EAGE

INCLUDING SPE International EUROPEC

2022 EAGE ANNUAL
83RD CONFERENCE & EXHIBITION
MADRID | SPAIN

Leading GEOSCIENCES in a New Era

Time-dependent Scattering in Reverse Time Holography method

Gennady Erokhin

6-9 JUNE 2022 | WWW.EAGEANNUAL2022.ORG

Outline

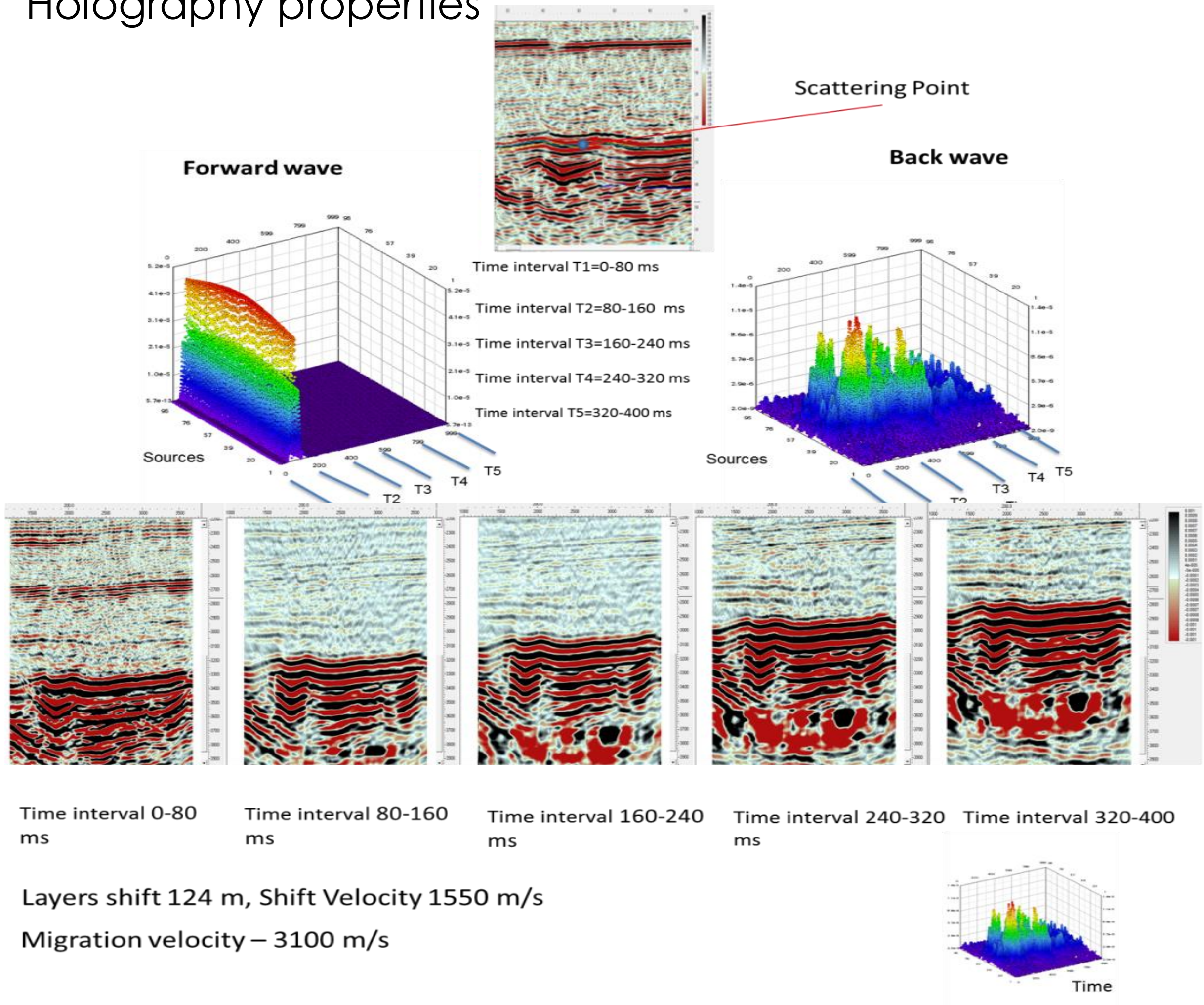
1. About RTH
2. RTH data processing workflow
3. RTH Time-Dependent Scattering
4. Comparison of PSDM/PSTM and RTH
5. List of the main features of the RTH method
6. Comparison the RTH and the RTM data processing workflow
7. RTH Interpretation road map
8. Verification
9. Conclusions, Acknowledgements

1. About RTH.

Mathematical and software base of the RTH method

Reverse Time Holography – RTH is the method of seismic data processing based on the reversal of the wave field in time and seismic holographic interferometry

Holography properties



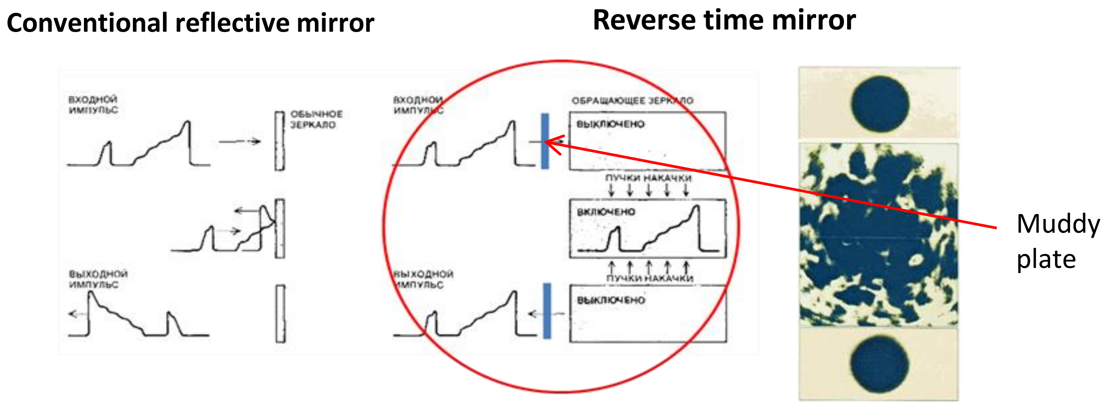
The RTH method is based on:

1. Theories of adjoint equations and reversing the wave field in time
2. Numerical modeling of wave interference (holography)
3. Statistical accumulation of interference results (analogue - a set of photographic plates)
4. Filtering events of multidimensional statistical distribution
5. Statistical estimation of multidimensional distribution parameters
6. Multidimensional imaging technologies
7. Parallel Computing on Supercomputers
8. Extra large data processing

Prerequisites of RTH Approach

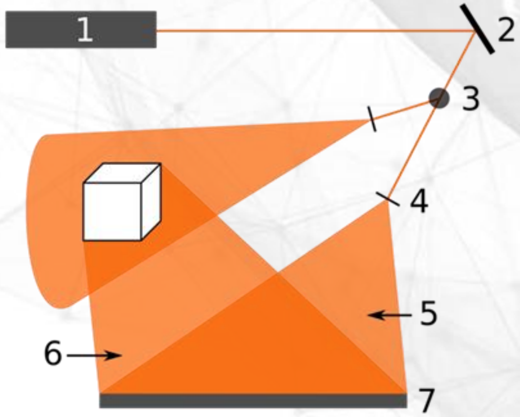
I. *Two Fundamental Physical Discovery*

1. Reverse time mirror (1972 ,B.Y. Zeldovich's team)

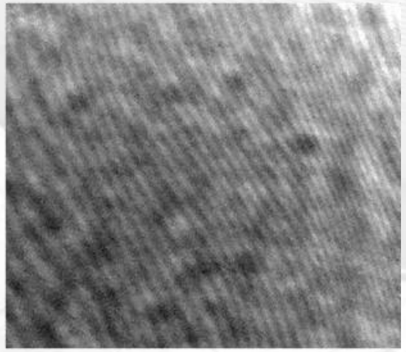


Zel'dovich B.Ya., Popovichev, Ragulsky VV, Fayzullov FS, 1972, On the relationship between the wavefronts of reflected and exciting light in stimulated Mandelstam-Bryullen scattering. Letters to JETP, vol. 15, No. 3 pp. 160-164.

2. Two beams interferometry in Gabor's optical holography (1948)



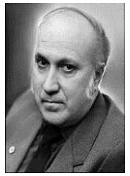
Photographic plate



II. *Main Mathematical & Computer Prerequisites*

- Theories of adjoin equations and reversing the wave field in time
- Parallel Computing & Supercomputers
- Extra large data processing
- Simultaneous Joint Inversion Theory

Siberian school of seismic holography 1975-1990

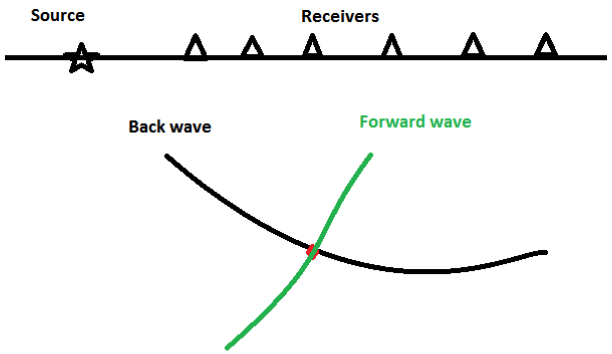

Academicians of the USSR Academy of Sciences:
Alekseev A.S., Lavrent'ev M.M., Gol'din S.V.

Alekseev A.S., and Erokhin G.N., 1989, Integration in geophysical inverse problems (Integrated Geophysics),
USSR Academy of Sciences Proceedings, Volume 308. № 6.

EAGE ANNUAL 2022 83RD CONFERENCE & EXHIBITION MADRID | SPAIN

Prerequisites of RTH Approach

Reverse Time Migration - RTM



$$I(x) = \sum_s \int_0^T p^f(x,t;x_s)p^b(x,t;x_s)dt$$

Imaging Condition

Baysal et.al.,1983; Whitmore, 1983; McMechan, 1983

<u>RTM:Forward waves (green)</u>

$$\frac{1}{c^2(x)}p_{tt} - \Delta p = r(t)\delta(x - x_s),\ (x,t) \in \mathbb{R}^2 \times (0,T),$$

$$p|_{t=0} = 0,\ \ p_t|_{t=0} = 0,$$

$$x_s \in \Gamma = \{x \in \mathbb{R}^2 \,|\, x^2 = 0\},$$

$$p_0(x,t;x_s) = p^f(x,t;x_s),\ (x,t) \subset \Gamma \times [0,T]$$

<u>RTM: Back waves (black)</u>

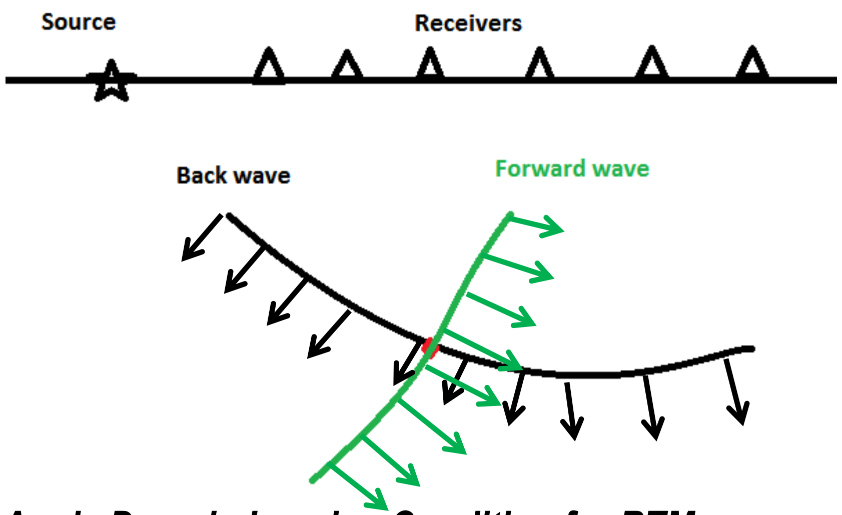
$$\frac{1}{c^2(x)}p_{tt} - \Delta p = \delta_\Gamma p_0(,;x_s),\ \ (x,t) \in \mathbb{R}^2 \times (0,T),$$

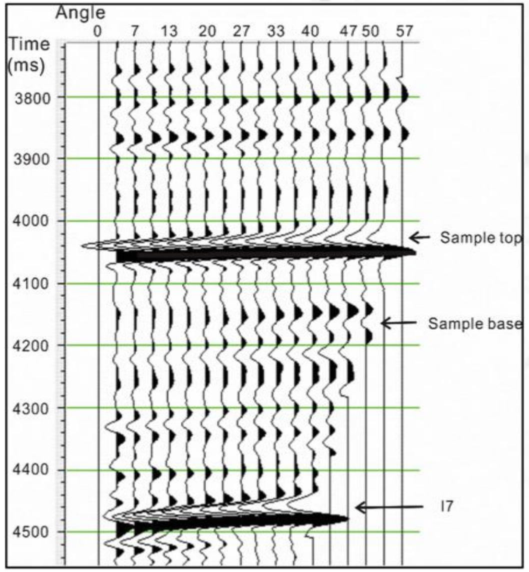
$$p|_{t=T} = 0,\ \ p_t|_{t=T} = 0.$$

Widespread use in MVO/AVO/AVA/AVAZ data analysis of the Common Image Gathers, Angle Domain CIG, Local Domain CIG *(Biondo Biondi and William W. Symes, Xie and Wu, 2002; Yan and Xie, 2009 Yoon and Marfurd, 2006; Sava and Fomel, 2006; Costa et.al.,2009, Zhang and McMechan, 2011, Vyas et.al., 2011, Yan et.al., 2014)*

Prerequisites of RTH Approach

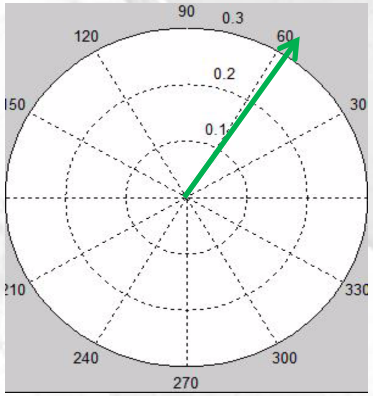
Angle Domain CIG



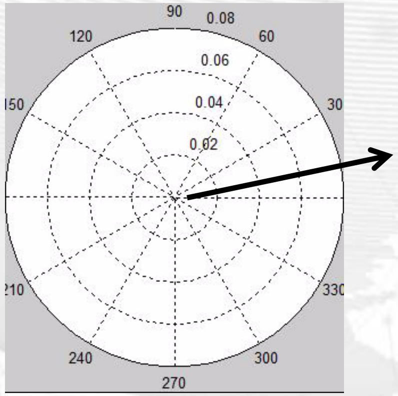


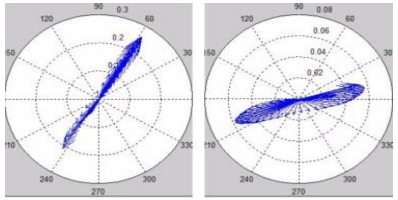
Angle Domain Imaging Condition for RTM

$f = \vec{u}^f$



$b = \vec{u}^b$





RTH: Forward waves

$$p^f{}_t - c^2 div(\vec{u}^f) = r(t)\delta(x - x_s)$$

$$\vec{u}^f_t = \nabla p^f$$

$$p^f\big|_{t=0} = 0, \quad \vec{u}^f\big|_{t=0} = 0.$$

$$(p^f, \vec{u}^f)(x, t; x_s), t \in [0, T]$$

$$p_0 = p^f\big|_{\Gamma\times[0,T]}$$

Vector particle velocity

$$f = \vec{u}^f$$

$$b = \vec{u}^b$$

RTH: Back waves

$$p^b{}_t - c^2 div(\vec{u}^b) = 0$$

$$\vec{u}^b_t = \nabla p^b + p_0\delta(x^n)\vec{v}_\Gamma$$

$$p^b\big|_{t=T} = 0, \quad \vec{u}^b\big|_{t=T} = 0,$$

$$(p^b, \vec{u}^b)(x, t; x_s), t \in [0, T]$$

$$x_s \in \Gamma = \{x \in \mathbb{R}^n \mid x^n = 0\}, \ t \in (0, T)$$

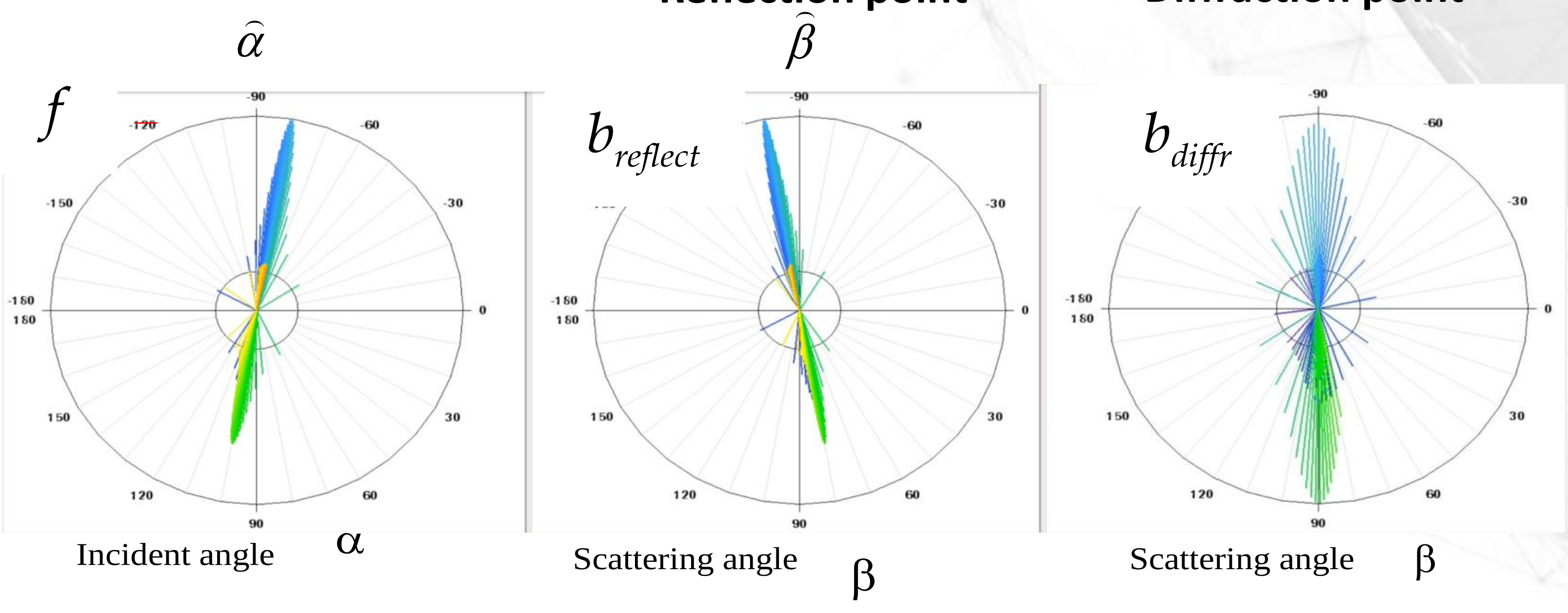
2022 EAGE ANNUAL 83RD CONFERENCE & EXHIBITION MADRID | SPAIN

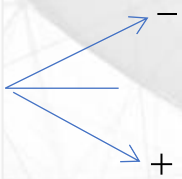
Interconnected Vector Pair

2D

Reflection point **Diffraction point**

$3D\ Scattering\,(\alpha\ ,\beta,t\ )$





Source is fixed. Angles for each instantaneous time :

$\gamma = (\alpha - \beta)/2$ Opening Angle

$\theta = (\alpha + \beta)/2$ Dip Angle

$\alpha - incident\ angle$

$\beta - scattering\ angle$

Source is fixed. Average angles:

$\hat{\gamma} = (\hat{\alpha} - \hat{\beta})/2 \simeq 10^{\circ}$

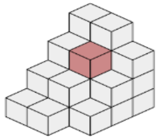
$\hat{\theta} = (\hat{\alpha} + \hat{\beta})/2 \simeq -90^{\circ}$

Figure Incident and scattering behavior of interconnected vector pair (f,b)
for the point of reflection (a), (b) and for the point of diffraction (a) , (c).
Here the color shows the time from blue up to red.

