A review of stratigraphic simulation techniques and their applications in sequence stratigraphy and basin analysis

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Abstract— Stratigraphic simulation is a modelling methodology that can be used for exploration purposes to understand the key factors (sea-level change, subsidence, sediment supply rate) that control the stratigraphic geometries and architecture of a basin. Its application offers many advantages to scientists and researchers, as it provides a useful platform for analyzing and unraveling the complexities of sequence stratigraphy and basin development. A stratigraphic simulator models the stratal patterns of basins in various tectonic settings, such as in passive margins, foreland basins, retroarc foreland basins, interarc basins, remnant ocean basins, growth-faulted deltaic basins, and basins with salt diapirs. It enhances biostratigraphic interpretation by providing age constraints on stratal boundaries identified through sequence stratigraphic interpretation. This can lead to a systematic prediction of other geological aspects such as the distribution of source rocks, seals, and reservoirs. Furthermore, it may also lead to the identification of new accumulations or reservoirs within existing oil and gas fields.

One type of stratigraphic simulation that is often used is a "forward stratigraphic simulation". This forward modelling method is usually applied to predict sediment distribution of a basin. In this paper, four simulation techniques (CSM, SEDPAK, DIONISOS, and SEDSIM) and their applications are presented. The models are typically applied to verify and infer the potential for hydrocarbon entrapment and accumulation in the basin. For this reason, stratigraphic simulation is useful for petroleum exploration and development. The simulation models are also useful as teaching tools for young geologists.

Keywords: stratigraphic simulation, stratigraphic modelling, basin analysis

INTRODUCTION

Stratigraphic simulation or stratigraphic modeling is a computer modeling technique used in sequence stratigraphic and basin analysis to understand the depositional sequence geometries and stratigraphic architecture of a sedimentary basin. The technique allows the geoscientist to model stratal patterns in various tectonic settings, such as passive margins and foreland basins, as well as the sedimentary architecture associated with different structural settings, such as growth faulting and salt diapirism (Bowman *et al*., 2002). It can enhance biostratigraphic interpretation by providing age constraints for the stratal geometries in sequence stratigraphic interpretation. Furthermore, it may also help identify new reservoirs within existing oil and gas fields.

Stratigraphic simulation investigates the key factors that control the sedimentation in a basin. These factors include the rates of subsidence and uplift, changes in eustatic sea level, and changes in the rates and directions of sediment supply (Figure 1). A potentially useful application of stratigraphic simulation is as a means of validating seismic sequence stratigraphic interpretation and predicting main controlling factors in the identified sequences.

Most stratigraphic simulation techniques use the "forward modelling" approach, in which the basin stratigraphic development is simulated using a set of pre-determined parameters, such as basin topography, water depth, sea-level change, and sediment flux into the basin. A common application of this type of model is in petroleum exploration, to predict the distribution of source and reservoir rocks. In a typical petroleum exploration application, a basin simulation requires the following main geologic inputs: (1) depth-converted seismically defined sequence boundaries, (2) sequence boundary ages and paleo-water depth profiles derived from biostratigraphic analysis, (3) lithologic distribution defined in well logs, and (4) sand distribution interpreted from seismic character variations (e.g. Bowman *et al*., 2002). The results of simulation are then compared with the actual seismic interpretation. Hence, stratigraphic simulation also provides a means of validating the seismic interpretation and refining our geological model (Figure 2).

The objective of this paper is to review the main stratigraphic simulation techniques available in the market (including the freeware packages on the Internet). This technology may prove to be one of the key areas of developments within the petroleum industry, because of its predictive potential in petroleum exploration and development applications. Much of the information in this review is obtained from a survey of the relevant internet websites, as well as the more traditional source of information such as books and journals. A reference list of the public domain literature is given at the end of this paper.

FACTORS THAT CONTROL SEQUENCE GEOMETRIES

Three major factors (sea-level change, sediment supply rate, and tectonic subsidence/uplift) have strong effects on stratigraphic geometries in basins (Figure 1). The relative importance of these factors is determined by examining the stratigraphic response in the stratigraphic simulator as those different parameters are changed.

Sea-level fluctuations control the sedimentation patterns in a basin, such as the stratal geometries and associated stratal terminations (onlap, downlap and toplap). Any change in the relative sea level will affect the accommodation space available for sediment deposition. Allen & Allen (1990) discussed four possible factors that are associated with global sea-level changes. Firstly, change in the volume of water in the oceans may happen due to continued differentiation of lithospheric materials resulting from plate tectonic processes. Second, the volumetric capacity of the ocean basin may change due to sediment accumulation or by sediment extraction. Third, the volumetric capacity of the ocean basin may also change as a result of volume changes in the mid-ocean ridge systems. Finally, the reduction of available water that is locked up in polar ice caps and glaciers may also induce changes in global sea level. All of these factors play essential roles in shaping the sediment fill of basins.

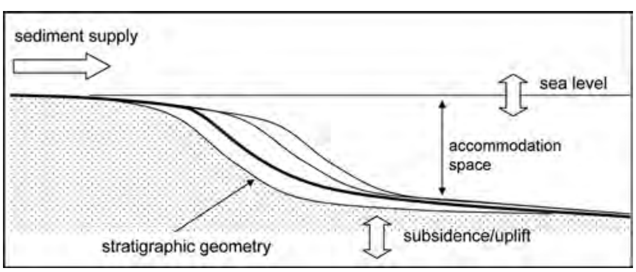

Figure 1: The main objective of stratigraphic simulation is to study the relative importance of the three primary factors controlling sequence development and stratigraphic geometries: sediment supply, subsidence/uplift, and sea-level change.

