THREE-DIMENSIONAL SIMULATION OF SMALL-SCALE HETEROGENEITY IN TIDAL DEPOSITS – A PROCESS-BASED STOCHASTIC SIMULATION METHOD

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Abstract

Small-scale heterogeneity at the bed-set scale (ca 1 mm to 1 m) represents an important target for reservoir modelling. In particular, tidal deposits, which are typified by bi-directional currents and deposition of alternating mud and sand layers, have a high degree of architectural complexity at the bed-set scale. To quantitatively assess the impact of these small-scale heterogeneities on reservoir performance, we need a method to realistically reproduce 3-D permeability distributions. In this paper, we present a process-based stochastic simulation method to simulate 3-D permeability distributions in tidal bedding structures such as flaser and wavy bedding. Our process-based stochastic simulation method differs from existing geostatistical methods in that the formation process of bedding structures has been included in the simulation algorithm. The 3-D bedding geometry and grain-size distribution can be realistically reproduced. The new method is different from previous process-response models because we use geostatistical terms to describe the variation of bedding surfaces. Variations of bedform migration and deposition speed, as well as permeability and porosity distributions along individual bedding surfaces are modelled. In our method, we model bedding surfaces by a 2-D sine function and a stochastic component described by 2-D Gausssian random functions. Four stages of deposition, migration and erosion processes have been included to model each tidal cycle of deposition. To generate the correct 3-D geometry, we need to model variations of bedform migration speed, direction and deposition rate at each stage. Because of the periodic nature of flow in tidal deposits, these variations are modelled by a sine function. In addition, a 1-D Gaussian function is used to provide flexibility and introduce variability.

A proprietary method has been used to generate realisations of permeability fields on a 3-D regular grid based on the simulated bedding geometry. This method allows us to generate permeability simulations that honour both permeability data and 3-D bedding geometry. Models are evaluated in terms of the sedimentologist's interpretation of the formative processes of tidal bed forms and the ability to reproduce core heterogeneity (including mm-scale permeability grids).

1. Introduction

Sedimentary reservoir heterogeneity occurs at different spatial scales, ranging from laminae (< 0.05 m), sets (0.05 - 2 m), beds (0.5 - 5 m), to sequences (5 - 100 m or more). Heterogeneities at different spatial scales are known to have different impact on fluid flow simulation in reservoir models. Previous studies in fluvial reservoirs indicate that heterogeneity at the cross-bedding scale has a relatively large impact on the uncertainty of reservoir simulation [1]. Small-scale heterogeneity in tidal deposits is likely to have an even larger impact on the field scale simulation than in fluvial deposits, because of the mud drapes and layers in tidal bedding structures.

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It is difficult to reproduce realistic tidal bedding structures in simulations by a straightforward application of existing geostatistical methods, because the 3-D geometry of the bedding structures cannot be realistically represented by either pixel based or object-based method. Numerical simulations indicate that bedding structures have a significant impact on the fluid flow performance (e.g. [2]). In this study we have developed a new methodology of heterogeneity simulation based on the formation processes of tidal bedding structures. The main procedure of our process-based stochastic simulation method is presented in this paper, with simulated examples of typical tidal bedding structures.

2. Assumptions of the Process Based Stochastic Simulation Method

Fundamental assumptions of our process based stochastic simulation method are:

1) Sediment within two bedding planes (laminar surfaces) has similar permeability and porosity.
2) Bedding planes are the controlling factors of 3-D distribution of grains and hence permeability and porosity.
3) Spatial distributions of permeability and porosity along bedding and laminar surfaces can be modeled by 2-D Gaussian surface.

The first two assumptions are supported by outcrop studies in fluvial deposits. For example, Hartkamp-Bakker [1] measured permeability distribution in a core-section with cross-bedding structures. She found that permeability variation patterns within the cross-bedding structure follows bedding surfaces [1]. Boundaries of permeability contrast are consistent with the laminar boundary surfaces. From geological point of view, this is nothing surprising, because sediments with the same type of lamination were deposited under similar hydrodynamic conditions. It is also reasonable to expect some variation of permeability and porosity along the same bedding surface. These variations can be conveniently modeling by a 2-D Gaussian surface, which is our third assumption.