2. RTH data processing workflow

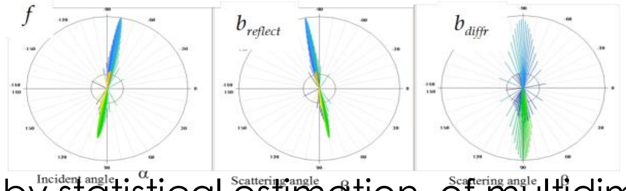
The seismic voxel-based attributes estimation by the RTH method is carried out in two stages for each voxel:

1. Full **Decomposition** (Vector Domain Common Image Gathers dataset - simile photograph plate in optical holography), based on two vectors : the incident wave vector and the time-reversed "backward" scattered wave



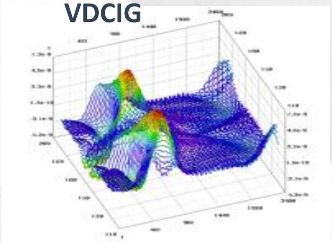
Voxel

two vectors



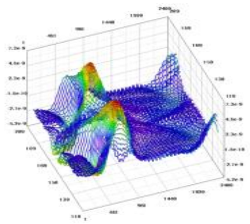
Decomposition

VDCIG



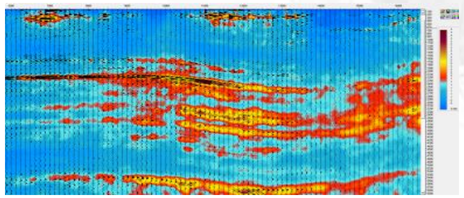
2. **Synthesis-** seismic attributes by statistical estimation of multidimensional dataset

VDCIG



Synthesis

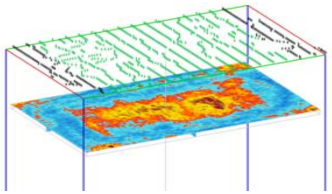
RTH attributes

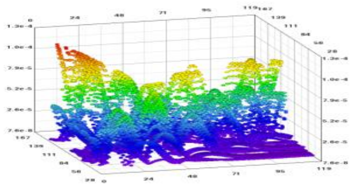


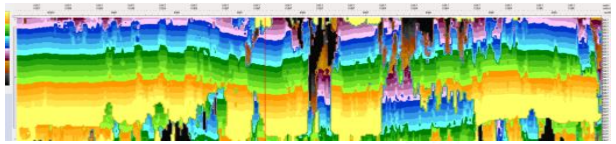
3D CDP Gathers → **Vector Domain Common Image Gathers** → **RTH Voxel-based Attributes**

$R^6 : p(x,t,x_s)$

$R^{10} : (|f|,|b| \alpha , \beta , \omega_f, \omega_b, t, s, \varphi, \theta)$

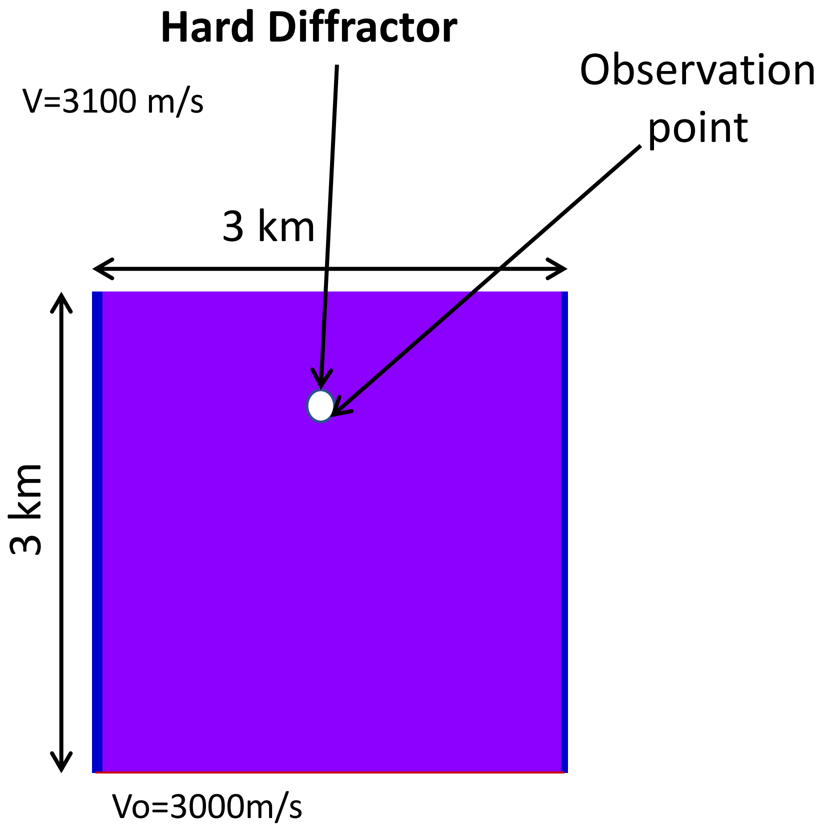






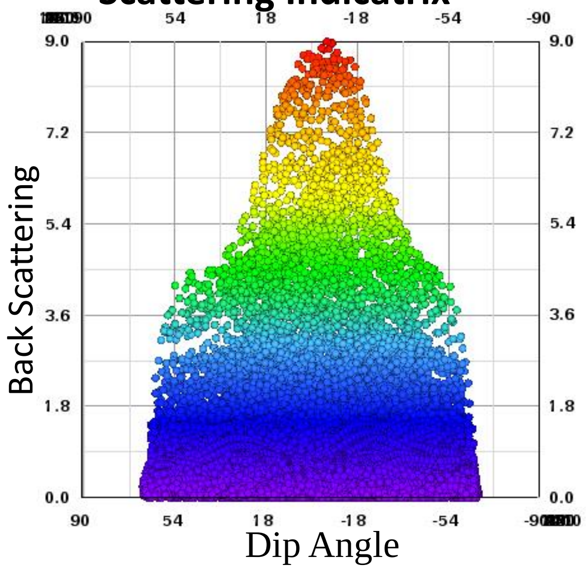
3. RTH Time-Dependent Scattering

Time-Dip Angle Distribution in Diffractor Point based on Discrepancy of two Arrival Times

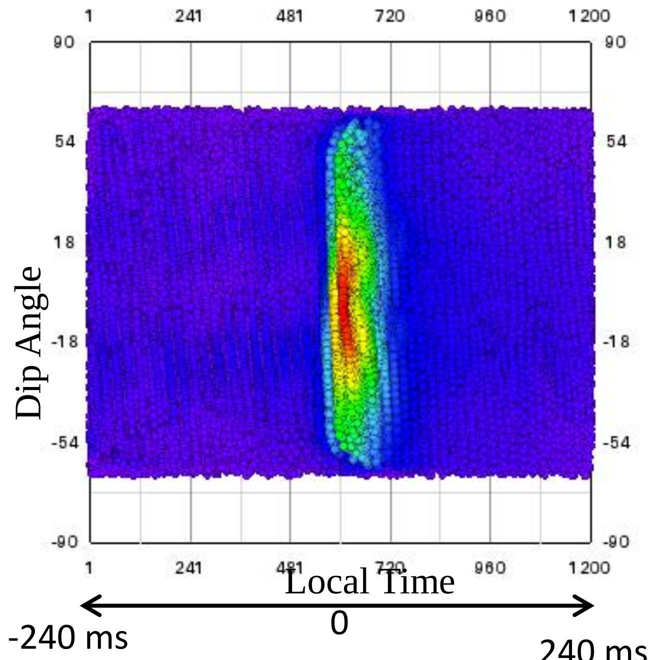


The number of sources is 181, the step between the sources is 25 m, the step between the receivers is 25 m, the receivers offset is 2000 m.

Scattering Indicatrix

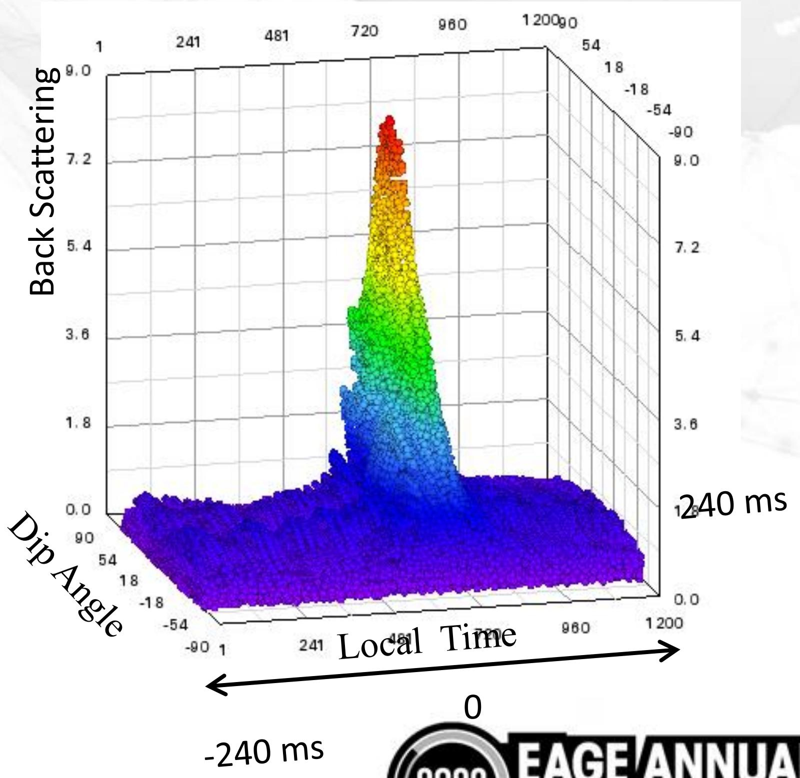


Time-Dip Angle Distribution



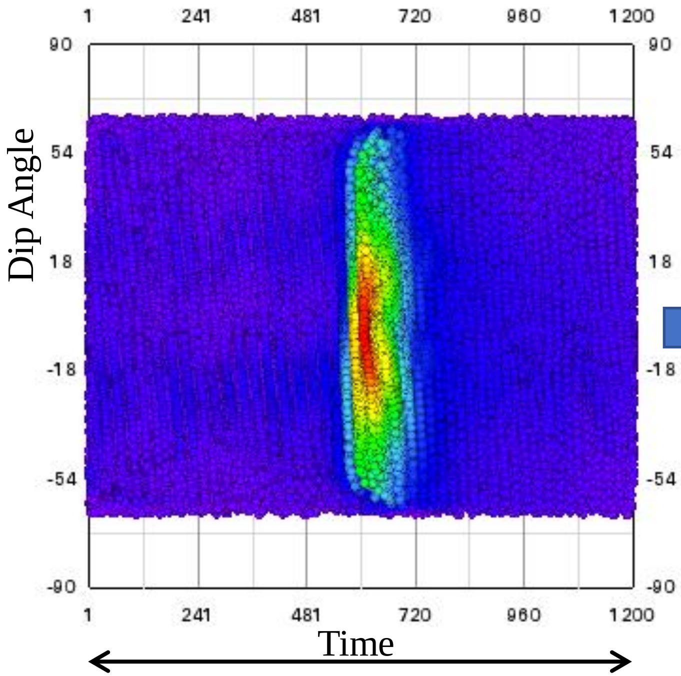
Local time =
Discrepancy time=
Forward time – Back time

Time-Dip Angle Distribution



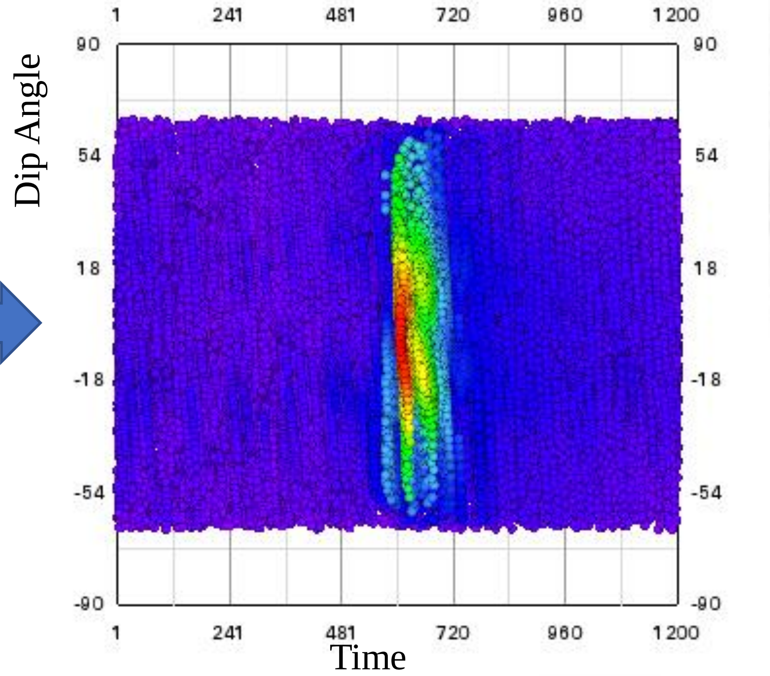
Decomposition due to Time-Dependent Scattering

Time-Dip Angle Distribution



-240 ms 0 240 ms

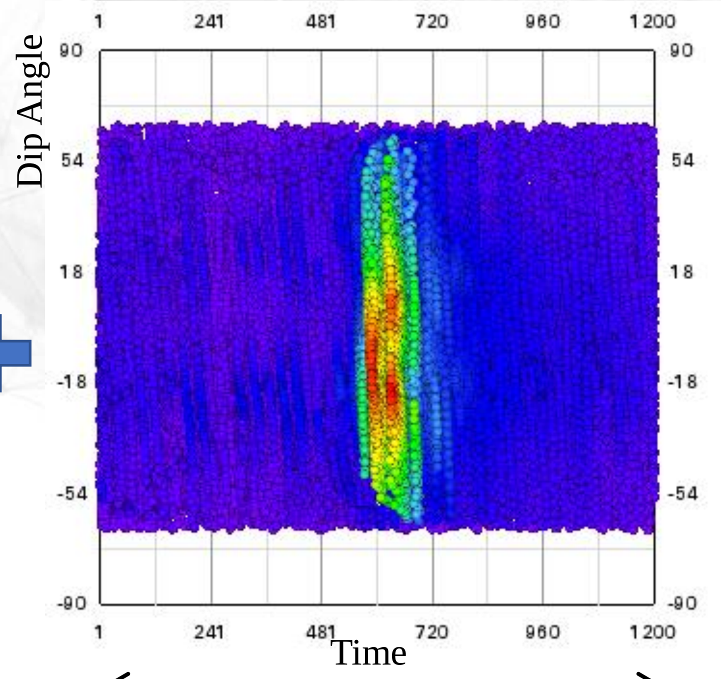
Conventional Scattering: Backscatter without Phase Inversion



-240 ms 0 240 ms

Hard Vector Scattering Pattern (HardVSP)

Reverse Time Scattering: Backscatter with Phase Inversion

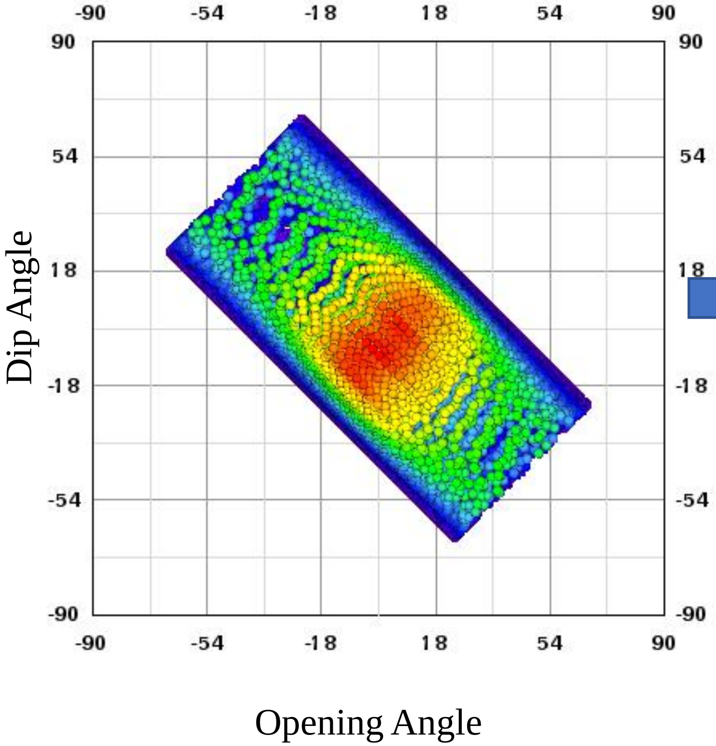


-240 ms 0 240 ms

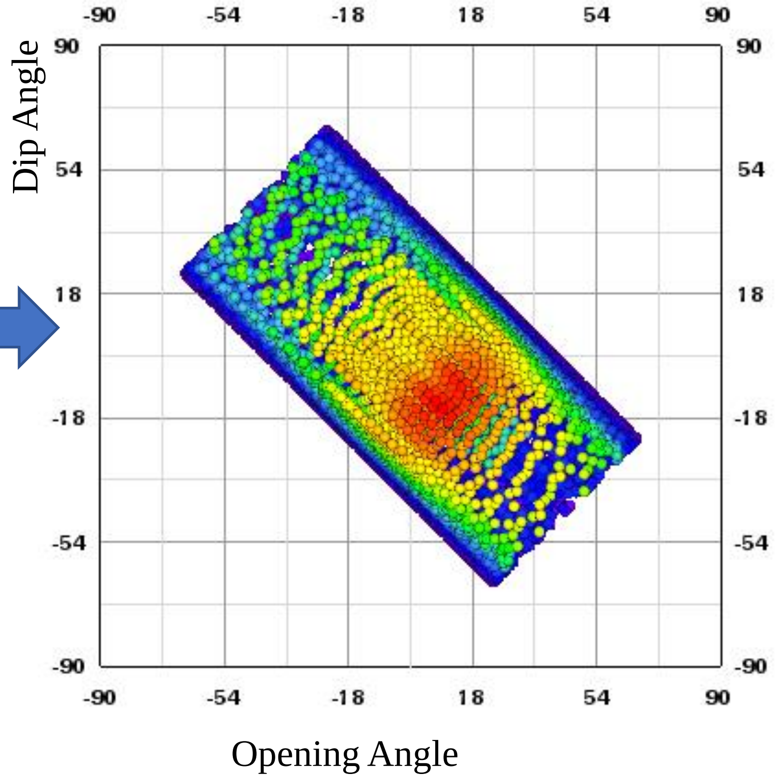
Soft Vector Scattering Pattern (SoftVSP)