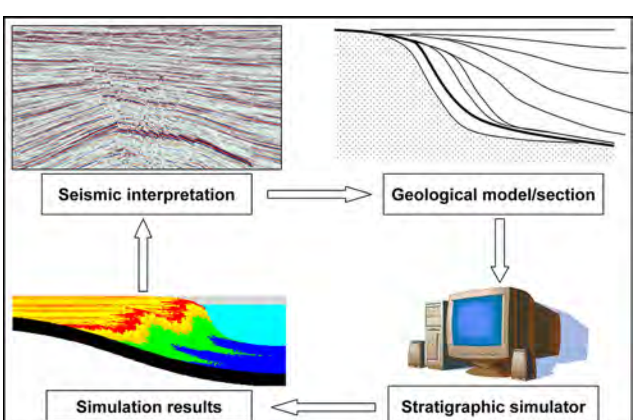

Figure 2: A possible workflow for stratigraphic simulation application in a petroleum exploration environment.

In areas of positive crustal topography, rocks will undergo mechanical weathering such as erosion. Through this process, rocks will be eroded into sediment and be transported into low areas of subsidence (basins). The rate of sediment supply of a basin is controlled by topographic, climate/vegetation, and oceanographic factors.

Tectonic subsidence is a mechanism that creates an accommodation space in a basin, i.e. the space available for sediment to accumulate. In areas of high subsidence rates, larger accommodation space is generated and vice versa. The available space can be filled by sediments. The accommodation space in basins is created through a continuous process of subsidence, either by lithospheric loading, lithospheric stretching or extension, strike-slip faulting, or gravitational collapse. Isostasy is the key mechanism that drives subsidence. This mechanism responds to compositional changes in the crust or mantle, heating and cooling of the lithosphere, and crustal or sediment loading on the lithosphere. Stratigraphic simulation investigates the effect of tectonic subsidence on the accommodation space and the development of sediment fill.

EXAMPLES OF STRATIGRAPHIC SIMULATION TECHNIQUES

CSM Stratigraphic Simulation Techniques

The CSM suites of stratigraphic simulators comprise separate packages that are used for different sedimentary environments, from non-marine through shelf to deep marine. They were all developed at the Colorado School of Mines, USA. The following is a summary of the simulators in the CSM suite.

(1) The 2D Non-marine to Shelf Model (CSM 2D)

The CSM 2D is developed by Margaret Lessenger, a researcher from the Department of Geology and Geological Engineering at the Colorado School of Mines, USA. The model simulates stratigraphic processes and responses for continental, shoreface, and shoreface environments. It generates a topographic slope of different environment due to changes in base level, accommodation space, and sediment supply. It supports faulting and other subdivisions into a tectonic block. This model has a flexure algorithm for isostatic compensation of sediment and water loads. However, the CSM model has three limitations: (1) it does not simulate grain size, (2) it does not simulate tidal processes but only wave processes, and (3) it is only a 2D simulation.

(2) The 3D Carbonate Model (CSM Carbsim)

Carbsim simulation is primarily developed by Taizhong Duan, one of the geoscientists from the Department of Geology and Geological Engineering at the Colorado School of Mines. In general, Carbsim is a purely carbonate model. Its function is based on energy and sediment flux. It deals with basins and reservoirs in space that are up to 10 million years duration. It is able to examine the sources and distributions of kinetic energy in the carbonate depositional system. An example of the kinetic energy distribution, which is related to wind-driven waves and oceanic swells, is shown in Figure 3.

Carbsim is able to show the relationships between three important factors; (1) carbonate productivity, (2) kinetic energy, and (3) water depth. Carbonate productivity depends on many factors such as the light intensity, temperature, nutrient, salinity, oxygen and the clay content. Water depth can affect the light intensity, temperature, nutrient, oxygen and the salinity. The distribution of kinetic energy can also affect the nutrient, salinity and the oxygen in the water. Therefore, it is important to see these relationships. Figure 4 shows the relationship between carbonate productivity, kinetic energy, and water depth in the carbonate depositional system.

Carbsim simulation can be applied to understand the effects of sea-level changes on the geometry of sedimentary packages. Figure 5a shows the initial topography and sea level before beginning the simulation. On the other hand, Figure 5b shows an image of a complete simulation to observe the true 3D behaviors of a carbonate system. The image shows evolution of a ramp to a platform and the variation of 3D lithofacies volume.

The color distinctions represent the lithofacies variations in an arbitrary carbonate system. These variations are divided by the differences in water depth and the distributions of kinetic energy. Red, light yellow, dark yellow and orange colors represent the facies at the water depths of less than 200 meters. The colors of red, light yellow, dark yellow and orange represent the facies that are arranged in order of decreasing kinetic energy. The colors of green and blue represent the facies at the water depth exceeding 200 meters. In terms of kinetic energy, green is higher than blue.

(3) The 3D Deepwater Model (CSM Turbsim)

Turbsim model is developed by Margaret Lessenger, a researcher from the Department of Geology and Geological Engineering at the Colorado School of Mines. Turbsim simulates the transport and deposition of sediment in the deepwater turbidite system. It conserves mass and simulates the realistic stratigraphic configuration. It provides output properties such as the thickness, grain size, depositional facies, porosity, and permeability (Cross & Lessenger, 1999). Turbsim outputs of 3D geometry of depositional facies and grain size distributions for petrophysical models are displayed in Figure 6.

