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A Visual Framework for Reservoir Connectivity Analysis

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SUMMARY

Static connectivity measures have been proposed for quick evaluation of reservoir performance to provide a potentially important link between the reservoir characterization and the simulation studies. These measures are easy in concept and inexpensive in execution, and create an important, intermediate level in the assessment of reservoir productivity. This paper proposes a framework for static connectivity analysis in reservoirs that use water flooding technique and pressure propagation fronts as it used in well testing. The software uses a fast marching method and a shortest path algorithm that both are sensitive to geological heterogeneities which can give some insights into finding the connective geobodies. An illustrative example is shown to describe the software interface and to present a simple but systematic connectivity analysis scenario. The distinct tasks contained in a typical reservoir development workflow may be benefited from the addition of connectivity analysis, such as the assessment of optimum well placements for injection-production wells and the evaluation of features of stratigraphic architectures that affect the recovery. The proposed tool is towards providing a geoengineering approach to use the geological knowledge for proposing better production scenarios.

Introduction

Reservoir connectivity is an important factor which can largely impact petroleum reservoir productivity. In secondary recovery scenarios, both injection and producing wells need to be connected to the same geobody in order to create better sweep zones. Furthermore, the connectivity strongly correlates with the efficiency at which hydrocarbon is recovered (Hovadik and Larue, 2010).

Due to its pertinence, much research has been devoted to develop some analytical methods to quantify the reservoir connectivity. This connectivity measure, in turn, is used as a reservoir performance estimator. On one hand, there are research focusing on using static reservoir properties as important underlying factors controlling the productivity of the reservoir. Some examples include the conventional geobody and reservoir-to-well connectivity (Hovadik and Larue, 2010) and percolation theory-based connectivity (Sadeghnejad et al., 2011). Despite being simple in concept and execution, these methods have severe limitations as they do not consider factors that influence the recovery efficiency such as tortuosity, fault transmissibility, and permeability heterogeneity. There have been attempts to redefine static connectivity that is more sensitive to these geological situations, such as connected hydrocarbon volume for SAGD performance estimation (Fenik et al., 2009) and the reservoir quality measure for primary recovery evaluation (Li et al., 2012). On the other hand, there are research focusing on using dynamic reservoir properties. For instance, the use of streamline simulators (Mohammed and Ahmad, 2012), the recent capacitance-resistance models (Moreno and Lake, 2014), and the approaches based on traditional flow simulations. Despite providing more accurate results, some of these methods are time-consuming and that it may take several hours to days to run and to obtain results for one single analysis scenario. Moreover, some others such as capacitance-resistance methods rely on the available production data and cannot be used to test various proposed scenarios on 3D geological models.

In spite of its relevance, current geologic modelling and reservoir simulation software do not offer a simple and straightforward means to assess connectivity in secondary recovery scenarios in a way that is computationally efficient, interactive, and visual. For filling this gap, this paper proposes a software for static connectivity analysis of geological models.

Method

We propose a visual analytics framework that includes interactive ways to quantify the inter-well reservoir connectivity. While using the proposed software, and prior to analyse connectivity, one or more reservoir property values can be defined that differentiate cells in which fluids may flow at some geologically reasonable rates from cells that are essentially impermeable. Once these potential flow units are defined based on the user specified cut-off ranges, a propagation algorithm is used to find the connected cells in the reservoir. These groups of connected cells are here called geobodies. After defining the geobodies in the reservoir model, the well locations and inter-well paths are specified and then the connectivity assessments are carried out to simulate the water flooding originating from the injector wells and propagating inside the connected path flow units.

In turn, our software provides a combination of a fast marching method (FMM) along with a shortest path (SP) algorithm for performing the connectivity analysis. On the one hand, the FMM method used here was introduced by (Sethian 1996). This method is based on an upwind first-order approximation to the Eikonal equation for calculating a front propagation time along the inter-well path on the basis of static reservoir properties. The FMM is generally used to track the pressure front in the single-phase problems and its use in multi-phase flow is not very well understood because of the coupling pressure and saturation equations (Sharifi et al., 2014). However, it is still a robust way to define the high speed passes of the pressure propagation (as in well test) which can heuristically indicates the connective paths and the spatial configuration of the diffusive regions. This is an important aspect as both FMM and well test response are function of diffusivity coefficient ($k/\varphi\mu c_t$, in which k is permeability, φ is porosity, μ is viscosity and c_t is the compressibility). Such strong indications can be used to correlate the well test response to 3D geological heterogeneities of the reservoir models (Hamdi 2014). On the other hand, the SP method calculates the least resistive paths from the injector to all locations on the inter-well path. This measure, in turn, is used as an indication of the times needed for the water front to reach the path cells. This method is similar in concept to the 'resistivity index' introduced by (Hird and Dubrule, 1998). The main difference lies in the resistivity function used to determine the minimum, cumulative sum of 'resistive indices'. In this sense, we use as the inverse of transmissibility a resistance measure as defined in various commercial reservoir simulators for corner point grids.

