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Seismic imaging of cavernous\fractured reservoirs in scattered waves

Abstract

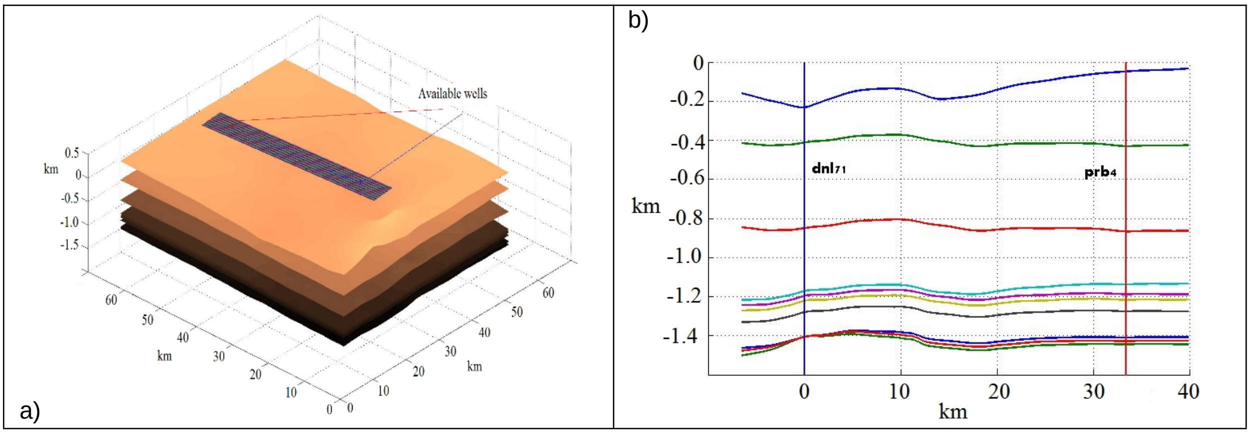
We have developed justified, verified and implemented for supercomputers with parallel architecture the reliable instrument for the studying complicated processes of waves' propagation in realistic 3D heterogeneous multiscale models of geological media – the special finite-difference method with local mesh refinement in time and space. On this base, it becomes possible to deal with realistic models and acquisitions and take into account both small-scale heterogeneities of a reservoir and mesoscale variations in overburden. This software was applied for simulation of seismic waves' propagation through realistic synthetic models developed for some East Siberian oil field. We have found that orientation of fracture corridors and fluid saturation of reservoir microstructure has very specific impact in synthetic images of scattered waves, which can be used to develop predictive criteria in real life data processing and interpretation. These criteria are verified by comparison of predictions with well log data (fracture orientation) and permeability (fluid saturation) of a collector by test results.

