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Digital Twin of Multiscale Geological Media: Faults, Fracture Corridors, Caves. Seismic simulation and imaging.

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Summary

The current level of development of numerical methods and high-performance computer systems opens way to obtain detailed information about the structure of geological objects using 3D seis-mic study. A universally recognized necessary component that ensures the successful develop-ment of modern high-tech technologies for acquiring, processing and interpreting geophysical data is the complete digital models of geological objects - their digital counterparts. It is on this basis that a detailed assessment of the resolution and information content of the proposed meth-ods and their comparison with the already known processing and interpretation algorithms using the example of a specific geological object becomes possible. In this paper the main efforts are paid to the construction of a realistic three-dimensional seismo-geological model containing a family of faults, as well as clusters of cavities and fracture corri-dors. After constructing such an inhomogeneous multi-scale model, we perform finite-difference numerical simulation of the formation and propagation of three-dimensional seismic wave fields. The data obtained are processed using the original procedures for extracting scattered / diffracted waves with the subsequent construction of images of the corresponding small-scale objects, which generate these waves. We perform the detailed analysis of the results obtained.

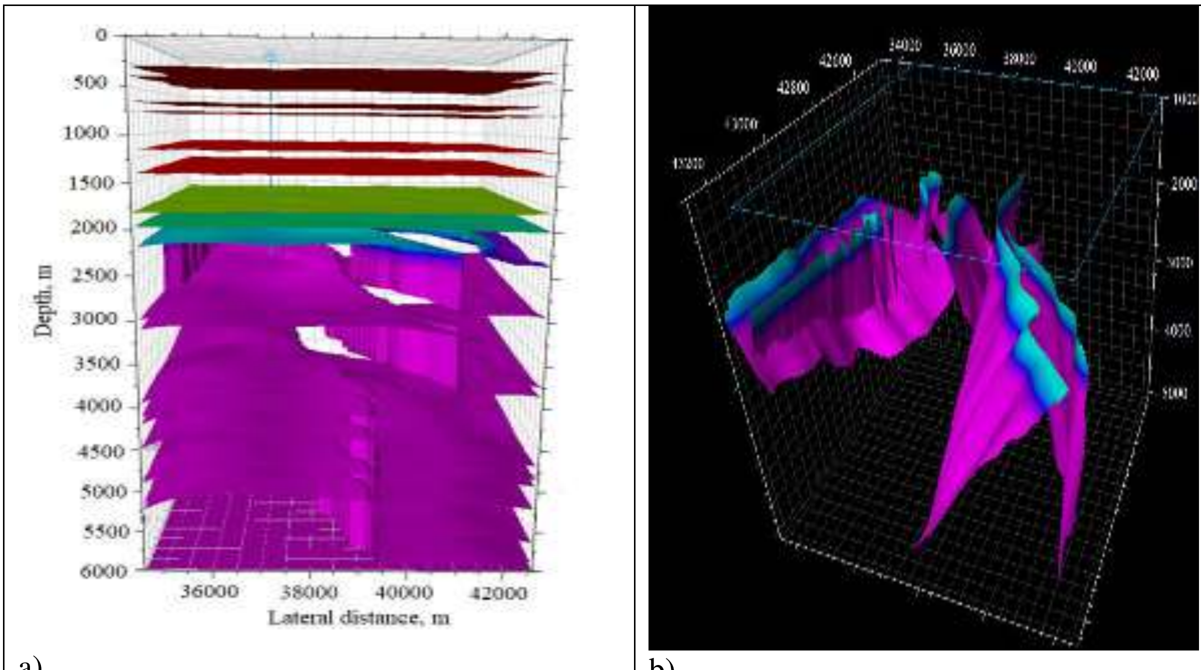
Introduction

Advances in a supercomputing technology make it feasible solving big data problems, which seemed to be unreal in the recent past, but became more and more common 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. To keep up-to-date on front-end technologies Oil and Gas companies spend huge budgets to buy, rent and upgrade / maintain currently owned supercomputers.
One of the principal direction of High Performance Computing in the Oil and Gas industry is development of special databases for understanding the main peculiarities of the wave field's propagation in 3D heterogeneous multiscale media and approbation and validation of new data processing techniques. This stage is becoming more and more confident using synthetic data sets, including large-scale seismic observations for multiscale 3D realistic geological media. Naturally, these data must to some extent correspond to real geological situations.
In this paper, we build a seismic geological model containing the main features inherent in geological objects at a number of licensed sites of Rosneft PJSC in the North of Eastern Siberia. They are:

1. Three-dimensional faults, including the damage zones surrounding them;
2. The system of cracks confined to these zones;
3. Areas of high cavernosity;
4. Fracture corridors.

