Digital Twins of Hydrocarbon Reservoir

Vladimir Cheverda[1,2(✉)], Vadim Lisitsa[1,2], Maksim Protasov[1], and Galina Reshetova[2,3]

[1] Institute of Petroleum Geology and Geophysics, Novosibirsk 630090, Russia
cheverdava@ipgg.sbras.ru
[2] Mathematical Centre in Akademgorodok, Akademgorodok, Russia
[3] Institute of Computational Mathematics and Mathematical Geophysics, Novosibirsk 630090, Russia

Abstract. The construction of a detailed geological model of the object under study is necessary to ensure the successful conduct of seismic exploration and the subsequent development of a hydrocarbon reservoir. This stage is crucial concerning fields in a carbonate environment, widespread in the north of Eastern Siberia, particularly for the Yurubcheno-Tokhomskaya zone. Indeed, such hydrocarbon reservoirs are characterized by an extremely complex internal structure represented by the presence of multiple accumulations of subseismic objects, such as caverns, fractures and fracture corridors. A definition is given in this work, and technology for constructing a digital twin of a geological object is provided. The digital twin of a geological object in our understanding is a set of data that determine its geometric and physical properties in conjunction with the corresponding synthetic geophysical fields. In this work, a seismic digital twin of one of the Yurubcheno-Tokhomskaya zone objects is constructed.

This work describes the technology for constructing a digital twin of one of the most complex geological objects - a cavernous-fractured hydrocarbons reservoir, complicated by geological faults. At this stage, we are interested in this object's elastic characteristics, which affect its interaction with seismic waves. Three-dimensional seismic data and borehole observations are used as input information. We pay special attention to faults' construction, given their thin internal structure filled with fractured breccias. To do this, we use discrete element modelling of fault formation, which allows us to take into account the fragmentation of the geological rock. The constructed multi-scale model destination performs full-scale numerical simulation; the main goal is to obtain an accurate description of the scattered waves. We use the previously developed finite-difference methods using grids with local refinement in time and space to describe their occurrence and propagation processes. As a result, we got a digital twin of a specific geological object. By this term, we mean a detailed full-scale elastic model together with the calculated seismic wave field.

Keywords: Numerical modelling · Seismic waves · Cavernous-fractured reservoir · Geological faults · Caves · Fracture corridors

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1 Introduction

The construction of a detailed geological model of the hydrocarbon reservoir is necessary to ensure the successful conduct of seismic exploration. This stage is especially crucial concerning fields in a carbonate environment, widespread in the north of Eastern Siberia, particularly for the Yurubcheno-Tokhomskaya zone. Indeed, such hydrocarbon reservoirs are characterized by an extremely complex internal structure represented by the presence of multiple accumulations of subseismic objects, such as caverns, fractures and fracture corridors.

This work describes the technology for constructing a digital twin of one of the most complex geological objects - a cavernous-fractured hydrocarbons reservoir, complicated by geological faults. At this stage, we are interested in this object's elastic characteristics, which affect its interaction with seismic waves. Three-dimensional seismic data and borehole observations are used as input information. We pay special attention to faults' construction, given their thin internal structure filled with fractured breccias. To do this, we use discrete element modelling of fault formation, which allows us to take into account the fragmentation of the geological rock. The constructed multi-scale model destination performs full-scale numerical simulation; the main goal is to obtain an accurate description of the scattered waves. We use the previously developed finite-difference methods using grids with local refinement in time and space to describe their occurrence and propagation processes. As a result, we got a digital twin of a specific geological object. By this term, we mean a detailed full-scale elastic model together with the calculated seismic wave field.

The successful development of hydrocarbon deposits requires a deep understanding of the multi scale features of its geological structure. Recently, scattered/diffracted waves have become more and more widely used for solving such problems. One of the main problems here is the need to perform reliable testing of the developed approaches. The most reliable way to do this is to build a digital geological model of the field, its digital twin, which describes the studied object's main geological elements: its geometry, stratigraphy, lithological and facies characteristics of reservoir layers, net thicknesses, reservoir properties, and others. Knowledge of these features is of particular importance in the development of carbonate reservoirs, which, as a rule, have a very complex structure of void space. When developing deposits of this type, it is necessary to consider the uneven distribution of cracks and caverns. They form a storage space (caves) and act as the main ways of fluid filtration (fractures) in carbonate reservoirs. Such deposits are distinguished by their diversity and concentrate a significant part of the world's hydrocarbon reserves.