Turbsim creates topographic compensation at all scales and allow a plane view of bathymetry. The compensation images are illustrated in Figure 7. The upper image shows the compensation of fans while the lower image shows the compensations of individual flows and lobes (Cross & Lessenger, 1999).

SEDPAK MODEL

SEDPAK is a 2D forward stratigraphic simulation program developed by Christopher Kendall and his Stratigraphic Modeling Group at the University of

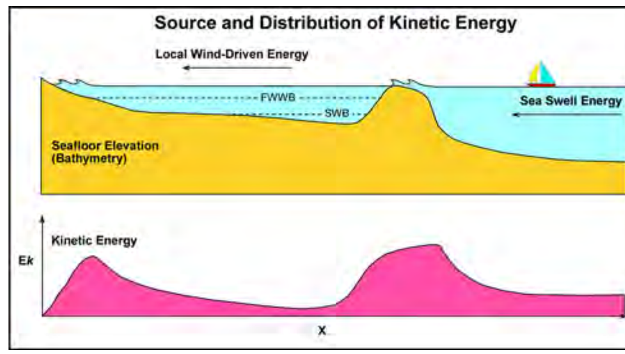

Figure 3: The kinetic energy sources and distributions in the carbonate depositional environment displayed by the Carbsim model.

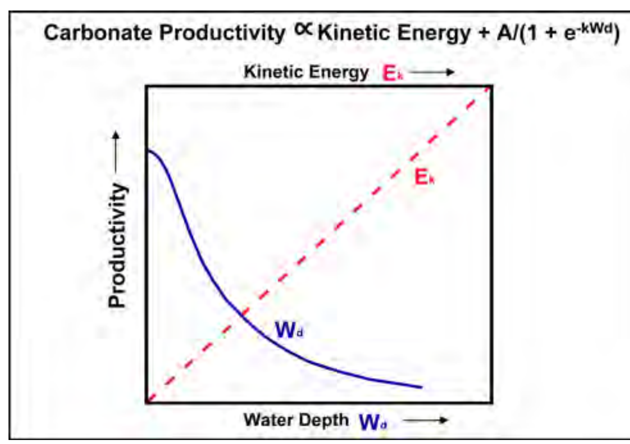

Figure 4: Carbonate productivity curves as a function of kinetic energy and water depth. From Carbsim Model Demonstration.

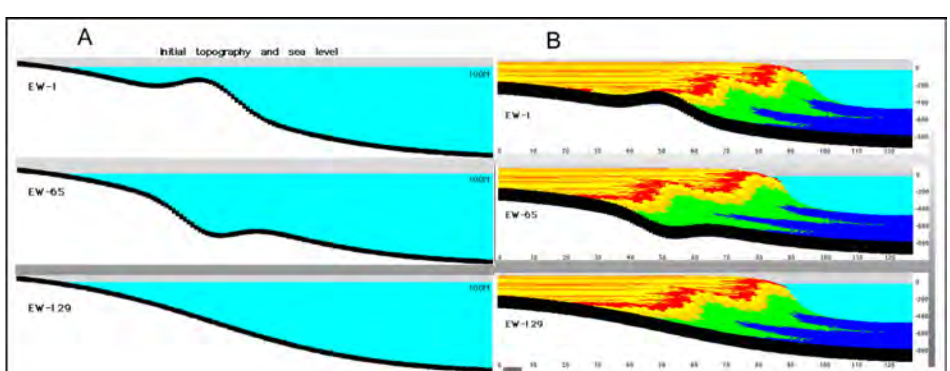

Figure 5: (A) An image of initial topography and sea level before beginning the Carbsim simulation. (B) A complete simulation by Carbsim to observe a true 3D behavior of a carbonate system. From Carbsim Model Demonstration.

