# GEOLOGIC PROCESS MODELING

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## RESUMEN

Modelado de procesos geológicos
El modelado de procesos geológicos es una técnica computacional cuantitativa para simular la erosión, transporte y deposición de sedimentos clásticos y el crecimiento y redistribución de carbonatos. Se basa en la simulación numérica de principios físicos de transporte sedimentario por ríos, corrientes de turbidez, olas, y corrientes marinas y provee una base cuantitativa para conceptos de estratigrafía secuencial.
El método modela la evolución de sistemas sedimentarios a través del tiempo geológico. Por ello, los datos de entrada consisten en condiciones pasadas (como cambios de nivel del mar, condiciones climáticas y paleogeográficas), y los resultados no se ajustan automáticamente a observaciones presentes (como datos sísmicos y perfiles de pozo). El usuario debe ajustar los parámetros de entrada mientras compara el resultado con datos observados. Este proceso iterativo conduce a uno o varios modelos plausibles que son consistentes con los procesos sedimentarios que originaron la estratigrafía observada. El conjunto de resultados permite evaluar la incertidumbre incorporando factores sedimentológicos y paleoambientales y no meramente geoestadisticos, como en otros metodos.
Los ejemplos de aplicación presentados se concentran en ambientes de aguas profundas e incluyen sistemas de turbiditas en Brasil, el margen continental del norte de Alaska y una secuencia fluvial en el Mar del Norte. En conclusión el modelado de procesos geológicos complementa a otros métodos de análisis geológico agregando una herraminenta cuantitativa al estudio de procesos sedimentarios que de otra manera se limitaría a descripciones conceptuales e intuitivas.

## INTRODUCTION

In recent years geology has become increasingly quantitative. Mathematical methods and software for structural reconstruction, sediment compaction, organic matter maturation, and hydrocarbon migration are now commonplace in hydrocarbon exploration, while geostatistical methods of reservoir characterization, reservoir flow modeling, and history matching have become essential tools in workflows to maximize returns in hydrocarbon production. This tendency toward quantification has been brought about by the availability of high-quality data such as 3D and 4D seismic, increased computer power, and an increasingly competitive environment in which smaller margins matter. Although data can still be uncertain (such as lithologies and petrophysical properties from seismic information), the uncertainty can be quantified.

A relatively recent and still underused addition to the geologist's set of quantitative tools has been geologic process modeling (or GPM, also called stratigraphic forward modeling). This technique aims to model the processes of erosion, transport and deposition of clastic sediments, as well as carbonate growth and redistribution on the basis of quantitative deterministic physical principles (Cross 1990; Tetzlaff & Priddy 2001; Merriam & Davis 2001). The results show the geometry and composition of the stratigraphic sequence as a consequence of sea-level change, paleogeography, paleoclimate, tectonics and variation in sediment input. In its scope, GPM is similar to detailed sequence stratigraphy. However, the latter has been developed on the basis of observations and inferences, mostly from seismic data, and conceptual models that specify what stratigraphic relationships should be expected under certain conditions (such as sea-level rise and fall, or variations in sediment input). GPM on the other hand, is based solely on numeric modeling of open-channel flow, currents, waves, and the movement of sediment. The observed stratigraphy is the result of modeling a physical system.

During numeric modeling of sedimentation, the modeler is faced with assigning values to several parameters that are difficult to estimate (sediment input, sediment diffusion and transport coefficients, for various environments and sediment types). Even after a result has been achieved that approximately matches observations, the model is usually run several times varying the unknown parameters within ranges of uncertainty. The ranges of uncertainty are selected so that the differences between results and data do not exceed a predetermined value. The set of results is used for statistical inference of model results, providing information such as uncertainty in reservoir geometry and petrophysical parameters, as well as geostatistical information for detailed reservoir modeling (Doliguez *et al.* 1999).

## MODEL DESCRIPTION

Several software packages from various vendors are available to perform geologic process modeling. For the work described here, an experimental package called GPM was used, implemented as a plugin within a major geologic modeling package. It is based on modeling principles that have been originally used in research models in the 1980's (Tetzlaff & Harbaugh 1989). Its usage and functionality are briefly described below.

## Basic input and boundary conditions

In GPM the user can choose which processes to model, but some input is common to all models (Figure 1). This input consists of:

- Sediment components and their properties
- Preexisting basin configuration
- Sources, sinks and boundary conditions
- Sea-level curve
- Modeling time interval

GPM works with a small number of pure sediment components and their mixtures in all proportions. Typically, four components suffice, as for example, “gravel”, “sand”, “silt” and “clay”, or “reef carbonate”, “silt”, “clay 1” and “clay 2”. The user specifies each component by its physical properties such as grain size, grain density, compaction coefficient, initial depositional porosity and permeability, and in the case of carbonates, growth rate dependency on light and wave action.

The preexisting basin configuration consists of a user-provided surface, that must be reconstructed (usually from seismic data) using an independent methodology, or by flattening or otherwise manipulating seismic reflectors. Typically this surface represents a basin floor or basement, but it can be any arbitrary surface from which modeling starts. This surface may be eroded or deposited upon during simulation. The sediment composition that is yielded by erosion of this basin surface must also be provided. The sea-level curve may be obtained from the literature, or from a previous sequence stratigraphic analysis such as with Extrema technology (Borgos *et al.* 2003, 2007). The time interval is simply the period of simulated geologic time that the user wants the model to run.

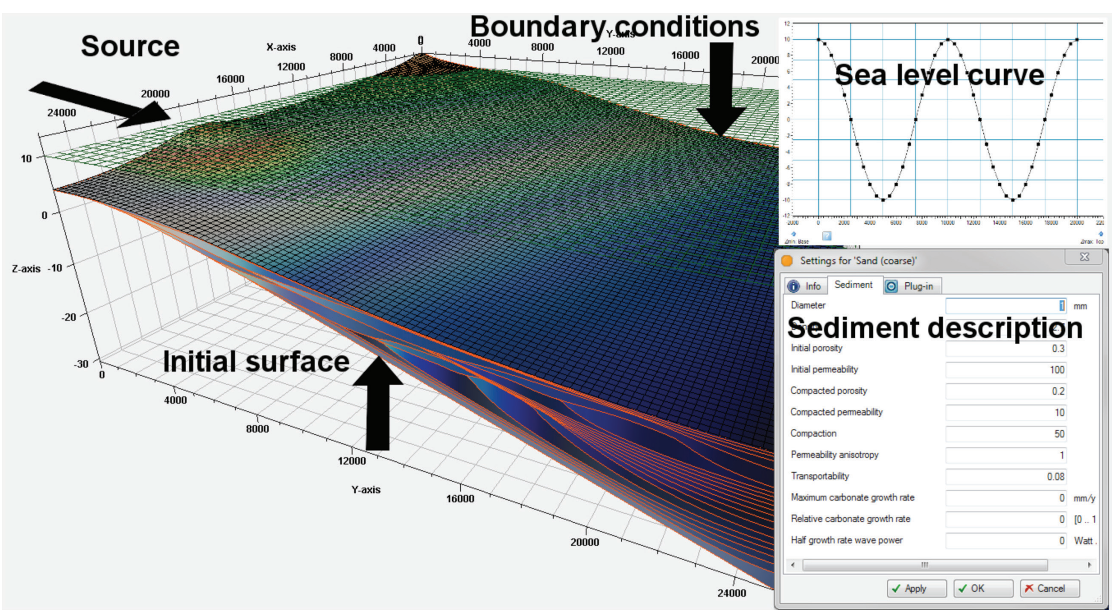


Figure 1. GPM basic input.

Sedimentary systems cannot be assumed to be closed. Usually there is sediment or water (rivers, turbidity currents, marine currents) entering and exiting the area that is being modeled. Similarly, in some models it is practical to assume that clay settles uniformly over a large area in a deep water environment. GPM offers two ways to model sources: Point sources and areal sources. Both may be modulated by curves that specify the flow as a function of time. They are useful for specifying detailed time variations of input. Conditions at the model boundaries (open or closed to flow and sediment transport) must also be specified.