Decomposition due to Time-Dependent Scattering

Opening-Dip Angle Distribution

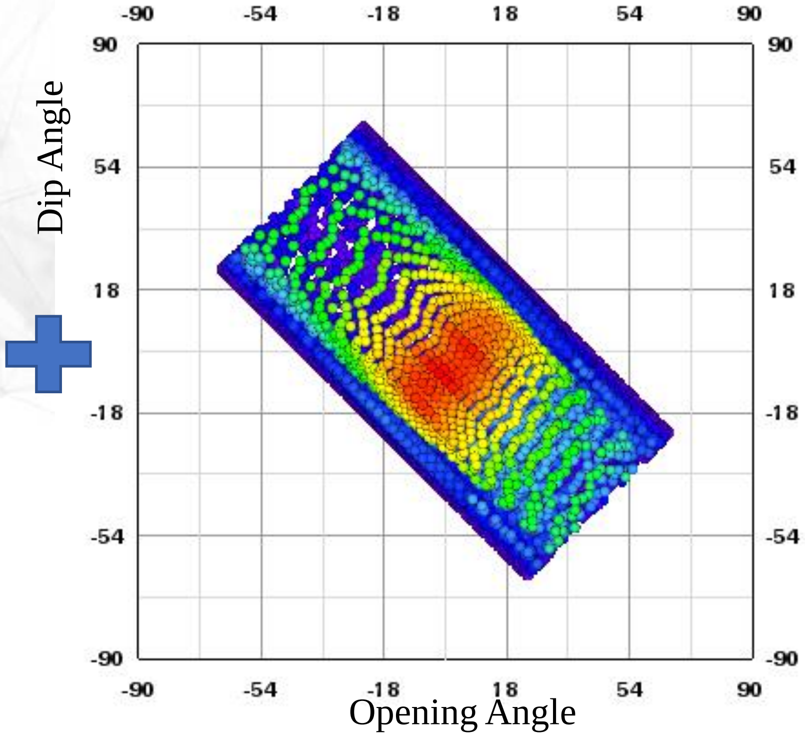


Conventional Scattering: Backscatter without Phase Inversion



Hard Vector Scattering Pattern (HardVSP)

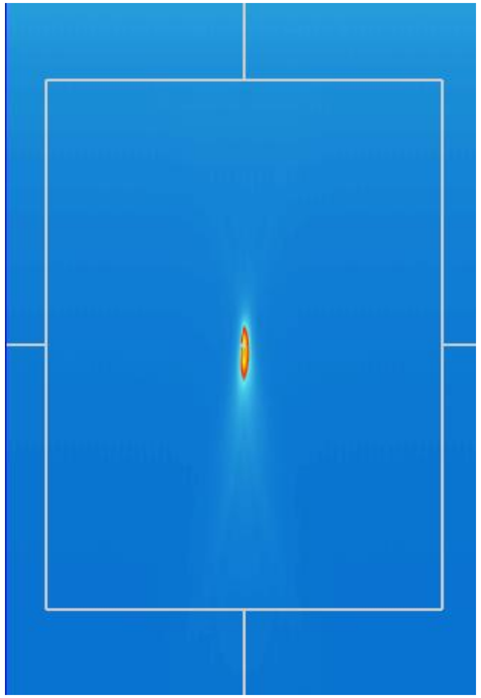
Reverse Time Scattering: Backscatter with Phase Inversion



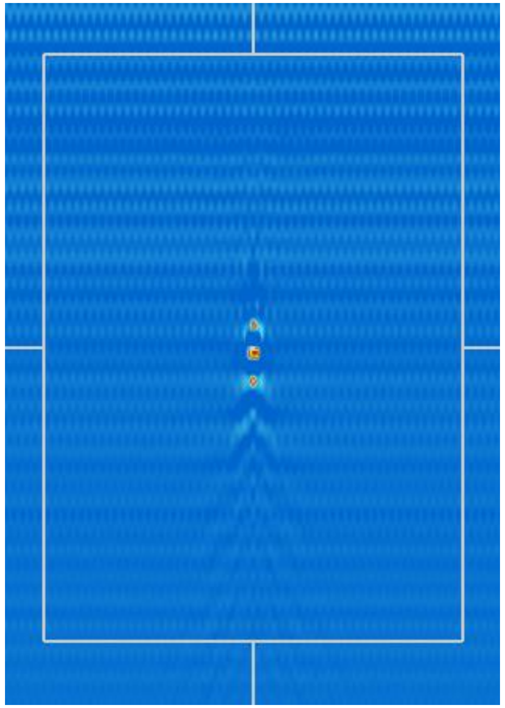
Soft Vector Scattering Pattern (SoftVSP)

RTH Imaging Condition based on a Combinations of the Hard&Soft VSP Back Amplitude

Hard & Soft VSP Decomposition is a kernel of the RTH Approach

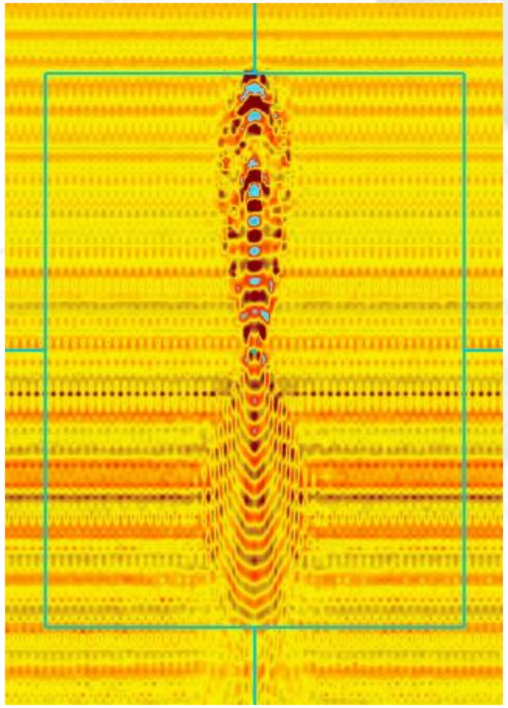


HardVSP+SoftVSP

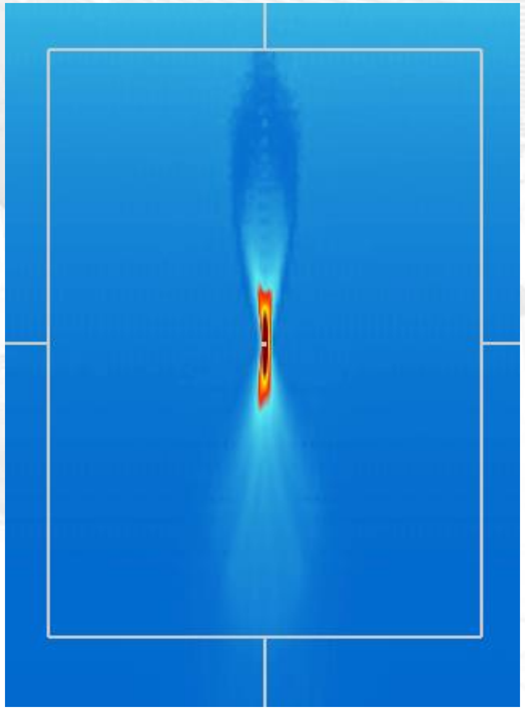


HardVSP-SoftVSP

RTH RTM

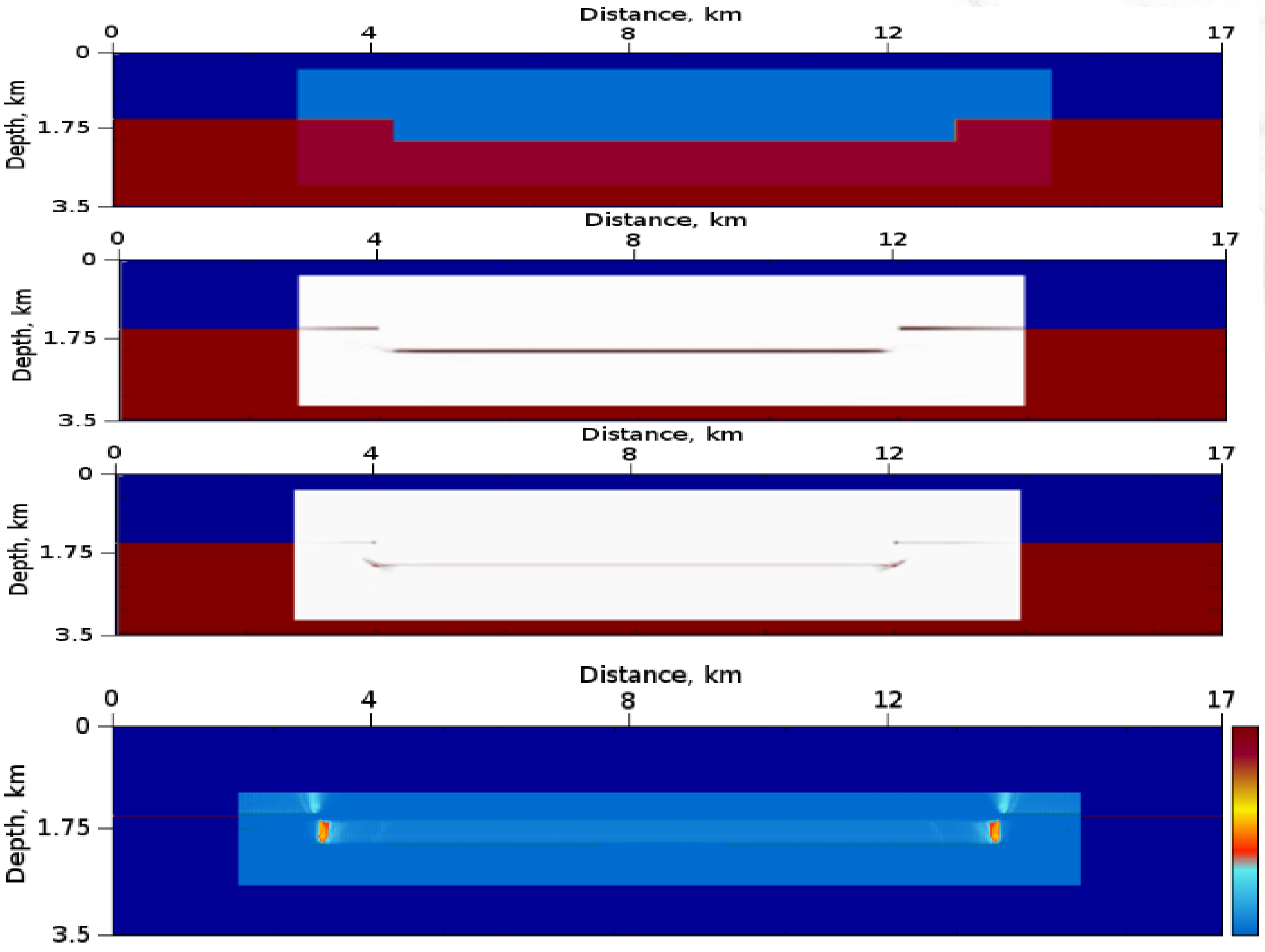


HardVSP/SoftVSP



HardVSP*SoftVSP

RTH Testing. Case HardVSP+SoftVSP Back Amplitude Imaging Condition



Initial Velocity Model is 3 km/s

Model consists of two layers. The velocity is 3 km/s in the upper media and 4 km/s in the down media.

Reflector (in-phase scattering) RTH
Select only reflector boundaries

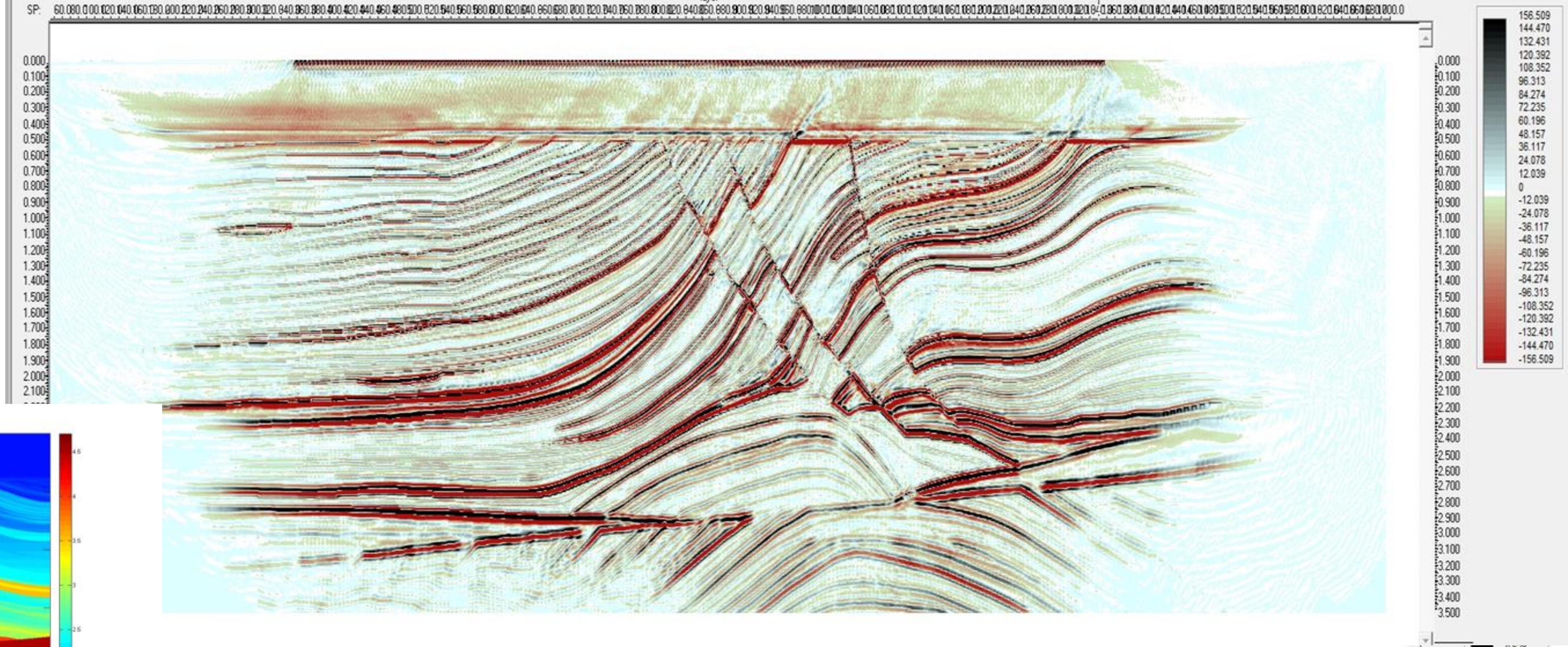
Diffractor RTH Select only diffractor events

Prism wave RTH
Select only vertical boundaries (Duplex wave)

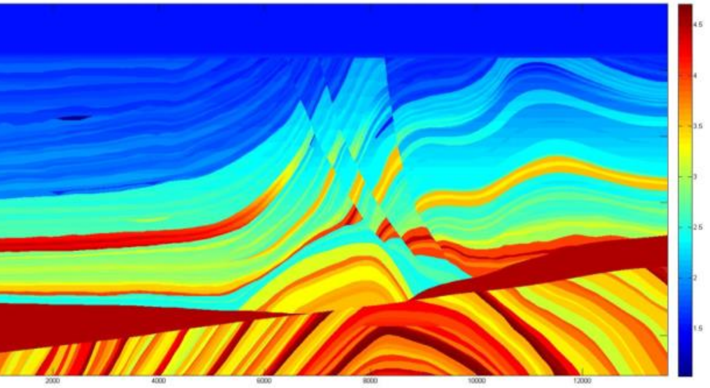
RTH Testing.