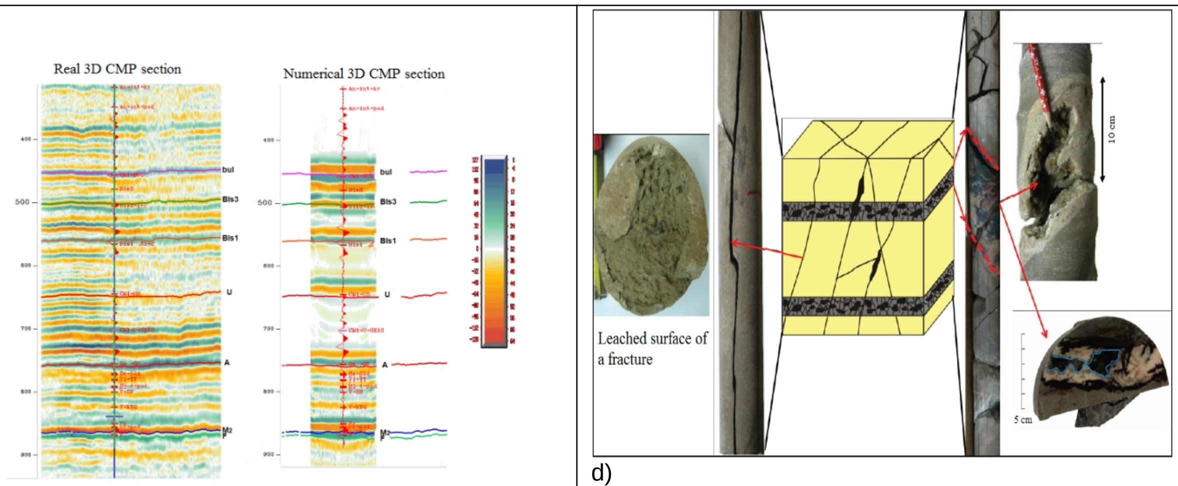
Introduction

One of the main goal of the modern seismic processing is recovering of the microstructure of hydrocarbon reservoirs. Recently various techniques have been introduced to solve this problem on the base of scattered seismic waves. Among them, the scattering index presented in (Willis et al., 2006) or a variety of the imaging techniques developed under the generic name of seismic interferometry (see e.g. book of G.Schuster, 2009).

It is obvious that all these attempts are doomed to fail without of clear understanding the main peculiaritites of the generation and propagation of scattered waves. The first step in this direction should be the development of reliable tools for accurate numerical simulation of these waves. But the limited computer resources even on the largest modern supercomputers place insuperable limitations on the straightforward implementation of full wavefield simulation for cavernous-fractured reservoirs. Really, reservoir beds typically are positioned at a depth of 2000 – 4000 meters, which is about 50 – 70 dominant wavelengths. The current practice for the finite-difference simulation of seismic waves propagation at such distances is to use grid cells of 0.05 - 0.1 of a dominant wavelength, usually between 5 - 10 meters. So, one needs to upscale heterogeneities associated with fracturing on a smaller scale (0.01 – 0.1 meter) and to transform them to an equivalent/effective medium. This effective medium will help reproduce variations in the travel-times and an average change of reflection coefficients but absolutely cancels the scattered waves that are a subject of the above mentioned methods for characterizing fracture/cavities distribution. Therefore for proper description of scattered waves one should take into account both scales of a medium – macro scale for overburden (first meters) and micro scale of fractures and caverns (at most first centimenters). As has just been mentioned one can not use everywhere the coarse spatial grid, but the fine one also is impractical. The simplest calculations prove that one need petabytes of RAM to do that.

To overcome this trouble we developed and implemented an approach of scattered waves numerical simulation for realistic 3D heterogeneous multiscale elastic media on the base of local grid refinement in time and space (see Reshetova et al., 2011; Kostin et al., 2012, 2015). The corresponding software for supercomputers with parallel architecture opened the way of detailed analysis of scattered and diffracted waves for realistic seismogeological digital models. The observed features was formed the basis of the methodology to recover the fine structure of the reservoir presented below.





c)

d)

Figure 1: a) General view of interfaces and two available wells. b) Vertical cross-sections of the model along profile connecting these two wells c) Comparison of real (left) and synthetic (right) 3D CMP sections. Note satisfactory coincidence of both kinematic and dynamic features of the wave field. d) Fine structure of a cavernous/fractured reservoir (general view and core sample analysis).

The development of the realisitc 3D heterogeneous multiscale digital model

The approach proposed is based on synthetic data simulation and processing. Hence, we need to start with the development of a realistic digital geological model which describes the specific reservoir and overburden. To do this we use 3D seismic observations and build on this basis macroscale model of overburden and reservoir itself, like it can be deen in Figure 1a and 1b. Next, to validate the model we compare synthetic and real 3D Common Mid Point (CMP) gathers (see Figure 1c). When there is reasonable coincidence we accept the model and use it to analyze specific features of the seismic waves' propagation through cavernous-fractured reservoir. Now we need to build the fine model of the reservoir. To do this the all available wellbore data are used – all kinds of logging and core sample analysis (Figure 1d). The main goal of this step – to recover some typical parameters of the reservoir fine structure and estimate on this base intensity of the scattered waves. Next this microstructure is used in multiscale numerical simulation in order to recognize which specific features are helpful in understanding microstructure.

Imaging of the scattering energy

Fracture orientation

In order to understand manifestation of fracture orientation in seismic scattered waves the model of some typical fractured reservoir was developed (Figure 2). Numerical simulation proved that dominant direction of scattered energy propagation coincides with fracture orientation (for details see (Reshetova et al., 2011; kostin et al., 2012)).

