Digital twins of multiscale 3D heterogeneous geological objects: 3D simulations and seismic imaging of faults, fractures and caves.

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Abstract. Numerical simulation of seismic waves’ propagation and imaging in a three-dimensional multiscale geological media is one of the main trends in the development of modern geophysics. We present the workflow for construction of the 3D digital twin of some real geological object. This object is cavernous fractured carbonate reservoir near the Riphean roof. One of the main features of this object is the presence of the family of faults filled with tectonic breccia. To simulate them, in particular, their interiors and surrounding damaged areas, we simulate paleotectonic processes with the use of 3D discrete elements technique. This simulation we do by GPU parallelization.

Next, when the fine digital geological model is done, we perform 3D finite-difference simulation of the seismic waves’ propagation and get the full 3D synthetic data set. To do this simulation we use an original technique based on local grid refinement in time and space. To be able to deal with huge amount of input/output data we use High-Performance Computing (HPC) systems with parallel architecture and hybrid parallelization strategy by simultaneous use of MPI and OpenMP.

The final step is validation of our original multiscale algorithm for seismic imaging, which suppresses specular reflection, but accumulates weak scattered/diffracted waves. This approach opens the way to the reconstruction of subseismic geological objects, like fractures, fracture corridors and clusters of caves. To construct these images we use HPC with parallel architecture and MPI+OpenMP programming.

1. Introduction
Advances in a supercomputing technology make it feasible problems, which seemed impossible in the recent past but become a common practice today. In the geoscience, those have been opening new horizons for understanding the subsurface structures by getting 3D images and velocity models of high fidelity and microscale reservoir characterization. The forward seismic
modeling and inversion, associated with field data processing and velocity estimation, may require terabytes of RAM and teraflops of computing power.

One of the principal directions of High-Performance Computing application in the Oil and Gas industry is the development of unique synthetic data sets for understanding the main peculiarities of the wave field’s propagation in 3D heterogeneous multiscale media and approbation and validation of new data processing algorithms. These data must, to some extent, correspond to the real one, collected by the industrial acquisition systems.

In this research, we build the 3D multiscale digital model containing the main features inherent in geological objects at several licensed sites of Rosneft PJSC in the North of Eastern Siberia. They are:

(i) 3D geological faults, filled with tectonic breccia and surrounded by damage zones;
(ii) The systems of cracks confined to these faults as well as fracture corridors;
(iii) Areas of high cavernosity.

In this model we took into account a number of scales:
a) Macroscale, first tens of meters, obtained by 3D seismic study (seismic interfaces forming the skeleton of the model);
b) Mesoscale, first meters, obtained by various well log measurements;
c) Microscale, first tens of centimeters, captured by sonic logs, FMI fullbore formation microimager and analysis of core samples.

2. Model Building

2.1. Skeleton of the Model

The initial stage of building the model is the definition of the skeleton; in other words, a description of the totality of all interfaces known in the result of processing and interpretation of all available data - both surface seismic and VSP as well as the entire spectrum of logs. We start with a mapping of all interfaces known by regular 3D seismic study, including 3D geological faults. Elastic parameters between interfaces are known on the base of a variety of additional data, like velocity analysis and well log. A general view of these surfaces one can see in Figure 1.

2.2. 3D Geological Faults

At present, the common knowledge is to treat a geological fault not like a slip surface, but as a complex 3D geological body [2]. Therefore, we consider faults as volumetric entities consisting of rocks deformed in the process of destruction caused by tectonic movements [1]. The products of this process are closely linked to a wide range of parameters, such as the tectonic regime, magnitude of fault displacement, and mechanical properties of the host rock. To perform numerical simulation of these complicated processes we apply the discrete elements technique with parameters calibration by comparing real observations and simulation results. Recall that when using this method the continuum medium is represented as a set of “discrete elements”/particles with simple geometric shape. In particular, we use their representation in the form of balls of different radii interacting according to a certain set of physical laws.

The main goal of 3D modeling is to determine and analyze the distribution of deformations in the horizontal direction along the fault at the macroscale level, especially for scenarios with displacement. The computational area was chosen in the form of a parallelepiped with dimensions of 500 meters vertically and 2000 meters in each horizontal direction. The size of the elements ranged from 0.5 to 15 meters with a uniform distribution. The modulus of

1 Vertical Seismic Profile - measurement of seismic waves within a borehole
stiffness of the elements was 16 GPa, regardless of which layer the element belonged to. To take into account the differences in the geomechanical properties of the layers, we varied the dynamic friction coefficient within them, which determines the intensity of tangential forces. The general scheme of the numerical experiments one can see in the Figure 2. These numerical experiments give the spatial distribution of deformations. Next, with the use of the empirical curve describing connection of deformations with the change of elastic modules we reconstruct microscale heterogeneities in the damage areas around faults (see Figure 3). Finally we come to the full 3D elastic model of the target area with interfaces, faults and damage areas presented in the Figure4.

