAIMM) and the Geostatistical Association of Southern Africa, where his wife Mrs Ansie Krige, the SAIMM and Professor R.C.A. Minnitt also spoke. The memorial lecture was presented by his previous PhD graduate student, Dr Winfred Assibey-Bonsu.

During that inaugural memorial lecture, the SAIMM highlighted three activities that the institute would hold going forward, so as to remember this great South African mining pioneer:

- The publication of a Danie Krige Commemorative Volume of the SAIMM Journal;
- An annual Danie Krige Memorial Lecture to be facilitated by the School of Mining Engineering;
- The annual award of a Danie Krige medal.

What follows is both a tribute to his work and a testimony to the great man's deep personal integrity, belief in family, humility and faith in God: All of which led him to become not only a giant in the South African mining industry, but in-deed worldwide.

Using classical Geostatistics to quantify the spatiotemporal dynamics of a neurodegenerative disease from brain MRI

Robert Marschallinger[1], Mark Mühlau[2], Paul Schmidt[3], Peter Atkinson[4], Eugen Trinka[5], Stefan Golaszewski[5], Johann Sellner[5]

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Keywords: Multiple Sclerosis, MRI, geostatistics, variography

Abstract We present a novel approach to characterize Multiple Sclerosis (MS) from brain Magnetic Resonance Imaging (MRI) with geostatistics. Brain MRI provides excellent, exhaustive input data to geostatistical analysis, typically several million voxels per MRT-scan. A dataset of 259 spatially normalized binary white matter MS-lesion (WML) patterns covering very mild to extremely severe MS-cases was subject to directional variography. Using an exponential variogram model func-tion, the observed spatial variability in x, y, z directions can be expressed by the geostatistical parameters Range and Sill which perfectly correlate with WML pat-tern surface complexity and lesion volume. A scatter plot of ln(Range) vs. ln(Sill), classified by pattern anisotropy, enables a consistent and clearly arranged presen-tation of MS-lesion patterns based on their geometry.

The geostatistical approach and the graphical representation of results are considered efficient exploratory data analysis tools for longitudinal, cross-sectional and medication impact studies.

Theory

Can Measurement Errors be characterized from Duplicates?

Chantal de Fouquet[1]

[1] *Mines ParisTech-PSL, Ecole des Mines de Paris*

Keywords: measurement error, replicates, kriging

Abstract Sample measurements (of grade, depth…) are almost inevitably affected by errors. Faucheux, Lefebvre et al. (2008) showed that, with the hypothesis of absence of spatial correlation between measurement errors, and between exact values and measurement errors, the variance of the measurement errors are calculable from the sample simple and cross-variograms of two measurement sets, even if the variogram of the exact value is pepitic.

But what about the other cases? When the error is additive, the presence of correlation with the exact value can remain undetectable, and the variance of the measurement errors is not always calculable. It's the same for an error of multiplicative type. Within a model for measurement errors, kriging in the presence of replicates presents no difficulty, the kriging matrix being regular. Except in some particular cases, keeping the different measurement values rather than their average improves the precision of the estimation.

Modeling Asymmetrical facies successions using Pluri-Gaussian Simulations

Thomas Le Blevec[1], Olivier Dubrule[2], Cedric M. John[1], Gary J. Hampson[1]

[1] *Imperial College*
[2] *Total*

Keywords: facies, asymmetry, plurigaussian, shift

Abstract An approach to model spatial asymmetrical relations between indicators is presented in a pluri-gaussian framework. The underlying Gaussian random functions are modeled with the linear model of co-regionalization and a spatial shift is applied to them. Analytical relationships between the two underlying Gaussian variograms and the indicator covariances are developed for a truncation rule with 3 facies and cut-off at 0.

The application of this truncation rule demonstrates that the spatial shift on the underlying Gaussian functions produces asymmetries in the modeled 1D facies sequences. For a general truncation rule, the indicator covariances can be computed numerically and a sensitivity study shows that the spatial shift and the correlation coefficient between the Gaussian functions provide a great flexibility to model the asymmetry between facies.

Finally, a case study is presented for a Triassic vertical facies succession in the Latemar carbonate platform (Dolomites, northern Italy) composed of shallowing upward cycles.

The model is flexible enough to capture the different transition probabilities between the environments of deposition and to generate realistic facies successions.

Considerations for the use of sequential sampling techniques

Jaap Leguijt[1]

[1] *Shell International*

Keywords: geo-statistical sampling, sequential sampling, sampling diagnostics

Abstract Sequential sampling is a well-known and efficient method to generate laterally continuous models based on two point statistics. This means that second order moments are defined by a variogram. It can be shown that the sequential sampling method correctly generates samples from a probability density function (pdf), when this pdf is only honouring the statistics that define the lateral continui-ty constraints. In Bayesian statistics, this is a prior pdf.

The sequential sampling method is also used to generate models from a probability density function that is constrained by observations, like those that are derived from seismic data. This is a posterior pdf. To justify this approach, some assumptions have to be made. These are not strictly valid and may result in significant errors. These errors will be investigated using a realistic synthetic example. The probabilistic seismic inversion program, Promise, contains a module that is able to account for lateral continuity.

In this module, an alternative approach has been used to mitigate the problems with the sequential sampling method. To realise this, each location needs to be visited many times in succession.

A truly multivariate Normal Score Transform based on Lagrangian Flow

Ute Mueller[1], K. Gerald van den Boogaart[2], Raimon Tolosana Delgado[2]

[1] *Edith Cowan University*
[2] *Helmholtz Zentrum Dresden-Rossendorf, Helmholtz Institute for Resources Technology*

Keywords: multivariate normality, affine equivariance

Abstract In many geostatistical applications a transformation to standard normality is a first step in order to apply standard algorithms in two-point geostatistics. However, in the case of a set of collocated variables marginal normality of each variable does not imply multivariate normality of the set and a joint trans-formation is required. In addition, current methods are not affine equivariant, as should be required for multivariate regionalized data sets without a unique, canonical representation (for example, vector-valued random fields, compositional random fields, layer cake models).

This contribution presents an affine equivariant method of Gaussian anamorphosis based on a flow deformation of the joint sample space of the variables. The method numerically solves the differential equation of a continuous flow deformation that would transform a kernel density estimate of the actual multivariate density of the data into a standard multivariate normal distribution. The inverse transformation is available as well as the back-deformation. Properties of the flow-anamorphosis are discussed for a synthetic application and the implementation is illustrated via two data sets derived from Western Australian mining contexts.

Functional Decomposition Kriging for Embedding Stochastic Anisotropy Simulations

J A Vargas-Guzmán[1], B. Vargas-Murillo[2]

[1] *Saudi Aramco*

Keywords: uncertain anisotropy, structural controls, random fields, multiple resolution models

Abstract This paper develops functional decomposition kriging (FDK) based on consecutive projections of vectors in Hilbert space, which generate conditional components. Weight functions are constructed with spatially variable anisotropy parameters. The method yields forecasted functions that are the summation of scalar random field components. Their spatial integration delivers multiresolution moment models for variable size and shape of elements or cells. FDK does not only forecast anisotropic scalar properties but also non-orthogonal uncertain anisotropy vectors, at non-sampled locations. Since FDK can be stopped, optimized and updated without repeating computations, it is suitable for inverse, adaptive, and real-time modeling with stochastic simulations embedding anisotropy. A 2D example is shown based on data obtained from Lena Delta.

Mining Engineering

Using samples of unequal length to estimate grades in a mineral deposit

Marcel Antonio Arcari-Bassani[1], João Felipe Coimbra-Leite-Costa[1]

[1] *Federal University of Rio Grande do Sul*

Keywords: kriging, support

Abstract During mineral exploration it is common to have multiple drilling campaings. Samples from these campaigns usually have distinct sampling lengths or supports. All the available information should be incorporated when constructing a grade model. However, the variations in length among the samples must be considered during estimation.

We propose to perform kriging using samples of different length. The kriging system is built using average covariances to account for the difference in support between the samples. The technique is applied in a mining case study and the benefits demonstrated.

New Approach to Recoverable Resource Modelling: The Multivariate Case at Olympic Dam

Colin Badenhorst[1], Shane O'Conell[1], Mario Rossi[2]

[1] *BHP Billiton*
[2] *Geosystems International Inc*

Keywords: recoverable resource model, multivariate conditional simulation, change of support and information effect, Olympic Dam

Abstract Traditional estimation techniques significantly under-call the true monetary value of the resource on which mine plans and operations base their business. At Olympic Dam, this is worth billions of dollars. Realising this value requires mine planning engineers to be supplied with an accurate recoverable resource model that correctly estimates the tonnes and grade for a specified support and time scale at the time of mining.

Models estimated using linear methods and wide-spaced drilling typically fail to accurately predict recoverable resources, mainly because of incorrectly accounting for the change of support and information effect. The unavoidable smoothing property of weighted averages is also a significant obstacle. These failures are more significant in underground mining scenarios where higher cut-offs (with respect to the average grades of mineralization) are applied. This paper discusses a different approach to recoverable resource estimation based on conditional simulation methods.

The Olympic Dam deposit is one the world's largest polymetallic deposits. The resource estimation practices at Olympic Dam are comprised of a combination of linear and non-linear techniques to estimate 16 different grade variables critical to mine planning. Measured resources are supported by 20m-spaced underground drilling fans where Kriged estimates perform well in terms of mine to mill reconciliation. However, this not the case for resources classified as Indicated and Inferred. Until infill drilling is undertaken, the accurate estimation of tonnes and grade to the mill is not

possible with the Kriged model. This has a significant impact on life of mine economic valuations and ore reserve estimates of Olympic Dam.

Conditional simulation has been used to generate a recoverable resource estimate from a single realization. This conditional simulation model takes into account both the change of support and the information effect, without the undesired smoothing effect that classic methods introduce. This paper describes the significant challenges faced in applying this approach, including issues such as which realization to choose; data conditioning in areas with little information; ensuring that the multivariate relationships among variables are respected at a block level; software and hardware challenges; and defining benchmarks for ensuring that the "correct" grade-tonnage curves are reproduced. These challenges have to be overcome while ensuring that the resulting estimate is a JORC-compliant model, and is also acceptable under BHP Billiton's corporate governance standards.

Comparison of two grade multivariate simulation approaches on an iron oxide copper gold deposit

Antonio Cortés[1]

[1] AMEC Foster Wheeler

Keywords: multivariate geostatistics, corregionalization, projection pursuit, simulations

Abstract Multivariate geostatistics allows taking advantage of auto-correlation observed between variables and represents a valuable tool for mining applica-tions. This study presents a comparison of a traditional multivariate simulation based on a model of corregionalization against another simulation where decorre-lation is first achieved by "projection pursuit", where independent variables are simulated, then correlated back by the inverse of the decorrelation trans-form. The deposit used for the comparison is an iron oxide copper gold (IOCG) orebody located in the Atacama Desert in the North of Chile. The project value is sensitive to grade, and simulation would help assessing this grade uncertainty. The correlations observed between the different economic elements represent an opportunity to improve the simulation results.This paper starts with a brief geolog-ical description of the orebody including some of the significant geological risks. A short recall of different multivariate simulation techniques is given.