In general, both FMM and SP methods calculate a time-based flow of the water and pressure front propagating from the wells to each cell along the inter-well path. Then, our software computes time-based measures that represent the pressure front, recovery efficiency such as the water breakthrough time (WBT), the recovered pore volume (PVR), and the connectivity value (CON). The WBT is here considered to be the minimum time required for the water front to propagate from the injector column to another vertical column such as the producer well. For example, in SP, with a user-determined threshold propagation time, the CON is a function of transmissibility and the PVR is a function of connectivity and hydrocarbon pore volume of the cells that are already contacted by water at the given time – that is, cells with a water reaching time less than or equal to the threshold time value. Furthermore, for each one of these measures, our software calculates it either as a global value – that is, one single measure for a specific inter-well path - and as a local, distance-based value – that is, one measure is calculated for each vertical column along the path.

Example

Figure 1 shows two snapshots of our software, which contains four different views. The first view allows one to see data distribution of reservoir properties and to filter the model based on one or more properties in order to determine geobodies. In Figure 1, the model is filtered based on permeability values ranging from 0.86 to 2.87 md. Note that such filtering feature can also be useful for well optimization studies, particularly for compartmentalized reservoirs with large numbers of isolated geobodies as the well placement is crucial to ensure connectivity. The second view allows one to visualize the filtered model either as 2D maps per layer, a 2D average map, or a 3D model. This view also allows one to define and observe various well designs. Figure 1.A displays the filtered first layer of the model, together with a well design that contains three injectors, five producers, and six inter-well paths. The third view shows a list of all defined paths. Each path is depicted as a row, where each location represents all the connected cells for one vertical column of the grid. As can be observed in Figure 1.B, a tooltip window provides recovery efficiency measures per distance such as the water reaching time for a specific grid column, as well as the connectivity value, and recovered pore volume for each pair of connected cells of the referred column. Note that, paths containing a red background are paths in which there is no inter-well connection at a given time. The fourth view shows a list of paths selected from the third view. Each path is depicted as a 2D cross section coloured according to a water flooding time scale. In addition, transparent path cells are cells in which no water sweep occurred at a given time. For each path, this view also shows the water breakthrough time, as well as the overall recovered pore volume and connectivity value. As can be observed in Figure 1.A, the first path has a lower water breakthrough time than the second path; however, the second path has a higher connectivity and so a higher sweep efficiency between injector and producer. In turn, with the evaluation of the measures per distance of both paths, one can conclude that this greater performance is due to the fact that the first path has lower transmissibility and oil saturation values and so, at the given time, more cells were swept in the second than on the first path. In Figure 1.B, the tooltip window shows some low pore volume and transmissibility values settled along the first path. Furthermore, Figure 1.A also shows that, at the given time, the third path is not connected. In addition, the producer grid column is black coloured, which means that the producer cells are never reached by the water front and so this path will never be connected at a finite time.

The hydrocarbon reservoir model depicted on Figure 1 has been constructed using a 3D training image through multi-point facies statistics. The model has 30x50x5 cells in x, y, and z directions, respectively. Each cell measures an average volume of 18x18x4 m3 of the reservoir volume. SNESIM algorithm (Strebelle, 2000) has been used to populate property data. The reservoir model represents a typical low permeable meandering channelized environment where the high permeable sand bodies are effectively isolated within the pervading very low-permeability reservoir facies. The permeability field is anisotropic and the horizontal permeability values are ranging from 0.001 md for the background facies to around 4 md for the channel deposits.