Case HardVSP-SoftVSP Back Amplitude Imaging Condition

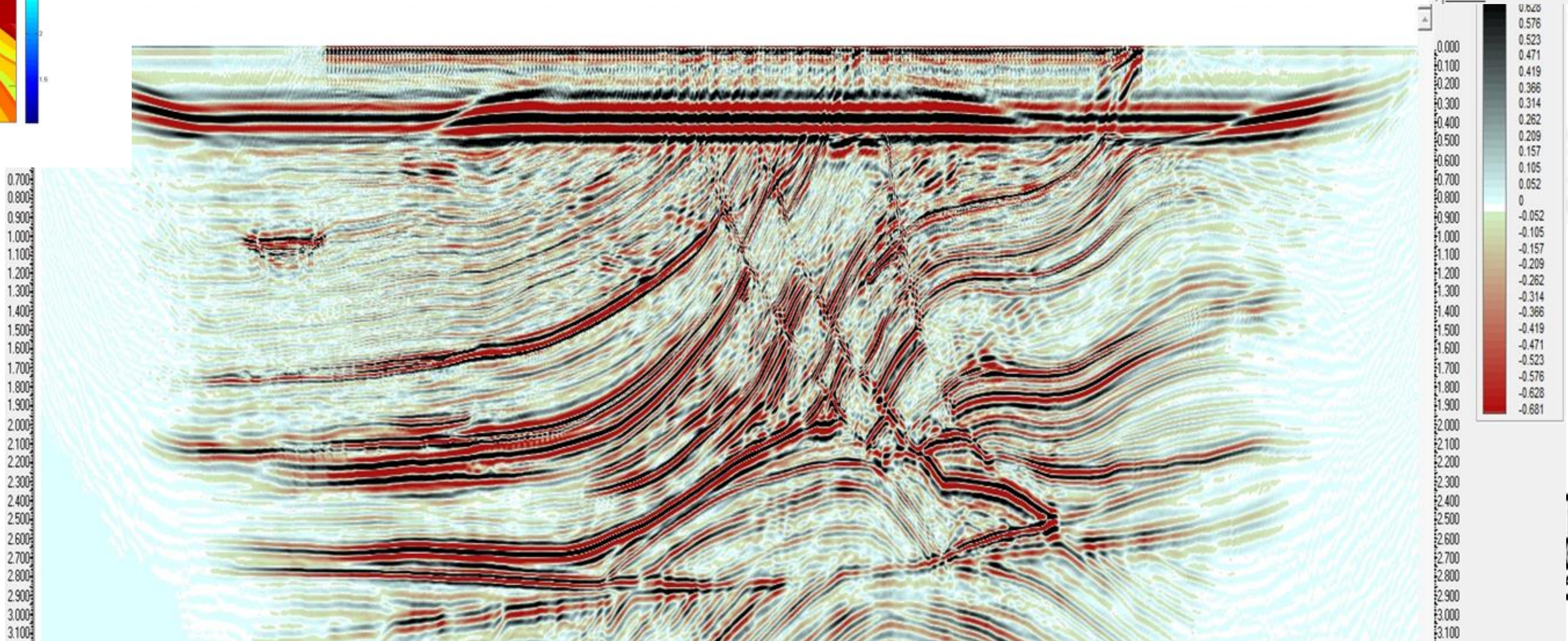
RTH RTM



Marmousi2 model

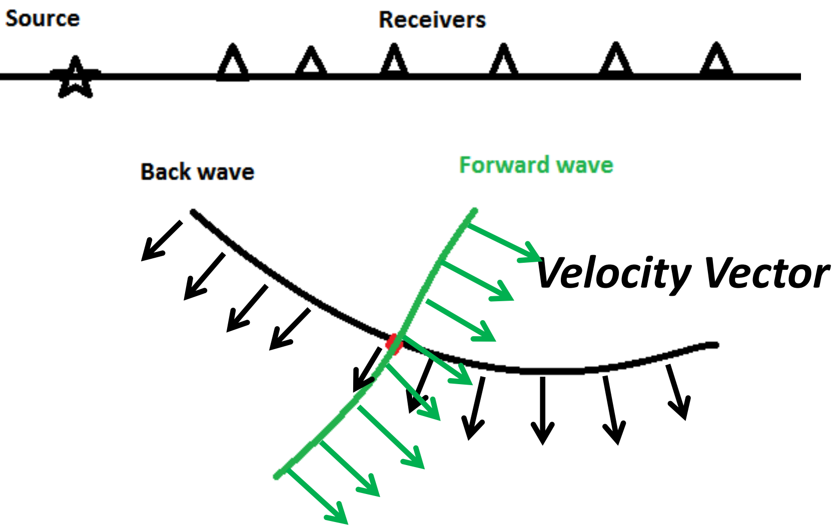


Conventional RTM

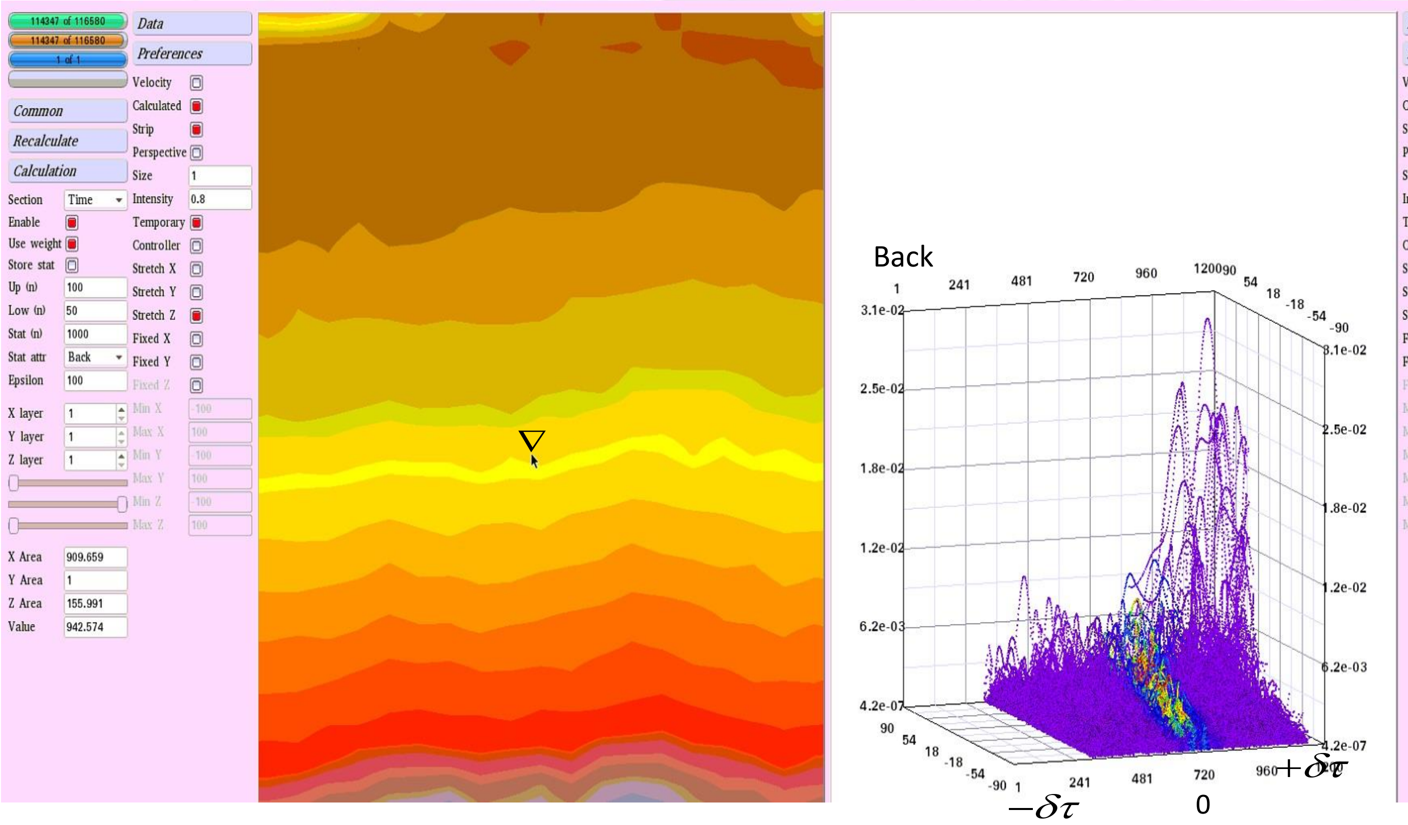


RTH velocity model building based on discrepancy of forward& back arrival times

Scalar Data



ATD –Arrival Time Discrepancy



$$(\nabla\tau)^2 = n^2 \quad n = 1/V$$

$\delta n/n \sim \delta\tau/\tau$

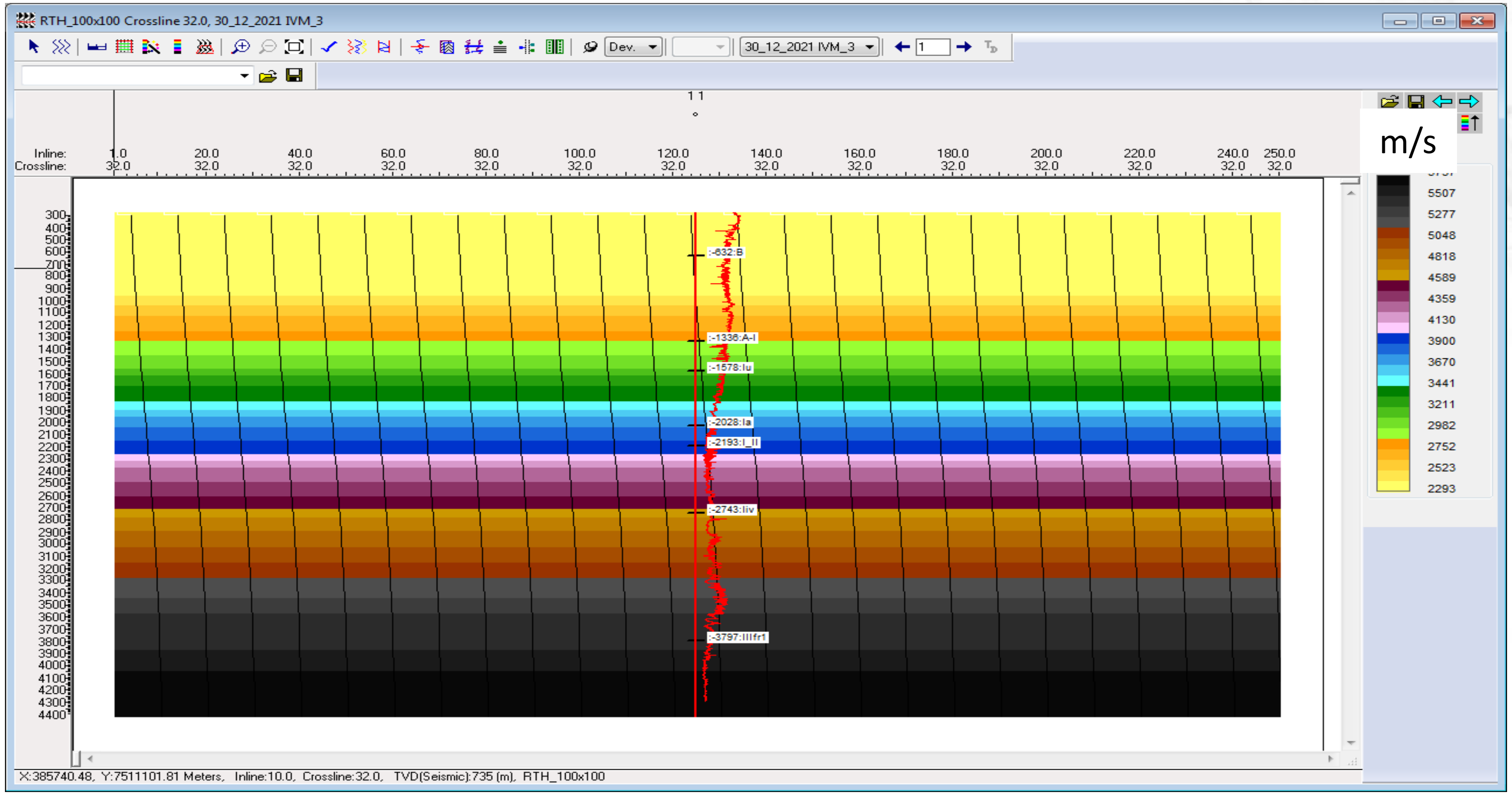
EAGE ANNUAL 2022 83RD CONFERENCE & EXHIBITION MADRID | SPAIN

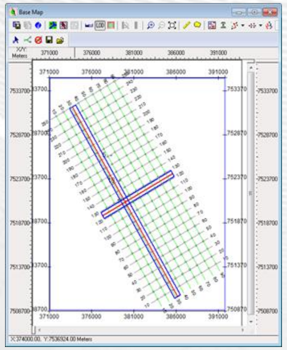
RTH Initial Velocity Model(м/с)

Example

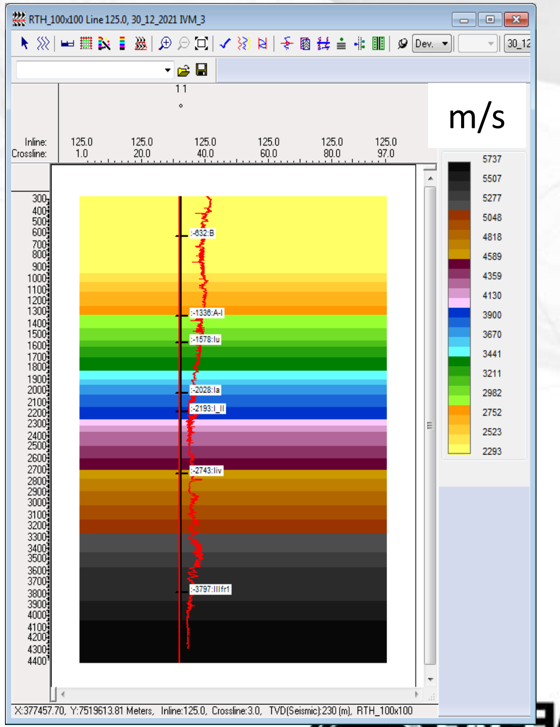
Inline

Gradient model





Crossline

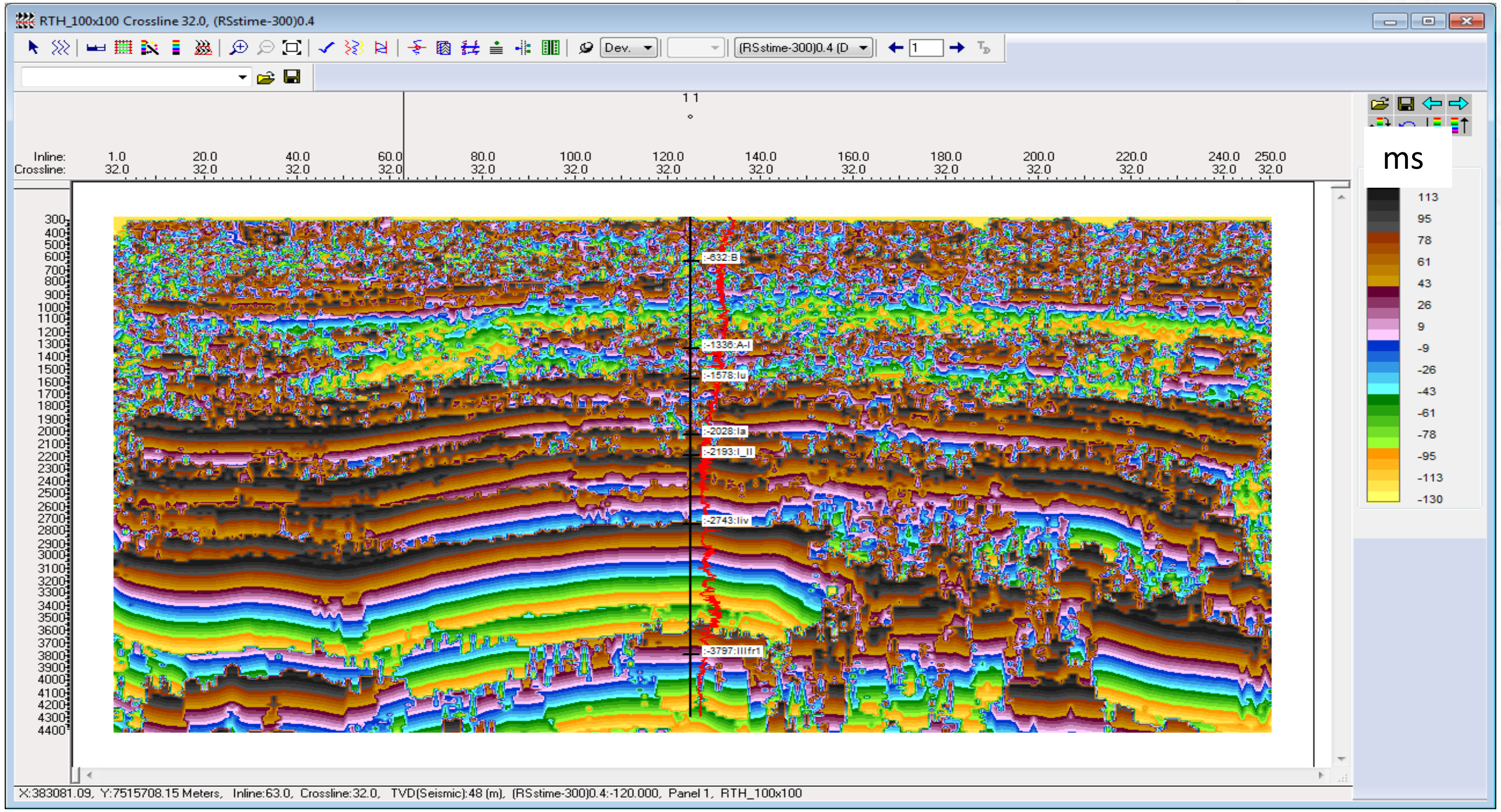


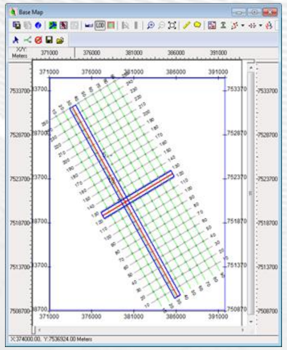
Example. Timano-Pechora, 200 sq.km

RTH ATD –Arrival Time Discrepancy (ms)

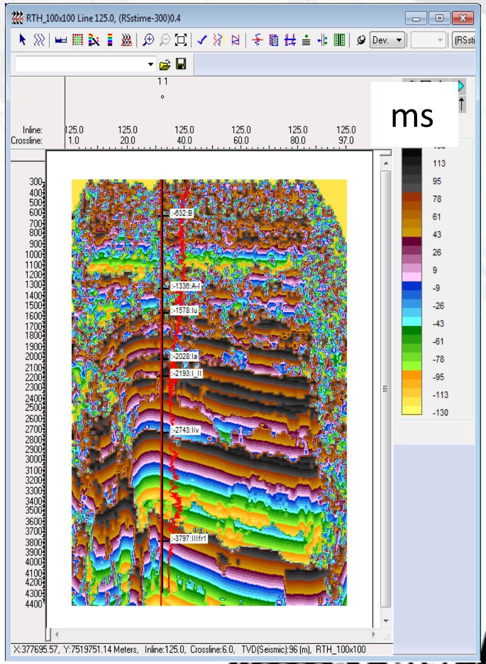
Example

Inline





Crossline

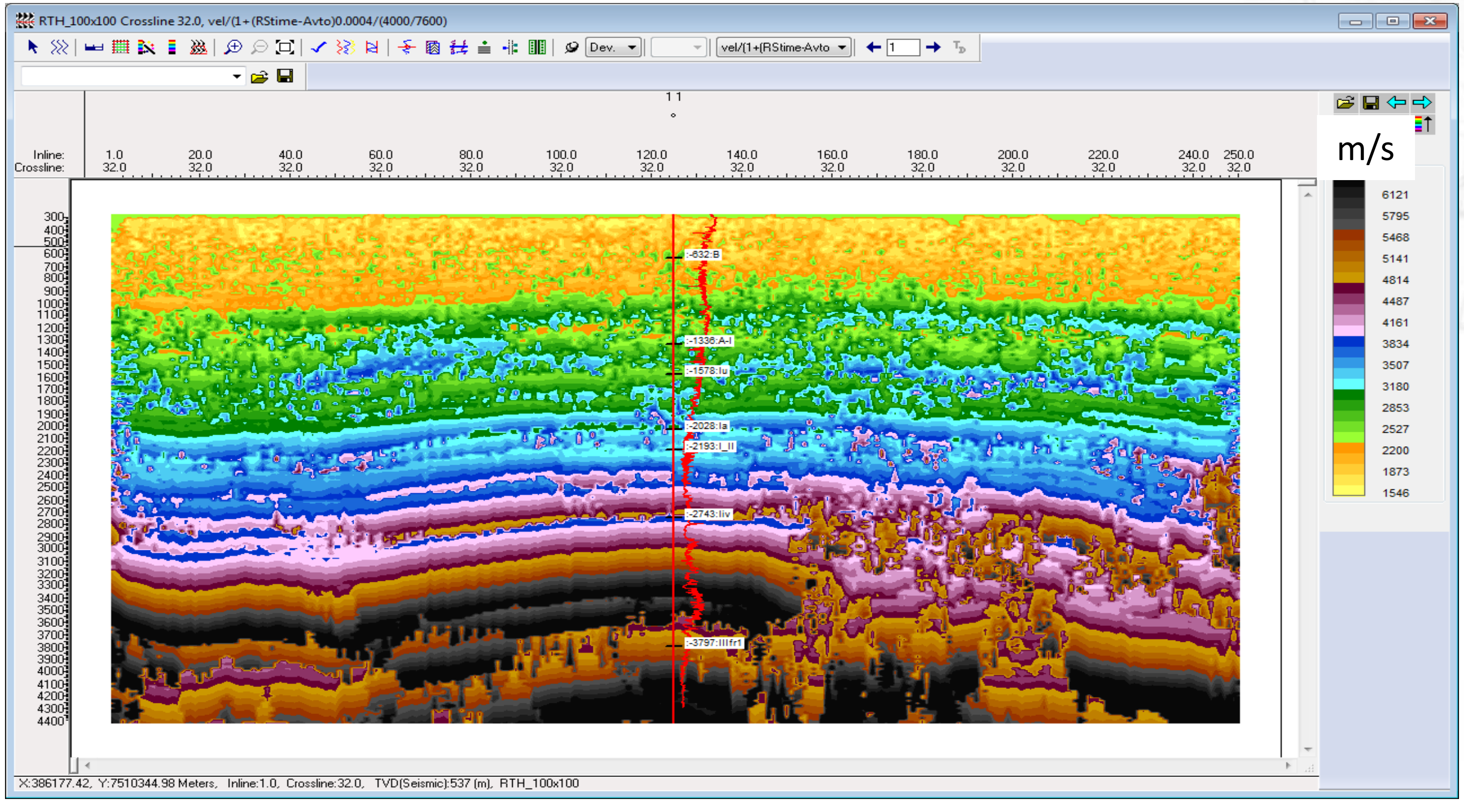


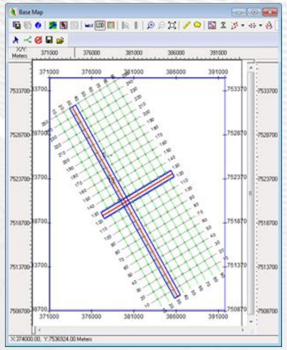
Example. Timano-Pechora, 200 sq.km

RTH velocity (m/s)

