Use of high-performance stratigraphic forward modelling to improve siliciclastic and carbonate reservoir depositional architecture description*

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Abstract: Exploration of siliciclastic deep-water frontier areas, but also lacustrine and shallow-water carbonate systems such as the pre-salt Aptian coquinas, are back to the present. These exploratory plays have yielded large petroleum discoveries along the South Atlantic margins but are still in their infancy. Accurate sedimentary facies models are mandatory to reduce exploration and development risks, but sedimentary systems are usually poorly imaged with seismic data in such frontier areas. Thanks to the seismic and wireline data acquired over the last decades, and to the recent development of big data management technologies, it is now possible to propose high-tech solutions to create an image of the subsurface geology. However, despite their reservoir scale increasing potentialities, these approaches are not yet fully applicable to assess plays in frontier areas where only few data are available.

To address these exploration challenges, we propose an innovative integrated workflow using the advanced numerical stratigraphic forward Dionisos model. Modelling the dynamics of sedimentary systems at a regional scale by simulating sedimentary processes makes it possible to bridge the gap between geophysical interpretation, geological conceptual modelling and field evaluation. Stratigraphic forward modelling is a numerical and process-based approach, which aims to simulate the evolution of a sedimentary basin or system in a sequence of time steps, from the past up to the present, taking into account basin deformation, sediment production, and sediment transport.

This workflow is applied to two case studies, a deep-water clastic turbiditic system and a shallow-water rudist-rich carbonate platform. This evidences that the potential of stratigraphic forward modelling to bridge the gap between seismic data, geological concepts and play fairway analysis. Furthermore, this workflow is not restricted to regional system analysis in preliminary exploration phases; it may be extended to field development and appraisal stages either in clastic, carbonate or mixed systems to better understand reservoir sedimentary heterogeneities.

Keywords: geological process modelling, stratigraphic forward modelling, deep-water turbidite, carbonate platform, exploration, basin evaluation

1. Introduction

One of the most critical challenges in exploration and production studies is to build reliable 3D digital models describing sedimentary basins and reservoir stratigraphy. These digital models are key elements to answer two main questions geologists are faced to: how much oil is there and how to get it out efficiently? Despite the paucity of data available during the exploration process, the building of good reservoir models is required to evaluate reservoir and sedimentary formations, identify and assess exploration opportunities, and reduce exploration risk. To that end, a strong geological and geophysical data integration is required. Recent progress in seismic interpretation and seismic geomorphology has improved a lot our understanding of sedimentary basin infill and heterogeneities (Posamentier et al., 2007, Prather et al., 2012). Up-to-date seismic geomorphology technology integrates 3D seismic reflection attributes analysis, to deliver detailed information about external and internal reservoir architecture, and resolve metre-scale geological features such as mass transport complexes, turbiditic channels and levees, or carbonate reservoirs (Posamentier and Kolla, 2003; Eberli et al., 2004; Clark and Cartwright, 2011; Hansen et al., 2017). Exploration is moving to more and more challenging frontier areas, such as deep-water environments, or subsalt sedimentary formations. These remote and difficult to image or drill
basins have only a few recorded geological, geophysical and petrophysical information. In parallel, exploration has been hunting subtle stratigraphic traps in well-known mature basins for years, but the resolution of seismic data has been too low to make these traps obvious to locate and evaluate even when using 3D seismic geomorphology. Assessment of frontier areas and subtle stratigraphic traps requires to develop novel integrative approaches to better understand the regional-to-local sedimentological and diagenetic processes, which have shaped source rocks, reservoirs and seals, and to estimate the distribution of petrophysical heterogeneities.

Sedimentary architecture is the result of the complex interplay between accommodation space created in the basin, sediment supply brought into or produced in the basin and transport of sediment within this basin. In addition to up-to-date seismic interpretation technology, it is thus highly valuable to study the sedimentary processes that are at the origin of the shape and structure of reservoirs. Stratigraphic forward models (SFM) have been developed since the late 1980s to get insight into sedimentary processes, and provide process-based digital basin and reservoir models. The rationale behind SFM is to quantify and simulate the evolution of the geography and stratigraphy of sedimentary basins over geological time scales, from the past up to the present, or at least from some age in the past up to another age not so far in the past. The main result is a 3D digital model, which represents the morphology and internal structure of sedimentary layers and stratigraphic bodies. It makes it possible to characterize the distribution of sediment, facies and depositional environments at basin to appraisal scales.