**Diffusion**

Perhaps the simplest way to model sediment transport processes is diffusion. Diffusion simply assumes that sediment will move down slope at a rate proportional to the slope and to sediment characteristics (fine sediment will move farther than coarse sediment).

Diffusion is often used in conjunction with other sediment transport modeling methods in order to model processes that occur at a sub-cell scale. For example, fluvial action would only move sediment within the river's flow, and would not affect any sediment above water. Therefore river banks would become vertical. In reality, this might not happen because there are slumps, soil creep, and biological activity that cause the banks to slope. These processes typically occur at a scale smaller than one cell in the model, and can be jointly modeled by diffusion.

Diffusion does not occur equally everywhere. It is often a function of elevation or depth below sea level. Therefore, the software accepts a vertical diffusion curve. If wave action is not modeled separately (as described later in this paper), it may be approximated by using a diffusion curve with high values at sea level, decreasing exponentially with depth. Diffusion may also be used to model the erosion of high mountains by glacial action in first approximation (without expecting details of glacial landforms).

**Free-surface flow and sediment transport**

Free surface water flow (by rivers, floods, turbidity currents, long shore currents) is the most ubiquitous mechanism of sediment transport. It is notoriously difficult to model with engineering precision. In a geologic setting this difficulty increases because the flow may be unsteady and the topographic surface and source intensity are constantly changing through geologic time.

The GPM model provides two ways of simulating flow:

- Steady flow is used when flow velocity and depth do not change rapidly through time, e.g. like in a river at normal stage.
- Unsteady flow is used when flow velocity and depth change rapidly as in a turbidity current or a river flood.

All flow in nature eventually changes and is thus unsteady. There is no clear division between the two processes, and some flow models might be simulated by either method. In general, when the flow does not change appreciably over the course of a few hours, it can be considered steady for the purpose of GPM.

In order to achieve a reasonable balance between accuracy and the flexibility needed to model flow in geologic settings, both methods simulate flow in two dimensions but keep track of flow depth at every point (this scheme is also known as a “shallow water” model, but it does not imply that the water must be shallow). Within the sea, a three-layer flow description is used: A bottom layer to model turbidity currents or hyperpycnal flow, an intermediate layer to model ocean currents or isopycnal flow, and a shallow layer to model hypopycnal flow. Although this is simplistic, it suffices to model the most fundamental interactions between sediment and flow in the marine environment.

Numerically, steady flow is modeled using a finite-difference scheme within a rectangular grid. Unsteady flow is modeled with a “particle-in-cell” method, which uses a large number of particles (or fluid elements), each of which representing a finite volume of fluid, while a grid keeps track of the local depth and average flow velocity (Grigoryev *et al.* 2002), . Both the steady and unsteady flow algorithms allow for the erosion, transport, and deposition of sediment. The flow is assumed to possess a transport capacity that depends on the flow velocity and depth. The flow will erode sediment until its transport capacity is fulfilled, and will transport it until the transport capacity diminishes to the point at which it can no longer carry its load. Each sediment type has a different transportability, so the method implicitly handles the coarse fraction differently from the finer fraction achieving the same effect that occurs in reality as a consequence of the different modes of sediment transport.

Figure 2 shows a test run in which a fan delta was created using steady flow and a constant sea level with four sediment types: coarse sand (red), fine sand (green), silt (blue), and clay (black). Sediment mixtures are displayed as additive color mixtures, so for example orange represents a mixture of coarse sand with a small amount of fine sand.

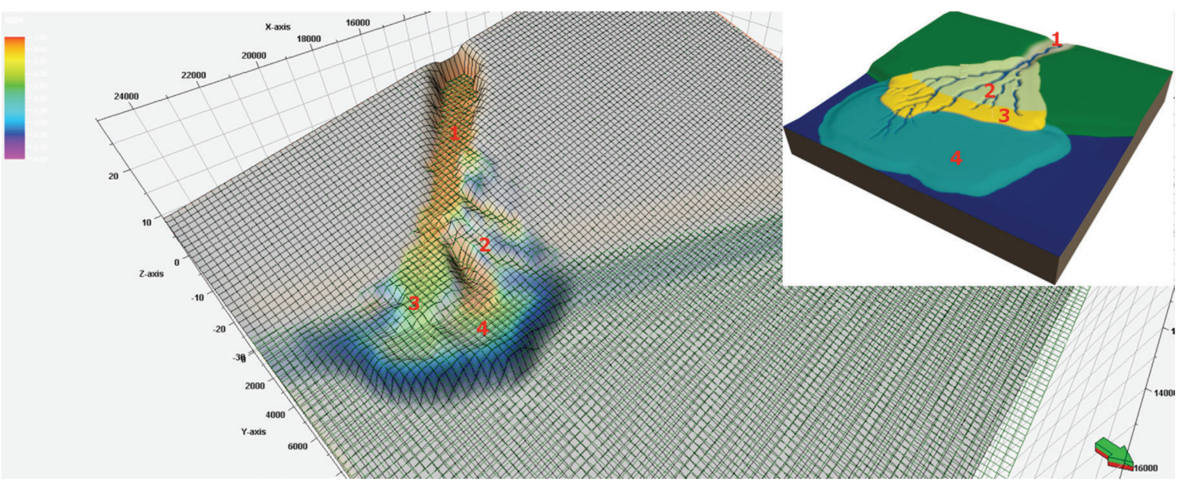


**Figure 2. Steady flow and transport example showing the formation of a river valley and a fan delta under constant sea level. Four sediment types were used: Coarse sand (red), fine sand (green), silt (blue) and clay (black). Schematic block diagram of main deltaic environments is shown on the upper right: 1. Alluvial valley, 2. Delta plain, 3. Active delta, 4. Undersea delta plain.**

Figure 3 displays a turbidite fan that developed using the unsteady flow algorithm. One hundred turbidity currents were modeled which resulted in the erosion of a channel on the slope and the deposition of a fan. The right side of Figure 3 shows a cut across the midsection of the fan to reveal its internal architecture.