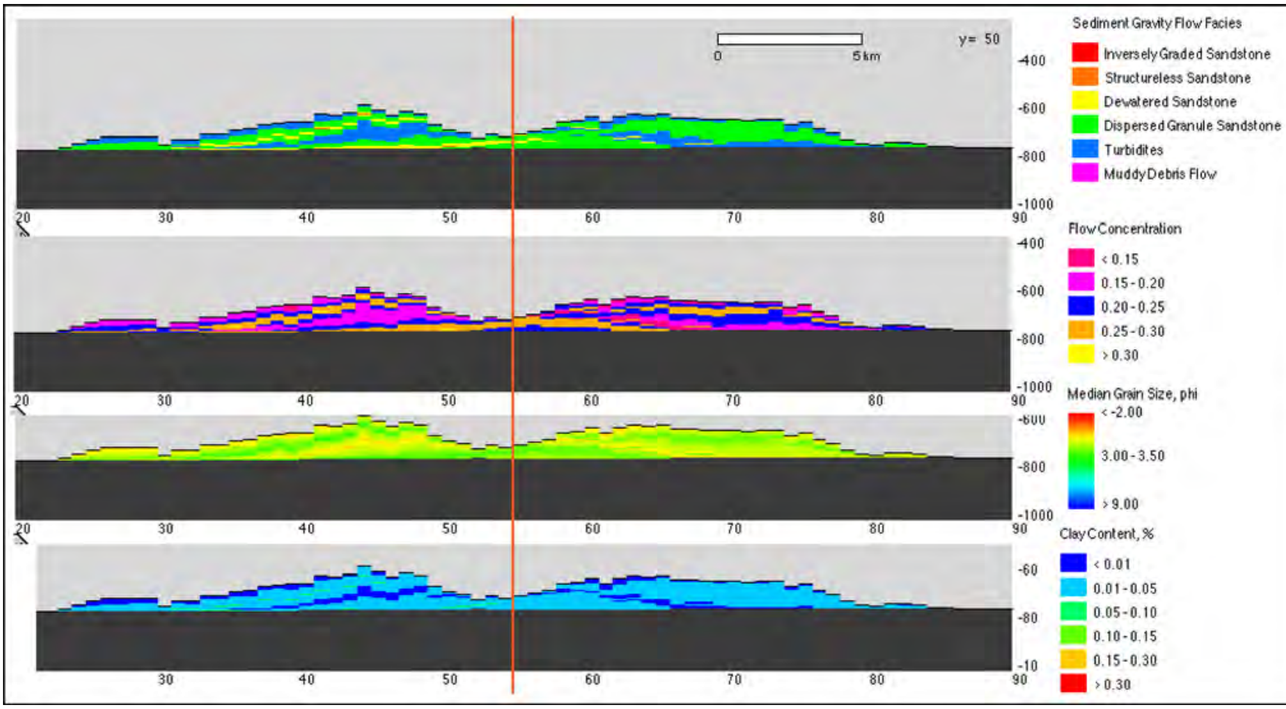

Figure 6: Turbsim outputs 3D geometry of depositional facies and grain size distributions for petrophysical models. From Turbsim Model Demonstration.

South Carolina, USA. This empirical model honors mass conservation, and the program is based on simple geometric rules that govern gradients and stacking patterns of sedimentary strata (Liu *et al*., 1998).

The SEDPAK program simulates the 2D geometry of sequence depositions for both clastic and carbonate depositions. The simulation allows the tracking of the evolution of the sedimentary fill of a basin by considering principally four major geological factors: eustasy, tectonic movement, sediment accumulation, and the initial and evolving basin geometry. Besides those main factors, SEDPAK also models additional influences on sediment geometries including water depth, erosion of previously deposited sediments, faulting, compaction of sediments, and the isostatic response of the basin to sediment loading (Csato & Kendall, 2002).

The program is able to define the chronostratigraphic framework for the deposited sediments. In addition, it provides the illustration of the relationship between sequences and system tracts observed in cores, outcrop, well, and seismic data (Kendall *et al.*, 1991). The results from the simulation can be analyzed to find the best match with the existing data (cores, outcrop, well, and seismic). This certainly can lead to a systematic prediction of other geological aspects such as the identification of source rocks, seals, and reservoirs.

Since SEDPAK is a freeware program that works in Linux, we have downloaded the program to assess its usability in simulating basin geometries. SEDPAK can be utilized by setting up various input data including an initial basin surface, a sea-level curve, sediment input rates and basin subsidence rates. A number of user-specified depositional parameters for clastic sediments, for instance, alluvial and submarine depositional angles, bypass angles, depositional distance, and various carbonate parameters are available in the program

The output of SEDPAK includes two 2D diagrams with various different modes of displays such as lithology ratios (sandstone, shale, and carbonate fractions), facies, chronostratigraphy, stratigraphic units, and burial history. The facies output can be defined in a number of ways such as paleo-water depths, distances from paleo-shoreline, percentages of certain lithofacies and porosity of certain lithofacies. The facies output can also be defined by combining several of these factors (Cannon *et al*., 1994). The examples of SEDPAK output for a hypothetical basin are demonstrated in Figures 8 to 10.

A few assumptions have to be made when applying SEDPAK program in stratigraphic simulation. Those assumptions include: (1) controlling factors (sea-level changes, sediment supply rates, and subsidence rates) will vary independently, (2) subsidence events due to compaction and tectonic are handled by SEDPAK separately, (3) clastic deposition is assumed to occur before carbonate deposition and the sediments are deposited as lithologic ratios (i.e., sand to shale ratios), (4) during deposition sediments can be removed or added simultaneously to the sediment supply in order to be deposited further into the basin, (5) carbonate accumulation is dependent on water depth and time, and (6) tectonic movement is only modeled vertically in which it substitutes for the combined effects of crustal cooling and the isostatic response to sediment loading.

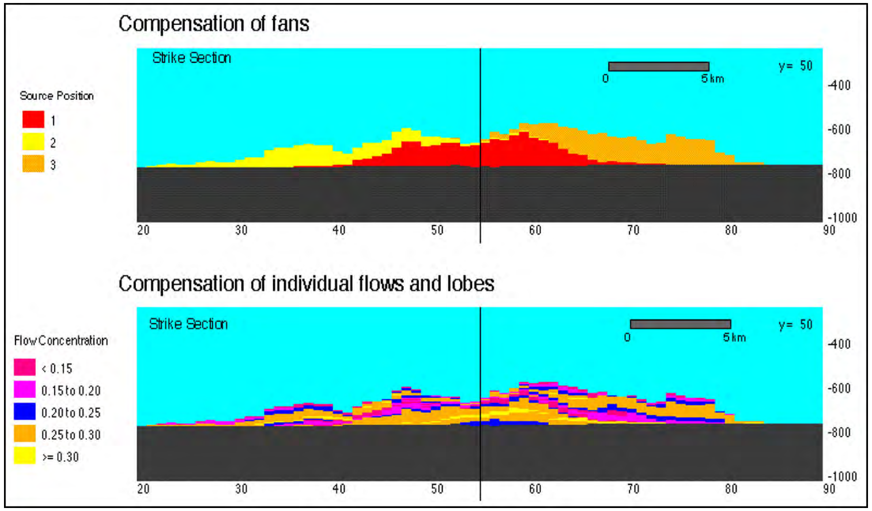

Figure 7: Turbsim images of topographic compensations (fans, individual flows, and lobes). From Turbsim Model Demonstration.

