Russian Supercomputing Days

IPGG

FINITE DIFFERENCE SIMULATION OF WAVES' PROPAGATION IN MULTISCALE MEDIA: impact of cavernous\fractured reservoirs

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Outline

1. Motivation.
2. Presentation of the modeling techniques.
3. Parallel implementation.
4. Synthetic examples.
5. Field examples.
6. Conclusion and road map.

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Motivation

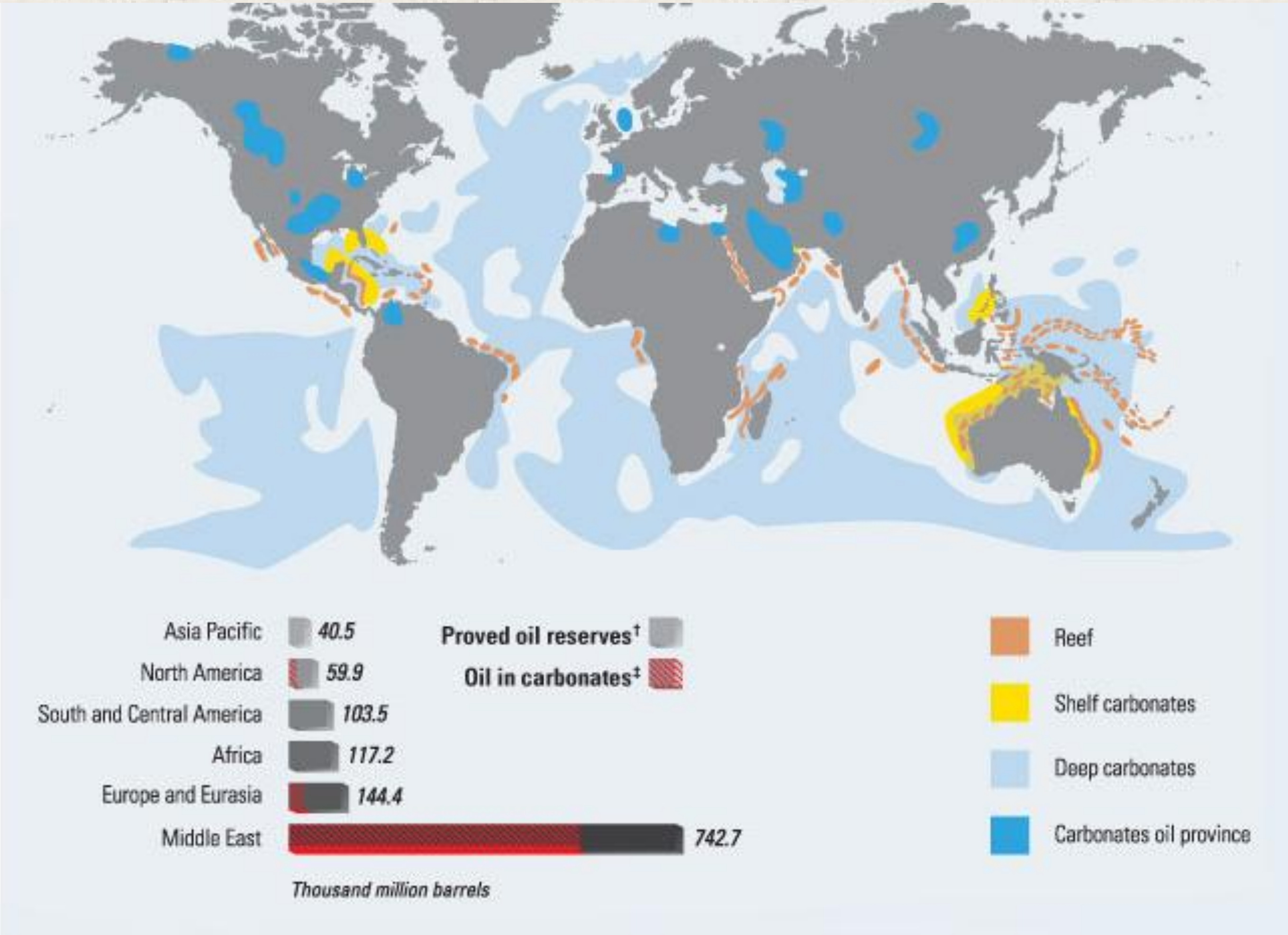
Oil in carbonate reservoirs

"... more than 60% of the world's oil and 40% of the world's gas reserves are held in carbonate reservoirs."

Excerption from Schlumberger site:
http://www.slb.com/services/technical_challenges/carbonates.aspx

Motivation

Oil in carbonate reservoirs



Distribution of oil from carbonate sources around the world.

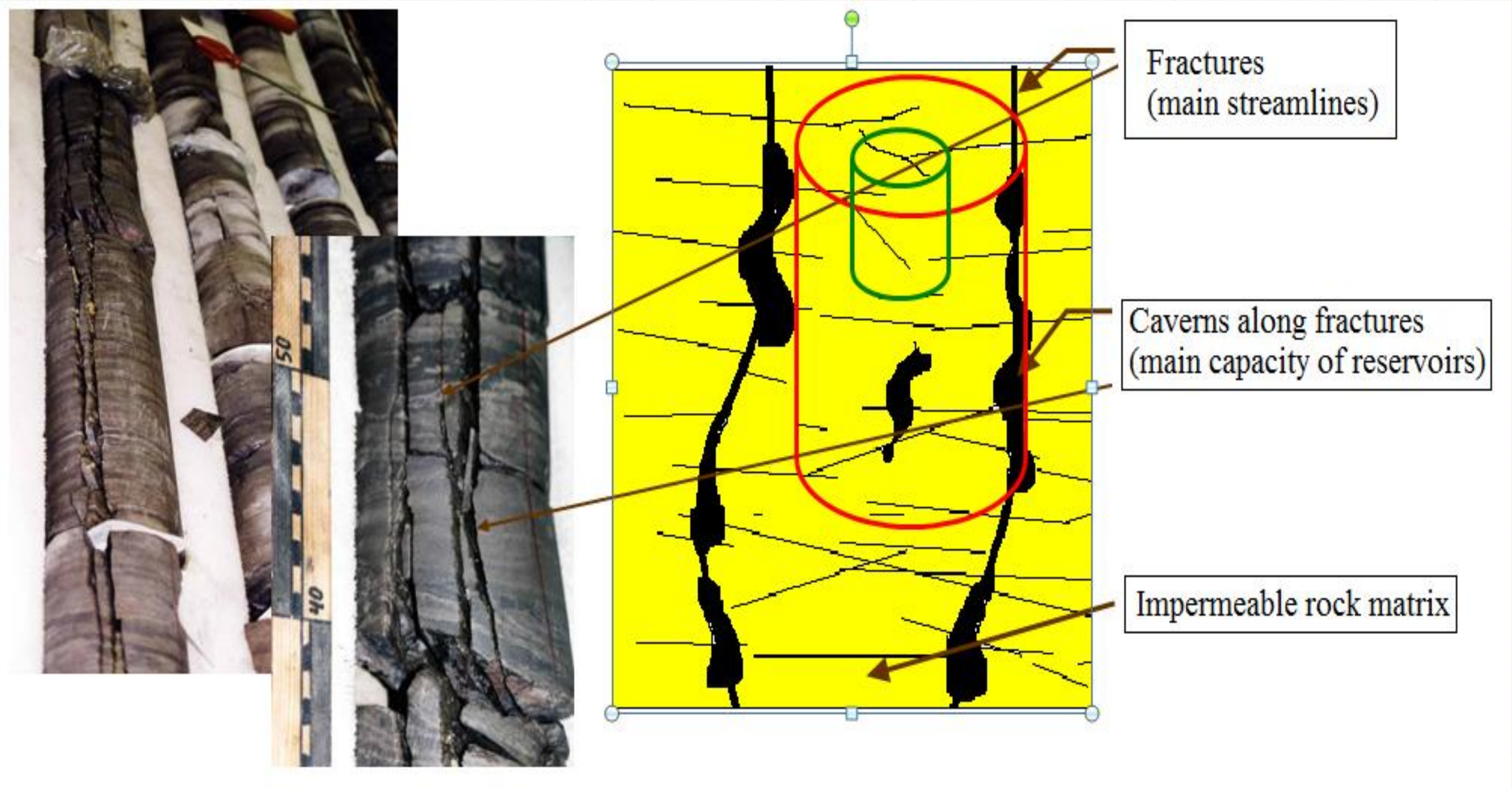
Motivation

Common situation for hydrocarbon reservoirs in the carbonate environment: oil is accumulated in caverns, but permeability is determined mainly by fractures. Rock matrix is not permeable.

Fracture orientation governs underground fluid flow in carbonate reservoirs and is of the primary interest in recovery and development of hydrocarbon reservoirs.

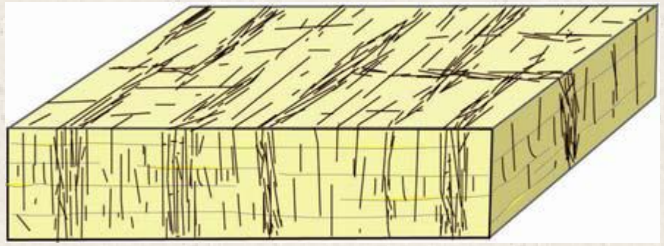
Motivation

Cavernous/fractured reservoirs: core sample



Motivation

Variety of fractures in the carbonate environment (following J.-P.Petit et al.)

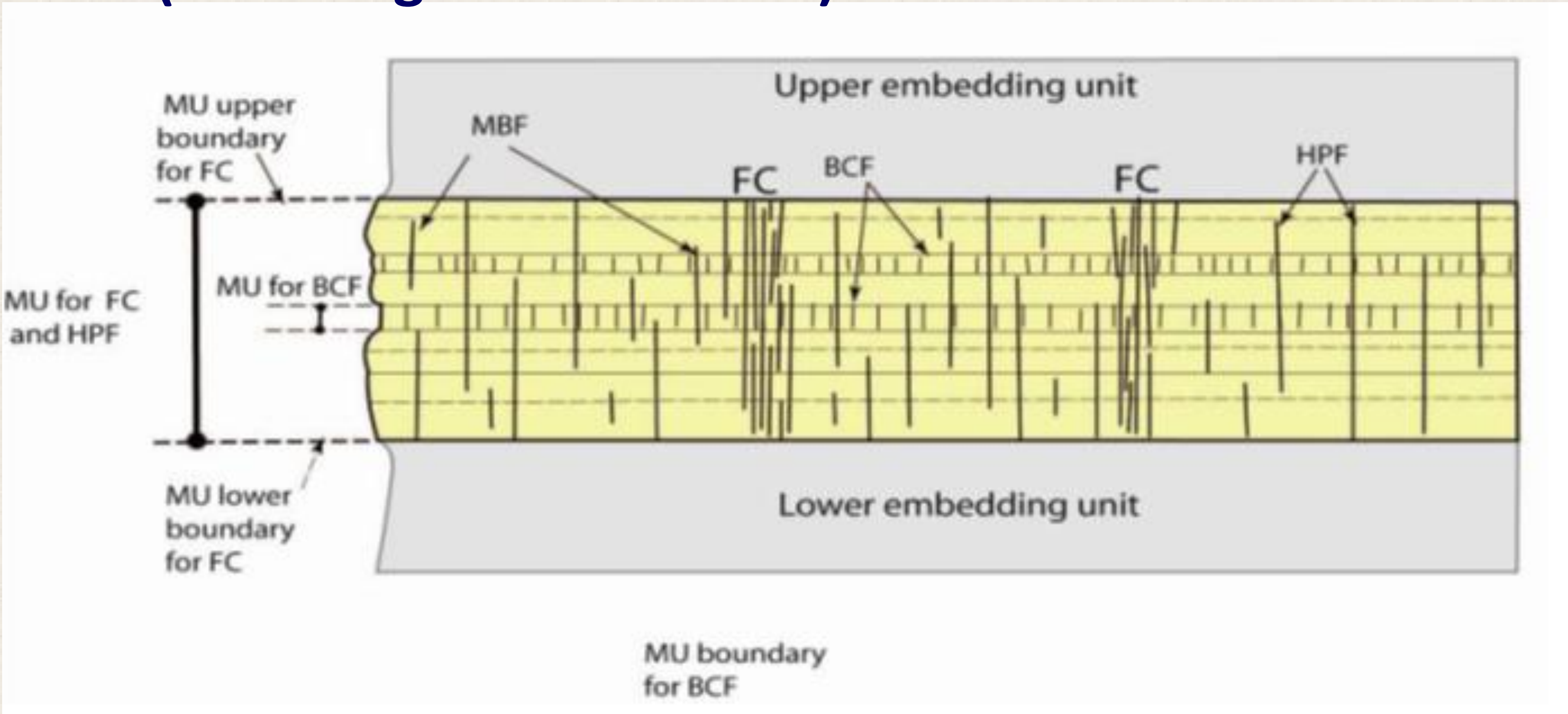


FC – fracture corridors

BFC – bed controlled fracture

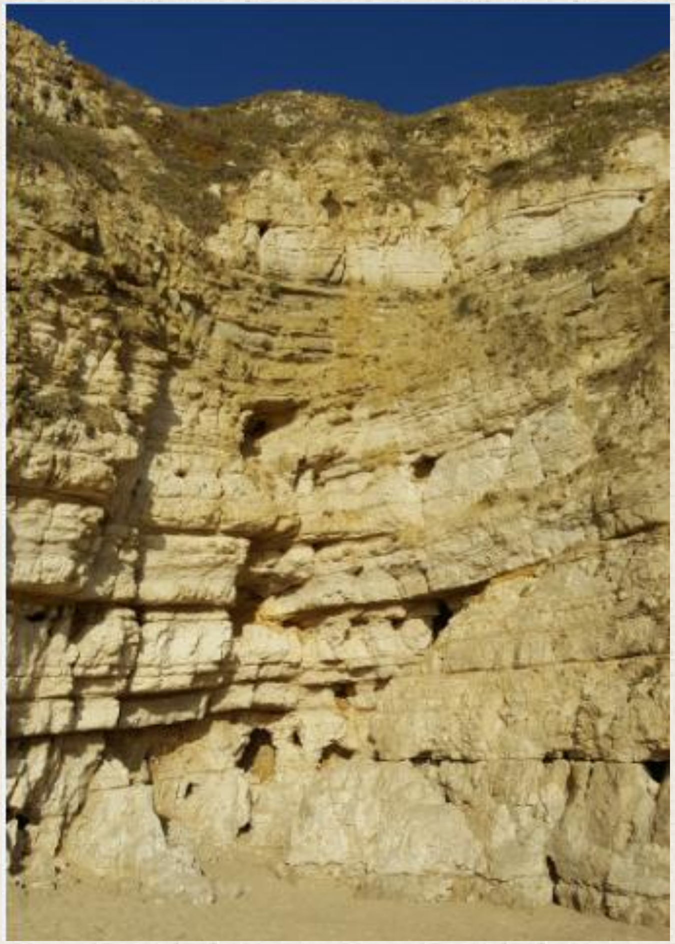
MBF – multibed fractures

HPF – highly persistent fractures



Motivation

Outcrop: fracture corridor (left) and caves (right) in carbonate environment



Motivation

Regular seismic technology based on reflected waves cannot reconstruct the fine structure of a fractured reservoir:
resolution of standard seismic techniques is of a few meters at best, while the typical thickness of fracture corridors does not exceed a few tens of centimeters.
Fortunately, these objects generate scattered waves which can deliver important knowledge about fine interior of hydrocarbon collectors.

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Presentation of the modeling technique

We need to perform reliable simulation of wave propagation in realistic 3D heterogeneous media taking into account microstructure (fractures, cracks, caverns etc.) to get a knowledge about propagation of a scattered energy.