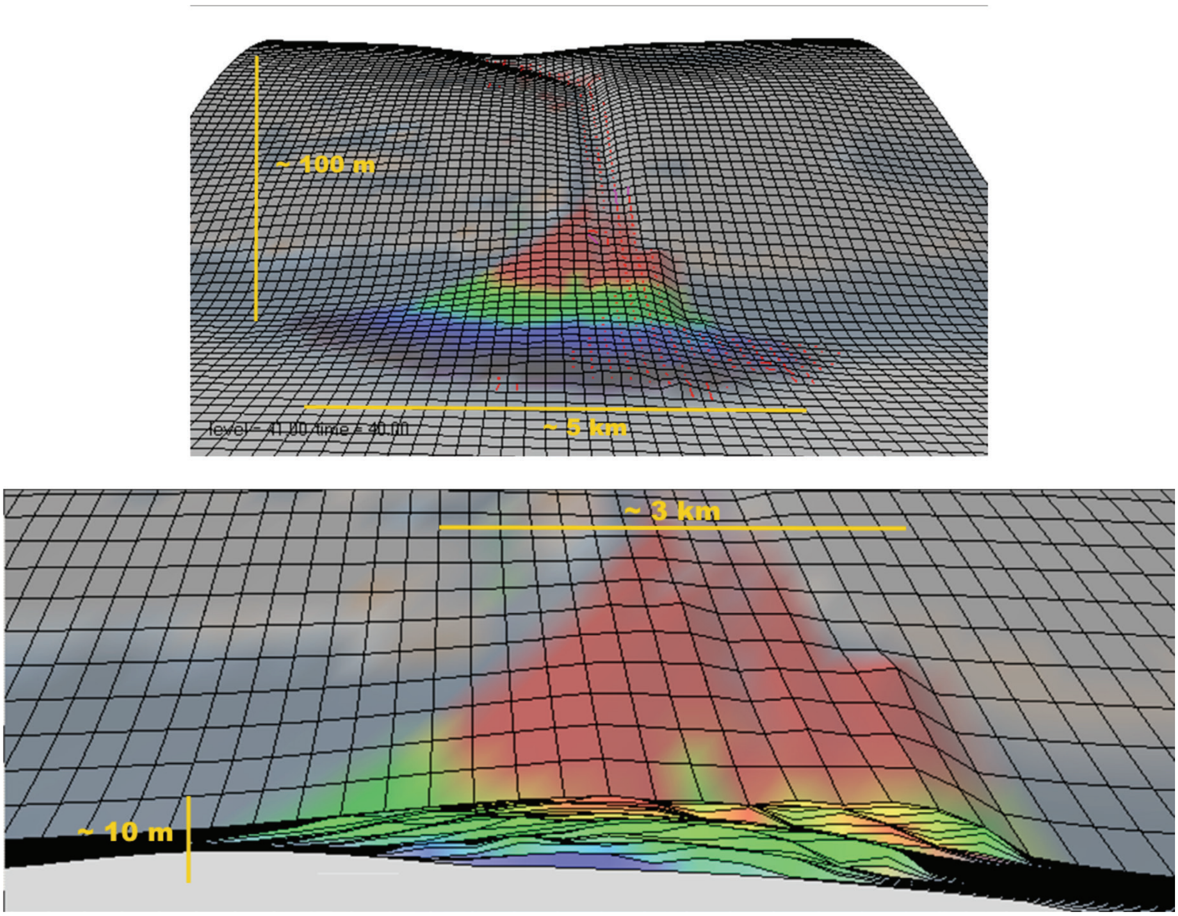


**Figure 3. Unsteady flow and transport example showing the formation of turbidite fan after 100 flows. Sediment types are the same as those used in Figure 2. Upper figure shows carved valley and entire fan. Lower figure shows detailed transversal section of fan.**

## Wave action

The detailed behavior of waves, particularly at depths that are shallow in relation to wave-length and wave height, is still a subject of research and has given rise to a number of different approximate mathematical descriptions (Allen 1977). In order to model the effect of wave action over geologic periods of time only the most basic known principles of wave motion are used (Martinez & Harbaugh 1993). GPM uses accepted formulas for wave celerity (the velocity of wave groups) to calculate wave trajectory (including refraction and diffraction), for a given set of wave sources as a function of wave amplitude, period, and depth distribution. For useful simulation of sediment transport, however, it is also necessary to model the water movement and wave power dissipated near the bottom due to friction. This model assumes that power dissipation is proportional to maximum water-bottom velocity, which is approximated by semi empirical formulas. Figure 4 shows modeling results for typical sea-floor configurations.

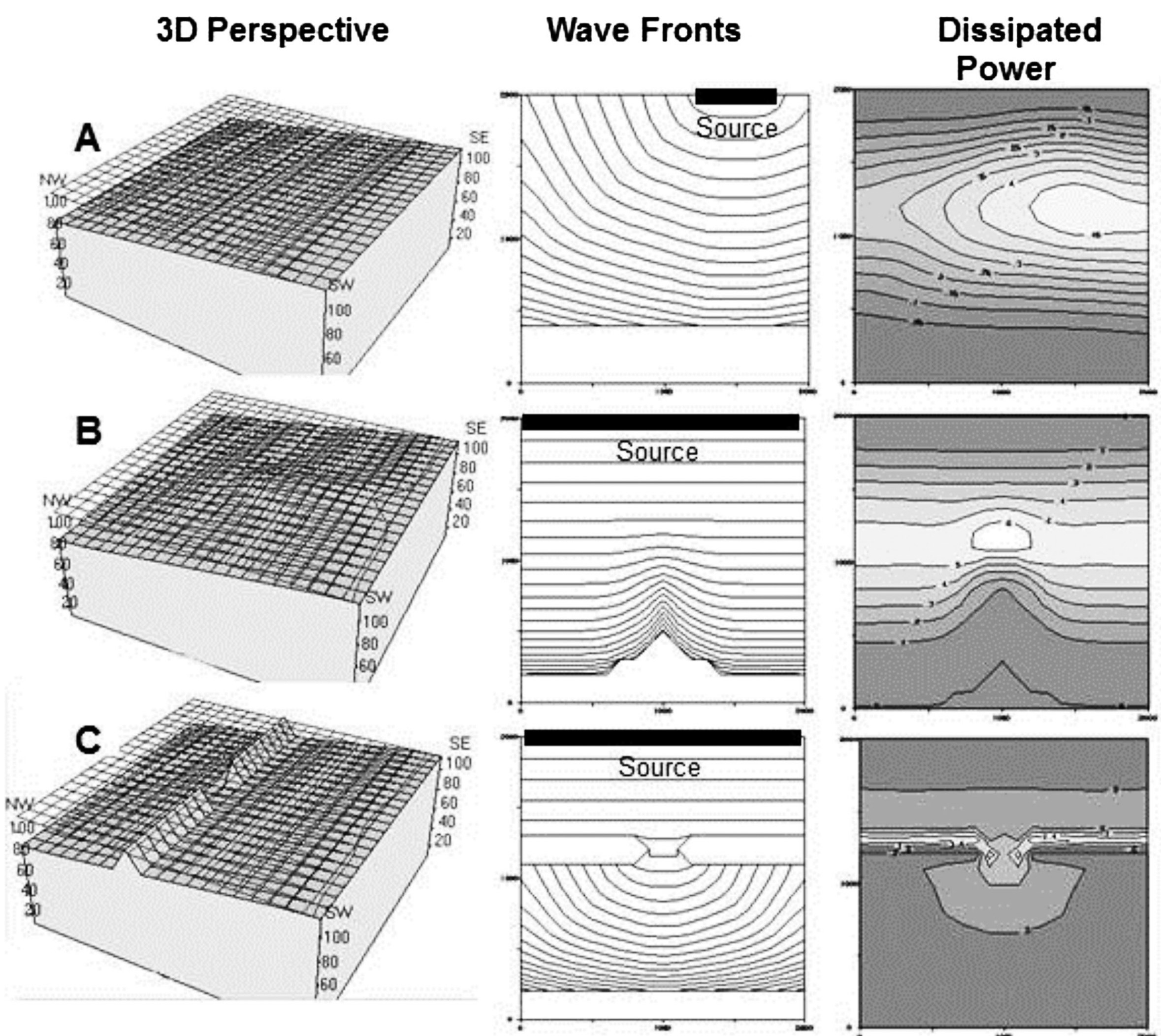


Figure 4. Wave-front geometry and power dissipation in three geometric configurations: A. Ramp, B. Ramp with a shallow underwater promontory, C. Reef with an opening.

The model further assumes that there are three effects associated to the power dissipation of waves in shallow water: (1) increased turbulence which in turn increases sediment diffusion (2) currents which carry sediment along the shore when waves incide at an angle, and (3) a net onshore movement of sediment particles, caused by the asymmetric movement of water during a wave cycle. These effects are schematically shown in Figure 5.

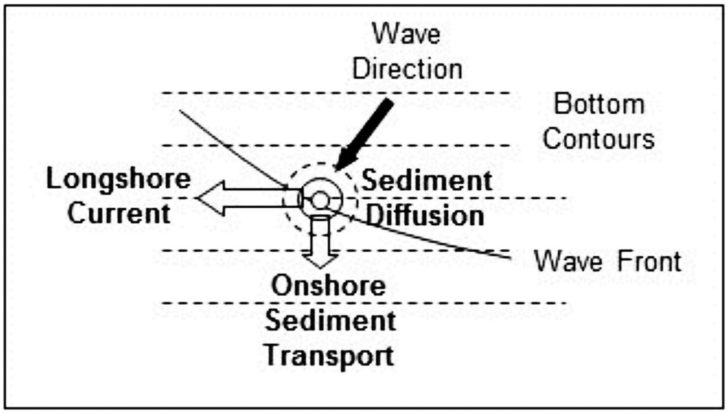


Figure 5. Effect of waves inciding on a shoreline.

Although the model is simple, it is effective in modeling the main behavior of wave fronts, energy and sediment transport in a wide range of wave regimes and shore configurations.