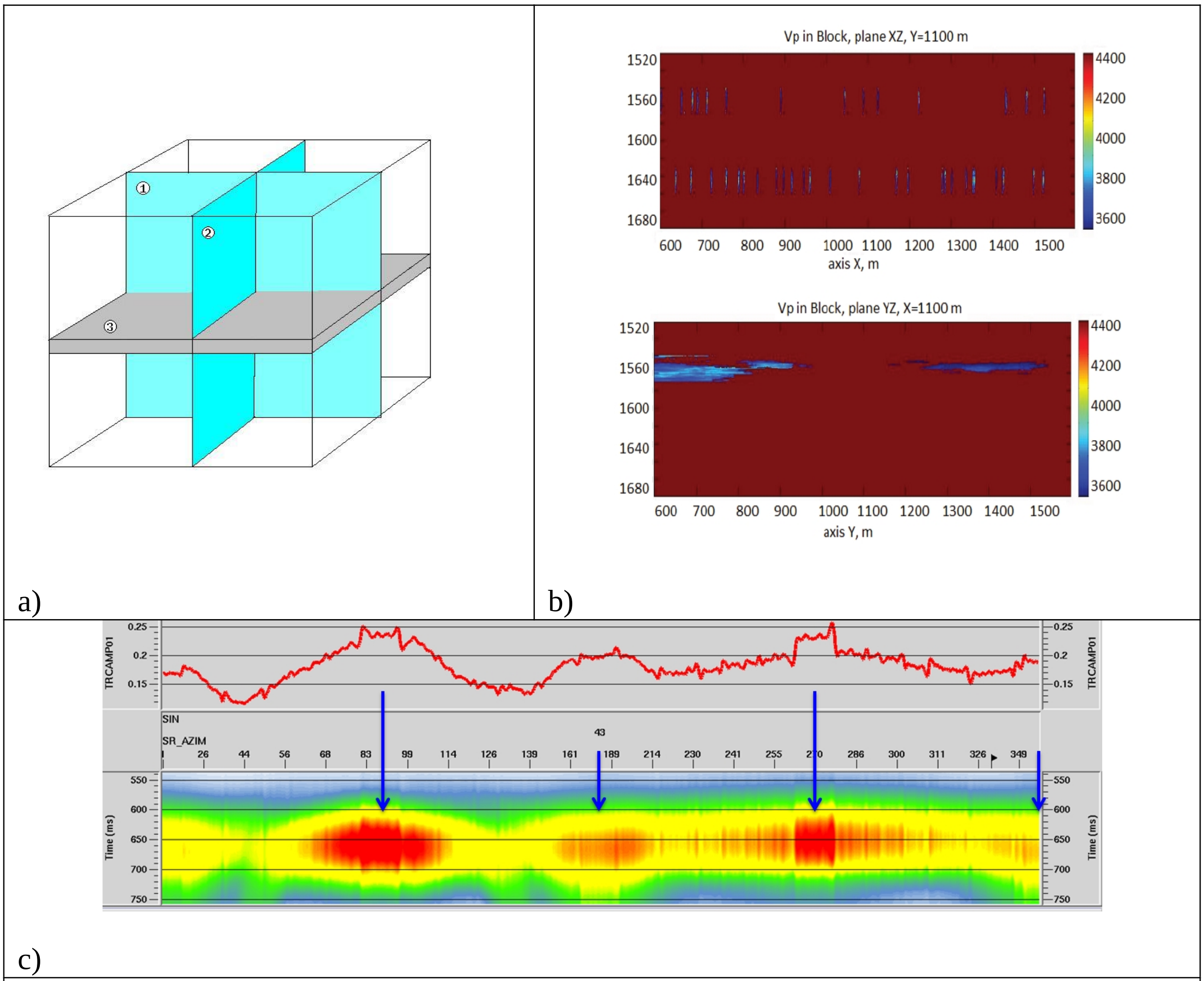
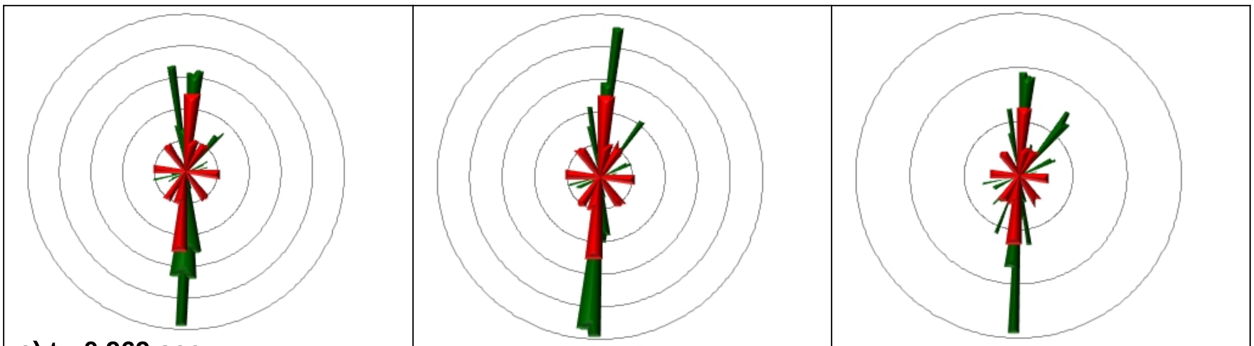


