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3D MARINE SEDIMENTARY RESERVOIR STOCHASTIC SIMULATION ACCOUNTING FOR HIGH RESOLUTION SEQUENCE STRATIGRAPHY AND SEDIMENTOLOGICAL RULES.

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ABSTRACT

Quantifying the proportions and distribution of rock types is a key step in modeling sedimentary formations, since it greatly determines the quality of petrophysical and dynamic flow models. While forward stratigraphic models well reproduce deposition processes, they rely on inversion for data conditioning, which critically raises the empty space problem. Therefore, several stochastic methods have been suggested to simulate proportions and distribution of rock types in reservoirs respecting the observation data while reproducing realistic spatial patterns. However, these methods are always limited by the stationarity decision. We propose a method to generate 3D facies probability cubes which account for well and seismic data, stratigraphic interpretation, sedimentological rules describing the spatial distribution of rock types, and sequence stratigraphy principles. Different probability cubes are computed by integrating various information controlling the lithofacies occurrence, for instance the stratigraphic control of the shoreline migration, by defining linear or inequality constraints at the spatial estimation stage. The generated P-field cubes can then be combined considering the redundancy of the data they express such as the tau model. This methodology is demonstrated on typical synthetic data sets and on a North Sea reservoir.

INTRODUCTION

Facies information is a critical ingredient of reservoir characterization studies. Indeed, facies are often used to regionalize the geostatistical modeling of petrophysical properties like porosity or permeability. The modeling of facies is generally done at reservoir scale by conditional geostatistical techniques like indicator kriging (Goovaerts, 1997; Deutsch and Journel, 1998), sequential

indicator simulation (Alabert, 1987), truncated Gaussian simulation (Chilès, 1984; Galli et al., 1994), multi-point simulation (Strebelle, 2002). Although these approaches account for both well and seismic data and a given spatial variability model, they rely only in part on geological principles. One major challenge is therefore to introduce more geological concepts within stochastic simulations in order to increase the realism of facies models and to reduce their uncertainty (Tamhane et al., 1999).

In this paper, we present an attempt to fill the gap between sedimentology, sequence stratigraphy and facies simulation by providing numerical rules, which are driven by geological processes and can be accounted for as 3D spatial trends in stochastic simulation algorithms. The notion of facies, as considered in this paper, follows a sedimentological definition, i.e., corresponds to lithological, biological and hydrodynamical criteria (Gressly, 1838). As such, the spatial variations of facies are mainly controlled by the ratio between the accommodation rate (A) and the sedimentation rate (S) through time, then by diagenetic transformations after sediment deposition. Two main principles have been integrated in our workflow: (1) the A/S ratio describes the seaward and landward migrations of sedimentary bodies in association with the regression and transgression cycles; (2) the sediment volume partitioning characterizes the preservation of sediments in respect to progradations and retrogradations.

INTEGRATING GEOLOGICAL CONCEPTS IN FACIES SIMULATIONS

Several integration strategies have been suggested to incorporate geological concepts into stochastic geostatistical models. For instance, multiple-point geostatistics consider training images as vector of geological knowledge (Strebelle, 2002), and truncated Gaussian simulations (Chilès, 1984; Galli et al., 1994) use adjacency rules between facies. Most methods can also account for pre-defined local probability density functions (pdf) to reflect spatial trends in the realizations. This last option is critical to obtain non stationary models which reproduce analog observations, but relies on appropriate techniques to estimate the local pdfs. For this, it is possible to use a deterministic mapping between the water depth and facies (Massonnat, 1999), the accommodation concept (Massonnat, 1999; Leflon, 2005), transition probabilities between the different facies (Mallet and Shtuka, 1997; Labat, 2004), and some maps of anisotropy depicting the main directions of sediment transport (Mallet, 2002; Labat, 2004).

We suggest to enlarge this set of concepts to those of genetic stratigraphy. These principles, which characterize the sedimentary structures in response to the accommodation and sedimentation rates, are integrated as numerical constraints in the interpolation of local probability functions of facies. This interpolation is achieved by *discrete smooth interpolation* (DSI, Mallet, 1992), which finds the optimal values of some unknown variable $\varphi(\cdot)$ by minimizing a quadratic form measuring how much the model violates a set of linear constraints. These constraints may be weighted by the deemed reliability of the data or phenomenon they represent. A DSI constraint c can be expressed as a system of linear equations

defined on the nodes α of some mesh Ω as:

$$\sum_{\alpha \in \Omega} \sum_v \mathbf{A}_c(\alpha) \cdot \varphi(\alpha) \bowtie b_c, \quad (1)$$

where: $\bowtie \in \{\simeq, =, >\}$, and $\mathbf{A}_c(\alpha)$ and b_c are given scalar coefficients corresponding to the problem at hand. Soft constraints are honored in a least squares sense while hard constraints are strictly honored.