We took into account a number of scales:

a) Macro scale, 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, obtained by sonic logs, FMI wellbore formation micro imager and analysis of core samples.



a) b)

Figure 1. *Skeleton of the model. a) Interfaces of the layers, b) Geometry of faults*

Model Building

Skeleton of the model. The initial stage of building the model is definition of the skeleton, in other words, description of the totality of all interfaces known in the result of processing and interpretation data of three-dimensional seismic study. We start with mapping of all interfaces known by regular 3D seismic study, including 3D geological faults.

A general view of these surfaces is in Figure 1. The first of them represents the geometry of all interfaces and the second looks of faults only.

The next step is to fill the layers with an elastic medium with the given parameters. In the Figure 2 one can see two orthogonal 2D view of the model with parameters used to fill the skeleton. We recover these parameters from 3D seismic observations and variety of logging data.

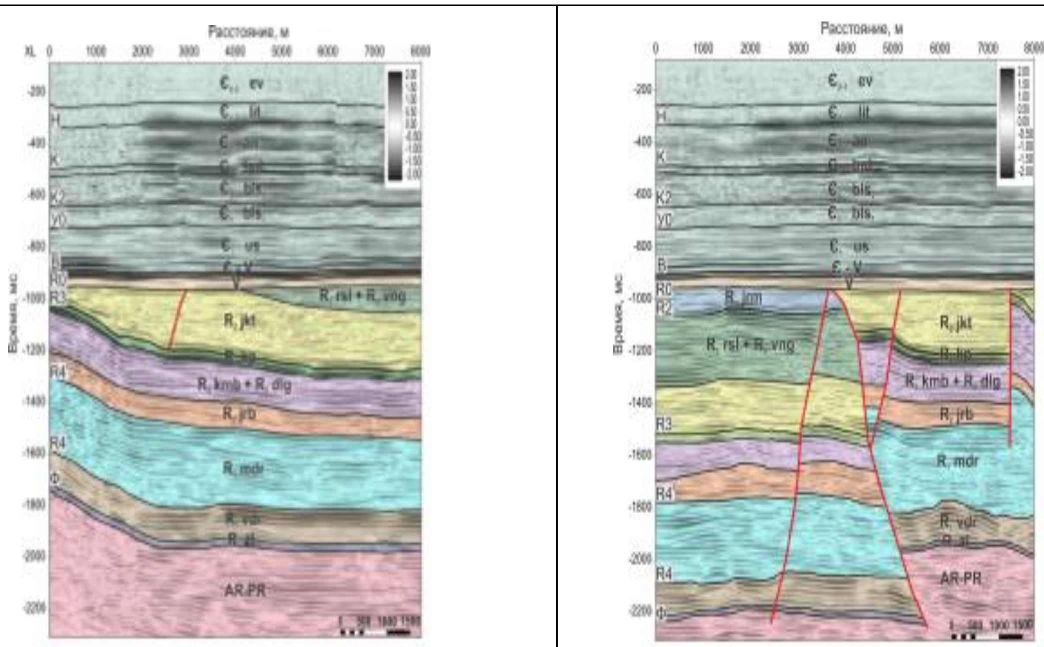
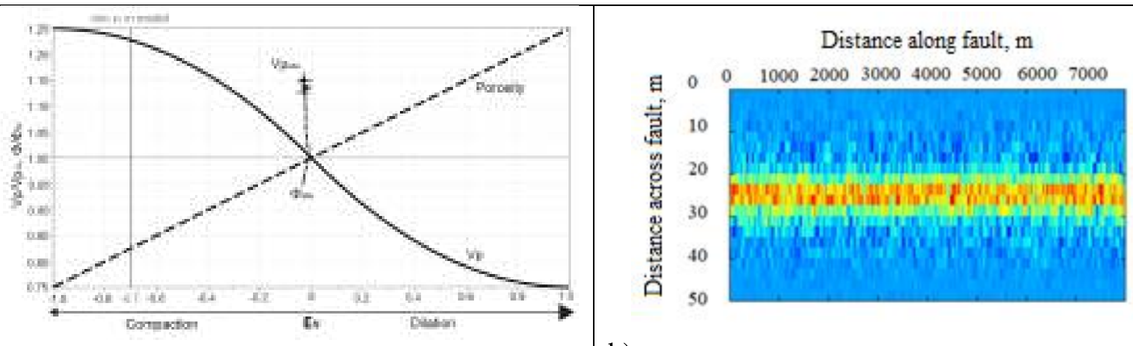