The process and results of multivariate simulation of total copper, acid soluble copper, gold and iron within the deposit using the two methodologies are presented. The focus will be on accounting for the validation, and comparison of process and results.

Complexities in the geostatistics estimation of minerals deposits Besshi type on the nor-west of Pinar del Río, Cuba

Abdiel Díaz-Carmona[1], José Quintín Cuador-Gil[2], Fernando Giménez-Palomares[3], Juan Antonio Monosoriu–Serra[4]

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[4] *Technical Superior School of the Design, Universitat Politècnica de València*

Keywords: lognormal distribution, lognormal kriging, selecting mining unit, Besshi

Abstract On the northwest of Cuba, the "Pinar del Río" province, exist a group of mineral deposits and mineral manifestations that are classified as of Besshi type. Among the most important are: "Hierro Mantua", "Unión 1", "Juan Manuel", "Unión 2", "Flanco Este". Some of them are in the feasibility phase of its studies for future explotation. They are associated to the rocks of the Esperanza Formation of the age (J3ox - K1ne), they are constituted by sequences of terrigenous silts, carbonated and volcanic manifestations of basic composition originated in a marginal basin. The rocks that prevail are calcareous, gritty, argillites, concordant bodies and diabasas and gabbros sub-concordant, representatives of a submarine magmatism, tholeite of rift.

The mineral bodies are presented in form of longer lens that associates to the hill direction NE, parallel to the coast. The elevations are between 60 and 75 meters on the sea level. They appear to the surface, concordant with the enclosing rocks. In some of them the secondary enrichment processes reach a total development, as a result of a process of extreme oxidation, lixiviation and concentration of cupper (Cu) in the primary sulfurous mineralization of volcanogenic - sedimentary origin, of Besshi type.

Historically, classic methods were used for the resources estimation in those mineral deposits. These methods do not guarantee the wanted precision due to the geological

complexities present in the north of Pinar del Río region. In this work two important objectives are developed in order to achieve an appropriate precision: first, a methodology for the determination of the rational selected mining unit for the quantification of the resources in the mineral deposits studied is presented, and second, non-lineal geostatistics methods like Lognormal Kriging and Multigaussian Kriging are used for the estimation of the resources, due to the presence of asymmetric distributions of the Cu values.

The Sequential Gaussian Simulation was used for the determination of the rational selected mining unit. In this sense, as the Cu values shows extremely asymmetric distributions, the logarithmic transformed values were simulated in order to propose possible real values, composed by the average of simulated values inside of blocks in different sizes of selected mining units. The above procedure allows comparing values of the possible real values with the Ordinary Kriging estimations for each block in the networks used. Next the median quadratic errors (MQE) are calculated to obtain the rational size of the blocks for the estimation from the low value of the MQE. This procedure guarantees the mayor precision of the resources so much for local and global scale. Next, the Lognormal Kriging is used for the resources estimation in the rational network obtained before. In some case Multigaussian Kriging are implemented for more accuracy of the estimations, when the logarithmic transformation do not guarantees normal distribution and consequently stationary data.

Definition of Operational Mining Unit (OMU) Size

Cassio Diedrich[1], Joao Dirk[1], Roberto Menin[1], Wellington Fabiano De Paula[1]

[1] *Vale SA*

Keywords: recoverable reserves, Operational Mining Unit, Selective Mining Unit, mining engineering

Abstract The calculation of recoverable mineral resources and reserves curves are generally based on Selective Mining Units (SMUs) represented by a block model. The size or support of the block estimates is characterized by its volume, shape, and orientation upon which it is assigned a grade which directly impacts variance and resulting confidence intervals. However, local geology variations associated with operational mining configuration and production rates are commonly disregarded when defining a SMU.

This paper aims to present an operational practice for defining mineral recoverable curves. It proposes a methodology for achieving more realistic values through an Operational Mining Unit (OMU), matching the expected production distribution of volumes and grades. This consists of initially computing expected actual production, taking into account mining sequencing and production rates, applied to a regular SMU using a common geostatistical resource estimation model. Then, calculation of planned dilution is implemented for a range of block sizes to finally select the one (OMU) that reasonable match to the actual production. OMU size (or sizes, if variable), will yield to tonnes, grades, and metal of ore at given cutoffs (ore and waste) considering its operating selectivity. Different depositional environment of the orebody, mining configuration, and production rates affecting the OMU, are also discussed.

Examples are shown to illustrate the methodology using the Walker Lake public dataset and a real (Cu-Au) operational mining case.

Optimizing Infill Drilling Decisions using Multi-armed Bandits: Application in a Long-term, Multi-element Stockpile

Rein Dirkx[1], Roussos Dimitrakopoulos[1]

[1] *McGill University*

Keywords: infill drilling, multi-armed bandits, long-term stockpiles

Abstract Every mining operation faces a decision regarding additional drilling at some point during its lifetime. The two questions that always arise upon making this decision are whether more drilling is required and, if so, where the additional drill holes should be located. The method presented in this paper addresses both of these questions through an optimization in a Multi-armed Bandit (MAB) framework. The MAB optimizes for the best infill drilling pattern while taking geological uncertainty into account by using multiple conditional simulations for the deposit under consideration. MAB formulations are commonly used in many applications where decisions have to be made between different alternatives with stochastic outcomes, such as internet advertising, clinical trials and others.

The application of the proposed method to a long-term, multi-element stockpile, which is a part of a gold mining complex in Nevada, USA, demonstrates its practical aspects.

A new high-order statistical simulation that is non-stationary and transformation invariant

Amir Abbas Haji Abolhassani[1], Frank P. Ferrie[1], Roussos Dimitrakopoulos[1]

[1] *McGill University*

Keywords: high-order statistics, sequential simulation, transformation invariant, Multi Point Statistics

Abstract Complex structures in natural phenomena, including geological compounds, manifest high order spatial connectivity between facies. This complexity excludes many traditional simulation methods such as single-point (mean) and two-point statistics (variogram), leaving Multi-point (MP) statistical simulation methods as the viable option.

The present work introduces a high-order MP statistical sequential simulation framework. It aims to simulate a set of sparse data given a set of training images, similar to other MP methods. The method first uses a coarse spatial template with a fixed number of data points and a missing value in the middle. The missing value is then conditioned on a data event found in the neighborhood of that point on the template under a Markovian assumption. The Maximum Likelihood Estimate of the weighted averaging over all training images estimates the parameters for this conditional distribution. These weights are calculated based on the similarity of the high-order statistics of the data event of the hard data compared to those of the training image.

The present work introduces a new high-order similarity measure, which is effectively invariant under all linear spatial transformations. The template is then moved on a raster path until all missing middle points are simulated and a realization is drawn from the estimated Conditional Probability Distribution Function. Then in a sequential simulation framework, Multiple-grid is used to allow for finer scale spatial templates with the same fixed number of conditioning data points, now including the points generated in the previous coarser scale realization steps. This sequential simulation continues until all points are realized on the simulation grid. The new high-order

similarity measure allows the present method to be fast as well as robust to all possible linear transformation of the training images. The method respects the statistical complexity of the hard data as it only considers training image (TI) replicates with similar high-order statistics data events. The method's results are promising and the method could be used for any continuous data field simulation given a set of exhaustive TIs.

Fixing Panel Artifacts in LIK Block Models

William Hardtke[1], Celeste Wilson[2]

[1] WCH Consulting LLC
[2] Newmont Mining Corp.

Abstract Three types of panel artifacts are created by the Localized Indicator Kriging (LIK) methodology. Two of these artifact types can be fixed (eliminated) by a two-step process that consists of averaging models with different panel origins and then performing a global relocalization.

The first type of panel artifact and probably the most important, is caused change-of-support transformations, which are independent and applied on a panel by panel basis. Because the transformations result in all of the block values in the panel approaching the mean of the panel, it accentuates the difference in the block grades along the panel boundaries. This effect gets worse when the mean grade of adjacent panels is very dissimilar and/or when the transformation is large.

The second type of artifact is the most common but is usually undetectable so in most cases it does not need to be addressed. This artifact is caused by the fact that there are several possible LIK models where the only difference is the panel origin and although each of the resulting models has the same global distribution the high-grade blocks change location. The third type of artifact is caused by using a search ellipse that is too large (non-stationary), which is more typical in areas where drill data is sparse. This artifact type puts isolated high-grade blocks in the middle of low-grade areas. Unlike the first two artifact types, this type needs to be fixed within the kriging parameters. Artifacts can be eliminated by using a two-step process that starts by creating an averaged model from all of the possible LIK models. This "averaged" model provides an excellent estimation of the individual blocks but the global dis-tribution is wrong because the variance has been reduced. The second step in fixing artifacts is to take one of the LIK distributions (they are all the same) and localize it using the "averaged" model as the localizer.

Implications of algorithm and parameter choice: Impacts of geological uncertainty simulation methods on project decision making

Arja Jewbali[1], Bruce Perry[1], Lawrence Allen[1], Richard Inglis[1]

[1] *Newmont Mining Corporation*

Keywords: geological uncertainty, categorical simulation

Abstract Uncertainty in geological models in combination with grade uncertainty are two major contributors to the total resource uncertainty of a mining project. Previous attempts at determining uncertainty in geological models using methods such as MPS (Multiple point statistics), SIS (Sequential Indicator Simulation) and RBF (Radial basis functions) have shown that it is non-trivial, the uncertainty profiles are dependent on the method and the parameters selected.

Most of the methods tested require additional information in the form of either local probabilities or proportions derived from the existing geological interpretation or a conceptual geological model in the form of a training image. This makes some methods amenable to use in the early stages of a project because the method allows for a more complete testing of different geological concepts with a wider band of uncertainty. In later stage projects where there is an increased level of confidence (due to the amount of data collected) in the geologic interpretation, methods that achieve ranges of uncertainty around the interpretation likely provide a more realistic assessment of uncertainty.

This paper details the continuation of research into geostatistical tools suitable for the evaluation of geological uncertainty in order to further understand the intricacies of the methods and the impact of the technique on the resulting uncertainty profile. Suggestions of which methods to use based on the amount of geological information available are provided.

