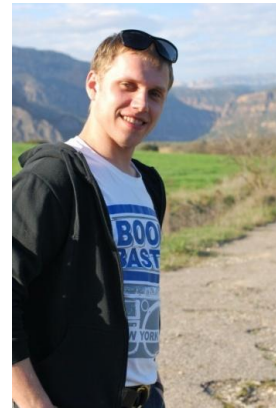


Статистический анализ волновых сейсмических изображений зоны разлома в рамках его фациальной модели

Докладчик Чеверда В.А.

Совместная работа с ООО РН КрасноярскНИПИнефть и
университетом гор. Берген



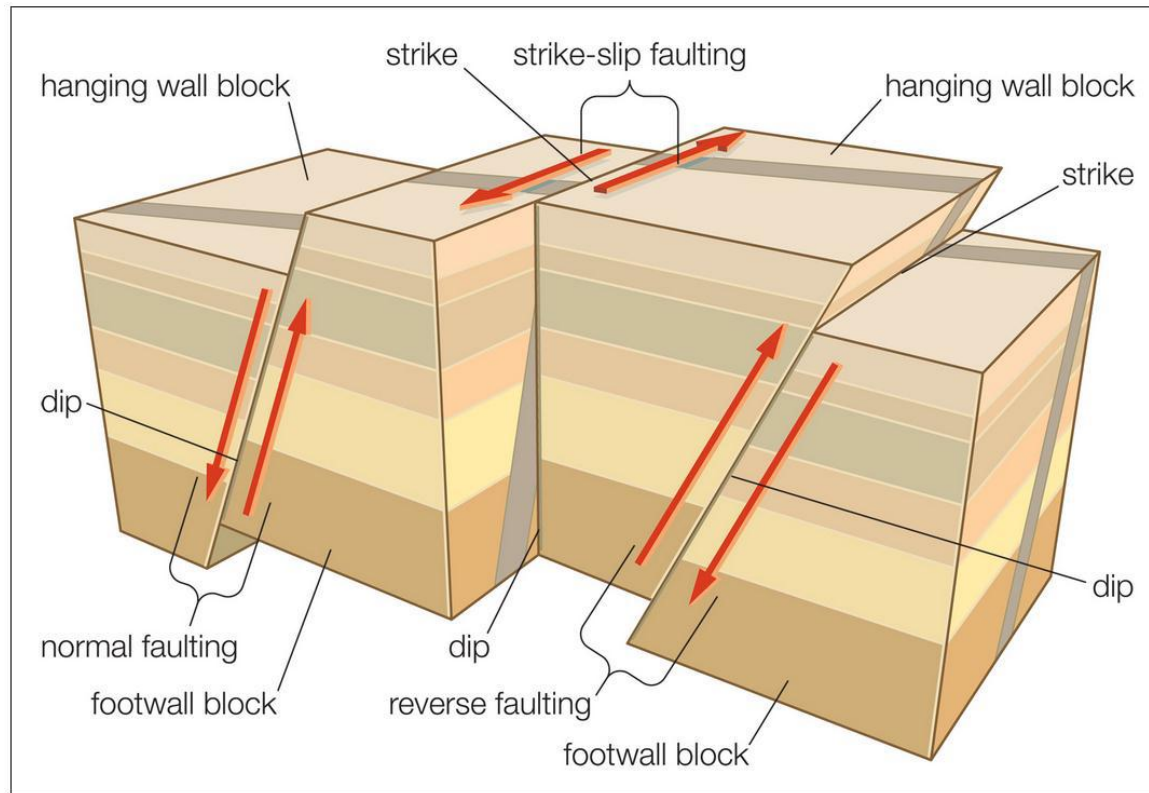
Content

1. General characterization of fault zones.
2. Fault zone model.
3. Seismic modeling and imaging:
 - 3.1. Seismic modeling;
 - 3.2. Seismic fault imaging.
4. Numerical experiments.
5. Conclusion.
6. Road map.

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General characterization of fault zones

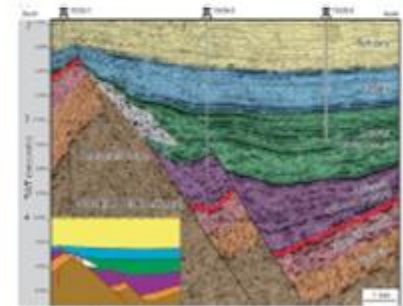
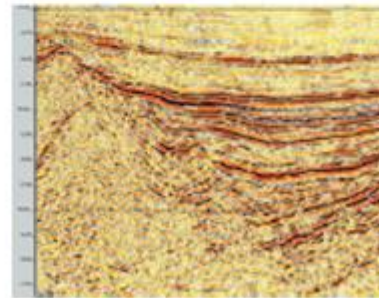


“A planar or gently curved fracture in the rocks of the Earth’s crust, where compressional or tensional forces cause relative displacement of the rocks on the opposite sides of the fracture”. *Encycl. Britt.*

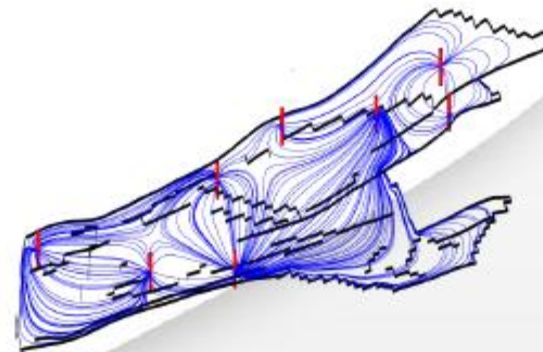
Characterization of fault zones

Significance of faults

- Geohazards
 - Earthquakes
 - Tsunamis
 - Mass movement
 - Construction
- Deposition
 - Extent
 - Geometry
- Subsurface fluid flow
 - Petroleum E & P
 - CO₂ storage
 - Groundwater flow



Stewart and Reeds (2003)



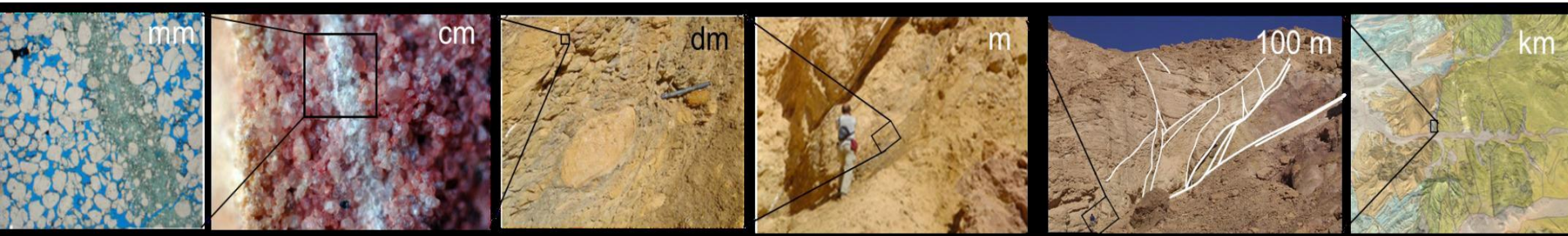
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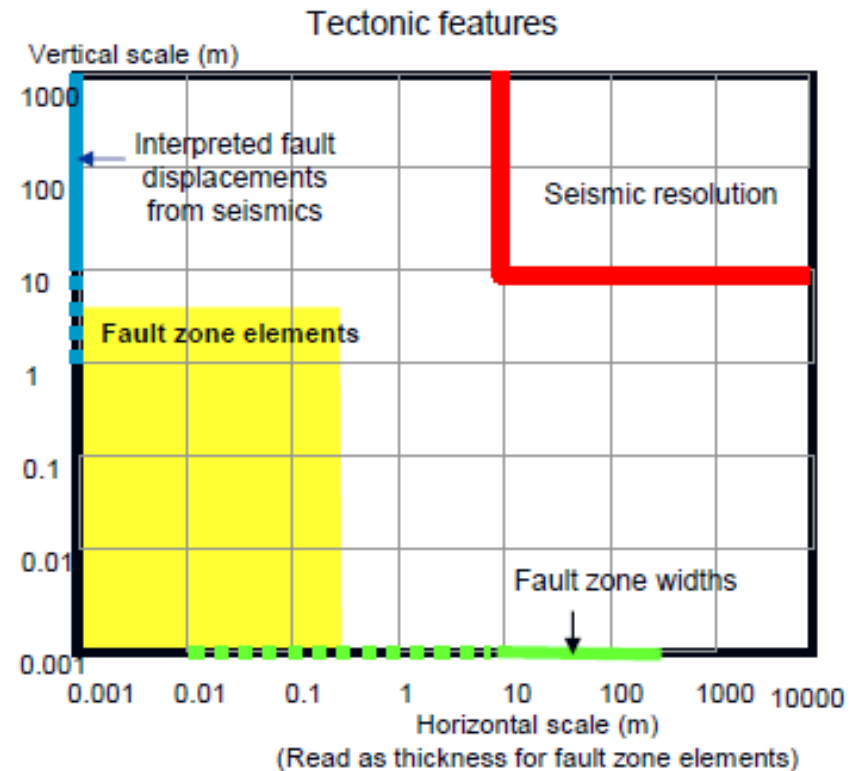
Geometric complexity of fault zones



Scales



- Heterogeneity on all scales
- Wide range of structures and geometries
- Composite features
- ...most of these features are sub-seismic....
- Description of sub-seismic elements: **outcrop data and core samples analysis**



Outcrop limitations



Erosion/weathering



Degradation/cover



Accessibility



Limited spatial exposure



Safety aspects

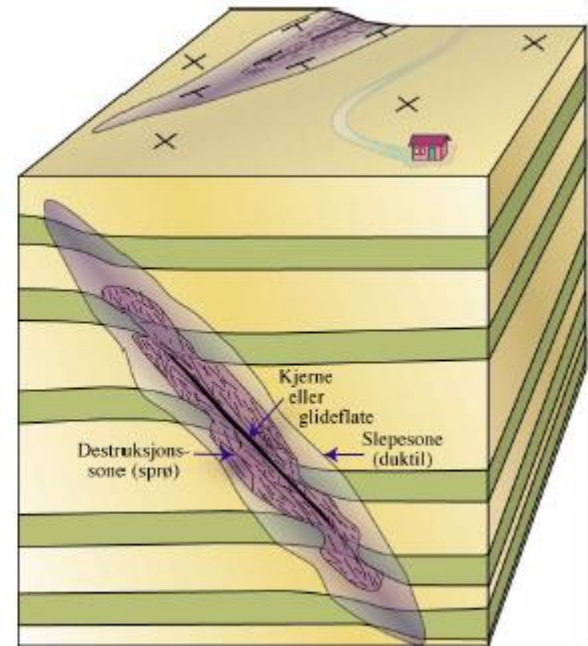
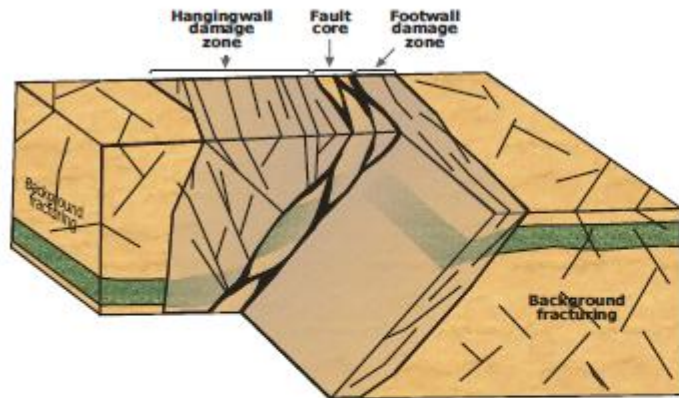
Core samples limitations

- Core samples are rare
- Risk of jamming while drilling
- Pressure problems
- Non-cohesive rocks
- Point data



Core from a fault zone in the Triassic Stockton Fm,
(USGS)

The whole picture?

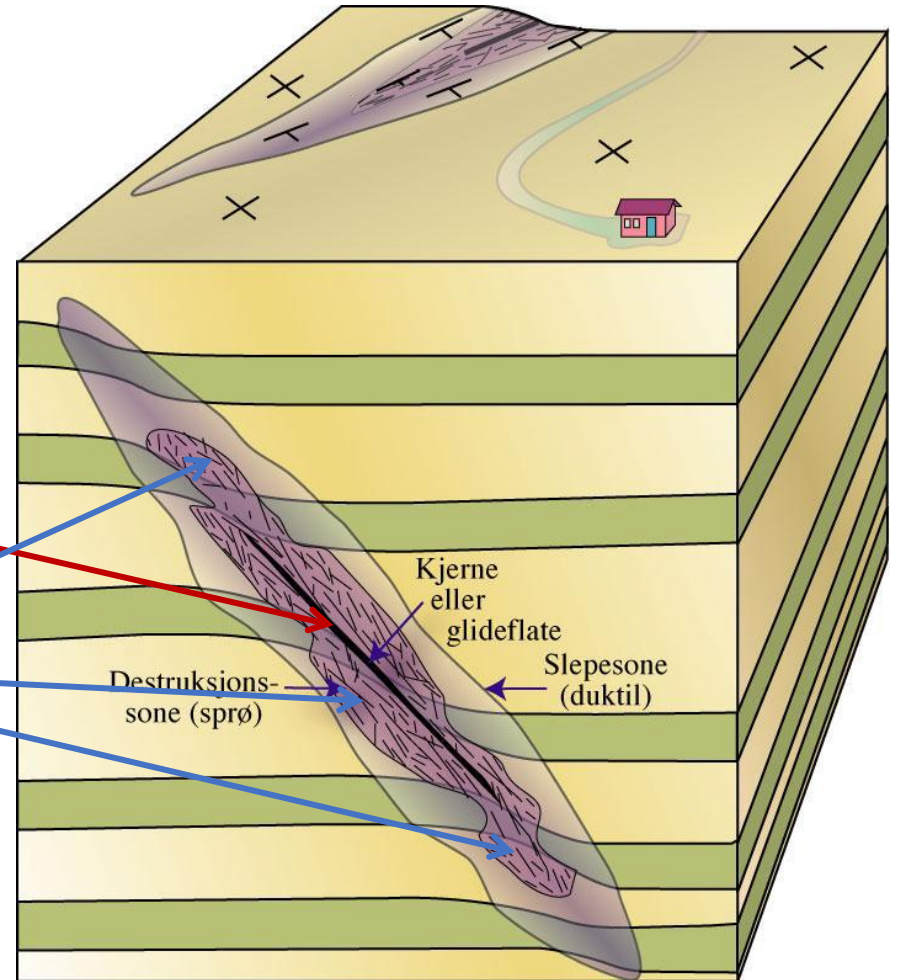


Fossen & Gabrielsen 2005

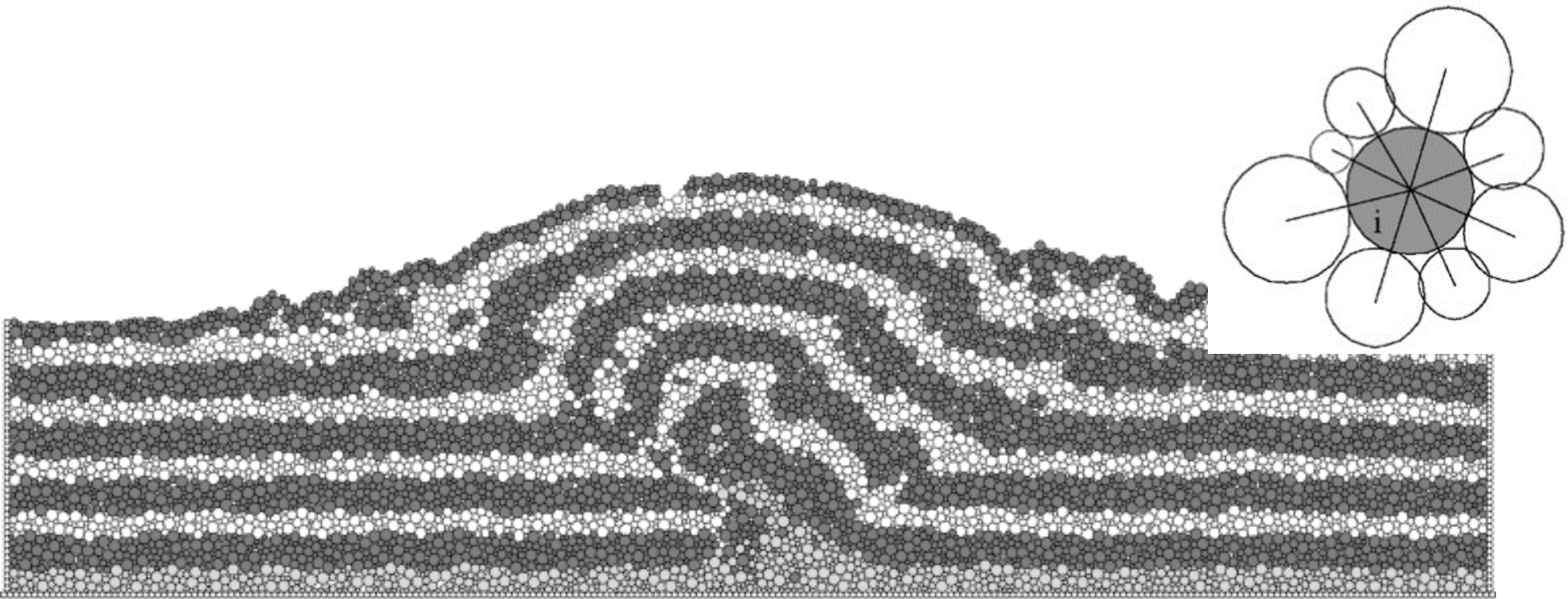
Nobody has ever seen complete fault picture in outcrops.
A complete 3D rendering of fault zone properties can only be achieved through modeling using compilations of empirical observations.