For a detailed study of carbonate reservoirs, it is necessary to use a wide range of geological and geophysical information, in which seismic exploration plays an important role. It should give an idea of the reservoir's internal structure and changes in reservoir properties in the interwell space. However, fundamental physical properties of seismic wave fields impose very severe limitations on the resolution of methods based on the use of reflected waves. Therefore, when it comes to fractured and fractured-cavernous reservoirs, standard seismic methods

based on the use of reflected waves are not as effective as in classical terrigenous ones. A distinctive feature of carbonate reservoirs is the absence of a sharp acoustic boundary on their top, which is associated with the diffuse nature of the voids formed during the dissolution and leaching of rocks. A significant expansion and deepening of information obtained using seismic methods can be achieved by attracting scattered/diffracted waves. Indeed, their presence indicates the presence of singular objects in the medium, such as faults, cracks, accumulations of caverns, and others. Consequently, the use of such waves opens up the possibility of a significant increase in the information content and resolution of seismic methods for studying the medium's internal structure.

In this paper, we present a technology for simulation of three-dimensional seismic data, focused on identifying hydrocarbon deposits in carbonate reservoirs and based on the use of scattered waves. These waves are formed on geological inhomogeneities, the characteristic dimensions of which is at least for one direction significantly less than the seismic wavelength. Usually, they associated with fracturing and cavernous rocks.

Let us mention, that we have developed technology using Gaussian beams for the separation of scattered waves. A Gaussian beam is a special kind of elastic waves, concentrated in a narrow neighbourhood of a preselected beam [Babich and Buldyrev 2009; Popov, 2002]. The imaging is performed at a fixed point from which a pair of beams is started - one towards the sources and the other towards the receivers (Fig. 1). Then, for these rays, we introduce the corresponding Gaussian beams. Then, on the receivers and sources' apertures, the traces of these beams are calculated, which are used as the summation weights of the initial multiple overlapping data to build an image at the selected point. As a result, a detailed three-dimensional image of the reservoir is obtained in scattered waves. Using the pair of P-rays one constructs the PP-scattered images, P- and S-rays waves give the PS-ones. It should be emphasized that neither for the construction of images in scattered PP nor in PS waves is necessary to perform preliminary separation of the total wavefield into longitudinal and transverse waves (see (Protasov et al. 2016, 2019)).

2 Building a Digital Twin of a Geological Object

The construction of a three-dimensional model was based on the known structure of one of the fields in the north of Eastern Siberia, the main object of which is the exposed carbonate reservoir of the Riphean age, containing massive deposits screened tectonically and lithologically.This reservoir has a complex structure with two types of voids - caverns and fractures and is characterized by strong heterogeneity and anisotropy of properties. It also combines low capacity (on average 1–2%) and high permeability (up to 4000 mD), mainly due to natural fracturing. The initial stage of the formation of the model consisted of constructing its skeleton, describing the interfaces between layers, built as a result of processing and interpreting 3D seismic data. Well log data determine the elastic medium parameters between these layers.

An important feature of the studied area is the presence of faults that break the reservoir into a series of blocks with displacement amplitudes reaching hundreds of meters. It should be emphasized here that at present, it is becoming generally accepted to understand a geological fault as a complex three-dimensional geological object [Kolyukhin et al. 2017; Vishnevsky et al. 2017]. Therefore, we treat the faults as 3D geological bodies consisting of rocks deformed due to tectonic movements [Faulkner et al. 2010]. Such movement's main characteristics are determined by a wide range of parameters, including the tectonic regime, the magnitude of the displacement of the layers, the mechanical properties of the surrounding rocks and others [Hardy and Finch, 2005; 2007].

Numerical modelling of a complex nonlinear process forming of geological faults was carried out using discrete elements approach. It treats the geological media as a set of "discrete elements/particles" of a simple geometric shape. In particular, here we use discrete elements in the form of various radii spheres, interacting with each other according to a certain set of physical laws.