Approaching simultaneous local and global accuracy

Danny Kentwell[1]

[1] SRK Consulting

Keywords: mine planning, smoothing, local, global

Abstract When estimating block grades for mining purposes, the currently available methods allow us to maximize the accuracy of either global grade and tonnage curve prediction or local block selection but not both at once. Locally accurate block estimates provide the best result during actual selection and mining but can give highly distorted global grades and tonnages at cut offs above zero. Globally accurate block estimates provide good prediction of grade and tonnage curves but perform badly during actual selection giving much higher misclassification rates leading to serious degradation of value of the material selected for processing. These statements holds true in varying degrees for all scales and combinations of sample spacing and block size. This paper puts forward a method that retains the properties of accurate global estimation whilst simultaneously approaching maximum local accuracy.

The process is a simple application of rank and replace combining two estimates, one that targets local block accuracy and one that targets actual block variability. The method is empirically demonstrated using a case study using real data. The conclusion, for this data set, is that local selection accuracy can be greatly improved (but not maximized), in comparison to existing methods, while maintaining grade and tonnage curve accuracy that results from true block variability.

Comparisons with ordinary kriging, sequential Gaussian simulation, turning bands, local uniform conditioning, and ordinary kriging with reduced sample numbers, are presented.

Geostatistics for Variable Geometry Veins

Alfredo Marín-Suárez[1]

[1] *Consultorio Geoestadístico Doctor Alfredo Marín*

Keywords: trihedrom, Riemannian, veins, Manifold

Abstract When it comes to performing geostatistical studies in vein-type deposits with variable widths, building the three-dimensional geological model that defines the domain for applying geostatistics is both difficult and potentially inaccurate. This is due to the limited extent of channel sampling, generally limited to some galleries, and all the more so when there are no exploration drillholes at all nor any type of exploration of the mineralized zones.

To this must be added the irregularity of the veins, with abrupt changes of azimuth and dip, as observed when walking through the narrow, polymetallic veins of copper, lead, zinc and silver mineralization at Casapalca, Yauliyacu, Morococha, San Cristóbal, Yauricocha and Huarón; through the filonian gold deposits of Marza, Horizon, Powerful and Acari in Perú; or through the silver deposits of Navalmedio in Almadén-Spain. Even in cases where sufficient information is available, the generally available software on the market is designed for massive deposits and calls for the definition of three-dimensional blocks hardly adaptable to the variable widths of narrow veins about 5 cm to 20 cm in lateral extent.

Hence the idea of applying a modified 'moving trihedral' borrowed from the Theory of the Geometry of Riemann, allowing us to model the random functions L^2 of geostatistics, in a plane of such trihedral, a feature not available in any software existing in the market. Thus, from working in the R^2 space in that trihedral plane, we obtain our results in the R^3 physical space, in which we can then derive the desired linear or non-linear geostatistical results.

And so, among other applications of this method, it becomes possible to apply geostatistics simply, without the need for a detailed, three-dimensional geological model of the mineralization, defining instead its contours in a simple plane, and to

estimate the resources, along with a calculated degree of reliability of great usefulness to classify resources.

Drilling Grid Analysis for Defining Open Pit and Underground Mineral Resources Catego-rization Using Brazilian Sulphide Deposit (Cu-Au) Production Data

Roberto Menin[1], Cassio Diedrich[1], João Dirk[1], Wellington Paula[1]

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Keywords: resource classification, drilling grid analysis, reconciliation process, back analysis

Abstract The varied types of mineral deposits and geological features around the world have led the creation of a large amount of techniques, methodologies and def-initions for mineral resource categorization. The most common methods used in the mineral industry are kriging variance, neighborhood restriction and conditional simulations. These methods generally do not use reconciled production information but long term borehole information based on personal judgment for defining confident intervals/limits on the mineral resource categorization. A drilling spacing back analysis study based on short term production reconciliation of analogue deposits was taken into account for defining mineral resource categorization through the consideration of tonnages and grades confidence intervals related to its respective production volumes. The definition of adequate borehole spacing for categorizing mineral resources and detailed results are demonstrated by both an open pit and an underground project adjacent to an existing mining operation.

This study has considered a Brazilian sulphide deposit (Cu-Au) operating mine as analogue information.

A High-Order, Data-Driven Framework for Joint Simulation of Categorical Variables

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Keywords: high-order statistics, non-Gaussian simulation, categorical variables, multi-point statistics

Abstract Stochastic simulation of categorical variables is often used in the modelling of mineral deposits, petroleum reservoirs or contaminated sites. Relatively recent techniques for categorical simulations are based on multi-point statistical approaches where a training image is used to derive complex spatial relationships using patterns. However, simulated geological realizations are driven by the training image utilized, while the spatial statistics of the hard data is ignored.

This paper presents a data-driven high-order simulation approach based upon the approximation of spatial joint distributions. The high-order joint distribution of categorical variables is expressed as a function of spatial distances similar to variogram models for two-point methods. It is shown that the higher-order relations are connected with lower-orders via boundary conditions. Using an advanced recursive B spline approximation algorithm, the joint distribution is reconstructed from hard data. Finally, conditional distribution is calculated using Bayes rule and random values are simulated sequentially for all unsampled grid nodes.

The main advantages of the proposed technique are its ability to simulate without a training image, which reproduces the high-order relations of hard data, and to adopt the complexity of the model to the information available in the hard data. The approach is tested with a synthetic dataset and compared with a conventional second-order method, SISIM, in terms of cross-correlations and high-order spatial statistics.

Conditional Bias in Kriging - Let's Keep It

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Keywords: resource, estimation, conditional, bias

Abstract Mineral resource estimation has long been plagued with the inherent challenge of conditional bias. Estimation requires the specification of a number of parameters such as block model block size, minimum and maximum number of data used to estimate a block, and search ellipsoid radii. The choice of estimation parameters is not an objective procedure that can be followed from one deposit to the next. Several measures have been proposed to assist in the choice of kriging estimation parameters to lower the conditional bias. These include the slope of regression and kriging efficiency.

The objective of this paper is to demonstrate that both slope of regression and kriging efficiency should be viewed with caution for resource optimization. Lowering conditional bias may be an improper approach to estimating metal grades, especially in deposits for which high cut-off grades are required for mining. A review of slope of regression and kriging efficiency as tools for optimization of es-timation parameters is presented and followed by a case study of these metrics applied to an epithermal gold deposit.

The case study compares block estimated grades with uncertainty distributions of global tonnes and grade at specified cut-offs. The estimated grades are designed for different block sizes, different data sets and different estimation parameters, i.e., those geared towards lowering the conditional bias and those designed for higher block grade variability with high conditional biases.

Operational SMU definition at a Brazilian copper operation

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Keywords: SMU definition, operational dilution, planned dilution, recoverable model

Abstract Fulfilling estimated grade and tonnage curves is a common challenge in mining operations. One of the most impacting parameters in the estimation process of these curves is the Selective Mining Unit (SMU) size, defined as the smallest volume of material that can be selectivity extracted as ore or waste. Such an important parameter as SMU is often defined by generalist practical and theoretical rules based on sampling grid without taking into account aspects such as local geology, mining configuration and production rates.

This paper presents a short-term and production reconciliation application study on the block support size calculation at a copper and gold operation in Brazil. This operational SMU geometry definition is aiming to generate block models with more realistic recov-erable grade and tonnage curves.

Results with the operational SMU show estimates that matches more accurately the actual recoverable curves at given cut-offs compared to the ones obtained using traditional SMU definition, commonly applied at mining industry.

From the spatial sampling of a deposit to mineral resources classification

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Keywords: geostatistics, spatial sampling density, sampling pattern

Abstract In the mining industry, estimated mineral resources of a deposit are classified into inferred, indicated or measured resources, upon their level of confidence. From a geostatistical point of view, this depends on the hole spacing and continuity of the mineralization in the deposit or in the different parts of the deposit. This also depends on some nominal volume on which level of confidence is sought. This corresponds typically to an annual expected production volume, not to the next week production block nor to the whole deposit (unless it is small). We propose here a geostatistical classification of mineral resources in two steps.

The first step consists in measuring the spatial sampling density of the deposit (or throughout the deposit when this density varies). This is done using a specific volume, which is similar to the inverse of the classical density of sample points in space (this density being a number of samples per volume, its inverse is a volume), but which takes into account the variographic structure of the regionalized variable of interest. This first step allows comparing objectively the spatial sampling density of different deposits or parts of deposit.

The second step first converts such a specific volume into a coefficient of variation on the nominal production volume resources. Then a mineral resource category is obtained by thresholding this coefficient of variation. By choosing fixed thresholds for a given commodity and type of deposit, this provides an objective classification of the

resources from different deposits or parts of deposits. The proposed method is illustrated on three case-studies.

Resource Model Dilution and Ore Loss: A Change of Support Approach

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Keywords: change of support, dilution and ore loss, discrete Gaussian Model, misclassification

Abstract The estimation of ore dilution and ore loss factors are critical for the evaluation of mining projects, with the proper estimation of these effects essential for Ore Reserve Estimation. Unplanned ore dilution occurs when excessive amounts of waste are mined with ore, and such dilution may result in the processing of lower than economic cut-off grade material with the ore. Unplanned ore loss occurs when material that is above the economical cut-off grade is hauled to waste stockpiles, due to poor mining practices and/or poor information regarding the local grade of the critical components.

The sources of dilution and ore loss in mining operations are many. This study focuses on the assessment of the ore dilution and loss in a Mineral Resource model, specifically, the proportion and average grade of blocks that are misclassified as ore and waste, which can be referred to as Resource Model Ore Dilution and Model Ore Loss respectively. Unlike the well-established geostatistical conditional simulation approach for assessing model dilution and loss, in this study analytical expressions are derived that are defined under the theoretical framework of the discrete Gaussian method for change of support to quantify the expected model dilution and ore loss.

Practical application of this method is demonstrated through a case study from an Iron ore deposit in Australia.

Diamond Drill Holes and Blast Holes, a Formal Study

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Keywords: blast holes, drill holes, cokriging, deconvolution

Abstract This paper is a geostatistical study of diamond drill holes and blast holes and their potential use together in a cokriging system.

Both measurements of a real copper deposit are formally compared, leading to a model where a blast hole can be considered as a regularization of the drill information up to a nugget effect characteristic of the blasts.

This formal link makes it possible to build a cokriging system that accounts for the different supports and leads to a block model based on blast and drill holes.

The model is tested on a realistic simulation where the true block grades, which are known, are compared to their estimate obtained by: (i) Kriging using only drill holes; (ii) Kriging using only blast holes, and (iii) Cokriging using drill and blast holes together.

The first conclusion is that the best estimate is obtained when only blasts or blast and drill holes are used together, there is no significant difference, this is due to the important amount of blast information. Such result justifies the usual practice consisting in basing the short-term planning on blasts only. But another conclusion appears when kriging is compared to moving average (another common practice), both based on blasts: depending on the number of data used in the neighborhood, the moving average produces a strong conditional bias, and this is a useful reminder of the reason why Kriging was created more than fifty years ago. As a byproduct, we also show how it is possible to filter the blast error by kriging and to make a deconvolution for estimating a point support values using blast measurements.

