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Method for constructing diffraction images of fractured-cavernous zones on the basis of multidimensional spectral filtration and new possibilities for studying the properties of geological media on the basis of multidimensional seismic data analysis of a common image point

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Abstract. The article describes the results of applying the original seismic data processing methods: Common Scattering Point Dip (CSPD) and Vector Pair Reverse Time Migration (VPRTM). Specific examples show that the CSPD method allows to effectively solve a wide range of tasks at various stages of geological exploration: search for fractured-cavernous zones, isolation of the cured faults, contouring of granite intrusion, identification of hazardous drilling zones and geonavigation of horizontal drilling. The VPRTM method is effective not only for detecting weak diffractors but also promising for simultaneous accurate analysis in various procedures.

Keywords: processing, scattered waves, diffractors, vector pairs, fracturing

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Fractured reservoirs contain more than a half of the world's hydrocarbon resources, and a significant amount of hydrocarbons is situated in low-porosity Carbonate rocks. Reservoirs in such rocks are mainly confined to fracture zones, for which the main source are tectonic faults. Very often it is the disjunctive faults through which hydrocarbons migrate to traps, and accumulate there. Due to good reservoir properties, such zones provide high flow rates in wells. Fracture tectonics determines the structure, level of capacitance characteristics and saturation of the fracture space. Deposits in the fracture-type reservoirs are referred to complex ones. Effectiveness of prospecting operations in such deposits applying conventional methods is much smaller than in regular porous reservoirs. Russia actively develops a seismic exploration trend aiming at identification of increased fracturing zones over scattered seismic waves. Transnational oilfield servicing companies are also active in Research & Development on the issues related to application of scattered waves.

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The limitations of an original pre-stack multi-channel processing method applied by us – Common Scattering Point Dip (CSPD) – are defined due to a high quality division of the full wave field into reflected and scattered components and the quality of data to be processed. The method was tested on synthetic and field data and proved its efficiency. Verification of the method included processing of more than 20 thousand line kilometers of seismic lines and over 6 thousand sq.km of 3D seismic data at 50 fields. The survey areas are situated in many oil and gas-bearing provinces of the world and in various geologic environments. These include West Siberia, Lena-Tunguska and Volga-Urals oil and gas provinces, as well as some survey areas and seismic lines in Poland, Kazakhstan, China, the Barents Sea, Brazilian and Antarctic offshore areas. The following geologic targets were surveyed by the CSPD method:

- fracture reservoirs in clay rocks of Bazhenov and Abalaksky suites;
- pre-Jurassic complex in West Siberia: fracture-cavernous reservoirs in Triassic magmatic rocks, Devonian Carbonate rocks, basement's weathering crust;
- Cambrian Carbonate and Vendian-Riphean deposits in East Siberia;
- Devonian reefs in Volga-Urals Oil & Gas Province;

- Carbonate, volcano-genetic rocks, magmatic rocks of Pre-Caspian Province;

- volcano-genetic Terrigenous Triassic rocks (China, Latin America).

Let us illustrate the link between scattering index generated by CSPD method, and reservoir's productivity in horizontal wells, by comparing Mud Logging data acquired while drilling horizontal wells with scattered waves (diffractors) amplitudes in a borehole zone within the boundaries of a productive horizon.

Mud Logging data is used to identify within a well section intervals with oil and gas potential, and to evaluate formations' saturation type. In order to interpret Mud Logging data (TG), it is necessary to have information concerning some technological parameters of the drilling process. Therefore, along with Mud Logging, they conduct Mechanical Logging – recording the rate of penetration (ROP). One of the parameters affecting the drilling speed is fracturing. Information on its presence can be obtained from scattered waves interpretation data. Taking these zones into consideration will allow to adjust planned well path before start of drilling, and to avoid complications and accidents during drilling (Anokhina, Zhegalina et al., 2017). Data selection represents amplitudes of scattered waves on the horizontal part of wells, recorded right along the wellbore and in bottomhole zone where values have been summarized in volumes with 25 m, 75 m, 125 m, 175 m diameters (so called «pipes»).

Available data was used to generate average values curves TG/ROP from average diffractor values. For each row of data, a trend line and data approximation reliability value (R^2) were loaded (Fig. 1). All (R^2) values from all generated curves were entered in Tables and this data was used to generate a curve showing the relation between R^2 and averaging diameter (Fig. 2). Along the horizontal axis is the "pipe" diameter, along the vertical axis are R^2 values.

The physical reason is in an attempt to find a "feeding zone" of the wellbore's horizontal part. As seen on the plot (Fig. 2), R^2 values gradually grow along the increase in diameter of the "pipe" from which average diffractor values were derived, then reach maximum for 75-125 m diameter pipes, and begin to decline.