Depending on the type of model used to describe the transport of sediment, process-based SFM can be grouped into two main model types: deductive and rule-based models (Paola, 2000; Burgess, 2012). To simulate water flow and sediment movement, the deductive dynamic models use very detailed physical equations deduced from the Newtonian mechanics equations and bed-load transport laws (Syvitski and Hutton, 2001; Storms, 2003; Blanchette et al., 2005; Nittrouer et al., 2007; Birman et al., 2008; Geleynse et al., 2011; Dalman and Weltje, 2012; Dalman et al., 2015; Li et al., 2018). This method is used rather in sedimentology to get insight into short-term sedimentary processes, for example to simulate shoreline evolution and spit formation over a few thousands of years (Ashton et al., 2001). These deductive models may provide accurate evolution of sedimentary systems, but are computationally highly expensive to solve and thus difficult to constrain to well log or seismic data. Furthermore, the governing equations over geological time spans of many sedimentary or diagenetic processes are not yet fully understood.

Rule-based models are simpler models based on empirical rules that capture the large-scale and long-term behaviour of sedimentary systems. They do not simulate in detail each geobody, for example each channel on a fluvial plain, or each tidal bar on a tidal flat. Thus, the simplicity of this methodology allows the user to easier fit the model outputs to real data. In essence, rule-based SFM are simplified descriptions of actual sedimentary systems and some loss of reality is inevitable. Anyway, recent studies have proved that even a simple 2D rule-based model can reproduce the grade and equilibrium evolution of ponded slope system (Prather, 2000), or submarine canyon development (Gerber et al., 2008, 2009). Diffusive rule-based carbonate models have been used to investigate the interactions between sediment production and transport along carbonate ramps and evaporitic basins (Williams et al., 2011; Seard et al., 2013; Kolodka et al., 2016). Furthermore, integrated sedimentary basin studies have demonstrated that rule-based SFM can provide valuable insights into the basin stratigraphy beyond seismic resolution (Alzaga Ruiz et al., 2009; Hawie et al., 2017; Csato et al., 2013). Indeed, this approach allows fast evaluation of many scenarios. The recent increase in computing power and decrease in cost make it possible to integrate more and more complex description or deductive laws into large-scale rule-based models (Granjeon, 2014).

The aim of this paper is to present the principles and applications of Dionisos, a 3D rule-based SFM, and to show how it can contribute to the exploration process. We first describe the models used to simulate the key geological processes, such as basin deformation, sediment supply or sediment transport. We then introduce two Dionisos applications. The first one is a synthetic case study that outlines how Dionisos can be used to simulate the large-scale architecture of a siliciclastic turbiditic fan. The second one illustrates the application of Dionisos to a shallow-water rudist-rich carbonate platform.

2. Methods

Dionisos is a 3D numerical stratigraphic forward model that simulates the geomorphologic and stratigraphic evolution of sedimentary basins over geological time scales, from tens of thousands to hundreds of millions of years, and over regional spatial scales from several tens to a few hundreds of kilometres (Granjeon and Joseph, 1999; Granjeon et al., 2014). Temporal resolution is usually set at around a few thousand to hundreds of thousands of years, and spatial resolution is usually set at a few hundreds of metres to a few kilometres. A stratigraphic simulation is performed from the past up to the present in a sequence of time steps. At each time step, several sedimentary processes are taken into account such as the creation of accommodation space, the erosion, transport by water flow and deposition of sediment, or the production of carbonate sediment.

