Abstract
Geostatistics has entered a new age. Until few years ago, geostatistics could still be considered a leading-edge technology, developed and applied by a handful of specialists. Today, geostatistics is routinely applied to most of the reservoir characterization projects worldwide, providing the ‘quantitative geology’ support needed in the reservoir simulation phase.

This paper describes how a geostatistical model can be built by integrating all the information generated in the individual disciplines, namely Geophysics, Petrophysics, Sedimentology, Stratigraphy and basic Reservoir Engineering. This approach guarantees the internal consistency of the reservoir study and provides a robust model to be upscaled in the forward simulation phase. The information contained in the 3D geological model can also be averaged and exported to a conventional mapping algorithm, thus providing a consistent set of traditional 2D maps of reservoir properties (Net to Gross, net sand, porosity, permeability).

A case study is presented, relevant to a Venezuelan oil and gas condensate field. The geostatistical model uses almost 400 wells and includes a stratigraphic section almost 3000 feet thick, with 60 productive sands and about 500 reservoirs. In this field, where a conventional map-based approach would have been a long and cumbersome job, the complete geostatistical model has been built and input to the simulator in less than 6 months. In such a context, geostatistics represented a fast and efficient tool for the integrated study.

Introduction
Reservoir geologists became familiar with geostatistics starting at the end of the eighties, when several key papers demonstrated the potential of this technique when applied to petroleum reservoirs. However, for some years, geostatistics remained a sophisticated technology, accessible only to specialists. The theoretical development was driven by the quest for new algorithms, while less importance was given to the integration of the method within the routine work process of reservoir studies.

In recent years, however, it became evident to most geoscientists that geostatistics, or stochastic modeling, not only could provide better distributions of the geological parameters, but also has a tremendous potential for integrating data coming from different sources. In particular, general geological knowledge (lithological and depositional models), geophysics and structural geology, petrophysics and basic reservoir engineering can provide useful inputs to the geostatistical model, which in turn become the real heart of the modeling process.

The possibility of integrating data coming from different sources and relevant to different support volume (scale), makes stochastic modeling the most powerful technique currently available for reservoir characterization. When such integration is achieved, we could talk about geologically oriented geostatistics.

This paper discusses the practical issues related to the use of geologically oriented geostatistics for geological modeling, as well as the results that have been obtained in the integrated study of the Zapatos-Mata R field (Eastern province, Venezuela).

Geologically Oriented Geostatistics for Integrated Reservoir Studies
A conventional reservoir geology work, in terms of stratigraphic correlations, log interpretation and facies definition, represents the basis for the geostatistical workflow. This initial stage of the study is very important, as it conditions all the following phases of the work and hence the final results of the integrated study. The flow chart of the process is resumed in Fig. 1. Several key disciplines are involved:
**High Resolution Sequence Stratigraphy**

Sequence stratigraphy is considered the basis for the identification of the genetic units, which in turn define the basic geometric framework of the geological model. Emphasis is made on flooding surfaces and/or surface boundary as reference horizons, as well as the bedding mode within the unit (parallel to a reference level, truncated, proportional between top and base).

**Sedimentology**

Core description allows to define a facies classification scheme and a depositional environment for each litho-unit. A conceptual sedimentological model based on present day analogue can be useful in the definition of the orientation, shape and size of the main sedimentary bodies.

The lithological and the depositional model of the reservoir are represented in the stochastic model by means of facies and relevant distribution functions (variograms, proportion curves,…), that can be established by means of well data as well as conceptual models.

**Geophysics**

Geophysics represents an invaluable source of potential information, both from a structural and a stratigraphic point of view.

On one hand, seismic analysis provides the structural framework, the main faulting scheme and the structural blocks. Large scale structural features, e.g. major faults, determine the main compartments of the model and can be input deterministically. Small scale features, on the other hand, can be stochastically simulated.

From a stratigraphic point of view, on the other hand, geophysics is the only static discipline that offers the possibility to directly investigate the interwell area. Both lithological and petrophysical attributes can be modeled using the seismic volume, and these results can be integrated in the stochastic process to improve the geological modeling. In particular, attribute maps can be generated (e.g., amplitude or seismic impedance), which can be correlated to reservoir properties like average porosity, net to gross or facies distribution. These, in turn, can be used as templates to guide the geostatistical simulation, especially in cases dominated by strong horizontal non-stationarity.