In the case of several pdf's coming from different methods or accounting for different geological concepts, the combination of these information is a way to reduce the model uncertainty if the information is consistent (Tamhane et al., 1999). Formally, the problem of estimating the probability for some event A_i corresponding to the occurrence of the facies i among the n possible facies at a given location conditionally to all M data D_m can be expressed as a function ψ of conditional probabilities $P(A_i|D_m)$:

$$\forall i \in \{1, \dots, n\}, \quad P(A_i|D_1, \dots, D_M) = \psi\{P(A_i), P(D_1|A_i), \dots, P(D_M|A_i)\}. \quad (2)$$

Several exact or approximate formulations exist for ψ functions, depending on the way to aggregate the data (Clemen and Winkler, 1999; Journel, 2002; Krishnan and Journel, 2005). We suggest to use a model that can account for the redundancy between the various data types when combining several probability cubes coming from several concepts, for instance the tau model (Krishnan and Journel, 2005).

REPRODUCING LANDWARD AND SEAWARD MIGRATIONS

High-resolution sequence stratigraphy states that the architecture of the sedimentary deposits is controlled by three factors: the sea-level, the tectonics and the sedimentary influx. The sea-level and the tectonic vertical movements are commonly gathered in the accommodation term, defined as the space available for potential sedimentation (Jervey, 1988; Cross, 1988). According to the A/S ratio concept, the migration of the system tracts (*i.e.* transgression and regression) is induced by the variations of the ratio between the accommodation rate A and the sedimentation rate S (Cross et al., 1993; Sonnenfeld and Cross, 1993). This genetic concept illustrates the dependence of stratigraphic architecture on rates of change in accommodation and sediment supply (Figure 1):

- $A/S > 1$: the available space is bigger than the sediment supply, due to a transgression inducing a landward stepping (retrogradation of the sedimentary bodies);
- $A/S = 1$: the equilibrium between available space and sedimentary influx results in a vertical stacking (aggradation);
- $A/S < 1$: the accommodation space is smaller than the sediment supply inducing a progradation of the system tracts.
- $A/S < 0$: available space is reduced (negative accommodation) creating erosion. Eroded sediments are shifted seaward inducing a forced regression.

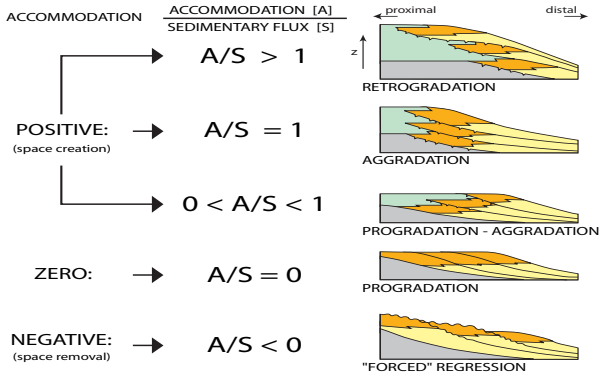


Figure 1: Control by the accommodation rate and the sedimentary flux: the stratigraphic architecture is driven by the A/S ratio changes. Modified from Homewood et al. (1999)

This geological concept can be integrated in the facies probability interpolation when the different facies express topographical attributes. For instance, the Neptune model (Massonnat, 1999; Leflon, 2005) or the Thalassa model (Kedzierski, 2007) associate facies probabilities to the palaeobathymetry or to functions of the water depth. In both cases, facies probabilities are deduced from the function B describing the topography. Moreover, the sequence stratigraphy links the bathymetric variations to the accommodation and sedimentation rates thanks to the accommodation equation (Massonnat, 1999):

$$\frac{\partial B}{\partial t} = A - S. \quad (3)$$

The Thalassa model computes bathymetry curves on wells, then deduces the accommodation rate from the computed water depth and some input sedimentation rate coming from chronostratigraphic interpretation in 3D (Mallet, 2004) (Figure 2). The accommodation rate is then interpolated with DSI in chronostratigraphic space. By combining this computed accommodation rate A and the sedimentation rate S deduced from 3D chronostratigraphic interpretation, we obtain the topographic variation rate $\partial B/\partial t$ as described by (3). This topography derivative is then integrated using paleotopography at the wells using DSI, before being translated into a facies probability cube, still using DSI (Figure 2).