Figure 6 shows a simple example similar to case B of Figure 4 (ramp with underwater promontory) under rising sea level for a period of 1000 years. A wave source is located in the south of the area, and waves move toward the north (away from the observer). Due to wave refraction, waves incide sideways on elevated areas, and sand beaches accumulate on both sides of the promontory, which stays linked to land by a ridge of sediment.

## Carbonate growth

While most of GPM focuses on the erosion, transport, and deposition of siliciclastic sediment, a module for carbonate growth has been recently added. Unlike siliciclastics, carbonates grow in situ in response to environmental conditions (such as light, temperature, nutrients, and energy of the environment). After they are formed, however, carbonates behave as clastics – albeit with their own distinct mechanical and chemical characteristics. All the existing modules for flow and sediment transport apply to carbonates as well. Because carbonate production, and not just destruction and redistribution, depends on paleoenvironmental conditions, carbonate systems are complex and react differently to external influence than siliciclastic systems (Burgess 2006). Forward modeling can help clarify these interactions.

Modeling all the factors that affect carbonate growth would call for dedicated research simulation models, but the most important factors can be reduced to a manageable number implemented in GPM. The model allows the user to specify different carbonate types and their growth rates as a function of paleoenvironmental factors. The influence of light and temperature on carbonate

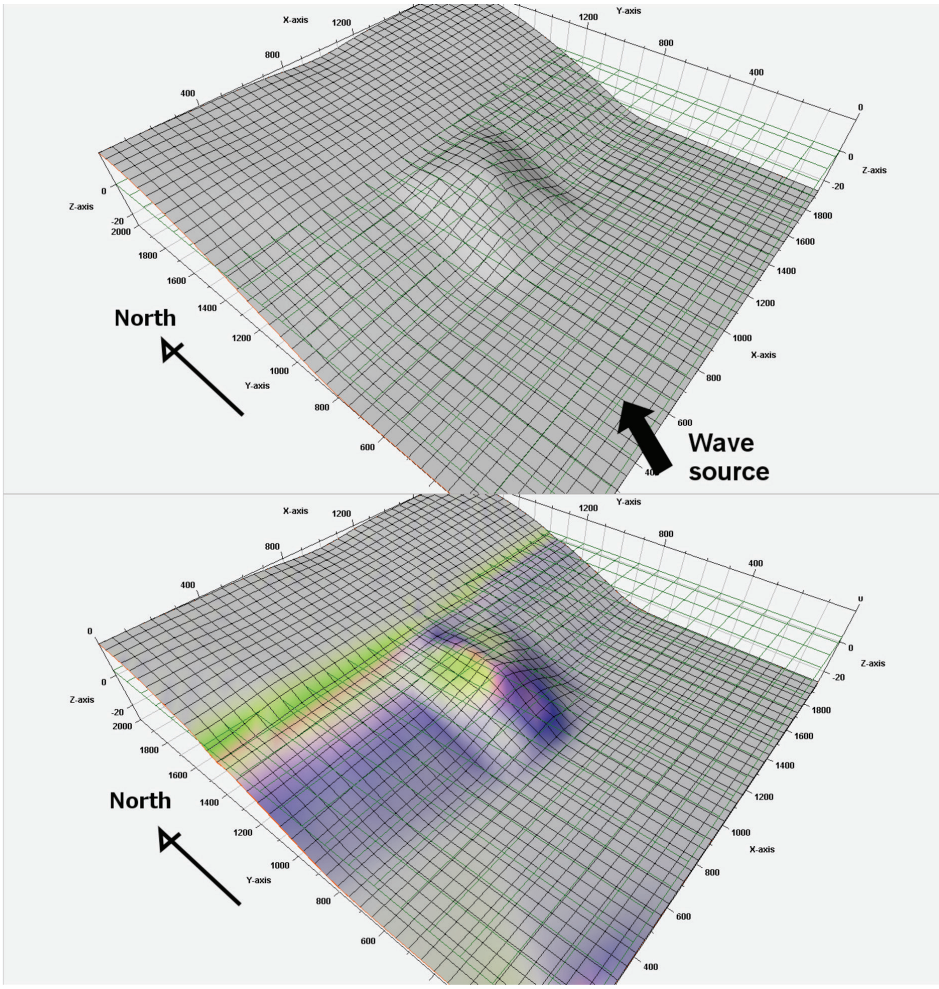


Figure 6. Example of wave simulation and sediment transport under rising sea level. Top: Initial state. Bottom: After 1000 years simulated time. Sediment types are: coarse sand (red), fine sand (green), silt (blue), and clay (black). Fine sand tends to form beaches, whereas clay is carried farther offshore and coarse sand tends to stay in place while it is depleted of finer sediments.

growth is modeled by a vertical curve that represents how these growth factors vary with depth. The influence of nutrients (presumed to be related to turbulence created by waves) is modeled by using the dissipated wave energy calculated by the wave module, and applying it to modulate carbonate growth rates.

The following two examples (Figures 7 and 8) illustrate the carbonate model. Both examples consider a wave source in deep water offshore. Carbonates are shown in green and the original basement in gray. Bed boundaries are highlighted in red. The first example assumes that wave energy has no effect on growth (although it does have an effect on redistribution). According to modeling parameters used, light increases growth, leading to faster carbonate growth near the surface. The example shows the development of a platform during two sea-level cycles. As sea-level rises, carbonate production keeps pace with it and aggradation ensues. When sea level falls, carbonates are partly destroyed and carried downslope.

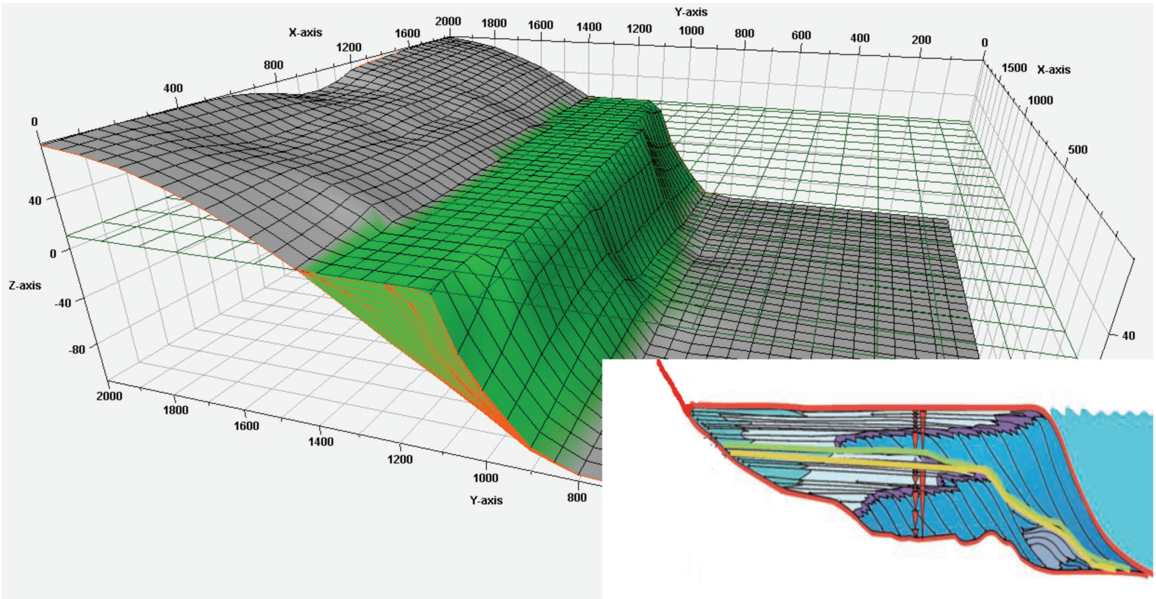


**Figure 7. Carbonate platform formation during two sea-level cycles (all coordinates in meters). Diagram at the lower right shows idealized carbonate platform stratigraphy during two sea-level cycles (from Catuneanu *et al.* 2011).**

The second carbonate example assumes that wave action, in addition to light, favors carbonate growth, as may be the case in reefs (Figure 8). After a simulated time of 20,000 years a reef has developed in the area exposed to waves. Behind the reef, wave action is less, and carbonates grow at a reduced rate, thereby forming a shallow lagoon. An accumulation of siliciclastic sediments (pink to purple colors) is present at the bottom of the slope and is the product of early basement erosion by waves.