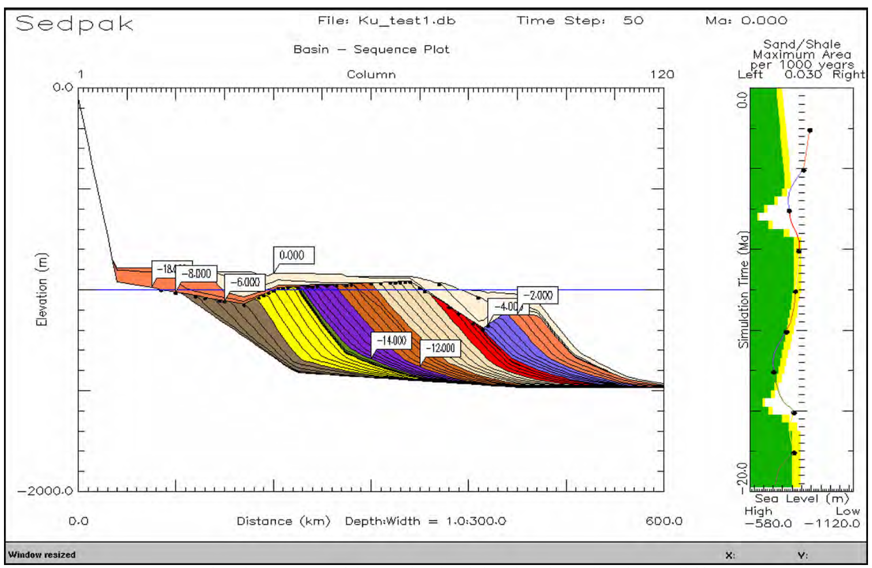

Figure 9: SEDPAK final output of hypothetical basin that displays different sequences. The color of the individual sequence corresponds to the color on the sea level curve on the right.

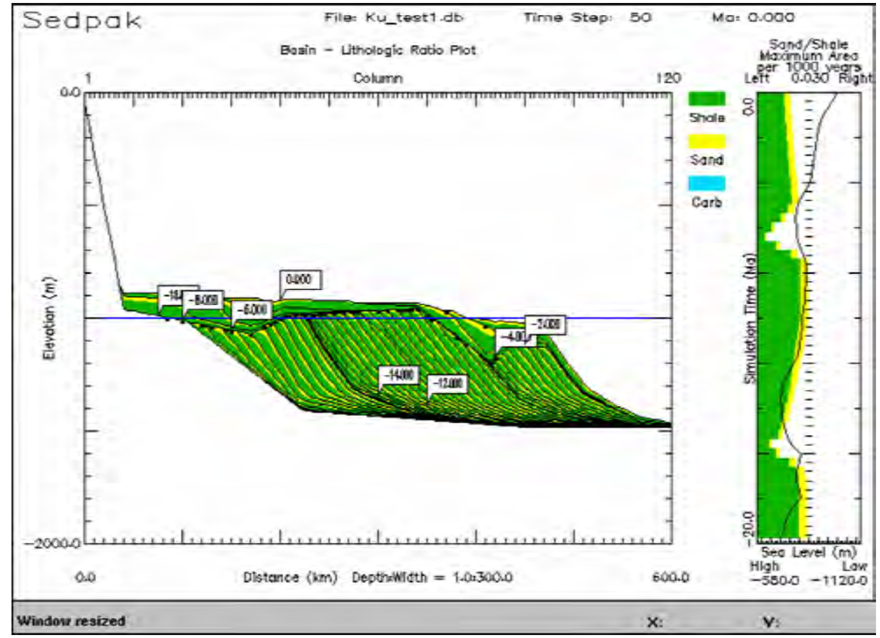

Figure 8: SEDPAK final output of hypothetical basin (deepwater setting) that displays lithologic ratio of sand and shale. The numbers on the stratigraphy mark the age of the deposition.

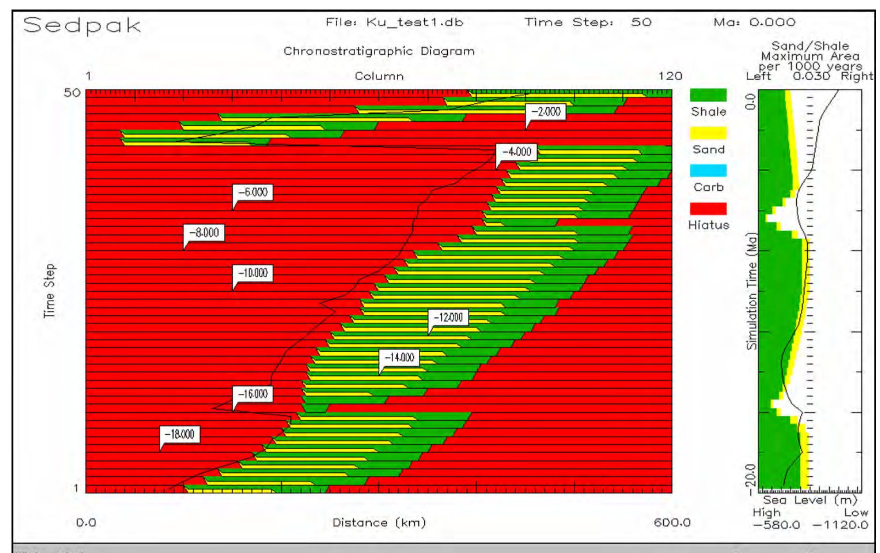

Figure 10: The SEDPAK output of hypothetical basin that displays the chronostratigraphic chart with lithologic characteristics.