Fault zone model

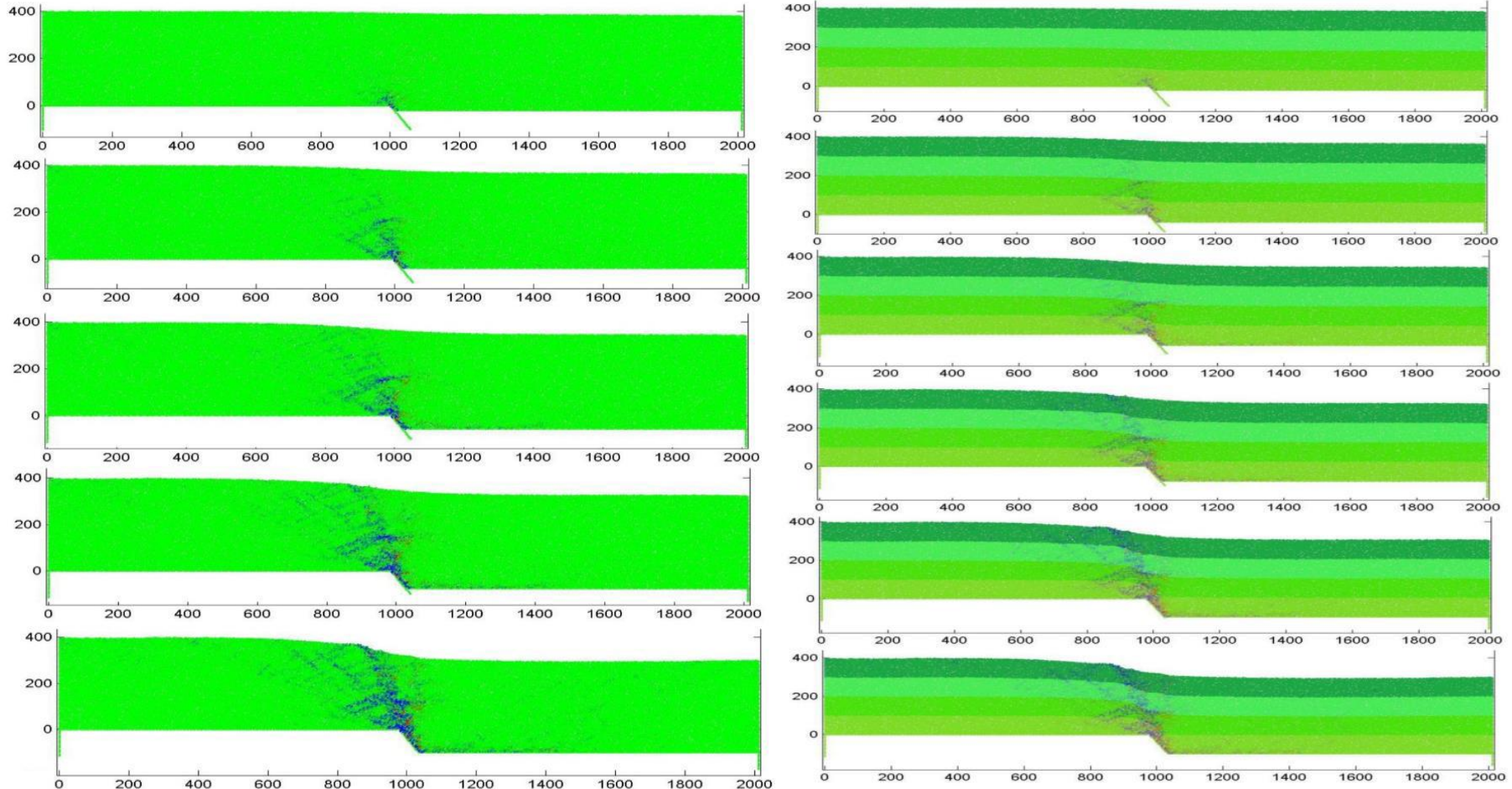
Fault is composed of
a fault core
and
a damage zone



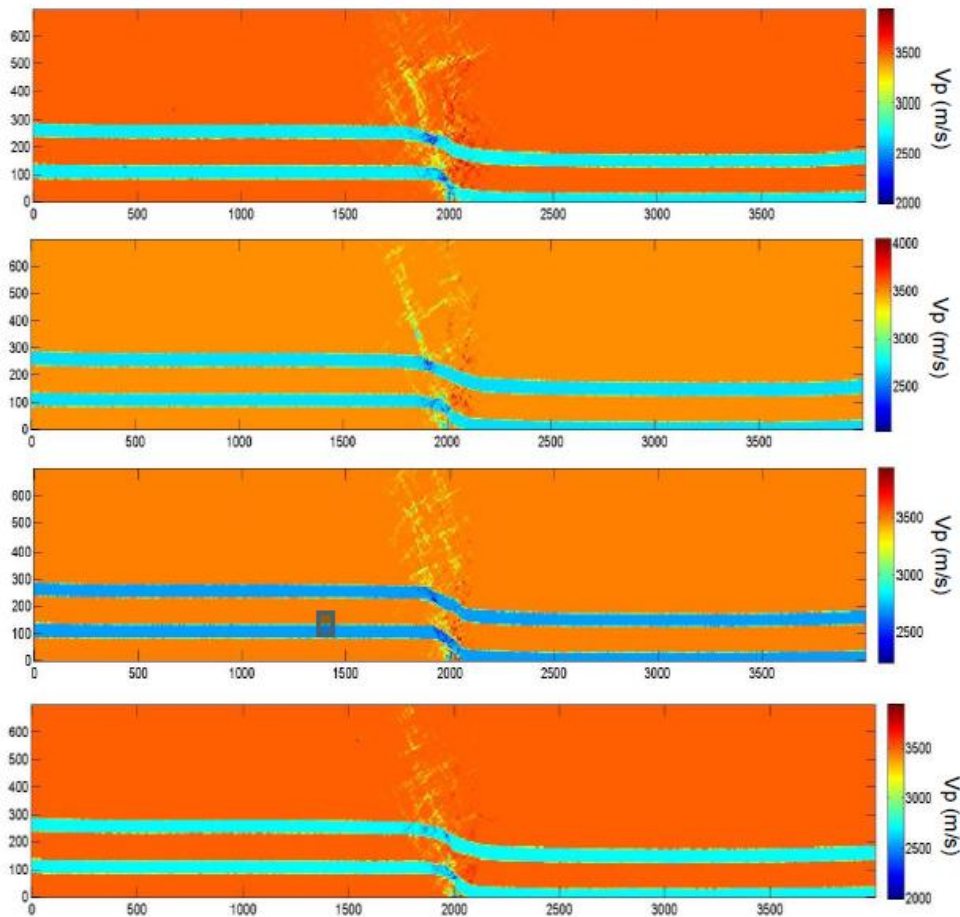
Geomechanical fault modelling: discrete elements



Geomechanical fault modelling: discrete elements



Geomechanical fault modelling: discrete elements



Porosity vs dilatation

$$\rho = \rho_0 (0.25\varepsilon + 1)$$

P-wave velocity vs dilatation

$$V_P = \begin{cases} V_P^0 (-0.25\varepsilon^2 - 0.5\varepsilon + 1), & -1 \leq \varepsilon < 0 \\ V_P^0 (0.25\varepsilon^2 - 0.5\varepsilon + 1), & 0 \leq \varepsilon \leq 1 \end{cases}$$

Fault zone model: Fault Facies (FF)

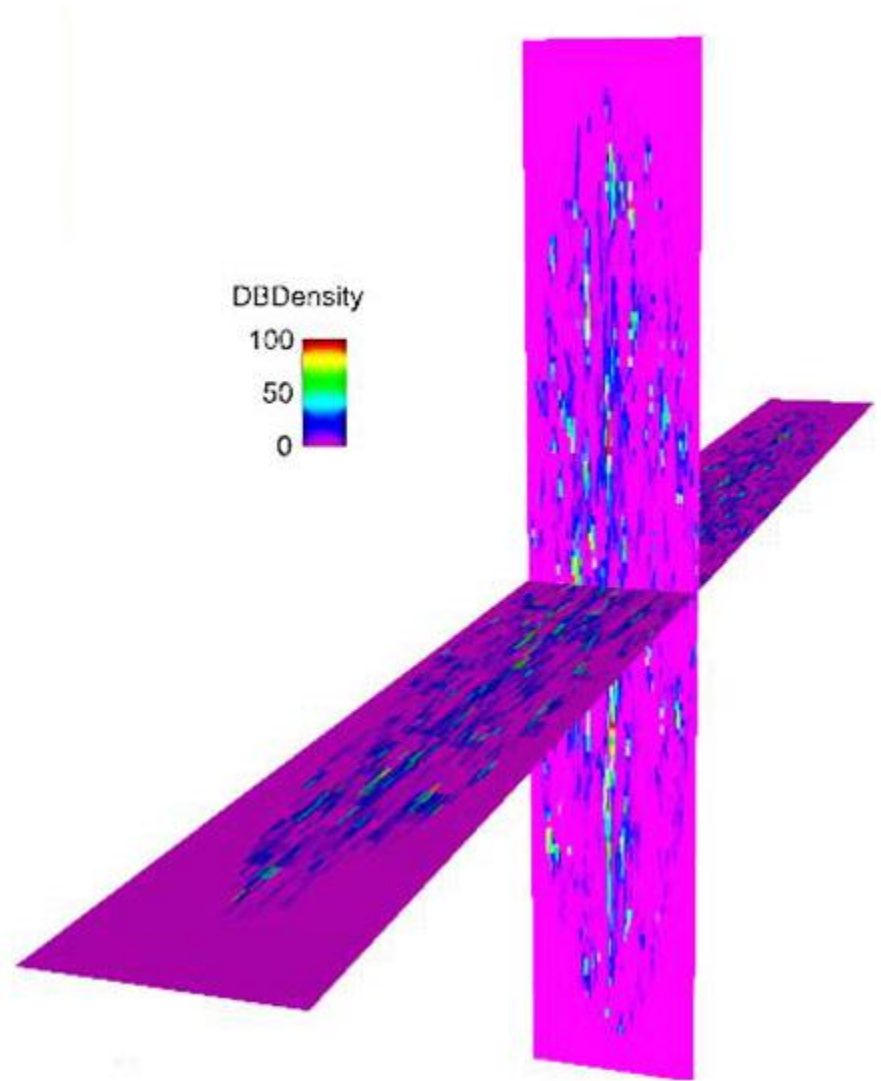
Deformation bands: millimeter-to-centimeter thick tabular features developed during deformation of porous rocks. Internal structure of the damage zone is modeled using four explicitly rendered **Fault Facies (FF)** defined by discretizing deformation band densities:

- 1) H $>20/m$ (H),
- 2) M $6-20/m$ (M),
- 3) L $1-5/m$ (L), and
- 4) U: $0/m$ (U) – these facies define undeformed hostrock elements present in the fault zone.

.

Fault Zone Model

Field studies show that deformation bands are not uniformly distributed in fault damage zones: Fault Facies with high deformation band densities are close to the main fault slip-surface, and fault facies with low deformation band densities are farther away from it. The spatial distribution of fault facies inside the fault damage zone is modeled using **Truncated Gaussian Simulation (TGS)**.



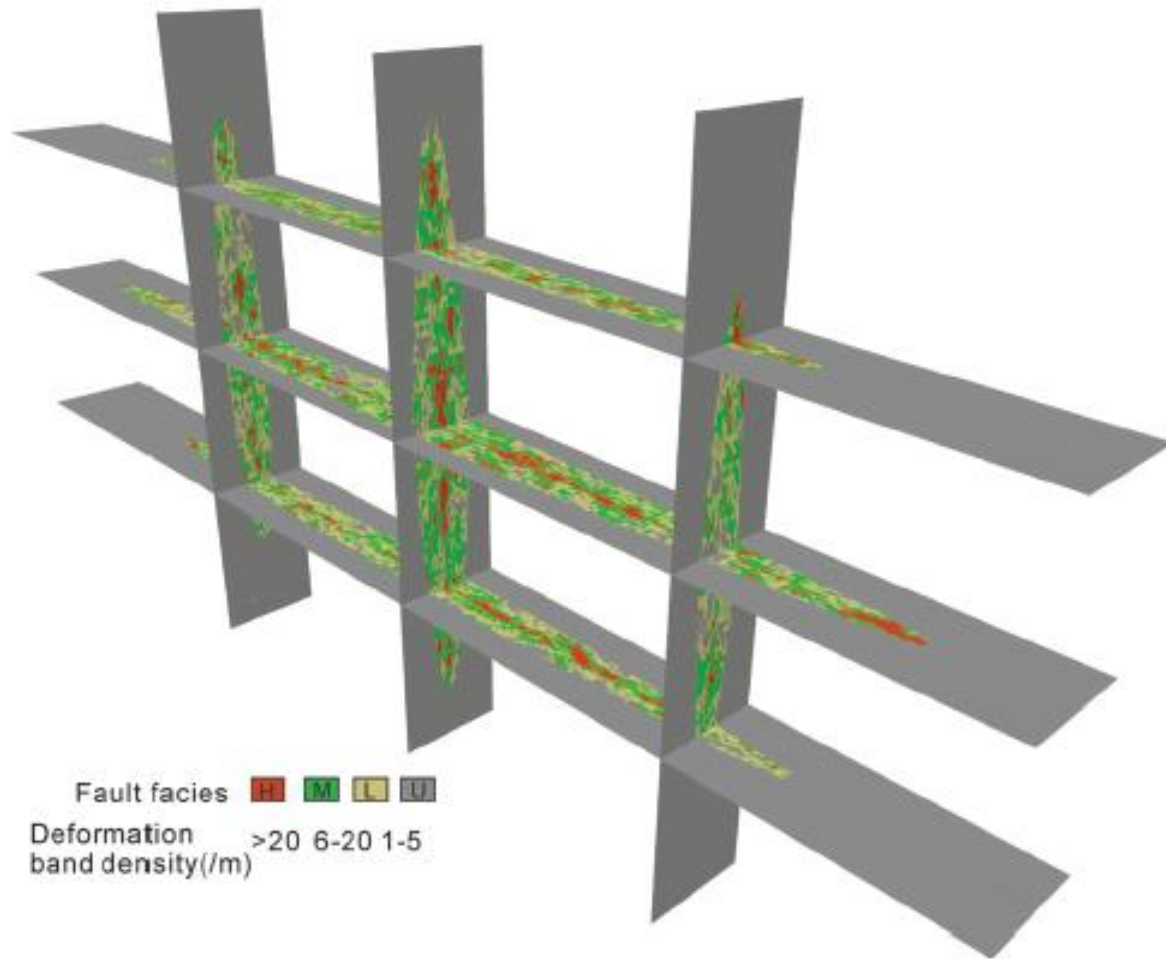
Fault Zone Model:

The variogram is the **main input parameter** of Truncated Gaussian Simulation (TGS). The variogram of a statistically homogeneous isotropic random function F with constant mean is described by the following equation:

$$2\gamma(h) = \text{Var}\{F(x) - F(y)\} = E\{(F(x) - F(y))^2\}$$

Variogram and proportion trends for TGS were constrained using an extensive empirical data set consisting of deformation band density logs from 106 scanlines across damage zones of extensional faults in multiple outcrops (CIPR, Norway).

3D fault zone model used in this study: 100m x 1200 m x 600 m



$$h_x = h_y = h_z = 5\text{m}$$

Total number of
cells = 2.88×10^6

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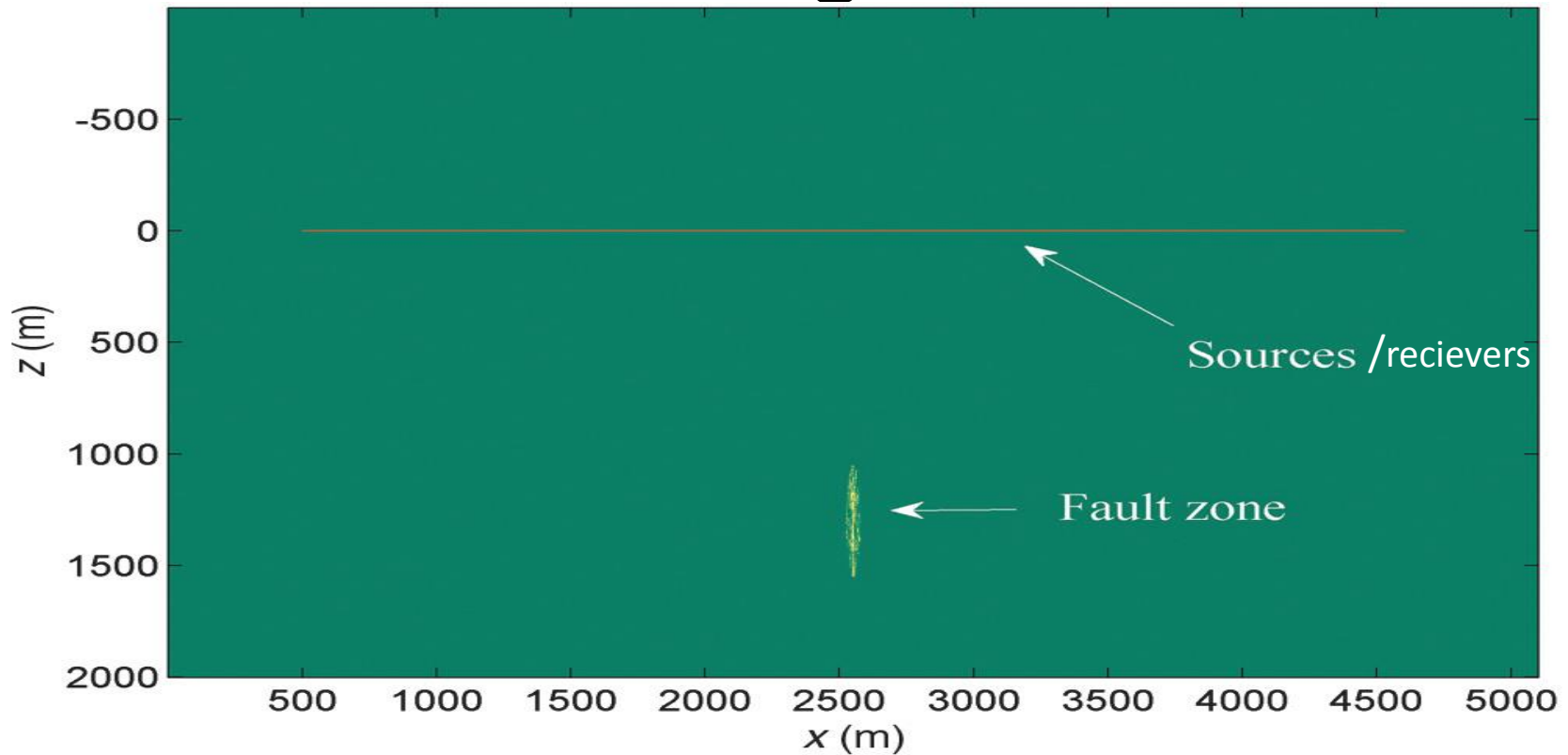
Seismic modeling

For numerical simulation of seismic wave propagation we used the standard staggered-grid finite-difference scheme. As discussed in a series of papers this scheme allows accurate handling of sharp interfaces of a model, which in turn provides a correct representation of reflection coefficients.

We use the model with spatial discretization of 1 m, which yields approximately 10 grid points per minimal wavelength. However, to represent the small-scale structure of the fault zone, it was necessary to use spatial steps of 0.2 m. To preserve numerical simulation efficiency, a local time-space mesh refinement was applied inside and adjacent to the target object. The details of the algorithm can be found in:

Kostin, V., V. Lisitsa, G. Reshetova, and V. Tcheverda, 2015, Local time-space mesh refinement for simulation of elastic wave propagation in multi-scale media: Journal of Computational Physics, 281, 669–689.