To do this we are going to use the “working horse” for seismic wave simulation:

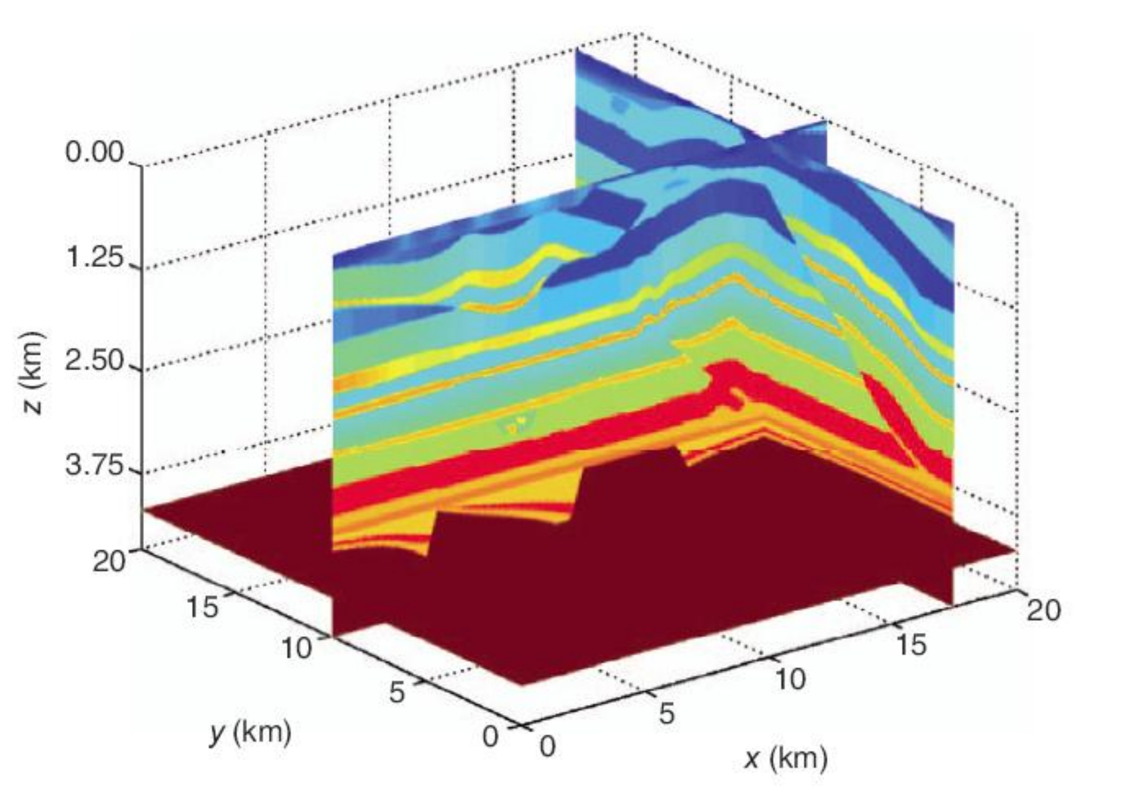
Time domain explicit finite-differences methods

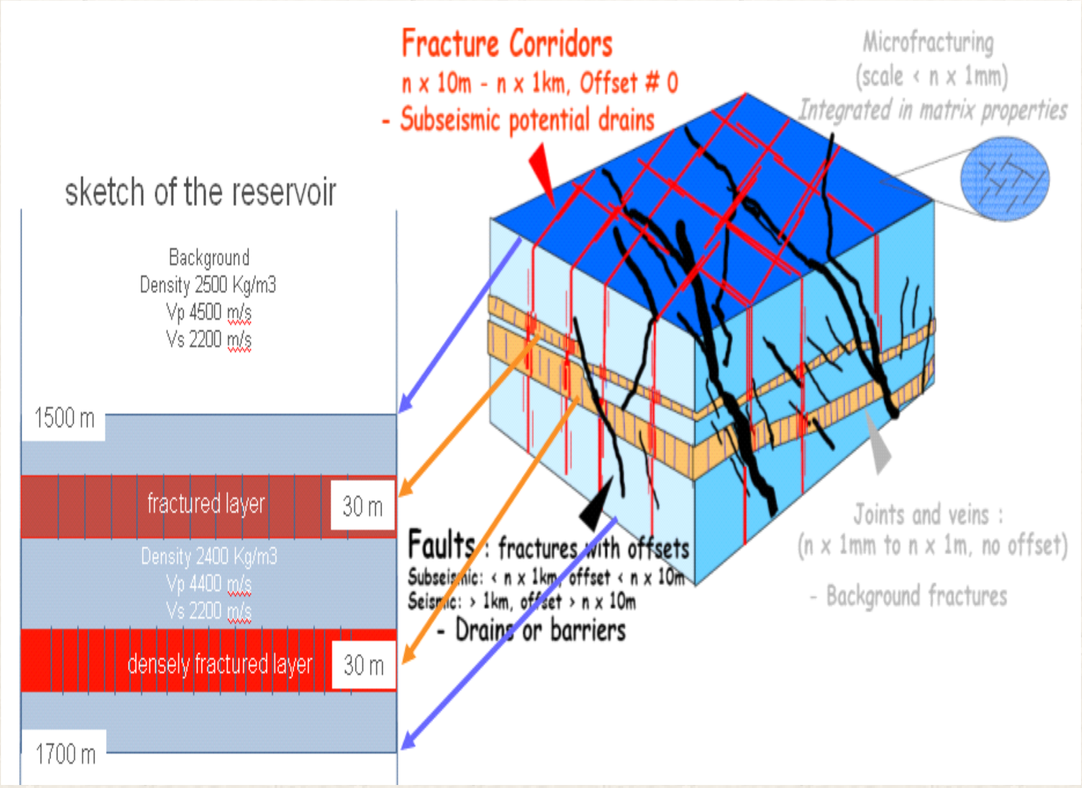
But with

local grid refinement in time and space within target area.

Presentation of the modeling technique

Multiscale 3D heterogeneous model





Presentation of the modeling technique

First order system of viscoelastic wave equations

$$\rho \frac{\partial u}{\partial t} = \nabla \cdot \sigma$$

$$\frac{\partial \varepsilon}{\partial t} = \left(\nabla u + \nabla u^{T} \right)$$

$$\frac{\partial \sigma}{\partial t} = C_1 \varepsilon + \sum_{l=1}^{L} r^{l}$$

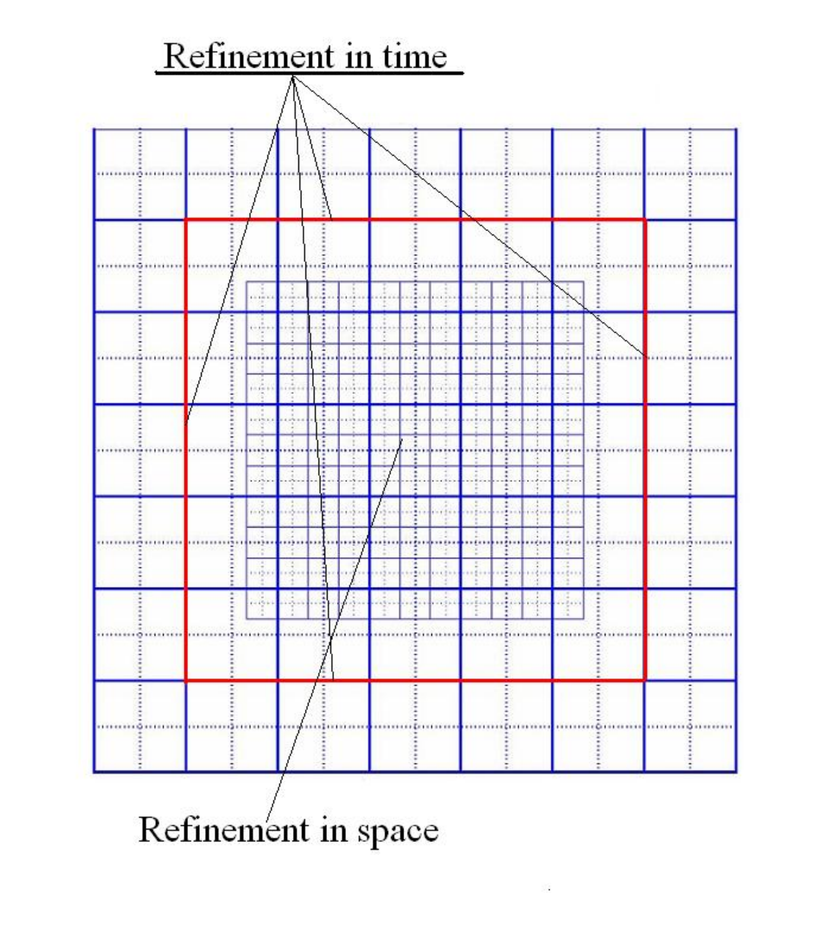
$$\tau_{\sigma,l} \frac{\partial r^{l}}{\partial t} = -C_2 \varepsilon - r^{l}$$

Presentation of the modeling technique: local grid refinement

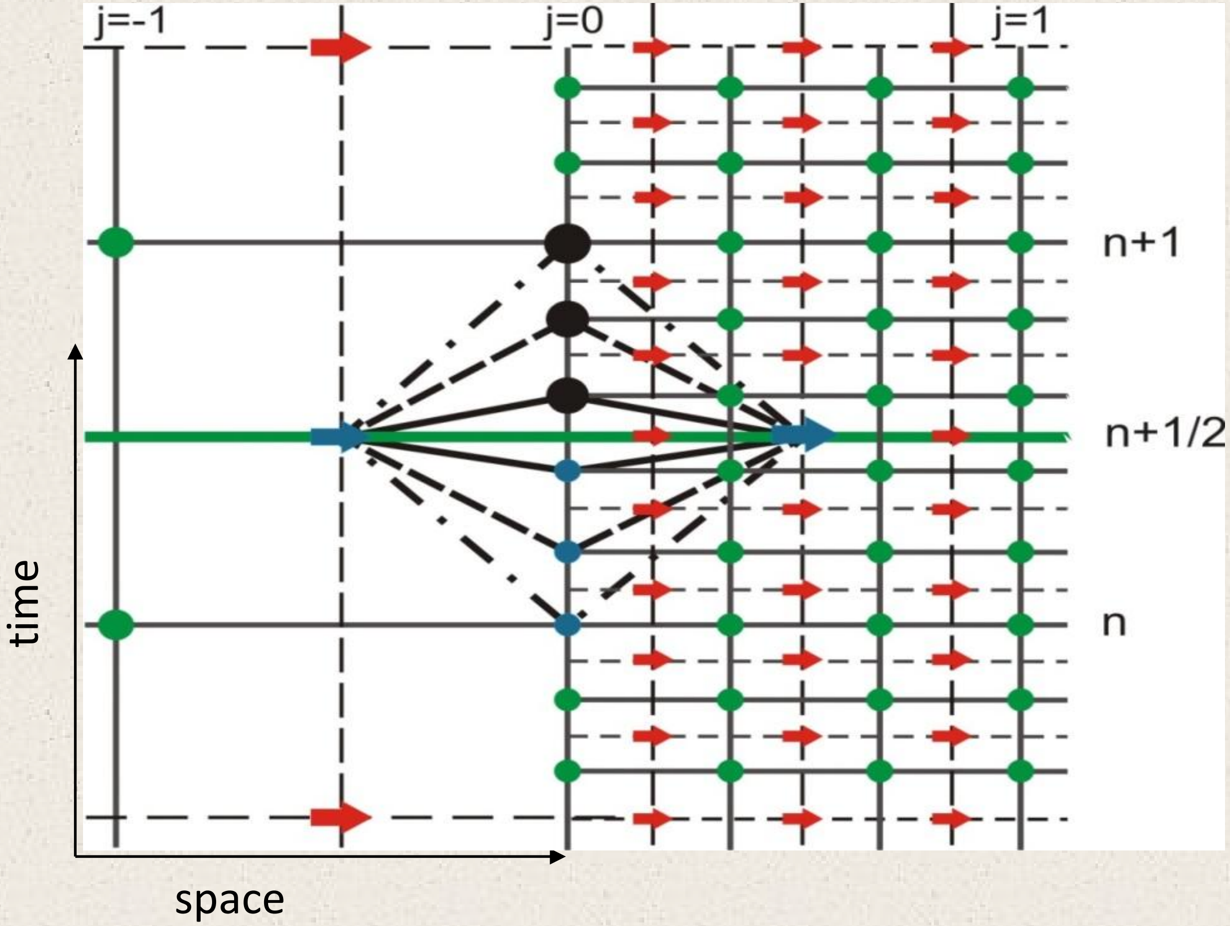
1. Fine grid should be used only where \caverns\cracks\fractures are presented in order to avoid unrealistic demands on computer resources.
2. Different grids cause artificial interface reflections due to different numerical dispersion.
3. These artificial reflections must be around 10^{-3} - 10^{-4} with respect to incident wave.
4. Finite-difference scheme must be stable.

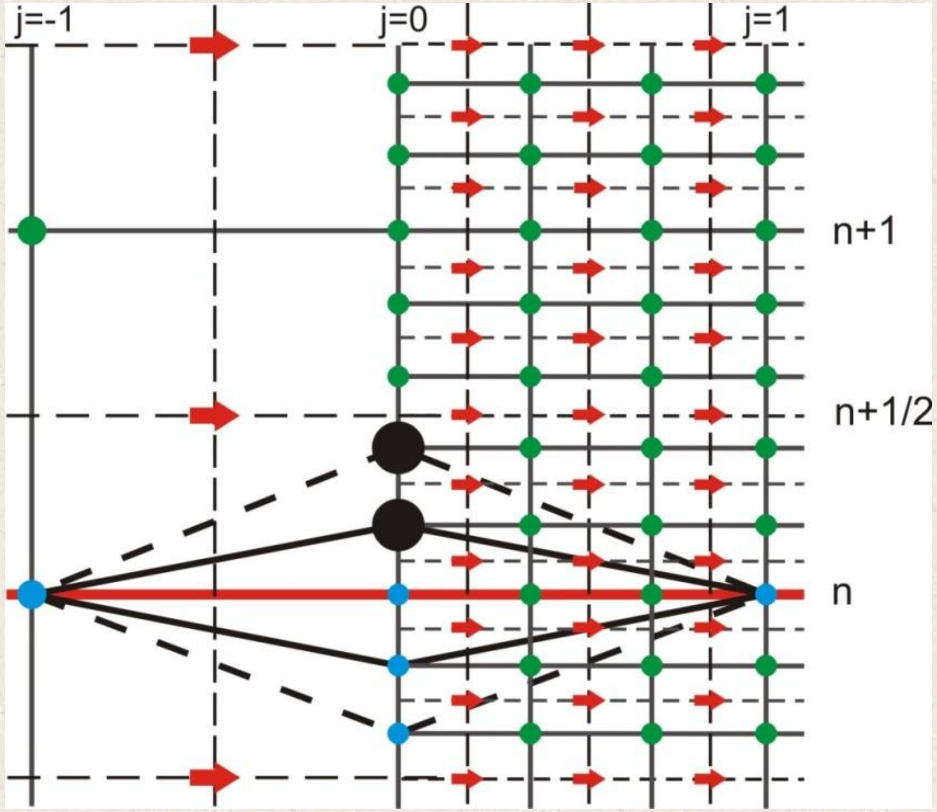
Presentation of the modeling technique: local grid refinement

Grid refinement in time and space is doing on different interfaces:

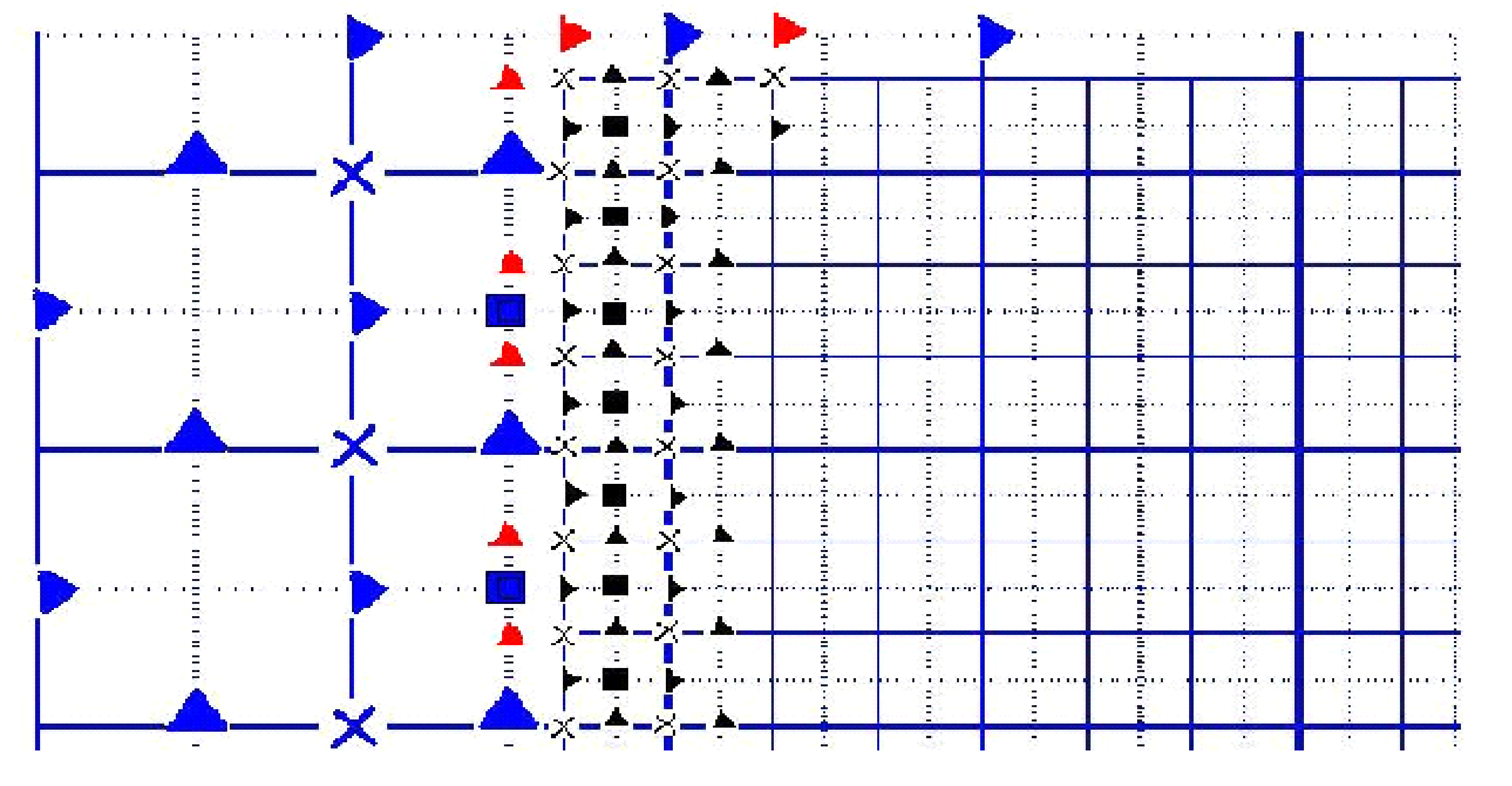


Presentation of the modeling technique: local grid refinement in time



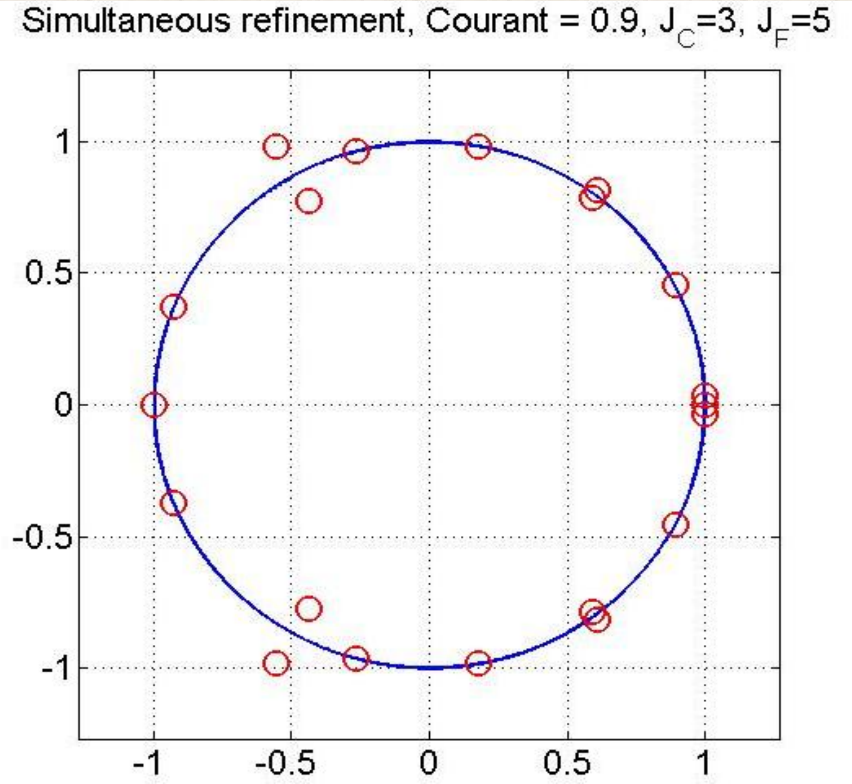


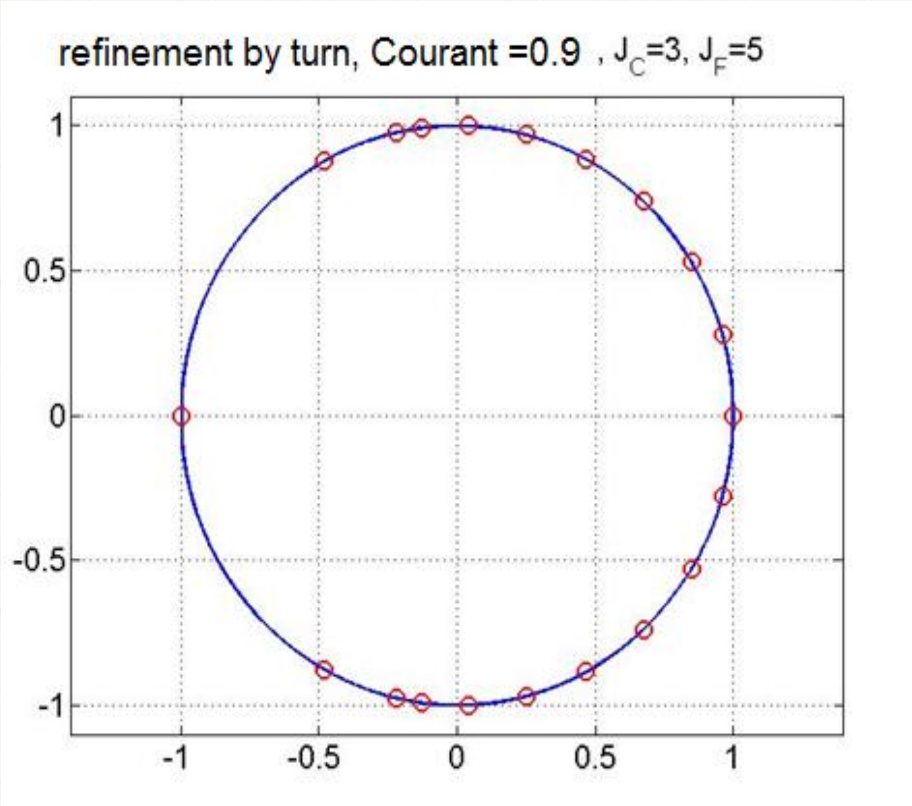
Presentation of the modeling technique: local grid refinement in space



Presentation of the modeling techniques: stability of the grid refinement (spectral criterium)

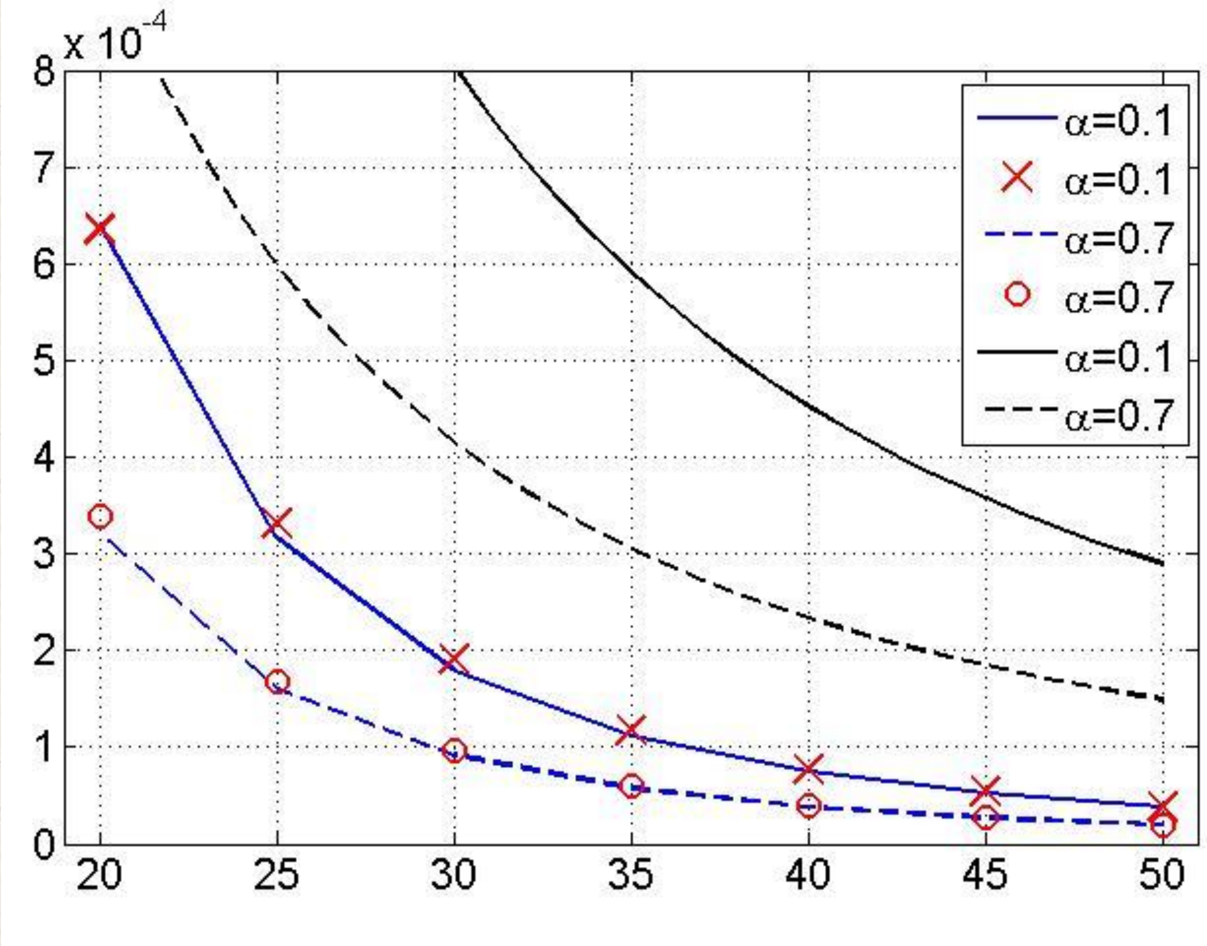
If finite-difference scheme is stable, eigenvalues of operator used to update solution must be within the unit circle





Presentation of the modeling technique: local grid refinement

Artifacts due to local grid refinement



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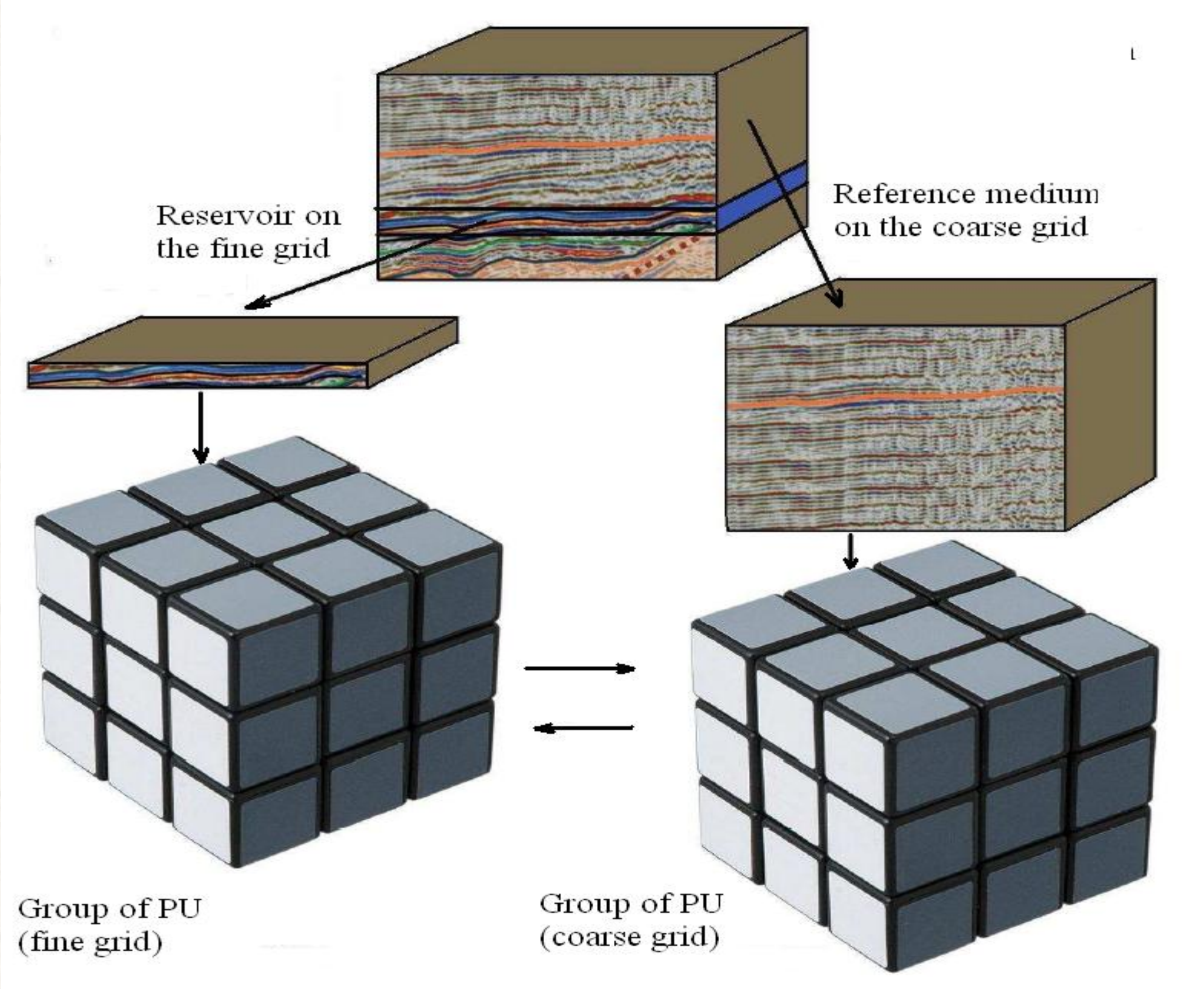
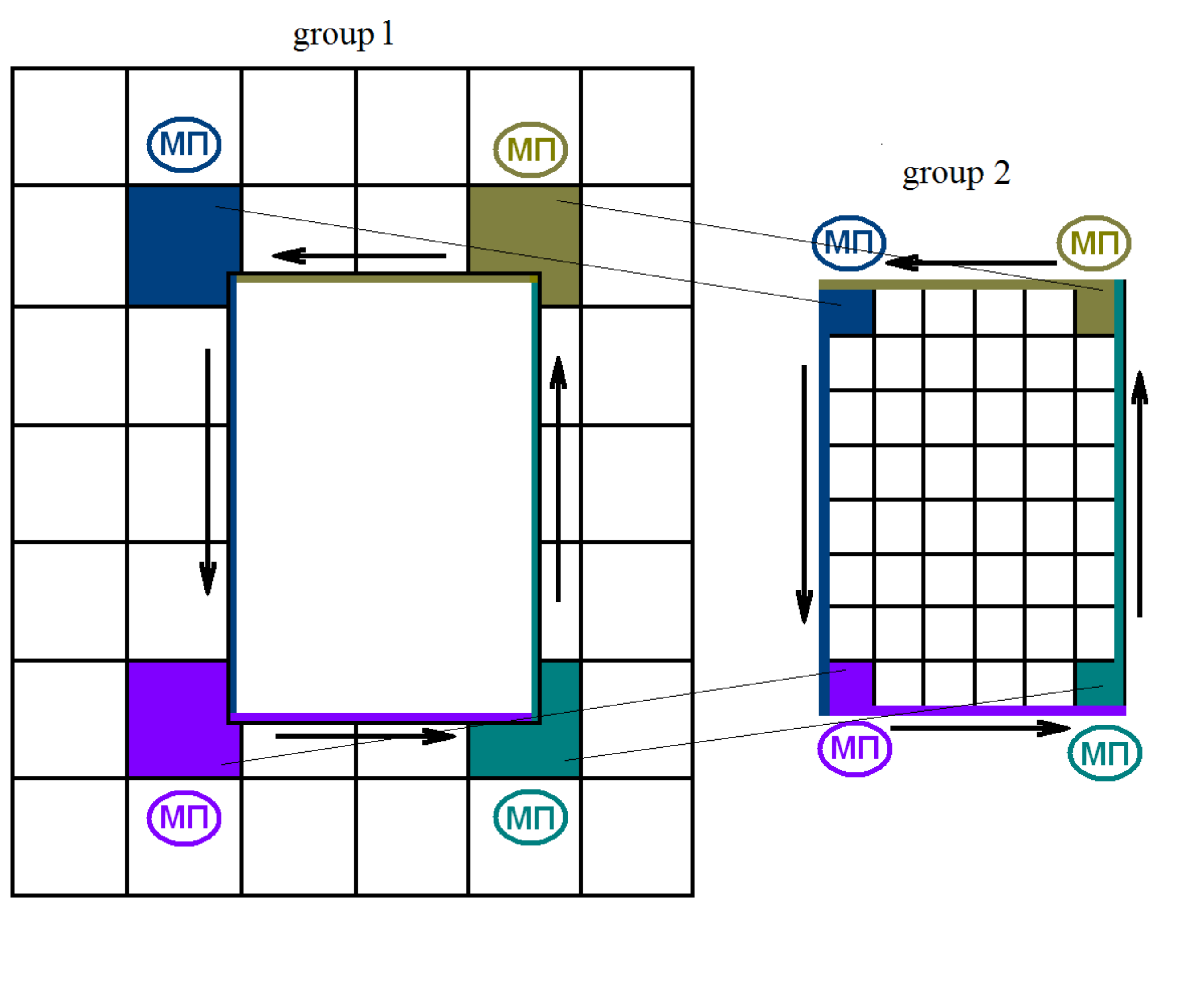
Parallel implementation: 3D domain decomposition



Fine-grid area can be placed anywhere within the reference model **regardless** to the specific domain decomposition used in coarse-grid model.