3. Conceptual Models of Tidal Bedding Structures

A realistic heterogeneity model of tidal, wavy-bedded structures should at least reproduce the following three features [3]:

1) Bi-direction of foresets: one is formed during ebb period; another is formed during flood period.
2) Mud drapes formed during slack water periods after ebb and flood.
3) Periodical patterns of laminar characteristics, because of tidal processes.

In order to reproduce these genetic characteristics in the simulations, we have to include the formation process in the simulation algorithms. An idealistic wavy- or flaser-bedded, tidal structure is formed during four deposition, migration, and erosion events (3):

Event 1: Deposition of sand lamina during ebb period. Lamina migrates in the ebb flow direction. Erosion may occur on the stross side of a bedform. Mud lamina deposited at foregoing slack water period will commonly partly be eroded.

Event 2: Deposition of mud lamina during slack water period after ebb.

Event 3: Deposition of sand lamina during flood period. Lamina migrates in the flood flow direction, which is approximately opposite to the direction of ebb flow. Mud layers deposited during event 2 commonly will be (partly) eroded.

Event 4: Deposition of mud lamina during slack water period after flood.

These four events will repeat periodically. The length of each event, their deposition and migration rates usually vary periodically as well. It is the variation of these formation parameters and their spatial distribution that leads to the complicated heterogeneity in tidal sediments at the bedding structure scale. Therefore, our modeling and simulation methods should focus on these genetic aspects.

4. Method of Process-Based Stochastic Simulation

In our process-based stochastic simulation method, we follow three steps to generate 3-D permeability or porosity realizations in a tidal, wavy-bedded structure:

Step 1: Simulate geometry of bedding structures. The results are (x, y, z) coordinates of each laminar surface.

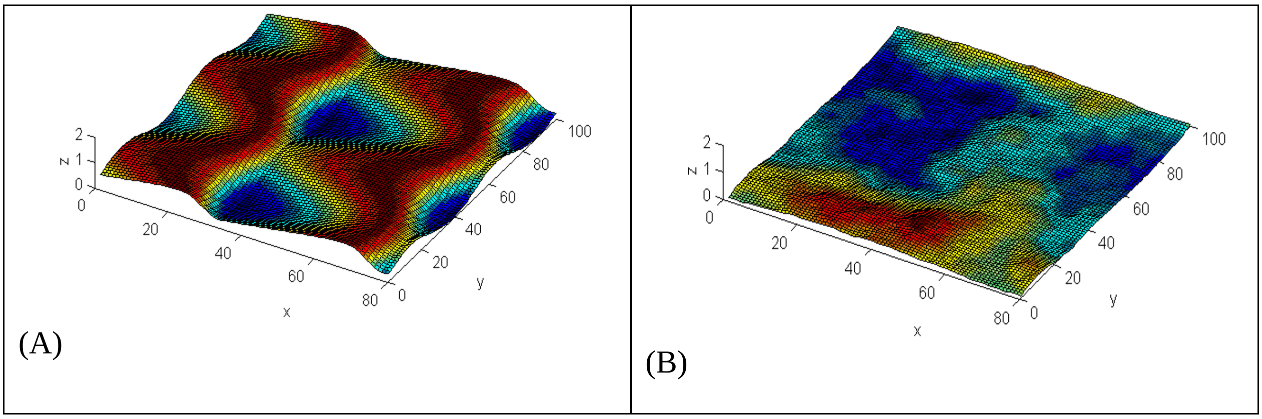
Step 2: Simulate petrophysical distributions (permeability or porosity) on each laminar surface.

Step 3: Generate 3-D petrophysical model on a regular grid sampled from petrophysical data on the laminar surface.

In this way the heterogeneity in the final 3-D model is largely controlled by the geometry of bedding structures. This is, of course, consistent with intuitive knowledge from a geological point of view.

4.1 Bedform geometry

Elevation of a bedform surface is modeled by a sine function and a 2-D Gaussian random function (Fig. 1). The input parameters of bedding surfaces include wave length, amplitude, crest sinuosity, and parameters of their periodical variations.