3. 3D Multiscale Seismic Simulation
Let us present the formal parameters of the model and acquisition.

Model fills 8km × 10km × 6km parallelepiped with uniform cells of 5m × 5m × 5m everywhere out of localization of small-scale heterogeneities. Within areas with this kind of heterogeneities (damaged areas filled with tectonic breccia, clusters of caves and fractures and fracture corridors)
Figure 3. Left: The empirical dependence of perturbations of elastic modules of deformations. Right: Elastic parameters of tectonic breccia in the damage area around a fault

Figure 4. The full seismic model (left) and its seismic image (right). One can see 3D structure of the faults and their mapping on seismic wave imaging (right)

we use the locally refined grid with cells of 0.5 meters that allows us to describe the variability of elastic properties with reasonable accuracy.

**Acquisition** is the $8km \times 10km$ rectangular with:

- 3C receivers placed uniformly on the grid $25m \times 25m$;
- Vertical force point sources placed with the step of 50m along lines which are 300m from each other, 5280 sources at all;
- Source function is Ricker pulse with dominant frequency 40 Hz;
- Recording length for each receiver is 4 seconds with sample of 2 ms.

We perform numerical simulation of seismic wave’s propagation in this 3D heterogeneous multiscale medium by explicit in time finite-difference technique with locally refined staggered grids in time and space [3].

4. Scattering Imaging
We use the synthetic data obtained and known velocity model to image small-scale heterogeneities. To do this we do asymmetric summation with the help of elastic Gaussian
Figure 5. 3D seismograms for the source in the center of the acquisition. Left - along the short axis (8km), right - along the long one (10 km)

beams following paper [5]. The key feature of the method of scattering imaging is decomposition of full velocity model onto two constituent - smooth propagator given by smooth functions $\lambda_0(\vec{x}), \mu_0(\vec{x}), \rho_0(\vec{x})$ and its sharp perturbations (reflector) described by sharp oscillating functions $\lambda_1(\vec{x}), \mu_1(\vec{x}), \rho_1(\vec{x})$. The propagator does not return seismic energy back to the acquisition, but prescribes the time of wave’s propagation between two distant points. In the contrast, reflectors do not change travel time, but turns the seismic wave towards the acquisition. In this paper we suppose the depth velocity model known and will image its perturbations, especially clusters of small-scale heterogeneities. To compute these images we use the 3C data $\vec{\phi}(x_r, y_r; x_s, y_s; \omega)$ produced by the sources $(x_s, y_s)$ and acquired by receivers $(x_r, y_r)$ and perform the asymmetric summation with weights computed by tracing two Gaussian beams from the target point towards sources and receivers (see details in [5]).

$$f(\vec{x}_i, \beta) = \int T^{gh_2}(x_s, y_s; \vec{\vec{x}}_i; \gamma, \theta, \beta; \omega) T^{gh_1}(x_r, y_r; \vec{\vec{x}}_i; \gamma, \theta, \beta; \omega) \tilde{\phi}(x_r, y_r; x_s, y_s; \omega) \times k(\gamma, \theta, \beta) dx_r dy_r dx_s dy_s d\omega d\gamma d\theta$$

The microlocal analysis done in [4] proves that left hand side of (1) is the local impedance and, hence, provides the variability of medium parameters at the imaging point.

In the Figure 6 one can see microscale heterogeneities in the model (left) and their image computed by the formula (1). There are all of them on the image and the intensity is proportional to the contrast of the impedance.

5. Conclusion

In this study we applied the variety of numerical methods which essentially use High-Performance Computations.

(i) Discrete elements based GPU simulation of the tectonic processes to estimate the elastic parameters of breccia filling geological faults;
(ii) Finite-difference technique on the base of 3D domain decomposition using huge high-performance computers and MPI/OpenMP parallel programming;
(iii) Original imaging technique on the base MPI/OpenMP parallel programs processing Terabytes of synthetic 3D seismic data (big data).
Figure 6. Small-scale heterogeneities in the model (left) and their scattering image (right)

Author contribution
Vladimir Cheverda proposed and together with Maksim Protasov justified the asymmetric summation with Gaussian beams to image small-scale heterogeneities. Dmitry Kolyukhin and Vadim Lisitsa applied discrete elements simulation to describe fault formation and estimate parameters of tectonic breccia. Maksim Protasov developed asymmetric summation for 3D imaging and constructed 3D images of small-scale heterogeneities; Galina Reshetova applied finite-difference technique with local grid refinement in time and space and computed 3D synthetic seismic wave fields. Boris Glinsky dealt with optimization of parallel programming, Igor Chernykh determined the technology of the workflow of high performance computations and Igor Kulikov learned the elasto-plastic processes within faults. Anastasiya Merzlikina developed 3D skeleton of the model, Victoriya Volyanskaya supervised simulation of tectonic motions creating faults, Denis Petrov is responsible for filling the skeleton with seismic parameters (density and wave propagation velocities), Valery Shilikov did interpretation of the data processing, Arjem Melnik developed faults geometry.

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