Simulation of transport and deposition of siliciclastic sediments in platform, slope, and basin environments

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Abstract

Sedimentary Geology deals with the physical, chemical and biological processes that affect and transport sedimentary rocks. One of the main focus inhabits in determining the parameters and processes that controlled the in-fill of sedimentary basins.

In this work the development of a 3D numerical stratigraphic simulator, called STENO, is presented. Its emphasis is on the depositional processes in platform, slope, and basin environments. The algorithm is based on the formulated quantitative concepts of Sequence Stratigraphy, as primary control mechanisms of the sedimentary strata architecture, and in a numerical analysis of the 2D steady state flow of a incompressible non-viscous fluid in function of the bathymetry. The velocity field is calculated from boundary conditions (cross-shore and long-shore currents velocities) and is used to determine the direction of streamlines for sediment transport.

The algorithm of STENO is innovative because it considers that, for each step of the simulation, the sediments are transported following streamlines. The movement/deposition of sediments is controlled by an angle of stability of each grain size (sand, silt or clay) and by the volume of the available space for accommodation in each one of the columns formed in the cells of the discrete model.

1 Introduction

A geologic model is of fundamental importance in several fields and research areas. In the mining industry, it will be the explanation for the economic concentration of a given mineral. Based upon concepts of Stratigraphy and Tectonics, a geologic model can propose a way of evolution for the in-fill of a sedimentary (Popp, 1998).

A geologic model may be classified according to the parameters and processes that are considered in its representation (Figure 1):

- Conceptual model: theoretical, based on premises and qualitative descriptions;
- Interpretative model: based on the correlation of data and space association;
- **Physical model**: based on an experimental or physical simulation;
- Mathematical model: based on mathematical/numerical algorithms.



Figure 1 – Types of geologic models and involved processes. Adapted from Faccion (2002).

In simple cases, the use and formulation of an interpretative or conceptual model might be sufficient. However, for situations that require synchronous or quantitative answers, the benefits of numerical modeling in general justify its use in spite of its intrinsic complexity. The main advantages of a numerical model are (Faccion, *op cit*):

- a) To supply coherent qualitative answers for complex situations;
- b) To generate quantitative answers for simple problems;
- c) To provide qualitative and quantitative coherence to interpretative models.

The latter is the main advantage, since interpretative models consider a degree of uncertainty that, in many situations, might prevent the precision or even the consistency of a final solution.

Numerical geologic modeling adopts two distinct approaches (Figure 2). In the first, called **forward modeling**, the simulation of the evolution of a sedimentary basin is performed from the past to the present days. The initial conditions are defined by a group of parameters and specified processes. The objective of the simulation is to obtain a final sedimentary architecture, which is then compared to the interpretative model. In the second approach, called **backward modeling**, the objective is to find the parameters and processes that determine the current sedimentary architecture, which is based on data interpretation. In the latter case, the processes and parameters are obtained using, for example, backstripping or restoration techniques (Tearpock & Bischke, 1991; Ferraz, 1993).

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Figure 2 – Classification of the Programs of Numeric Simulation in Geology with relationship to the sense of Modeling. Adapted from Faccion (2002).

The simulation performed in this work is in the direct modeling group. The initial conditions are described by the initial time and initial depositional surface. The geologic processes are represented by subsidence rates along the geologic time (defined in selected points), sediment supply variation along the shore line, sea level variation along time, and sea current boundary profiles. Sediment transportation is performed along streamlines. These streamlines are computed based on a velocity field that is defined in a regular grid representing the simulation area. In each time step of the simulation, the velocity field is obtained from a numerical analysis of a two-dimensional, steady-state, Navier-Stokes flow of an incompressible fluid, in a non-viscous regime. The input data to the fluid flow analysis are the sea current boundary profiles and the bathimetry of the simulation area.

The main advantage of the proposed approach of numerical sedimentation simulation is the combination of the main geologic processes (subsidence rates, sea level variation, and sediment supply) with sediment transport/deposition based on a fluid flow numerical analysis. This forward modeling simulation approach is implemented in a three-dimensional numeric simulator, called STENO (Carvalho, 2003). Figure 3 shows the main stages of the algorithm developed in STENO for transport and deposition of siliciclastic sediments.



Figure 3 – Main stages of the algorithm developed in STENO.

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2 Geologic processes used in the simulation

According to Vail (1987), the main processes that control the patterns of strata and distributions of lithologies facies in sedimentary basins are (Figure 4): tectonic subsidence, variation of the sea level (eustatic curve), and sediment supply. The accommodation, that is, the available space for potential accumulation of sediments in the basin, is function of the eustatic variation and subsidence (Figure 5).



Figure 4 – Geologic processes responsible for the formation of sedimentary basins.