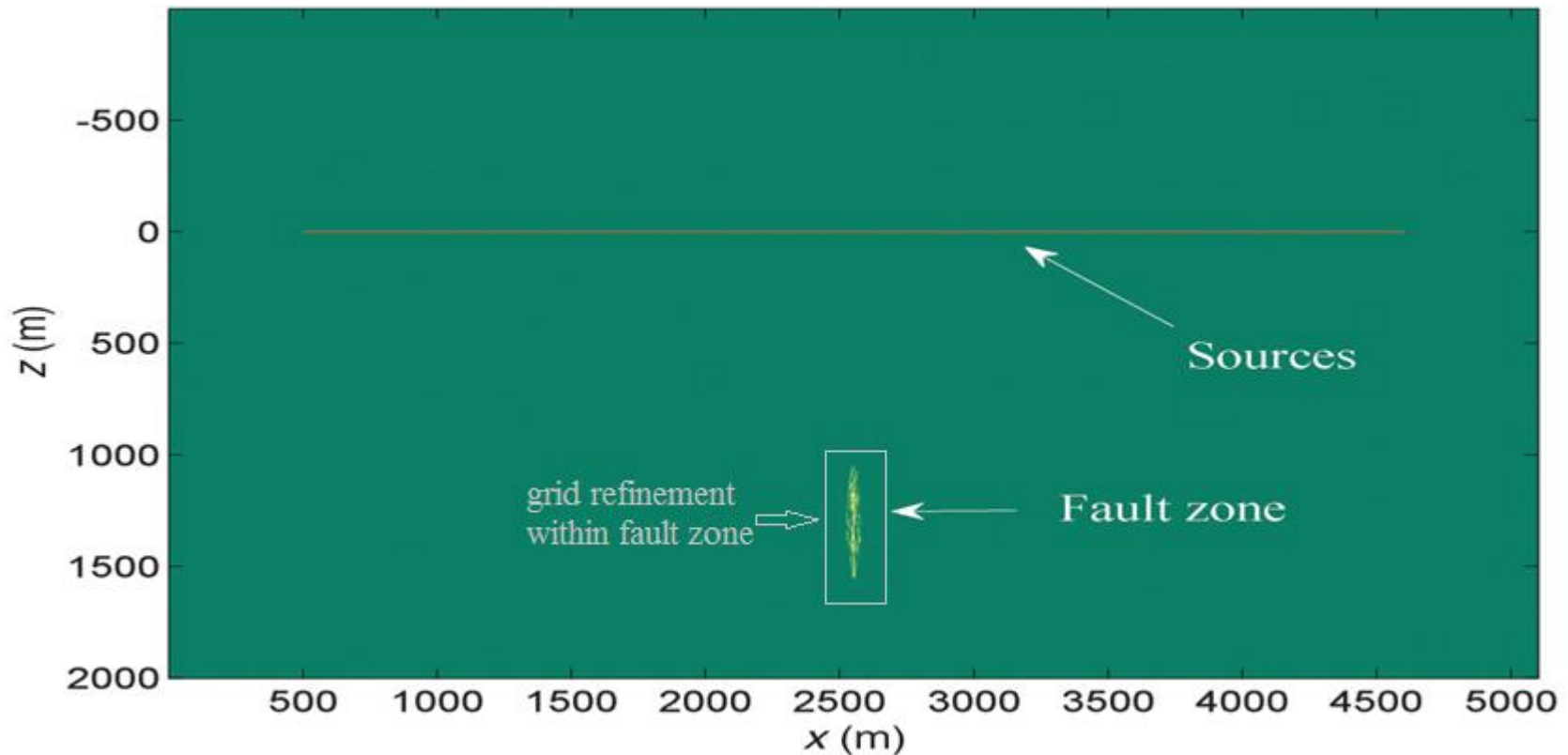
Seismic modeling



Source function: Ricker pulse with dominant frequency 25 Hz.

Totally 83 sources spaced with 50 m, receivers along the same line with step of 25 m.

Seismic modeling



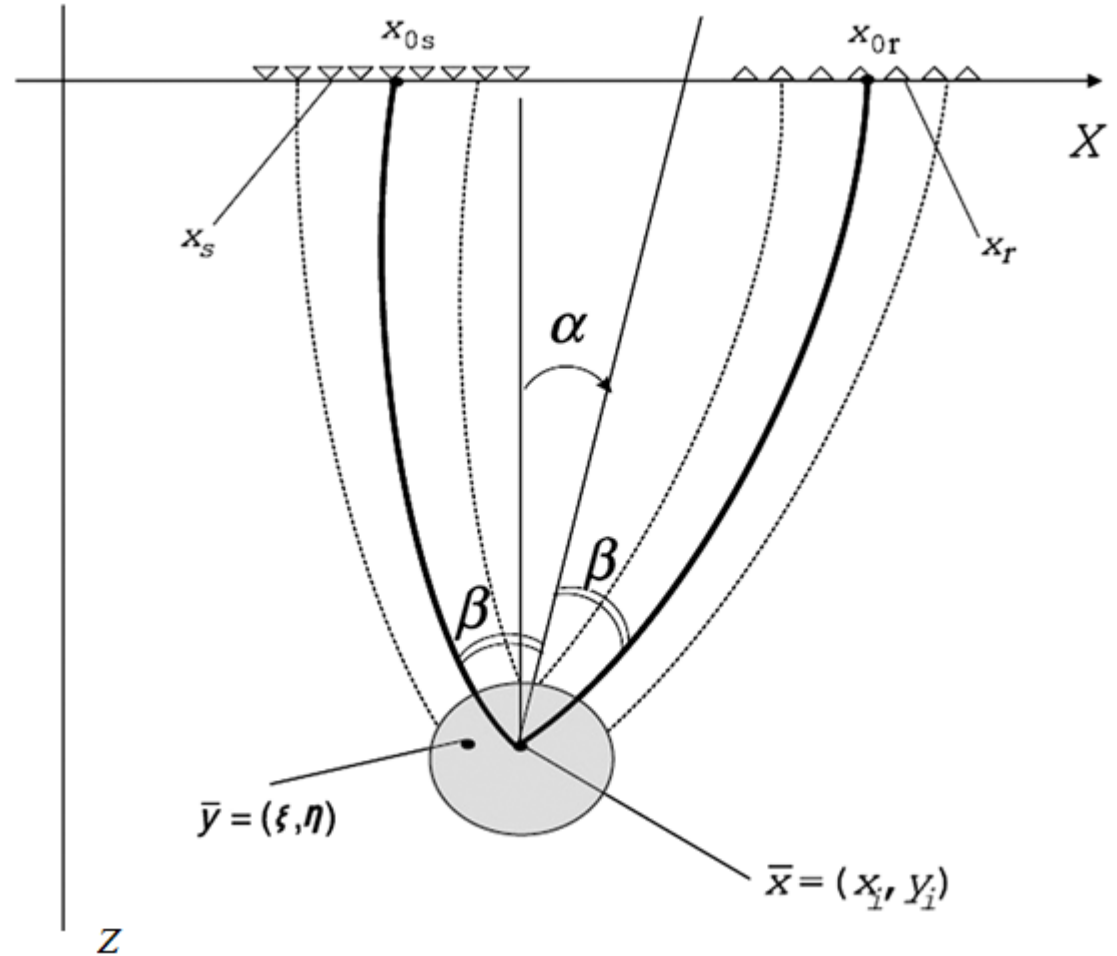
To provide reliable numerical simulation for seismic waves' propagation within a fault area for a reasonable cost we perform local refinement of a grid in time and space: from 1 m to 0.2 m (see Kostin et al., 2015).

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Seismic fault imaging

We are doing seismic fault imaging by diffraction/scattering imaging procedures based on asymmetric summation



Seismic fault imaging in scattered waves

We do GB tracing from the target point (x_i, z_i) towards acquisition system and do asymmetric summation Of data $\Phi(x_r, x_s; \omega)$ produced by the source X_s and recorded in the receiver X_r :

$$f_{pp}(x_i, z_i) = \int \tau_s^{gb}(x_s; x_i, z_i; \alpha, \beta; \omega) \Gamma_r^{gb}(x_s; x_i, z_i; \alpha, \beta; \omega) \Phi(x_r, x_s; \omega) dx_r dx_s d\alpha d\omega$$

Asymptotic analysis of the right hand side proves that f_{pp} is PP-impedance at the target point (x_i, z_i) .

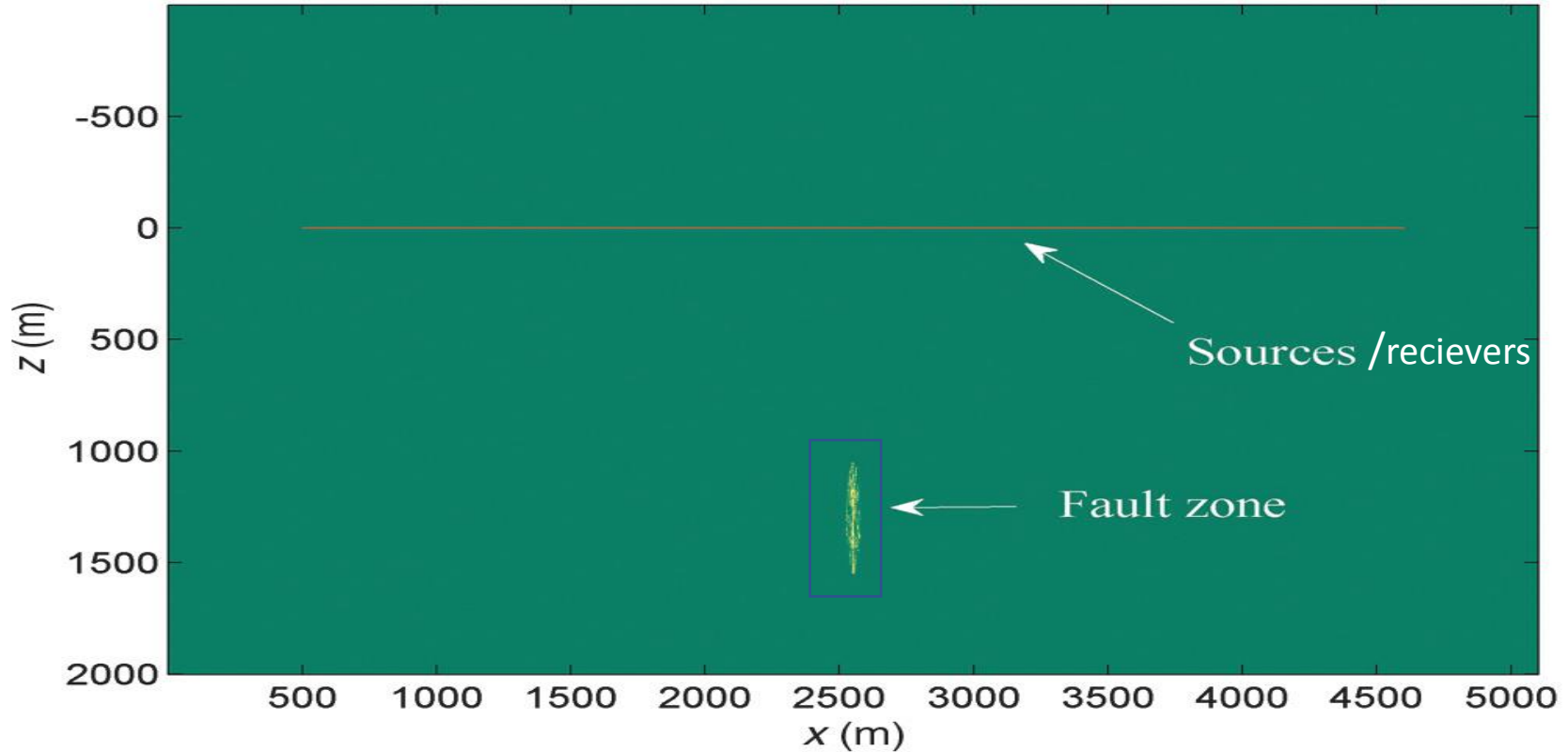
Remarks: the image in each point is computed independently and, hence, ensures excellent parallelization and scalability.

For details see Protasov M., Reshetova G. and Tcheverda V. Fracture detection by Gaussian beam imaging of seismic data and image spectrum analysis // Geophysical Prospecting. – 2016. – v.64(1). – 68 – 82.

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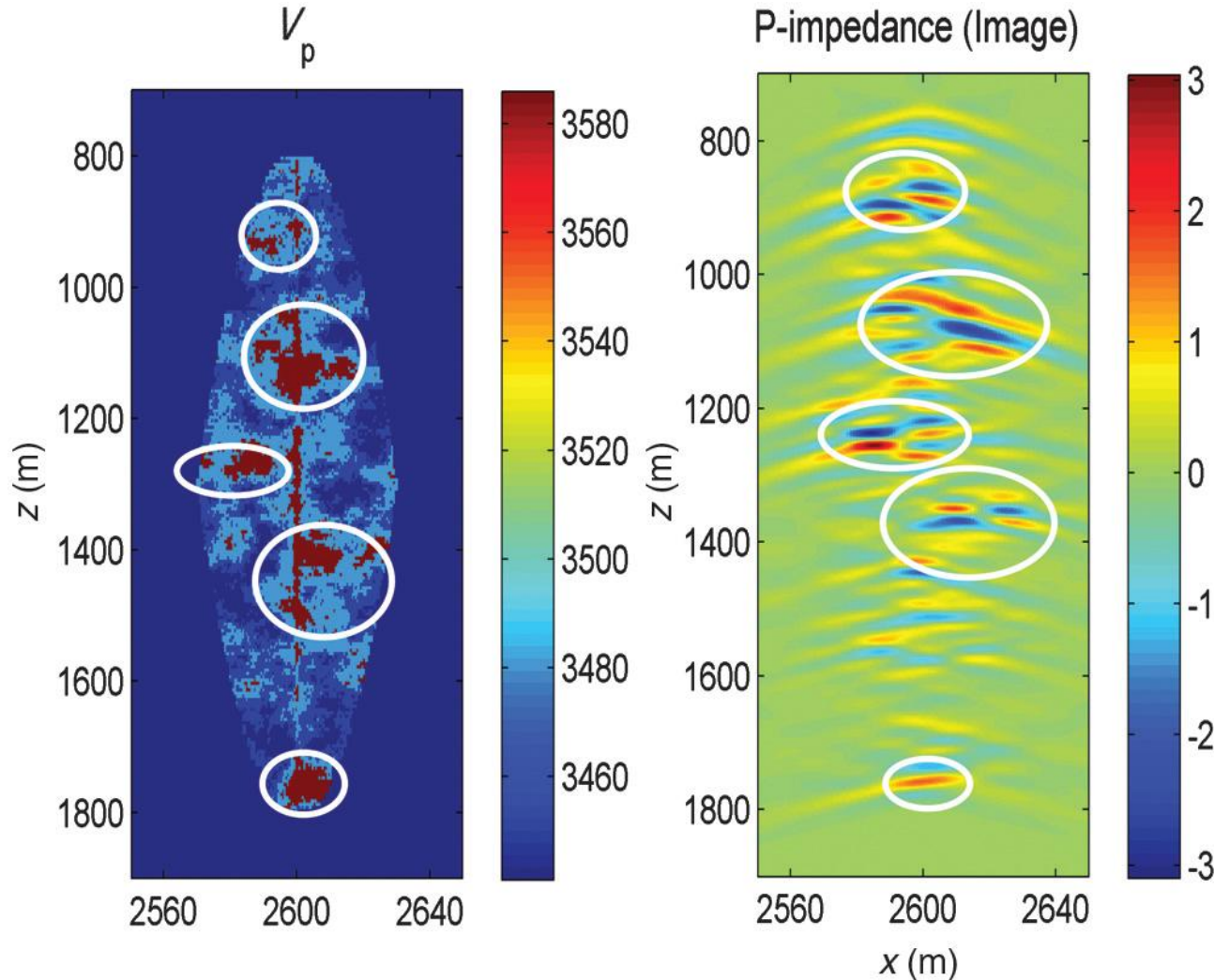
Numerical experiments



Source function: Ricker pulse with dominant frequency 25 Hz.

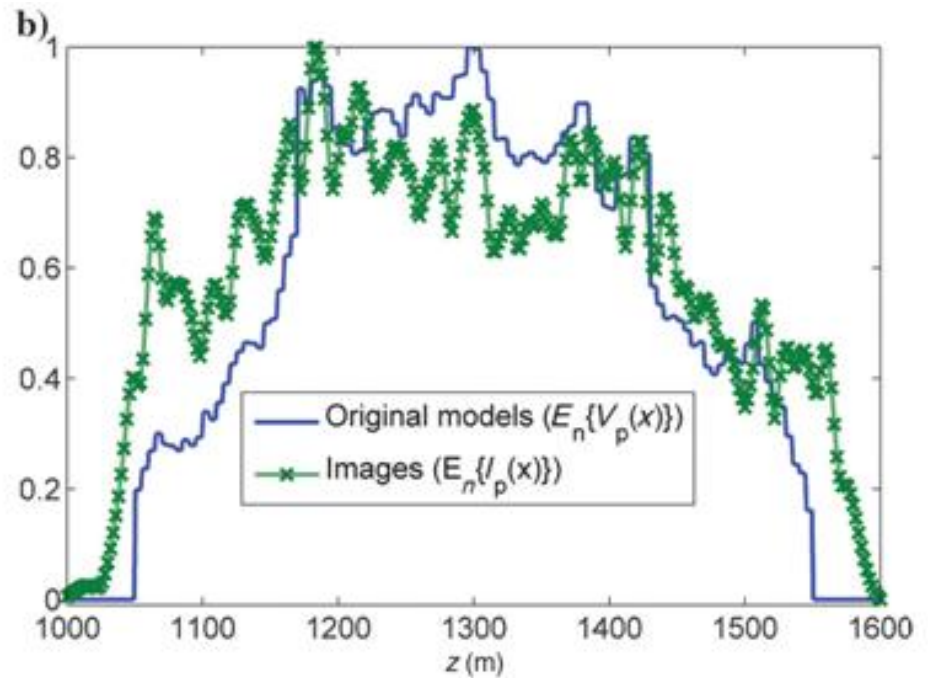
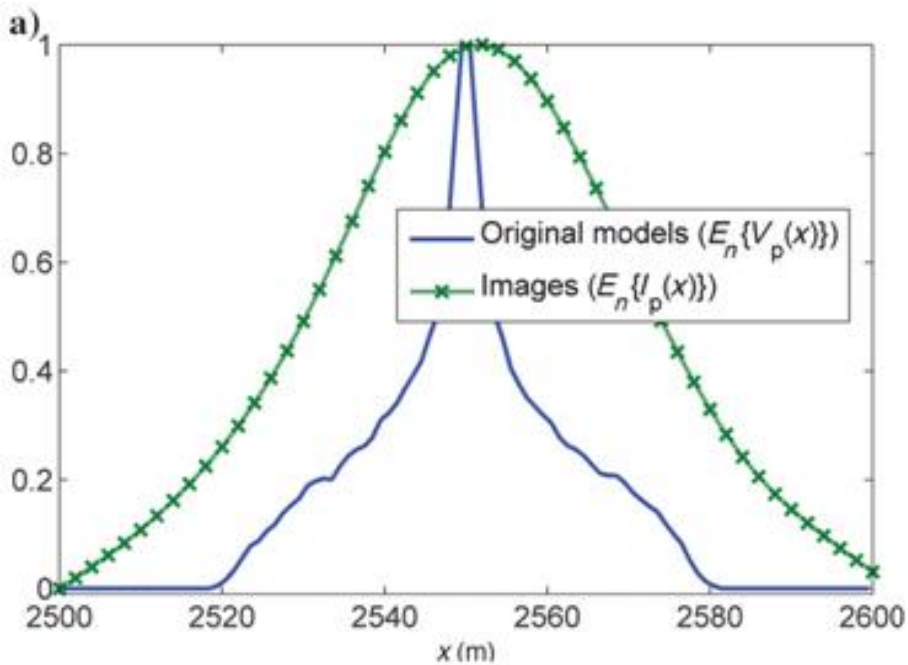
Totally 83 sources spaced with 50 m, receivers along the same line with step of 25 m.