The A/S ratio concept can be integrated at two levels in this methodology: (1) when the bathymetry B is interpolated on wells and, (2) when the accommodation rate is interpolated in the chronostratigraphic space.

Interpolation of bathymetry on wells

The bathymetry is interpolated on wells while: (1) ensuring that the interpolated water depth belongs to the range associated with each facies, and (2) ensuring that available space is created during transgressions and reduced during regressions, as

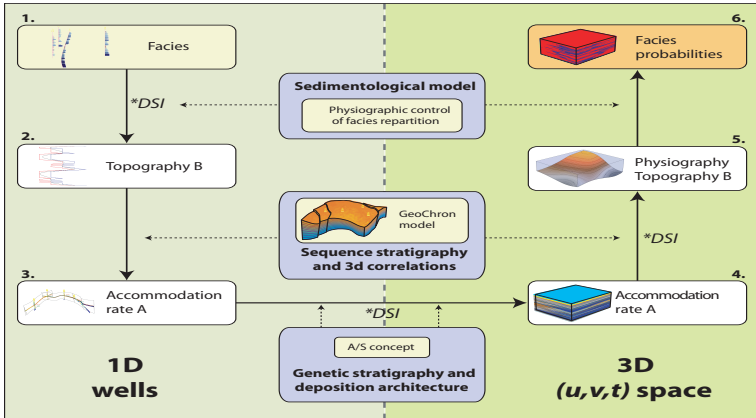


Figure 2: Modeling the facies probabilities as the expression of topographic variations constrained by sequence stratigraphic concepts. The A/S ratio interferes in the interpolation of the bathymetry on wells and in the interpolation of the accommodation rate in the chronostratigraphic space.

expected from the A/S ratio concept. Indeed, by combining the expression (3) to the A/S ratio and by assuming that $S > 0$, the following relation comes:

$$\frac{A}{S} \bowtie 1 \iff \frac{\partial B(\alpha, t)}{\partial t} \bowtie 0, \tag{4}$$

with $\bowtie \in \{>, <\}$ for retrogradation or progradation, respectively. This equation is non-linear and can be linearized using a forward finite difference scheme:

$$\frac{\partial B(\alpha, t)}{\partial t} = \frac{B(\alpha + 1, t + \Delta t) - B(\alpha, t)}{\Delta t}, \tag{5}$$

where the nodes α and $\alpha + 1$ are two neighboring well samples belonging to the same sedimentary sequence and fault block, and the times t and $t + \Delta t$ are the corresponding stratigraphic ages. After linearization and some simplifications, (4) is then translated as a *signed gradient DSI constraint* of the form:

$$B(\alpha + 1) - B(\alpha) \bowtie 0 \iff \sum_{\beta \in \Omega} \mathbf{A}_{c_{sg}}(\beta) \cdot B(\beta) \bowtie b_{c_{sg}}, \text{ with:} \tag{6}$$

$$\left| \mathbf{A}_{c_{sg}}(\beta) = \begin{cases} 1 & \text{if } \beta = \alpha + 1 \\ -1 & \text{if } \beta = \alpha \\ 0 & \text{otherwise} \end{cases} \right., \quad \bowtie = \begin{cases} > & \text{if transgression} \\ < & \text{if regression} \end{cases}, \quad b_{c_{sg}} = 0.$$

Interpolation of accommodation rate in chronostratigraphic space

From the bathymetry computed on wells, the accommodation rate is estimated by applying equation (3). These local values of the accommodation rate A are then interpolated in chronostratigraphic space. Practically, two criteria are used to

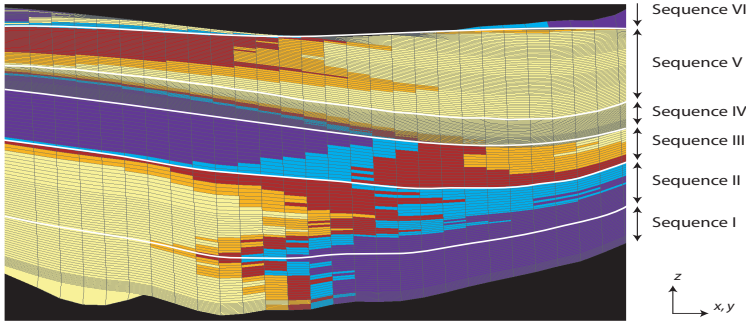


Figure 3: Cross-section of a North Sea stratigraphic reservoir model showing the most likely facies after estimation accounting for the A/S ratio. Note the reproduction of transgressive and regressive cycles. Data courtesy of Total.