Figure 2. Fractured reservoir. a) General view b) Side views, planes 1 (top) and 2 (bottom) of fractures distribution within reservoir 3.c) Distribution of scattered energy in plane 3 in dependence with azimuth (counterclockwise from east direction).

This feature was validated on the real field data. To do this some proper 3D seismic acquisition around a deep well which penetrated to a fractured reservoir. Special procedures to seismic data processing oriented to imaging of scattered energy were applied. Results obtained are presented in Figure 3 as the series of green rose diagrams for different vertical times. For the same depths in Figure 3 one can see results obtained by Ultrasonic Borehole Imager as red rose diagrams. As one can see there is almost ideal coincidence of the results obtained on the base of these two different approaches which is confirmed by their high correlations (correlation coefficients about 0.9). The reliability of the recovered fracture orientation is provided their stability along the depth of the reservoir as well.



a) t_v=0.969 sec
b) t_v=0.973 sec
c) t_v=0.978

Figure 3. Comparison of fracture orientation recovered by scattered energy (green) and Ultrasonic Borehole Imager (red) for a productive fractured reservoir for different vertical times. Correlation coefficients are: a) R=0.94 b) R=0.93 c) R=0.88

Scattered waves and fluid saturation of a microstructure of cavernous-fractured reservoir.
To analyze the behavior of the scattered energy in dependence of the fluid saturation of the

microstructure the model presented in Figure 4 is used. This model is developed on the base of the previous model (see Figure 1), but within the target layer some microstructure is introduced. The parameters of this microstructure are determined by well log and laboratory analysis of core samples. Next, the model is split in three pieces: the most left has fluid saturated microstructure, the most right – mineralized microstructure and the central has no microstructure at all.