Numerical experiments



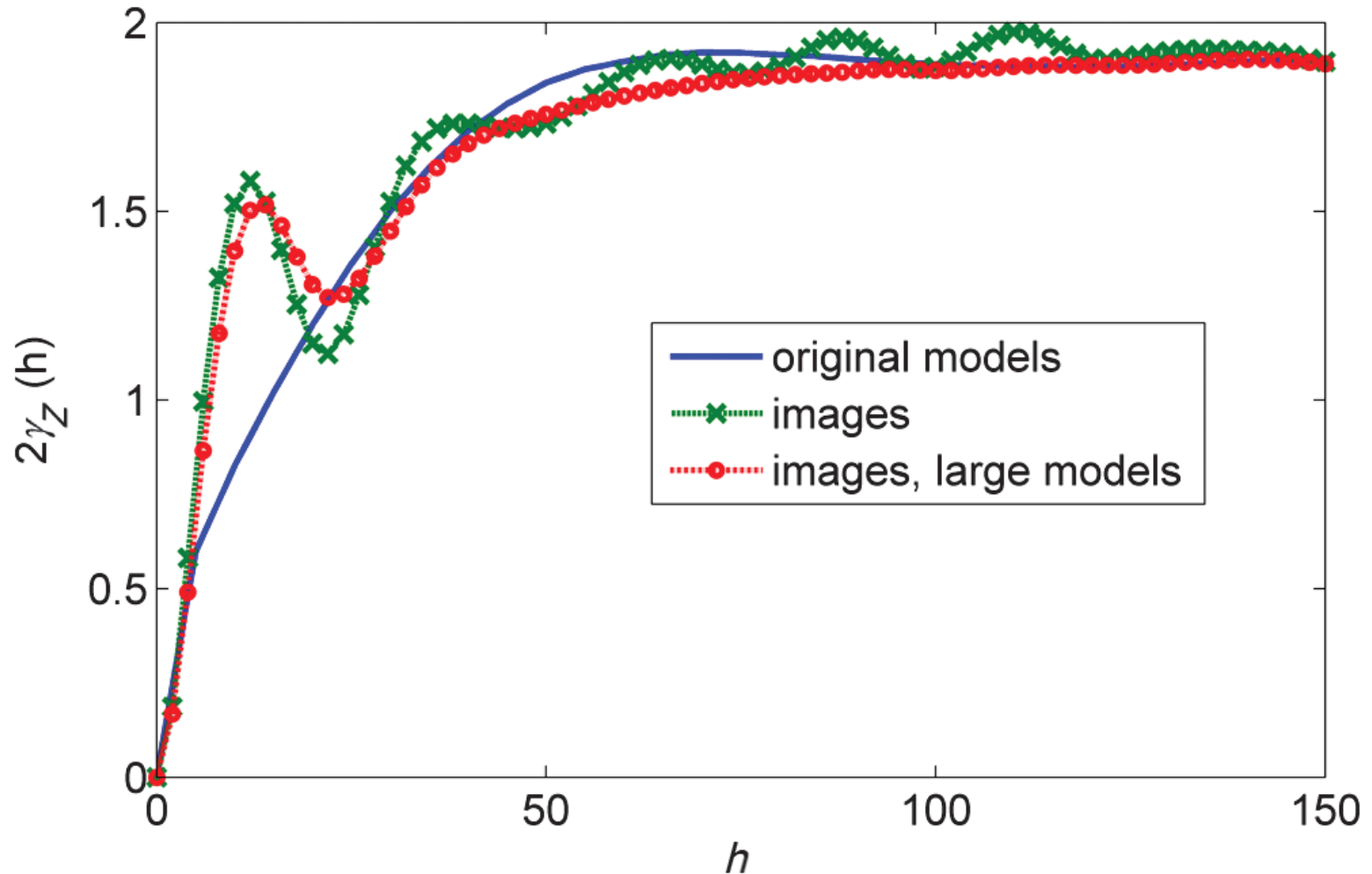
Comparison of
the (a) models
and (b) seismic
images:
 $l_x = 25$ m,
 $l_z = 50$ m.

Numerical experiments



Normalized profiles of averaged V_p for the facies model and impedance for the seismic images in the (a) x and (b) z -directions.

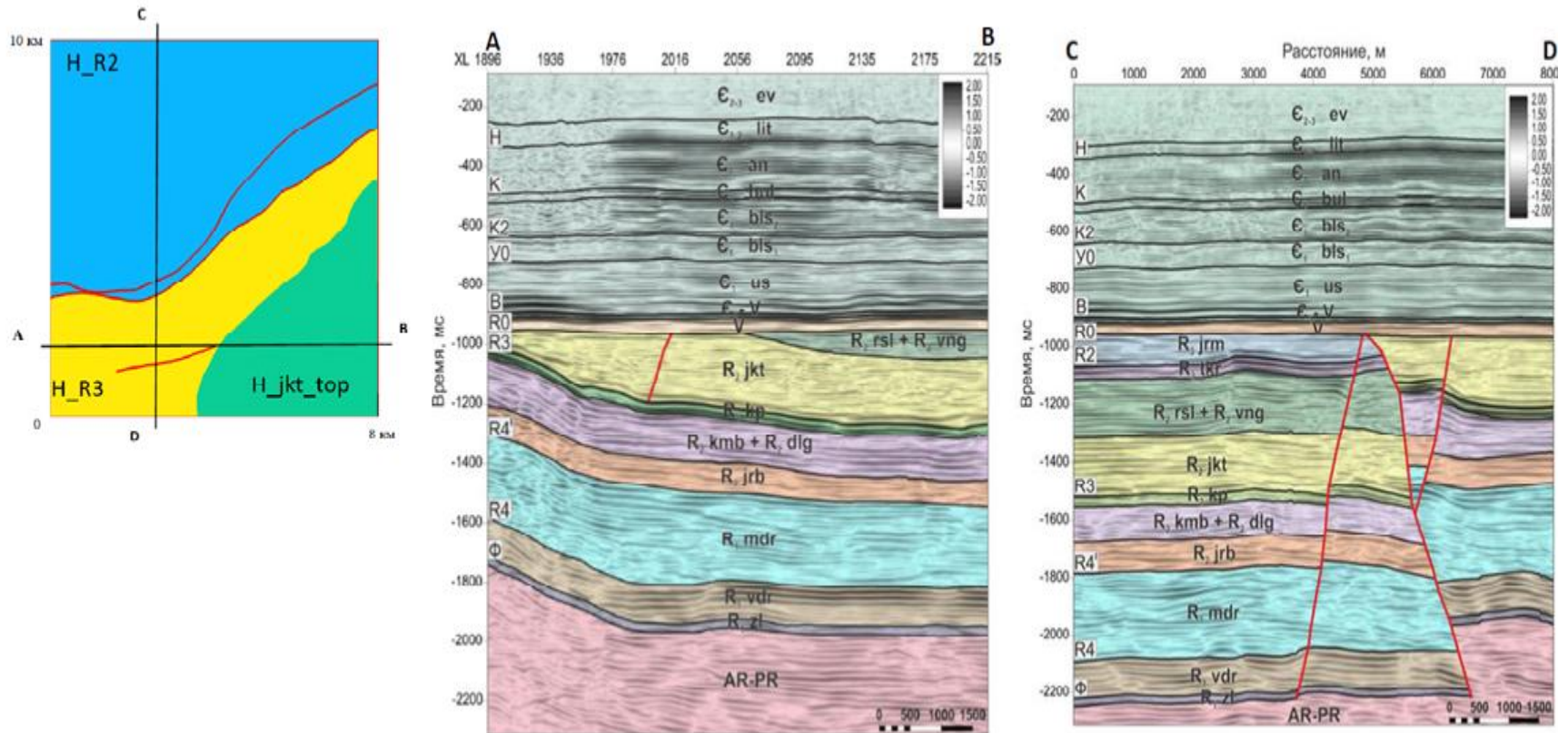
Numerical experiments: variograms



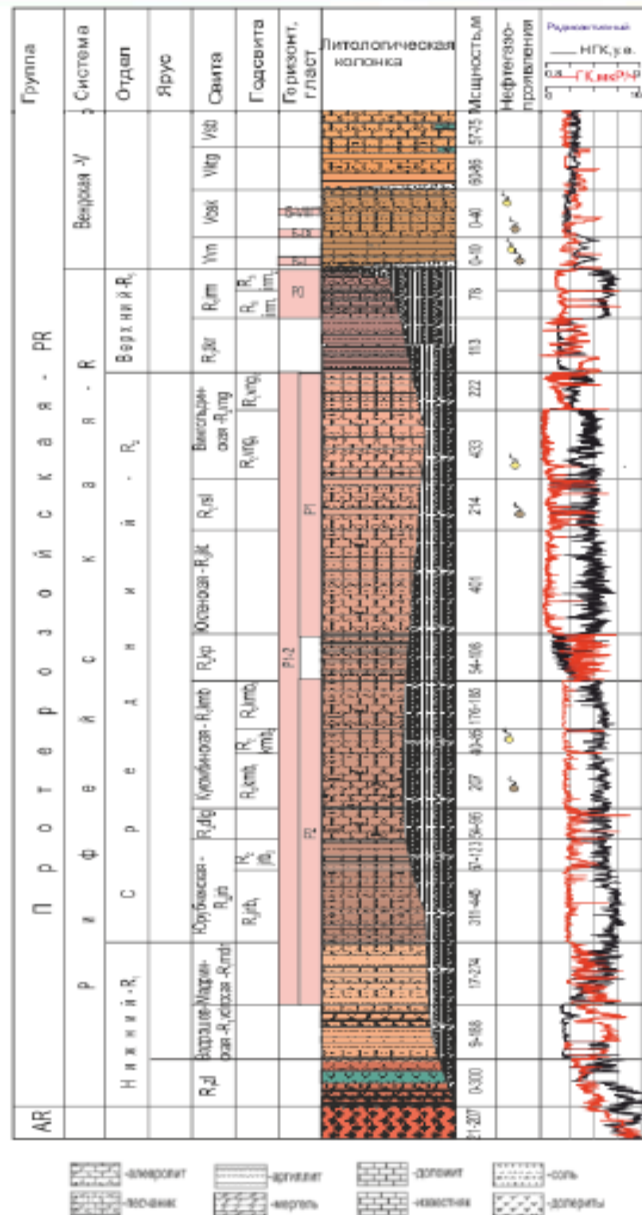
Variograms in the x-direction estimated for the input model (solid line) and seismic images: dashed line for small models and dashed-dotted line for large models.

Трёхмерные постановки: Апробация на синтетических данных для реалистичной модели

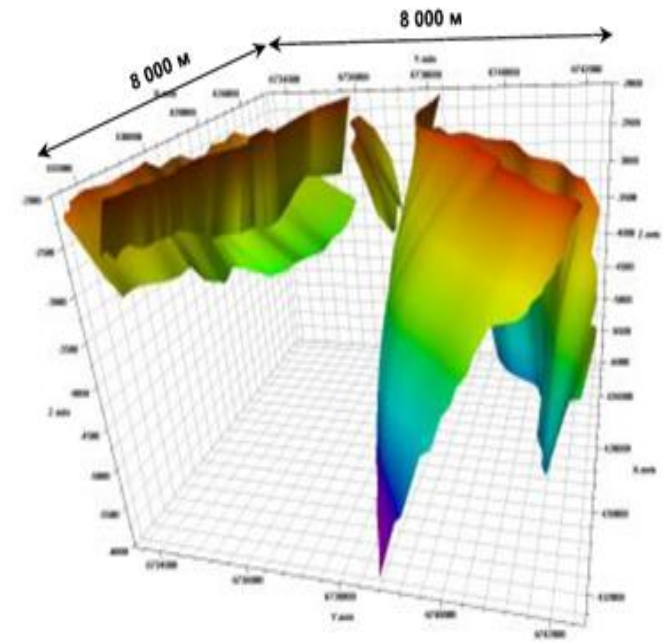
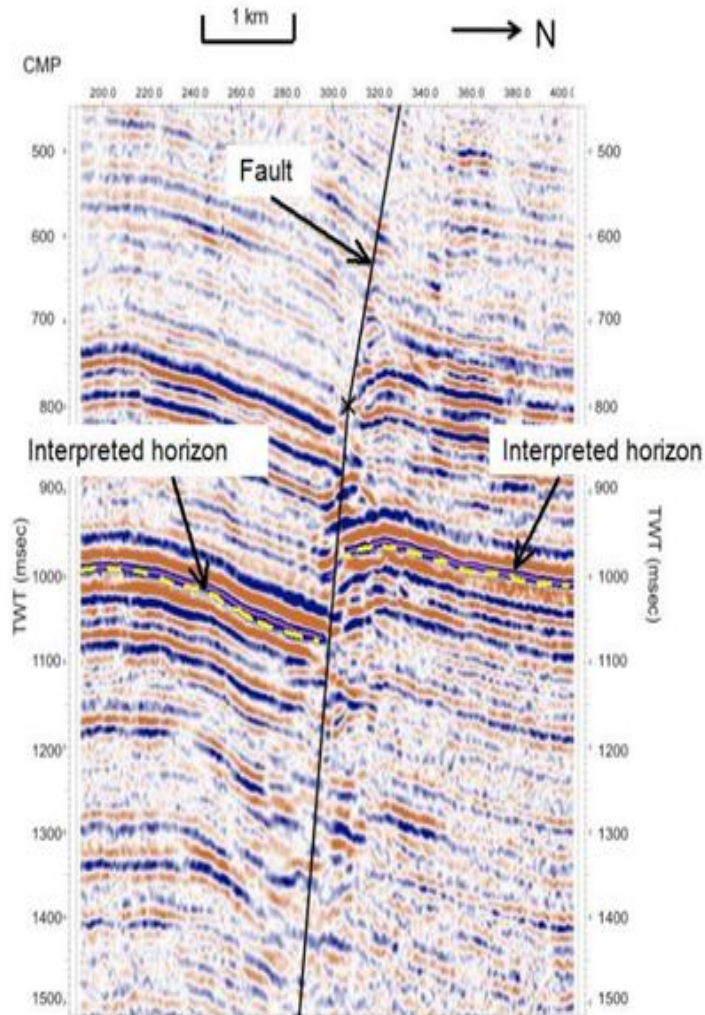
Построение 3D модели: структурная модель



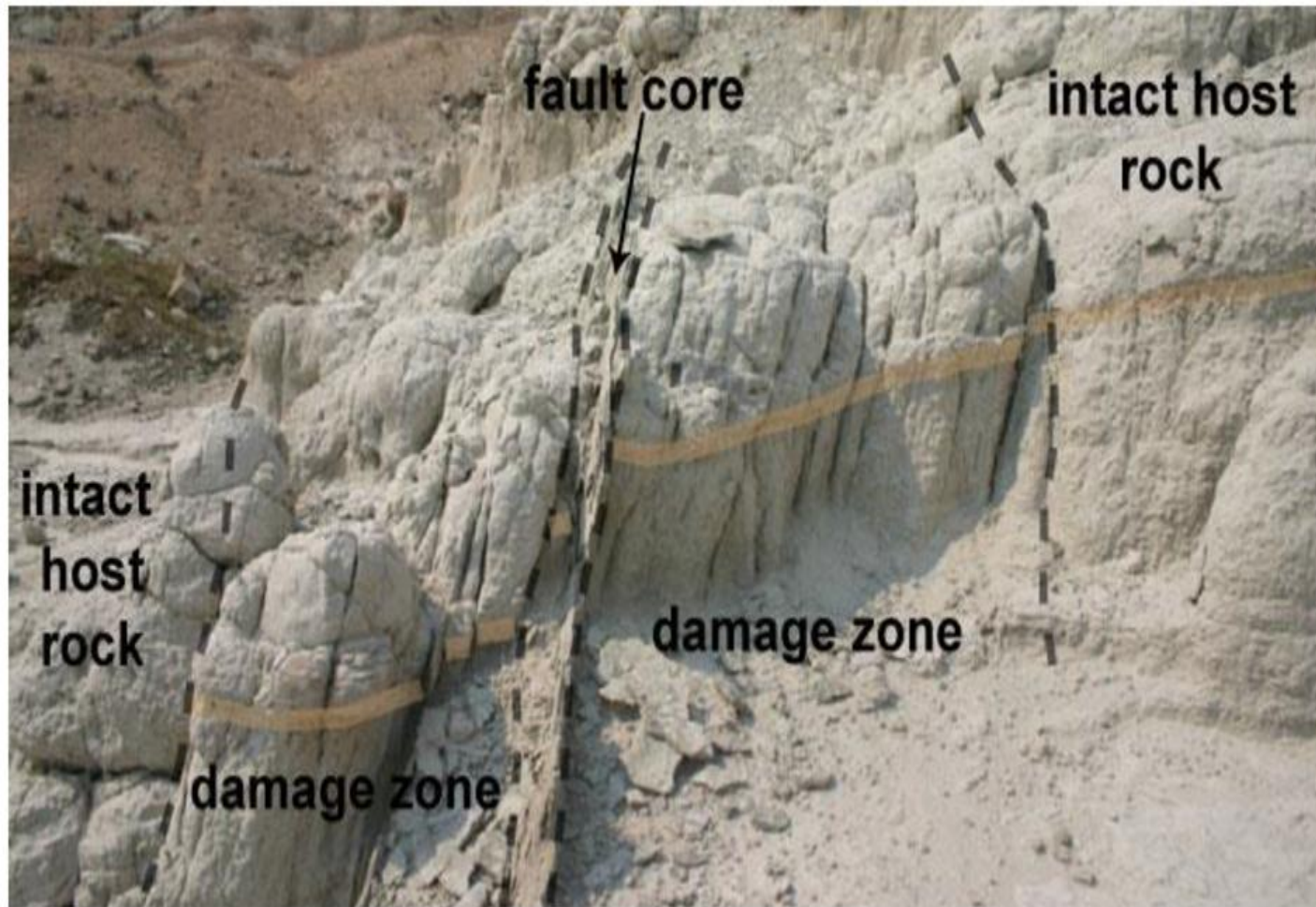
Параметры среды между слоями



Построение 3D геологической модели: разломы и приразломные зоны

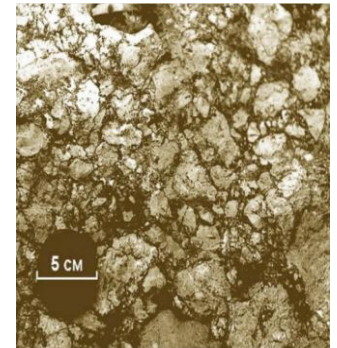
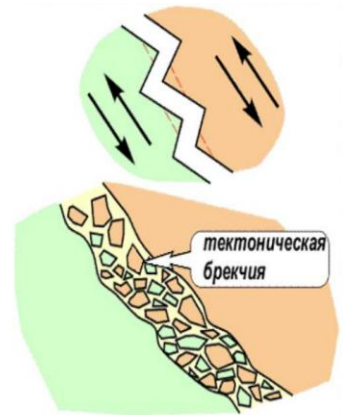