interpolate A . First, the spatial continuity is such that accommodation variations are smooth laterally and driven by the stratigraphic signal vertically (Kedzierski, 2007). Second, in transgressive (resp. regressive) system tracts, the accommodation rate should be higher (resp. lower) than the sedimentation rate S derived from 3D chronostratigraphic interpretation on seismic data. Then, for any grid cell β where the sedimentation rate is positive, this condition can be formulated as a *variable inequality DSI constraint*:

$$A(\alpha) \bowtie S(\alpha) \Leftrightarrow \sum_{\beta \in \Omega} \mathbf{A}_{c_{vi}}(\beta) \cdot A(\beta) \bowtie b_{c_{vi}}, \text{ with:} \quad (7)$$

$$\left| \mathbf{A}_{c_{vi}}(\beta) = \begin{cases} 1 & \text{if } \beta = \alpha \\ 0 & \text{otherwise} \end{cases} \right., \quad \bowtie = \begin{cases} > & \text{if transgression} \\ < & \text{if regression} \end{cases}, \quad b_{c_{vi}} = S(\alpha).$$

Application

These constraints on the bathymetry and on the accommodation rate have been tested to interpolate facies probabilities on a North Sea field. The estimated facies probabilities are consistent with the well data, the 3D stratigraphic interpretation and the expected lateral and vertical facies variations (Figure 3).

PARTITIONING THE FACIES ALONG THE DISTALITY DIRECTION

Facies repartition may be controlled by the physiography of the topographic surface at the deposition time (Kedzierski and Mallet, 2006). However, the bathymetry and the slope angle are insufficient to completely describe sedimentary systems, and other parameters such as the distance to the sediment source, or the degree of confinement should be considered. For this, the facies proportion estimation should somehow express energy gradients as functions of the sedimentary influx. We are considering in this paper that the facies are distributed along distality axes; the information about distality is carried by orientation and direction vectors, deduced

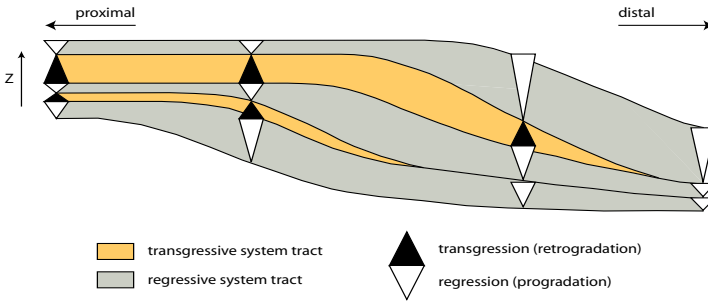


Figure 4: Stratigraphic expression of the sediment volume partitioning.

from the stratigraphic record or provided by a trend map.

Stratigraphic record of the distality

The sediment volume partitioning rule states that the sediments are better preserved in distal zones during the regressions and in the proximal ones during the transgressions (Figure 4) (Cross et al., 1993; Sonnenfeld and Cross, 1993): during the relative sea level rise (transgression), sediment storage increases landward, reducing the amount of sediments in the distal pole; in a regressive phase (sea level fall), sediments are further transported towards the basin center. This principle means that the gradient of the sedimentation rate, computed on an isochronous surface, points toward the basin center (resp. sediment source) in regressive (resp. transgressive) system tracts. For some distality vector \mathbf{d} , we can then write:

$$\nabla_{uv}S = \lambda \cdot \mathbf{d}, \quad (8)$$

where λ is a positive (resp. negative) scalar in transgressive (resp. regressive) phases. The variables (u, v) represent the palaeogeographic coordinates on the isochron surface, and $\nabla_{uv}S$ the orthogonal projection of the sedimentation rate onto that surface. This equation tells that the distality vector field can be defined from the lateral gradient of S , since the sedimentation rate S is exhaustively known *per* the chronostratigraphic interpretation. It also provides a valuable self-consistency check for the stratigraphic and sedimentological interpretations.

Constraining the facies probabilities to honor distality vectors

In our work, the local facies proportions are interpolated by membership functions (Mallet, 2002; Labat, 2004), which are similar to the indicator formalism, except that indicator variables need not be ordered. Accounting for distality directions when interpolating these functions can only be performed in a fuzzy manner: whereas both the direction and orientation of variation of the extreme facies can be characterized, only the direction of variation of the intermediate facies can be defined (Figure 5). A first constraint therefore ensures that the probability gradient $\nabla\varphi$ is colinear to the distality \mathbf{d} (the equation of this constraint, omitted here for

