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Research paper

Modeling the deposition of turbidite systems with Cellular Automata numerical simulations: A case study in the Brazilian offshore

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ABSTRACT

Turbidite reservoirs frequently consist of massive sandstones with excellent reservoir properties, but showing a heterogeneity which is difficult to characterize with only well and seismic data. The physical and numerical modeling of the depositional processes is then a way to predict the heterogeneity pattern and to assist the geological interpretation.

Recently, Cellular Automata (CA) modeling was adapted to simulate turbidite flow deposits. In this study, CA modeling incorporates the main submarine physical processes involved in turbulent flows, such as water entrainment, erosion, deposition and particle fall-out. These processes are developed through CA simulations, in which the cells interact by exchanging energy and flow properties. In this work, the CA modeling was applied in real oilfields of the Campos Basin (offshore Brazil), in a case where the palaeotopography played a major role on trapping of turbidite sand deposits.

The sensitivity tests performed on this case study highlighted that the parameters of flow concentration, composition of the substratum and the deposition model greatly impact the simulation results. The simulation results also realistically reproduced sedimentation patterns, such as successive filling of contiguous sub-basins, increasing flow velocities in confined settings, run-up effects with lateral deposition of fines and concentration of coarser sediments in topographic lows.

An important characteristic of the studied turbidite reservoirs is the presence of multiple-stacked depositional cycles. For this reason, CA code was adapted to allow the simulation of multiple flow events and, by this way, to reproduce stacked turbidite cycles. The reservoir distribution and the thicknesses of the geological model fit very well with the results of CA simulations for multiple flow events. A blind test performed thanks to the drilling of a new well in the study area also confirmed the forecast capacity of the CA modeling for both sediment distribution and thickness.

The results of the simulations are consistent with the geological model of the study area, and predict reservoir distribution in locations away from the wells. These results also point to the potential of such numerical techniques in improving the prediction of the turbidite reservoir extension, especially in the case where palaeotopography controlled the turbidite sedimentation.

1. Introduction to Cellular Automata modeling

1.1. The challenge of numerically modeling turbidity flows

Turbidite reservoirs (and reservoirs, in general) have been usually modeled by using stochastic object or Gaussian sequential methods (Deutsch, 2002; Mallet, 2004). These are numerical approaches well fitted to model the architecture and physical properties of the reservoirs, but they do not deal with dynamic

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flow processes. First numerical approaches dealing with sedimentation processes were those proposed by the stratigraphic forward numerical modeling, based on advective, diffusion and dispersive terms of sediments transport (Granjeon and Joseph, 1999; Gratacos et al., 2009; Salles et al., 2010). Although being successfully used to reproduce reservoir architectures at the basin scale, this method reaches its limit at the reservoir scale, the diffusion and other laws being not able to simulate the inertial component of the gravity flow. During the last decade different numerical methods have been proposed to numerically model turbidity flows. Currently, most of them are still not completely appropriate to deal with the related complex hydrodynamic and physical processes. In the following paragraphs we briefly discuss some of these methods.

Waltham et al. (2008) were the first to use numerical turbidite modeling to determine the importance of the palaeotopography, using a modified Monte Carlo approach. Immediately after that, some other methods were applied to numerically reproduce deep marine processes. Miller et al. (2008) solved a set of depth-averaged governing equations in 2D, aiming to use the simulation results to improve the reservoir modeling. Groenenberg et al. (2009) and Athmer et al. (2010) used a 3D process-based model to simulate turbidity current hydrodynamics in synthetic case-studies; this method considers mathematically the turbidity current model of Parker et al. (1986) and takes into account the conservation equations for fluid momentum, continuity and suspended sediment mass.