Построение 3D геологической модели: разломы и приразломные зоны

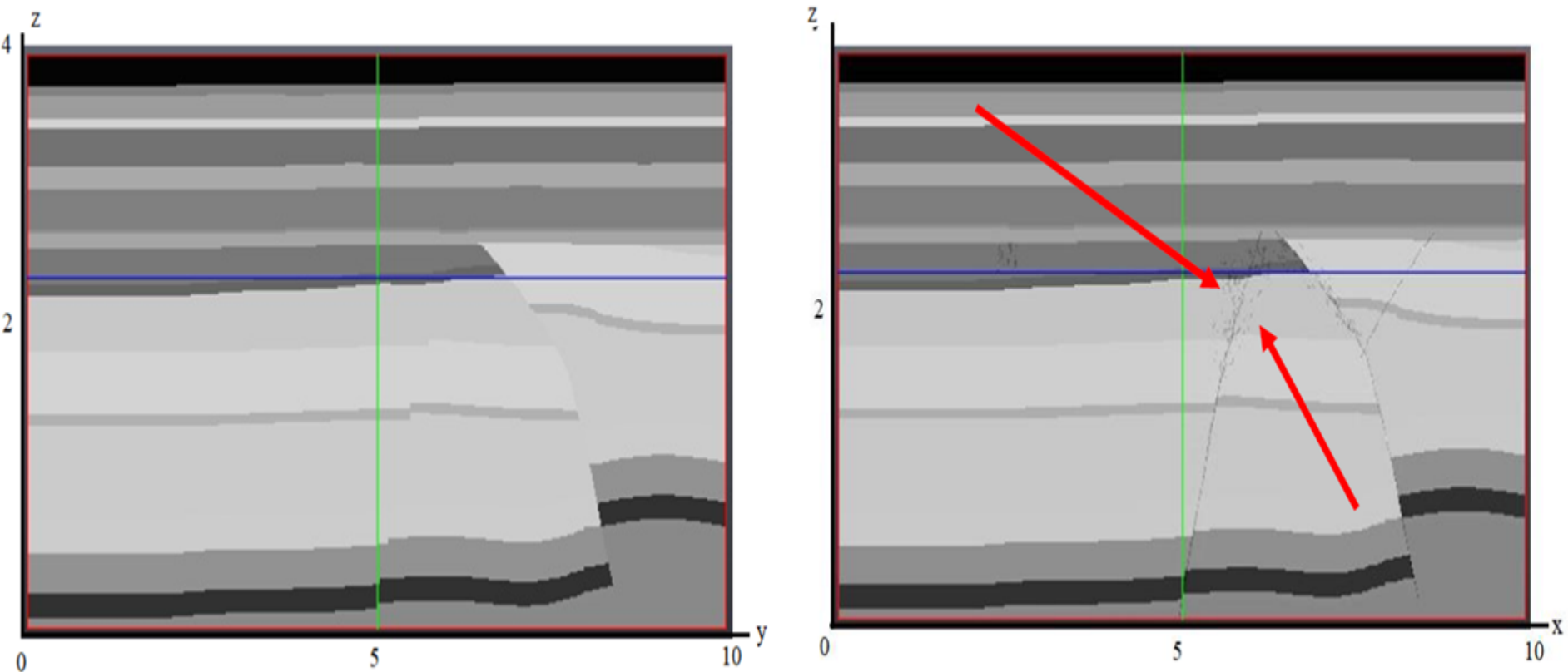


Построение 3D геологической модели: разломы и приразломные зоны

Сбросы и взбросы образуются при растяжении земной коры. Первоначально возникают трещины отрыва, для которых характерны неровные стенки и наличие между ними некоторого пустотного пространства. При смещении блоков неровности скалываются, а обломки заполняют промежутки между стенками трещинами. Впоследствии обломки цементируются более мелкими продуктами истирания и минералами, отложившимися из гидротермальных растворов.

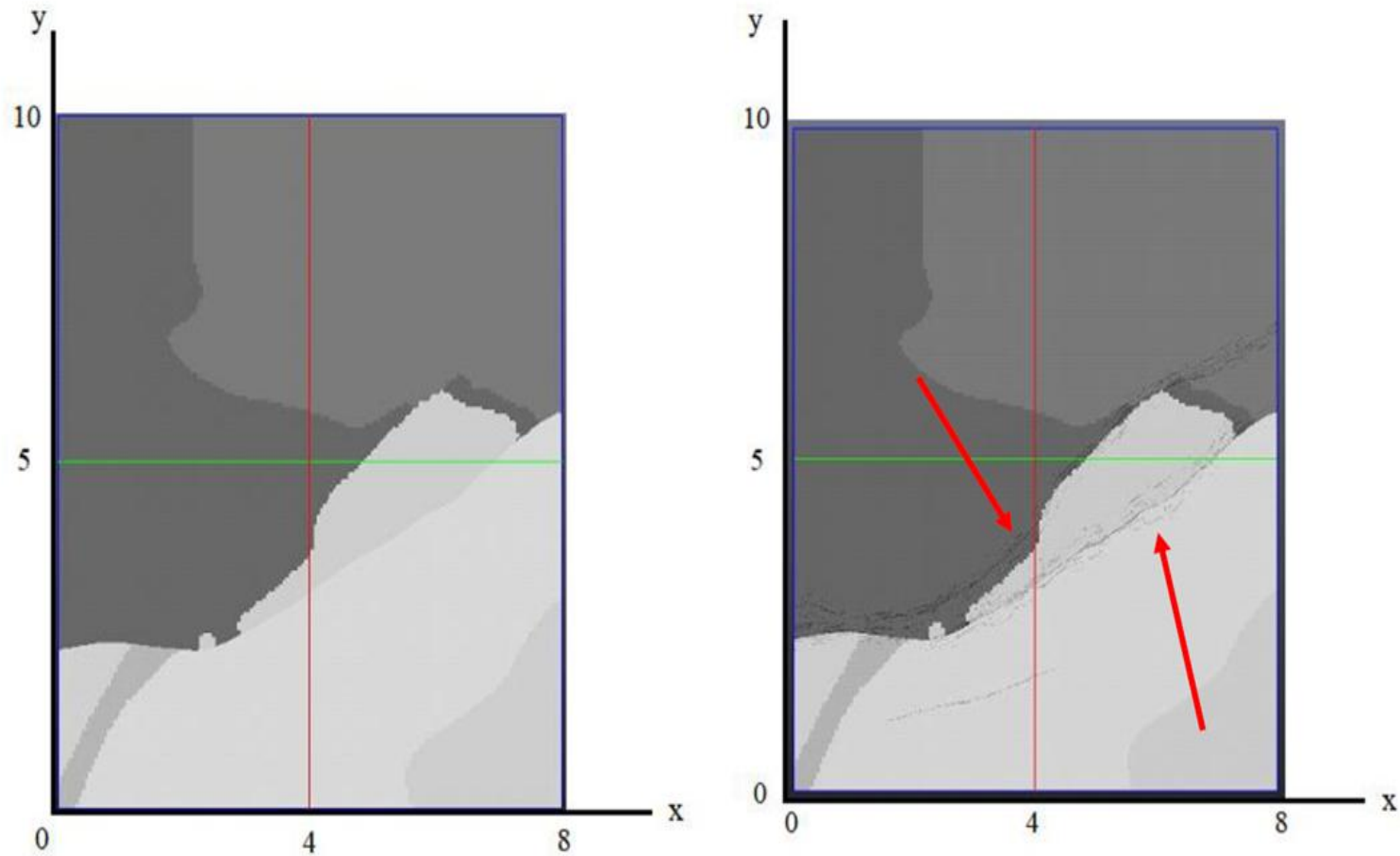


Построение 3D геологической модели: разломы и приразломные зоны



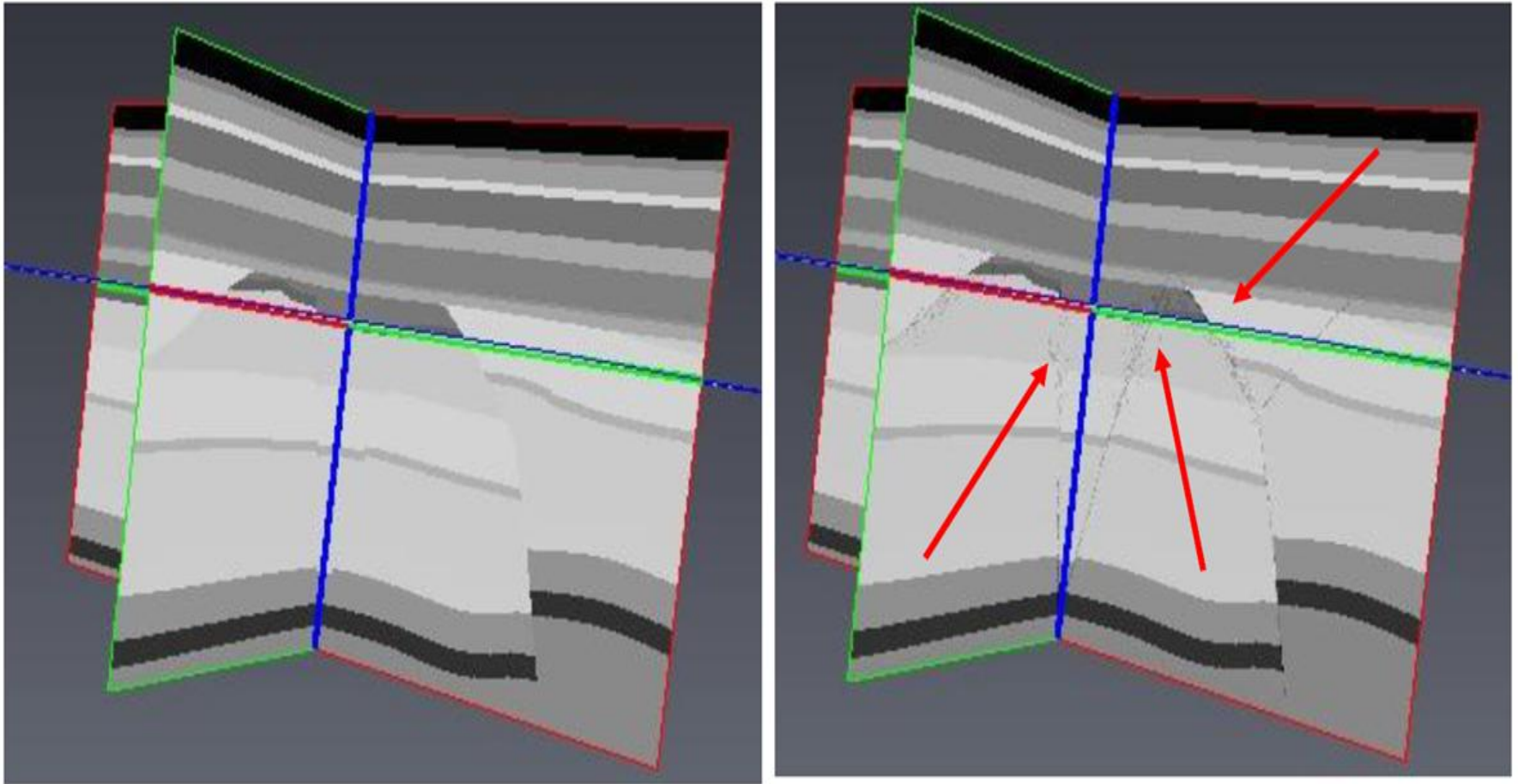
Слева: разломы без зоны дробления, справа – с зоной дробления

Построение 3D геологической модели: разломы и приразломные зоны



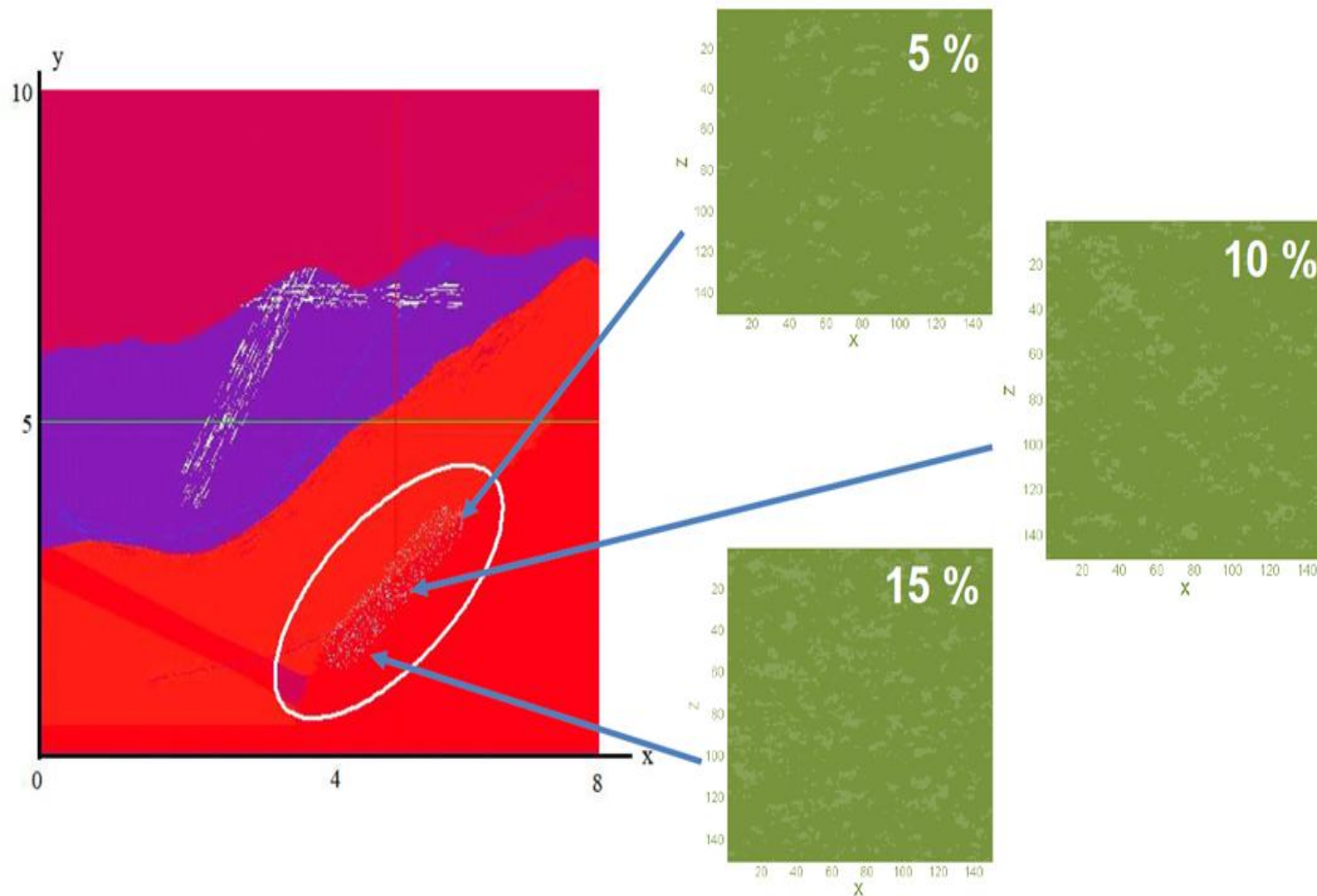
Слева: разломы без зоны дробления, справа – с зоной дробления

Построение 3D геологической модели: разломы и приразломные зоны

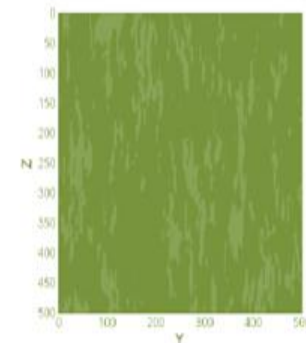
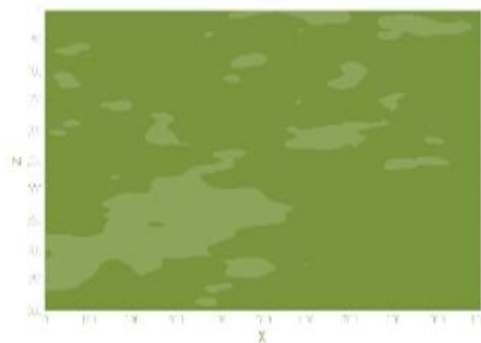
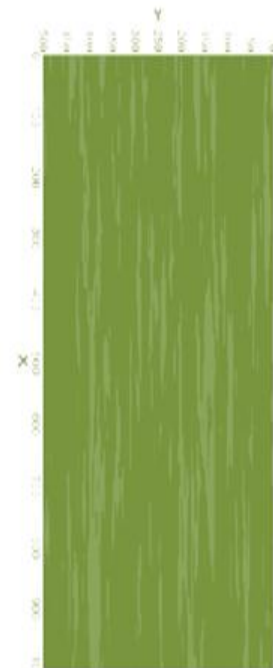
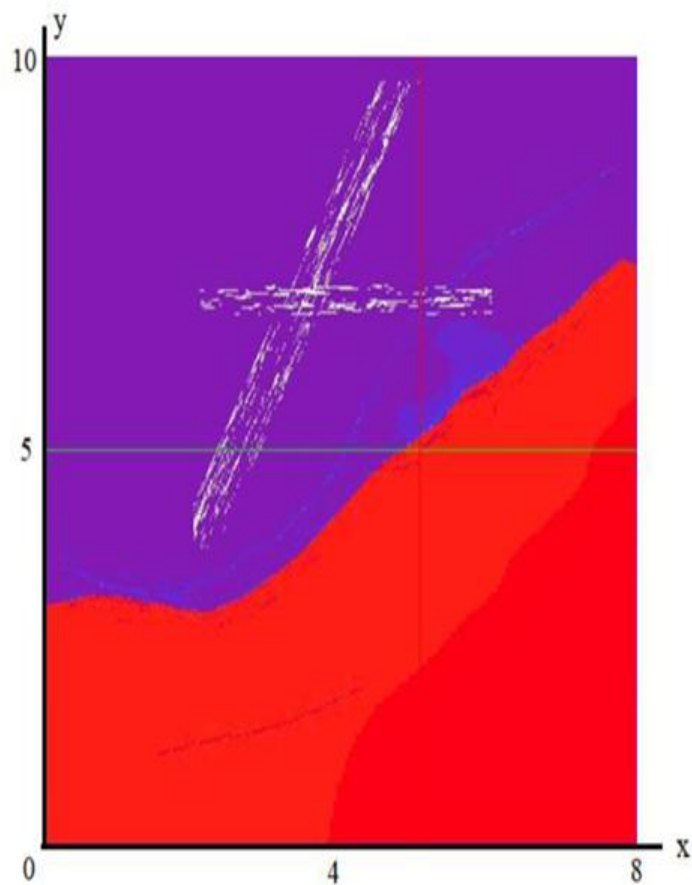