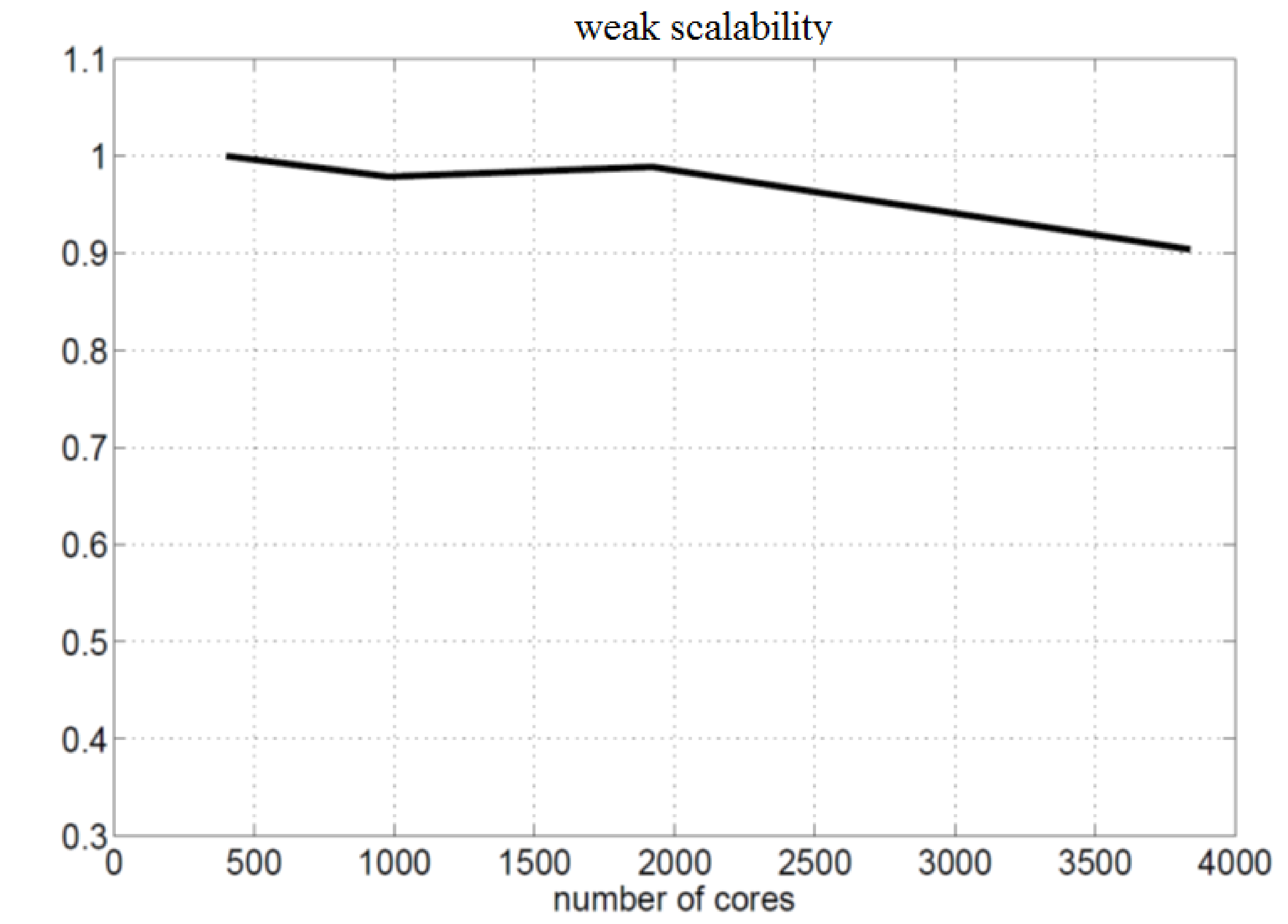
Parallel implementation: data excange



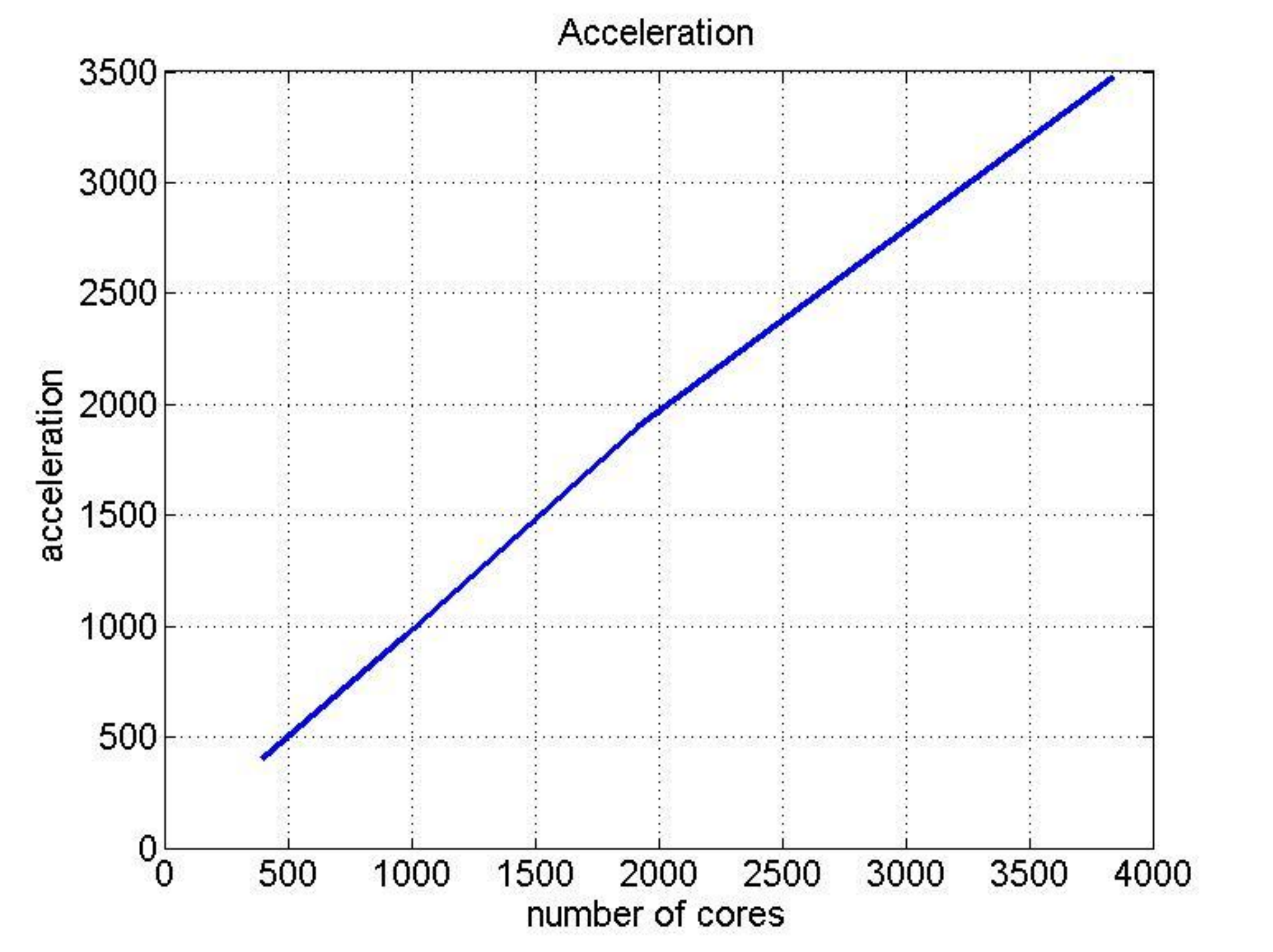
Parallel implementation: Scalability

1. Optimal 3D Domain Decomposition via **METIS**.
2. Non-blocking send/receive procedures.
3. Computations are starting from the most interior point and are expanding towards neighboring domain
4. Send/Receive of partially sampled data

Parallel implementation: weak scalability



Parallel implementation: strong scalability (acceleration)



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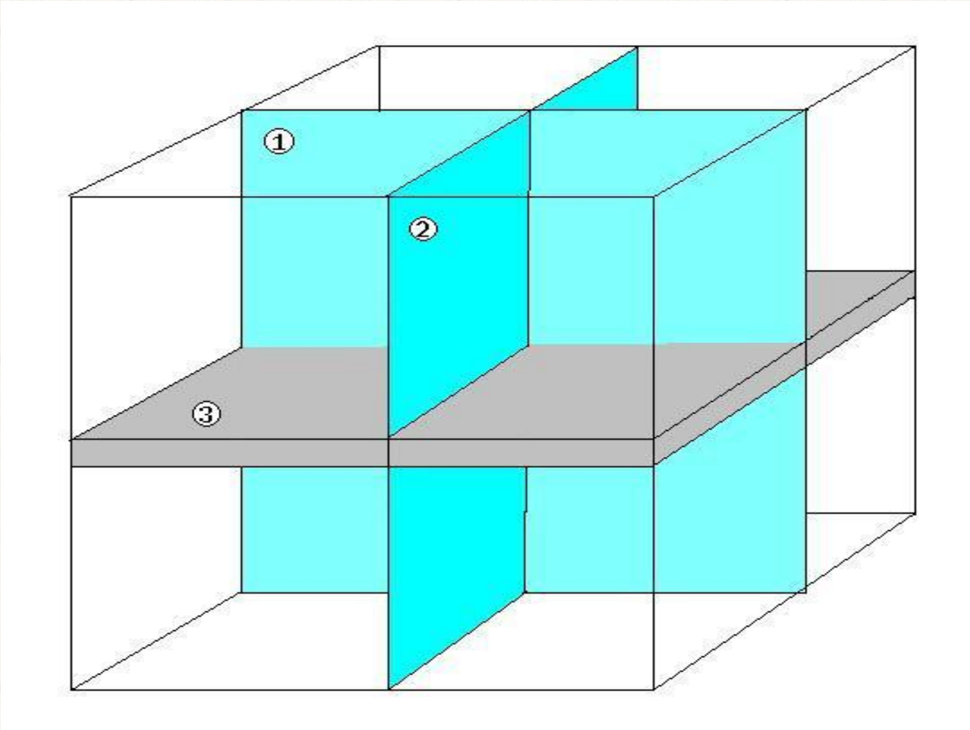
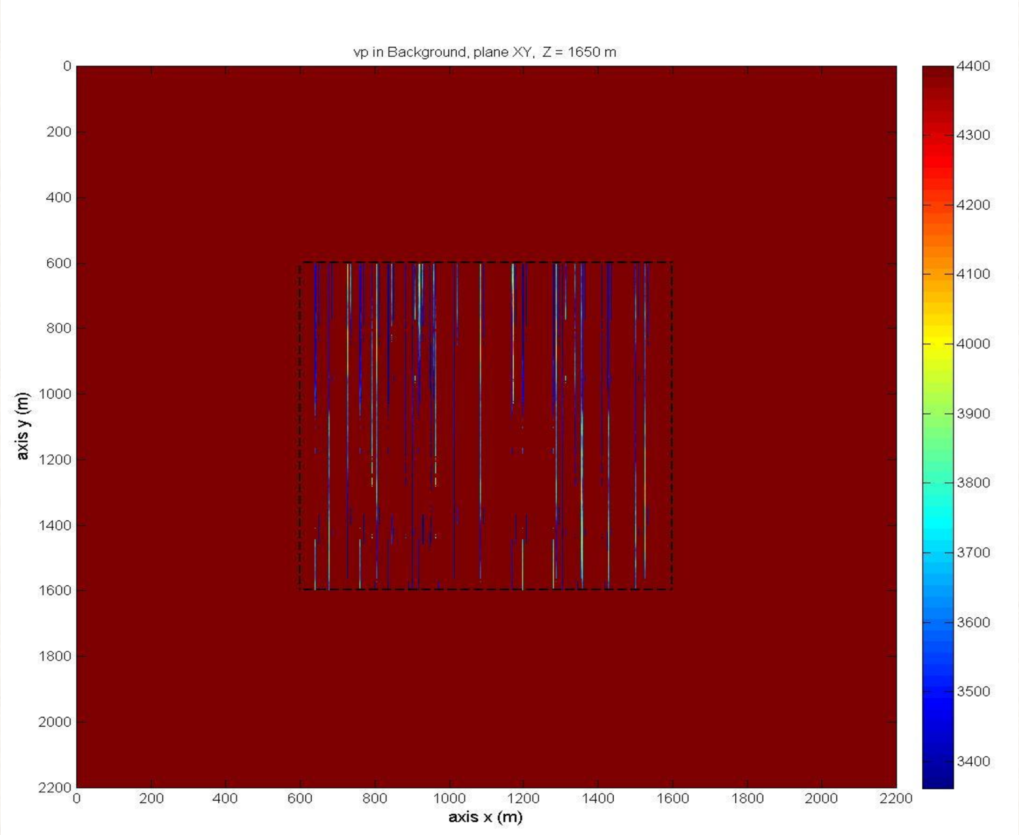
Synthetic example: realistic model of a fractured reservoir