When considering tectonic processes, one of the main types of interaction is friction between elements, which determines the so-called angle of rocks' internal friction. Simultaneously, it is convenient to separate the forces that determine the normal and tangential interactions.

Tangential forces, in particular friction, mainly determine the properties of the medium at the macro-level [Duan et al. 2017]. Coulomb's law is most often used to describe internal friction. According to this law, static friction determines the interaction between discrete elements/particles until it exceeds a certain threshold value, after which sliding friction becomes dominant. For most geomaterials, the static friction coefficient is 0.9, and this value we used in our computations. Another important quantity is the coefficient of dynamic friction. It usually ranges from 0.0 to 0.4. It is this coefficient that determines such a significant parameter as the angle of internal friction. In this work, we used a dynamic coefficient of friction that changes with depth, and this change was set in the range from 0.1 to 0.3.

The main goal of numerical modelling of the formation of a fault is to determine and analyze the distribution of deformations in its vicinity, especially for a fault with displacement. The computational area is a parallelepiped $2000\,\text{m} \times 2000\,\text{m} \times 500\,\text{m}$ (Fig. 1). The size of the discrete elements (balls) varied from 2.5 to 15 m. The stiffness module is equal to 16 GPa, regardless of the layer. To consider the variability of the medium (layers)' geomechanical properties (layers), we changed the coefficient from layer to layer, which controlled the intensity of the tangential forces. To simulate tectonic movements on fault banks, horizontal and vertical displacements were set as boundary conditions. Figure 2 shows the distribution of deformations in the vicinity of the fault with a fault amplitude of 100 m and a displacement in the positive Y direction equal to 50 m. The performed numerical experiments made it possible to estimate the distribution of deformations in the faults' vicinity. Further, following the empirical law describing the relationship between the variability of the relative volumetric

deformation and the variations in the P-wave velocities [Botter et al. 2014], we determine the variations in the elastic parameters in the vicinity of the faults 2.

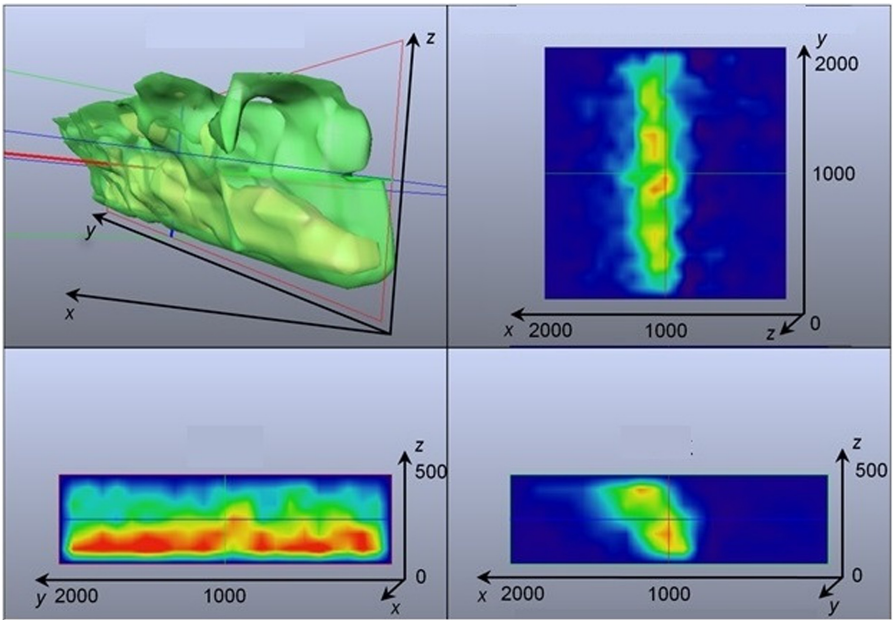


Fig. 1. Volumetric deformations in the vicinity of the fault: general view and projections.