Слева: разломы без зоны дробления, справа – с зоной дробления

Построение 3D геологической модели: зоны повышенной кавернозности



Построение 3D геологической модели: коридоры трещиноватости

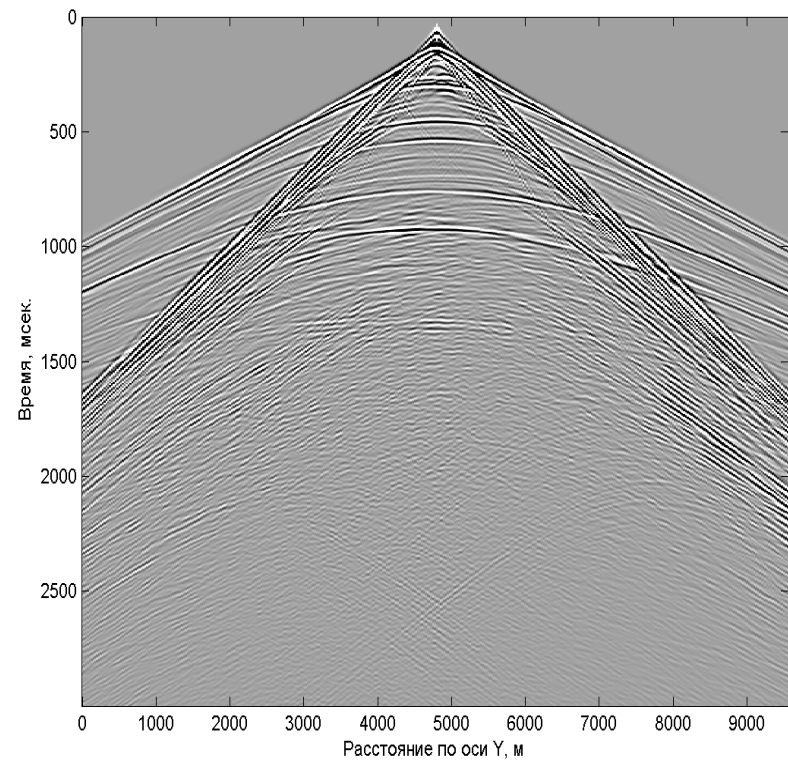
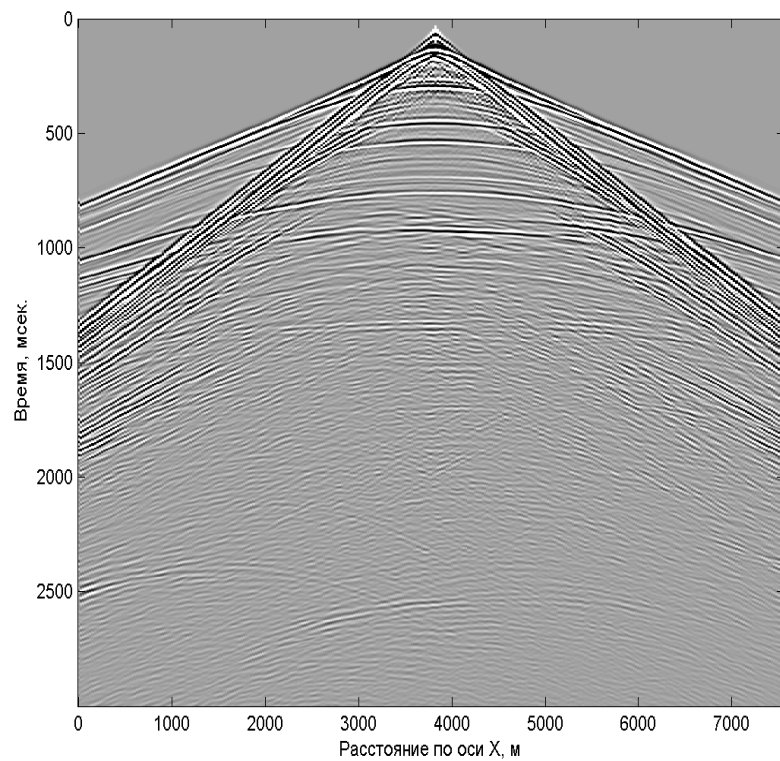


Конечно-разностное моделирование

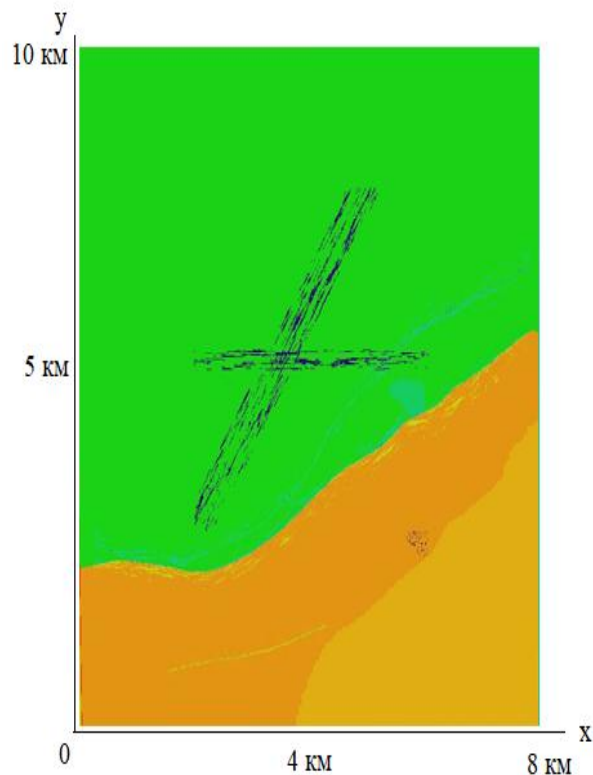
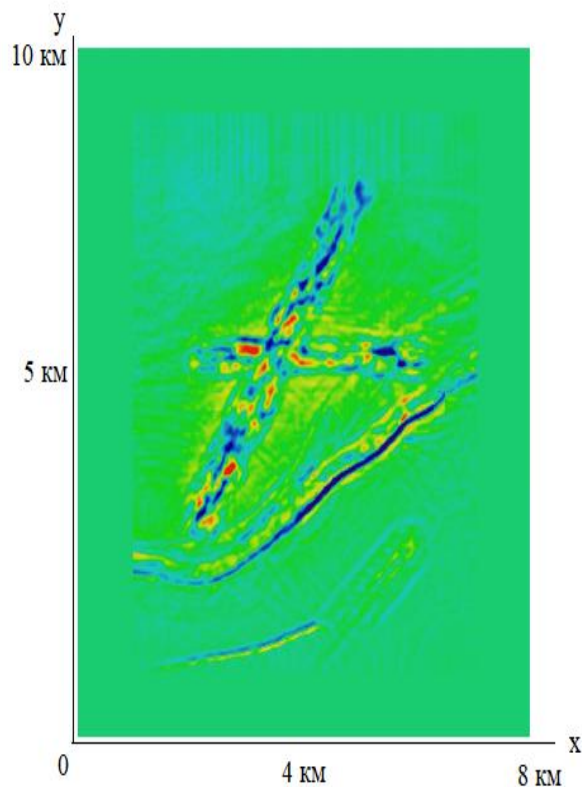
Полномасштабное численное моделирование системы многократного перекрытия проводилось для фиксированной системы трёхкомпонентных приёмников, расположенных на всей апертуре 8 км x 10 км с равномерным шагом 25 м x 25 м. Источники типа центра расширения (взрыв) располагались на линиях вдоль оси X с шагом 50 м, а сами линии отстояли друг от друга на 300 м. В качестве сигнала в источнике мы использовали импульс Рикера с доминирующей частотой 30 Гц.

Ниже приведены взятые вдоль оси X и Y вертикальные компоненты площадных сейсмограмм, полученных для источника, расположенного в центре апертуры.

Конечно-разностное моделирование

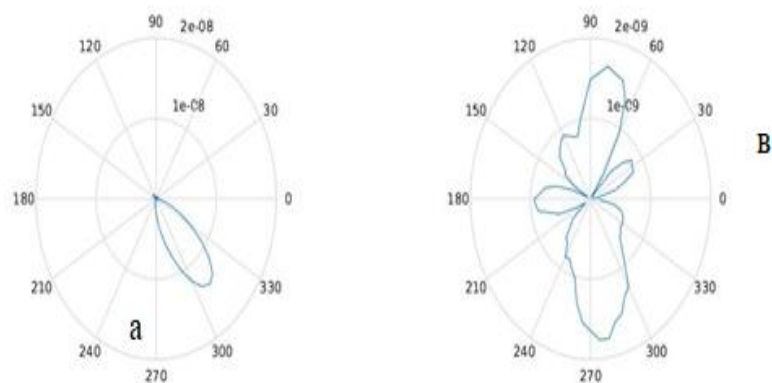
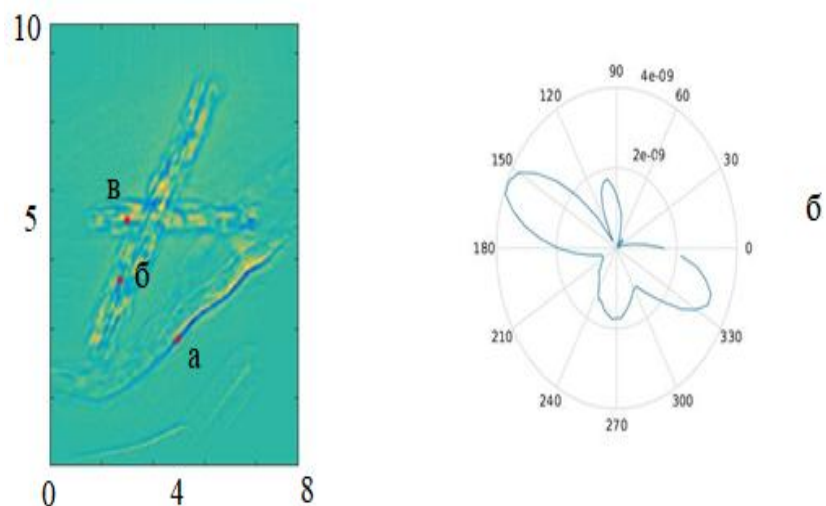


Изображения в рассеянных волнах



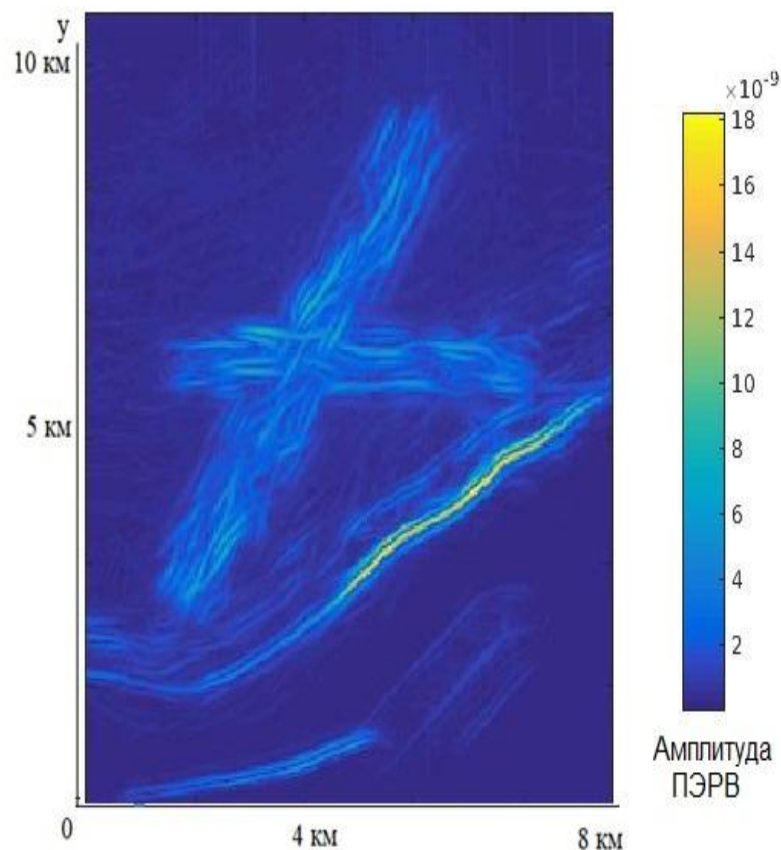
Слева — полноазимутальное изображение, справа —
исходная модель

Изображения в рассеянных волнах



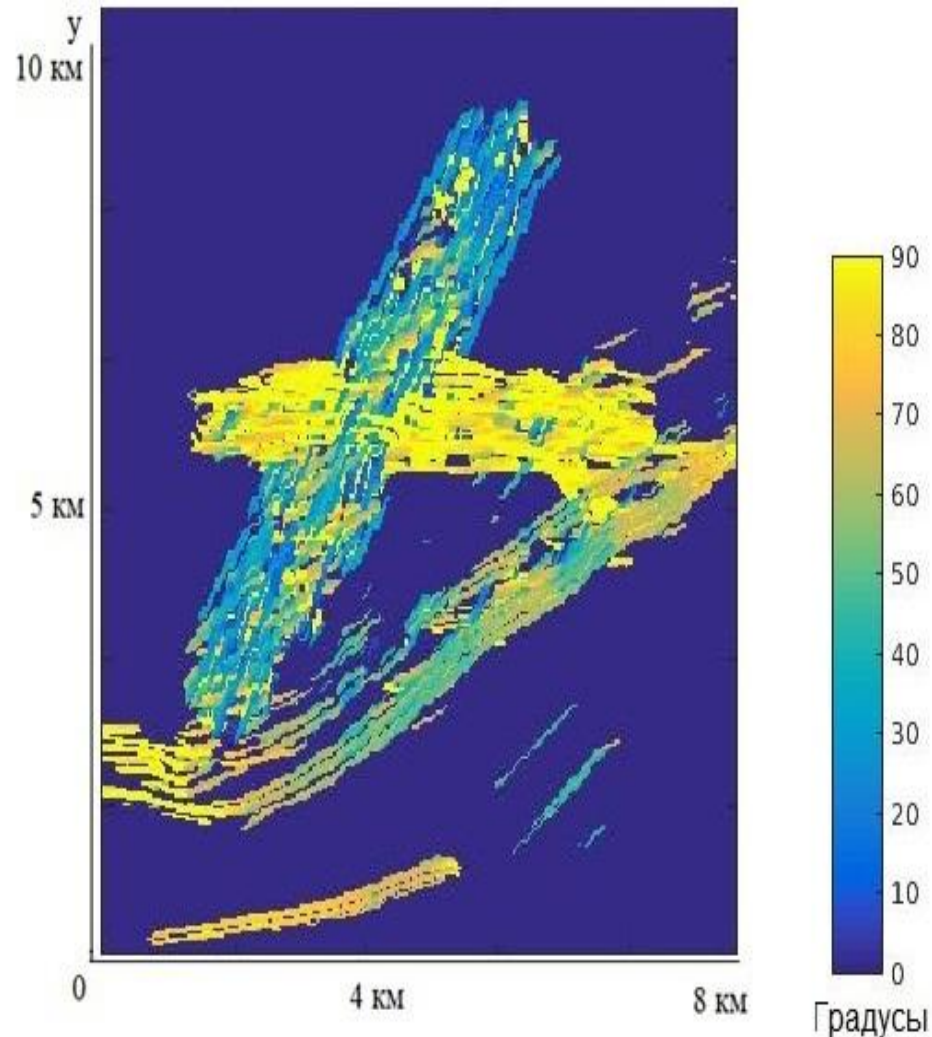
Индикатрисы рассеяния для трёх точек модели