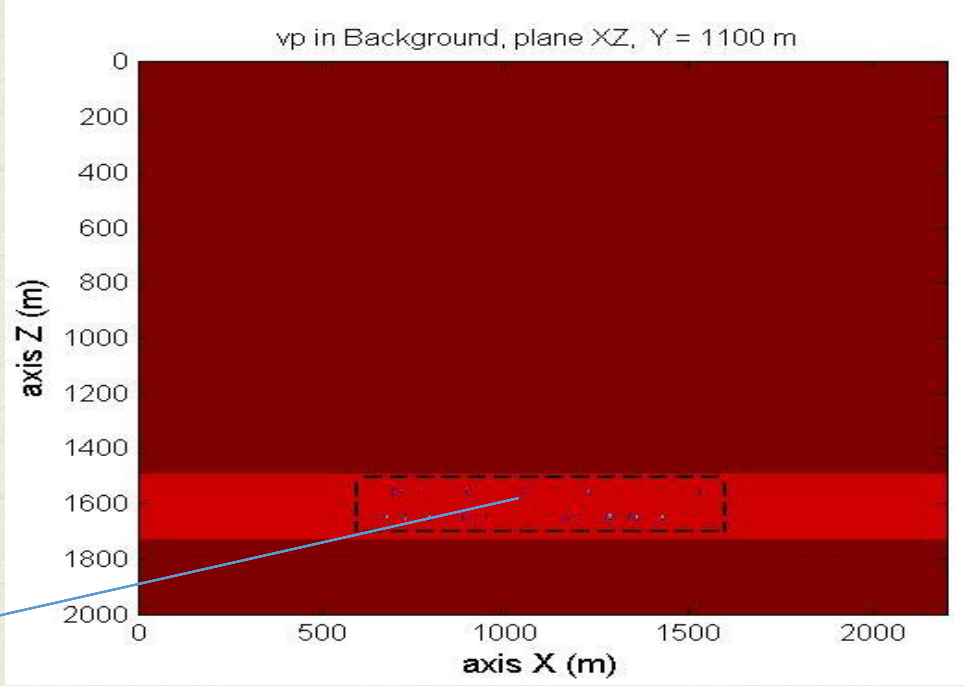


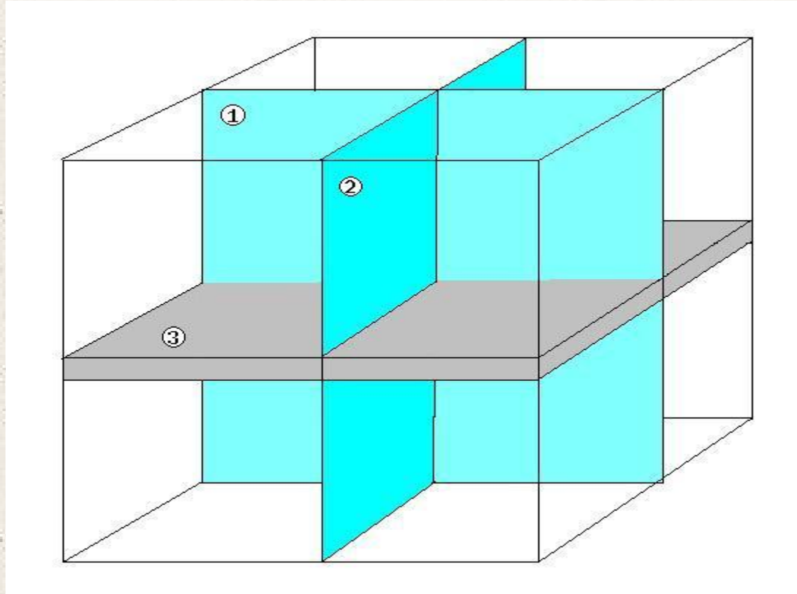
Top view

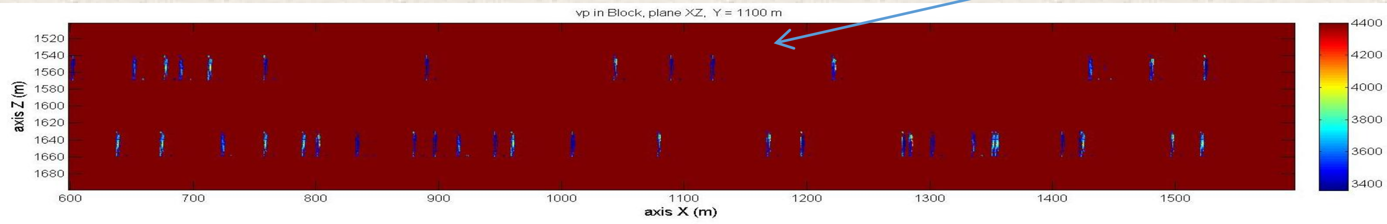


Synthetic example: realistic model of a fractured reservoir

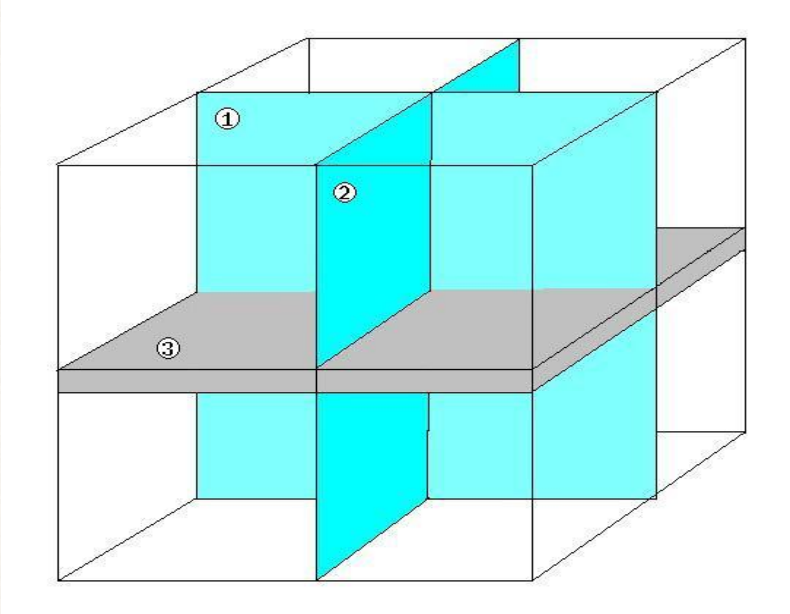
Side view x-line



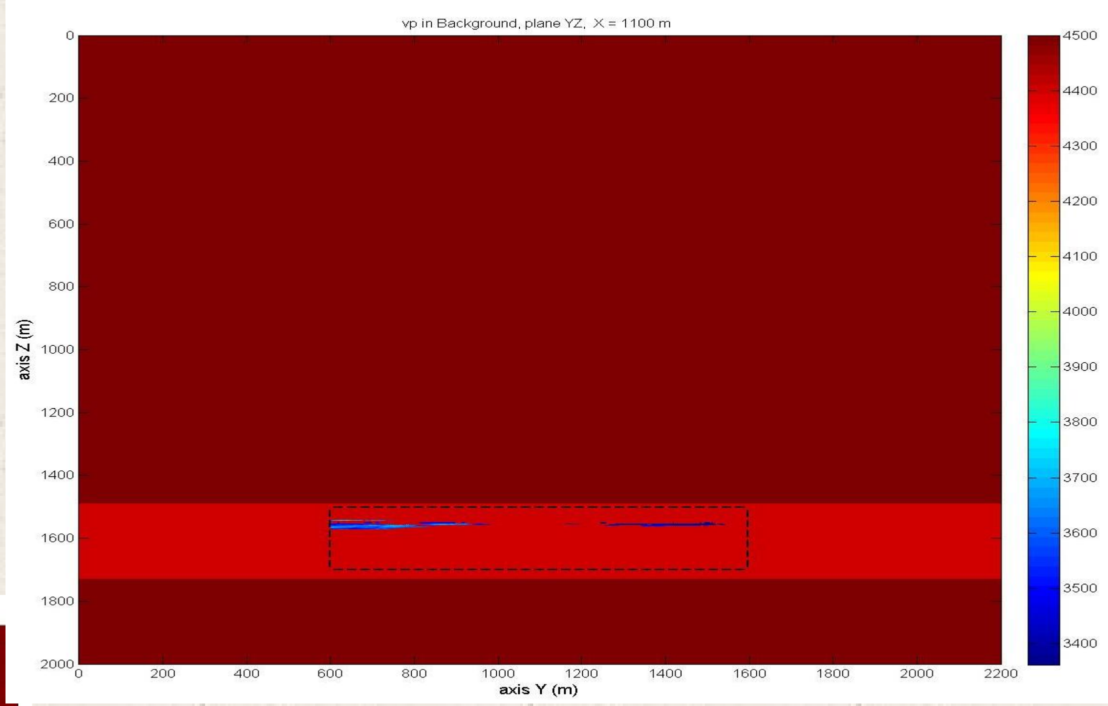


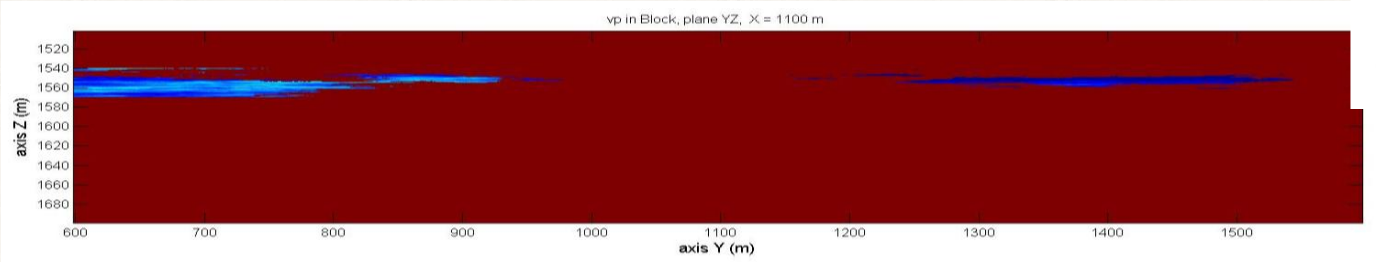


Synthetic example: realistic model of a fractured reservoir

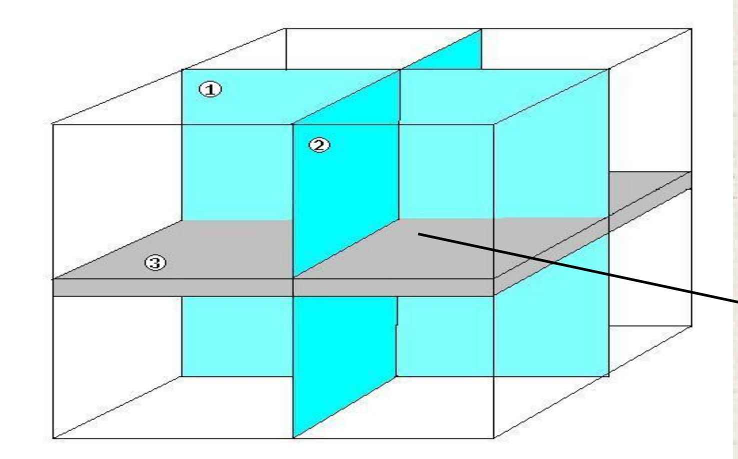


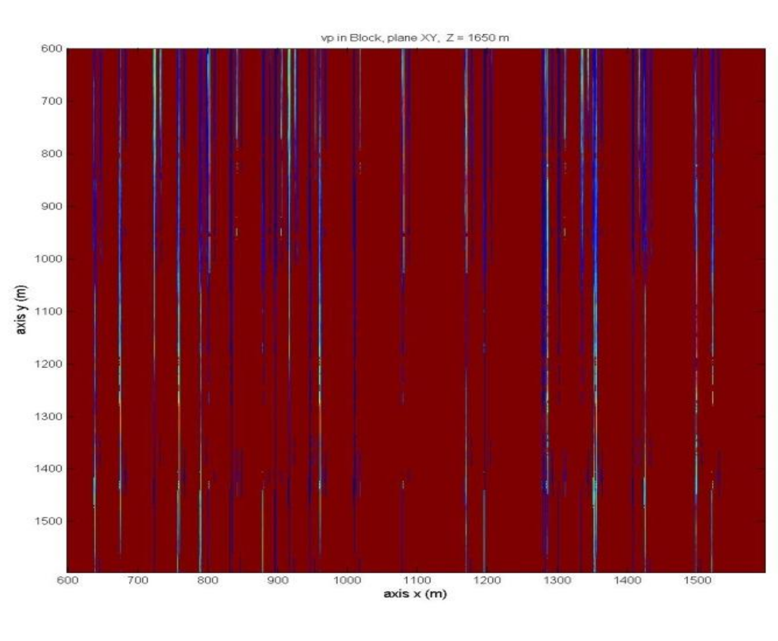
Side view in-line

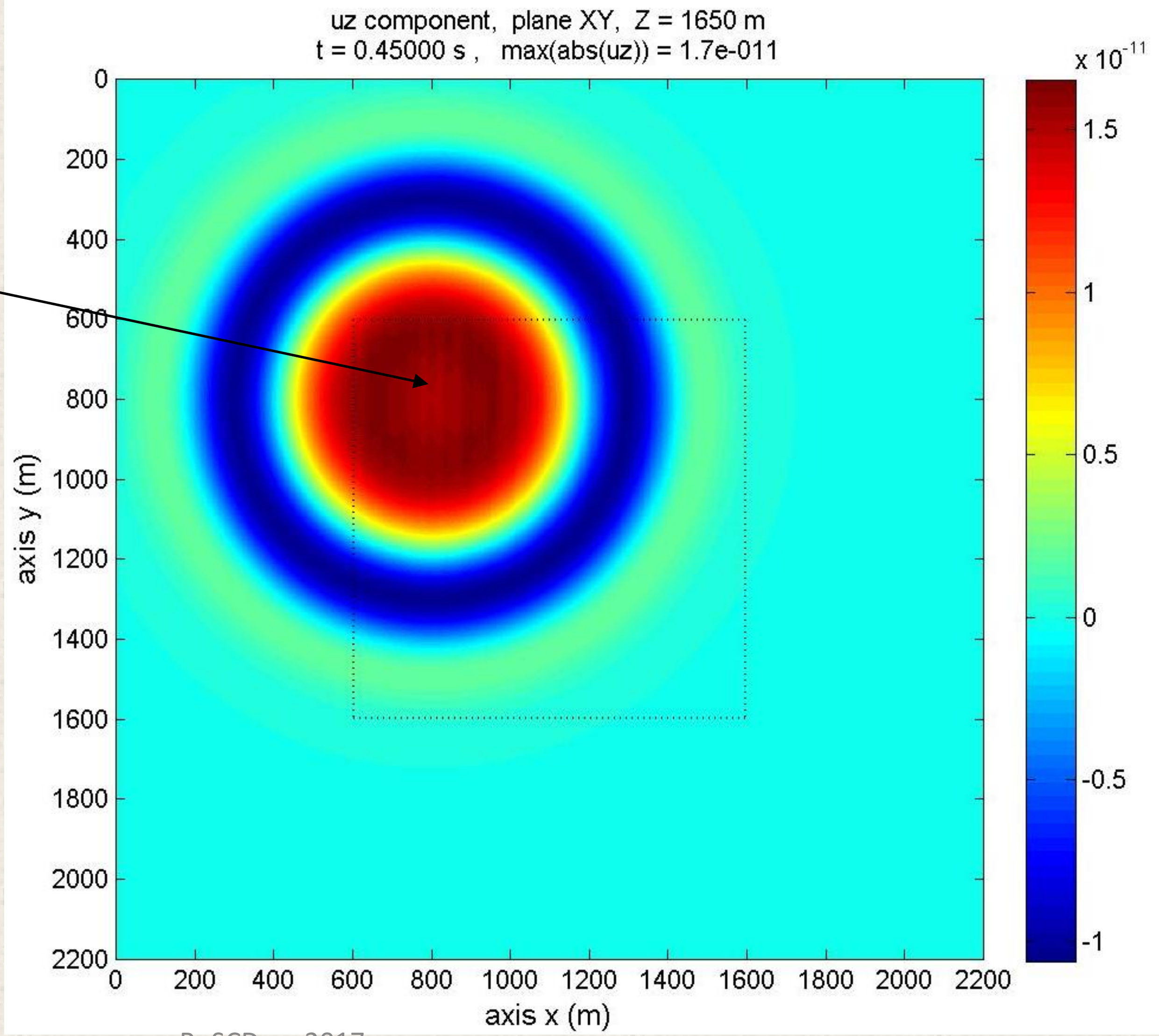




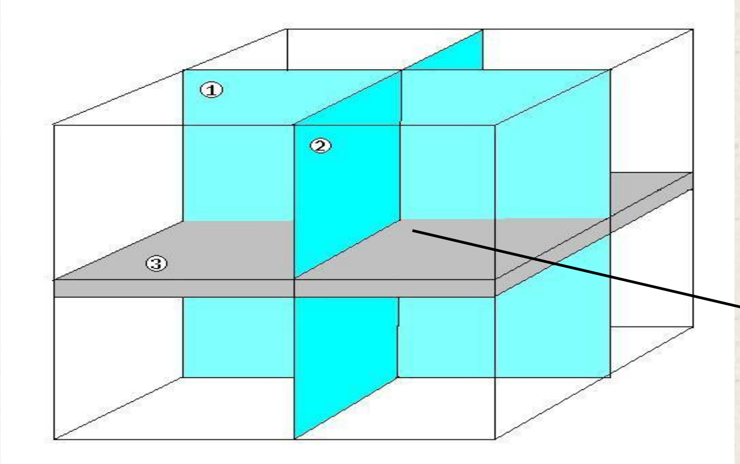
Wavefield inside the reservoir, top view

