HCA methodology applied to model the interaction of faulting and salt movement in Campos Basin, Brazilian Atlantic Margin

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Abstract

The kinematic evolution along an offshore regional cross-section was studied by using the forward modelling HCA approach implemented in the software FORC3 (©Salvini - Roma Tre University). This approach consisted in the comparative analysis of the time evolution of the tectonic elements present in the sections (namely salt domes activity and faulting) with the thickness and architecture of the syntectonic sediments. The link between sedimentation and tectonics was carefully replicated during the evolution of the sections from late Cretaceous to recent, and allowed to set the time constraints of the tectonic evolution of the region, together with its velocity and the interaction between salt doming and faulting.

The FORC3 modeling tool allowed to compute along the cross-section a distribution of the expected brittle deformation intensity.

Introduction

This work presents the kinematic study of an offshore regional cross-section, located at Campos Basin, Brazilian Atlantic Margin. The main objectives of the analysis were:

- to detect the tectonic processes that led to the dissection of the Albian-Cenomanian Carbonate Platform;
- to clarify the relative interactions between faulting and salt tectonics in the area
- to infer the timing of the tectonic evolution (faulting and salt diapirs).

The software FORC3 (©Salvini - Roma Tre University) was used for this study. It provides the possibility to model and simulate the spatial evolution of fault related structure in a purely kinematic way and to predict the spatial distribution of longitudinal fractures developed during fault-related folding.

This software allows to produce balanced cross section involving both single and/or multiple faulting through a forward modeling process, thus simulating even complex tectonic evolutionary paths, independently of the fault and fold kinematics or geometry. It takes into account the influence of several natural features like synsedimentary and erosional processes, salt tectonic evolution, basement movements.

Method

The developed forward modelling algorithm (Hybrid Cellular Automata - HCA; Salvini et al., 2001) in the software FORC3 is a numerical, hybrid methodology between the cellular automata (CA) and the finite element method (FEM) philosophies. From the CA method (e.g. Wolfram, 1986) it follows the principle of using large amount of cells with simplified links. From the FEM philosophy, each point is temporary linked by physical and geometrical laws to the surrounding ones (Zienkiewicz and Taylor, 1991). One of the advantages of the HCA method is its self-predicting capability that allows the study of the geometry and deformation intensity without imposing any determined final geometry. Layered rock units are simulated by a mesh of a very large number of semi-independent cells (Fig. 1) and the relations among various cells can be tuned in order to simulate various medium rheology (Salvini and Storti, 2004). Cells are related to the surrounding ones by three types of links:

1. Intra-layer relations link cells belonging to the same layer and consist of rigid relationships derived from average volume and surface preservation conditions, physical boundary conditions, and rock rheology.

2. Inter-layer relations regulate the relationships among adjacent layers. These relations take into account the weaker rheologies of interlayer material, physical boundary conditions, and volume preservation conditions, while partial freedom is given to surface variations.

3. Discontinuity relations correspond to the presence of ruptures such as faults. No kinematic links exists across them, but physical boundary conditions and slip-induced stresses.

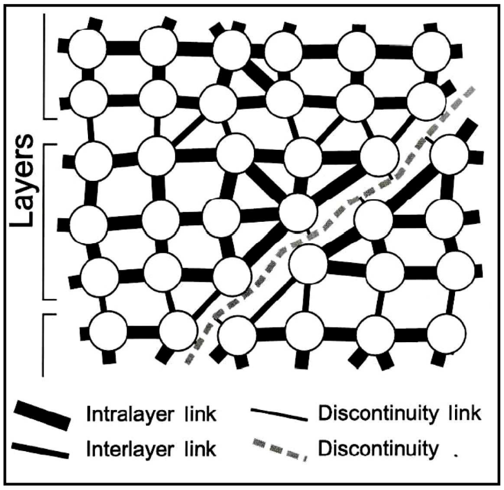

Figure 1. Types of links in a hybrid cellular automata (HCA) multilayer. (Salvini and Storti, 2004)

The relative position of each cell changes at each step and these relations are recomputed only among adjacent cells. Preservation of volumes and surfaces results by using large amount of cells and preserving the average distance among adjacent cells.

The models run in a forward modeling fashion and the pace is selected small enough to ignore the influence of not-neighbour cells. This results in reducing the links to first order computations.