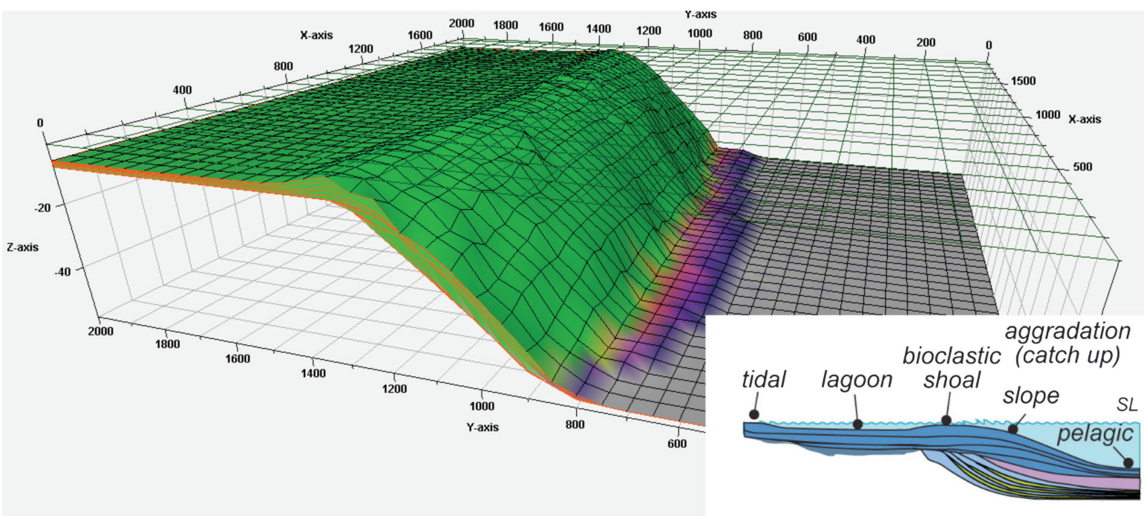


**Figure 8. Carbonate reef and detrital apron formed under rising sea level (all coordinates in meters). Carbonates are shown in green color, basement in gray, sand in red, silt in blue and clay in black. Diagram at the lower right shows idealized carbonate sequence during sea-level rise (from SEPM 2014).**

## Tectonics

In the present version of GPM, tectonics can be represented in the form of vertical movement of the basement which raises or lowers the overlying sediments. It is possible to model vertical faults, subsidence or uplift, the vertical component of folds, tilting, and the surface effect of diapirs. Tectonic movement is specified in the form of a surface in which each node contains the local uplift rate in units of meters per 1,000 years. Negative uplift corresponds to subsidence. In order to model faults, the user generates a surface that contains a sharp boundary of uplift rates. One side of the boundary will move at a different rate than the other side, thereby modeling a vertical fault.

It is also possible to model tectonics at rates that vary – or even reverse – through time. This is achieved by specifying a curve that contains multiplier values (positive, zero, or negative) that vary as a function of time. The multiplier value of the curve for a given time is applied to the tectonic rate surface, to yield an uplift value for a given place and time. Thus it is possible to model tectonic movement that varies through both space and time.

## Compaction

Presently, GPM contains an algorithm for sediment compaction based on simple load. It models the elastic compaction of sediment due to the load above it. Despite its simplicity, it is adequate to model the increase in accommodation space due to compaction and the ensuing changes in sedimentation patterns, as well as the changes in geometry and thickness due to differential compaction of contrasting lithologies such as sand and shale.

A model of compaction that takes into account pore pressure and fluid flow in full three dimensions within the sediment accumulation is in preparation. This algorithm is similar to the ones used in basin modeling programs. This will result in more realistic compaction calculations, and will enable the use of GPM as a tool to predict overpressure, independently from other methods (such as seismic velocities) and possibly with more precision than basin modeling programs due to the higher stratigraphic resolution of GPM.

# INTEGRATION

GPM should be used in conjunction with other quantitative modeling tools. It is usually necessary to perform a reconstruction of the initial basin surface before the actual modeling can commence, thereby requiring the use of a tectonic reconstruction method. GPM only models sedimentation, but not post-depositional processes other than compaction. Full understanding of diagenetic processes (*i.e.*, compaction, cementation, grain replacement and dissolution), would require running a separate package to model in detail. However, GPM does provide the setting for the geological evolution for every volume of sediment (depth of deposition, primary lithology, overburden, and compaction), thus adding greater certainty and detail about deposition and burial history, so that some diagenetic effects could be better understood when evaluating reservoir quality risk.

Detailed structural modeling after deposition is also feasible in conjunction with GPM. GPM only models vertical movement and compaction. Complex structural deformation and the modeling of stresses and strains leading to the presence of fractures require a different modeling package, but structural modeling benefits from detailed information of sedimentation and stratigraphy while providing the structural process details that GPM lacks. Similarly, heat flow and hydrocarbon migration and maturation are not modeled by GPM. In all these cases GPM may provide a detailed description of the primary depositional geometries and properties that these packages require.

## EXAMPLES

Five application examples are briefly described below. They involve siliciclastic sedimentation in deep water as well as shallower shelf environments. The first two examples were chosen to underline the applicability of this technology to nonconventional exploration settings in Argentina. Due to proprietary restrictions and the ongoing nature of these studies, they do not show seismic or well-log data on which the models are based. The final two examples include seismic sections in order to provide an rough idea of the degree to which typical GPM models are able to fit seismic and complement it with information derived from depositional history.

### Alaska North Slope

The North Alaska Slope is a prosperous hydrocarbon province with big discoveries and resources. The case study described here involves reconstructing parts of the progradational Brookian sequence in the Early Cretaceous. The model is located at the northern part of the slope and comprises a total area of 2.11 x $10^{\wedge 6}$ $km^2$, and spans a length of 1,600 km. In total a time span of 7 Ma was modelled, from 122 Ma to 115 Ma.

In the Cretaceous period sediment provenance was from the Brooks Range orogen in the west and south, slowly and progressively filling the Colville foreland basin, which was bounded to the north by the Barrow Arch. Siliciclastic material accumulated in the form of condensed marine mudstone (Hue Shale), turbiditic sandstone (Torok, Seabee and Canning formations) and shallow marine sandstone, mudstone and conglomerate (which includes the Nanushuk, Tuluvak, Prince

Creek, Schrader Bluff and Sagavanirktok formations) (Schenk *et al.* 2012).

The input to GPM includes a base surface reconstructed from seismic data in a previous basin model by Schenk *et al.* (2012) (Figure 9).