Figure 2. *2D orthogonal slices of 3D field seismic images.*

Simulation of 3D geological faults

Modern geology treats the fault not like a sliding surface, but as a complex 3D geological body (Kolyukhin et al., 2017). Here we consider faults as volumetric entities consisting of damaged rocks, formed in the process of destruction caused by tectonic movements (Hardy and Finch, 2007). The products of this process are closely linked to a wide range of parameters, such as tectonic regime, magnitude of fault displacement, and mechanical properties of the host rock. The reasonable way to perform numerical simulation of these complicated processes is application of discrete elements technique with parameters calibrated by comparing real observations and simulation results (Botter et al., 2016).



a) b)

Figure 3*. a) Experimental dependence of elastic parameters with respect to deformations. b) "Tectonic breccia" used to fill the damage zones in the model.*

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 500 meters in vertical and 2000 meters in each horizontal direction. The size of the elements ranged from 2.5 to 15 meters with a uniform distribution. The modulus of stiffness of the elements was 16 GPa, regardless of which layer the element belong 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 numerical experiments provide the distribution of deformations near the fault. The next step is to transform these deformations to the variations of elastic parameters on the base of some experimental curve presented in the Figure 3a. In the Figure 3b we give the fine-scale distribution of elastic parameters describing the tectonic breccia within the faults which we use to fill their 3D structure.

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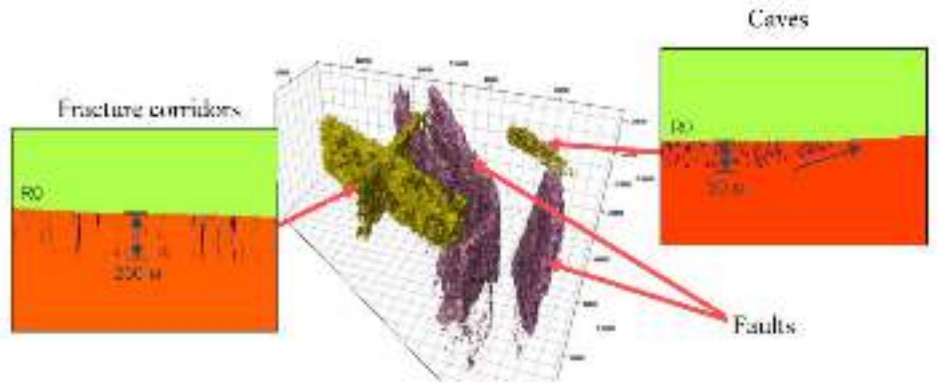

Figure 4. Faults and microscale heterogeneities in the synthetic geological model.

Small-scale heterogeneities

In addition to constructing faults filled with tectonic breccia, we introduced two additional families of small-scale heterogeneities, presented in the Figure 4:

1. Two intersecting fracture corridors each 300 meters long;
2. The thinning cluster of caves.

3D seismic simulation

The synthetic data are generated for the rectangular acquisition 8000m × 10000m with receivers uniformly placed on the grid 25m × 25m. The maximal depth of the model is 4000 meters. For the excitation of seismic waves, we used volumetric sources, emitting a Ricker pulse with central frequency 40 Hz. These sources are placed on the lines along short lateral direction stepped with 50m, the distance between lines is 300m. For simulation, we use the finite-difference technique with local grid refinement in time and space in the area filled with small-scale heterogeneities (see details in (Kostin et al., 2015).

Imaging in Scattering Waves

We present results of synthetic data processing/imaging in Figure 5. As one can see, there is almost unambiguous correspondence between the model (on the top left) and the image (on the top right).