**Petrophysics**

The quantitative log interpretation phase, established for individual wells on the basis of core and log data, can be distributed throughout the reservoir by means of the stochastic model. A conventional quantitative well log analysis or a neural network-based approach, allows to characterize the litho-facies from a petrophysical point of view ($\Phi, K, Sw$). As a consequence, the petrophysical distribution is closely linked to the sedimentological model. In the stochastic modeling phase, litho-facies are usually simulated first, while petrophysical properties are simulated in a later stage, as continuous or discrete variables, within the litho-facies framework.

**Basic Reservoir Engineering**

The integration of dynamic data into the stochastic model has been a topic of intense research in the last decade, since this type of information is invaluable in the definition of a static reservoir model that will be used in a forward simulation phase. The use of basic reservoir engineering sources as production and pressure data, flowmeter logs and Build-Up tests, may help the geologists to better define and characterize both litho-units and lithofacies. While straightforward solutions are not available yet, several interesting approaches have been proposed.

**Geostatistical Database**

The geological data base is exported as well files into the geostatistical data base, in terms of surfaces, facies and petrophysical properties.

The facies is the building block of the geostatistical database. Facies are defined in the sedimentological study and characterized from a petrophysical point of view by integrating the results of the petrophysical study. The distribution of facies in the reservoir space is described by spatial correlation functions, such as the covariance (or its inverse, the variogram) and the vertical proportion curve (VPC). The VPC statistically summarizes in a single diagram the vertical distribution of facies (Fig 2). VPC are simple tools for describing the vertical evolution of lithofacies. Initially developed by geostatisticians to handle vertical non-stationarity, they are now widely used by sedimentologists, reservoir geologists and geomodelers for reservoir description.

Seismic data are also part of the geostatistical database. Being laterally continuous, they have the potential to improve the mapping of the geological attributes, when a correlation exists between seismic attributes and geological parameters (average porosity, net to gross, net sand thickness…). Specific modeling techniques allow to integrate geological grids derived from seismic data or from stratigraphic models to build matrices of VPC that are used in the non-stationary conditional simulations (Fig 2).

Analogue sedimentological models (outcrop studies, remote sensing images, airplane photos…) can be part of the geostatistical database, especially for boolean simulations, in the definition of the geometry of the geological objects.

**Geostatistical Simulations**

Geostatistical modeling techniques are routinely used to build the geological model before scaling-up. These methods provide possible images of the area under investigation, that honor well data and have the same
Recent stochastic modeling algorithms allow a better integration of more and more external constraints and data to obtain accurate and realistic images of the internal architecture of the reservoirs. Among the most used algorithms we can mention the following (Fig. 3):

- **Truncated Gaussian simulation.** This is a pixel-based technique, suited for fluvio deltaic reservoir context, where the net to gross is higher than 60% (amalgamated channels with associated crevasse splay) and where there is a direct relationship between litho-facies and petrophysical properties (no diagenetic effects). It is a variogram-based algorithm which can take into account only one directional anisotropy by litho-unit. The non-stationary option allows to restitute lateral variations and semi-regional trends in terms of both litho-facies and petrophysics.

- **Pluri-gaussian simulation.** It is a pixel-based technique, particularly used in complex siliciclastic or carbonate environments, where concurrent independent geological events can be found (sedimentological and diagenetic for example), with different directional anisotropy. Non-stationary pluri-gaussian algorithms allow to restitute several kinds of heterogeneities linked to different geological processes. The contacts between litho-facies are managed with a logic threshold diagram between the two Gaussian functions.

- **Boolean simulation.** It is an object-based technique, usually applied to deltaic siliciclastic contexts where the net to gross ratio is lower than 60% (distributary channels with mouth bars and associated shoreface). The algorithm can take into account various directional anisotropies for each litho-unit (e.g., shoreface bars perpendicular to the distributary channels). This methodology needs a strong sedimentological support, in terms of a detailed conceptual depositional model.

- **Nested simulation.** This is a mixed object and pixel-based technique, sometimes used in siliciclastic reservoirs where one facies is predominant and erodes the others.