2.1 Accommodation: subsidence, eustasy, flexure and compaction

The accommodation space at any point in a basin determines the amount of sediment that may fill up from the substratum to the base level (Jervey, 1988). Accommodation is thus controlled only by eustasy and tectonics. A global sea level curve, and a set of user-defined cyclic and broken-
line curves, are combined to define the relative sea level. Tectonics are defined from a set of subsidence/ uplifting maps, that characterize the substratum deformation at different key time markers. Subsidence/uplifting for each individual grid node is then calculated by a linear interpolation of these maps through ages. Internal deformation of stratigraphy due to salt and shale diapirs, or growth faults, thrust stacking and decollement levels, can also be defined (Alzaga-Ruiz et al., 2009; Balazs et al., 2017). Sedimentary units above decollement surfaces are moved to account for horizontal displacement of sedimentary rocks, using the horizontal deformation rate imposed by users and assuming vertical shear deformation. Loading effects on stratal geometries and deformation rate imposed by users and assuming vertical displacement of sedimentary rocks, using the horizontal compaction formula, and not the actual burial. We thus intervene the maximum burial reached by the sediments in the compaction formula, and not the actual burial.

2.2 Erosion, transport and deposition of sediments

2.2.1 Gravity-driven and water-driven sediment transport

Fluvial processes acting over very large distances are the main causes of sediment transport from the feeder channels to the deep basins. Channels are formed, maintained, and altered by two things: water flow and sediment load. Since the work of Du Boys (1879) sediment transport has been studied by many researchers, especially to understand the stability of banks and beds of rivers. Lane (1955) was one of the first to propose a dynamic model. The transport capacity is controlled by river energy, being itself a function of slope and water flow. If the river energy is larger than the actual sediment load, then the water flow will erode the banks or bed of the channel to increase the load. Otherwise, the load will be released and will create a sediment deposit. Equilibrium is achieved through a balance of four factors (Eq. 1): the sediment flux is proportional to the slope and water flow; and is inversely proportional to particle size.

\[ Q_{s,D} \propto Q_{w}S \]  

Eq. 1: The Lane’s model, describing the equilibrium between sediment load, with \( Q_s \), the sediment transport capacity and \( D \), the grain size, and river energy, with \( Q_w \), the water flow, and \( S \), the river slope.

The Lane’s model was the basis for many geomorphological and stratigraphic forward models (e.g.; Willgoose et al., 1991 a, b; Tucker and Slingerland, 1994; Granjeon and Joseph, 1999; Coulthard et al., 2002).

Following the classical approach used in landscape evolution models, we lumped all processes leading to the movement of sediment grains into two large-scale diffusion processes: a slow long-term gravity-driven and a fast water-driven diffusion transport (Gra...
variability, and in particular extreme events. We can either simulate all seasonal events, floods and river flows, which happen during a single time step, or only capture the long-term behaviour of the sedimentary and hydrologic system.

In Dionisos, as the water-driven long-term law is an empirical rule designed to simulate the sum of all fluvial and flood plain processes acting over long time spans, typically a few hundreds of years, the average water flow is usually not an actual river flow, but a time-average water flow. We assume that over long time spans, the landscape evolution can be simulated assuming an overlaid sheet flow (Granjeon, 2014). A shallow-water equation is used to characterize the movement of water at the surface of the basin. In its discrete form, this equation is similar to the multiple-direction method, in which water is routed to all the local lower neighbours of a given cell according to the slope ratio. This multiple direction method better handles diverging flow and is suitable to simulate overlaid sheet flow (Tarboton, 1997).

To take into account climatic events and seasonal variations, we use a statistical approach, and group all actual floods into three groups: (1) the short-term high-energy floods, or HEST, corresponding to the extreme floods, which very rarely occur but contribute to 50% of the total sediment load, (2) the long-term low-energy floods, or LELT, containing all the low water floods which contribute together to 50% of the total sediment load, and corresponding more or less to the average annual flow of the river, and (3) the too low daily floods, unable to transport sediment, and thus which are not taken into account in the simulation.

### 2.2.3 Mass-balance and maximum erosion rate

These two non-linear diffusion equations define the transport capacity of the system. Availability of grains is constrained by weathering and incision rate. This rate is highly variable and depends on climate, topographic elevation and slope (Tucker and Slingerland, 1994; Coulthard, 2001). A maximum erosion rate is defined as a function of the excess of shear stress, that is the difference between the basal shear stress induced by fluvial water flow and the critical threshold stress below which no incision can occur. The actual transport rate is finally defined as the minimum of the transport capacity and the sediment fraction availability. Sedimentation and erosion rates for each sediment fraction at each point of the basin are computed from the mass conservation equation and the actual sediment flux.