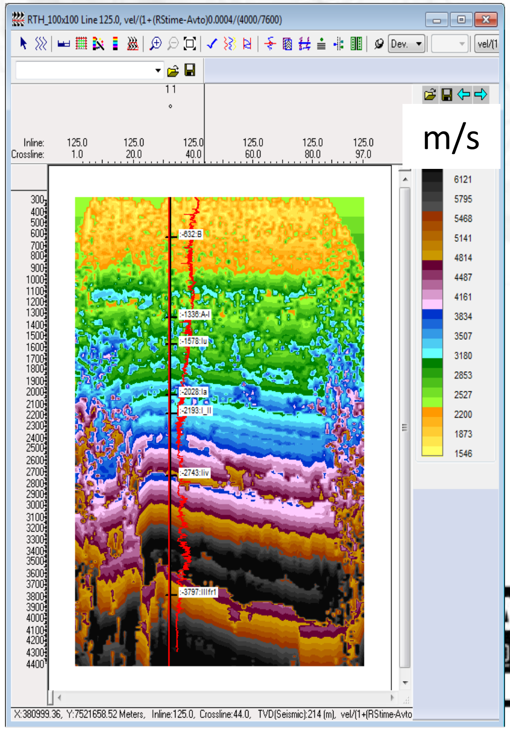
Example

Inline





Crossline



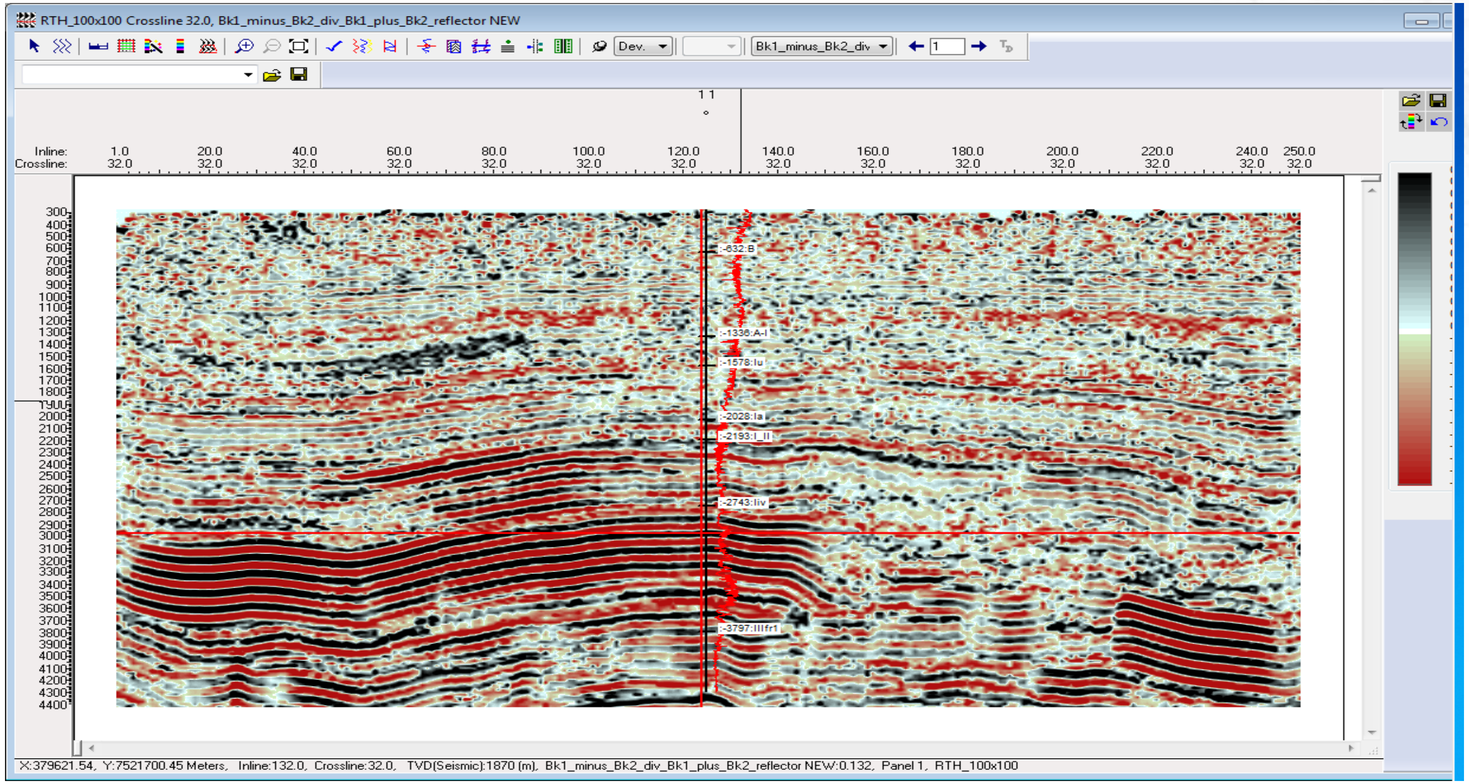
Example. Timano-Pechora, 200 sq.km

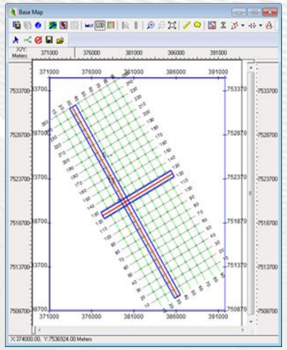
RTH Reverse Time Migration

Example

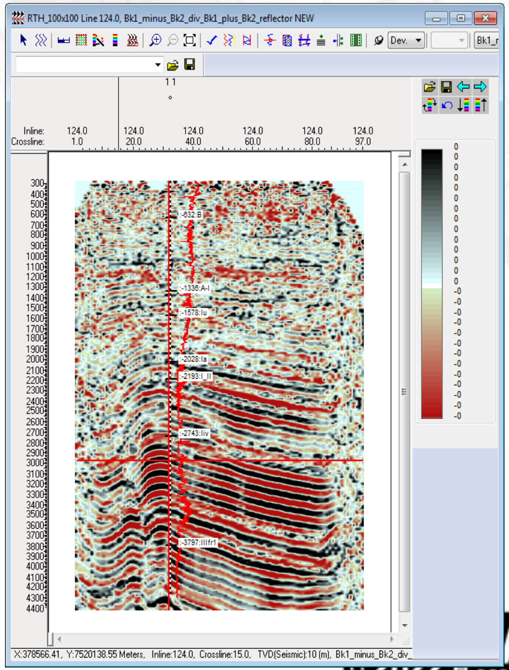
Case HardVSP-SoftVSP Back Amplitude Imaging Condition

Inline





Crossline



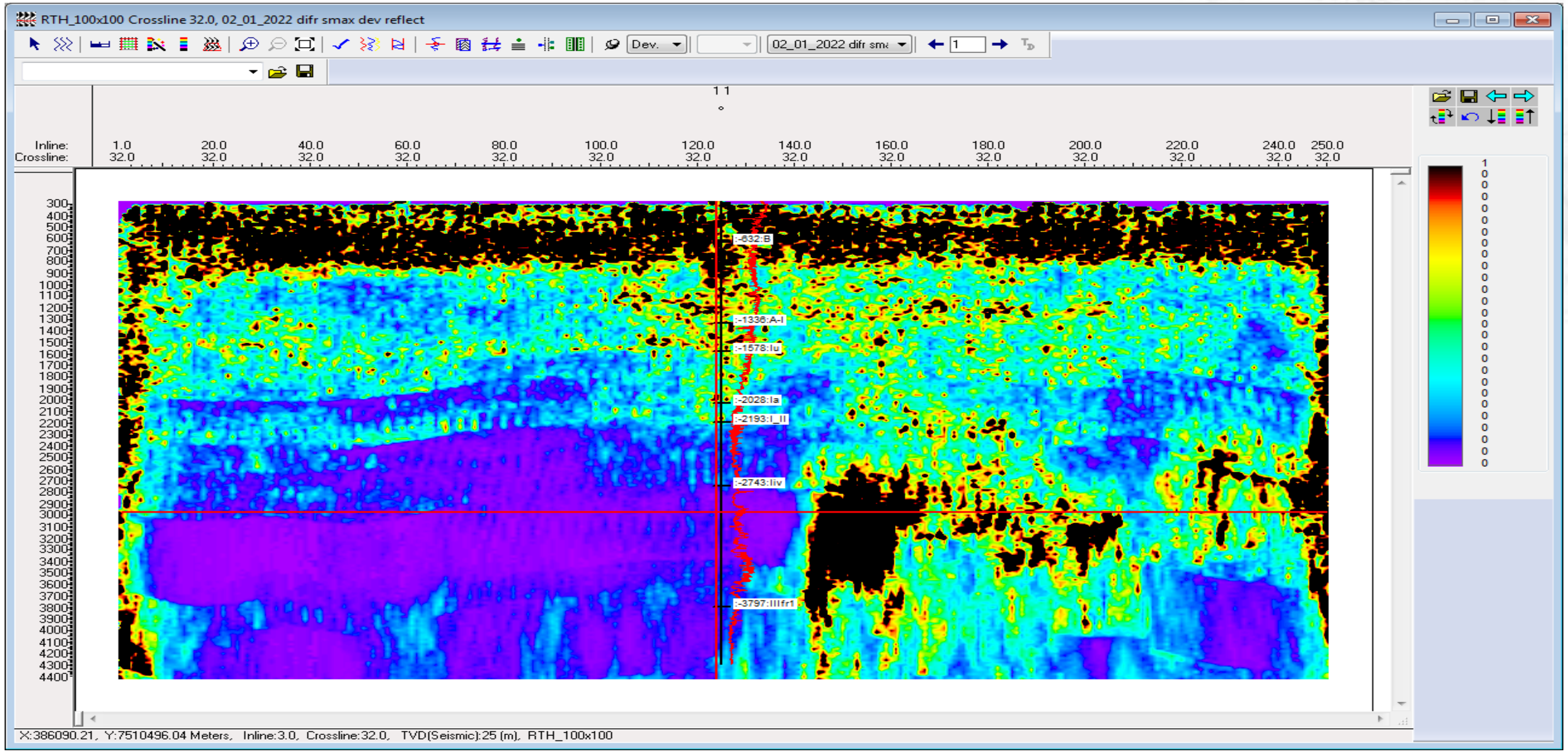
Example. Timano-Pechora, 200 sq.km

RTH Diffraction/Reflection Ratio

Example

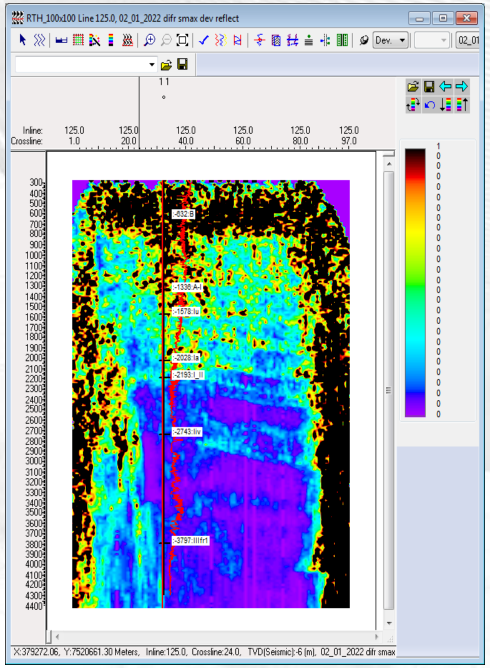
Case HardVSP+SoftVSP Back Amplitude Imaging Condition