The position $P(i,t+\Delta t)$ of the -i cell at time $t+\Delta t$ is computed by equation 1:

$$P(i,t+\Delta t) = P(i,t)+ \Sigma_k [\Sigma_j [F(j) \Delta t^2 / D(i,k,t)^2]] \quad (1);$$

where:

- Δt, is the step time increment
- K, is the pointer to the surrounding cells
- F(j), are the links between -i and -k cells
- D(i,k,t), is the distance at time t between -i and -k cells

Natural layered rocks are simulated by a multilayer of model beds made up by group of elementary cells with identical properties that constitutes mechanical units. A multilayer of different mechanical units constitutes the mechanical stratigraphy. The physical parameters and type of links within the mechanical stratigraphy can be modified by the operator or are modified by the local conditions at any step during the run. For this reason the HCA can be considered a self-constraining algorithm. In this way faults are directly traced on the model section. Apart from rate of displacement, erosion, sedimentation, compaction, salt movement, and basement movement, no other conditions are imposed to the model and the hangingwalls and footwalls "self-decide" their evolutionary pathway obeying the physical boundary conditions. Due to the large number of cells, typically of the order of hundreds of thousands for a medium-high resolution experiment, results are independent from the location of each individual cell.

The developed algorithm for the numerical modeling allows to compute at each step during the run the stress and deformation condition at each cell related to the kinematic deformation. Stresses result from the combination of boundary conditions (including overburden) and stresses induced by the kinematics. Three kinematic effects were considered:

a) torsion-induced fiber stress;

b) flexural slip (i.e. interlayer slip) induced stress;

c) slip along the discontinuities.

Time-Stress Integral (TSI)

The incremental distribution of brittle deformation within the HCA mesh is provided as Time-Stress Integral (TSI). The TSI value represents the time-cumulative deformation function (DF) that acted on the given part of the structure and is measured in Pa by time (year). The DF (equation 2) is computed as the difference between the rock strength (according to Coulomb-Navier criterium) and the shear acting on the weakest internal surface (Storti et al., 1997).

$$D_f = \tau^* - \Sigma \quad (2);$$

where:

D_f, is the deformation function

τ^*, is the total shear;

Σ, is the rock strength.

Comparison with field analogs showed that TSI value, when above the strength threshold of the rock multilayer, is proportional to the total deformation expected at a given point of the modeled natural structure (i.e. it relates to the fracture intensity).

The distribution of the TSI values provide a useful tool for a quantitative prediction of fault- and folding-related fracture distribution (TSI values at each position can be displayed). Areas expected to be more fractured than adjacent ones can be easily identified and, sometimes, they are located in unexpected positions.

Campos Basin regional section

For the actual kinematic modeling was used a regional cross-section (Fig. 2), 40.187 m long and 6.000 m deep. This cross-section is based on a regional seismic line, which crosses an area were major faults and salt diapirs are representative of the regional tectonic style. The line is oriented SW to NE, perpendicular to the axis of major structures, that allows the deformation modeling in a cylindrical way.

By considering the section size, it was been necessary to split it into three parts (Fig. 2). Each part shows a different relationship between salt movement and major faults creation and evolution.

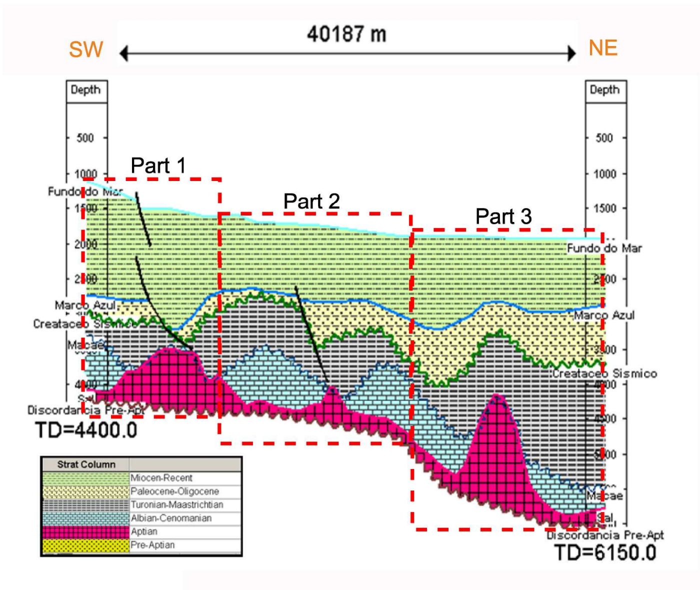

Figure 2. Modeled cross-section

In this figure are represented the schematic cross-section used in the kinematic modeling, the limits of each part the section was splited in, and the lithology stratigraphy taken into account to create the mechanical stratigraphy: Pre-Aptian Basement (older than 119 Ma); Aptian salt and evaporitic sequence (119-113Ma); Albian-Cenomanian carbonate sequence (113-91Ma); Turonian-Maastrichtian turbiditic sediments (91- 65Ma); Paleocene-Oligocene marine sediment sequence (65-22.7Ma); Miocene to Recent marine sediment sequence (22.7-0Ma). The vertical scale exaggeration is 6:1.