Building of a tonnage-surface function of metal grades and geological dilution: application to the massive and stockwork Zambujal ore deposit, Neves-Corvo mine

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Keywords: cut-off surfaces, relative grades, copper grades, massive and stockwork ores

Abstract The aim of this study is to build a high-resolution stochastic model of the morphology and metal grades of the Zambujal deposit and, in a second step, to present the results as a tonnage-surface function of the metal grades and of geological dilution (proportion of waste rock in a mining block of stockwork ores). Usually, resources of metal deposits are presented as grade-tonnage curves, but a more complete parameterization involving the morphology is preferable. For instance, if we have two blocks of stockwork ores with the same metal grades, the metal recovery is higher for the block with the higher geological dilution, thus the cut-off metal grades should also take the geological dilution into account.

To build a model in such a type of deposit in which metal grades are zoned by ore types, it is important to take into account the local proportion of sulphides to waste rock in the block. As the local proportion P(x) of ore sulphides to waste rock is not measured in the laboratory, in this work it is proposed to use rock density as a proxy of the sulphide proportion within the rock matrix. If this proportion is quantified, the grades can be modelled using relative grades (i.e. metal grades divided by the proportion of ore sulphides to the waste rock).

Application of direct sequential simulation and co-simulation for evaluation of resources and uncertainty of the Ncondezi coal deposit in Mozambique

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Keywords: coal resources evaluation, principal componentes, Direct Sequential Simulation and Cosimulation, corregionalization model

Abstract This work aims to present a model of the morphology and quality variables of the Ncondezi coal deposit, based on borehole data surveys assigned by the company Ncondezi Coal-Company. It starts with univariate, bivariate and multivariate statistical analysis (Principal Component Analysis – PCA) of the coal-quality variables. Then, it generates a morphological model of the deposit, which is the spatial characterization of the random variable proportion of coal (volume of coal within a selection block). It follows the generation of a coal-quality variables model by simulation.

To model these quality variables, and as they are several and some pairs of variables exhibit good correlations, a methodology involving simulation of PCA as secondary variables is proposed. First, a few principal components are simulated by DSS and then the quality variables are cosimulated conditional to the previous simulated principal components, requiring the correlation coefficients between the variables and the principal components.

This approach works as a global coregionalization model. At the end, both models (the morphological model and the coal quality variables model) enabled the calculation of quantities and parametric curves.

Castelo de Sonhos: Geostatistical quantification of the potential size of a Paleoproterozoic conglomerate-hosted gold deposit

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Keywords: exploration target, conditional simulation, precious metals

Abstract Castelo de Sonhos, a gold deposit in Pará State, Brazil, has seen several phases of exploration since the mid-1990s. These programs have provided drill hole data, surface mapping of outcrops, geophysical surveys, geochemical surveys of soil samples and preliminary metallurgical test work. All available data from these exploration programs have been integrated with recent advances in paleoplate reconstructions, in modeling sedimentary depositional systems, in geostatistical simulation, and in data mining.

This integration of ideas and methods from petroleum geostatistics, from classical statistics and from plate tectonics makes it possible to predict the range of the project's potential tonnage and grade, and to assess the project's up-side and down-side risk. This leads to an exploration target range that is probabilistically quantified, that is well-grounded in data, in field observations and science, and that is testable through drilling. Not only does this quantitative risk assessment improve analysis of the project's technical and economic viability but also, importantly, it builds confidence among investors whose support is critical for advancing the project.

A hybrid model for joint simulation of high-dimensional continuous and categorical variables

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Keywords: joint simulation, Gaussian random field, Plurigaussian model, Min/Max autocorrelation factors

Abstract It is a common challenge for the geosciences to jointly model the uncertainty in continuous and categorical regionalized variables and to reproduce observed spatial correlation and complex relationships in realizations. The demand for computational efficiency in the case of high-dimensional data and large simulation domains, has led practitioners to utilize approaches based on decorrelation/recorrelation and independent simulation. Among such approaches the method of Min/Max Autocorrelation Factors (MAF) has proved to be a practical technique for industrial purposes.

This study presents a hybrid model for joint simulation of high-dimensional continuous and categorical variables. Continuous variables are transformed to Gaussian random functions (GRF) via anamorphosis functions and categorical variables are obtained by truncating one or more GRFs based on the plurigaussian model. MAF factors are then derived from all GRFs. After independent simulation of MAF factors, different realizations of continuous and categorical variables are achieved via back-transformation of MAF factors followed by back-transformation for continuous and truncation for categorical variables respectively. The proposed algorithm is illustrated through a case study.

Performance Analysis of Continuous Resource Model Updating in Lignite Production

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Keywords: ensemble Kalman filter, lignite mining, industrial application, performance analysis

Abstract Recently an efficient updating framework was proposed aiming to improve the raw material quality control and process efficiency in any type of mining operation. The concept integrates sensor data measured on the production line into the resource model and continuously provides locally more accurate resource models. A demonstration in lignite production is applied in order to identify the impurities (marine and fluvial sands) in the coal seams to lead better coal quality management. The updating algorithm applies different algorithmic parameters.

This study aims to investigate the sensitivity of the performance with respect to different parameters for optimal application. Main parameters include the ensemble size, localization and neighborhood strategies and the sensor precision. The results should assist in future applications by determining the impact of the different parameters.

Petroleum Engineering

Geostatistics on unstructured grids, theoretical background and applications.

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Keywords: unstructured grid, support size effect, geostatistical simulation

Abstract Traditionally, geostatistical simulations are performed on regular grids, in IJK coordinates system, simulating centroids of the cells. This approach (commonly used) has a severe drawback: the support size effect is not taken into account and second and some artifacts due to cells distortion may appear. On the other hand, reservoir engineers and hydrogeologists are increasingly referring to new generation of grids to perform dynamic simulation (Voronoï grids, tetrahedral grids …) which require addressing the volume support effect.

In this paper, we present a theoretical framework to simulate variables directly on this new generation of grids, using a depositional coordinates system (UVT) and taking into account the support size effect.

A real field case study is subsequently presented (lithology and petrophysical modeling) to illustrate the possibilities of the new generation of simulation tools. A final conclusion is provided and the remaining problems are discussed to propose some guidelines for future works.

Using Spatial Constraints in Clustering for Electrofacies Calculation

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Keywords: geological modeling, electrofacies, classification

Abstract Petroleum reservoir geological models are usually built in two steps. First, a 3D model of geological bodies is computed, within which rock properties are expected to be stationary and to have low variability. Such geological domains are referred to as "facies" and are often "electrofacies" obtained by clustering petrophysical log curves and calibrating the results with core data. It can happen that log responses of different types of rock are too similar to enable satisfactory estimation of the facies.

In such situations, taking into account the spatial aspect of the data might help the discriminative process. Since the clustering algorithms that are used in this context usually fail to do so, we propose a method to straighten out their outcomes. It consists in post-calibrating the estimated probabilities of presence of each facies in the samples, using geological trends determined by experts. The final facies probability is estimated by a simple kriging of the initial ones.

Measurement errors reflecting the confidence in the clustering algorithms are added to the model and the target mean is taken as the aforementioned geological trend. Assets and liabilities of this approach are reviewed; in particular, theoretical and practical issues about stationarity, neighborhood choice, and possible generalizations are discussed. The estimation of the variance to be assigned to each data point is also analyzed. As the class probabilities sum up to one, the classes are not independent;

solutions are proposed in each context. This approach can be applied for extending class probabilities in 3D.

Pore network modeling from multi-scale imaging using Multiple Point Statistics

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Keywords: pore-network modeling, Multiple Point Statistics, multi-scale

Abstract Petrophysical characterization through pore-network modeling has become a very active field in reservoir core analysis. The technique of X-ray microtomography allows an accurate imaging at the micrometer scale. But the engineer often faces a difficult choice – whether to resolve the heterogeneities directly influencing the petrophysical characteristics but on the small volumes, or to capture less-resolved global tendencies on the statistically representative volumes.

The idea of this work is to reconcile different scales by reconstructing the internal rock structures from the available scan images using Multiple Point Statistics method. This method was successfully used to reconstruct 3D pore network from 2D images. In this work we want to demonstrate on the real cases application how Multiple Point Statistics can be used to solve multi-scale and multi-support problem.

Bernstein copula-based spatial stochastic simulation of petrophysical properties using seismic attributes as secondary variable

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Keywords: Bernstein copula-based spatial stochastic simulation, petrophysical properties, seismic attributes, reservoir characterization

Abstract Modeling the spatial distribution of petrophysical properties in the framework of reservoir characterization is a crucial and difficult task due to the lack of data and hence the degree of uncertainty associated with it. For this reason, in the last years a stochastic simulation approach for the spatial distribution of petrophysical properties has been adopted.

Seismic attributes have been extensively used as secondary variable in static reservoir modeling for petrophysical property prediction but usually assuming linear dependence and Gaussian distribution.

In recent years copulas have become popular for being a flexible way to represent dependency relationships in the financial sector and is already emerging its application in the field of Geostatistics.

A geostatistical simulation method based on Bernstein copula approach as a tool to represent the underlying dependence structure between petrophysical properties and seismic attributes is proposed. The procedure basically consists on applying the simulated annealing method with a joint probability distribution model estimated by a Bernstein copula in a completely non-parametric fashion.

The method has the advantages of not requiring linear dependence or a specific type of distribution. The application of the methodology is illustrated in a case study where the results are compared with sequential Gaussian co-simulation method.

Efficient Uncertainty Quantification and History Matching of Large-Scale Fields through Model Reduction

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Keywords: geomodel structure identification, experimental design, sensitivity analysis, PCA

Abstract Uncertainty quantification (UQ) and history matching (HM) have become a regular routine for reservoir management and decision making in petroleum industry. The zonation method was widely used to reparametrize correlated fields with one lumped constant or multiplier specified for each zone such that the dimensionality of problems can be reduced and the HM problem can be efficiently solved. However, this ad hoc method faces a challenge to find the optimal zones. Moreover, it may fail to honor the geological (or geostatistical) features after the lumped constants or multipliers are applied.

In this work, we present several PCA-based techniques to address this problem by reducing the dimensionality of problem but not subject to the limitations of the zonation method.

Revealing multiple geological scenarios through unsupervised clustering of posterior realizations from reflection seismic inversion

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Keywords: multiple geological scenarios, unsupervised clustering, reflection seismic inversion

Abstract In this study, we analyze 26000 posterior realizations obtained through Monte Carlo sampling from the posterior distribution of a reflection seismic inverse problem and show that the posterior realizations cluster around multimodal peaks. This problem is based on a seismic trace recorded in the southern part of Jutland, Denmark. Prior information is based on observations of lithology sequences of the geology in the area, and the multimodal modes in the posterior realizations will hence represent different geological scenarios. In order to uncover the multimodal nature of the posterior distribution, grouping of posterior realizations is done using an unsupervised clustering technique, namely the K-means clustering algorithms. In order to quantify the choice on the number of clusters in the realizations, the gap-statistic-method is used.