Изображения в рассеянных волнах: сейсмические атрибуты рассеяния



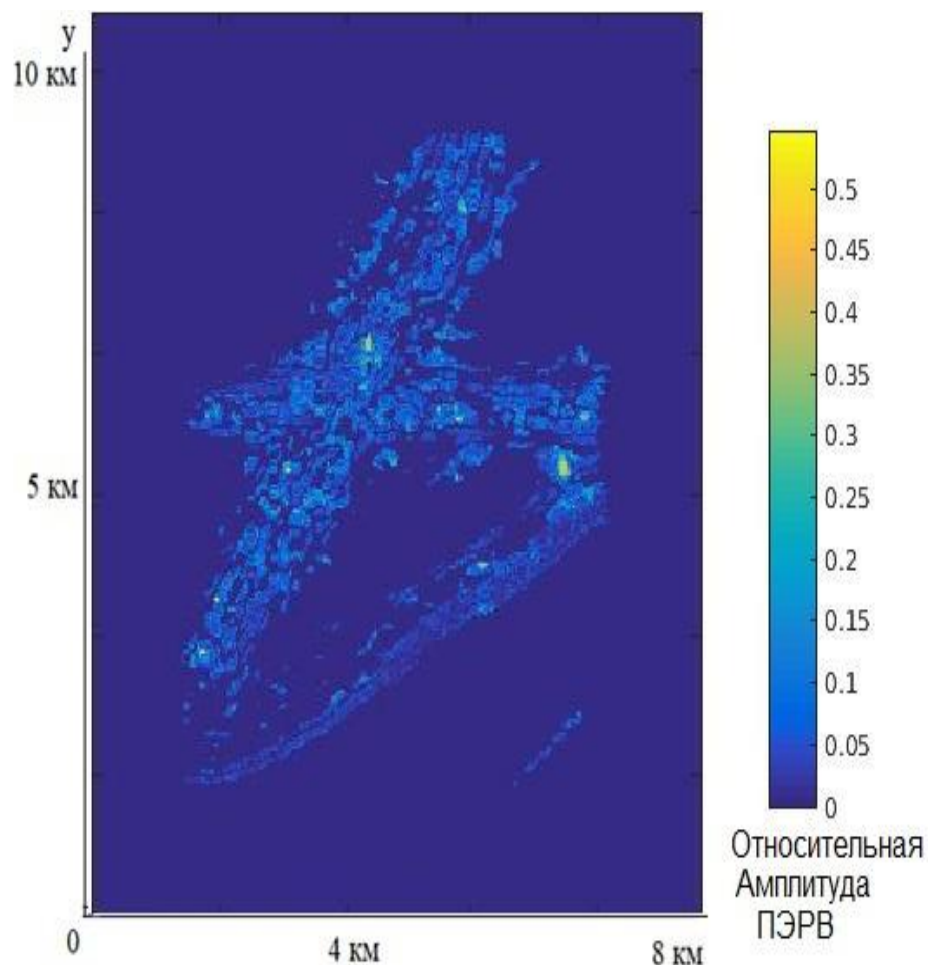
Атрибут структурной дифракции

Изображения в рассеянных волнах: сейсмические атрибуты рассеяния



Атрибут азимут структурной дифракции

Изображения в рассеянных волнах: сейсмические атрибуты рассеяния

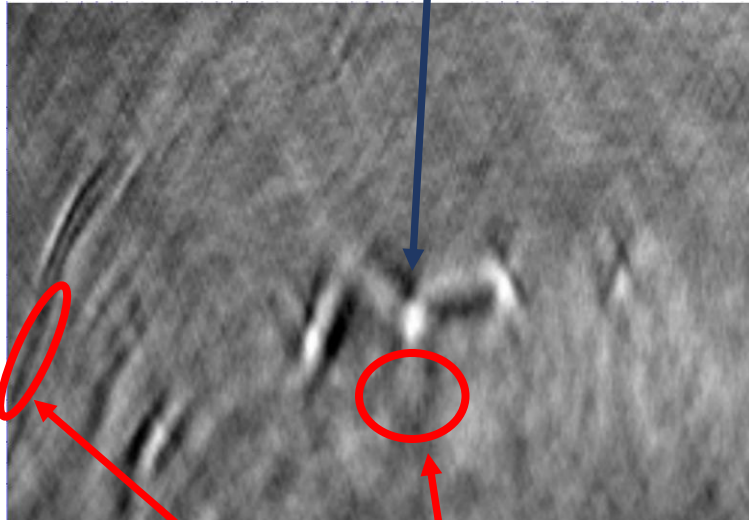
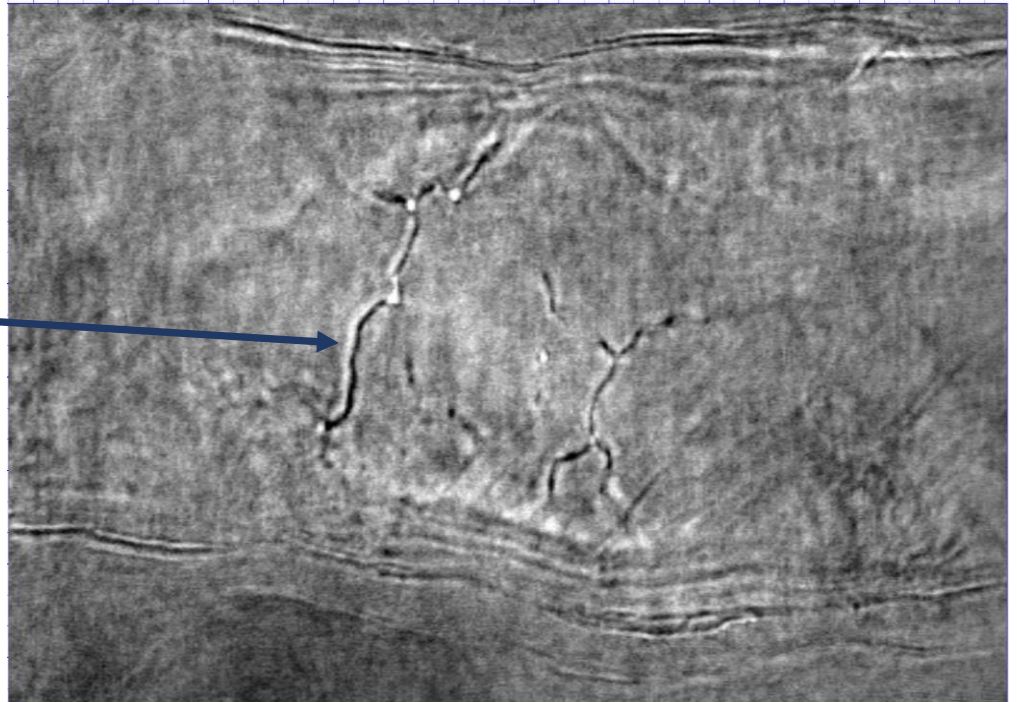


Атрибут точечной дифракции

Результаты тестирования на полевых данных: Лабаган, артефакты от рифов

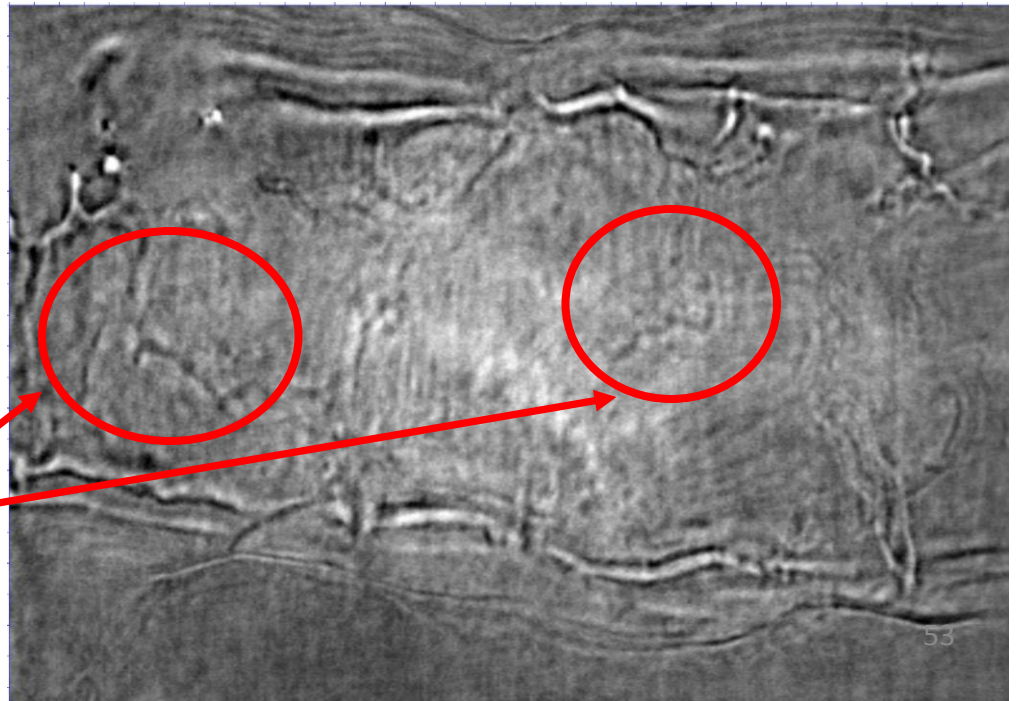
Time slice $t=1.208$

Рифовые постройки



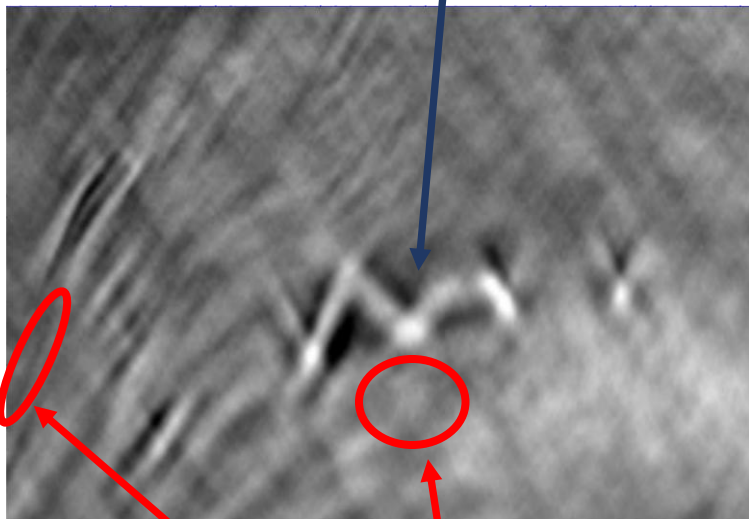
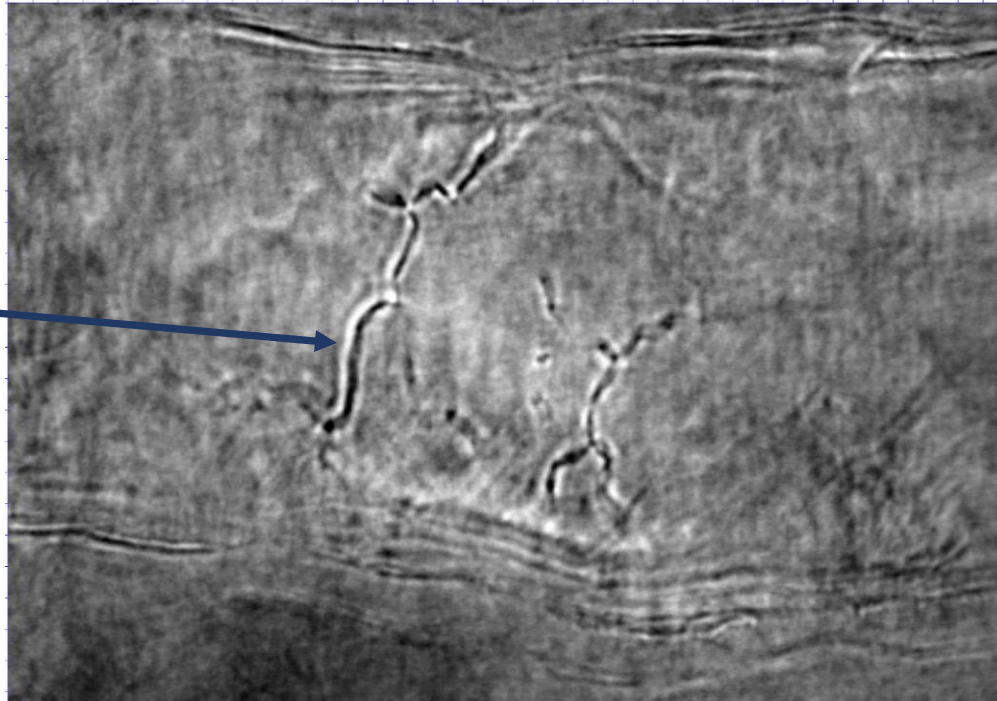
Артефакты