Discussion of Results

The results of FORC kinematic modeling highlighted different evolutionary path:

1. The deformation evolution along the section, considering all the three parts, results in important lateral variations of post Cenomanian sediments. This is due to a syntectonic origin of these deposits and their interactions with the salt tectonics triggering.

2. In the Part 1 (Fig. 3a) the modeling showed that salt movement started at the base of an important preexisting listric fault, just after the deposition of the Albian-Cenomanian limestones. In the next Turonian-Maastrichtian sequence the thickness distribution of turbidites results from the contemporaneous salt mobilization and faulting.

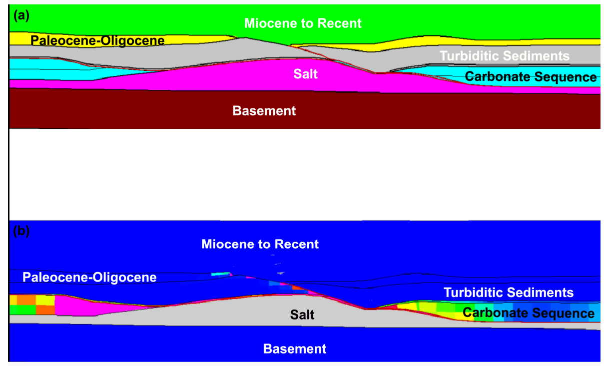

Figure 3. FORC kinematic modeling Part 1

(a)Are shown the stratigraphy along the cross-section. (b) The colors represent the Deformation Function (DF) intensity, where the blue colors indicate non- to low-deformation and the pink and red colors indicate higher deformed regions.

3. In the Part 2 (Fig. 4a) the modeling showed that an important listric fault was active and initially responsible for the dissection of the carbonate platform. In Paleocene time, salt started to move at the base of the same fault that terminated its activity in Miocene time. Comparing to the previous sector the tectonic evolution of the actual sector is characterised by a sharper shape of salt, related to the stronger influence from fault activity.

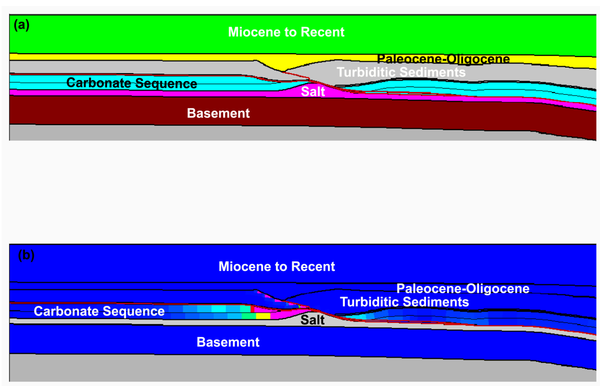

Figure 4. FORC kinematic modeling Part 2

Equal Figure 3.

4. In the Part 3 (Fig. 5a) the tectonic framework was largely dominated by the development of the salt dome, again linked to a large preexisting listric fault on its top. Tectonics started in Turonian time and the activity of the fault can be tracked until Paleocene time. Afterwards, the salt dome alone was active since possibly recent time.

5. The deformation intensity distribution modeling for all the three parts of the section (Figs. 3b, 4b,5b) showed that the fault-salt interaction results in higher values of DF along the borders of the Albian Carbonate Platform. In parts 1 and 2 (Figs. 3b, 4b), due to the fault-salt interaction, the TSI values achieved on the footwall of the main listric faults indicate a grater deformation than the corresponding hangingwall sector.

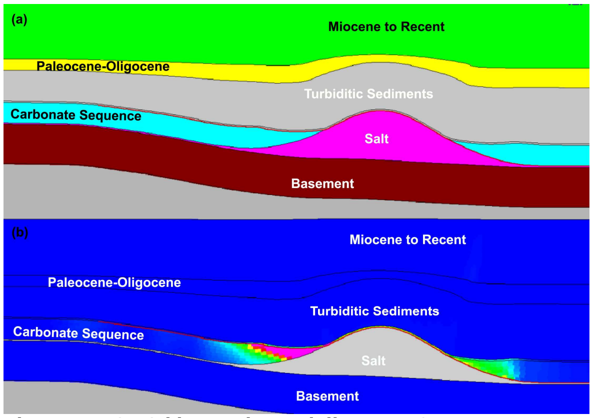

Figure 5. FORC kinematic modeling Part 3

Equal Figure 3.

Conclusions

The self-predicting capability in the FORC HCA (Hybrid Cellular Automata) algorithm proved to be efficient on modeling complex structural environments, involving salt tectonics and major faults evolution. The capability of the software to compute the time-cumulative deformation (DF) along a section, allowing a quantitative prediction of fracture distribution, can be a useful tool for exploration activities and reservoir management.

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