The clustering method is applied on both categorical model parameters representing lithological units, and on the continuous parameters representing the acoustic impedance. These techniques allow quantifying the probability of the different possible geological scenarios that are consistent with the seismic and geological observations.

Results demonstrate that the cluster characteristics are significantly dependent on the types of parameters considered. If the goal of the inversion is to identify different geological scenarios using a parameterization based on lithological units is more informative than a parameterization based on acoustic impedance.

Object modelling in a time of modern well data configurations

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Keywords: object modelling, well conditioning, fluvial

Abstract It is generally recognized that object models have convergence issues when conditioning on complex well patterns. This is true even when in synthetic cases, so the problem is not due only to mismatch between object geometry and true geology. It also stands to reason; as the amount of conditioning data increases, the space of both realisations and potential objects that fits the data decreases. It is thus more difficult for an algorithm to generate valid objects and realisations.

It is common to look at the object model as a marked point process, and simulate using a Metropolis-Hastings algorithm. This algorithm works by proposing new states, typically adding, removing or changing one object, and then accept or reject the new state based on likelihoods. Some of these stochastic proposals are, by random luck, more successful when it comes to well conditioning. This is natural, since a perfect and statistically correct analysis of a full complex well pattern is intractable due to all the possible well configurations. There is also a trade-off between generating many proposals fast where we accept that some of them are failures, versus using more time to generate better proposals.

As the well density increases, it is necessary to have algorithms that are able to handle complex well patterns with less reliance on luck, while still being reasonable fast. We present one such algorithm, where we generate each object sequentially, always conditioning on all data locally. The crucial factor is to have the correct size of local area: Too small will lead to reliance on luck, since the local solution will be less globally valid. On the other hand, a too large local area makes the analysis complicated and

time consuming. This is particularly true since we must balance the likelihood of all valid outcomes, and not just find one possibility.

We also account for two other problems for object model convergence. One is object flexibility, where we add Gaussian fields to all trends in order to get flexibility for well conditioning. The other is well location uncertainty. For long wells, there is a significant uncertainty in the well location. Our approach to handling this is to increase the variance in our Gaussian field close to wells, thus approximating the well uncertainty by adding it to the object uncertainty.

Machine learning methods for sweet spot detection: a case study

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Keywords: sweet spots, classification, machine learning, Support Vector Machine

Abstract In the geosciences, sweet spots are defined as areas of a reservoir that represent best production potential. From the outset, it is not always obvious which reservoir characteristics that best determine the location, and influence the likelihood, of a sweet spot.

Here, we will view detection of sweet spots as a supervised learning problem, and use tools and methodology from machine learning to build data-driven sweet spot classifiers. We will discuss some popular machine learning methods for classification including logistic regression, k-Nearest Neighbors, Support Vector Machine and Random Forest. We will highlight strengths and shortcomings of each method. In particular, we will draw attention to a complex setting and focus on a smaller real data study with limited evidence for sweet spots, where most of these methods struggle. We will illustrate a simple solution where we aim at increasing the performance of these by optimizing for precision.

In conclusion, we observe that all methods considered need some sort of preprocessing or additional tuning to attain practical utility. While the application of Support Vector Machine and Random Forest shows a fair degree of promise, we still stress the need for caution in naive use of machine learning methodology in the geosciences.

Theoretical generalization of Markov chain random field in reservoir lithofacies stochastic simulation

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Keywords: Markov model, posterior probability, reservoir simulation, transiogram fitting

Abstract This paper mainly focuses on the inner relationship between Markov random field (MRF) and Markov chain random field (MCRF). We first discuss the fully independent and conditional independence assumptions of multidimensional Markov chain models. The Equivalence of Markovianity and conditional independence is derived explicitly based on the Bayes' theorem, which completes the theoretical foundation of MCRF. By choosing appropriate potential function, the distribution pattern of an MRF is demonstrated by a Markov chain in a specific MCRF, so that the complicated parameter estimation algorithm and iteration process can be avoided. The computation cost is largely reduced compared to traditional MRF theory used in reservoir modeling.

The MCRF model was then applied to the lithofacies identification of a region and the results were compared with those by the sequential indicator simulation (SIS). Analyses show that this approach can image sandbodies' spatial distribution features more objectively.

Deepwater Reservoir Connectivity Reproduction from MPS and Process-mimicking Geostatistical Methods

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Keywords: multiple-point simulation, process-mimicking modeling, reservoir modeling

Abstract Deepwater unconfined lobe depositional systems are important reservoir targets. High drilling cost and subsalt imaging greatly limit the quantity and quality of data. In the absence of sufficient data, analog architectural studies have identified a variety of potentially important reservoir quality related geometries and trends resulting from the well understood depositional processes. Internal lobe trends (proximal, dominated by amalgamated sands, to distal, dominated by non-amalgamated sands) impacts horizontal connectivity and coupled with compensational lobe stacking impacts vertical connectivity (alternating proximal and distal lobe components are superimposed locally).

Current geostatistical algorithms, pixel-based or object-based, using semivario-grams, training images or geometric parameters, enable the reproduction of spatial statistics inferred from available conditioning data and analogues, but rarely integrate information related to depositional processes. Indeed, because conventional geostatistical models are constructed without any concept of time or depositional sequence, their ability to incorporate sedimentological rules, which explain facies geobodies interactions and intrabody porosity/permeability heterogeneity, is quite limited.

Process-mimicking methods provide an improve ability to honor these flow unit stacking patterns and trends, but trade-off precise conditioning to [moderate to dense] well data and detailed seismic informed trend models. To guide geostatistical reservoir modeling practice, a study assesses the incremental value of process-mimicking relative

to a common multiple-point statistics (MPS) approach with respect to reservoir flow response.

A surface-based (a variant of process-mimicking) method coupled with hierarchical trends efficiently reproduces realistic deepwater lobe geometry, stacking patterns and internal lobe heterogeneity. A wide spectrum of deepwater lobe reservoir models, using archetypal well log data, flow diagnostics and benchmarked with the current MPS approach, quantifies incremental flow significance of these reservoir features. This quantification provides guidance for geostatistical reservoir modeling decisions in the case of unconfined deepwater lobes.

Modeling of depositional environments - Shoreline trajectory - The link between Sequence Stratigraphy and Truncated Gaussian Fields

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Keywords: modelling of depositional environments, sequence stratigraphy, Truncated Gaussian Fields, basin scale modeling

Abstract The key in depicting reservoir and fluid properties of both siliciclastic and carbonate systems lies in the ability to understand the distribution of sediments in time and space. Over the years it has become apparent that sediment distribution is not random but follows as a logical consequence of the changes in the depositional systems over time. With the introduction of sequence stratigraphy some thirty years ago the ability to logically predict sediment distribution in time and space became possible. However, it was not until the introduction of the concept of shoreline trajectory in 1994 that a logical prediction could be made as to the extension of sedimentary facies belts in time and space. The shoreline trajectory is the theoretical path in time and space of the genetic sedimentary successions reflecting the architecture of the sedimentary system.

This paper showes how to directly link the principle of shoreline trajectory to the controlling parameters of the Truncated Gaussian Fields algorithm and thus be able to physically demonstrate the sediment distribution in time and space of any geological model. The approach is demonstrated at several scales, from basin models (seismic scale) to reservoir models (core scale). We will further demonstrate how this systematic geological modelling approach can be undertaken for the entire value chain, from exploration through appraisal, field development and into production.

The main controls of a Truncated Gaussian Field model are the 3D-trend of the underlying Gaussian Field and truncation levels. It is possible to link the X and Y

components of the trend of the Gaussian field to the coastline and the Z component to the Shoreline Trajectory. Thereby, a coherent set of belts with similar facies will be generated, where the geometries (width, height) of these belts are linked to the truncation levels defined for the Truncated Gaussian Field model.

This means that the Truncated Gaussian Field model is fully defined by the understanding of the depositional model. The results from the modelling will therefore be a direct prediction of the geology and can be used as an invaluable tool in elucidating the consequences of the geological understanding. Rather than passively reproducing statistical measures or geological sketches it is possible to actively predict geology.

This is illustrated by a full-scale 3D model of the Post-Permian succession of the Norwegian Barents Sea including Svalbard. The model covers an area 6,5 million square kilometres and a total of 12 identified sequences through the Triassic, Jurassic, Cretaceous and Cenozoic. 255 data points, including all released exploration wells, shallow stratigraphic wells and outcrop sections together with seismic and other information have been applied in the modelling. This model allows a prediction of the distribution of both reservoir quality and source sediments for exploration purposes. Regional and semi-regional models, using the large-scale model as boundary conditions in a sequence stratigraphic context, have also been built for prospect generation, appraisal and field development.

Facies inversion with Plurigaussian lithotype rules

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Keywords: plurigaussian simulations, seismic inversion, stochastic inversion

Abstract Accurate incorporation of geological concepts such as lithological facies distributions is an important aspect of building reservoir models. Consequently, accounting for facies in seismic inversion generates models conditioned to geological concepts, and plays an important role in decision making. Shell's proprietary probabilistic model-based seismic inversion engine Promise is generally applied to invert for continuous variables, such as NTG, saturation, and layer thickness from seismic data. Depending on the scale at which a model is created, bulk reservoir properties tend towards discrete rather than continuous distributions, hence, an implementation of facies in seismic inversion is desirable. In this study, we propose a novel methodology for lithological facies inversion utilizing Plurigaussian rock-type rules. Direct inversion of facies may result in unrealistic facies contacts, therefore, the proposed technique instead inverts for a pair of "guide" variables using Promise.

The guide variables are then classified into facies using a methodology inspired by Plurigaussian simulations, where a defined lithofacies rules map is used to constrain facies proportions and contacts. The required inputs for the workflow are the lithofacies rules and variogram estimates of the guide variables. Both of these can be derived from a prior estimate of the facies distribution, and can also take into account geological constraints from a human expert.

We demonstrate the workflow for a three facies case with a synthetic wedge model and seismic data of a marine survey.

Combined use of object-based models, multipoint statistics and direct sequential simulation for generation of the morphology, porosity and permeability of turbidite channel systems

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Keywords: turbidite channels, object-based simulation, multipoint statistics of classes of azimuth, direct sequential simulation with local histograms

Abstract Turbidite channel systems are a common type of siliciclastic hydrocarbon reservoirs in deep-water settings and by some estimates account for between 1200 and 1300 oil and gas fields worldwide. Geologically, they are composed of series of channels with similar architecture or channel complexes. The considerable size and the detritic properties of these complexes make them good hydrocarbon reservoirs, prompting great interest in the petroleum industry to better characterize these structures. However, modeling these complexes is a challenging procedure because of their curvilinear geometries, the connectivity between channels, and the internal distribution of facies or rock types.