Inline

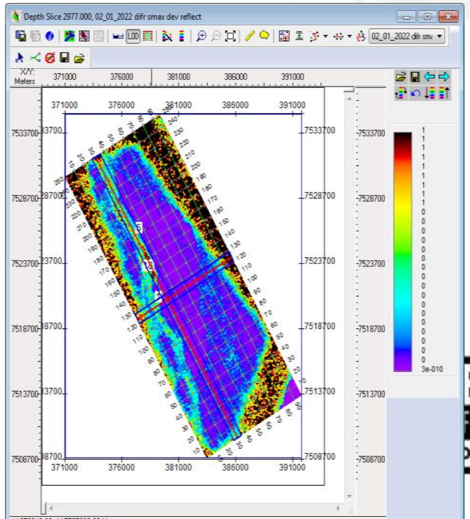


Example. Timano-Pechora, 200 sq.km

Crossline



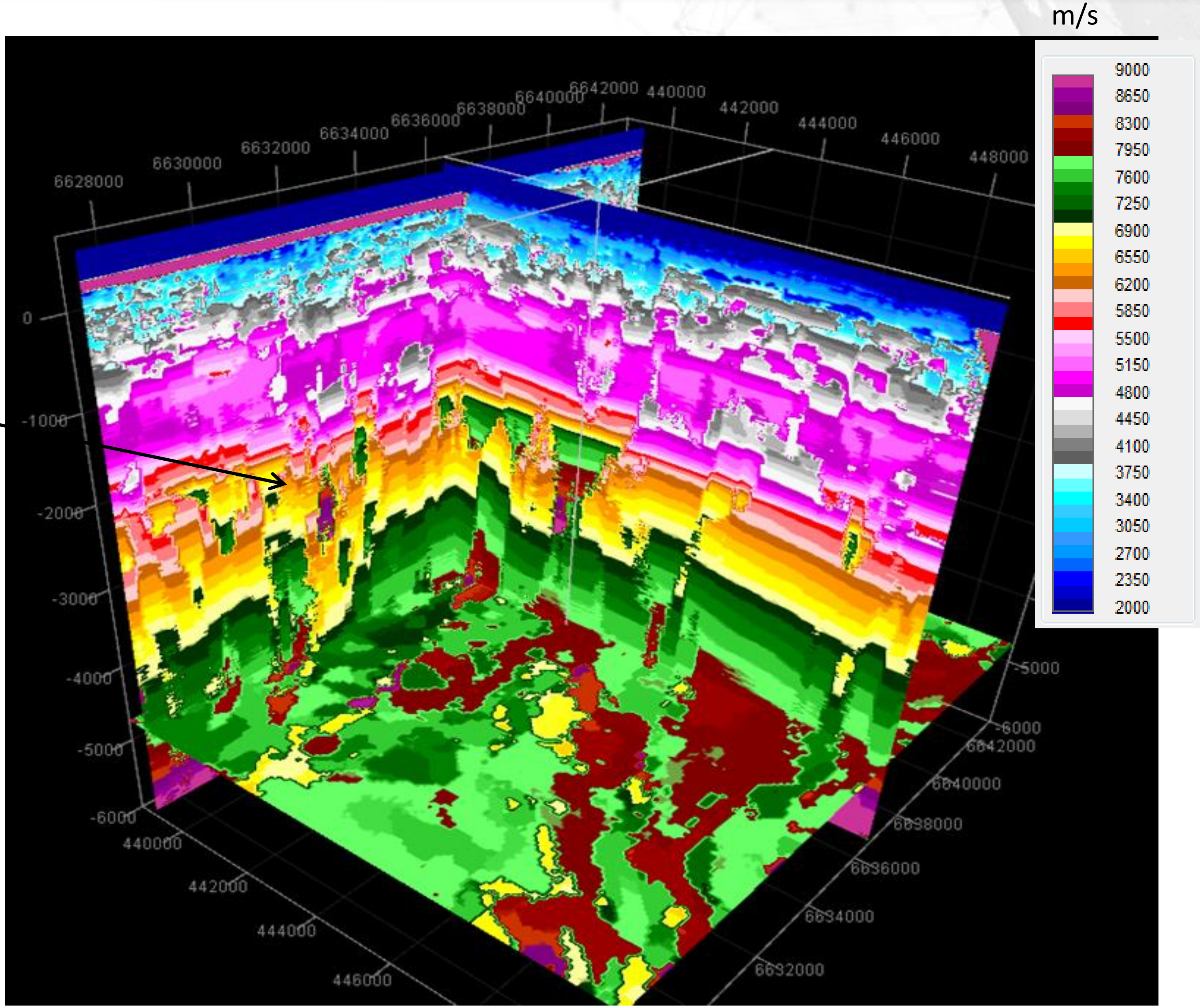
Depth slice



RTH velocity cube. 200 sq.km, East Siberia

Example

Low Velocity, Riphean

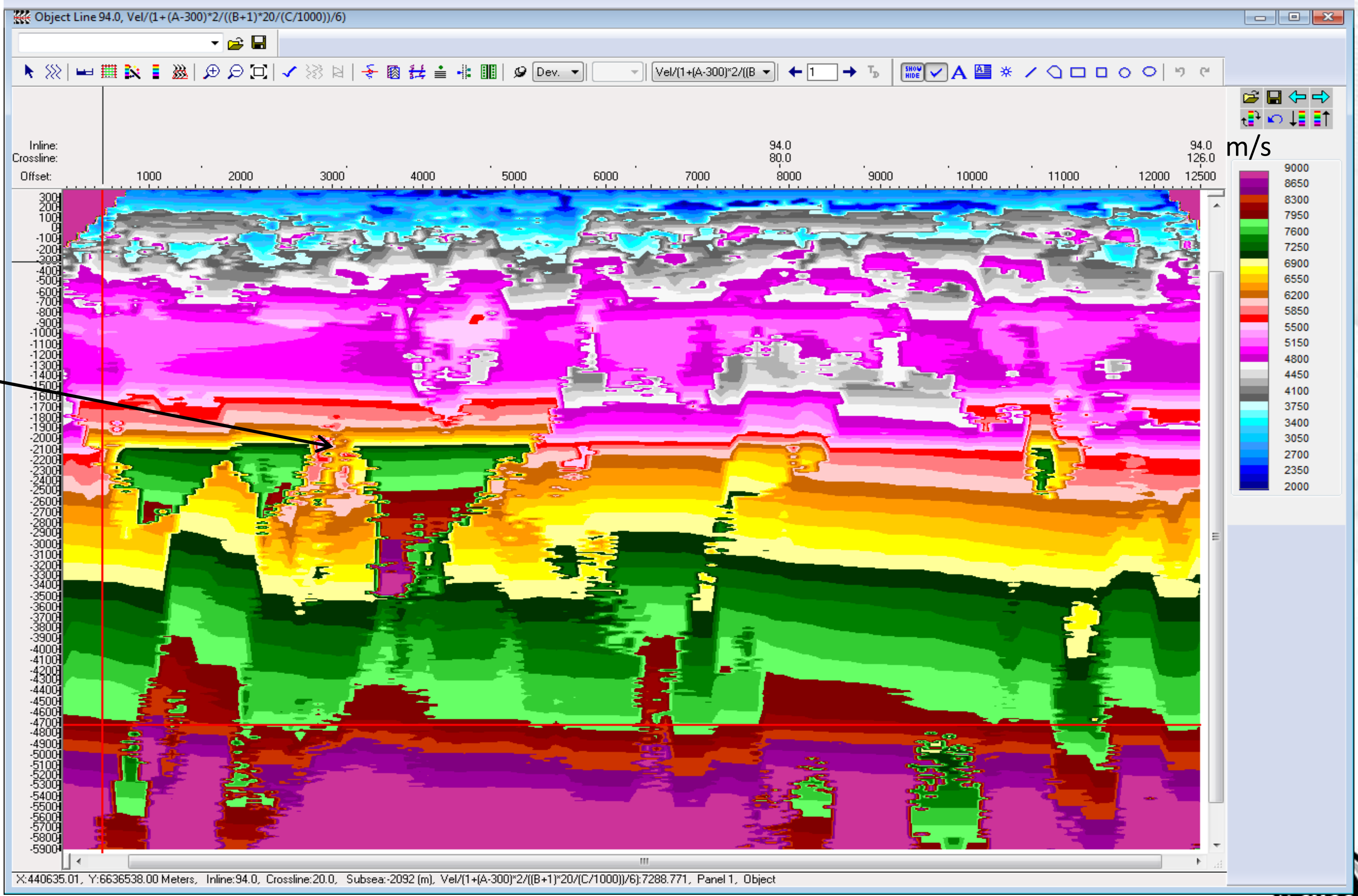


Depth 6 km

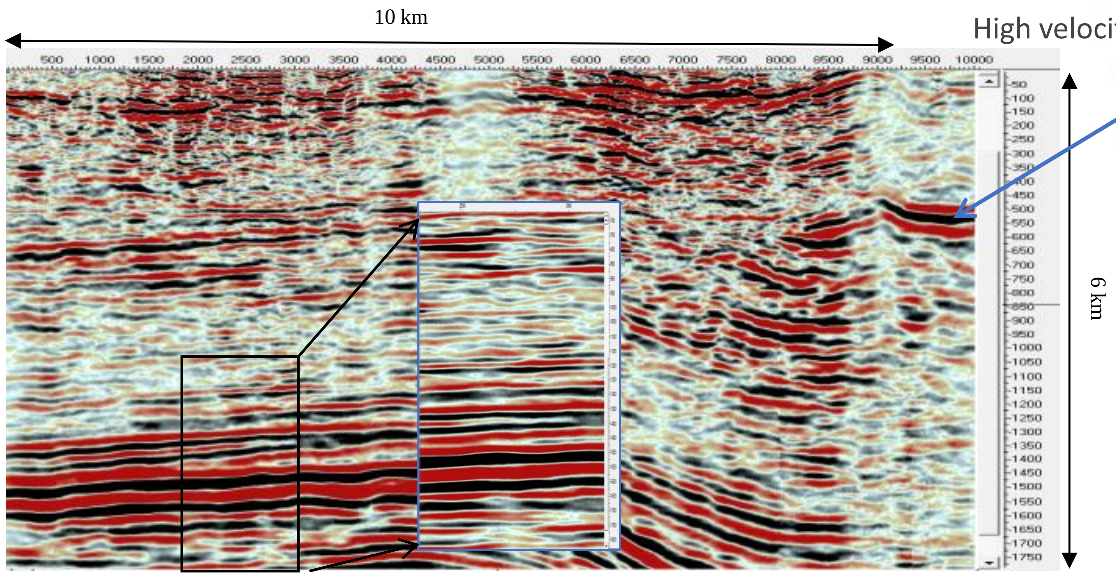
Inline 94

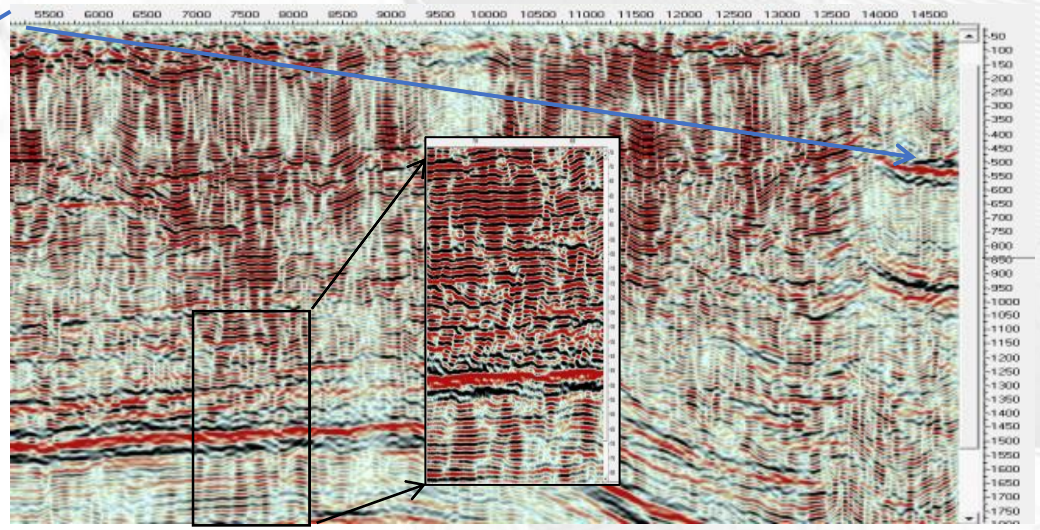
Example

Low Velocity, Riphean



4. Comparison of PSDM/PSTM and RTH RTM

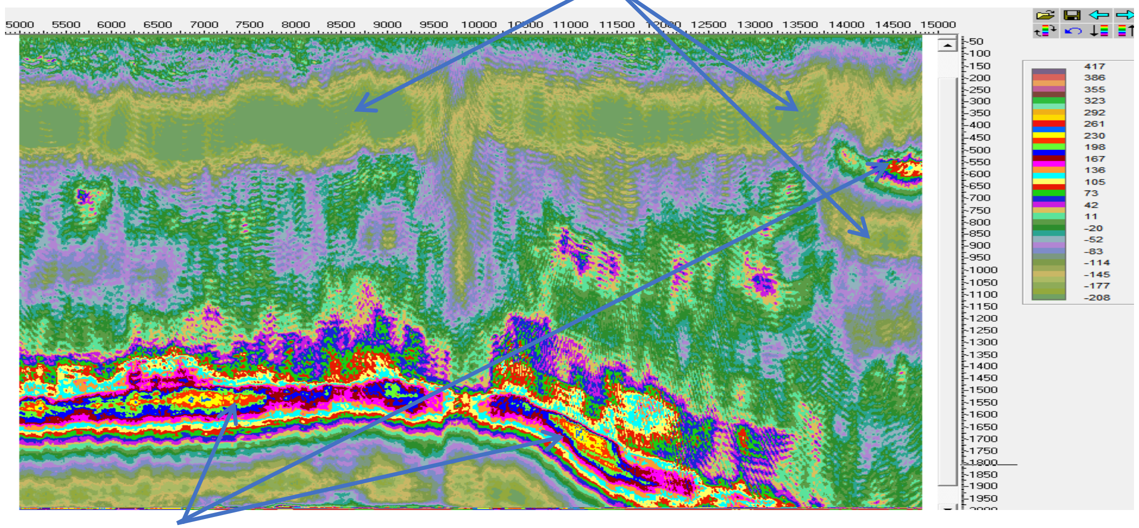




a

Low velocity

b



High velocity

c

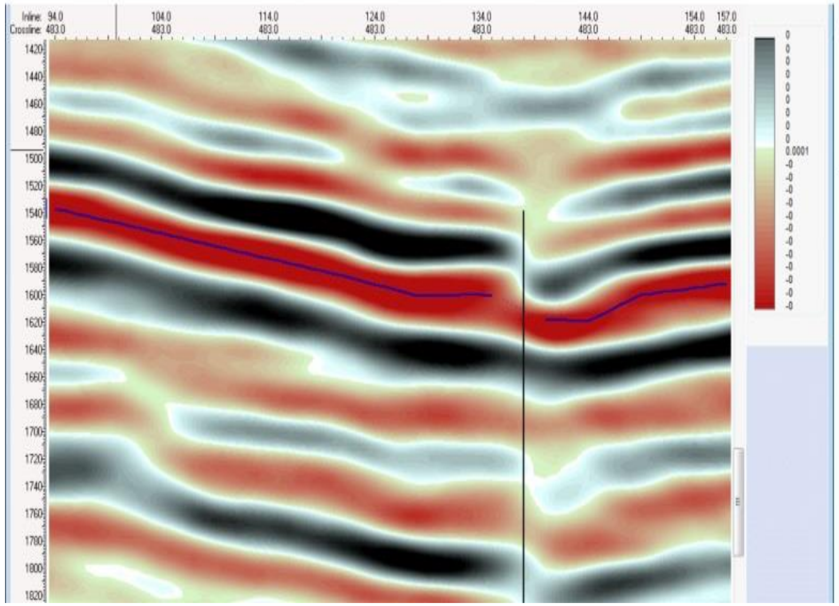
Comparison PSDM & RTH.

Voxel size is 5x5 m.
a - The Kirchhoff Depth Migration
b- RTH Velocity Residual
c- RTH velocity perturbation from -208 m/s (bottom) to 417 m/s (top) (c)

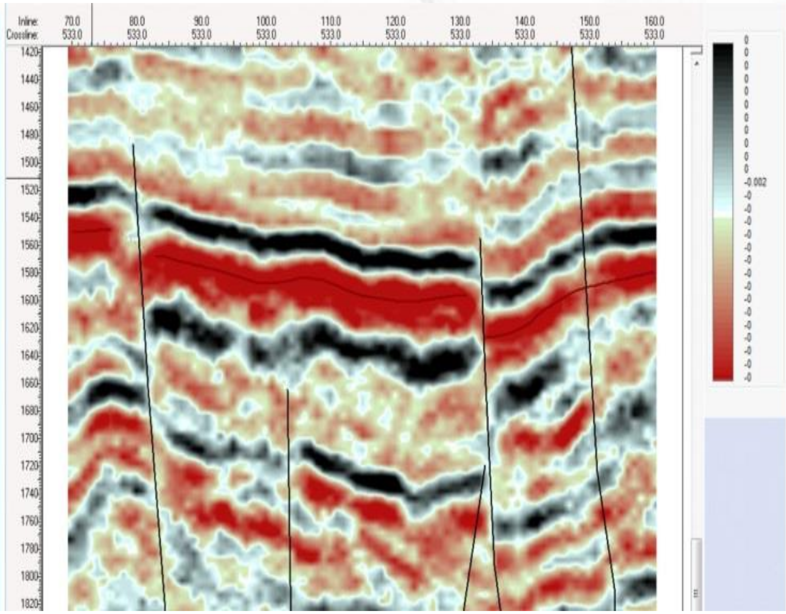
The spatial resolution of RTH migration images is 2-3 times higher compared to conventional depth migration before summation

Comparison of PSDM and RTH

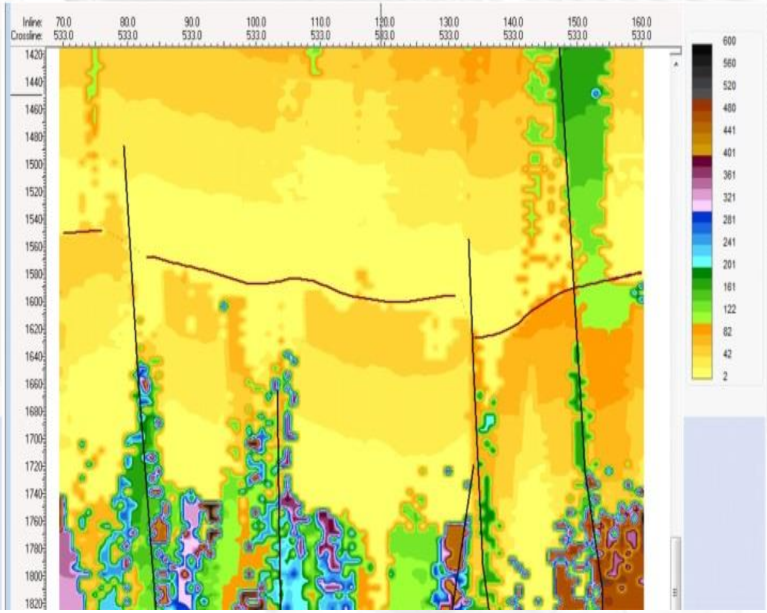
PSDM



RTH ATD Phase



RTH ATD



Field in the north-east of the Nepa-Botuobinsk oil and gas region of the Lena-Tunguska oil and gas province. Profile length 3.5 km, depth up to 1.9 km. Industrial accumulations of oil and gas have been established in a wide range of the section - from the Vendian-Lower Cambrian presalt carbonate complex to the Vendian terrigenous basal sequence.

In the figure on the left is the result of a standard PSDM migration, in the center is the RTH ATD Phase attribute that allows you to get the maximum resolution picture while maintaining dynamic features, on the right is the RTH ATD attribute responsible for the velocity changes in the section.

5. List of the main features of the RTH method

1. RTH is based on the analysis of total scattering vector diagrams depending on time at each point in space. In other words, the RTH Scattering Indicatrix is not only a function of spatial angles, but also of time.
2. Initial Velocity Model in RTH - Arbitrary Piecewise Gradient Continuous Function of Spatial Variables
3. The RTH method is focused on revealing the spatiotemporal anisotropy of total scattering at each point of the medium. The traditional reflection boundaries in the RTH paradigm are interpreted only as an effect of "in-phase scattering“
4. Simultaneous and independent calculation of all known seismic attributes, such as: Reflection, Diffraction, AVO, Dip, Opening Angle, azimuthal and spatial scattering anisotropy and even more than 50 new, previously unknown attributes
5. The RTH method includes, as a special case, the RTM method and is an alternative to the FWI, AVO/AVA/AVAZ, Acoustic Inversion, MVA methods.
6. The result of HPC RTH processing is an original set of seismic depth attributes of high spatial resolution, which serve as the basis for further RTH interpretation system.

5. Comparison the RTH and the RTM data processing workflow

RTM

1. CDP Data Preprocessing

- *Removal of various interferences using band-pass filtering, spatial frequency-separated filters, Radon transform, etc.*
- *Amplitude recovery and surface-matched amplitude correction*
- *Surface-consistent deconvolution*
- *Construction of the velocity model Vrms and the depth-velocity model Vint*

2. Depth migration

RTH

1. RTM graph preprocessing
2. RTH decomposition settings:

- Choice of voxel size, choice of initial velocity model, duration of the time interval, sampling frequency,
- Source regularization,
- Choice of difference scheme parameters, PML parameters.

3. Decomposition of CDP data. Creation of VDCIG (HPC/GPU)

4. Interactive setting of attribute synthesis parameters on test cubes (HPC/CPU)

5. Stream processing of VDCIG data. Synthesis of full size seismic attribute cubes (HPC/CPU)

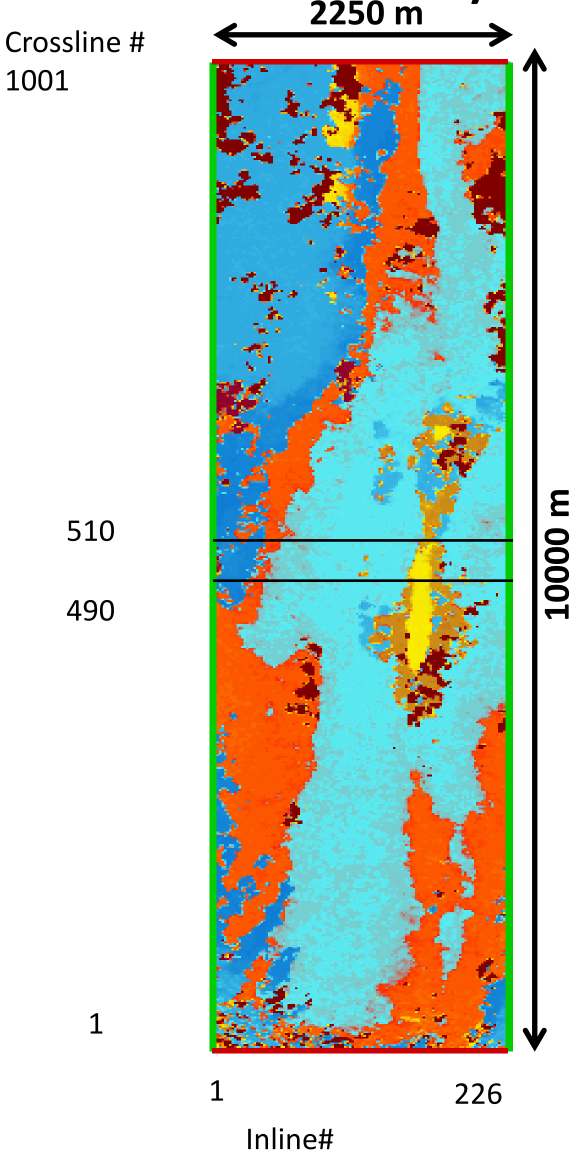
EAGE ANNUAL 2022 83RD CONFERENCE & EXHIBITION MADRID | SPAIN

6. RTH Interpretation road map

##	Problem	RTH solution
1	Target horizon identification	RTH velocity-based horizons splitting
2	Target structure mapping	RTH-based high-precision structure mapping
3	Thickness of productive horizon	RTH-based thickness mapping
4	Sweet spot problem	RTH velocity-based sweet spot mapping
5	Faults forecast	RTH-based faults identification
6	Forecast an anomalies along horizontal well	RTH-based geomechanic properties prediction
7	Highly productive deposits and zones of improved reservoir properties localization	RTH-based multi attributes approach