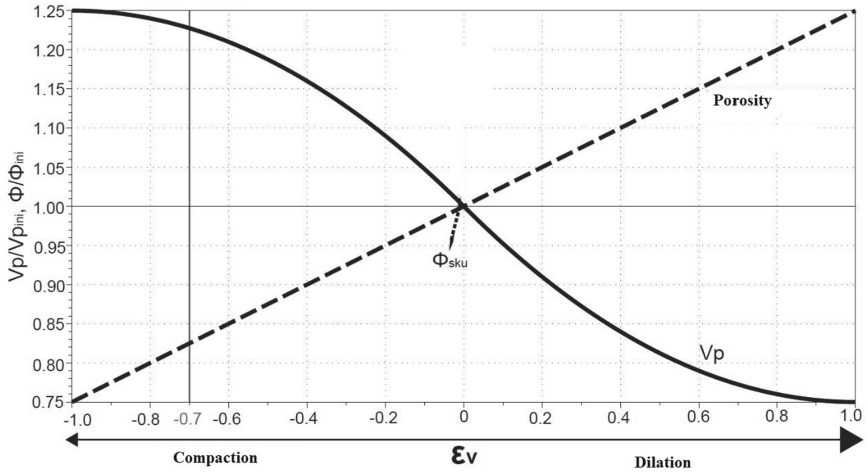


Fig. 2. The laboratory derived empirical dependence of volumetric deformations and P-wave propagation velocity.

To simulate the faults' internal structure, we used the data of geophysical studies in a horizontal well, opening the fault in the studied field (see Fig. 3). Of course, we know that the data from one well is not enough to describe the tectonic breccia in detail. However, the P and S wave velocities and densities set in the well allowed us to calibrate the parameters used in the geomechanical modelling, which provided a close to a realistic description of the tectonic breccia filling the geological faults (Fig. 4).

In addition to faults, the studied carbonate reservoir contains fracture corridors and caverns in various proportions: the main reservoir (caves) and transport routes (cracks) of the fluid. We introduced fracture zones in the form of two multidirectional systems of subvertical fractures obtained by statistical modelling using the spectral decomposition of random fields. This allowed the generation of fractures from 5 to 300 m long, forming realistic fracture corridors. Additionally, the model has been added to the intervals of intense cavities, which are regularly encountered in the field. According to core studies, these intervals have increased voidness reaching 15–20 % and small thicknesses from one to ten meters. To determine these cavities' parameters, we performed a statistical analysis of ten digital core models constructed by X-ray computed tomography [Bazaikin et al. 2017].

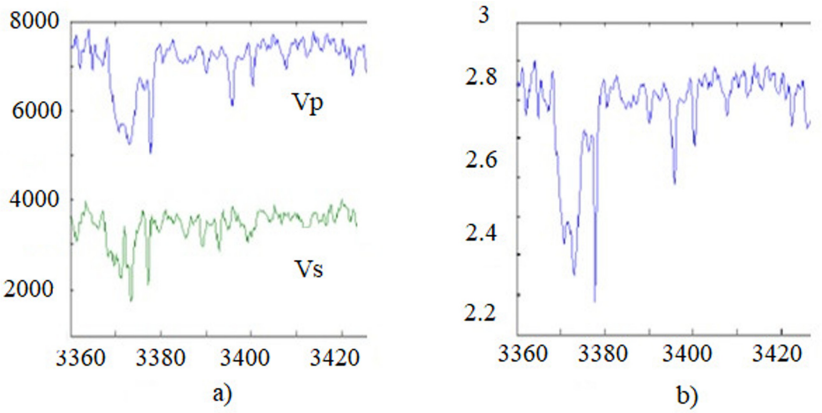


Fig. 3. Seismic velocity (a) and density (b) behaviour along a horizontal well bore. Horizontal axis - distance along well bore. The fault zone corresponds to distances of 3370 m–3380 m. Vertical axis: a) m/s b) 1000 kg/m^3.

It should be stressed that we do not seek to describe each crack when constructing a geological model, several millimetres thick. Instead, we construct fracture corridors [Questiaux et al. 2010], representing a cluster of fractures with one or more selected orientations. Fracture corridors can extend for several hundred meters, have a height of the first tens of meters and a thickness of the first meters. When constructing them in the geological model, direct observations on outcrops and data from borehole measurements are used. In this work,

we relied on the results obtained earlier (see [Kolyukhin et al. 2017]), describing the structure of such objects based on a statistical analysis of the results of field observations, including outcrops and UIB formation micro scanner observation data.