Geologically oriented geostatistics focuses on the facies simulation, in order to generate a realistic distribution of the geological bodies in the reservoir space. Petrophysical properties are assigned in a later stage, within the established facies distribution. The underlying assumption is that the fluid flow, hence the petrophysical model, is mainly governed by the large scale heterogeneities. When good correlation exists between litho-facies and petrophysics (no compaction, no diagenesis effects), a direct assignment can be done. If not, petrophysical properties can be independently simulated, as continuous or discrete variables. In the latter case, specific rock-types or petro-facies can be defined and simulated within each lithofacies (Fig 4).

### Case Study: ZAPATOS – MATA R Integrated Study

The Zapatos-Mata R field has been the object of an integrated reservoir study, which started in 2000 and is still in progress in its dynamic modeling phase. This project has shown the interest of using geostatistics, also in terms of efficiency and time-effectiveness of the project. Past experience shows that large scale geostatistical studies are possible and practical for mature reservoirs, within the usual constraints of time and resources of an integrated study. In the case of Zapatos-Mata R, the complete geostatistical model was built in 6 months, despite the complexity of the field and the number of units and wells involved.

### The Field

ZAPATOS/MATA-R field is located in the Eastern Gas and Oil province of Venezuela (Fig 5). It produces mainly from the Miocene Oficina formation and contains large amounts of gas condensate reserves. Over 400 wells have been drilled in the area since 1955 and gas injection has been implemented in most of the main reservoirs since the early 1960.'

### Geological Framework

From a general point of view, the geology of the ZAPATOS/MATA-R field is characterized by a relatively simple structural setting and a remarkable degree of sedimentological and stratigraphical heterogeneity. Note that these features make this reservoir particularly suited for a geostatistical study.

Fig 6 shows a North-South structural section across the field, where it can be appreciated a gently North dipping monocline (3 to 4°), limited by two antithetic normal faults. Fault throw is usually enough to put in communication different reservoir units.

From a stratigraphic point of view, the Oficina formation is composed by a thick sand/shale interbedding (about 3000’ of impregnated section), deposited in a marine-dominated deltaic front context. The total net to gross ratio of the producing section is about 48%. Six major flooding surfaces have been identified, which bound five major transgressive sequences of 3rd order (called L, M, N-O, R, S). Lower-order elementary genetic sequences have been defined within each major unit (Fig 7). Well-to-well correlations have evidenced drastic lateral facies variation in terms of sand content. A total of 40 litho-units have been identified and correlated, which represents 60 productive
Sedimentological framework

Various cores have been described, with the purpose of identifying the litho-facies and establishing a conceptual depositional model for each litho-unit. Eight main lithofacies have been described along the entire section: upper shoreface, foreshore, mouth bar, distributary channels, bioturbated fine sand, laminated rich organic silt fine sandstone, coal, shale. This association facies, observed on cores, is related to a type 1 delta front environment\(^1\), whose analogue is the present day Orinoco delta (Fig 7). In a later stage, these lithofacies have been grouped into four lithotypes, which have been identified for every well by means of conventional cut-off on the SP/GR/IR log curves. These are:

1. Clean Sandstone (shoreface bars or distributary channels, depending of the litho-unit)
2. Bioturbated Fine Sandstone
3. Siltstone
4. Shale

Out of these, only lithotype 1 is productive and it has been further divided into 4 facies of lower order (rock-types), each characterized by a distinct range of petrophysical properties. Conventional core analysis and quantitative log interpretation have been used to define the petrophysical ranges of each rock-type. In this way, both the sedimentological and petrophysical aspects are restituted by the stochastic simulation.

Petrophysical framework

A conventional quantitative log analysis, calibrated with core data, has been carried out on 40 key wells. From this study, the four rock-types associated to the clean sandstone litho-type have been characterized with distinct \(\Phi-K-S_w\) functions. Later, the rock type definition has been extended to all the wells by generating a synthetic porosity curves based on empirical relationships between SP/resistivity log curves.

The porosity varies between 16% in the best horizons (L and M Sands) and 10% in the lowest ones (R Sands), depending on the facies and the depth (compaction and cementation effects).

Geostatistical modelling

The simulation grid has cartesian geometry. Its dimensions are 50 m x 50 m x approximately 1 foot in the vertical direction. The depositional mode has been assumed proportional to the top and base.