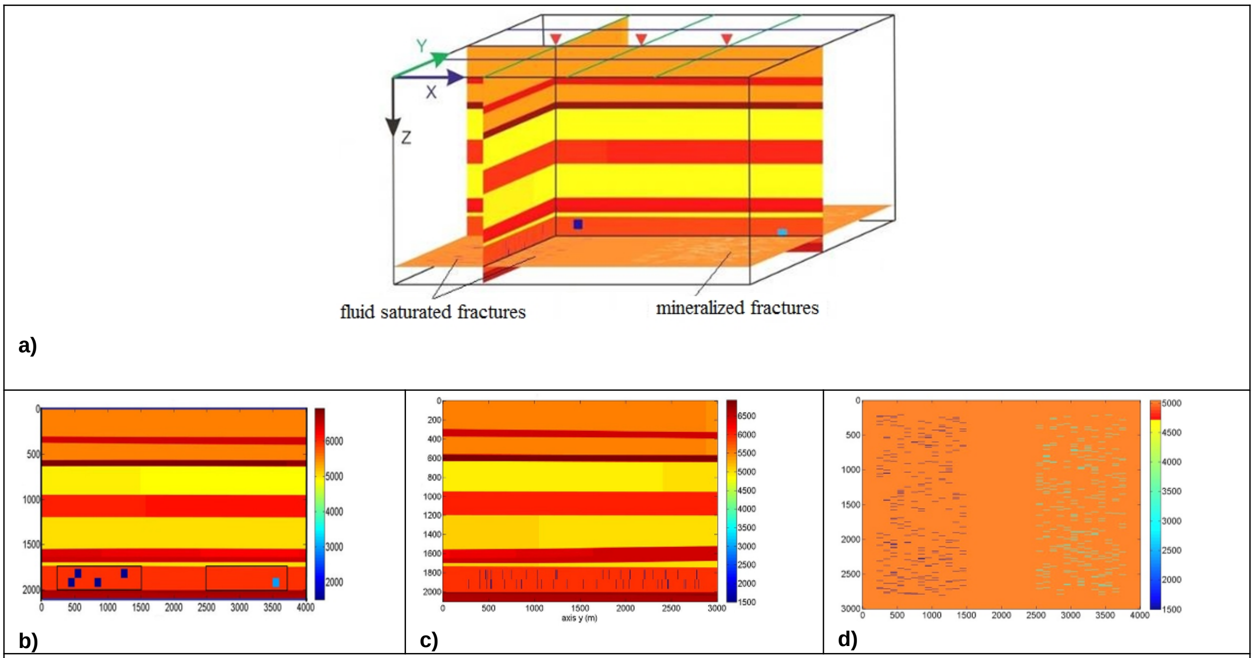


Figure 4. Synthetic model used to analyze manifestation of a saturated microstructure in scattered waves. a) General view b), c) and d) – different 2D views.

Distribution of the scattered energy one can see in Figure 5. Please, pay attention to the specific shape of the energy distribution in the area filled with fluid saturated microstructure. It is droplike with the top attached to the target fluid saturated layer. We believe this shape is prescribed by multiple scattereing within fluid saturated layer. In turn, the multiple scattering is due to the higher contrast of fluid saturated microstructure. Really, in the area with dry fractures there is almost single scattering. Very similar behavior of the scattered energy is observed on results of real data processing as one can see in Figure 5b.

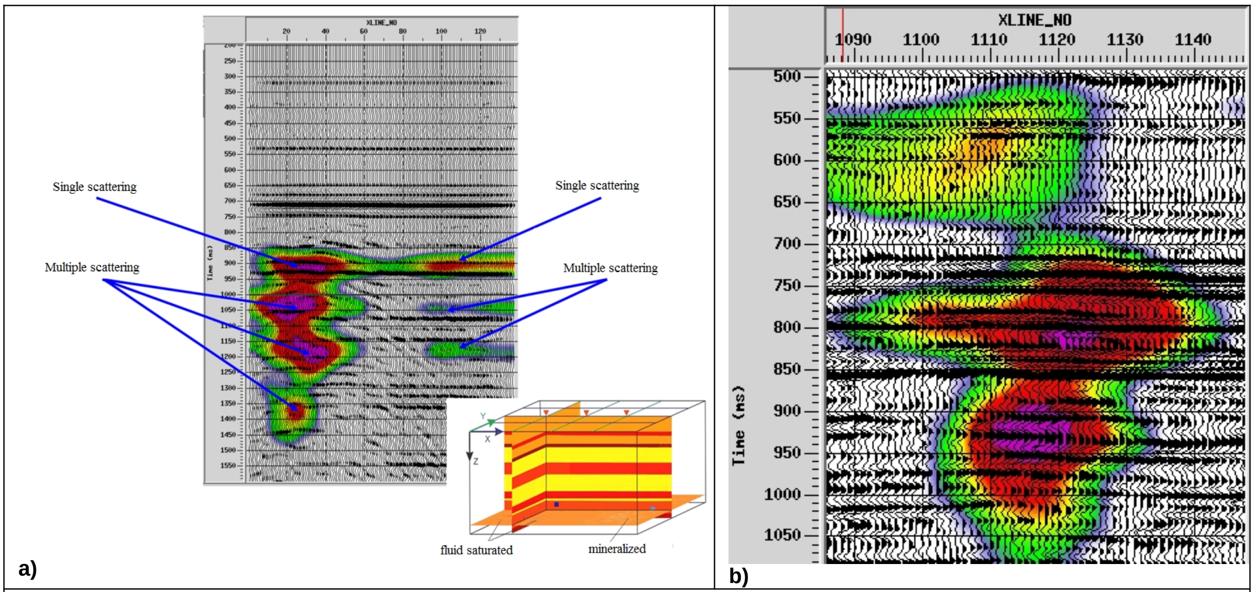


Figure 5. Distribution of the scattered energy in dependence of fluid saturation for synthetic a) and real b) data.