Figure 5 shows a general view of the constructed 3D model's skeleton with faults and other small-scale irregularities. The framework is defined as a set of reflective boundaries, geological faults, fracture corridors and zones of increased cavernosity. To determine the medium filling this frame's elastic properties, we used the results of velocity analysis, well data, and laboratory measurements of the core material.

3 Seismic Synthetic Data

3.1 Finite-Difference Scheme with Locally Refined Grids

The next step completes development of a digital twin of the object under study by finite-difference modelling of three-dimensional seismic data. Let us emphasize that it is on this basis that it opens the possibility of a detailed analysis of the

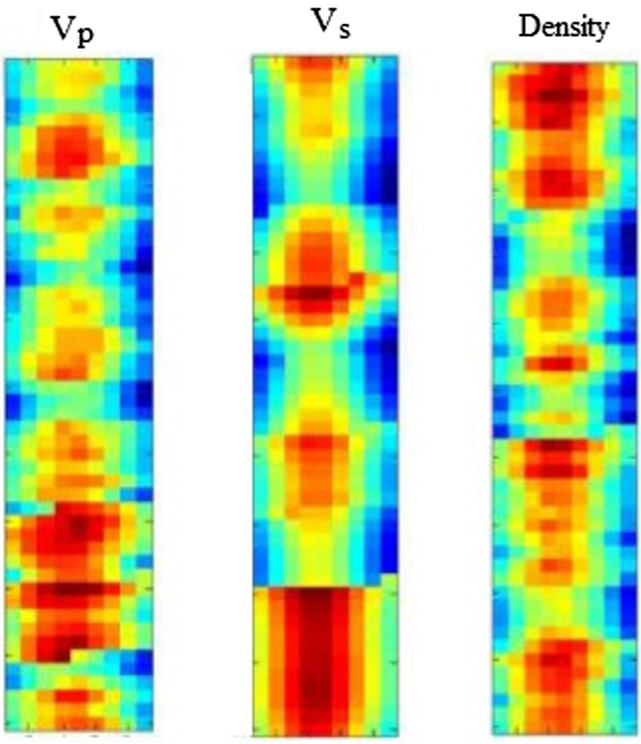


Fig. 4. Variations in elastic parameters of tectonic breccia filling the faults.

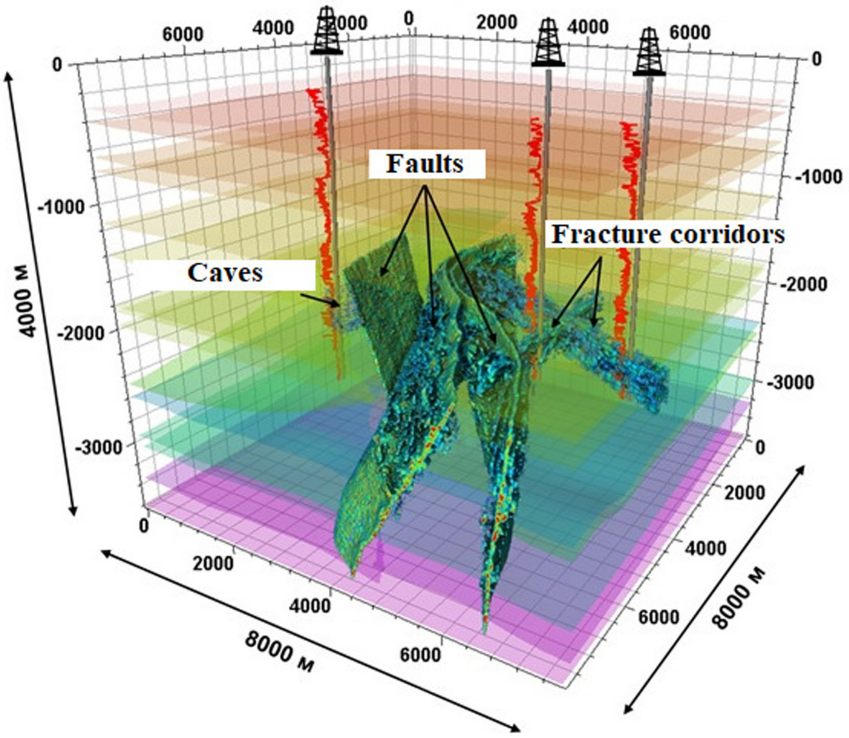


Fig. 5. 3D view of synthetic test model.

specific features of scattered waves generation within the reservoir. On this way, it becomes possible to carry out fully controlled numerical experiments to verify the developed methods for reconstructing the structure of hydrocarbon reservoirs on a sub-seismic scale to localize the accumulations of cracks and caves. It is the distribution of such micro-heterogeneity that provides a strategy for the optimal development of reservoirs in a carbonate environment.