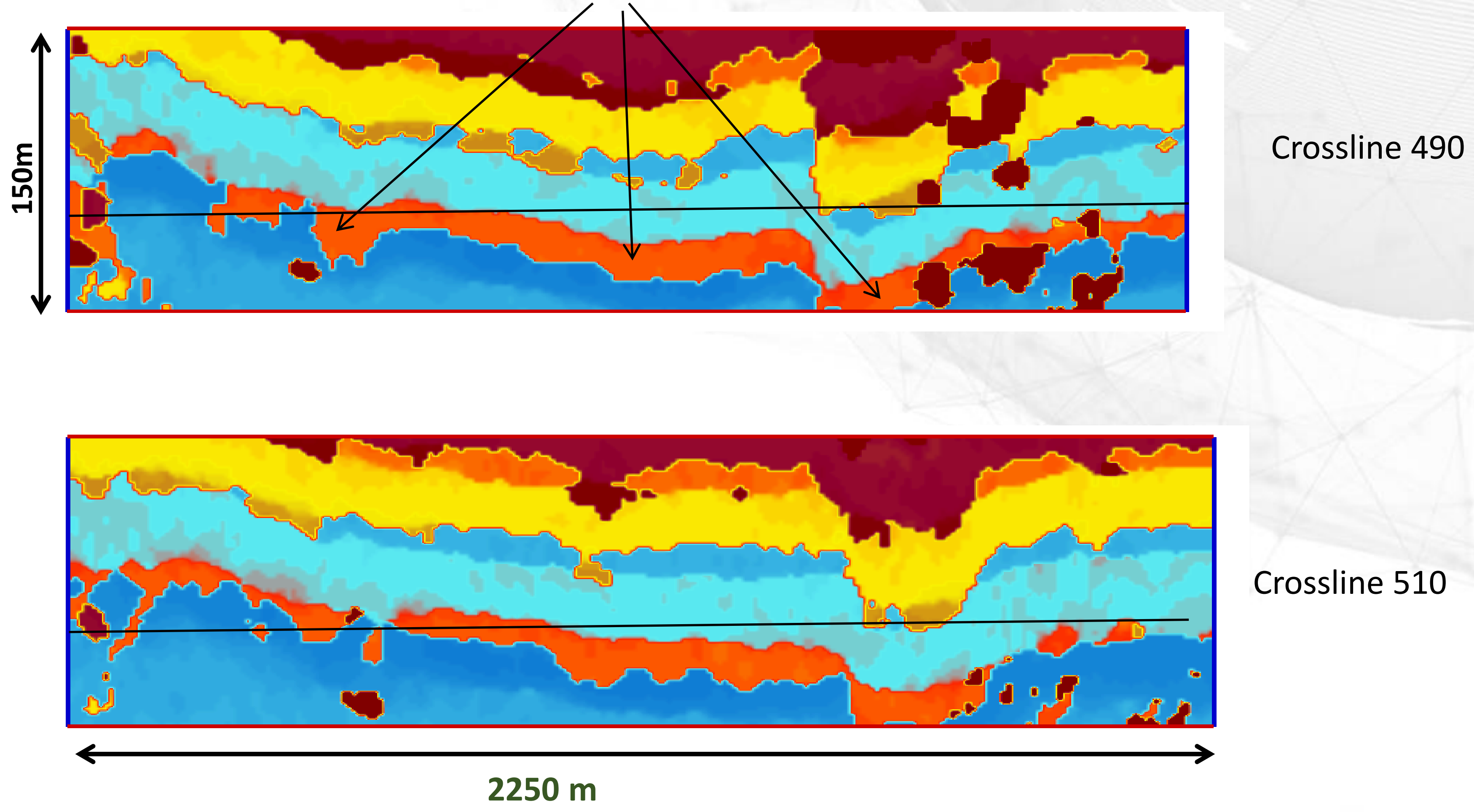
Problem #1. Target horizon identification

Solution: RTH velocity-based horizons splitting



Depth Slice 1580 m

Boutobinsky (event top KV) oil sandstone reservoir mapping



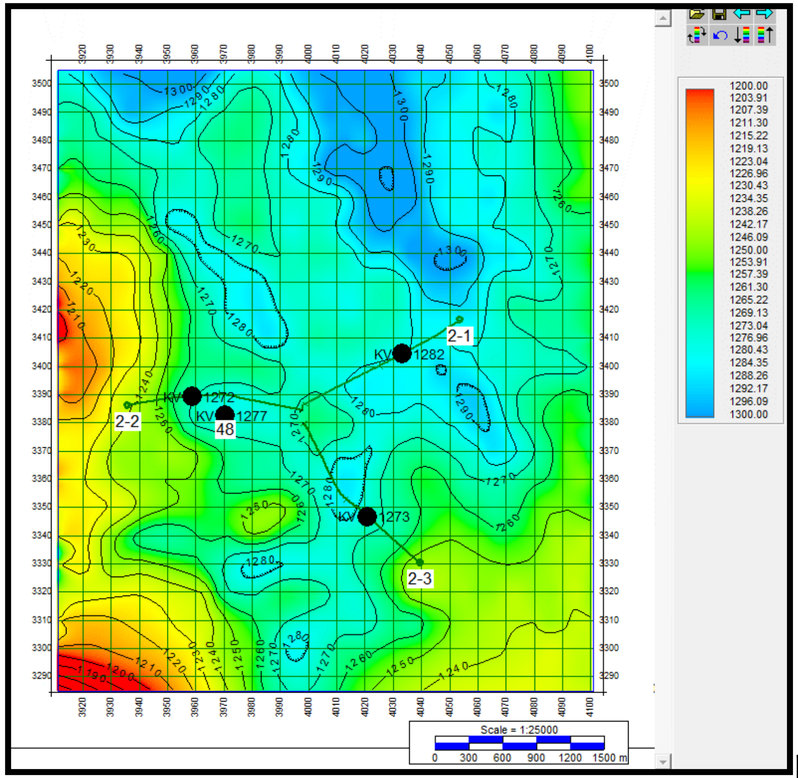
Botuobinsky Oil Reservoir Delineation. Eastern Siberia.

Voxel size 10x10x2 m

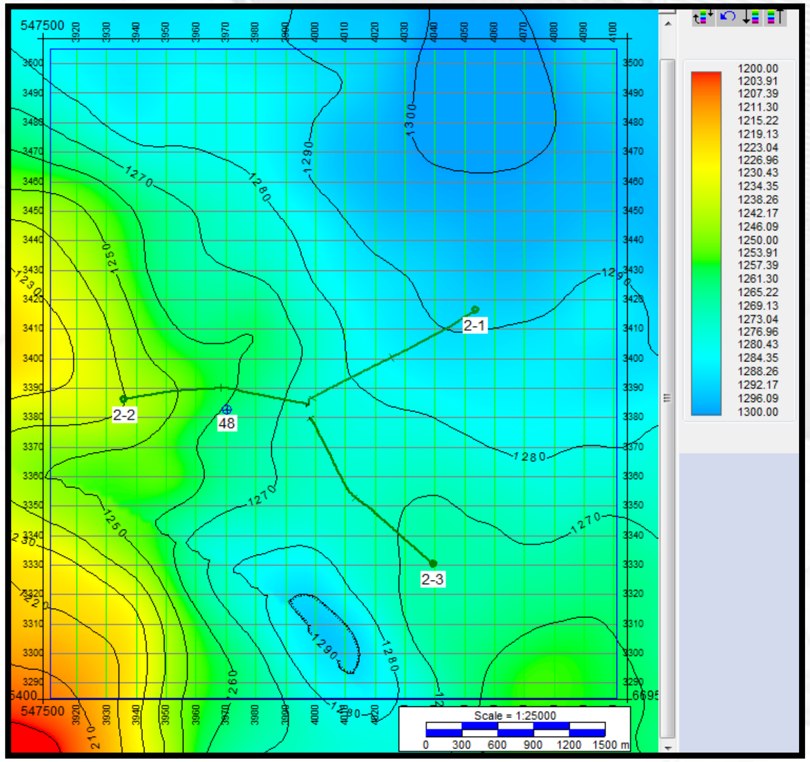
Problem # 2. Target structure mapping

Solution: RTH-based high-precision structure mapping

4 km



RTH map, m



PSDM map, m

Voxel size is 12,5x12,5x2,5m

Black dots on the map - KV's depth by inclinometry

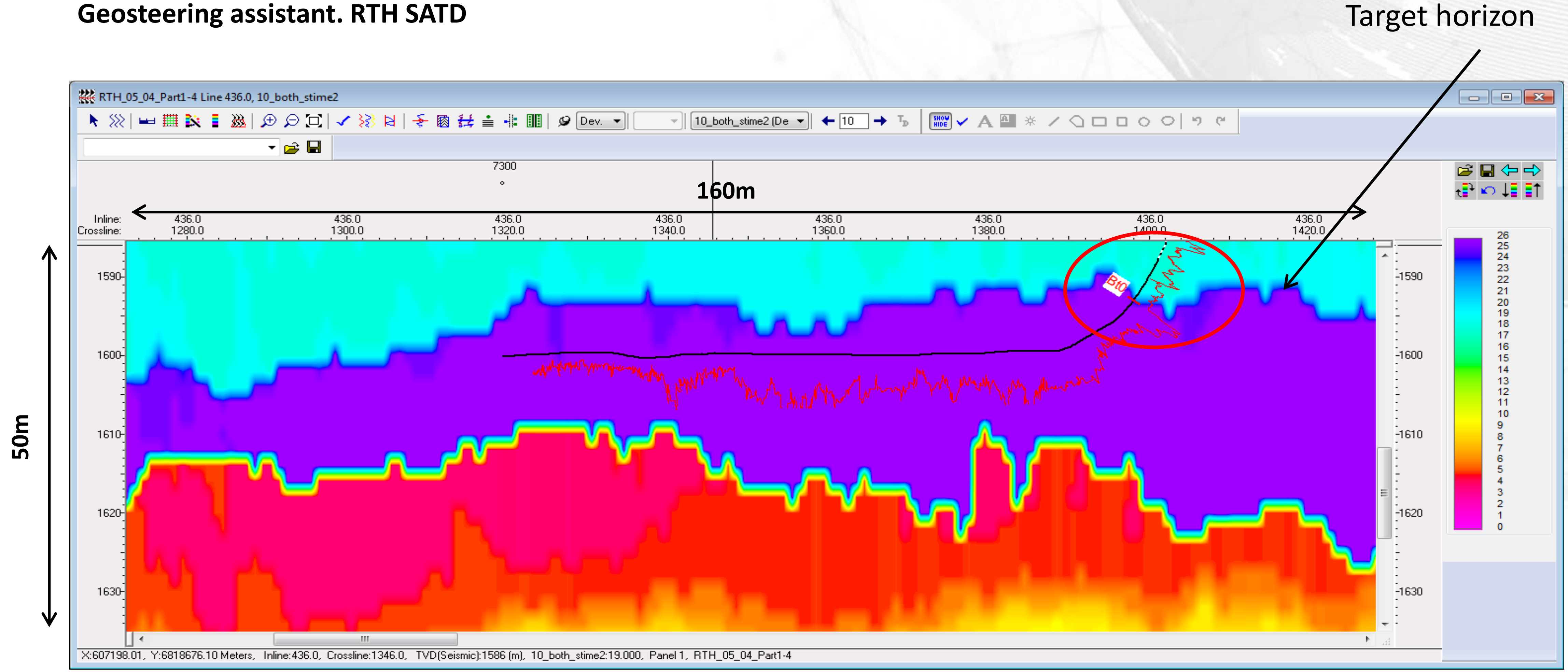
Well #	Depth, well (m)	Depth, RTH map (m)	Error (m)
48	1277	1272	5
2-1	1282	1280	2
2-2	1272	1271	1
2-3	1273	1274	1

Gas deposit of East Siberia. Hamakin... (Hm) horizon.

Problem # 2. Target structure mapping

Solution: RTH-based high-precision structure mapping

Geosteering assistant. RTH SATD

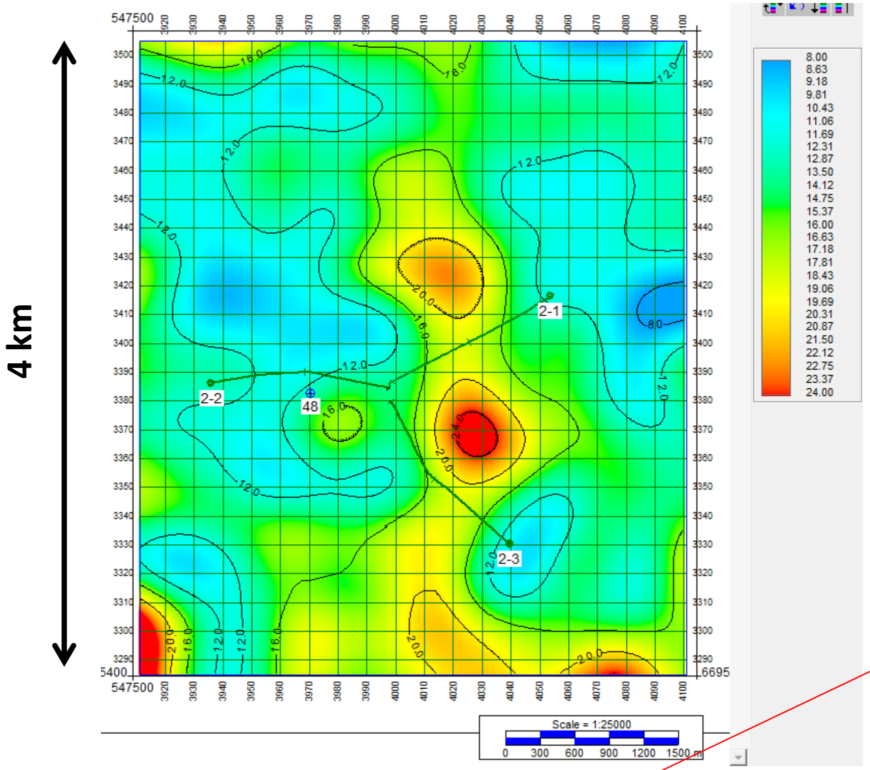


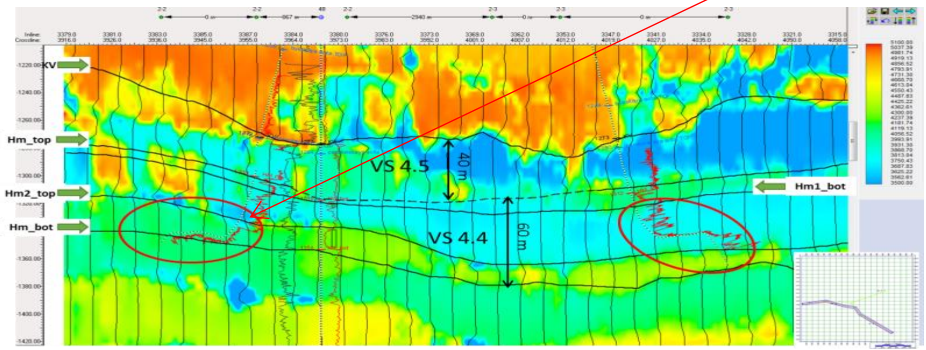
Real geosteering accuracy for horizontal drilling - 2 meters

Problem # 3. Thickness of productive horizon

Solution: RTH-based thickness mapping

Thickness map, meters





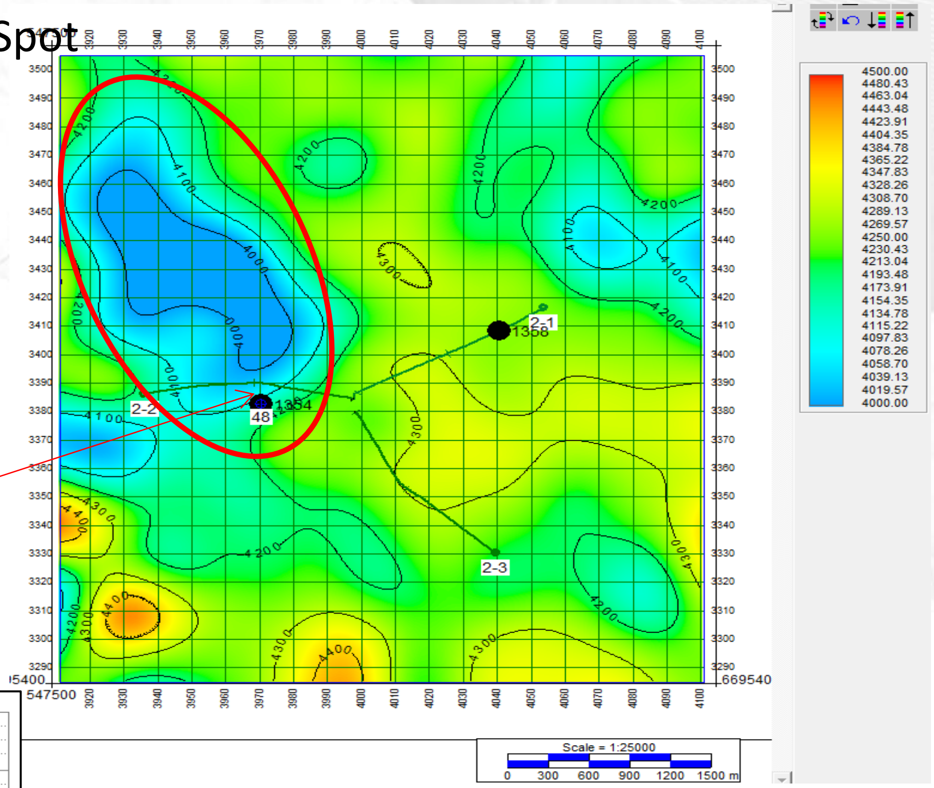
Problem #4 Sweet spot problem

RTH high-precision horizontal drilling assistance

Solution: velocity-based sweet spot mapping

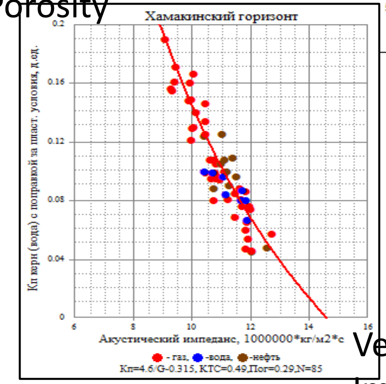
Velocity map, meters per second

Sweet Spot



Multiple excess of accumulated gas production than in neighboring wells

Porosity



Velocity/ Impedance

Voxel size is 12,5x12,5x2,5m

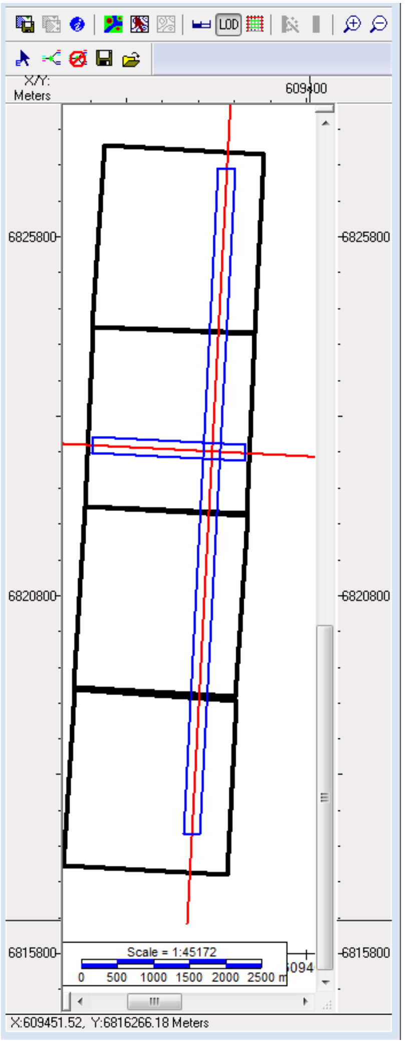
Gas deposit of East Siberia. Hamakinsky (Hm) horizon.