DIONISOS

DIONISOS (Diffusion Oriented- Normal and Inverse – Simulation of Sedimentation) is a 3D numerical stratigraphic forward model developed by the Institut Français du Pétrole. The model is based on a water-driven diffusion methodology, which allows the simulation of erosion, transport, and sedimentation process in continental and shallow marine environments.

DIONISOS simulates sediment transport based on two sets of fundamental equations in order to regenerate the interaction between the long-term evolution of sedimentary process (controlled by long-term fluvial and gravity transport) and the short-term evolution (induced by catastrophic rain fall, slope failures, and turbidity flow). In this approach, transport rate is split into a long-term component dependent on topographic slope, diffusion coefficient, and water discharge volume while the short-term component is dependent on water velocity and inertia (Granjeon and Joseph, 1999; Granjeon *et al*., 2002).

DIONISOS simulates a wide range of processes to reproduce both siliclastics and carbonate sedimentary architectures at basin scale. A diffusion equation is used in the DIONISOS simulation program. This equation links sediment flow to ground slope (water energy), water flow (water transport capacity), and diffusion coefficient (transport efficiency).

To simulate transport of different lithologies, an altered layer that takes into account for all the sediment transport is defined. Different diffusion coefficients are used to model different lithologies with different behavior in different environment of depositions. DIONISOS also considers other important processes that usually are neglected by conceptual models such as tectonic subsidence, flexural isostatic loading, mechanical sediment compaction, eustasy, and slope failure in its simulation. Therefore, this kind of numerical stratigraphic forward model has an advantage over the conceptual models (Granjeon *et al*., 2002).

DIONISOS has the ability to adopt an experimental approach and to deal systematically with more parameters than are considered in most sequence-stratigraphic analyses (Burgess *et al*., 2006). It is physically and geologically consistent. Thus, it allows different geological and structural scenarios to be simulated. This progress in DIONISOS makes a plausible linkage with other models such as tectonic models that ultimately improve our understanding of the influence of tectonic process on sedimentation at various scales. This stratigraphic simulation also allows validating the depositional model derived from outcrop and seismic analyses which finally lead to a better understanding of stratigraphic geometries and basin evolutions.

The 3D image in Figure 11a illustrates the stratigraphic geometry generated by the DIONISOS program. The image demonstrates shoreface/shelf sequences that are modeled for the last 540, 000 years. The model simulates the geometry that is similar to the architectures observed on seismic profiles. Moreover, the image (A) in Figure 11b illustrates the initial bathymetry showing coastal plains, shelves, and slopes on two margins and a basin floor at 600 – 1000 m water depth with some local highs and lows. The image (B) in Figure 11b shows a final stratal architectures produced by the DIONISOS. The delta has prograded across the western shelf, the submarine canyon on the western margin is filled with sediment, and the complex basin-floor topography shows an obvious impact on the distribution of deep-marine sandstones.

SEDSIM MODEL

SEDSIM is a 3D stratigraphic modeling program initially developed at Stanford University in the 1980's by a consortium of European and American oil companies. The software was then developed and refined as a commercial package at the University of Adelaide, South Australia in 1994. SEDSIM eventually switched to CSIRO and underwent enormous development by Stratigraphic Forward Modelling group in 2000. The application of SEDSIM enables users to perform sedimentary studies on systems that range from a few meters to hundreds of kilometers in size. The most important application of SEDSIM is that it helps geoscientists, particularly in Petroleum Industry, to test play concepts and model complex reservoir heterogeneity. Furthermore, it can be used to model both modern depositional environments and the formation of sedimentary systems over the geological time scales.

SEDSIM utilizes part of Navier-Stokes equations rather than the full Navier-Stokes equations describing the fluid flow in three dimensions. This is because of the limitations in computer speed (it would take longer to simulate a flow than the real event). SEDSIM simplifies the flow by applying isolated fluid elements to represent continuous flow (Tetzlaff and Harbaugh, 1989). The core of SEDSIM is a hydrodynamics module that applies a Particle-in-Cell method for moving fluid across a surface. This Particple-in-Cell Lagrangian approach to the hydrodynamics allows a significant increase in the computational speed and simplification of the fluid flow equation.

SEDSIM numerically models the physical processes in near shore and marine environments that influence the way sediment is distributed in many sedimentary systems. Those processes include sea-level fluctuations, carbonate growth, geostrophic currents, ocean currents, wave and storm effects, turbidity and fluvial. It also includes subsurface processes such as loading effects and isostasy, tectonic subsidence, and compaction (Griffiths *et al*., 2001).