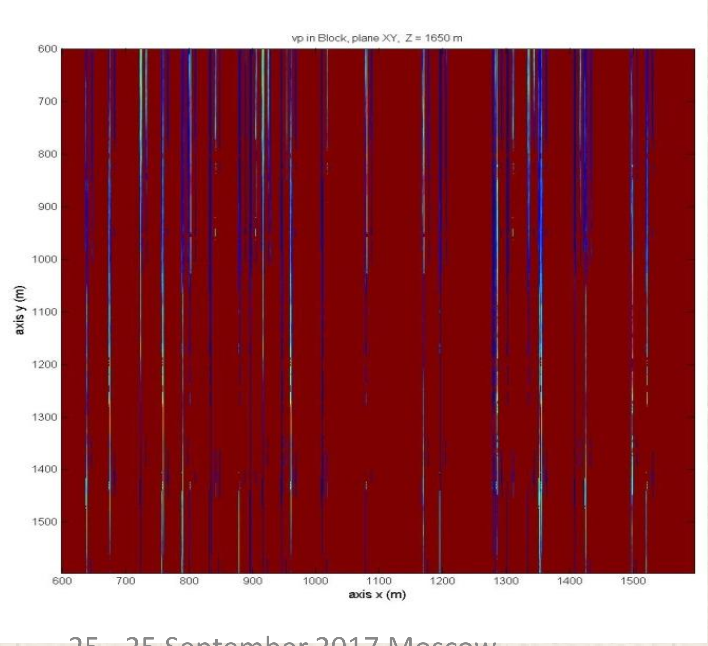


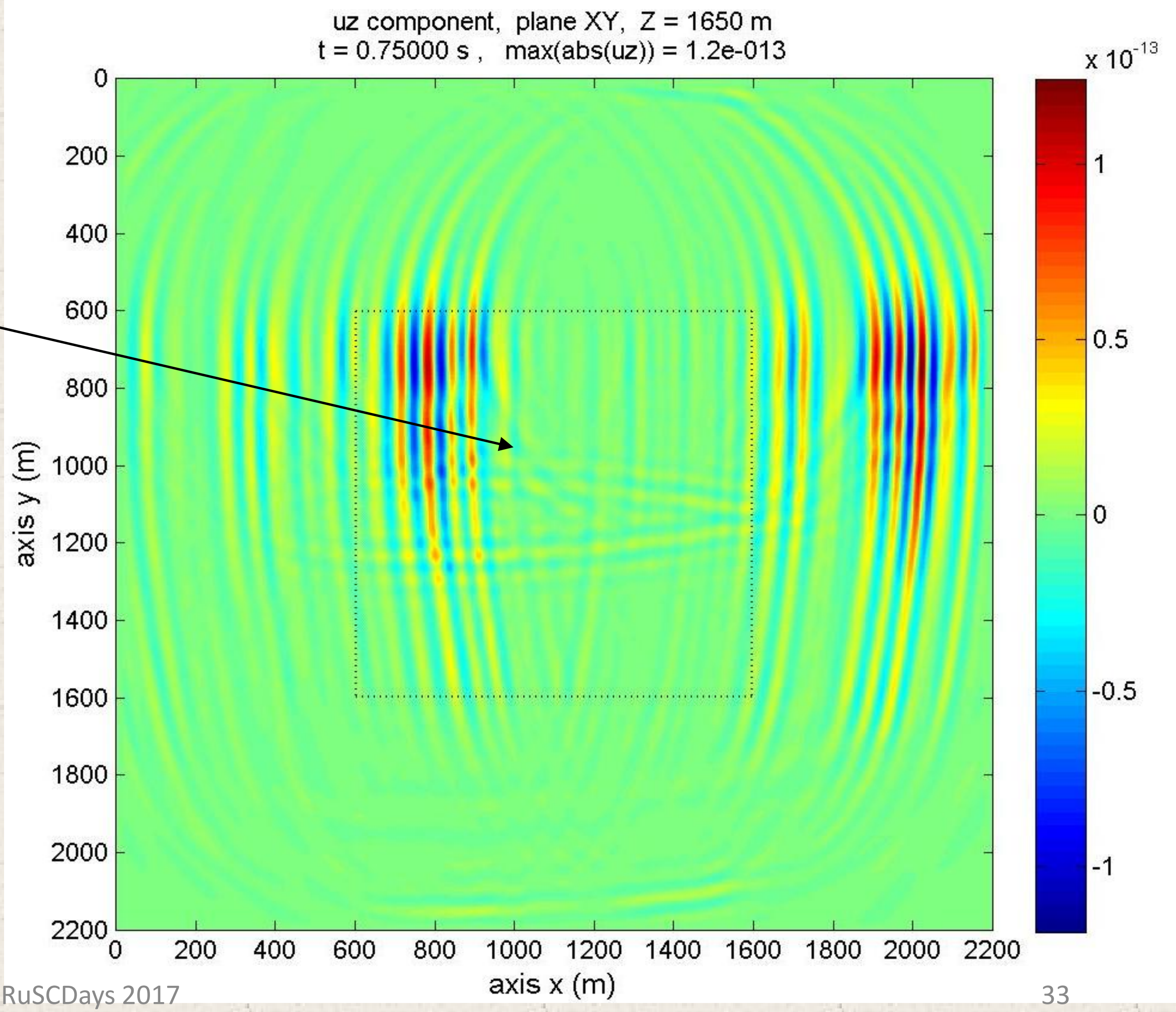




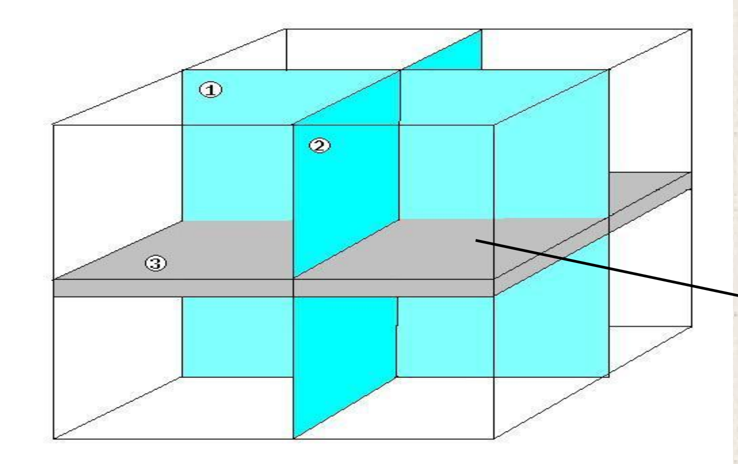
Wavefield inside the reservoir, top view. P-wave scattering

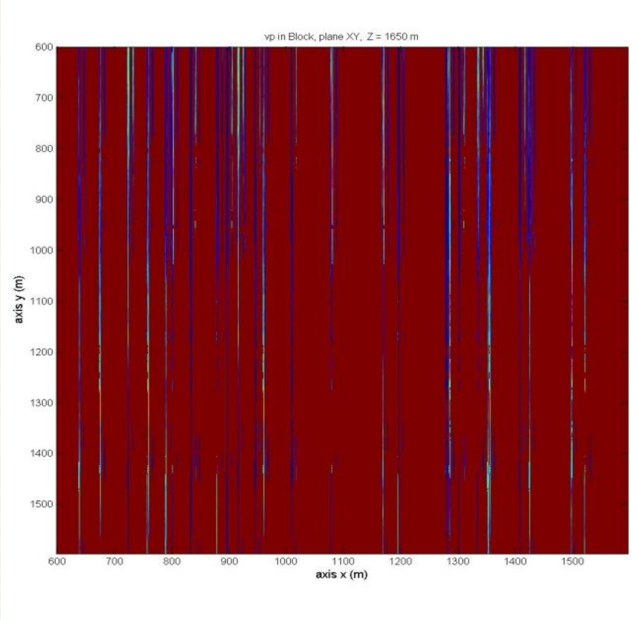


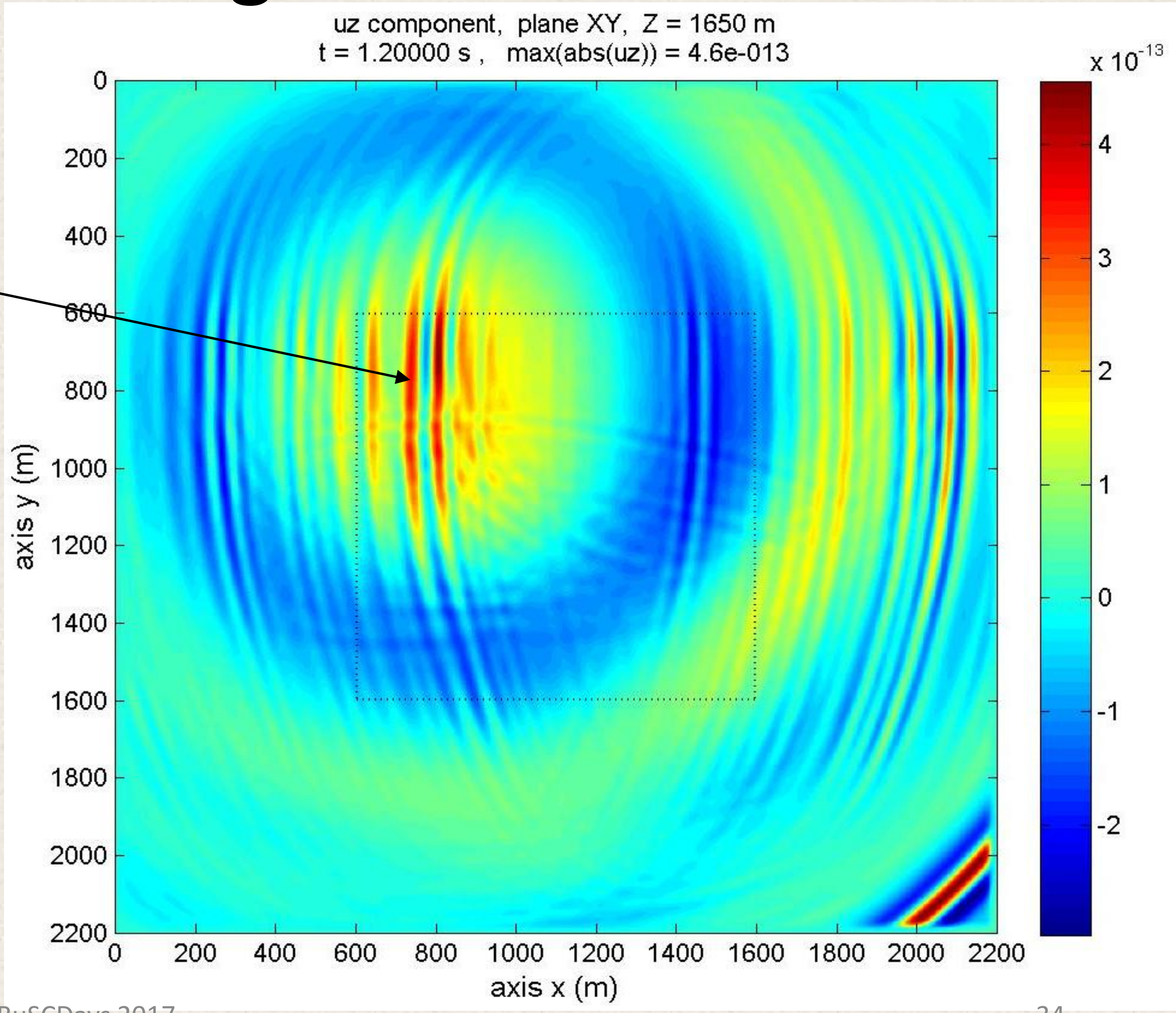




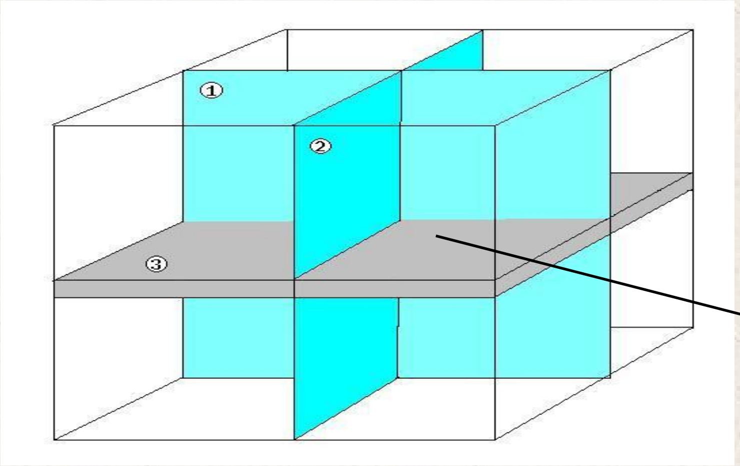
Wavefield inside the reservoir, top view. S-wave scattering