### 2.2.4 Slope failure and mass flows

Slope stability of the depositional profile is checked at the end of each time step. At any point of the basin, if the local slope is higher than the static angle of repose, then all sediments above the safety plane move downslope until the new depositional slope is lower than the dynamic slope angle. The transport of this unstable sediment layer is simulated assuming a viscous sediment flow.

### 2.3 Carbonate production

Carbonate sediment can be produced either in continental or marine systems, and either in pure carbonate environments, or in mixed carbonate-clastic environments.

Following the time-averaged sediment transport approach, we lumped all chemical and physical processes leading to the production of carbonate sediments into large-scale production laws, which aim to capture the behaviour of the main carbonate factories (Granjeon and Joseph, 1999). The concept of carbonate factory was defined by Schlager (2005). As a function of environmental constraints and mode of carbonate precipitation, this concept groups all carbonate depositional systems into five main carbonate depositional systems, from the classical tropical shallow-water biotic reef factory, to the abiotic microbialite mud-mound factory. Recent studies suggest that such a conceptual cut-off classification into a discrete finite number of carbonate factories and depositional geometries can be useful, but a more meaningful approach consists in describing carbonate depositional systems in terms of a continuous stratigraphic parameter space such as sediment production, sediment transport, tectonics and sea level (Burgess et al., 2011). We thus defined the carbonate production rate at each point of the basin by setting a maximum growth rate curve for each carbonate sediment producer, such as coral, algae or microbialites (Granjeon, 2018). This maximum rate can be modulated by local parameters, such as water depth, wave energy, temperature, salinity, or hydrothermal and ionic fluxes.

The evolution of the production rate with water depth depends on the carbonate producer. For example, the tropical euphotic factory (Schlager, 2005), mainly related to autotrophic organisms, is highly sensitive to light, and thus to water depth and sea water turbidity. Not all living organisms depend on light. Oligophotic organisms, such as large benthic foraminifera and red algae, require less light, while aphotic species such as bryozoans and crinoids, sponges do not need light. The range of depth of the euphotic-oligophotic limit is around 20 – 30 m on average, and the oligophotic-aphotic limit evolves from 50 m to over 100 m in clear waters (Pomar and Hallock, 2008).

We use also long-term average oceanic wave and drift energies as two proxies to control carbonate production. These proxies are not used to simulate actual daily oceanic waves, or to forecast the impact of wave actions on beaches or harbours, or littoral drift induced by breaking waves. They characterize the long-term influence of ocean wave energy fluxes on the sea floor. In order to capture the daily temporal variations of wave characteristics, we grouped together all possible waves statistically observed during a time step into a few representative waves. The propagation of each representative wind-generated wave on the ocean surface is computed using the fundamental equation of geometric optics, also known as the eikonal equation. This equation describes the refraction and diffraction processes of waves during their propagation in oceans, seas or lakes. We used the total average wave and drift energy fluxes as two proxies to characterize depositional environments, and for example differentiate a shallow-water high-energy reef barrier from a
shallow-water protected lagoon.

2.4 Numerical scheme

An unstructured finite volume discretization scheme, and a fully and semi-implicit time discretization scheme are used to obtain robust and fast simulations. The set of nonlinear sediment production and transport equations is solved using a Newton algorithm (Gervais and Masson, 2008). To meet the requirements of multidisciplinary high-performance computing in geosciences, Dionisos is fully massively parallel, and is developed on the C++ dedicated platform ArcGeoSim, which eases the development of numerical models and simulators for parallel platforms, and gives access to advanced numerical methods and common utilities.

3. Results and Discussion

3.1 Deep-water clastic system

Numerical stratigraphic forward modelling experiments have been recently used to better understand clastic lacustrine, margin to deep-water systems, and notably the interaction between tectonics and climate on sediment pathways and facies distribution (Alzaga-Ruiz et al., 2009; Csato et al., 2013; Deville et al., 2015; Balazs et al., 2017; Yin et al., 2017; Hawie et al., 2018). To better assess the Dionisos capability to simulate submarine channel complexes our first set of numerical experiments was performed to simulate the evolution of a siliciclastic deltaic to deep-water formation.