SEDSIM helps to visualize a conceptual carbonate and siliclastics depositional model. The image in Figure 12a shows an example of a 3D SEDSIM output of a carbonate reef that interacts with siliclastics in a shelf setting. The grid system used range in sizes from centimeters to kilometers. The picture in Figure 12b shows pseudo-gamma ray logs that can be produced by using SEDSIM. The logs are located at well intersections to compare them with the observed wireline or core data. The color variations signify the different grain sizes. Sequence stratigraphy can be

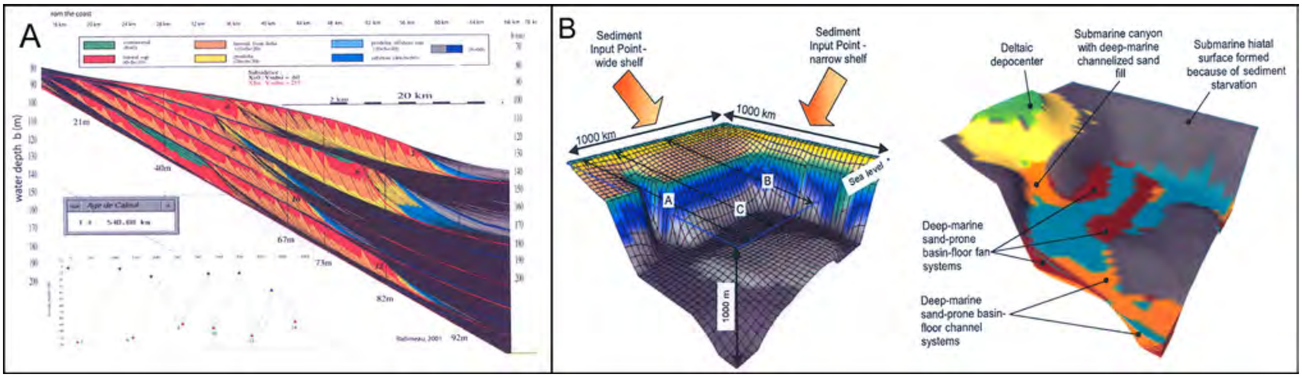

Figure 11: (A) Stratigraphic geometry (shore face sequences) modeled by DIONISOS stratigraphic simulation. (B) Initial bathymetry showing coastal plains, shelves, and slopes on two margins and basin floor generated by the DIONISOS model. After (Burgess *et al*., 2006).

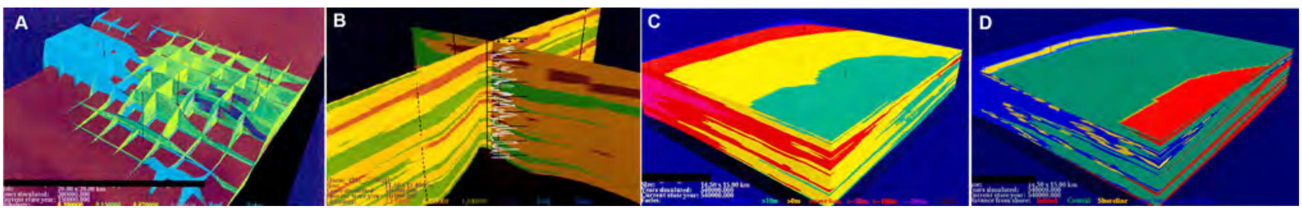

Figure 12: (A) The 3D SEDSIM output showing a carbonate reef that interacts with siliclastics in a shelf setting. (B) Pseudo-gamma logs at well intersections generated by SEDSIM program to compare with observed wireline and core data. (C) A 3D SEDSIM output showing a deltaic succession with four parasequences. The color variations signify water depth of position. (D) A 3D SEDSIM output of a deltaic succession with different depositional settings and distances from the shoreline. From SEDSIM model demonstration.

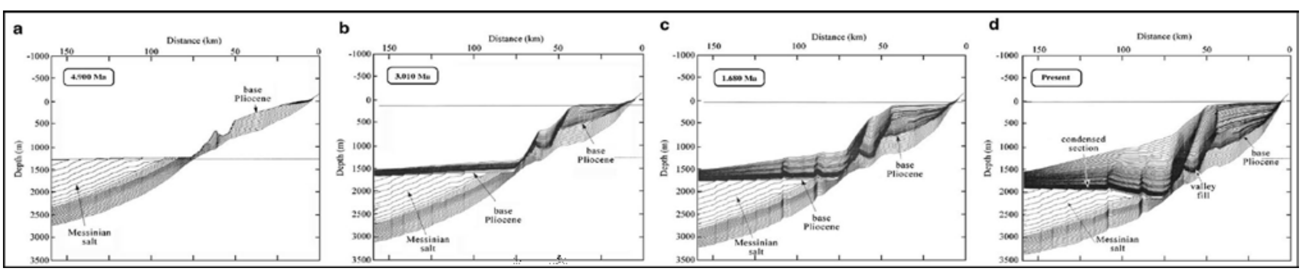

Figure 13: SEDPAK simulation results of Levant Basin from 4.9 Ma to the present time. The salt tectonics effects obviously disturbed the Messinian evaporitic sequence during 1.68 Ma.

understood better by using SEDSIM. For example, Figure 12c demonstrates a deltaic succession consisting of four parasequences that are presented by different color codes. This helps the users to predict reservoir or seal locations and qualities. Another advantage of SEDSIM application is that it facilitates the users to model paleoenvironment maps; for instance, Figure 12d shows a 3D output of a deltaic succession with different depositional settings.