Time slice $t=1.378$



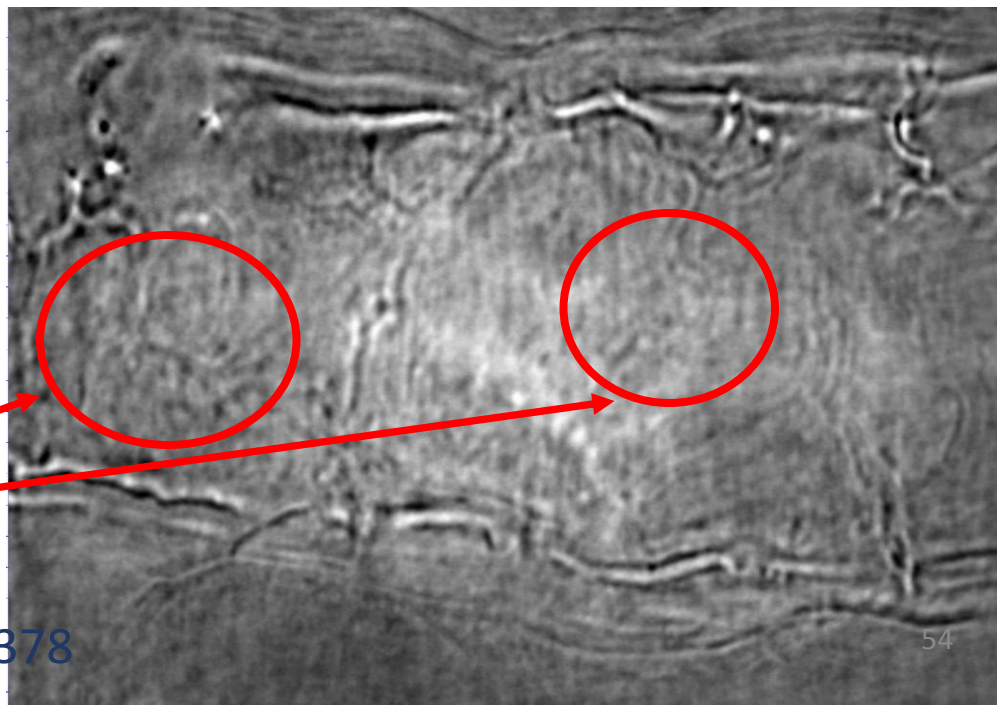
Time slice $t=1.208$

Рифовые постройки

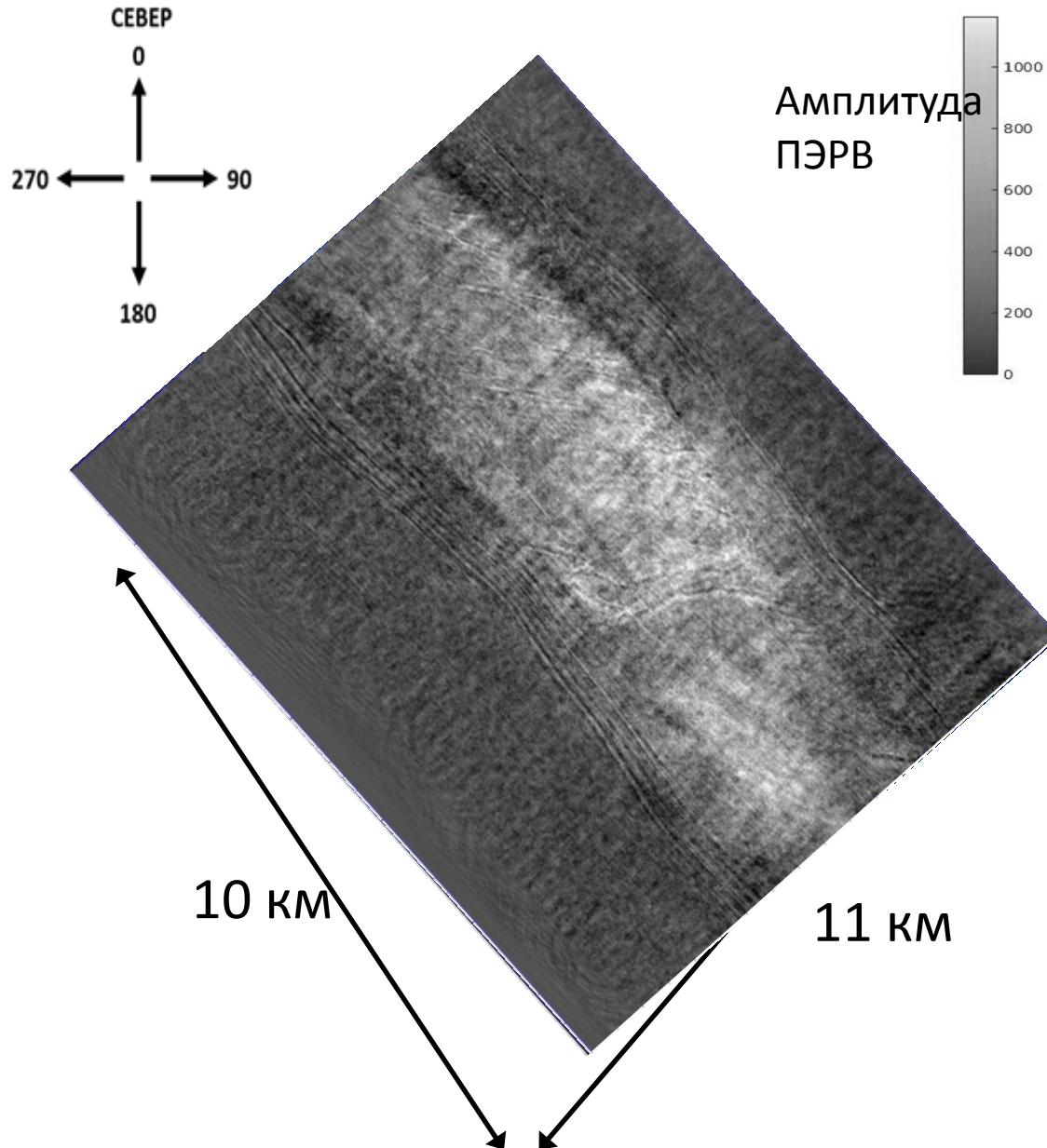


Подавление
артефактов

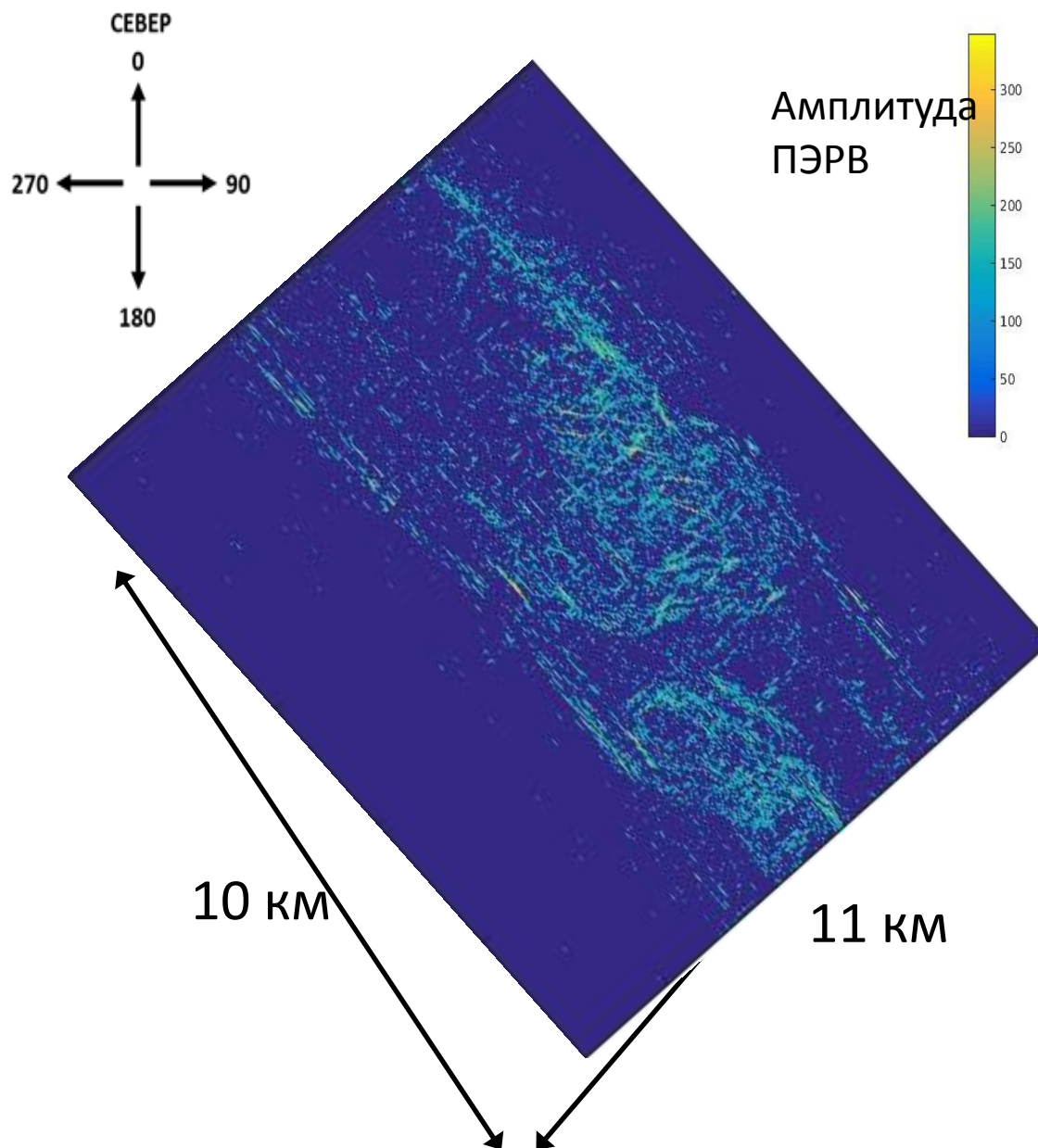
Time slice $t=1.378$



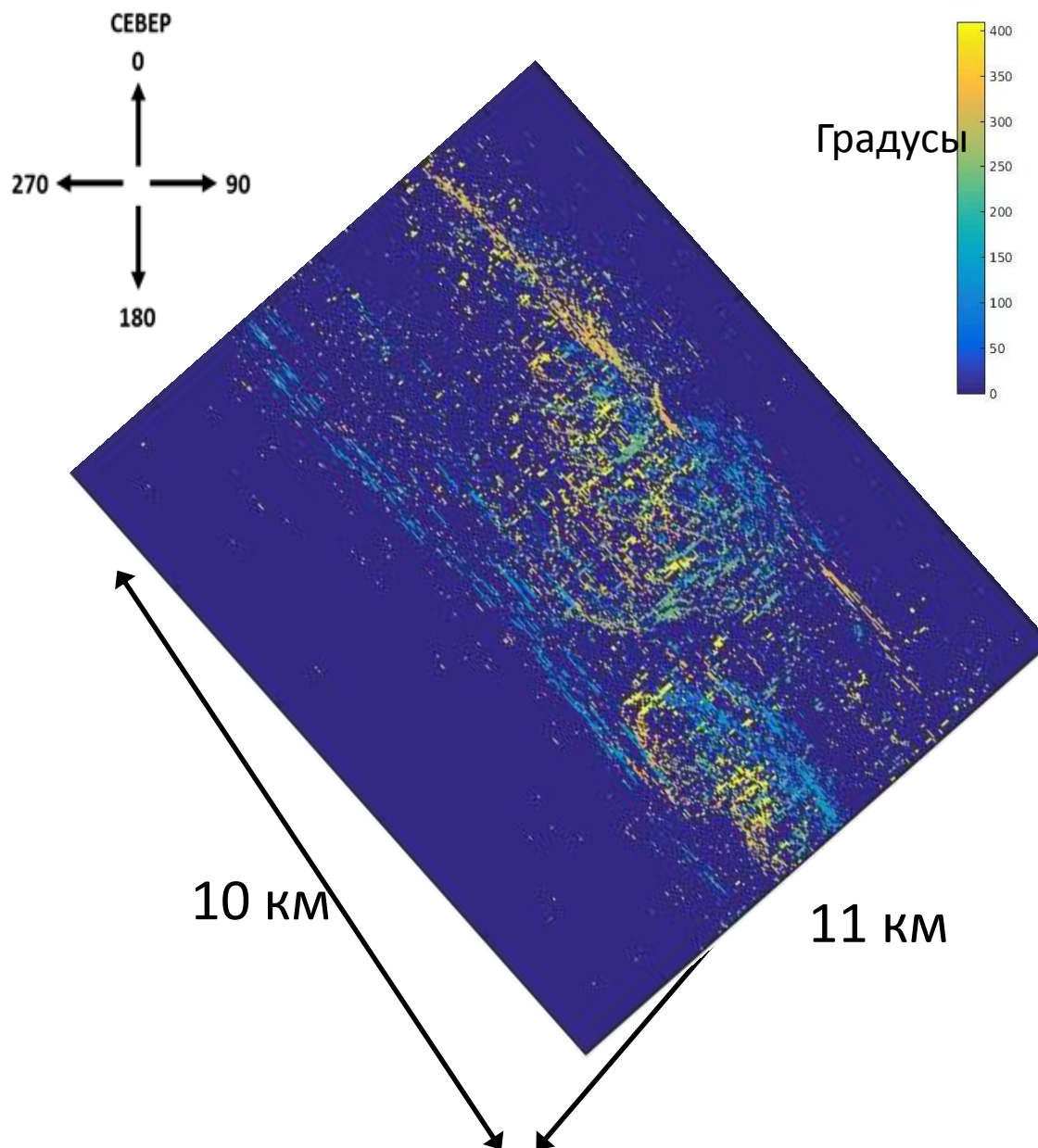
Суммарный куб ПЭРВ: Триас (1008 мс)



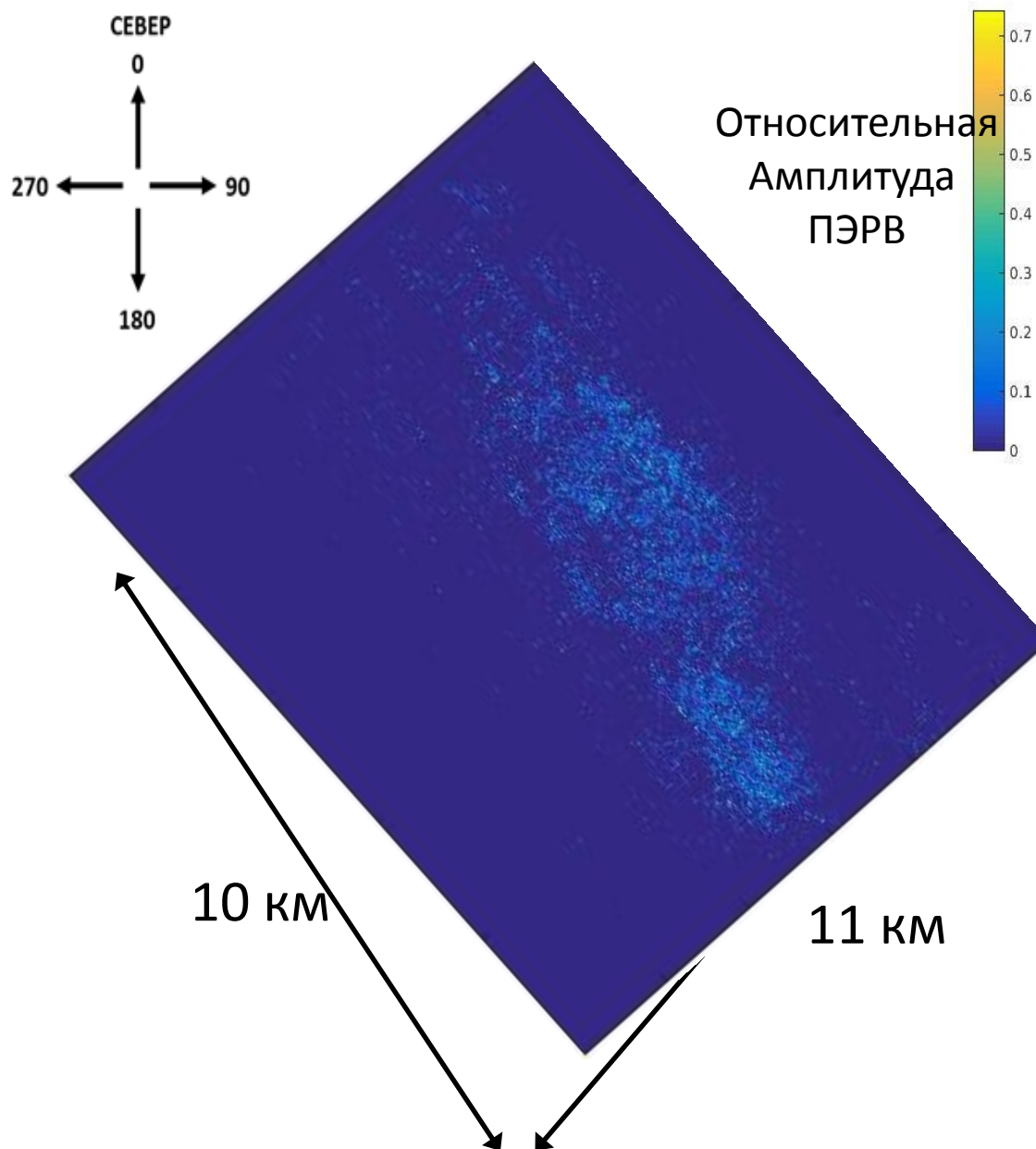
Атрибут «структурной» дифракции: Триас (1008 мс)



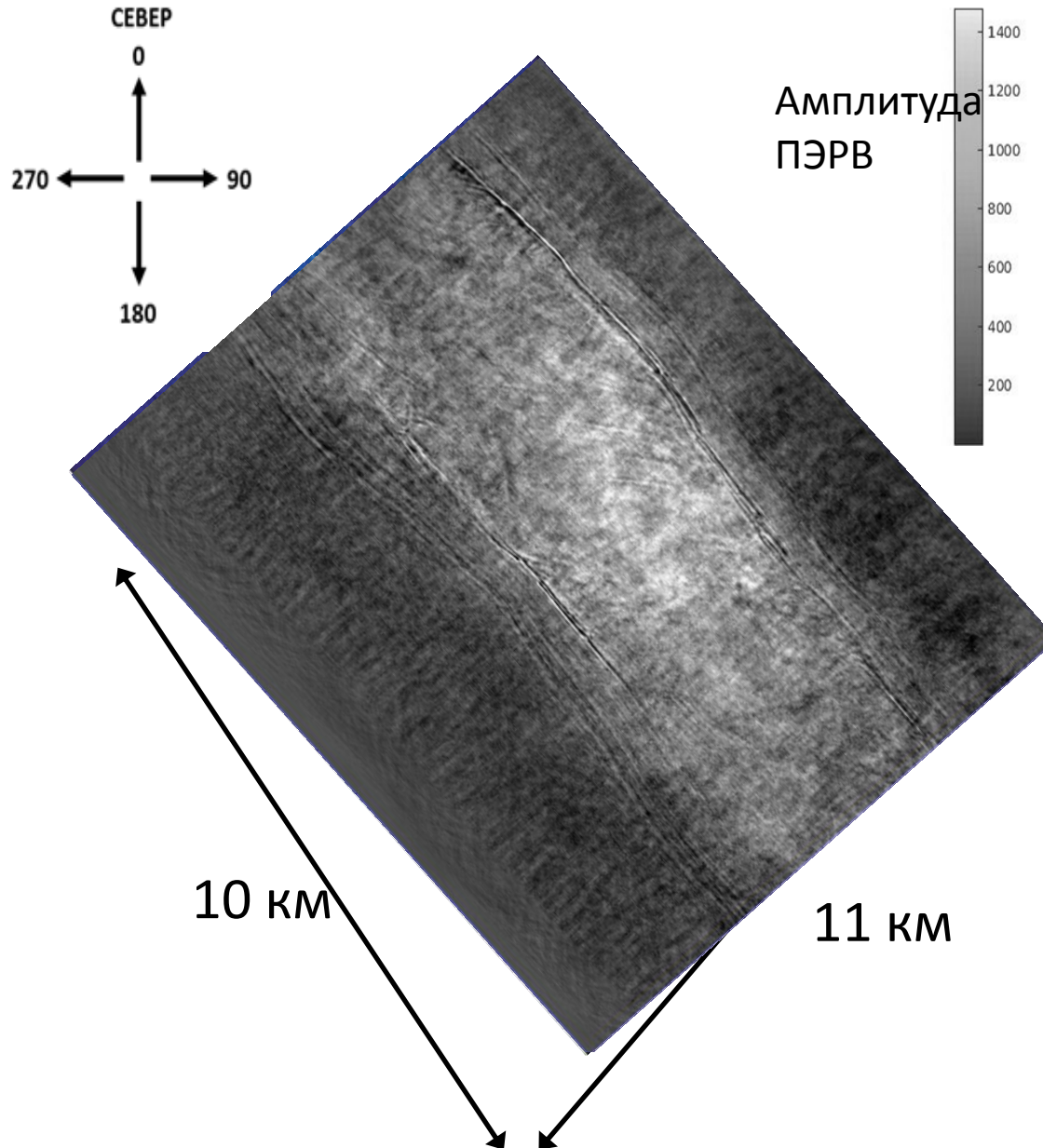
Азимут «структурной» дифракции: Триас (100



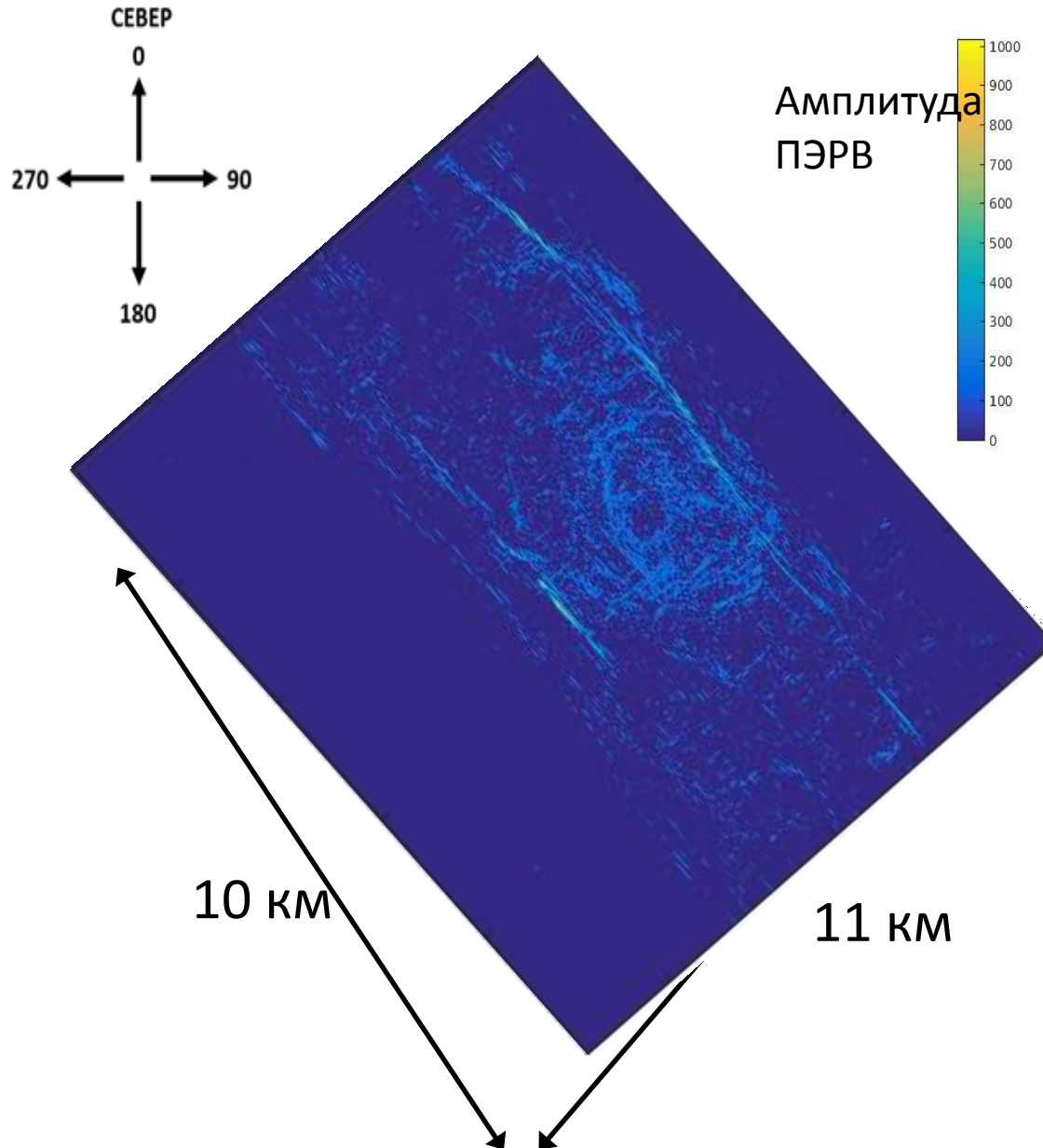
Атрибут «точечной» дифракции: Триас (1008



Суммарный куб ПЭРВ: Артинский (1100 мс)



Атрибут «структурной» дифракции: Артинский (1100 мс)



Content

- 1.Characterization of fault zones.
- 2.Fault zone model.
- 3.Seismic modeling and imaging:
 - 3.1. Seismic modeling;
 - 3.2. Seismic fault imaging.
4. Numerical experiments.
5. Conclusion.
6. Road map.

Conclusion



We present results of our study of the potential for capturing structural details in subsurface fault zones through seismic data processing and analysis. To do this we develop 3D model of a fault zone on the base of empirical data from fault zones:

2D/3D seismic images, outcrops, core samples.

Our main conclusion:

The seismic imaging on the base of scattered waves reproduces fairly accurate some statistical properties of the spatial distribution of fault facies (variograms).

Road map



1. Построение глубинной скоростной модели по сейсмическим данным.
2. Реконструкция приразломной зоны. Прогноз проницаемости разломов.
3. Использование трёхмерных цифровых моделей керна при моделировании флюидопотоков в резервуарах с разломами.

Благодарности:

Данная работа на начальном этапе выполнялась при поддержке РФФИ и РНФ.

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Спасибо за внимание!