However, the currently existing numerical modelling methods of seismic waves for solving such problems cannot consistently be implemented even with the use of the most powerful high-performance computing systems today. The fact is that, as a rule, for this purpose, people use explicit finite-difference schemes, based on uniform grids with a spatial cell size equal to 0.1–0.2 of the dominant wavelength, which, as a rule, is 5–10 m, while the typical size of the inhomogeneities is 0.01–0.1 m. To model seismic wavefields' interaction with such inhomogeneities, it is necessary to use a spatial step comparable to their size. However, using a grid step of 0.05 m across the entire target area will require huge computational resources - terabytes of RAM and teraflops of performance. To avoid the need for such unrealistic computer resources, we developed finite-difference schemes with local space-time refinement of the grid in the areas filled

with clusters of subseismic heterogeneities (Kostin et al. 2015; Landa et al. 2018). In this case, grids with varying spatial steps correctly represent various components of the model: relatively large steps - to describe a three-dimensional heterogeneous reference medium and much smaller ones - inside the reservoir and fault zones (see 6). The computations are doing to ensure the uniform load of processor elements involved. This approach significantly reduces the requirements for the amount of RAM and the number of computing processes.

3.2 Communication Between Groups of Processor Units

The computational area for full multiscale elastic simulation is parallelepiped 8 km×10 km×6 km. To carry out numerical simulation, we divided the elastic model into two classes:

- the reference medium containing reflective borders and smoothly changing elastic parameters between them;
- with small-scale heterogeneities, such as faults with tectonic breccias, as well as accumulations of caves and fractures.

In the reference medium, we use a grid step of five meters. Inside the target reservoir, we choose a grid of 0.25 m, which made it possible to describe the medium's elastic properties' with acceptable accuracy.

Thus, the entire studied medium is represented as a superposition of the enclosing medium (coarse grid), and the reservoir contained in it (fine mesh) and all processing elements are divided into two groups, performing computations on coarse and fine grids, respectively. Consider the organization exchanges between these groups.

From Coarse Mesh to Fine Mesh. First of all, the first group's processor elements are determined (coarse mesh), covering the reservoir (see Fig. 7, left), and are grouped along each of the faces contacting the parallelepiped on the fine mesh. A particular master processor is defined for each face (abbreviation MP in Fig. 7), which collects the solution's current values and sends them to the corresponding MP on a fine grid. All subsequent processing of this data, which ensures the matching of the grids by interpolation based on the FFT (Fast Fourier Transform), is performed by the MP for the fine grid, sending data to the corresponding processors from the second group (fine grid). Interpolation in place significantly reduces the amount of the data transferred and, hence the time of unproductive waiting.