The results obtained lead to the formulation of the following suggestion:

While scattering energy indicates the presence of microstructure, its elongated shape can be a sign of fluid saturation.

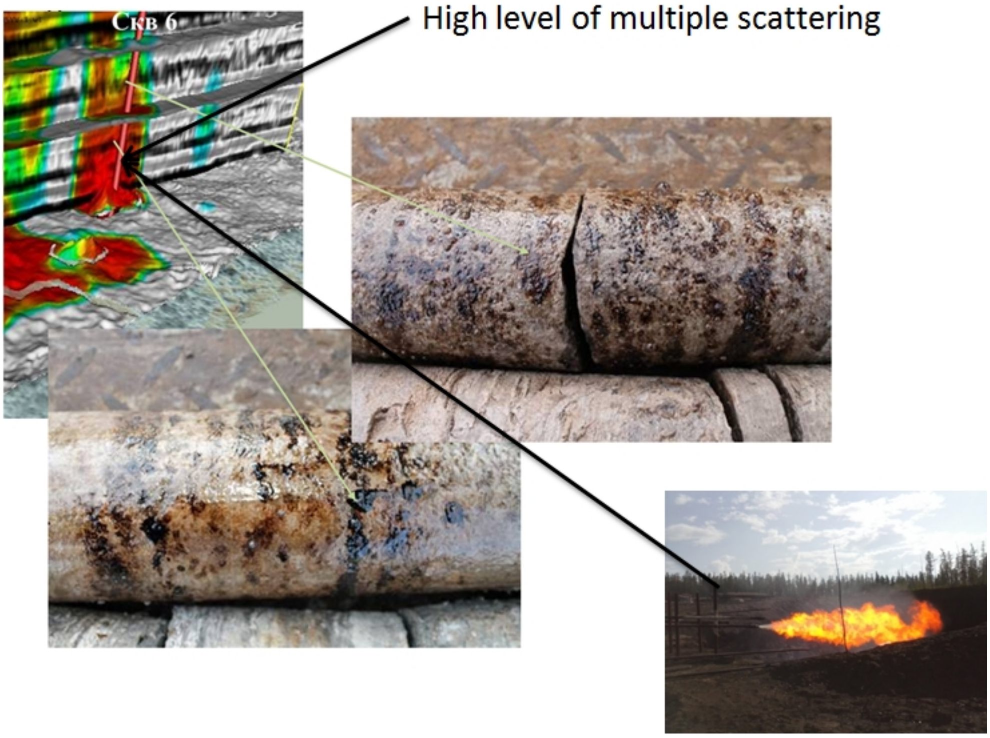


Figure 6. Deep well with the influx of gas. Top left – high level of multipke scattering (red). Middle – core samples with traces of bituminous. Bottom right – gas influx from the pointed horizons.

At the moment have validation of this suggestion for one real case presented in Figure 6. Again, here is a deep well surrounded by 3D seismic acquisition so there is possible to reconstruct distribution of the scattering energy now with depth. As one can see, core samples corresponding to the depth intervals with high level of multiple scattering have clear bituminous traces and there is a valuable gas influx from these intervals.

Conclusion

Seismic data processing oriented to reveal and carefully analyze scattering and diffracted waves becomes more and more popular in petroleum industry (Landa, 2010; Moser et al., 2013; Pelissier et al., 2012; Pozdnyakov et al., 2012). However, so far the scattering waves are used only as an indicator of the microstructure within reservoir. In the paper, we have presented our recent results proving that from these waves one can extract much more information about internal structure of cavernous-fractured reservoirs. In particular, to reveal the very important knowledge about fracture orientation and fluid saturation.

Our nearest plans are to provide high quality separation of specular reflections and scattering-diffraction in order to improve the reliability of these methods and to increase on this basement the seismic resolution and information content.

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