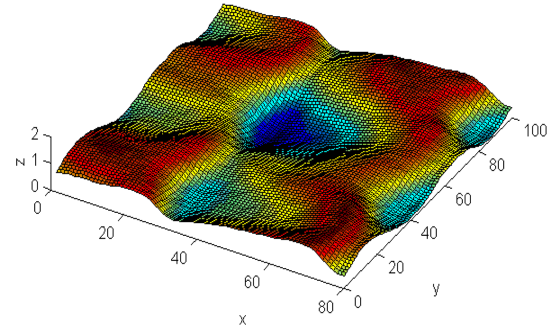


Fig. 1. Elevation of a single bedform surface (C) is modeled by a sine function (A) plus a spatially correlated random component (B). Color represents relative height of the bedform surface.

4.2 Migration, erosion and depositional processes

Migration of bedform is simulated by a periodical variation and a random component that is modeled by a 1-D Gaussian function. The migration direction of bedform during ebb and flood period is approximately opposite. The migration direction, speed, as well as the deposition rate during ebb and flood periods can be changed periodically.

The geometry of mud layers, deposited during slack water after ebb and flood periods, is modeled by adding a flat surface on the top of previous laminar surface. The mud layer will be subjected to erosion in the subsequent depositional phase during the ebb or flood period.

4.3 Petrophysical properties of bedforms

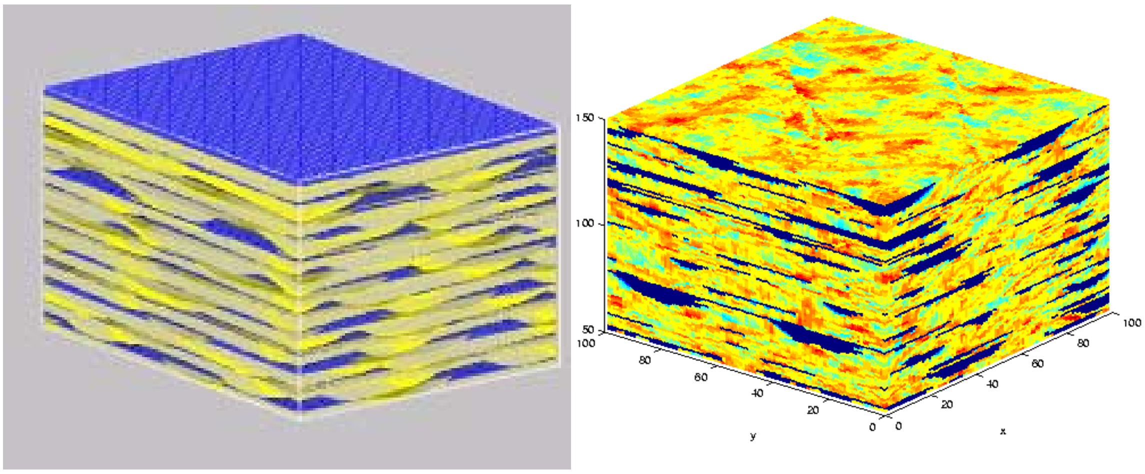
Permeability or porosity values on single bedform are generated by non-conditional simulation algorithm using conventional geostatistical methods. Variogram models with different nested structures can be used. A simple alternative may be using use a constant value. As a result, the permeability heterogeneity is completely due to the geometrical configuration of bedding structures. Petrophysical values in the final 3-D grid are converted from values in the lamina surfaces by a proprietary method.

5. Simulated Examples

We have implemented our process-based stochastic simulation method in the TBED program. The following two examples are simulated results using TBED.

5.1 Flaser

Flaser bedding is characterized by sand ripple foresets oriented in opposite directions with isolated mud drapes in ripple troughs [3]. Fig. 2 (a) is the geometrical model of flaser bedding formed under idealistic conditions. Fig. 2 (b) shows the permeability model of this structure.