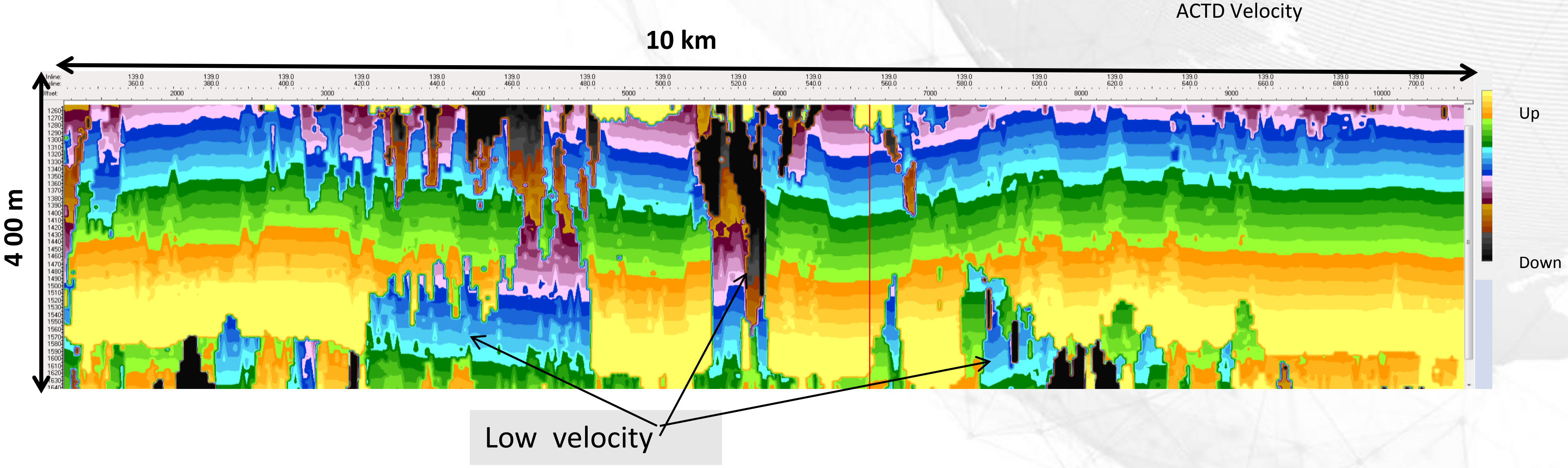
2022 EAGE ANNUAL 83RD CONFERENCE & EXHIBITION MADRID | SPAIN

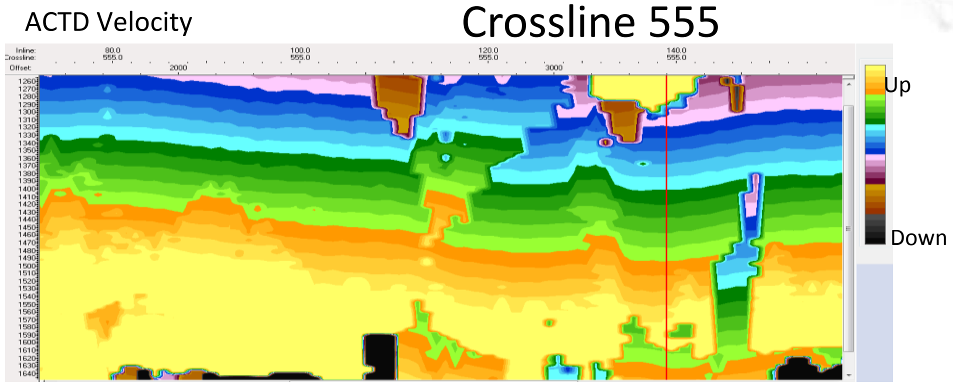
Problem #5 Faults forecast

Solution: RTH-based faults identification

Inline 139



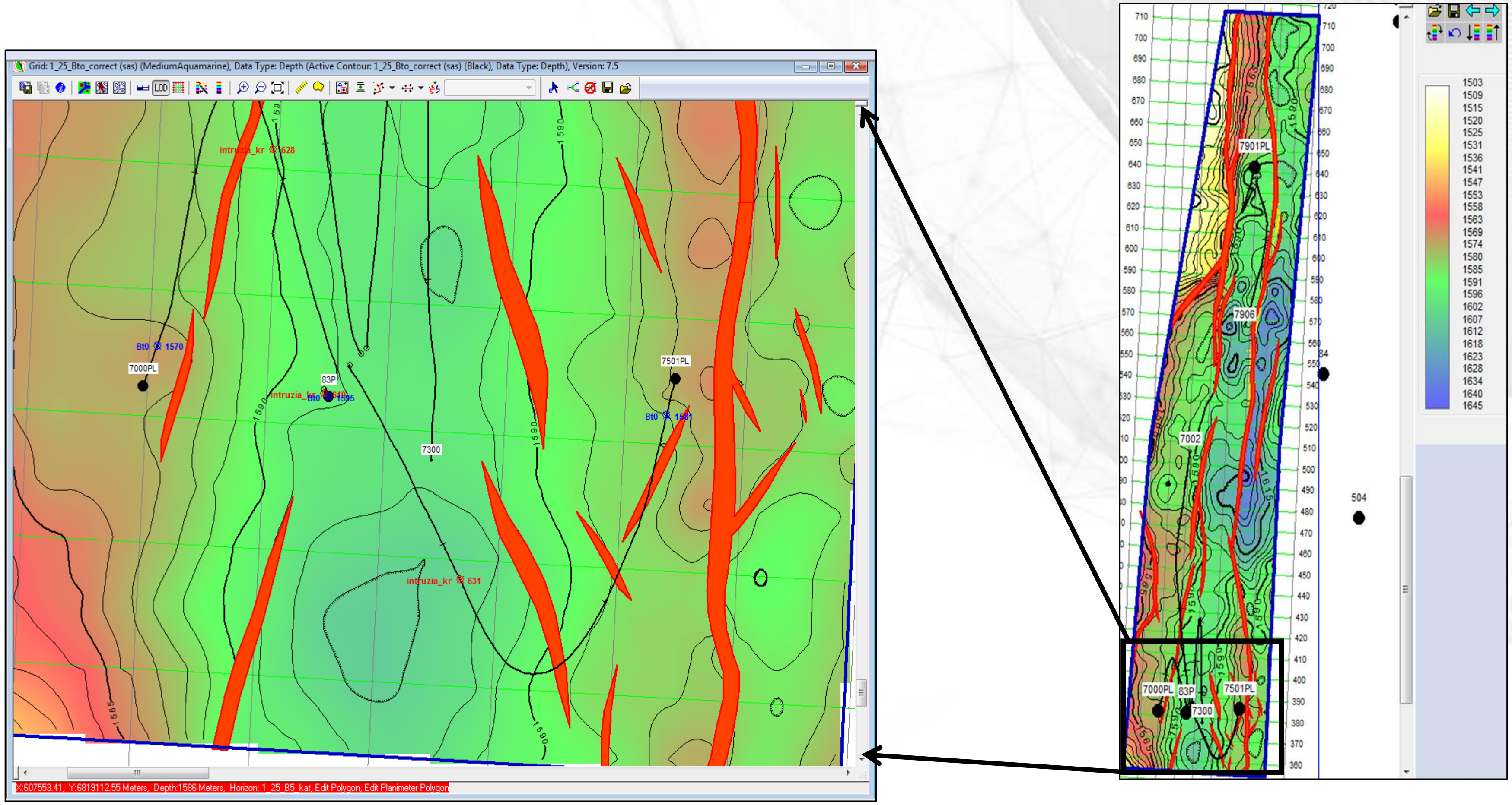




Faults and low-velocity anomalies in the ACTD attribute (Arrival Convolution Time Discrepancy)

Problem #5 Faults forecast

Solution: RTH-based faults identification



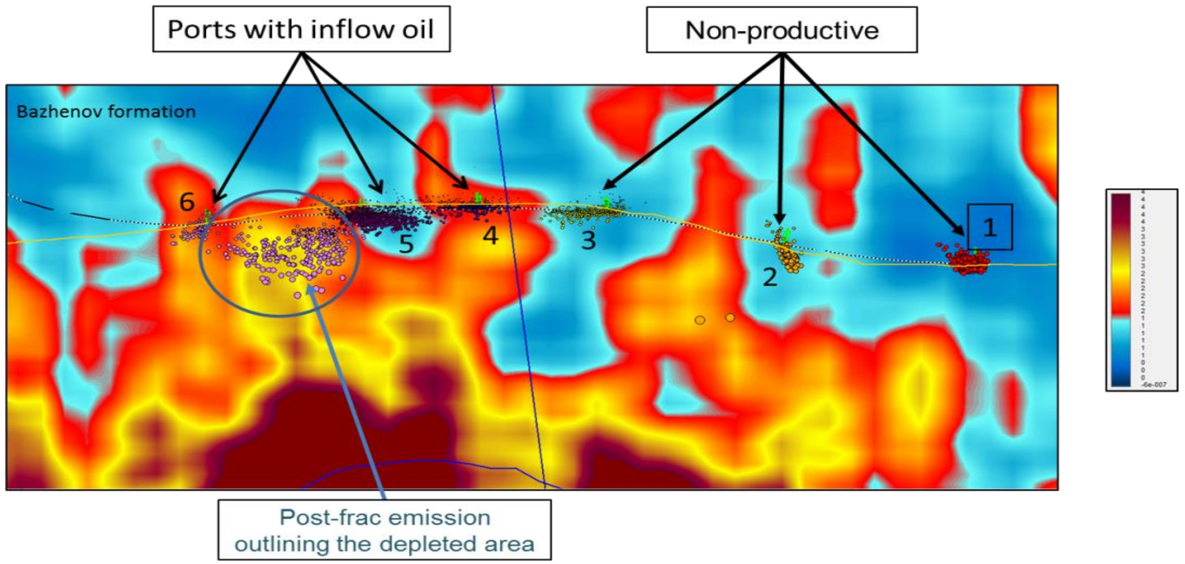
Map of faults along the top of the botuobinsky horizon.Eastern Siberia.

RTH high-precision horizontal drilling assistance

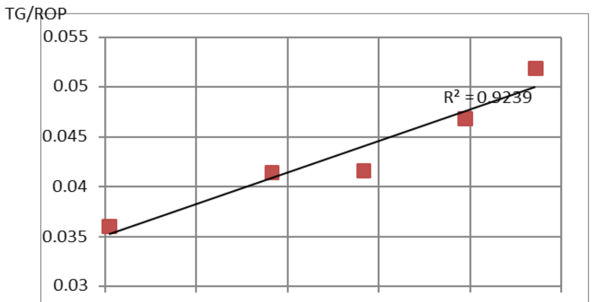
Problem #6 Forecast an anomalies along horizontal well

RTH high-precision horizontal drilling assistance

Solution: RTH-based geomechanic properties prediction

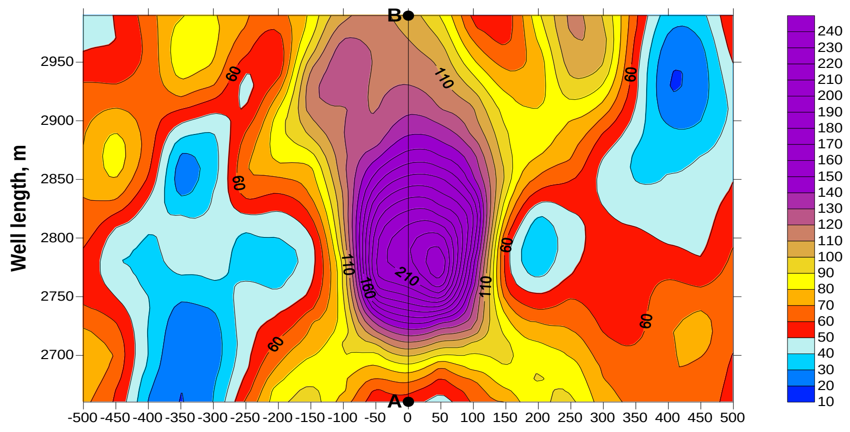


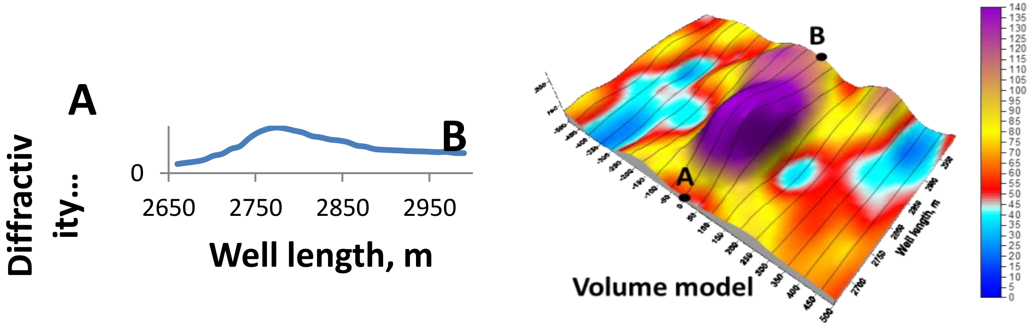
A vertical section of a fracture cube (sweet spot) along a horizontal wellbore. Ports ## 1-3 are dry, ports ## 4-6 are with oil. Western Siberia.



Correlation between fracture (sweet spot) and productivity based on horizontal well statistics.

Providing geosteering through fracture



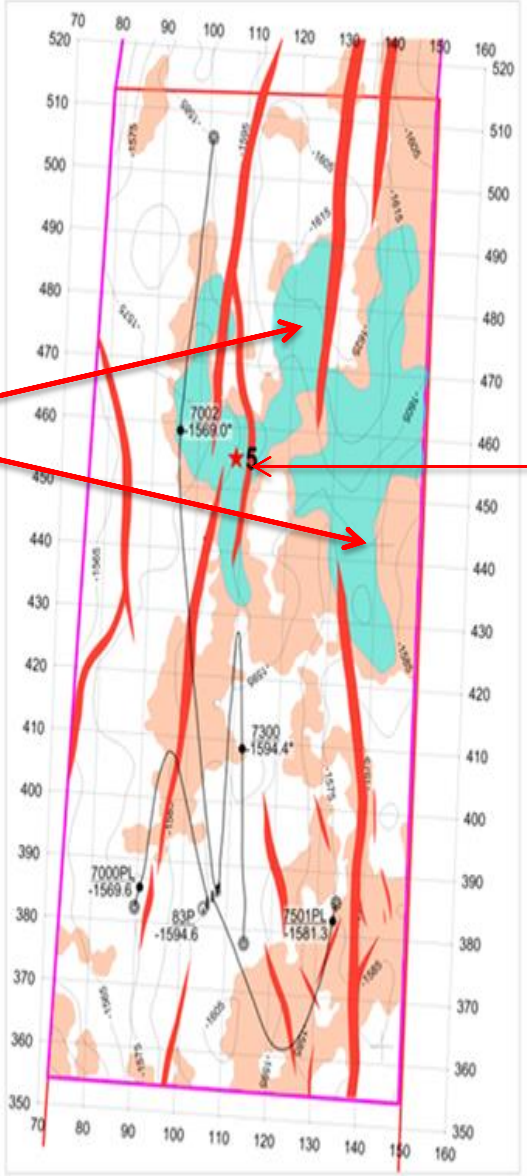


A horizontal section of a fracture cube along a horizontal well (A-B). Gas field. Eastern Siberia.

Problem #7 Highly productive deposits and zones of improved reservoir properties localization

Solution: RTH-based multi attributes approach

Highly productive deposits and zones of improved reservoir properties



Well placement recommendation

Map of highly productive deposits and zones of improved reservoir properties

9. Verification

1. **Lena-Tunguska oil and gas province:**
   - Nepa-Botuobinskaya anteclise. *Vendian-Lower Cambrian* (Talakhsky, Khamakinsky, Botuobinsky, Osinsky horizons) - 4 fields
   - Katanga saddle. *Vendian Riphean*. - 2 field

2. Timan-Pechora oil and gas province:

- Paleozoic, *Perm - Carboniferous* - 2 field

3. Baltic oil and gas province:

- Curonian depression. *Paleozoic - Cambrian* oil and gas horizons, *Permian* horizons of industrial salts - 3 fields

4. Caspian oil and gas province:

- Pre-board stage. Volgograd-Ural system of uplifts. *Paleozoic, Carboniferous,* Bobrikovsky, Radaevsky, Tula horizons - 1 field
- Astrakhan vault, *Paleozoic - Devon-Carbon* -1 field

5. **West Siberian oil and gas province:**

- Krasnoleninskaya oil and gas region. Frolovskaya megadepression. *Pre-Jurassic structural floor*, *weathering crust* - 2 fields
- *Pre-Jurassic structural level, weathering crust and Mesozoic - Jurassic - Cretaceous*, Bazhenov horizon. -1 field

6. North Caucasian oil and gas province:

- Tersko-Caspian trough. *Cenozoic - Paleogene* - 1 field

Total 17 fields. 2017-2022

10. Conclusions

- The RTH method is based on two physical discoveries of the 20th century: the discovery of reversing media in laser optics (1972) and optical holography (1948)

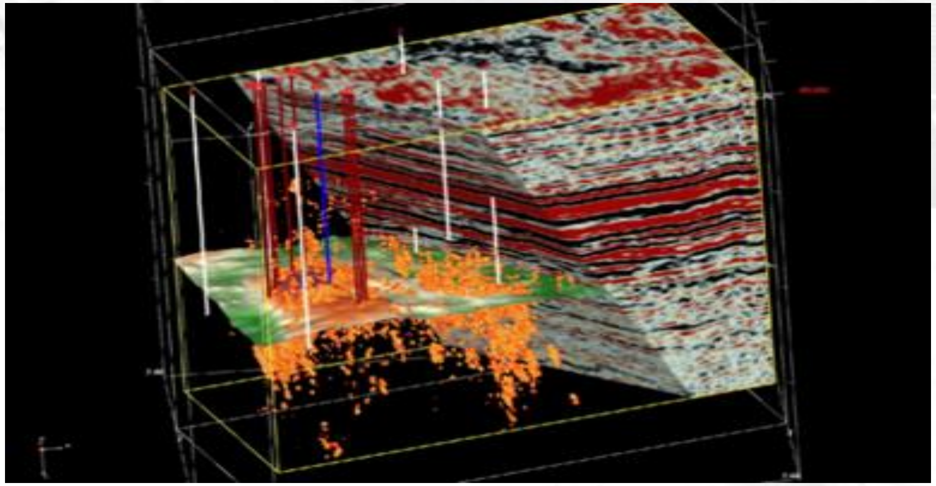
- The RTH method is based on the analysis of time-dependent scattering vector diagrams at each point in space, which makes it possible to significantly expand the range of geological and geophysical problems solved by the method. Traditional reflection boundaries in the RTH paradigm are interpreted only as an effect of "in-phase scattering".

- Scattering Decomposition to Hard and Soft components based on possibility of inverting signal in time is a kernel of the RTH Approach

- An end-to-end RTH technology based on the RTH method is an alternative to all existing traditional migration technologies for processing and interpreting seismic data. New RTH-attributes form their own original interpretation workflow, providing a solution to the most complex geological and geophysical problems of exploration and development of hydrocarbon deposits.

- The RTH technology is resistant to sparse irregular source collection system, automatically takes into account the near surface and provides high spatial resolution velocity tomography.

- The entire RTH technology is implemented in the form of original HPC parallel information processing programs and well-established RTH-attribute interpretation workflow in the standard software environment of a geologist-interpreter.



Acknowledgements

Bitaly Bryksin,

Sergey Sergeev,

Maksim Kozlov,

Ekaterina Anokhina,

Svetlana Shevchenko

Thank You