3.1.1 Model setup

We modelled a theoretical passive margin for the late Pleistocene period. Simulations were conducted over the last 240,000 years with 5,000 years time steps. The model dimensions were 200 km (strike direction) x 300 km (dip direction) with cell sizes of 1 km x 1 km. The initial bathymetry was an irregular smooth ramp setting with an average slope of 0.005 and a maximum water depth of 1,800 m at the distal edge of the basin (Fig. 1). To focus our attention on sediment transport processes, we preferred to keep the parameter set as simple and realistic as possible. We did not account for any differential subsidence or flexure in this first set of simulations. The water and sediment supplies were inferred from the modern Niger delta (Milliman and Syvitski, 1992). Two sediment fractions were defined: sand and mud. The average water supply was 6300 m³/s, and the average total sediment load 15800 km³/My with 20% of sand and 80% of mud. The short-term high-energy floods, or HEST, were assumed to represent 10% of the total flood event, and to carry 50% of the total sediment load. Sea level, water supply and sediment load cycles, with a period of 120 ky, were finally defined to simulate the impact on source-to-sink sedimentary systems of recent climate changes with the associated glacial cycles (Fig. 2). Gravity-driven diffusion coefficients were 0.001 km²/ky for all sediments. Based on recent stratigraphic modelling and sensitivity analysis studies (Prince and Burgess, 2013; Gvirtzman et al., 2014) sand and mud water-driven diffusion coefficients in continental and marine environments were respectively set to 200 and 500 km²/ky and 0.1 and 0.5 km²/kyr. The m and n non-linear exponents were 1.5 and 1.

3.1.2 Simulation results

This first numerical simulation was performed to simulate the evolution of a passive margin in response to climate changes. Our stratigraphic forward model is based upon a simple description of sedimentary processes. In particular, water flow routing is simulated using a continuous overland sheet flow model, and sediment transport is modelled using a water-driven non-linear diffusion equation. Detailed fluid dynamics are not considered in this model. No specific rules are applied to differentiate individual channels, or to simulate for instance channel avulsion. Even though using such a very simple process-based model, allogenic and autogenic cycles were reproduced. At a large scale, two main sedimentary units were deposited, corresponding to the two climatic cycles. A first prograding-aggrading-retrograding unit was deposited from 240 to 120 ky (Figs. 3a to c). A second one was deposited from 120 ky to 0 ky (Figs. 3d to f). These two allogenic units were controlled by water supply and sediment supply long-term changes.

Stratigraphic parameters such as sediment or water

Fig. 1 Initial morphology map of the deep-water clastic simulation

Fig. 2 Sea-level, water-supply and sediment-load history applied in the deep-water simulation. Simulation was performed from 240 ky to present-day. Two saw-tooth cycle were defined, with a period of 120 ky
Fig. 3  Simulation of the paleogeographic evolution and sand distribution of a deep-water system

During the first 120 ky cycle (3a to 3c), three main autogenic channel-belts were formed, while two others autogenic channel-belts were formed during the second cycle (3d to 3f).
supplies evolved in a linear and continuous way during each prograding phase. Despite this linear evolution these units were composed of a set of individual channel-levee systems. Due to the initial topography shape, a first water flow pathway was initiated from 240 to 200 ky on the eastern side of the simulated area (Fig. 3a). This water course induced erosion and transport on the proximal area, and deposition of a 10 km-wide channel-levee system on the distal part. A topographic high was progressively created by the water-sediment flow, until it was too high compared to the local neighbourhood topography. At that time, an autogenic avulsion of the water course induced a new water course (flow path 2 on Fig. 3b), then two other channel-levee systems (flow paths 3 on Fig. 3b, and 4 on Fig. 3c), before the backstepping of the full sedimentary system. During the second allocigenic cycles, two new autogenic channel-levee systems were formed (flow paths 6 and 7 on Figs. 3d to f).