The more refined numerical models take into account the Navier–Stokes equations (Frisch et al., 1986). After the development of powerful computing machines, complex numerical models were developed to finely describe the phenomenology of gravity flows. However, density flows associated to deep submarine fans and channels are true 3D processes that require very long computation times for a single event, and the deposition of deep marine sediments by gravity flows usually results from the succession of many single flows with different magnitudes and durations. Consequently, analytical solutions to the Navier–Stokes differential equations governing density flows are very difficult to be attained, except for few simplistic cases. Other problems of using the Navier–Stokes approach in simulations are connected to geological aspects: (a) the complexity of the topography makes it difficult to define closure equations; (b) these models do not fit to geological time scale. There are still additional difficulties related to the computation time involved in the simulations. The computation time required to numerically solve the hydrodynamic equations is not justified as the availability and accuracy of field data is usually too sparse to constrain the simulation with accurate parameters. Approximated numerical methods for the solution of differential equations, accurate resolution of boundary layers and turbulence scales in the solution of governing equations are also complex because of the large computational resources necessary to obtain well approximated solutions (*in* Salles, 2006). In spite of the recent developments in hardwares and softwares, it seems that the effective application of the Navier–Stokes approach to model real 3D turbidite systems still remains a challenge for the future. To mention a recent example, the work of El-Gawad et al. (2012), one of the most recent and complete on numerical modeling, it still required a hard machine-consuming period of about 18–24 days for just one simulation, even using a high performance computer cluster such as that of the University or South Carolina (College of Engineering and Computing), what is an unfeasible situation for a routine work in the industry.

Despite these problems, several initiatives to use Navier–Stokes approach have been conducted. The use of Navier–Stokes method for laboratory experiments and sedimentological studies (Heimsund, 2007; Aas et al., 2010a and b) resulted in the computational-fluid-dynamics (CFD) model. Although without presenting details on the erosion-deposition mechanisms of the model, the results of Aas et al. (2010a and b) improved the understanding of the role of the palaoebathymetry to control sediment distribution in both study areas (subsurface data in the Central North Sea and outcrops of the Annot Sandstone in the region of Peïra Caiva, France). Even if one considers that thickness and facies variation of the resultant deposits were not obtained, what are still important limitations, a promising use of the method is foreseen, as indicated by the work of El-Gawad et al. (2012). In this later case the authors use a model which includes the Reynolds-averaged Navier–Stokes, turbulence closure and sediment conservation equations; the results are compatible with bed thickness and grain size trends observed in cores of the study area (submarine canyons related to the Niger Delta).

More sophisticated numerical methods have been proposed, focusing the physics acting in the particle scale during the flow, most of them integrating the Navier–Stokes equations. A series of studies may be grouped into the name of direct numerical simulation (DNS) method, an Eulerian-Lagrangian point-particle approach (Soldati and Marchioli, 2012). DNS governing rules were explained in detail by Necker et al. (2002) and were also taken into consideration by Waltham et al. (2008) in their work. Meiburg and Kneller (2010) point to the importance of DNS approach when considering the fluid dynamics. Very recent developments on this method (Yu et al., 2013) present an alternative scheme for turbulent-resolving simulation of fine particle transport, especially in bottom layers, and considering the rheological effect as well as the flow laminarisation. Such very detailed propositions although perfectly adapted to turbulent flows are not still solved at intermediate scales to produce practical results to be applied at the reservoir characterization, except by using some simplifications as previously applied by Waltham et al. (2008). While also promising but further away from DNS as a usable method, the smooth particle hydrodynamics (SPH) numerical technique, initially used in astrophysics, was immediately extended to computational fluid dynamics due to the great advantage of not requiring explicit treatment of interfaces (Vacondio et al., 2013). However, this method has not yet been applied specifically to describe turbulent flows in deep marine environment.

Even considering these significant developments of Navier–Stokes and other numerical approaches, but taking into account the still existing limitations in these methods, the Cellular Automata approach proposed by Salles (2006) appears as an alternative method, practical but still robust, to model turbidity flows.

1.2. Cellular Automata (CA) development and concepts

1.2.1. From the CA definition to turbidite flow simulations

Although Cellular Automata (CA) concepts have been developed since the '40s, only more recently CA was applied for modeling physical systems, and especially fluid dynamics (Toffoli, 1984). CA describe systems whose overall evolution is based only on local interactions of the different model components (Toffoli and Margolus, 1987). CA is easily and naturally implemented on parallel machines and able to treat simultaneously several identical calculations; for this reason it was one of the first models to be implemented in parallel computation.

Salles (2006) used for the first time CA to model the hydrodynamics of turbidity currents. He developed a model to simulate the transport and sedimentary fill of canyons and channels in deep turbidite systems, with low computation time and allowing the simulation of multiple events. T. Salles worked with two