The usual geostatistical methods for modeling reservoirs use two-point or multipoint statistics for the continuity analysis of rock types and properties. Both have limitations when applied to channel systems; two-point statistics do not capture the curvilinear behavior of the channels and multipoint statistics as usually applied are computationally very intensive.

In this work we present an integrated methodology to simulate both the morphology and the petrophysical properties (porosity and permeability) of turbidite channel complexes. The simulation of the morphology encompasses two main stages: first, the simulation of the complex of channels and then, the simulation of the channels

conditional to the complex. Both structures are simulated using an innovative algorithm combining multipoint statistics of classes of azimuth angles embedded within a stochastic object-based modeling approach. This algorithm first computes the multipoint statistics of azimuth classes from training images, and the probabilities of their occurrence are stored in a dynamic data structure called "search tree". These statistics are then used to generate the complex and the channels within the study area. To assess porosity and permeability, the previously simulated channels are intersected as individual objects by a high-resolution grid of blocks. A facies is assigned to each small block according to a conceptual distribution of facies laterally and vertically. Then, as each facies of the conceptual model has a prior probability distribution function for porosity and another for permeability, simulated images of these petrophysical properties are generated using direct sequential simulation with local histograms. Finally, the high-resolution grid of blocks is upscaled to a larger grid to be used in flow simulators.

The results showed a correct representation of the complex geometry and architecture of these systems and the parameters involved are deducted from distribution functions. The proposed methodology can thus be used in all case studies in which the distribution functions are known or assumed. Also, the case study demonstrates that this methodology can be applied to real sizes of reservoirs.

How to model interactions between reservoir properties for complex data structures

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Keywords: Kernel smoothing, Cloud Transform, Local Gaussian Density Estimator, directional smoothing

Abstract We will discuss recent advances in nonparametric density estimation and demonstrate their potential in the petroleum industry, where traditional parametric models and standard kernel methodology may prove too limited. This is especially the case for data possessing additional structure, such as pinch-outs, nonlinearity and heteroscedasticity.

Here, our main focus is on the Cloud Transform (CT) with directional smoothing and Local Gaussian Density Estimator (LGDE). Both are flexible nonparametric methods for density (and conditional distribution) estimation, and well suited for data types commonly encountered in reservoir modelling. However, they have different strengths, e.g. the LGDE method is more stable and easier to work with in high-dimensional data. The methods are illustrated for high- and low-dimensional cases, and in both real and synthetic datasets.

Geostatistical Methods for Unconventional Reservoir Uncertainty Assessments

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Keywords: unconventional reservoir, statistical play, uncertainty modeling

Abstract New methods are required to support unconventional reservoir uncertainty modeling. Unconventional plays add additional complexity with greater uncertainty in direct reservoir measures (e.g. unreliable permeability measures in low permeability rock) and weakened relationships between currently measurable reservoir properties and production results (production mechanisms may not be well understood). As a result unconventional plays are often referred to as "statistical plays", suggesting the reliance on statistical characterization of production distributions as a function of well counts. The application of the techniques de-scribed herein can be utilized to integrate all available information to determine appropriate levels of drilling activity to reduce uncertainty to an acceptable level.

Geostatistical approaches provide opportunities to improve the rigor in the dealing with statistical plays. Rigor is introduced through integration of methods that account for: representative statistics, spatial continuity, volume-variance relations and parameter uncertainty.

Analog production data from US shale gas plays are utilized for demonstration. These data sets, after debiasing, are sources for analog production rate distributions and spatial continuity. Given, these statistics along with a decision of stationarity, geostatistical workflows provide repeatable uncertainty models that may be summarized over a spectrum of model parameters, drilling strategy and well counts.

These geostatistical methods do not replace the need for expert judgement, but they improve the rigor of statistics-based approaches that are essential in statistical plays.

Productivity prediction using Alternating Conditional Expectations

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Keywords: Alternating Conditional Expectations, production prediction, regression

Abstract We present an approach to predict spatial distribution of a variable from a set of geophysical and interpreted grids using Alternating Conditional Expectations (ACE). This technique is based on non-parametric transformations of the predictor and response variables in order to maximize the linear correlation of the transformed predictors with the transformed response. ACE provides a powerful method to detect underlying relationships between the variables and use them as regression to predict the response variable.

A case study is presented illustrating the approach using a set of grids derived from geophysical attributes (gravity, magnetic, electromagnetic) and interpreted grids (isopach, total organic carbon, …) as predictor variables to estimate early hydrocarbon production.

The adaptive plurigaussian simulation model (APS) versus the truncated plurigaussian simulation model (TPS) used in the presence of hard data

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Keywords: adaptive plurigaussian simulation (APS), facies probability fields, soft data conditioning

Abstract In this study, we show why is important and helpful to have prior probability fields of facies occurrence when one wants to use the plurigaussian methodology for the simulation of the facies fields in the presence of hard data (facies observations). The prior probability fields of the facies are developed by a group of experts (geologists, geophysicists, geo-modellers) using information gathered during the exploration phase of the reservoir (seismic data, well logs, outcrops, etc.) and incorporate hard data collected at the well locations.

We perform a comparison between the truncated plurigaussian simulation (TPS) model conditioned to hard data and the adaptive plurigaussian simulation (APS) model in the presence of facies probability fields that incorporate hard data. The APS could be characterized as the TPS conditioned to soft data (facies probability fields). Consequently, in the APS the truncation map is changing with location and the facies observations are always honored irrespective of the Gaussian field values. This is always happening when the prior probability fields of the facies incorporate the hard data (in probabilistic terms). The TPS uses a single truncation map for the entire domain and the Gaussian fields are generated such that in combination with the truncation map render facies fields conditioned to facies observations. Consequently, the Gaussian fields used in the TPS (conditioned to hard data) are not stationary whilst in the APS, the Gaussian fields are typically stationary.

We show in an example that the facies fields obtained with the TPS conditioned to hard data exhibit a bias in theirs spatial distribution. We conclude that aspect analyzing the spatial distribution of the probability fields of the facies, calculated from an ensemble of realizations. The geostatistical properties of the Gaussian fields used for the facies field simulations with TPS, drastically influence the facies fields, introducing a bias in the spatial distribution of the facies. This means that the TPS constrains the prior too much, especially when many facies observations are available and when some of the observations are inside the correlation range of the Gaussian fields. In contrast, when the APS is used, the probability fields of the facies types calculated from an ensemble of realizations reproduce very well the prior probability fields and the geostatistical properties of the Gaussian fields have little influence. Moreover, the prior probability fields incorporate the information about the expected facies proportions because the mean of the probability fields is the global proportion of the facies types. The APS is able to condition the facies simulation to this indicator because the APS uses stationary Gaussian fields and each grid cell has its own truncation map. The TPS uses a single truncation map of which parameters are defined based on the prior information about expected facies proportions but for the stationary case (using stationary Gaussian fields). In order to generate facies fields conditioned to hard data, the TPS truncates Gaussian fields that are not stationary. Consequently, the simulated facies fields with TPS are no longer conditioned to expected facies proportions.

The experiment is performed using a synthetic example with three facies types of which facies fields exhibit a particular topology, characteristic of a real field from the North Sea.

A MPS Algorithm based on Pattern Scale-down Cluster

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Keywords: multiple-point geostatistics, clustering, SIMPAT, pattern

Abstract A key evaluation indicator of multiple-point geostatistics algorithm is balancing contradiction between simulation time-consuming and space-consuming of computer memory, at the same time ensuring model quality. Due to the inherent flaws of SIMPAT, poor efficiency of similarity match computation between data event and whole pattern of train image,leading to impracticability of SIMPAT many years after proposed. Improved algorithms based on SIMPAT, such as Filtersim and DisPat, still not resolved that problem substantially. After researching key points of SIMPAT, this paper proposes PSCSIM algorithm based on pattern scale-down clustering strategy which introduce interval sampling technique into MPS. Unlike SIMPAT, PSCSIM replaces one-step similarity match with two-step similarity match.

Firstly comparing represent pattern of pattern cluster to data event for finding the most similar pattern cluster, and secondly matching similarity of whole patterns in pattern cluster with data event for looking for the target pattern. With same condition, making a comparison of modeling in two-dimension and three-dimension among with PSCSIM, SIMPAT, Snesim, Filtersim and DisPat in the end. As a result, PSCSIM greatly improves computing efficiency on the premise of quality assurance and low memory need.

Integrating new data in reservoir forecasting without building new models

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Keywords: direct forecasting, forecasts updating, uncertainty modeling, multiple-point statistics

Abstract In most hydrocarbon reservoir development projects, geological models are fully rebuilt on a regular basis to integrate new data, in particular observations from new wells, for up-to-date forecasts. Not only this common practice is very time consuming as rebuilding models can take weeks or even months, but it also leads to major, hard to justified, fluctuations in reservoir volume or flow performance forecasts, especially when the modeling staff changes, or a new modeling technology, workflow or software is adopted. Rationalizing the geological model updating process is required to provide stable and reliable forecasting, and make timely, well informed, reservoir management decisions.

This paper presents an innovative methodology to quickly reassess model forecasts, such as reservoir oil-in-place or oil recovery, without rebuilding any geological models provided that the new data observations are reasonably consistent with the current models. The proposed methodology uses a Bayesian framework whereby the multivariate probability joint-distribution of new data predictions and forecast variables needs to be modeled. Assuming that this joint-distribution is multi-Gaussian, the first step consists in computing proxies, e.g. response surfaces using experimental design, to estimate from the set of current geological models the distribution (mean and variance) of new data predictions and forecast variables as a function of the input modeling parameters (e.g. property variograms or training images, trends, histograms). Because model stochasticity (i.e. spatial uncertainty away from wells) typically entails significant uncertainty in the prediction of new local data observations, computing the previous proxies requires generating multiple stochastic realizations for each combination of input modeling parameters. Then, using those proxies and Monte Carlo

simulation, the full multivariate probability joint-distribution of new data predictions and forecast variables is estimated. Plugging the actual new data values into that joint-distribution finally provides new updated probabilistic distributions of the forecast variables.

This new methodology is illustrated on a synthetic case study. In addition to quickly reassess reservoir volume and flow performance predictions, this new approach can be used to select new data observation types and impact maps to assess potential well locations that would optimally reduce forecasting uncertainties.