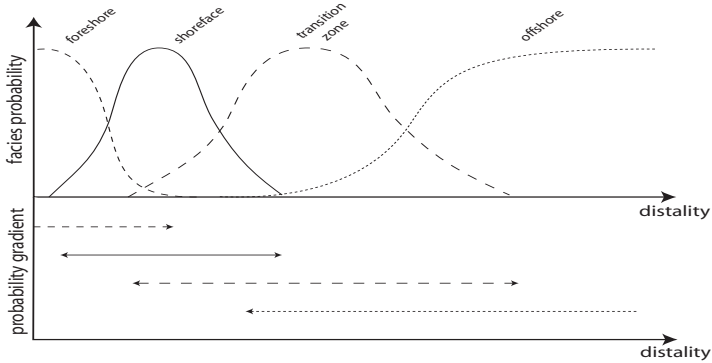


Figure 5: Trend of a probability vector: when the facies probabilities are distributed along trend vectors, the probability gradient of the most proximal and most distal facies has a unique direction while the probability gradients of the other facies is increasing and then decreasing.

brevity, comes from the linearization of $\nabla\phi \times \mathbf{d} = \mathbf{0}$. The second constraint forces the interpolated probability gradient $\nabla\phi$ to be oriented in the same (or opposite) direction of a specified vector field \mathbf{g} (in which case $\nabla\phi \cdot \mathbf{g} > 0$).

Application

Consider the synthetic data case presented in Figure 6. The distality vector field may be computed from the sedimentation rate using (8). From the observations of five facies on wells, a membership function characterizing the facies probabilities is interpolated with DSI using collinearity between the probability gradients and the trend vectors. For the facies A (resp E), the probability gradient is also constrained to point towards the same (resp. opposite) direction as the trend vectors. The obtained facies probabilities are consistent with the specified trend vectors and the facies realization with a probability field simulation show lateral variations consistent with sedimentological and stratigraphic interpretations.

CONCLUSIONS

We have proposed a method to incorporate sedimentological concepts into the computation of facies probability cubes, based on a mathematical formulation of these concepts. Several probability cubes are generated, and may be recombined as one final facies cube using for instance the Tau model (Krishnan and Journel, 2005). Tools assessing the probability of early meteoric diagenesis of carbonates and diagenesis associated with fault systems have also been developed and integrated in the Thalassa code. These are not developed here for space reason, but they are similar in spirit to the method of Henion et al. (2008). Results show very good accordance with the sedimentological interpretations, which is extremely valuable. However, the model is sensitive to the input data and the quality of the chronostratigraphic interpretation. Attempts to apply this model without a good seismic quality have failed, because of a lack of control over the sedimentation

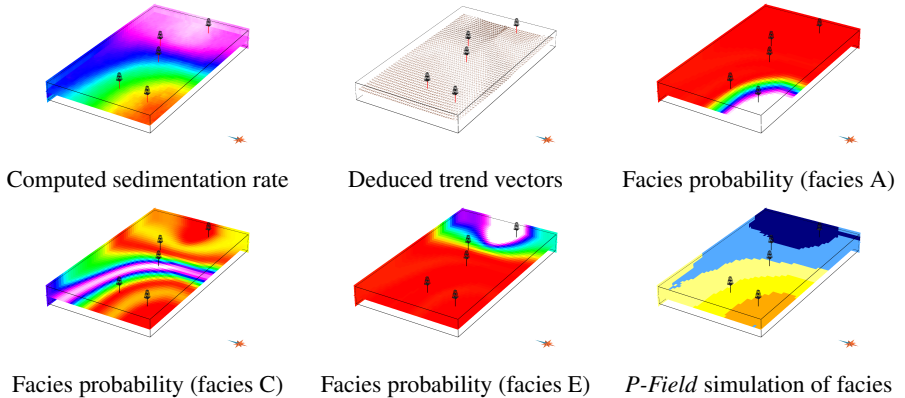


Figure 6: Estimating the facies probabilities according to trend vectors coming from the stratigraphic interpretation of the GeoChron-based sedimentation rate, or coming from an interpreted facies map. Red colors correspond to low probabilities while white ones represent high probabilities.

rate. Another question to ask about this methodology is whether it overfits interpretations, which could be a problem for realistic uncertainty assessment. However, the current practice of modeling, when discounting these concepts, tends to generate models that field sedimentologists are reluctant to accept. Therefore, our method can also be seen as a way to confront information from 3D modeling, seismic stratigraphy and sedimentology: artifacts become visible when the information is inconsistent, while facies probabilities match very faithfully interpretations when information is consistent. Nevertheless, an important avenue for further research lies in the propagation of uncertainties, both inside in our model and in its input parameters (well correlations, stratigraphic uncertainties, sedimentological parameters...)

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