This first set of simulations illustrates that numerical stratigraphic forward models provide an ideal method to test assumptions relative to transport laws and causal relationships between parameters and stratigraphy. The application of the non-linear water-driven diffusion model shows that the simulation results are consistent with the stratigraphic evolution of the depositional sequence offshore of recent deep-water systems (Hawie et al., 2018). Even though using a simple description for water flow routing and sediment transport processes, our model captures the characteristic autogetic compensational stacking of channel-levee deep-water systems (Deptuck et al., 2008; Jobe et al., 2017). However, we should keep in mind this autogenic nature of sub-seismic-scale processes and stratigraphy. The goal of our stratigraphic forward modelling approach is not to predict the accurate location of individual channels, but to provide 3D digital models, which permit geologists to better understand the large-scale architecture of sedimentary basins, to improve siliciclastic and carbonate reservoir depositional architecture description, and to evaluate reservoir presence and source rock quality (Burgess et al., 2006; Gervais et al., 2017).

3.2 Shallow-water carbonate platform

A second set of numerical simulations was performed for an intrashelf basin derived from the geological framework of the Upper Cretaceous Natih formation of Oman, part of the Wasia Group (Cenomanian and early Turonian). The Natih Formation was formed in an epeiric, shallow marine, tropical carbonate platform system. The inner to mid-ramp environment was dominated by abundant rudists while the basinal facies was organic-rich. Outcrop data from the Adam foothills of Northern Oman and wireline logs were used to build a stratigraphic and diagenetic model at an appraisal scale (van Buchem et al., 2002).

3.2.1 Model setup

Simulations were conducted from 99 to 92 My with 100,000 years time steps. The model dimensions were 200 km x 100 km with cell sizes of 1 km x 1 km. Third- and fourth-order sea level variations were inferred from the conceptual geological model defined by van Buchem et al. (2002). Two major sediment classes were distinguished: shallow-water rudist and carbonate mud. The maximum carbonate production rates were 200 and 40 m/My, respectively. Similar transport coefficients were used in our clastic and carbonate cases. All sediment gravity-driven diffusion coefficients were 0.01 km²/kyr, while rudist and mud water-driven diffusion coefficients in continental and marine environments were set to 200 and 500 km²/kyr and 0.1 and 0.5 km²/kyr, respectively. The m and n non-linear exponents were chosen as 1.5 and 1.

3.2.2 Simulation results

The purpose of this second numerical experiment was to simulate the evolution of an intrashelf basin in response to sea-level changes. The simulation started at 99 Ma with a very flat outer ramp environment with water depth ranging from 60 to 90 m. From 99 to 98 Ma, carbonate production was dominated by marls and mud sediments (Fig. 4a). Around 98 Ma, the water depth on the initial topographic highs was shallow enough to make possible the growth of the first rudist shoals. From 98 to 97 Ma, these rudist shoals merged into a large shallow-water rudist-rich carbonate platform, while organic-rich marls were deposited in the intrashelf basin (Fig. 4b). From 97 to 94 Ma, carbonate platforms progressively prograded into the intrashelf basin and finally merged around 94 Ma. Due to episodic sea-level falls, karsts and incised channels formed on the emerged part of the rudistic platform (Fig. 4c). From 94 to 92 Ma, a series of deepening pulses and a high supply of fine-grained clastic sediments inhibited the rudist production and progressively drown down the carbonate platform (Fig. 4d). This stratigraphic simulation made it possible to evaluate the location of potential rudist-rich wackestone and grainstone reservoirs, and organic-rich marly source-rocks (Fig. 4e).

To translate the simulation results into a synthetic seismic cube, we applied in each Dionisos cell the simple Reuss average that is relevant for layer-cake rock-fluid models. The bulk and shear moduli of the cell were defined from the volume fraction, and the bulk and shear moduli for each sediment. The compressive wave velocities and densities were then computed in each cell, thus leading to the definition of seismic impedance. The resulting 3D impedance model was converted to the time domain thanks to the average velocity model defined on the basis of sediment properties. It was then translated into an impedance contrast or reflectivity model.

The creation of the synthetic seismic cube from a Dionisos stratigraphic grid was obtained through a zero incident trace by trace reflectivity computation. The reflectivity model was convolved with a synthetic zero-phase Ricker seismic wavelet and a peak frequency of 60 Hz (Fig. 5).