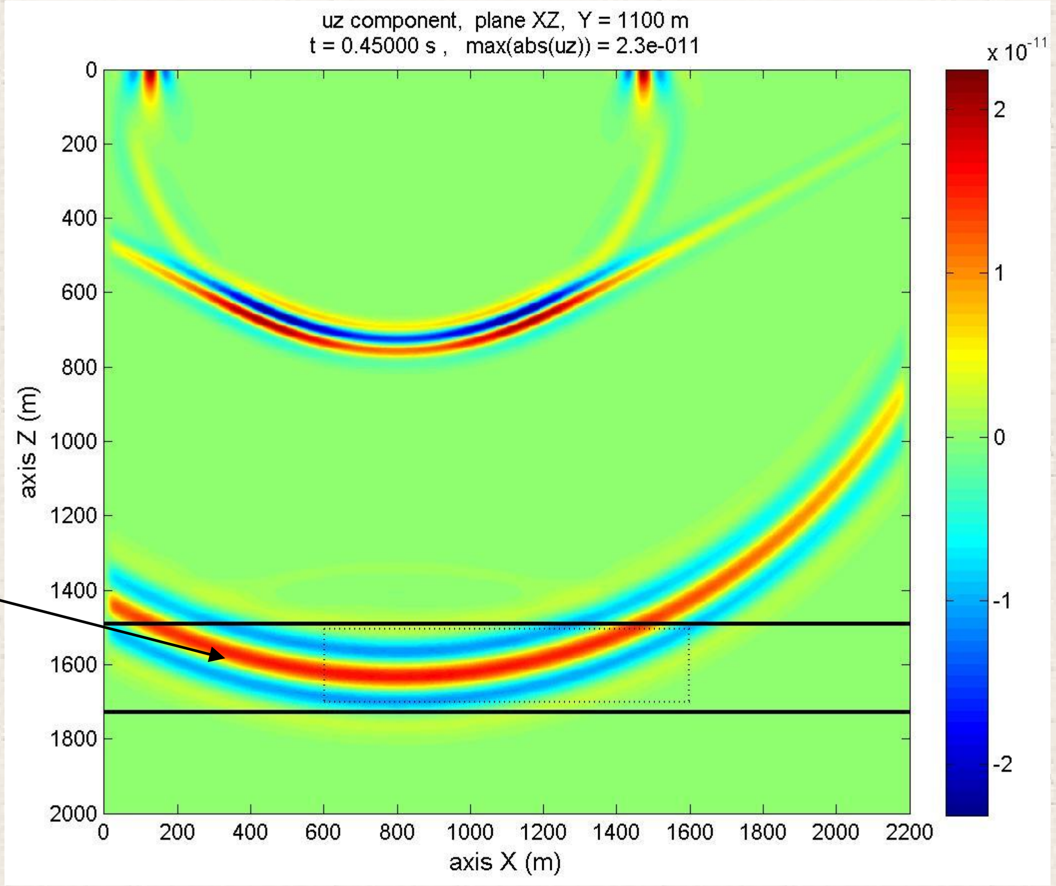


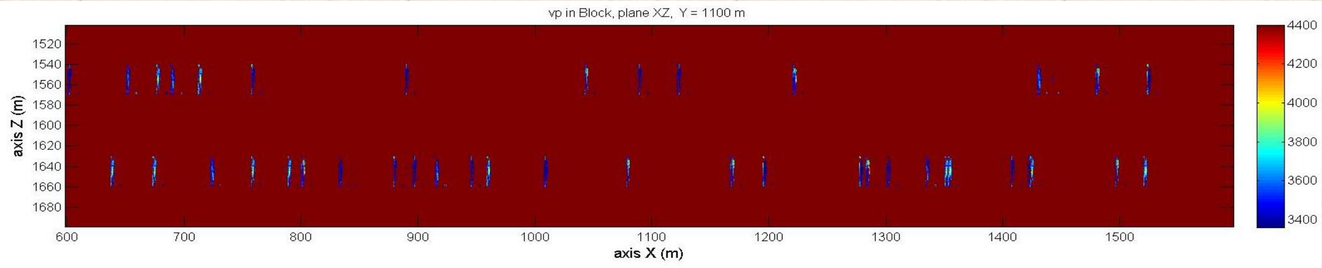




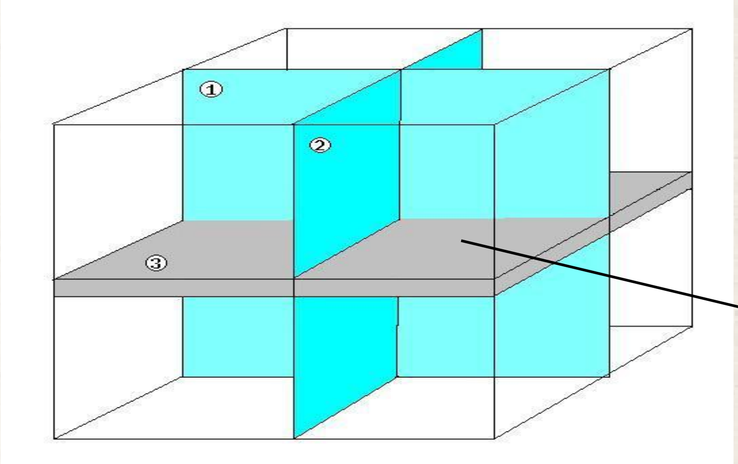
Wavefield, x-line view

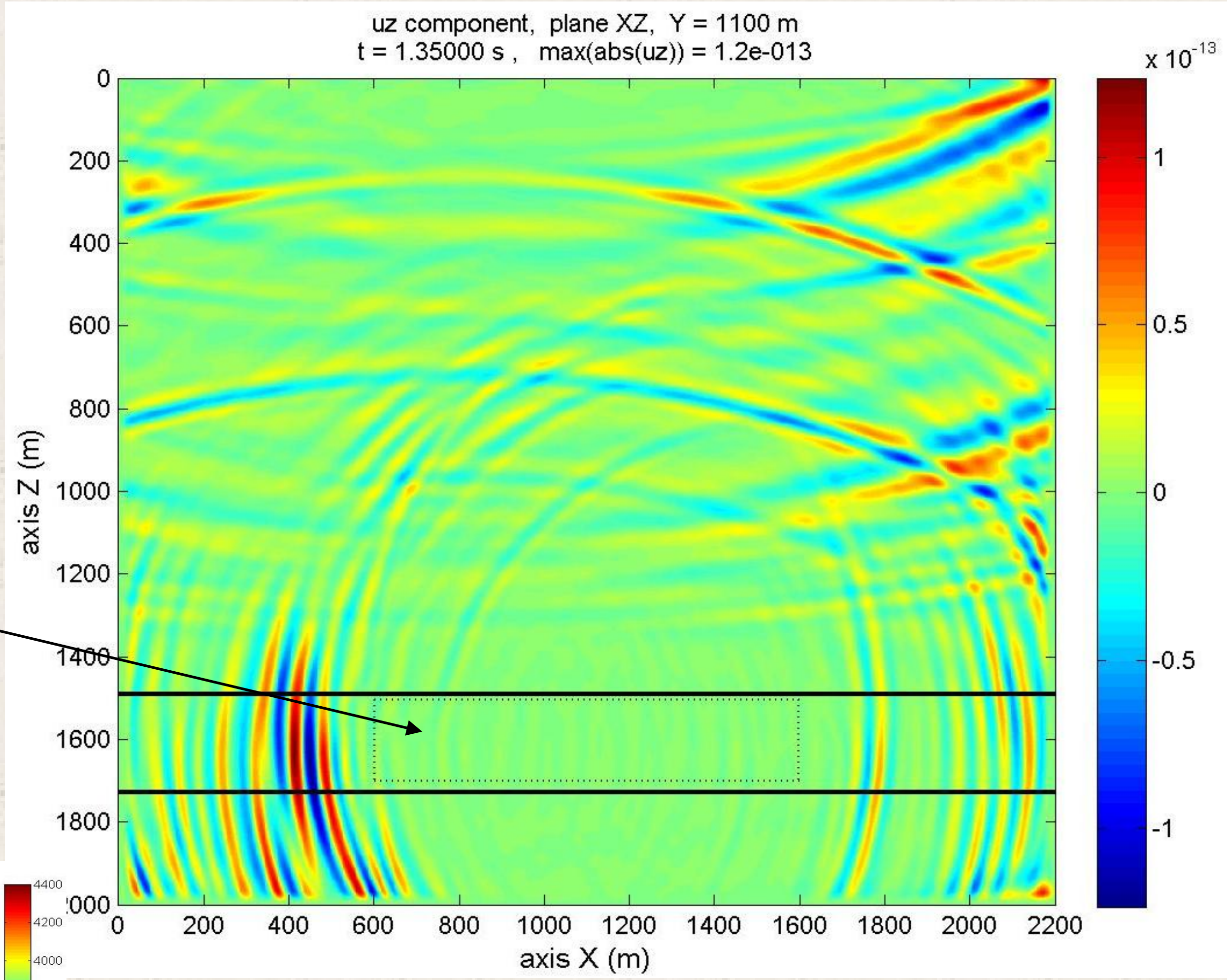


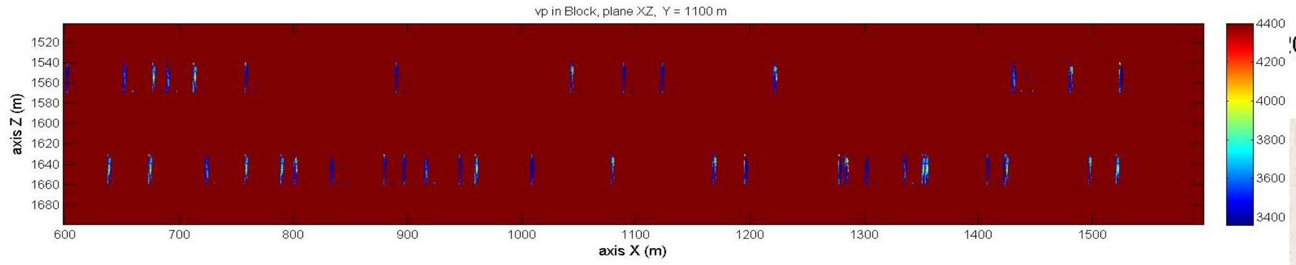




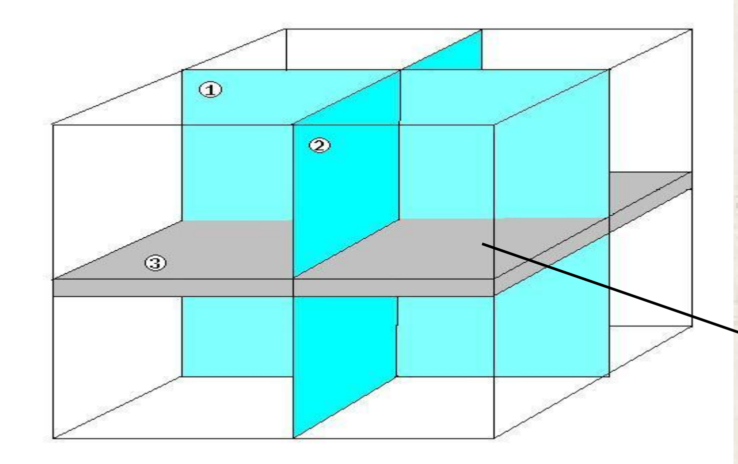
Wavefield, x-line view

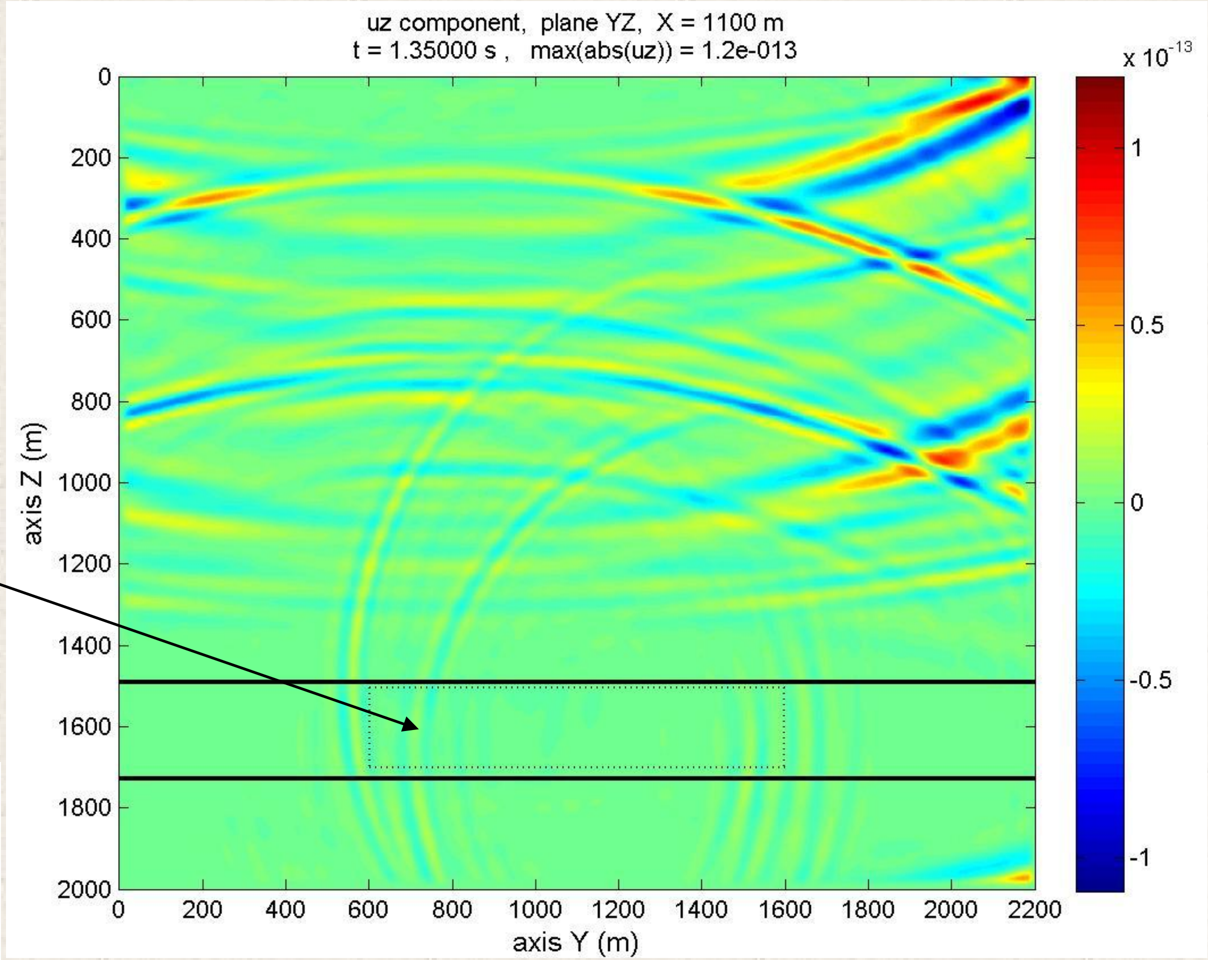


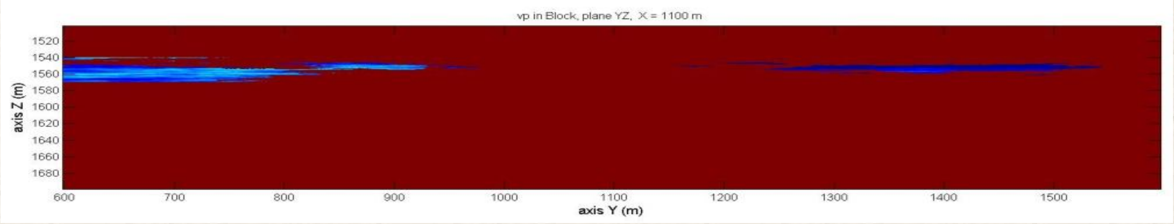




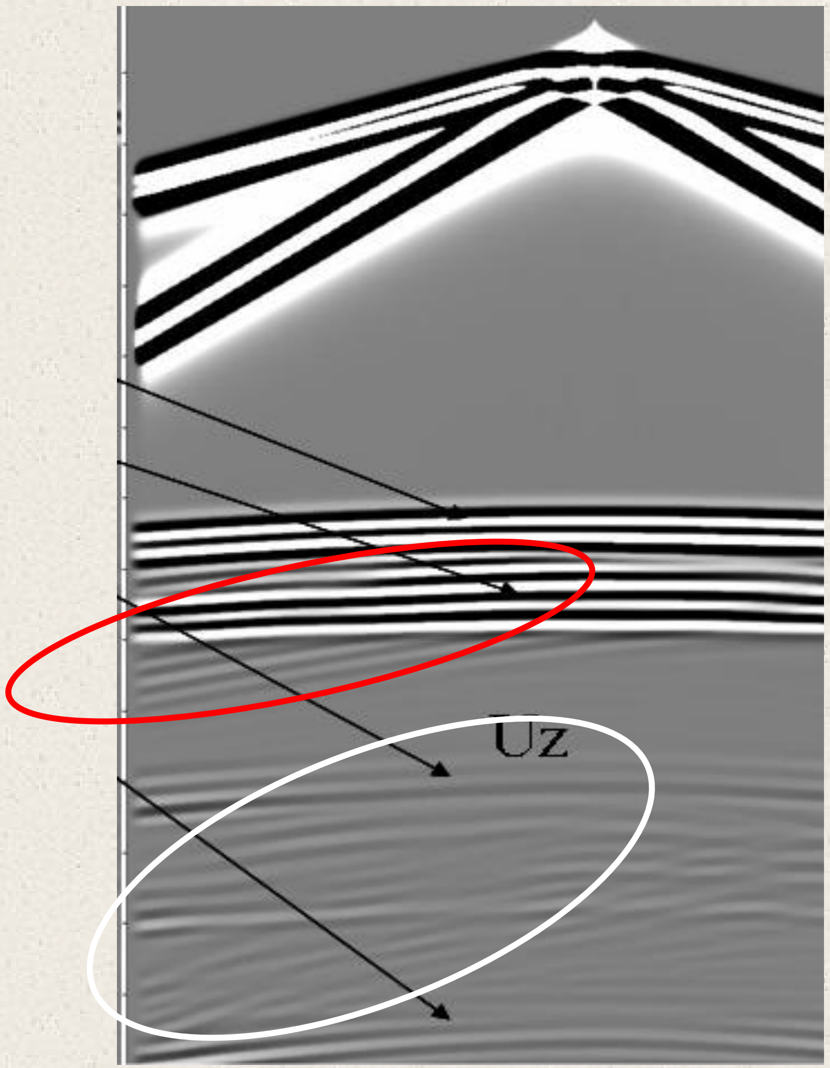
Wavefield, in-line view



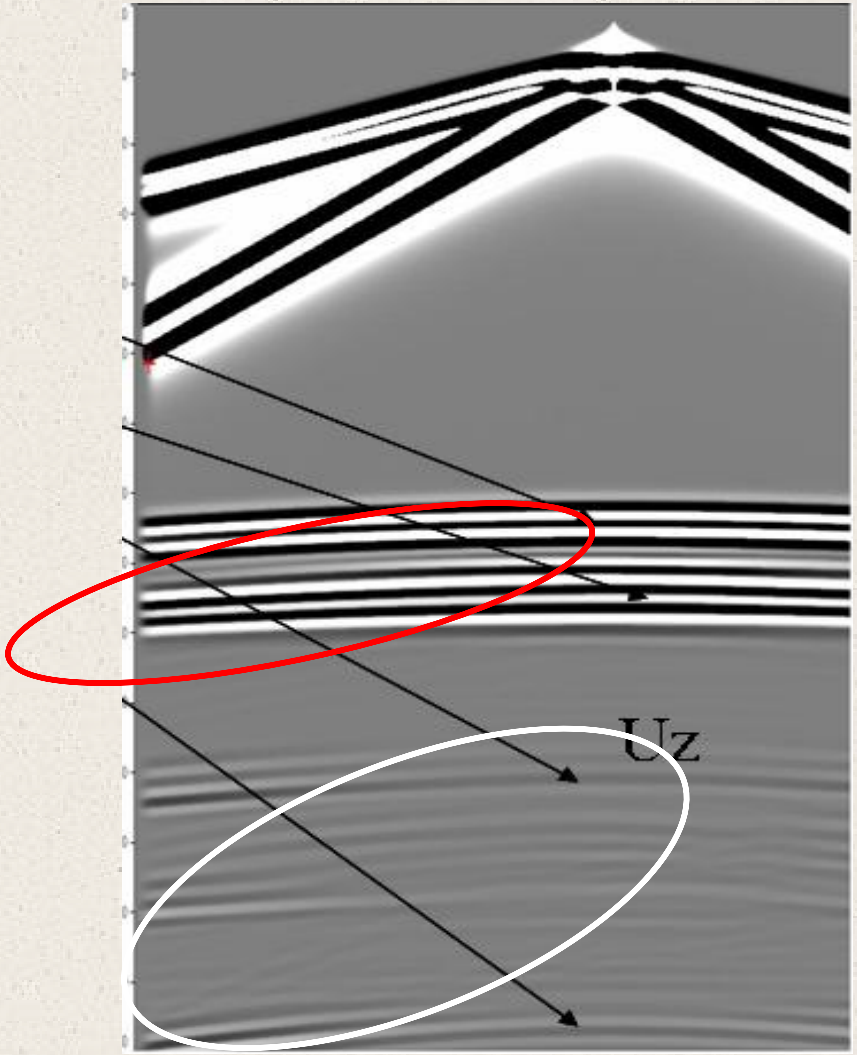




Scattered waves

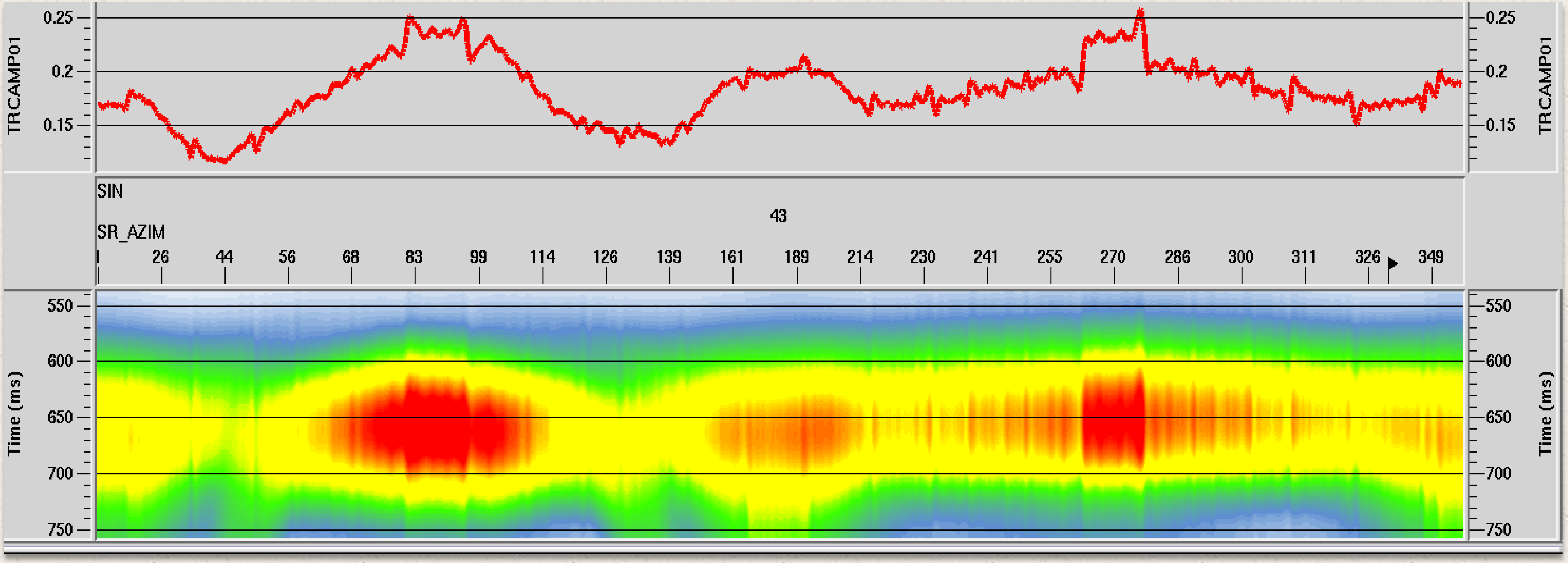


In-line



Cross-line

Azimuth distribution of scattering energy



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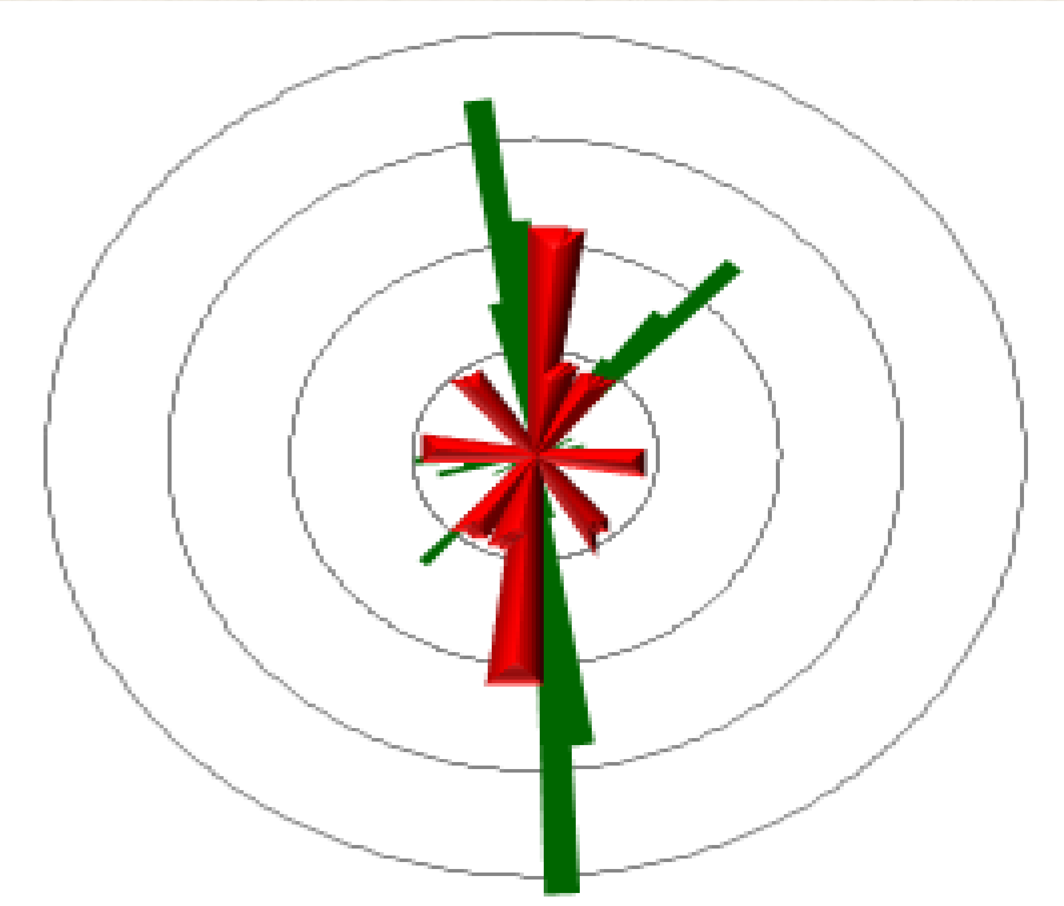
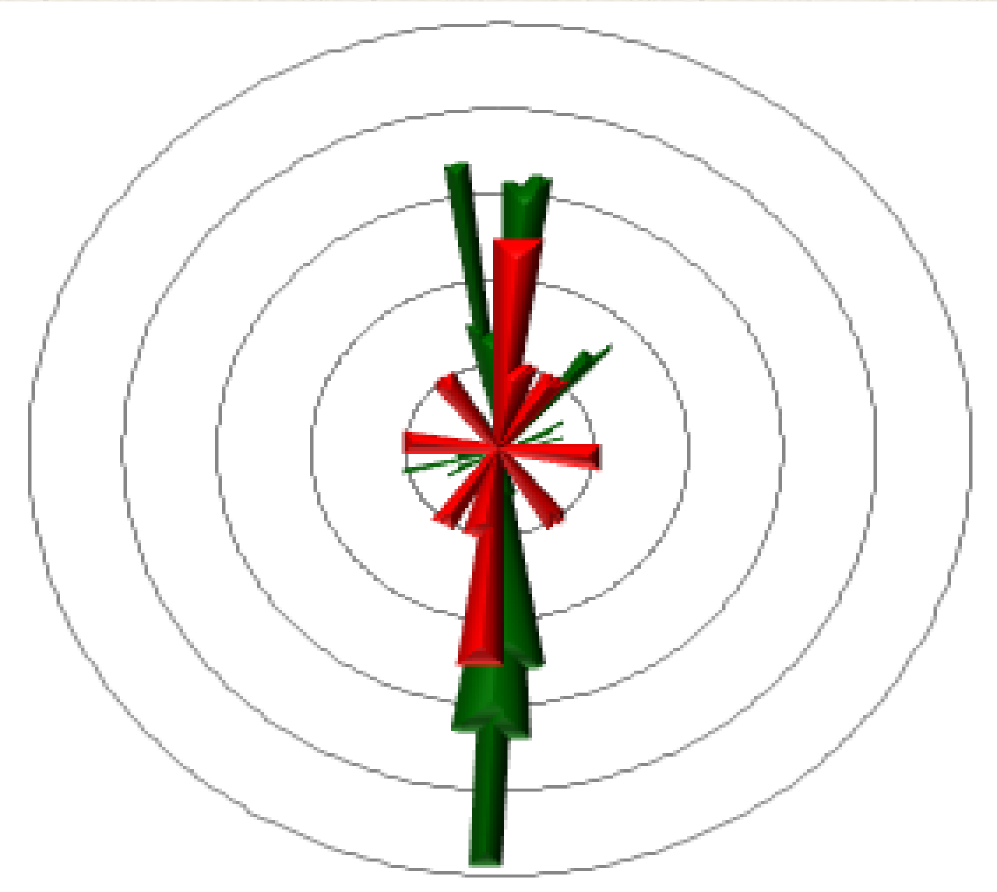
Fracture orientation: real case study (Yurubcheno-Tohomskoe). Azimuth distribution of the scattered energy vs UBI (Ultrasonic borehole imager)

Scattering energy (green) vs UBI (red)



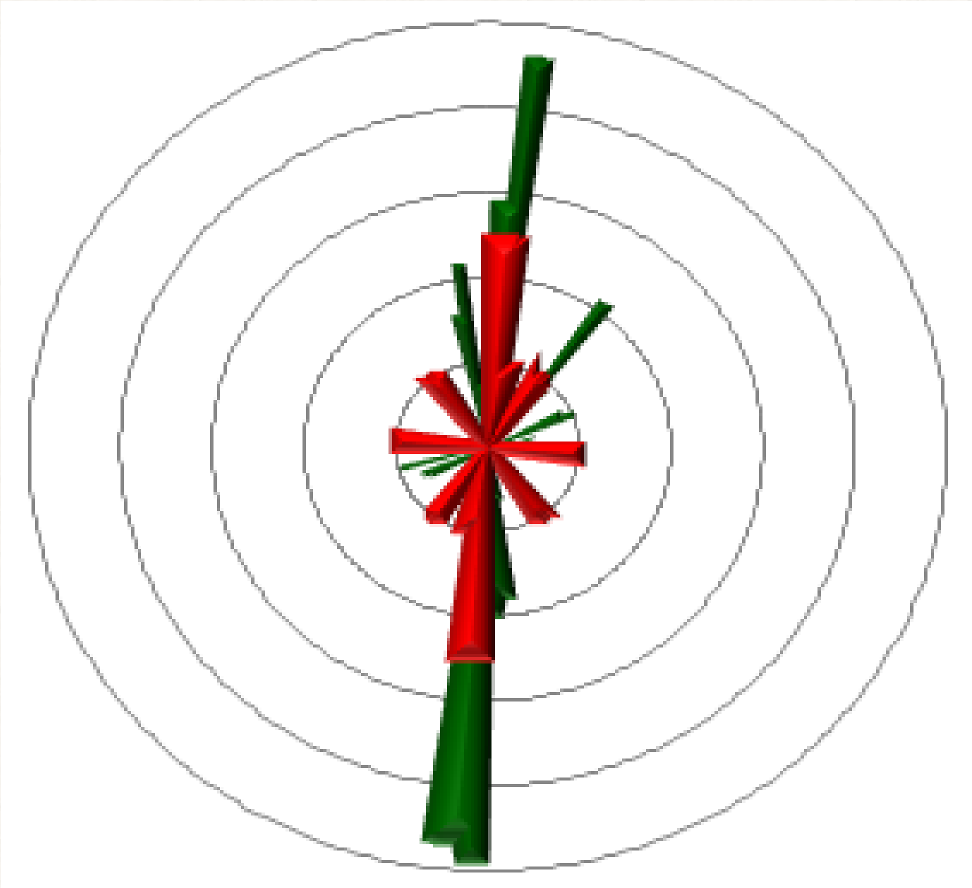
R=0.7, t=0.965

Scattering energy (green) vs UBI (red)



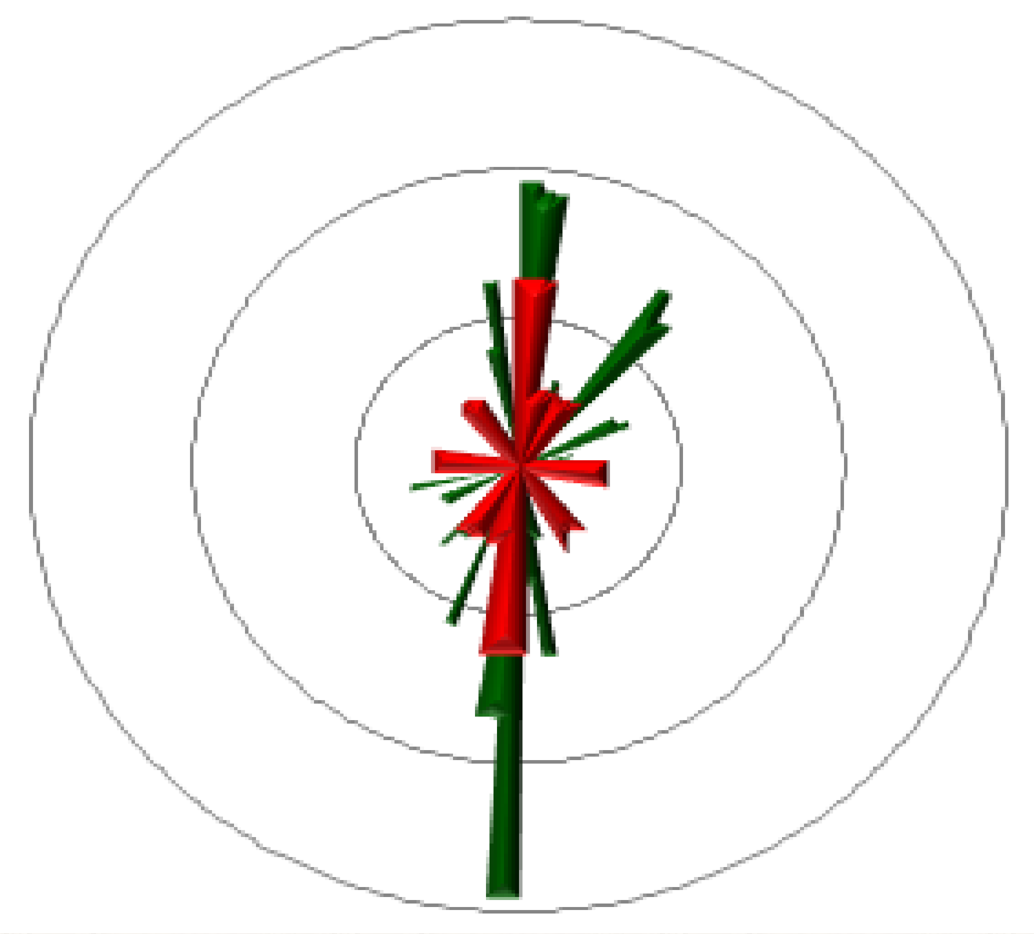
R=0.97, t=0.969

Scattering energy (green) vs UBI (red)



R=0.96, t=0.973

Scattering energy (green) vs UBI (red)



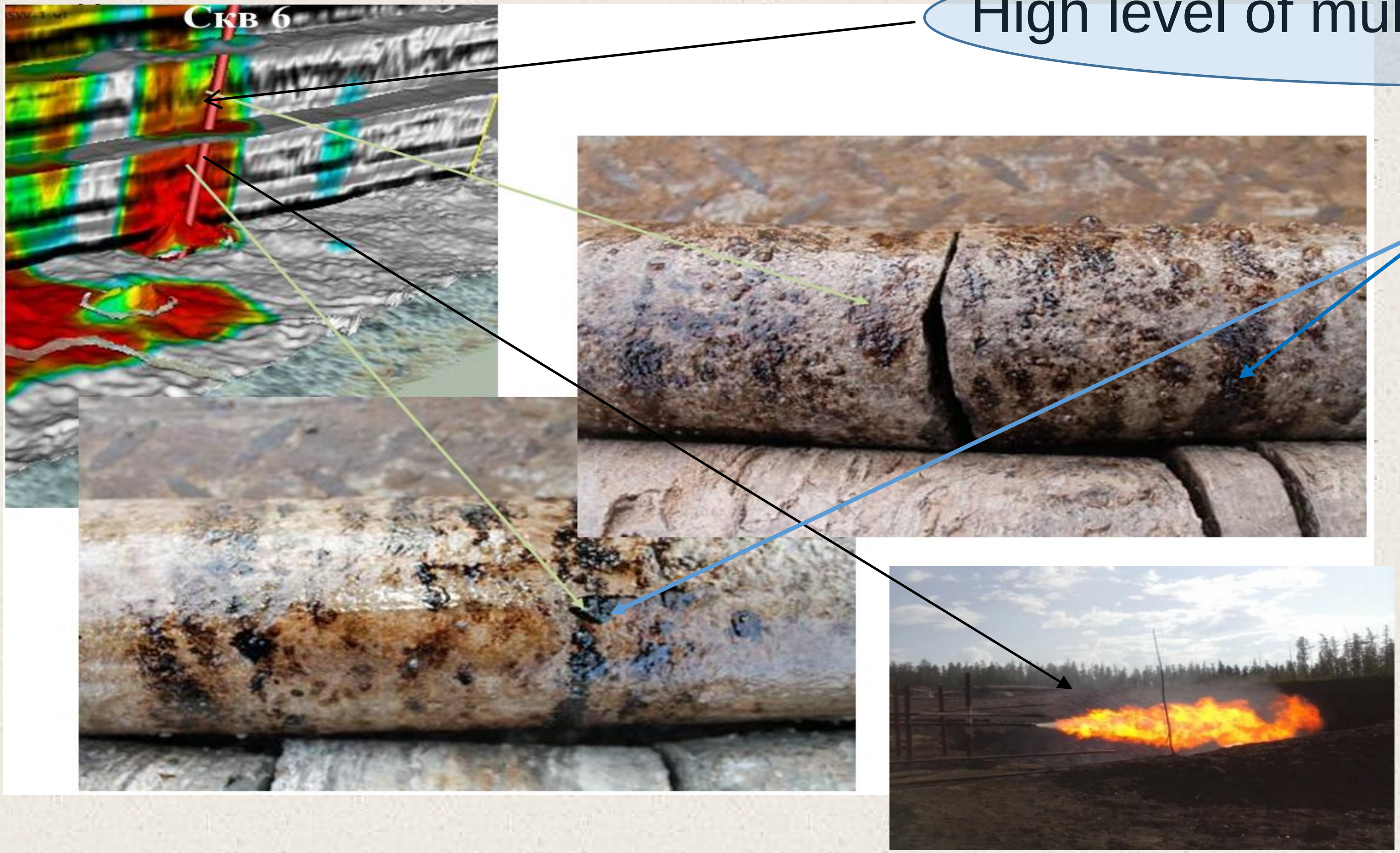
R=0.94, t=0.978

Conclusion:

Fracture orientation is given by azimuth distribution of the scattered seismic energy!

Scattered waves and fluid saturation: core samples and scattered energy

High level of multiple scattering