The analysis of the spatial variability has been performed using all the 400 available wells, by means of vertical proportion curves, matrix of proportion curves and variogram functions. After some preliminary tests, it appeared that the boolean technique was the most appropriate for the Oficina formation, for the following reasons (Fig 8):

- Very clear and well referenced sedimentological analogue (Orinoco delta), in terms of size and shape of the sedimentary bodies.
- Low net to gross of the productive section (lower than 60%).
- Lenticular sands.
- More realistic results with respect to the pixel-based techniques.

Boolean simulations have been carried out for each of the 40 litho-units in terms of lithofacies and rock-types. Each unit has been treated independently, with its own geostatistical parameters, consistently with the results of the sedimentological study and the petrophysical analysis. Simulation time for each unit was approximately 30 minutes, using a Sun Ultra 80 machine. The comparison of different realizations for the same lithounit showed that differences are minor and on a local scale. This result was somehow expected, due to the high density of conditioning wells and the good knowledge of the sedimentological model.

Fig 9 shows the simulation results of 2 lithounits, M1U and R1, in terms of facies and porosity. M1U unit is composed of a large scale shoreface bar with a NW-SE orientation, while R1 unit is composed of distributary channels and mouth bars in the perpendicular direction. We can appreciate in the figure the good restitution of the depositional model of these sands, as well as the porosity degradation northward (compaction and cementation effects).

In the final stage of the study, these units have been stacked together in structural position. The final geological model is then constituted by a fine scale 3D grid with over 40 millions cells, populated with lithologic and petrophysical properties.

Applications

The geostatistical model has been built mainly with the purpose of feeding a full field dynamic simulation, which is currently ongoing.

However, another interesting application has been identified in the course of the study, which relates to the generation of maps for OOIP calculations, corporate database storing and government approval.

These maps represent the official documents of the reservoirs and must be consistent with the data used in the numerical simulation study. An original procedure was applied to the 3D grids coming from the stochastic model, in order to generate these maps.

The procedure basically consists in exporting the results from the geostatistical package, applying a
vertical average by taking into account the relevant cut-off on the facies and/or on the petrophysical parameters, and importing them into a commercial mapping software. Here, maps are smoothed and prepared following the official company requirements, while preserving the vertical average data at the well locations (Fig. 10).

Average porosity and permeability maps, net to gross, net sand and most likely, facies maps have been generated in this way. These maps provide traditional views of the main reservoir parameters and have been used for OOIP calculations. It should be noticed that, through this methodology, consistency is ensured among the geological maps themselves (e.g., between the porosity and the net sand map), as well as with the data used in the dynamic simulation. Moreover, the procedure proved to be very time effective, since it allowed to generate a set of more than 250 maps in a matter of weeks.

Conclusions
A geostatistical model has the potential to integrate all the information generated in the individual disciplines, namely Geophysics, Petrophysics, Sedimentology, Stratigraphy and basic Reservoir Engineering. This approach, here defined as geologically oriented geostatistics, guarantees the internal consistency of the reservoir study and provides a robust model to be upscaled in the forward simulation phase. Results of a case study relevant to a complex, heterogeneous, multilayer reservoir demonstrated the feasibility of the approach, also in terms of time effectiveness. When necessary, the information contained in the 3D geological model can eventually be averaged and quickly exported to a conventional mapping algorithm.

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References
Fig. 1 – Flow chart of an geologically-oriented geostatistical study

Fig 2 – Geostatistical data base: the vertical proportion curve and the proportion matrix
Fig 3 – Adaptative Simulation Algorithm. Mono, Pluri Gaussian, Boolean or Nested

PETROPHYSICAL ASSIGNATION FOR LITHOFACIES

FIRST, LITHO FACIES SIMULATION

THEN, PETROFACIES SIMULATION WITHIN THE SIMULATED LITHOFACIES

Fig 4 – Petrofacies methodology for petrophysic simulation
400 wells
3D seismic
60 productive sands
500 reservoirs

Fig 5 – Location map of ZAPATOS/MATA-R Field

Fig 6 – North-South structural section across the field.
Fig 7 – Stratigraphic and sedimentologic conceptual model

Fig 8 – Boolean parameters and simulation result
Fig 9 – Boolean simulations results and applications for 2 lithounits.

Fig 10 – Facies, net sand and porosity mapping from boolean simulation results.