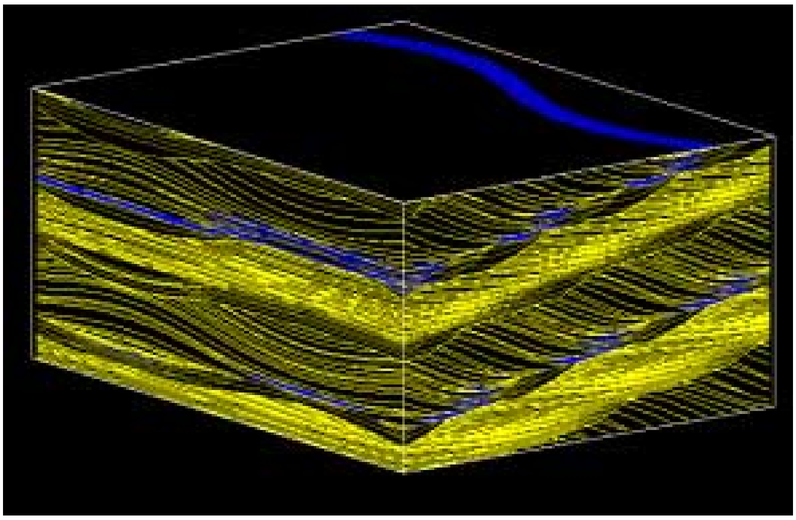


(a) (b)

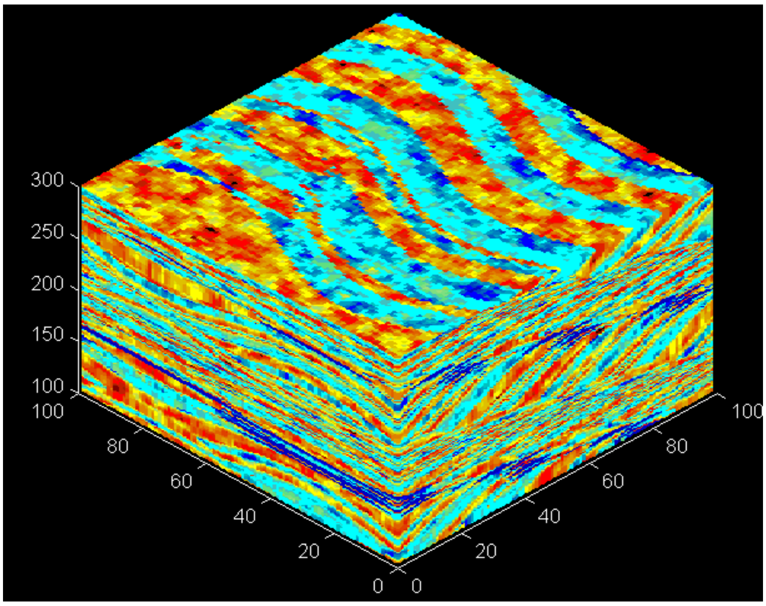
Figure 2. (a) Geometrical model of flaser bedding. (b) Permeability model of the flaser-bedded structure shown in (a).

5.2 Tidal bundles

Tidal bundle structures are characterized by a characteristic sigmoidal shape of individual sets and the occurrence of mud drapes in the lower part of the bedding structure ([4], [5]). Fig. 3 shows both geometry and permeability models of a tidal bedding structure simulated by TBED.



(a)



(b)

Figure 3. (a) Geometrical model of a tidal bundle structure. (b) Permeability model of the tidal bundle structure shown in (a).

6. Concluding Remarks

We have presented a methodology for petrophysical heterogeneity simulation based on the formation process of sedimentary structures. This process-based stochastic simulation method has been used to simulate realistic 3-D permeability models of tidal bedding structures. Compared with the conventional geostatistical simulation, the based-process based method has a number of obvious advantages:

1) The formation process of heterogeneity has been explicitly considered in the simulation algorithms. Input parameters to the simulation program, such as those specifying the geometry of bedding surfaces, have easy-understood geological meaning.
2) The complicated three-dimensional geometry of tidal sedimentary structures such as wavy and flaser bedding, and mud drapes can be realistically reproduced in the simulations. It is unlikely to be so in conventional geostatistical simulations which only use variograms and probability distributions.
3) The process-based method requires geologically-related input parameters. This makes it flexible for simulating petrophysical realisations in sedimentary structures with complicated geometry.

There are still improvements that could be made to make this model more realistic, but the current model captures many details of the complexities of tidal sedimentary heterogeneities.

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