Core samples with bituminous displays

Gas outflow

Somewhere in East Siberia

Conclusion

1. Local grid refinement in time and space opens a possibility to perform reliable simulation of seismic waves' propagation through cavernous fractured reservoirs.
2. Full multiscale numerical simulation forms the basis for mesoscale characterization of cavernous fractured reservoirs via scattered seismic waves;
3. Azimuth distribution of scattered energy gives reliable information about dominant orientation of fracture corridors, which is verified by synthetic and real data;
4. Multiple scattering seems to be useful to recognize fluid saturated fracture corridors.

Road map

Questions should be answered shortly:

- How can we define fractures density expressed as spacing between fractures;
- Connectivity of fractures;
- Fluid saturation;
- Aperture or width of fractures.

Acknowledgements

1. The research described was done in the framework of the contract of the Institute of Petroleum Geology and Geophysics SB RAS and RN KrasnoyarskNIPIneft.
2. We are thankful to the Geological Department of this company for their help in the development of realistic typical digital model of a reservoir on subseismic scales and joint efforts in validation of the approach.
3. This study would be impossible without PRACE Access Grant # 2012071274 for 32 million core-hours on supercomputer HERMIT at Stuttgart University and our tight cooperation with ***Siberian Supercomputer Center (Boris M. Glinsky).***