A

B

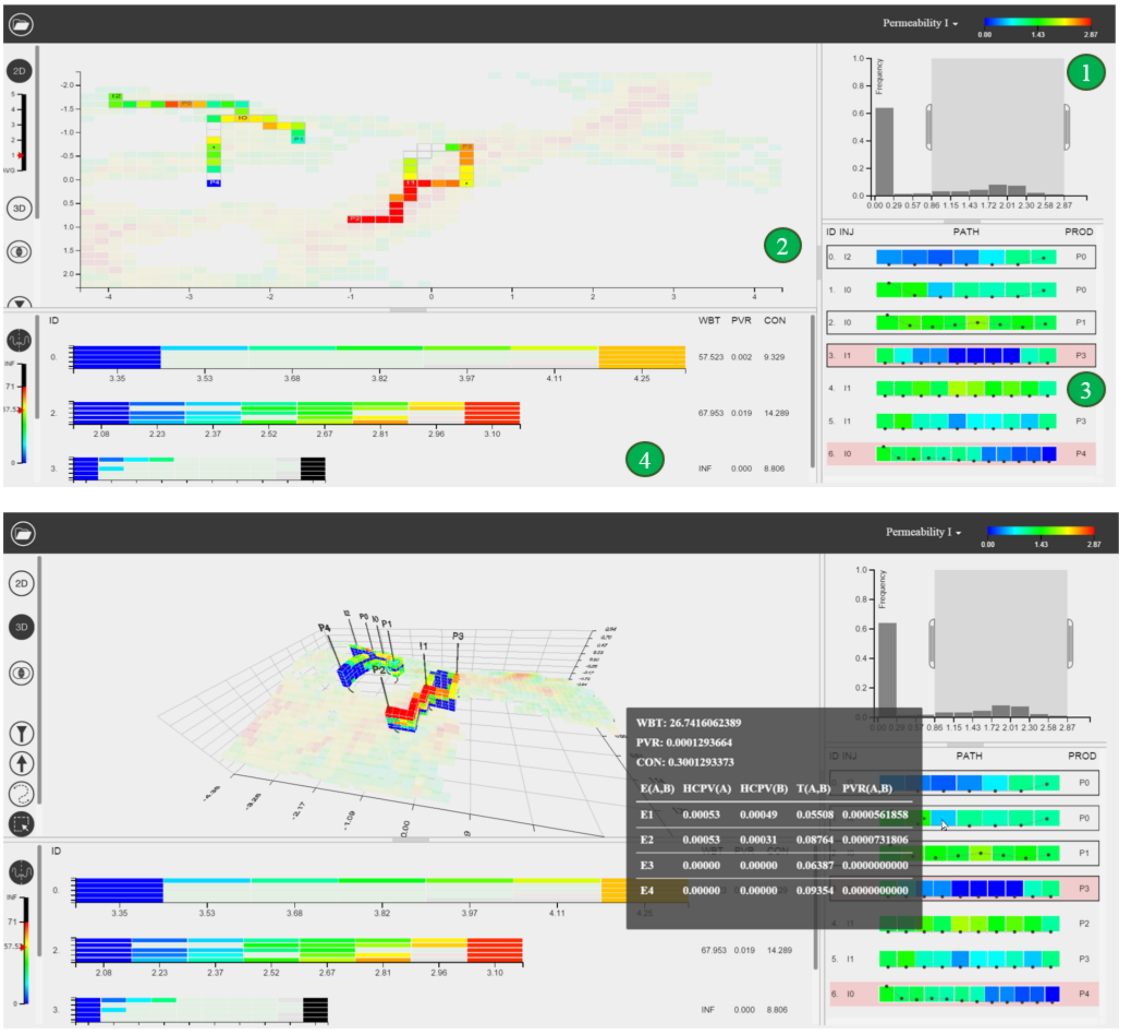

Figure 1 *Two snapshots of the software showing (A) the four different views that compose the environment and (B) a tooltip window displaying recovery measures per distance on a particular inter-well path.*

Conclusions

To summarize, this paper proposes a framework for static connectivity analysis in secondary recovery scenarios. In this sense, aspects of dynamic simulation of water floods were replaced by static information about distances and properties within inter-well paths to serve as a proxy for water flood performance estimation. For this purpose, the software uses a fast marching method for the single phase flow and a shortest path algorithm for the water injection. Both are computationally efficient approaches that are sensitive to geological heterogeneities, which can provide a better insight into the potential connective regions in producible geobodies in inter-well paths. An illustrative example is shown to describe the software interface and to present a simple but systematic connectivity analysis scenario.

Note that, distinct tasks contained in a typical reservoir development workflow may be benefited from the addition of connectivity analysis, such as the assessment of optimum well placements for injection-production wells that have better inter-well connectivity, the evaluation of features of stratigraphic architecture that affected recovery, and the evaluation of water flood performance. Thus, the proposed tool may benefit both geoscientists and engineers.

For future version of the framework, we aim to add support to irregular and complex reservoir models, and to extend the connectivity analysis from cross-sectional to volumetric-based inter-well paths.

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