Statistical scale-up of dispersive transport in heterogeneous reservoir

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Keywords: statistical scale-up, non-Fickian transport, multi-scale heterogeneity, unresolved variability

Abstract Numerical methods are often used to simulate and analyze flow and transport in heterogeneous reservoirs. However, they are limited by computational restrictions including small time steps and fine grid size to avoid numerical dispersion. The ability to perform efficient coarse-scale simulations that capture the uncertainties in reservoir attributes and transport parameters introduced by scale-up remains challenging. A novel method is formulated to properly represent sub-grid variability in coarse-scale models.

First, multiple sub-grid realizations depicting detailed fine-scale heterogeneities and of the same physical sizes as the transport modeling grid block are subjected to random walk particle tracking (RWPT) simulation, which is not prone to numerical dispersion. To capture additional unresolved heterogeneities occurring below even the fine scale, the transition time is sampled stochastically in a fashion similar to the continuous time random walk (CTRW) formulation. Coarse-scale effective dispersivities and transition time are estimated by matching the corresponding effluent history for each realization with an equivalent medium consisting of averaged homogeneous rock properties. Probability distributions of scaled-up effective parameters conditional to particular averaged rock properties are established by aggregating results from all realizations.

Next, to scale-up porosity and permeability, volume variance at the transport modeling scale is computed corresponding to a given spatial correlation model; numerous sets of "conditioning data" are sampled from probability distributions whose mean is the block average of the actual measured values and the variance is the variance of block mean. Multiple realizations at the transport modeling scale are subsequently

constructed via stochastic simulations. The method is applied to model the tracer injection process.

Results obtained from coarse-scale models where properties are populated with the proposed approach are in good agreement with those obtained from detailed fine-scale models. With the advances in nanoparticle technology and its increasing application in unconventional reservoirs, the method presented in this study has significant potential in analyzing tracer tests for characterization of complex reservoirs and reliable assessment of fluid distribution. The approach can also be employed to study scale-dependent dispersivity and its impacts in miscible displacement processes.

The comparative analysis of geostatistical methods on the square with a large number of wells

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Abstract The problem of interpolation of borehole data about properties of natural hydrocarbon reservoir is considered. Its main difficulty consists in the fact that the result has to correspond not only to concrete borehole data, but also to some additional criteria, like variogram and histogram view. In more common sense, the result of interpolation has to correspond to our knowledge about the geological environment formation.

Authors are interested what opportunities in this context give different stochastic methods: Sequential gaussian simulation (SGS), Multiple point statistics (MPS), and realizations of Fuzzy model.

Hydro(geo)logy

Building piezometric maps: contribution of geostatistical tools

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Keywords: piezometric map, kriging with boundary conditions, kriging with partial derivatives

Abstract The work presented has been carried out in the framework of an agreement entitled "Groundwater management in Aquitaine Region", signed between BRGM and Aquitaine Region for the 2008-2013 period, and financially supported by the Adour Garonne Water Agency.

This work aims at setting tools and procedures in order to facilitate the production of piezometric maps of the various aquifers of the Aquitanian Basin, using appropriate interpolation technique. The objective is also to propose as repeatable as possible workflows in order to facilitate and standardize the work, from data control to the final map.

Thus BRGM tested on two deep aquifers how geostatistical tools could be applied in order to answer to Aquitaine Region demand concerning :

- best practices for the construction of piezometric maps, as a function of available data and hydrogeological context, with computation of error maps, applying standard geostatistical techniques as well as more advanced ones,
- optimisation of piezometer monitoring network,
- production of a report showing how these methods can be applied on some "study cases", to be used by hydrogeologists in charge of building or using piezometric maps and not familiar with geostatistical tools.

Various geostatistical tools were tested and compared on two aquifers (a confined aquifer and an unconfined one) :

- standard (co)kriging including or not a polynomial drift,
- kriging with an external drift based either on the result of an hydrodynamic flow model or on other variables like a smoothed topography,
- co-kriging with partial derivatives in order to take into account boundary conditions and/or hydrogeological constraints like groundwater divide,
- cross-validation procedures to identify anomalous data or to optimize the monitoring network.

Except for kriging with partial derivatives, for which few applications are reported in the literature, this paper "standard" geostatistical tools. It shows the interest of introducing more geostatistics in construction of piezometric maps, a domain where geostatistics is less widely used compared to other domains like mineral industry. Consecutive to this study the Department of Gironde (main Department of Aquitaine Region) started producing annual piezometric maps using geostatistical techniques. These maps and their associated kriging standard deviation are built using external drift kriging and are delivered on their web site. Geostatistics can help hydrogeologist to produce piezometric maps, but expertise of the hydrogeologist is essential to introduce appropriate calculation parameters and to validate the result.

A gradient-based blocking Markov chain Monte Carlo method for stochastic inverse modeling

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Keywords: inverse problem, sampling, optimization, adjoint

Abstract Inverse modeling for subsurface flow and transport in porous media is expected to improve the reliability of predictions in that the realizations generated are consistent with the observations of states. A gradient-based blocking Markov chain Monte Carlo (McMC) method is presented for stochastic inverse modeling. The method proposed effectively takes advantage of gradient information for tuning each realization to create a new "candidate" proposal and hence it is capable of improving the performance of McMC. The gradients are efficiently computed by an adjoint method. The proposal mechanism is based on the optimization of a random seed field (or the probability field) and thus it is able to preserve the prior model statistics.

The method proposed has better performances than the single-component McMC and also avoids directly solving a difficult large-scale ill-conditioned optimization problem simply by turning it into a sampling procedure plus a sequence of well-conditioned optimization sub-problems. A synthetic example demonstrates the method proposed.

Geoestatistical modeling and simulation scenarios as optimizing tools for curtain grouting design and construction at a dam foundation

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Keywords: geostatistics, permeability, dam foundation, curtain grouting

Abstract Foundation treatment is a crucial phase in dam construction. With the increasingly overall quality and safety awareness regarding the foundation conditions most designers adopt a strong construction stage dedicated to ground improvement and quality control. The foundation permeability is the parameter to be monitored and optimized during the construction stage.

This work describes the application of Geostatistics to permeability data obtained by the Lugeon test at determined depths within boreholes during curtain grouting at a dam foundation. The curtain grouting is a series of parallel and vertical drill holes along the dam foundation which, after grouting, work as an underground barrier to water percolation. The usual construction methodology consists in applying a sequentially phased drilling strategy in which drill holes the curtain is materialized by successively drilling and grouting a first line of primary boreholes followed by a secondary collinear line of in-between boreholes. This implies that the permeability of the secondary drilling locations may be affected by the first phase grouting.

The studied site is located at Sabor river mouth, northeastern part of Portugal. This river crosses two main geologic settings along its course: schist and granitic complexes. At the site the dam foundation rock mass is described as a medium to good quality schist alternating with quartz rich wakes with a permeable fracture network developed in a very compact rock matrix. Regionally there is an important tectonic active fault - Vilariça Fault – crossing the center of the valley graben in direction of the west side of the site. Water flow in this fractured medium is governed by three main planar

orientations, with various fillings and close aperture. Due to the fractures network and the foliation/schistosity pattern the dam foundation has low permeability although some occurrences of small faults and altered veins work as preferred pathways.

The main objective of this study is assessing the advantage of a geostatistical modeling approach in identifying the zones in which the project design criteria may demand for a first and a secondary phase grouting treatment defined by a threshold permeability of 1 Lugeon unit, Lu. After a preliminary spatial continuity characterization and error study, estimation and probability maps are compared based on indicator kriging and indicator simulation. The obtained models are compared with the information of the acquired construction phase data. Obtained models are finally compared with the initial information indicative of the described approach as an optimizing tool for curtain grouting design at a dam foundation.

Inverse modeling aided by the Classification and Regression Tree (CART) algorithm

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Keywords: inverse modeling, regression tree, CART algorithm, ensemble Kalman filter

Abstract Inverse modeling in hydrogeology is a powerful tool to improve the characterization of hydraulic conductivity and porosity. In the last few years, the use of data assimilation techniques, such as the ensemble Kalman filter, has proven very effective in this field. However, in some cases, the parameter updates by the filtering process may create artificial heterogeneity in certain zones in order to reduce the estimation error. This may happen when observations are scarce in time or space, but also when the parameters being updated are not the only responsible of the behavior of the aquifer (for instance, when high piezometric heads are due to an undetected recharge event, and the filter keeps reducing the conductivity to increase the gradients around high piezometric head observations).

This study pretends to avoid those artifacts by the use of classification and regression trees. The decision and regression trees will be implemented using the CART algorithm with the aim of discriminating whether an updated parameter field is acceptable, and in case it is not acceptable how to proceed. When the algorithm marks as unacceptable a parameter field, it is swapped with another parameter field. The method is demonstrated for a contamination event in a synthetic aquifer based on real data. A numerical model has been created to reproduce flow and transport as observed in the real aquifer. The model has a rectangular shaped area of 3000 meters long by 500 meters wide. For the inverse modeling process two ensembles of fields are used, one for hydraulic conductivity and one for porosity; if needed, recharge can be modified smoothly using spline interpolation. The ensemble Kalman filter is used to update porosities and conductivities, and, if the decision algorithm requests it, the recharge is also modified.

Numerical Simulation of Solute Transport in Groundwater Flow System using Random Walk Method

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Keywords: random walk method, solute transport simulation, validation of model, model stability and sensitivity

Abstract This paper presents the new random walk solute transport model (RWSOLUTE) for solute transport simulation in groundwater flow system. This model is novel in using an efficient particle tracking algorithm. The proposed model is validated against analytical and other reported numerical solutions for chosen test case. The accuracy and stability of the RWSOLUTE model solutions are verified through mass balance error checks and Courant stability criteria. Further the sensitivity of the model solutions is analyzed for varying values of time step size and particle mass.

A Comparison of EnKF and EnPAT Inverse Methods: Non-Gaussianity

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Keywords: EnKF, multiple-point statistics, inverse method

Abstract The EnKF has been extensively used for real-time data assimilation in areas such as reservoir/groundwater modeling. One of the big challenge of the EnKF is how to handle the non-Gaussianity of aquifer properties, particularly for channelized aquifer where preferred flow conduits are encountered. EnPAT is a pattern based inverse method, and was developed to deal with the non-Gaussianity of model updating. In this work, we compared the EnKF and EnPAT on a benchmark ex-ample.

The results show that EnPAT can better reproduce the curvilinear geological features and thus has a better transport prediction. The EnKF has been extensively used for real-time data assimilation in areas such as reservoir/groundwater modeling. One of the big challenge of the EnKF is how to handle the non-Gaussianity of aquifer properties, particularly for channelized aquifer where preferred flow conduits are encountered. EnPAT is a pattern based inverse method, and was developed to deal with the non-Gaussianity of model updating.