This second set of simulations illustrates that a coupled numerical stratigraphic forward and seismic modelling workflow makes it possible to better understand the impact of sedimentary processes on large-scale carbonate reservoir properties. For instance, the prograding clinoforms of the shallow-water rudist-rich carbonate platform, but also...
the preferential karst belts and incised valleys induced by dissolution processes, are clearly imaged by the synthetic seismic cube (Fig. 5). Our integrated modelling workflow allows geologists and geophysicists to better interpret depositional environments and facies belts using seismic data, and thus to reduce uncertainties on the appraisal-scale reservoir characterization.

4. Conclusion

Thanks to the presented simulation results, we were able to show that modelling sedimentary basin dynamics at regional to appraisal scales by simulating geological processes provides a new means to quantify the influence of various driving sedimentary processes on stratigraphy, from basin deformation and sea-level changes to carbonate production and sediment transport.

Furthermore, this workflow provides an efficient and digital way to bridge the gap between seismic data, geological concepts and play fairway analysis. Stratigraphic forward modelling is thus an important tool to enhance geology-geophysics integration and communication. This stratigraphic and seismic modelling workflow is not restricted to regional system analysis in preliminary exploration phases. It may be extended to field development and appraisal stages either in clastic, carbonate or mixed systems. However, great care must be taken not to over-interpret the model results. Stratigraphic forward modelling makes it possible to assess large-scale facies and sedimentary heterogeneity trends. These results

Fig. 4 Simulation of the paleogeographic evolution and facies distribution of a rudist-rich carbonate system (4a to 4d)
Quantification of the rudist-rich wackstone and grainstone reservoir, and organic-rich marly source-rock location

Fig. 5 Synthetic seismic cube computed from the stratigraphic forward simulation of the rudist-rich carbonate platform
allow to test well logs and seismic interpretations, estimate reservoir or source rock presence and quality probability maps, and finally extrapolate information into areas of limited control.

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**高性能層序前進モデリングに基づく砂屑岩および碳酸塩岩帯留岩の堆積様式理解の促進**

ディディエール グランジェオン

深海成砂屑岩を対象としたフロンティア探鉱や、プレソルトのアブト期ベット石灰岩などの湖成-浅海域の炭酸塩岩システムの探鉱は、南大西洋沿岸域において大規模油・ガス田の発見をもたらした。しかしながら、その石油地質学的解釈については依然として未解決問題が多く残る。探鉱・開発リスクの軽減において、正確な堆積相モデルは不可欠な要素であることが知られている一方、とりわけフロンティア地域では、地震探査（震探）データから堆積システムを把握する際には常に困難がつきまとう。震探データや物理検層データの過去数十年間の蓄積や、ビッグデータ活用に関する近年の技術発展などに基づくハイテク技術ソリューションは、地下地質のイメージングや貯留岩スケールの潜在性を大きく向上させることに役立ったが、利用可能なデータが著しく限定されるフロンティア地域においては、これらのアプローチはいまだ最適なプレイ評価手段には成り得ていない。

これらの探鉱技術課題に対し、我々は高度数値層序前進モデル Dionisos を用いた革新的な統合ワークフローを提案する。すなわち、堆積過程の数値シミュレーションを通じて広域堆積システムの動的挙動を捉える手法であり、得られた結果は物探解釈、地質概念モデル、フィールド評価の間のギャップを埋める、いわば補完しの役割を果たす。層序前進モデリングはプロセスベースの計算手法を採用していて、堆積盆地の構造発達、堆積物の生成、堆積物運動などを考慮した堆積盆地や堆積システムの発達について、過去から現在に至るまで単位時間ごとに再現する。

本稿では、深海成タピピライトシステム、および浅海成の厚層二枚貝が卓越する炭酸塩プラットフォームの事例紹介を通して、同ワークフローの有用性を説明する。同ワークフローは探鉱初期段階の広域堆積システム解析は勿論のこと、フィールドの開発段階や評価段階においても有用であり、碎屑岩システム、炭酸塩岩システム、およびこれら混合システムにおける貯留岩不均質性をより良く理解する際に役立つ。