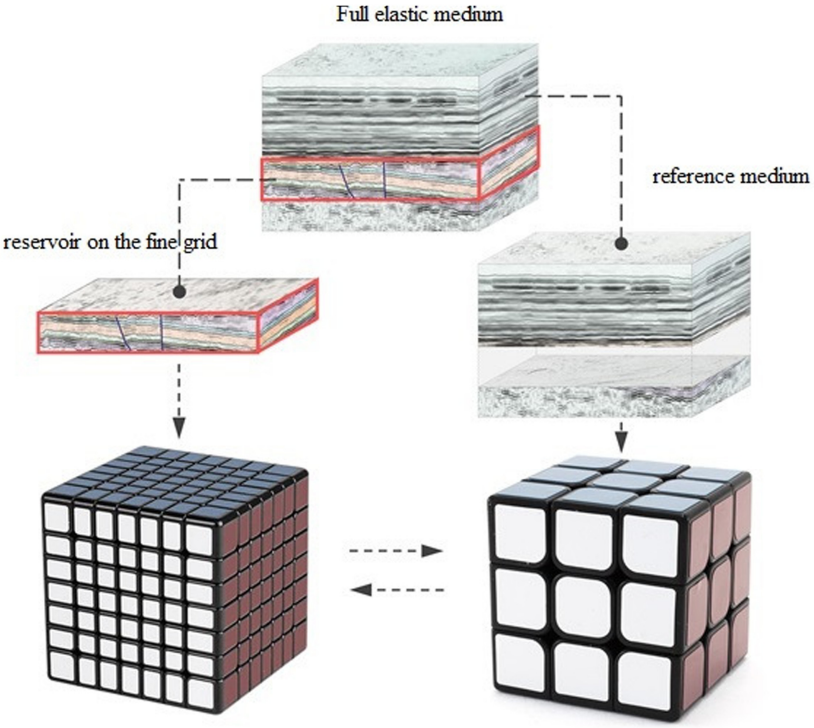


Fig. 6. Decomposition of the full elastic model in two components and loading them onto different groups of Processor Units.

From the Fine Mesh to the Coarse Mesh. As in the previous case we define processor elements performing computations on the faces of the fine-mesh parallelepiped that encloses the reservoir, and for each face is determined by a master processor (MP). It collects data from each of the faces for transmission to the corresponding master processor operating on a coarse grid. In this case, not all the data obtained is needed to calculate the solution values for the next moment in time with a small step, but only those that correspond to the coarse grid nodes. Formally, these data can be thinned out, but, as our experience has shown, noticeable artefacts arise, associated with the loss of smoothness of the solution. Therefore, FFT-based interpolation is also used here to restore values with a high accuracy. Performing such a thinning procedure in place by a master processor operating on a fine mesh significantly reduces the amount of data transferred and therefore reduces the unproductive waiting time.

3.3 Acquisition

The 3D acquisition is on the surface z = 0 within an 8 km × 10 km rectangle filled by three-component receivers evenly spaced over a 25 × 25-meter grid. The volumetric sources are set with 50 m along lines parallel to the X-axis at a distance of 300 m. This geometry provided the fold factor equal to 100 at most points of the observation area. We use Ricker wavelet with a dominant frequency 40 Hz as a source function.

In the Fig. 8, we present the vertical component of the displacement for a volumetric point source located in the centre of the acquisition, along with two mutually orthogonal profiles. As one can see, there are, along with reflected many scattered waves also.

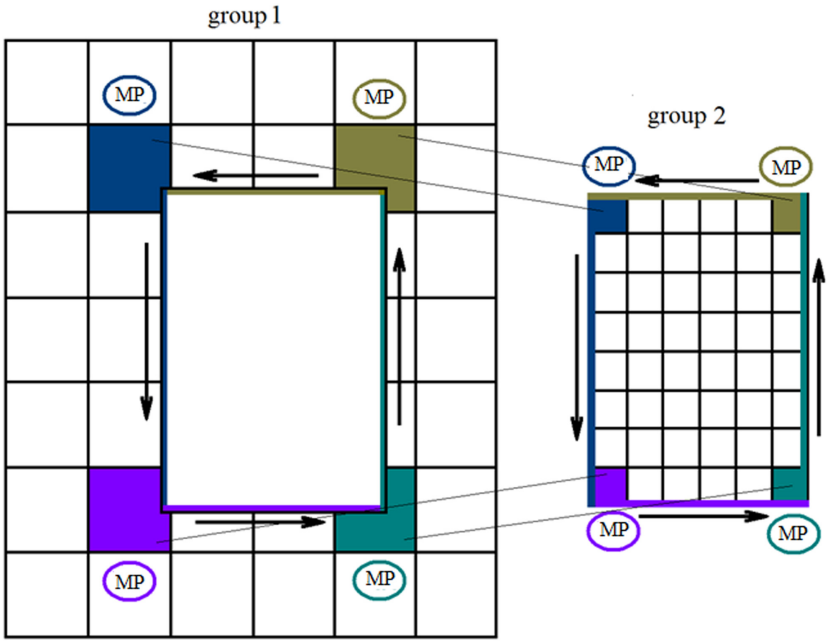


Fig. 7. Data exchange between groups of processing elements on coarse (left) and fine (right) meshes.