Figure 5 – Available space generated by the relation between sea level variation and subsidence. Adapted from Posamentier et al. (1998).

2.1 Eustatic Curve

An eustatic curve represents the absolute variation of the sea level along time. Concerning the frequency spectrum relative to the geologic time, eustatic curves can contain two types of low frequency components: long term cycles of 1st and 2nd orders and short term cycles of 3rd order. The curve available for the user is that of Haq *et al*, 1988. High frequency components from Orbital Ciclicity Range of Milankovitch can be also superimposed (Figures 6-a, 6-b and 7).

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Cancel Figure 7 – Dialog to select the eustatic curve for the simulation.

2.2 Subsidence

Subsidence that affects the initial depositional surface of the basin is another of the main controlling factors which can be handled by the user. According to Vail et al (1977), tectonic subsidence is the response of the lithosphere, under the form of vertical movement, to stress fields of tectonic nature. Thermal subsidence is the result of thickness variation of the lithosphere generated by heat processes.

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View Curve

In STENO, tectonic/thermal subsidence is supplied through a table of subsidence rates vs. geologic time (Figure 8) at some points within the simulated area (Figure 9). The spatial distribution of subsidence rates is determined in the whole simulation area using a digital terrain model (Method of the Inverse Distance Power – Landim, 2000). In this work, the subsidence curves are obtained using a specific program called BASS (Kiang, 1991).



Figure 8 – Dialog to specify tables of subsidence rate.



Figure 9 - Example of points in the model where subsidence tables are supplied.

2.3 Sediment Supply

Sediment supply is established through curves of sediment volumes along the shore line. These curves are furnished for each type of sediment grain size (sands, silt and clay - Figure 10). To help the user in the specification of sediment supply, STENO contains a database of sediment yield distributions that represent different depositional environments. These distributions are selected from several types of coastal systems, according to climate and sediment discharge of significant rivers (Hansen & Poulain, 1996 and Harris & Coleman, 1998 - Figure 11). Since the volumes are specified at some points, the supply curves are obtained by interpolation along the shore line (Figure 12).



Figure 10 – Sediment supply curves dialog.



Figure 11 – Interface to sediment supply distribution database.



Figure 12 – Example of model with sediment supply curves along the shore line.

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3 Transport and deposition of sediments

With the parameters and geologic processes defined, the next stage in the simulation is to determine the velocity field that will be used to transport the sediments. This work adopts a hydrodynamic approach for sediment transport that simplifies the actual fluid flow in the real phenomenon. Rather, a net distribution of velocities is considered in each time step of the sedimentation simulation.

A two-dimensional steady-state Navier-Stokes fluid flow analysis is performed in each step of the simulation. The transport of sediments is considered in the directions x and y (cross-shore and long-shore directions). An incompressible and non-viscous fluid flow is admitted. The objective of this simplified analysis is to obtain a velocity field distribution within the simulation area. The input data to this analysis are the sea bottom bathimetry and boundary profiles of cross-shore and long-shore velocity fluxes.

The formulation of this simplified Navier-Stokes fluid flow results in an elliptic differential equation written in Cartesian coordinates (Fortuna, 2000; Carvalho, 2003). The discretization of this equation was made using the Finite Differences Method (Carvalho, 2003). Figure 13 shows an example of a velocity field calculated using the proposed strategy for a given sea bottom bathimetry and a simple parallel boundary current velocity.



Figure 13 – Bathimetric contours of the simulated area (a) and corresponding velocity field (b) for a parallel boundary current velocity.

3.2 Sediment transport

The transport of sediments is performed along streamlines of the velocity field. The determination of the streamlines consists of solving an Initial Value Problem, in which the initial value of each streamline is a point (x, y) at the shore border of the simulation area, as shown the Figure 14. That initial point (x, y) is associated to a velocity vector that corresponds to the input boundary cross-shore velocity used in the flow analysis.



Figura 14 – Streamline starting at a point at the shore border.

Several numeric methods exist to determine streamline trajectories (Boyce, 1992). This work uses a Runge-Kutta interpolation method proposed by Royer (2001). This method combines accuracy, simplicity and is easy to implement. The errors are of h^5 order, where h is the step size. Figure 15 shows streamlines obtained from the velocity field of the example of Figure 13.

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Figure 15 – Streamlines from the velocity field of Figure 13.

3.3 Sediments Deposition

In the transport and deposition of sediments along the streamlines, it was considered that each streamline receives a volume fraction of the total discharge of sediments. That fraction is divided according to three grain sizes: sand, silt and clay. With the volumes of each of them defined for each streamline, the transport/deposition process can be initiated.