EXAMPLES OF STRATIGRAPHIC SIMULATION APLICATIONS

There are many examples of SEDPAK simulation applied in sequence stratigraphy and basin analysis. For example, Kim *et al.* (2007) used SEDPAK to investigate the stratigraphic response to tectonism in the late Tertiary southern Ulleung Basin back-arc basin, East Japan Sea. They found that the sequence development is sensitive to the changes in the sediment supply rate depending on whether those changes are in-phase or out-of-phase with the controlling local tectonism in the hinterland.

In another example (Figure 13), SEDPAK was used to analyze the structural evolution of Levant Basin following the so-called "Messinian Salinity Crisis" (Ben-Gai *et al*., 2005). The objective was to test the hypothesis that the thick Messinian evaporitic sequence was deposited in shallow-water in a topographically deep (eastern Mediterranean) basin, i.e. the basin essentially dried up due to a great drop in sea level. This type of hypothetical problem is well-suited for a stratigraphic simulation package such as SEDPAK, as it allows us to examine the response of the stratigraphic development to such factors as sea level and clastic supply. Hence, the thick Messinian evaporitic section in the Levant basin was simulated by using a high rate of pelagic deposition to form the basinal evaporite. Indeed, in that study, the observed stratigraphy was able to be replicated by allowing the sea level to drop at least 800 m below present level. Subsequent analysis of the 2D/3D

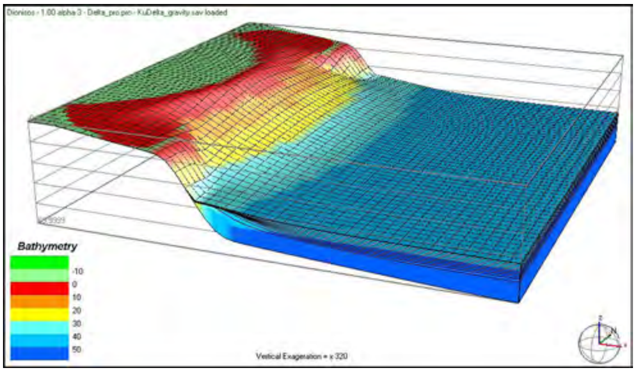

Figure 14: DIONISOS simulation results of a 3D prograding delta with different colors signifying different sequences

seismic and well data by Bartoni & Cartwright (2007) provides further evidence of a major event at the end of the Messinian Salinity Crisis.

Examples of studies using the more sophisticated 3D package, DIONISOS, include those by IFP themselves, e.g. in the Mahakam Delta, to investigate the interactions between deltaic progradation, carbonate platform development and deep-marine turbidity current processes (Granjeon *et al.*, 2004). Another example is in the Gulf of Mexico (Granjeon *et al.*, 2002) where the stratigraphic development is influenced not just by sea level and sediment supply, but a host of other structural effects such as growth faulting and detachment surfaces, as well as mud and salt diapirism. IFP has also applied it in fold-thrust belt situations, such as in the Zagros foreland basin in Iran (Vedrenne et al., 2006). Since the development of DIONISOS by IFP was sponsored by oil companies, its applications have been used more by the oil companies, including the supermajors. DIONISOS is used by Shell to model carbonate environments, e.g. in their Middle East ventures and elsewhere (e.g. Burgess et al., 2004). ExxonMobil has used it in carbonate applications in the British West Indies (Roehl and Becker, 2006). The example of a 3D output image from DIONISOS is shown in Figure 14.

The CSIRO package, SEDSIM, has been used more frequently on the NW Shelf of Australia to predict sand distribution and quality (Griffiths, 2001; Griffiths *et al.*, 2001). It has even been used to examine gold distribution in buried river channels in West Australia. All the above examples show the value of using stratigraphic simulation techniques in petroleum exploration and development studies.

CONCLUSION

This review paper gives an overview of the available stratigraphic simulation techniques, as an introduction to the subject, as well to provide an overview of the different types of software packages. Stratigraphic simulation is undoubtedly a potentially useful tool for studying basin-fill history and geometry, and when used with appropriate techniques, e.g., sequence stratigraphy and basin modelling, it may aid explorationists in identifying and delineating facies distribution, be it reservoir, source or seal. Major oil companies have even developed their own proprietary stratigraphic simulation software, which give them the advantage when analyzing basins, and help them in making the right exploration decisions. As this technique, especially the 3D version, is still an actively researched topic, the potential for further developments is high. No doubt, we will see more developments of this technique in years to come, particular in the linkage with the more established basin modelling techniques.

The SEDPAK modelling package is the best compared to the other 2D models reviewed. SEDPAK considers not only the major factors (eustasy, subsidence rate, and sediment supply rate) but also other factors that are neglected by other 2D models. These effects include faulting, erosion, water depth, and the isostatic response of the basin to sediment loading. Among the 3D models reviewed, DIONISOS is more preferable since it is able to handle the interaction between the long-term evolution of sedimentary processes (controlled by long-term fluvial and gravity transport) and the short-term evolution (induced by catastrophic rain fall, slope failures, and turbidity flow). DIONISOS is physically and geologically more consistent than other 3D models; therefore it is able to adopt an experimental approach that deals with parameters more systematically than are considered in most sequence-stratigraphic analyses. Besides, with further development, it may be linked with other models, such as tectonic or structural model, for enhanced stratigraphic analyses.

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