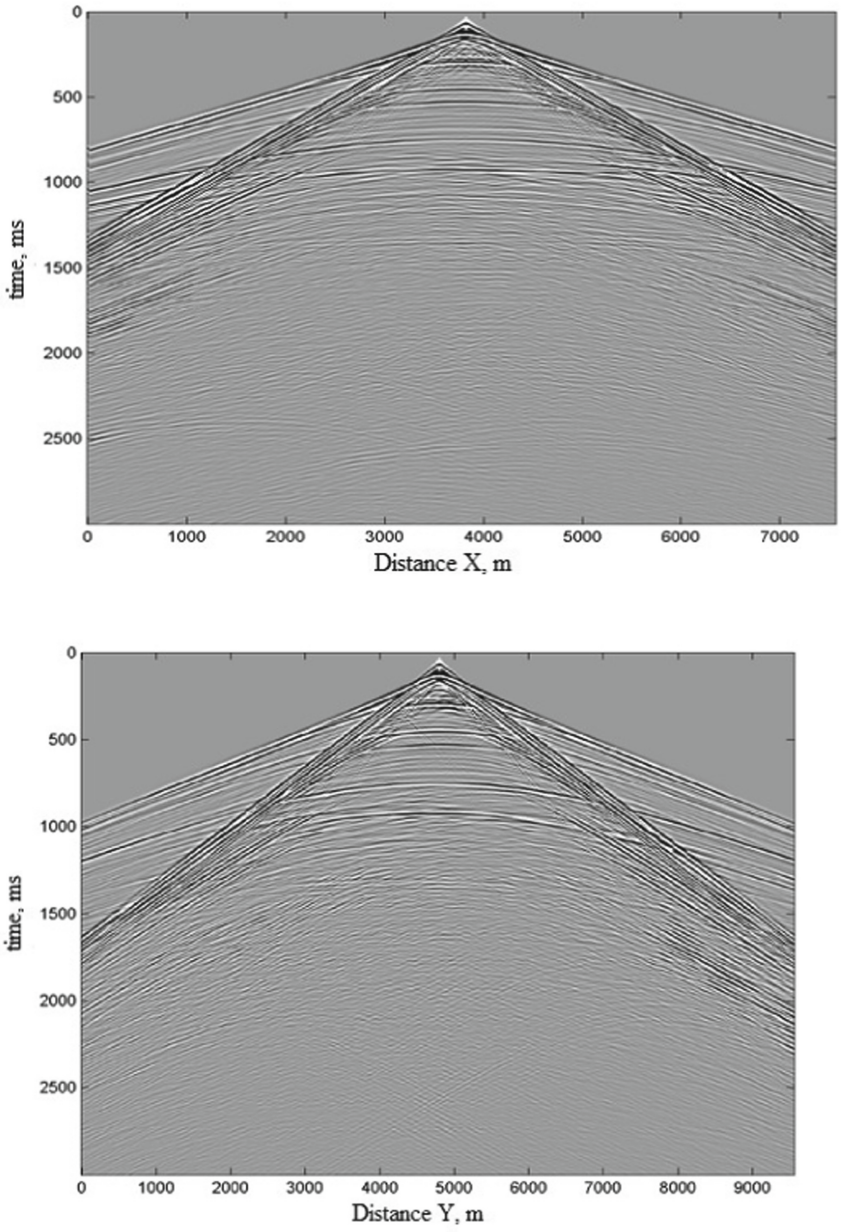


Fig. 8. Data exchange between groups of processing elements on coarse (left) and fine (right) meshes.

4 Conclusion

In this work, we focus on the development of the data sets for verifying various techniques for constructing images of multiscale geological objects. That is why we have created a digital twin of some real geology in the north of the East Siberia. Also, to enhance testing capabilities, we have added several specific features to this twin, such as fractured corridors and areas of high cavernosity. For the constructed digital object, numerical modelling was performed to synthesize seismic data were obtained. Thus, we got the opportunity to conduct a fully controlled numerical experiment. Having made sure that the developed procedures correctly restore the digital model structure, we carried out processing of real data, which also gave results that fully correspond to those previously obtained using other approaches and carry additional, essential geological information.

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