During this process, each streamline is traveled starting from the shore border where the sediment is supplied. Each streamline is defined by a set of points (Figure 16). At each point, there is an attempt to deposit each lithologic fraction coming along the streamline. Deposition depends not only on available space but also on the bottom bathimetry gradient. To take this into account, it is admitted that the streamline also follows the bottom bathimetry gradient. This gradient is compared to a stability angle for deposition of each lithologic fraction (sand, silt and clay).

The gradients are calculated at each the interval along the streamline (Figure 17 and 18), according to the following the steps:

- 1. Determination of distance (d) between the points in plane xy (Figure 18);
- 2. Determination of distance (*z*) between the points in plane *zx* (Figure 19);
- 3. Calculation of gradients.



Figure 16 – Top view of streamline.

Deposition will occur depending on the following conditions:

- There is available space for deposition; AND
- The calculated gradient is less than the critical gradient for **at least** one of the lithologic fractions.



Figure 17 – Lateral view of streamline of the Figure 16.





Figure 18 - Distance z between the points in plane xy.

Figure 19 – Distance between the points in plane *zx*.

4 Examples

4.1 Example 1

This example shows the simulation of parassequences sets. A parassequence is a relatively conformable succession of genetically related group of beds or bedsets of sediments bounded by flooding surfaces or their correlative surfaces; a parassequence set is defined by a succession of genetically related parassequences, forming a distinctive stacking pattern bounded by major flooding surfaces and their correlative surfaces (Van Wagoner *et al*, 1988). The three classic architectural sets of parassequences are: progradational, agradational and retrogradational settings, which depend on the ratio between the rate of deposition and the rate of accommodation (Swift *et al*, 1991).

The variation of available deposition space in this simulation considered only the variation of the eustatic curve. That is, no subsidence or erosion (which is not yet implemented) was considered. Therefore, the simulation considers for space variation a single growing limb of the eustatic curve, as shown in the Figure 20.



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This simulation uses a plane grid of 100 km along the coast line and 300 km basinwards, with 40 cells in each direction. The subsidence was maintained equal to zero and constant. The total time is of 2 Ma (millions of years) with steps of 0.25 Ma. The sinusoidal eustatic curve was adopted with an amplitude variation of 100 m. The results are visualized along a cross-section perpendicular to the coast line (at 50 km position). The sediment supply was defined in each step of the simulation as a function of the available space for deposition. Figures 21, 22, 23, 24, 25, 25, 26, 27, and 28 show the simulation steps.



Figure 21 – Step 1: beginning of simulation.



Figure 23 – Step 3: retrogradational sequence.





Figure 24 – Step 4: retrogradacional sequence.



Figure 25 – Step 5: agradational sequence

Figure 26 – Step 6: beginning of progradational sequence.

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Figure 27 – Step 7: progradacional sequence.

Figure 28 – Final aspect of parassequence set.

4.2 Example 2

The second example shows the sedimentation process in an area of 100 km along the coast line and 250 km basinwards. The bathimetry of this area was modified to simulate the platform, slope and deep basin environments and emphasizes some canyons at the border the platform, one of them related to the occurrence of a river represented by a high value of sediment supply at the shore border. Contourite currents at the base of continental slope and the occurrence of salt domes are also simulated (Figure 29). Initial time was of 265 Ma, final time was of -230 Ma, and time span was divided into 8 steps. Figures 30, 31, 32, 33, and 34 show some steps of the simulation with the deposited sediments and streamlines.



Figure 29 - Initial bottom bathimetry and some characteristics of the example 2.



Figure 30 – Example 2: step 1 of simulation.



Figure 31 – Example 2: streamlines of step 1 of simulation.

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Figure 32 – Example 2: step 2 of simulation.



Figure 33 – Example 2: step 3 of simulation.

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Figure 34 – Example 2: step 8 of simulation.

5 Conclusion

This work describes the development of a three-dimensional computational simulator of sedimentation processes in platform, slope and basin environments at a stratigraphic time-scale. The system has interactive, friendly and flexible interfaces with respect to the visualization of the results. Variations of sea level are based upon longterm curves that can be modulated by high frequency cycles. Subsidence rates can also be considered when calculating the evolution of the depositional paleosurface.

The algorithm for sediment transport has a hydrodynamic approach, and calculates streamlines for sediment transport and deposition, which is the main contribution of this work. Boundary conditions are long-shore and cross-shore velocities of sediment transport. Long-shore velocities can also vary according to bathimetry. The sediments deposition is controlled by the angle of stability of each lithologic fraction (sand, silt or clay) and by the available space for accommodation.

As shown in the examples, the adopted strategy allows the simulation of geologic basins with different types of topography. It considers deposition distribution according to the grain size and specific sources of sediments near the coast line, being able to transport sediments through platform into slope and deep basin environments.

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