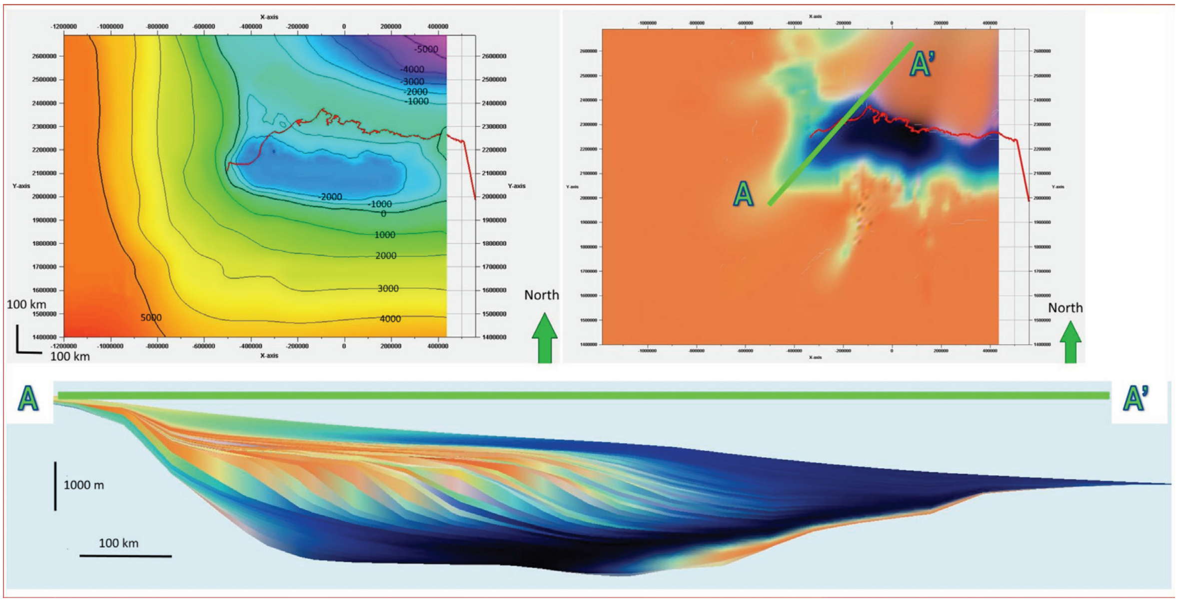


**Figure 9. Alaska North Slope model. The present-day shoreline is shown in red. Upper left: Initial surface (constours in meters). Upper right: Final model in plan view and location of cross section. Bottom: Cross section showing predicted stratigraphy and sediment composition (coarse sediments in red and green, fines in blue and black).**

This surface was extended towards the west and south to include the sediment provenance areas and to reconstruct the paleotopography at 122 Ma. Four different sedimentary point sources were placed on this surface at locations indicated by the topography and by paleocurrent information from Houseknecht *et al.* (2008). A tectonic map was generated with uplift rates from 0.05 mm/a in the Brooks Range, and subsidence in the basin area reaching 0.2 mm/a. These values were obtained from a conversion of a thickness map into tectonic movement per year derived from the previous basin modeling study.

The model shows prograding foresets building up from the Brooks Range in the SW into the basin. The grain sizes closer to the sources are larger, and diminish away from the sources. It takes about 3 Ma for the coarser grain fraction to reach the center of the Colville foreland basin. Validation of the extent and thickness of the modeled sequences was done through comparison to the surfaces derived from the basin model.

## Campos Basin

This case involves a deep water turbidite system from the Campos Basin, offshore Brazil, for which good-quality 3D seismic was available. In this province, turbidite systems have been proven as major reservoirs. In the first stage of geologic process modeling, a paleo-basin floor surface was reconstructed from seismic and sediment sources were placed at locations indicated by the inferred paleo-bathymetry (Figure 10). After adjusting the amount and type of sediment carried by turbidity currents, a reasonable match with observed seismic was obtained. This was assumed to represent a "base case":

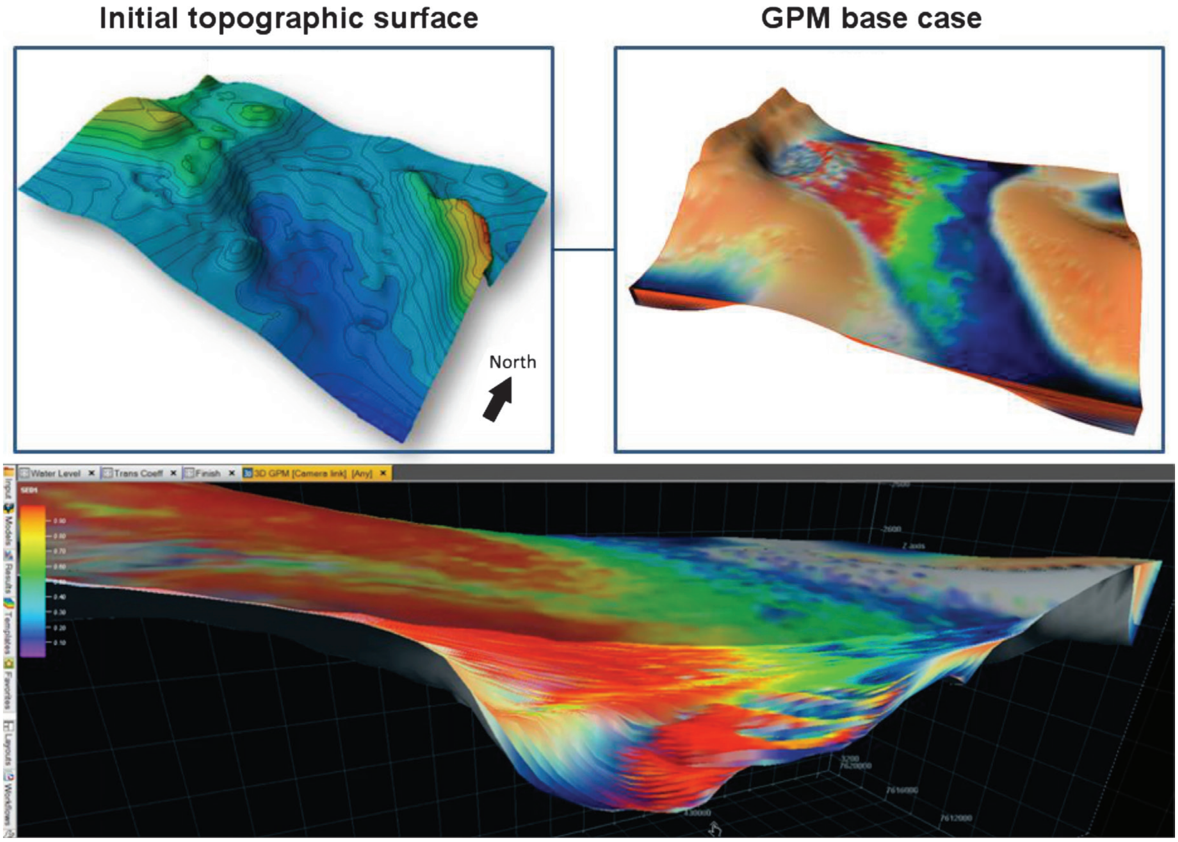


**Figure 10. Initial basin floor surface and base-case scenario of basin fill in the Campos Basin, offshore Brazil. The area modeled is approximately 40 km by 36 km and the maximum thickness is about 400 m. The color scale indicates sand content. Sands in the deep part of the basin represent basin floor fans deposited by turbidity currents originating in the upper end of the basin (upper left of the figure). Several episodes of incision and fill can be seen. Fine sediments in the section were deposited by shelf progradation from both sides of the basin.**

In the second stage, some of the modeling parameters were varied within ranges of uncertainty. The changed parameters were: overall sea level, transport coefficient (which determines the ease of sediment transport by water) and diffusion coefficient (which affects sediment transport due to slumps, creep, and wave action). As long as the resulting model was compatible (within a defined standard) with observed data, the altered values were considered plausible. The results of all plausible models, considered jointly, provided a picture of the uncertainty of the occurrence of observed features and sediment properties. Although the detailed features of each realization are not certain, the joint set of models provided an estimate of the chance of drilling a successful well. "Success" in this case was defined as a reservoir thickness and quality exceeding a defined minimum. This estimate was then mapped as a Chance of Success (COS) map. The workflow is briefly outlined in Figure 11.