In this work, we compared the EnKF and EnPAT on a benchmark example. The results show that EnPAT can better reproduce the curvilinear geological features and thus has a better transport prediction.

Stochastic Inverse Modeling of Interbed Parameters and Transmissivity Using Land Subsidence and Drawdown Data via EnKF

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Keywords: EnKF, Land subsidence, drawdown

Abstract Accurate modeling of hydraulic properties such as transmissivity and interbed specific storages is significant for reliable predictions of land subsidence modeling. Pumping well drawdown and land subsidence data are very important signals for identification of aquifer hydraulic properties. In this work, it is proposed that the Ensemble Kalman Filter is used to calibrate the transmissivity and interbed elastic and inelastic specific storages using both drawdown and subsidence data for the first time.

A synthetic example demonstrated that the characterization of transmissivity and specific storages is improved, and the uncertainties of predictions of both drawdown and subsidence are reduced, when additional dynamic observation data are used for inverse modeling.

Influence of Heterogeneity on Heat Transport Simulations in Shallow Geothermal Systems

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Keywords: heat transport, heterogeneity, stochastic simulation, thermal conductivity

Abstract The influence of parameter heterogeneity, such as permeability, porosity and thermal conductivity, over results of heat transport simulation is studied. A set of synthetic aquifer simulations considering different degrees of heterogeneity in the hydraulic conductivity, porosity and thermal conductivity fields were created by sequential Gaussian simulation techniques.

Heterogeneity of the hydraulic conductivity showed to have a significant influence on the evaluation of a cold plume in the porous media. Higher variances in the hydraulic conductivity distributions cause an important rise in the variability of the simulated temperature fields and a considerable increasing of uncertainty in the simulated heat distribution in the aquifer system.

Results show that considering heterogeneity on the permeability fields induces more impact on the model results than considering heterogeneity of both porosity and thermal conductivity.

Environmental Engineering and Sciences

Building a geological reference platform using sequence stratigraphy combined with geostatistical tools

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Keywords: sequence stratigraphy, borehole validation, French Geological Reference platform

Abstract In 2012 BRGM launched an extensive program to build the new French Geological Reference platform (RGF). Among the objectives of this program is to provide the public with validated, reliable and 3D-consistent geological data. Approx. 100,000 boreholes over the whole French national territory provide a preliminary interpretation in terms of depths of main geological interfaces, but with an unchecked, unknown and often low reliability. The aim of this paper is to present the procedure that has been tested on two areas in France, in order to validate (or not) these boreholes, with the aim of being generalized as much as possible to the nearly 100,000 boreholes waiting for validation. The approach is based on the following steps:

(i) Selection of a loose network of boreholes owning a logging or coring information enabling a reliable interpretation. This first interpretation is based on the correlation of well log data and allows defining 3D sequence stratigraphic framework identifying isochronous surfaces. A litho-stratigraphic interpretation is also performed. Be "A" the collection of all boreholes used for this step (typically 3 % of the total number of holes to be validated) and "B" the other boreholes to validate,

(ii) Geostatistical analysis of characteristic geological interfaces. The analysis is carried out firstly on the "A" type data (to validate the variogram model), then on the "B" type data and at last on "B" knowing "A". It is based on cross-validation tests. In this step, we take into account inequality constraints provided by boreholes that do not

intersect all interfaces, as well as the "litho-stratigraphic pile" defining the formations and their relationships (depositing surfaces or erosion). The goal is to identify quickly and semi-automatically potential errors among the data, up to the geologist to check and correct the anomalies,

(iii) Consistency tests are also used to verify the appropriateness of interpretations towards other constraints (geological map, maximal formation extension limits, digital terrain model ...),

(iv) Construction of a 3D geological model from "A"+"B" boreholes: continuous surfaces representation makes it possible to assess the overall consistency and to validate or invalidate interpretations. Standard-deviation maps allow visualizing areas where data from available but not yet validated boreholes could be added to reduce uncertainty,

(v) At last, truncated plurigaussian facies simulations can be realized using validated data. This allows checking the 3D consistency of interpretation. In some cases, a comparison between surfaces from sequence stratigraphy and borehole lithological information can be performed in order to check the consistency of this information faced to expected deposition environments. This step is currently in progress.

First results show that this procedure can quickly identify the main errors in the data. It guarantees rationalization, reproducibility and traceability of the various stages of validation. Automation aspect is obviously important when it comes to dealing with datasets that can contain tens of thousands of surveys. For this, specific tools have been developed by BRGM (GDM/ MultiLayer software, R scripts, GIS tools).

Constrained spatial clustering of climate variables for geostatistical reconstruction of optimal time series and spatial fields

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Keywords: cluster analysis, temperature zones, bootstrap, areal estimates

Abstract The purpose of this work is to present a new methodology for identifying geographical regions within which the climatic behaviour of a meteorological variable is coherent. We have chosen temperature as the variable of interest and thermal coherence is defined here in the sense of having a strong (negative) correlation between terrain altitude and temperature.

An improved method of constrained spatial cluster analysis is described in the form of a new constrained clustering algorithm. The methodology includes spatial bootstrap statistical tests to provide a more realistic measure of the uncertainty of the coefficient of correlation together with a spatial test of the correlation of residuals. The results are used as optimal estimates of areal temperature averages. The methodology is illustrated by applying it to the annual mean temperature measured at 1220 temperature stations across Spain.

Constraining geostatistical simulations of delta hydrofacies by using machine correlation

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Keywords: geostatistics, borehole correlation, similarity, hydrofacies simulation

Abstract In some hydrogeology applications the only subsurface geological information available comes from a small number of boreholes from which hydrofacies have been intersected and identified. Geostatistical simulation is a widely used stochastic technique for generating a set of possible hydrofacies images that cover the range of the complexity and heterogeneity of the structures. However, the uncertainty due to the very sparse data may be significant to the extent that the simulated images cover an unrealistically large range of possibilities for the hydrofacies characteristics. In such cases it may be desirable to constrain the simulations so as to provide a more realistic, or plausible, set of simulations. In the absence of wireline logging, outcrops, geophysics, production data or any other type of hard data, we propose the use of machine numerical correlation between hydrofacies at the boreholes as a means of constraining the range of plausible simulations.

The procedure is used to simulate delta hydrofacies in a coastal aquifer in Almería (Southern Spain) where the variability of the hydrofacies is critical for managing problems related to seawater intrusion.

Assessing the performance of the gsimcli homogenisation method with precipitation monthly data from the COST-HOME benchmark

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Keywords: geostatistical simulation, precipitation, irregularities, homogenization

Abstract Nowadays, climate data series are used in so many different studies that their importance implies the essential need of good data quality. For this reason, the process of homogenisation became a hot topic in the last decades and many researchers have focused on developing efficient methods for the detection and correction of inhomogeneities in climate data series.

This study evaluates the efficiency of the gsimcli homogenisation method, which is based on a geostatistical simulation approach. For each instant in time, gsimcli uses the Direct Sequential Simulation algorithm to generate several equally probable realisations of the climate variable at the candidate station's location, disregarding its values. The probability density function estimated at the candidate station's location (local pdf), for each instant in time, is then used to verify the existence of inhomogeneities in the candidate time series. When an inhomogeneity is detected, that value is replaced by a statistical value (correction parameter) derived from the estimated local pdf. In order to assess the gsimcli efficiency with different implementation strategies, we homogenised monthly precipitation data from an Austrian network of the COST-HOME benchmark data set (COST Action ES0601: Advances in Homogenization Methods of Climate Series: an integrated approach – HOME). The following parameters were tested: grid cell size, candidates order in the homogenisation process, local radius parameter, detection parameter, and correction parameter.

Performance metrics were computed to assess the efficiency of gsimcli. The results show the high influence of the grid cell size and of the correction parameter in the method's performance.

Ecological Risk Evaluation of Heavy Metal Pollution in Soil in YangGu

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Abstract The pollution of surface soils caused by heavy metals has been a focus problem discussed. To assess the ecological risk caused by heavy metal, 226 samples were collected in YangGu, Shandong Province, China. 7 kinds of heavy metals (Cu, Pb, Cd, Cr, Ni, Zn and As) in agricultural surface soils were analyzed in the paper. Based on the study of spatial variation of different kind of heavy metal, the author got the different realization of the 7 kinds of heavy metals respectively based on the sequential simulation methods. Then, the ecological risk of the region of heavy metals is assessed by Hakanson potential danger index. The result showed that Cd was the main problem in YangGu. The potential ecology risk caused by Cd is nearly 80. The classification is medium. The comprehensive potential ecology risk caused by all the 7 kinds of heavy metal is 114.656. So the pollution of heavy metal made the study area faced with the slight potential ecology risk.

Comparison of trend detection approaches in time series and their application to identify temperature changes in the Valencia region (Eastern Spain)

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Keywords: statistical tests, serial correlation, temperature trend, Monte Carlo simulation

Abstract The identification of systematic small- and intermediate-scale temperature changes (trends) in a time series is of significant importance in the analysis of climate data. This is particularly so in the analysis of local climate change trends and their potential impact on local hydrological cycles. Although many statistical tests have been proposed for detecting these trends their effectiveness is often affected by the presence of serial correlation in the time series. Hence, it is of both interest and necessity to compare the performances of these tests by applying them under a representative range of conditions. In this study, we use Monte Carlo experiments to compare and explore six commonly used tests for detecting trend.

For this purpose, we use the confidence level and power to assess the ability to detect trend in two groups of simulated random fields with and without serial correlation. The statistical tests are also applied to mean annual temperature measured at 13 weather stations located in the Valencia region (Eastern Spain).

Big Data

Urban Dynamics Estimation using Mobile Phone logs and Locally Varying Anisotropy

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Keywords: Locally Varying Anisotropy, mobile phone data, kriging, Big Data

Abstract In telecommunications, the billing data of each telephone, denoted Call Detail Records (CDR), are a large and rich database with information that can be geo-located. By analyzing the events logged in each antenna, a set of time series can be constructed measuring the number of voice and data events in each time of the day. One question that can be addressed using these data involves estimating the movement or flow of people in the city, which can be used for prediction and monitoring in transportation or urban planning.

In this work, geostatistical estimation techniques such as kriging and inverse distance weighting are used to numerically estimate the flow of people. In order to improve the accuracy of the model, secondary information is included in the estimation. This information represents the locally varying anisotropy (LVA) field associated with the major streets and roads in the city. By using this technique, the flow estimation can be obtained with a better quantitative and qualitatively interpretation. In terms of storage and computing power, the volume of raw information is extremely large, for that reason Big Data technologies are mandatory to query the database. Additionally, if high-resolution grids are used in the estimation, High Performance Computing techniques are necessary to speed up the numerical computations using LVA codes.

Case studies are shown, using voice/data records from more than 1 million clients of Telefónica Movistar in Santiago, capital of Chile.

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