An exceptional feature of the scattering energy imaging method is the ability to compute the so-called scattering indicatrices, which describe the direction of propagation of scattering seismic energy. In turn, this energy propagates orthogonally to the dominant fracking direction.

In the Figure 5 one can see these curves computed for the set of reference points and make sure that the principal direction of propagation of the scattering energy is orthogonal to the principal direction of fractures. We would like also to pay attention to the scattering indicatrix in the point a (see Figure 5) – it is one-sided there. The explanation is the slope of the corresponding fault, which cancels scattering energy propagation in this direction.

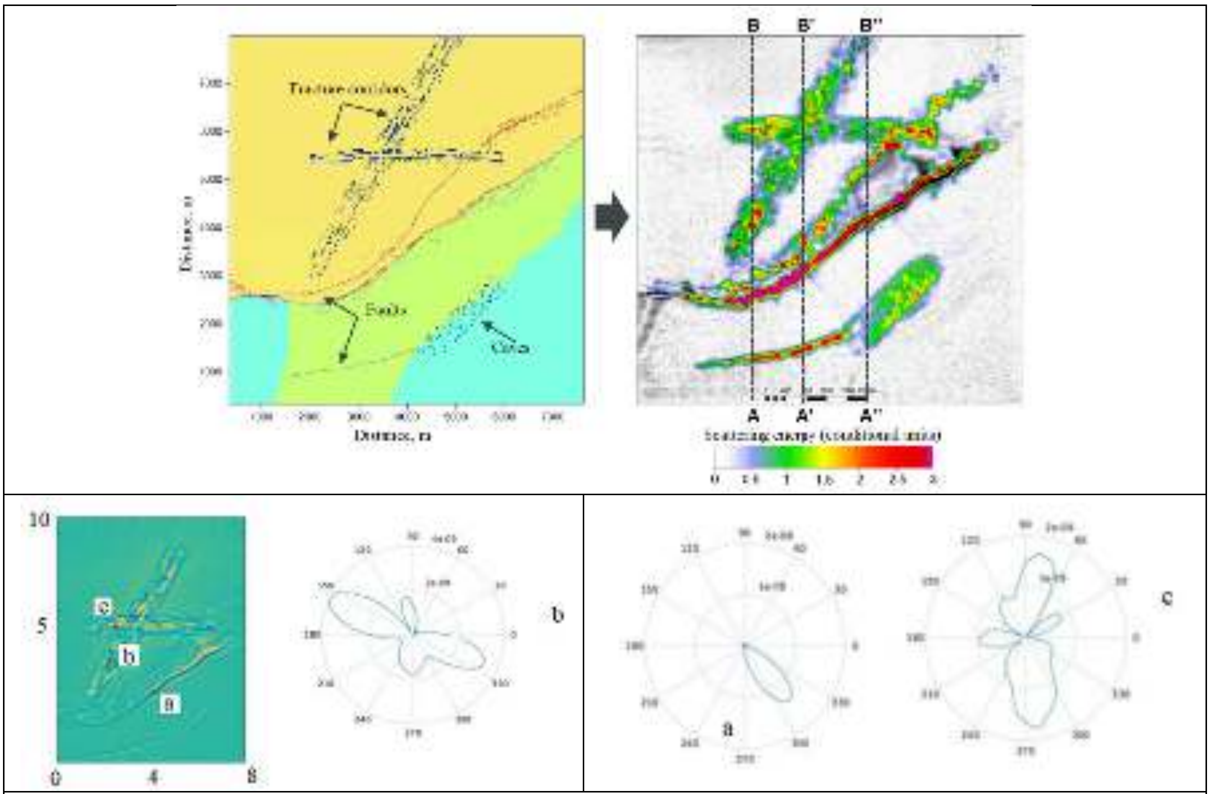

Figure 5. Top: Comparison of the model (left) and full azimuth image in scattered/diffracted waves. Bottom: From left to right: full azimuth image in scattered waves, scattering indicatrices at the points b, a and c.

Conclusion

We have developed the 3D digital twin for some real test site on the base of all available geological information about geometry of the existing faults, cluster of caves and fracture corridors. To populate the faults with tectonic breccia we performed geomechanical simulation of tectonic motions and interaction of blocks. Next, we performed 3D seismic simulation to obtain multicomponent synthetic data. We used this data to validate the scattering imaging technique.

Acknowledgements

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