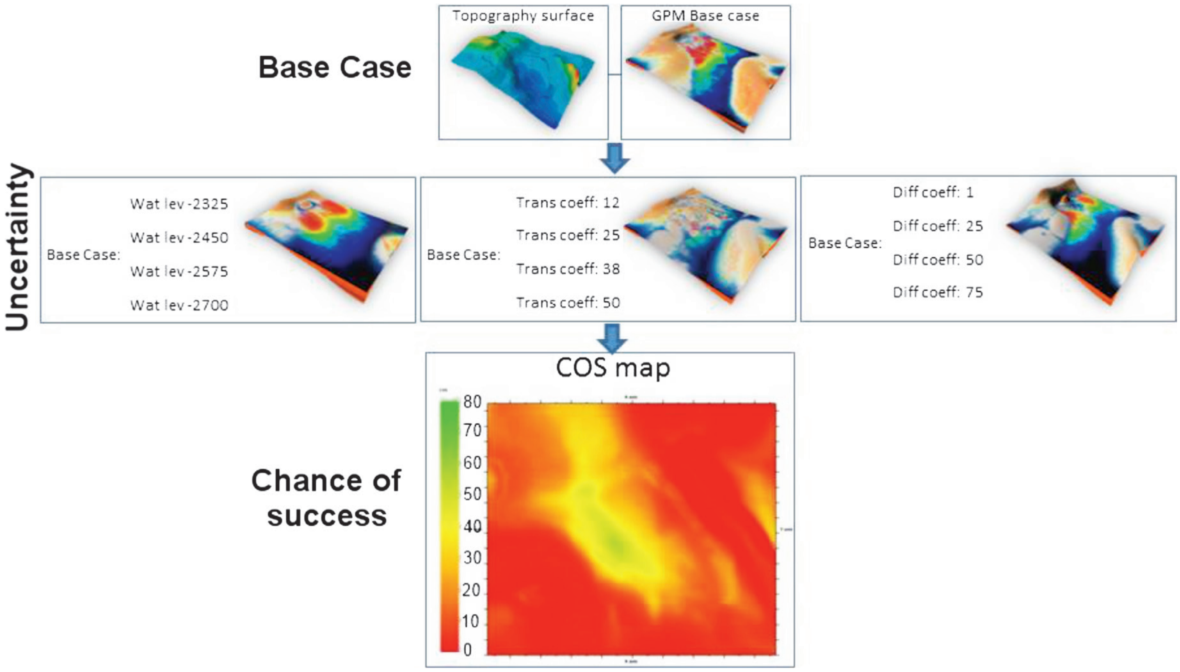


Figure 11. Schematic view of workflow to build a "chance of success" (COS) map. First, a likely base case is built. Then input parameters are varied within their ranges of uncertainty. Finally, results combined in a probabilistic chance-of-success map showing probability of success as a percentage.

## North Sea

This example involves the mid Jurassic Pentland Formation, a fluvial sequence in the North Sea. Logs from two wells were available. Several fluvial environments were identified by means of well logs. GPM was adjusted to reproduce channel thicknesses and characteristics inferred from the logs. When tied to the seismic, the results show a stratigraphic architecture with higher resolution than the seismic and compatible with what was known about the depositional system (Figure 12).

Sea level, slope, river flow and sediment input were varied to try to match the changes in the environment inferred from well logs. Post depositional structural deformation was then applied so that the modeled sequence can be compared to seismic directly.

This example is of interest because it shows a possible application to establish stratigraphic architecture at the reservoir scale. In this example, individual beds may be less than 1 m thick. While individual sands and shale may not be exactly at the locations shown in the model, the overall stratigraphic architecture is compatible with what is known about the environment of deposition and may be useful for predicting subsurface flow in a reservoir simulation model.

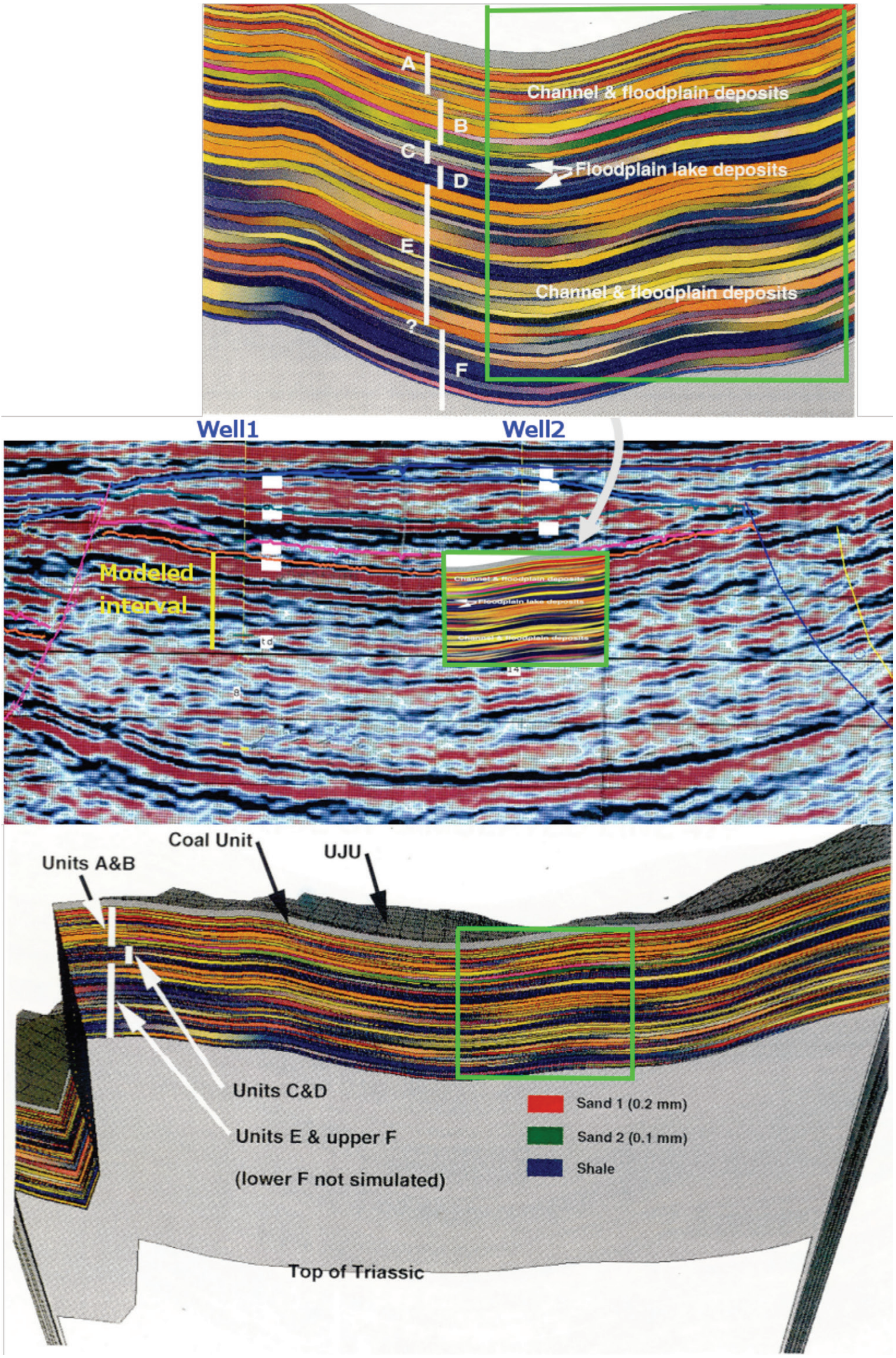


Figure 12. GPM model of fluvial sequence at the upper part of the mid Jurassic Pentland Formation reconstructed from two wells and 3D seismic. The length of the section is approximately 3 km and the depth of the modeled interval is approximately 200 m. Modeling ends at the coal unit located just under the Upper Jurassic Unconformity (UJU). The central figure shows the original seismic with part of the GPM model superimposed. The lower figure shows the GPM model at the same scale as the seismic. The upper figure shows the enlarged detail of the GPM model, which is also framed in green in all three figures. Facies shown in the upper figure have been interpreted from logs at Well 2. Letters A through F correspond to units in which the formation has been divided.

## Santos Basin

The next example is from the Santos Basin in Brazil, and involves the detailed simulation of an upper Cretaceous turbidite interval (Figure 13).

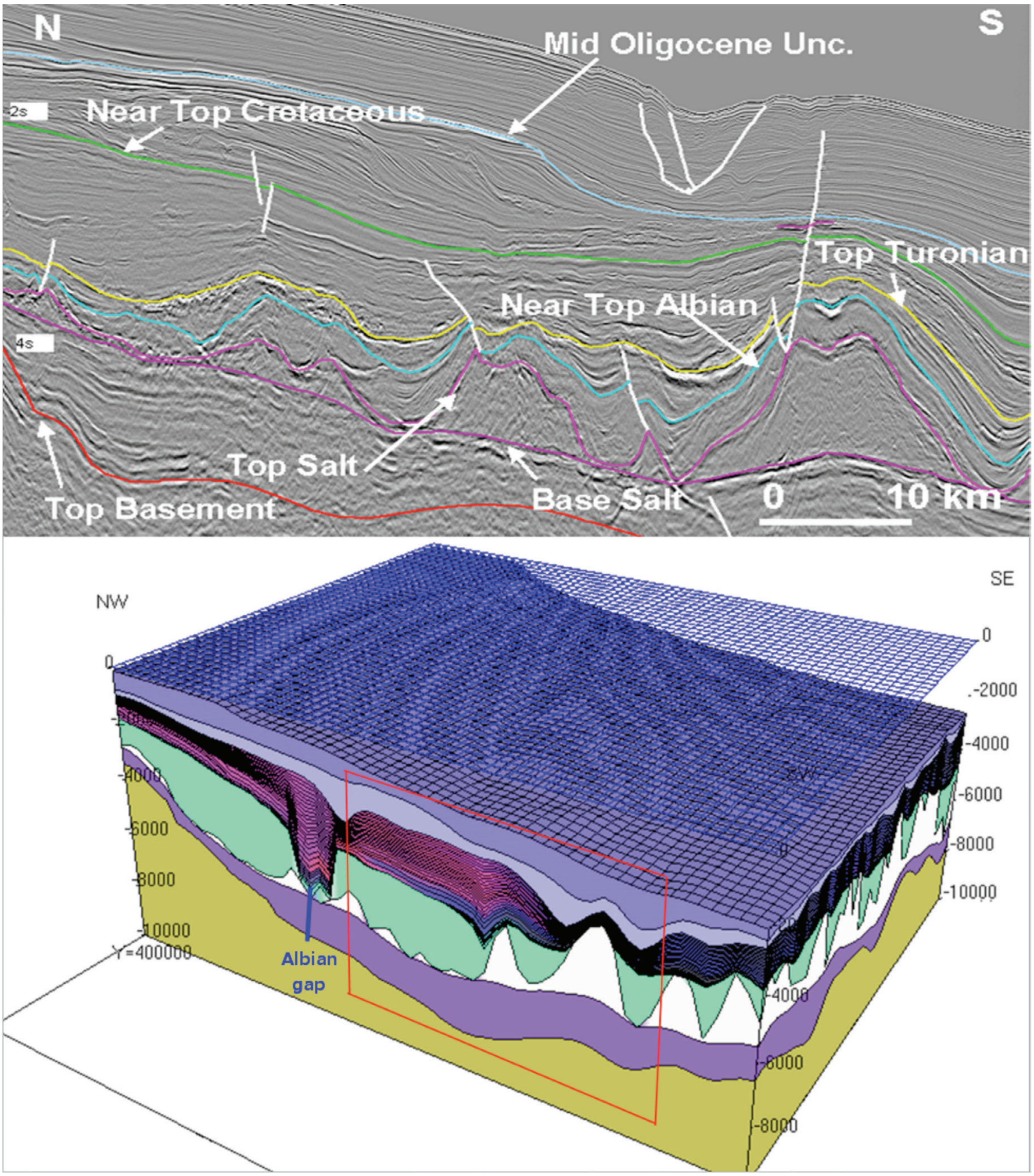


Figure 13. Seismic section from the Santos Basin, offshore Brazil (upper figure), and corresponding GPM model (lower figure) aimed at reproducing the turbiditic sequence bounded by the Top Turonian and the "Near Top Cretaceous". Other formations were not modeled in detail, but included as single layers to complete the model. The red frame in the model corresponds approximately to the seismic section shown above (Depth units in meters).

In the Santos Basin, syndepositional deformation may have been affecting the path of turbidity currents. A graben known as the "Albian gap" (shown in Figure 13 just North of the red frame that represents the seismic section) was opening as deposition was taking place. Simultaneously, salt started to flow under the weight of the overlying formation. While GPM does not directly simulate the flow of salt, it does predict the sediment pathways when salt deformation can be input into the model after being inferred from seismic.

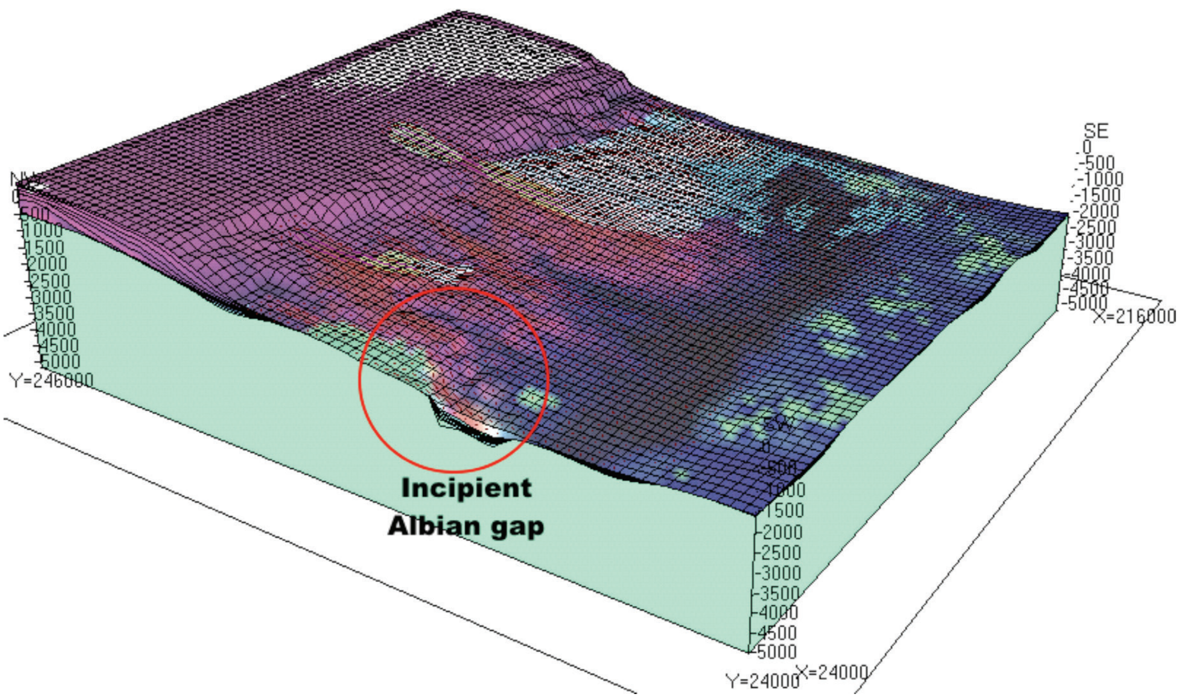


**Figure 14. Detail of the lower part of the modeled interval during deposition showing shelf progradation and turbidites (all units in m).**

The results permitted a detailed assessment of the distribution of clastic lithologies in the interval of interest as the sediment pathways were routed by the major structural features and modulated by sea-level changes. Figure 14 shows one snapshot of the continental margin during the earliest stages of deposition of the modeled unit. Turbidites are diverted into the "Albian gap" (red circle in the figure) causing coarser sediments (shown by lighter colors) to accumulate within it.

## CONCLUSIONS

GPM and similar stratigraphic forward modeling tools are only a part of a growing cluster of quantitative applications used in hydrocarbon exploration and production. The results of the examples mentioned in this paper show that modeling of sedimentary processes is ripe for quantitative treatment. This technology provides a quantitative framework that may help either confirm or discard preexisting conceptual models. It also provides a means to quantify uncertainty in situations that were heretofore left largely to intuition, such as the chances of success under varying sea-level change conditions.

GPM does require some *a priori* knowledge or assumptions about paleogeographic conditions and thus is most useful if some knowledge of the basin is already available. The technology is readily applicable in exploration and early production situations, in which alternative hypotheses may have to be selected, or existing conceptual models may need quantitative refinement. At the reservoir scale, GPM can predict the general architecture, geometry and connectivity of permeable beds. Its results may be useful as training images for geostatistical methods in areas where detailed analogs may not be available.

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