This means that main abnormal scattered waves values, whose appearance we associate with presence of a fractured reservoir, are situated in this zone. Considering this, we can assume that the well takes the largest amount of its extracted product from the 150 m diameter zone. But during drilling horizontal holes, the Mud Logging and ROP readings are affected by not only physical properties of the rocks (first of all, porosity and fracturing) and their lithology, but by well drilling technology as well. An attempt to link changes in TG and ROP values only with technological or only with geological matters may lead to erroneous interpretation of Mechanical Logging data.

Involvement of additional information in the form of scattered waves interpretation data, which identify fracture zone, allows to reduce uncertainty connected with a geological factor. This data plays an extremely important role during well designing and selection of its configuration, and make it possible to conduct drilling activities in optimum technological mode, avoiding emergencies (Erokhin et al., 2016).

Tasks accomplished by CSPD:

- search for fractured-cavernous reservoirs;

- outlining the granitic intrusion;

- identification of healed faults and faults with open fracturing;

- identification of areas dangerous for drilling activities;

- geo-steering of horizontal drilling.

Let us see a few examples of searching for fractured-porous reservoirs. Prediction of spreading zones of fractured and cavernous reservoirs by scattered waves is based on the following principles:

- scattered seismic waves with high amplitudes form in the zones with a significant concentration of open fractures and caverns filled with fluid. The less open fractures and caverns are in the rocks, the lower are amplitudes of the scattered waves field.

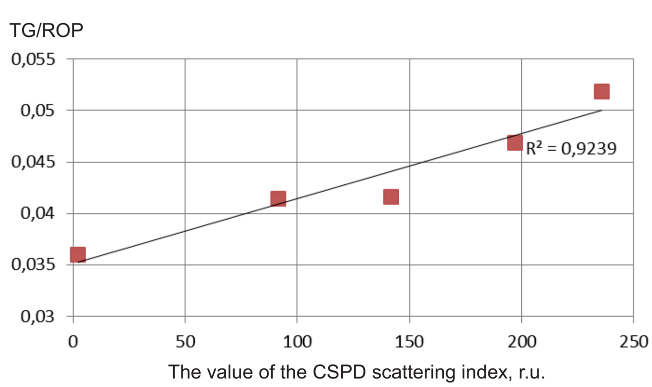

Fig. 1. Relation between average TG/ROP values and average diffractor values within 125 m diameter from the wellbore

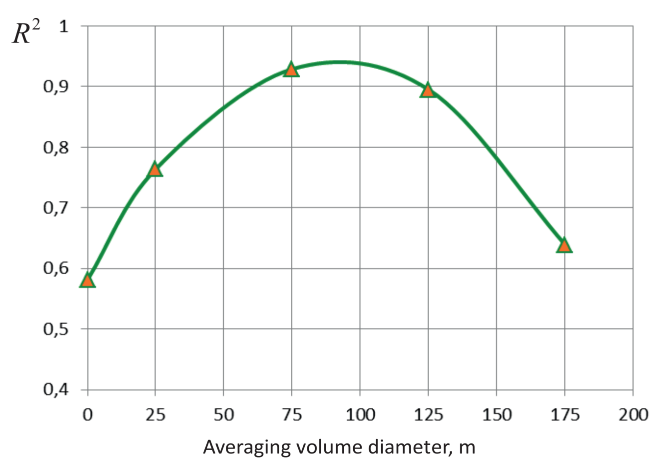

Fig. 2. Relation between average TG/ROP values and averaging volume diameter

- saturation of fractures has very little effect on scattered waves amplitudes, therefore there is no possibility to establish type of fluid which fills the fractures.

- porous reservoirs have low scattered waves amplitudes, almost close to background values. That's why when there are porous and fractured reservoirs in the surveyed productive interval, the scattered waves sections and maps only show increased fracturing zones but not porosity.

At the initial stage of interpretation, taking into account drilling materials, they identify intervals where complications are associated with fracturing zones. Further they establish a match between presence of fracture zones in a well and emergence of amplitude anomalies on scattered waves sections and maps. Then such places are examined in other parts of the area, and a prediction is provided for spreading of zones interpreted as zones with fracturing.

Fig. 3 shows sections with reflected (left) and scattered (right) waves acquired after specialized processing at a field in West Siberia. The reflected wave section does not enable any assumption on presence of fracture zones. By involving a scattered component of the wavefield, it is possible to unambiguously show the places which due to penetration of a fractured reservoir would ensure high flow rates in wells. On this and following Figures, blue color means low scattered waves amplitudes and absence of fracturing and cavernosity, whereas red and yellow correspond to high amplitudes relating to fracture and cavern zones.

We will substantiate the forecast made for drilling according to CSPD method with a case study of an oilfield in Kazakhstan. The main oil-bearing target is Mid Triassic deposits in which two members are identified: volcanogenetic-dolomitic and volcanogenetic-limestone, they are associated with productive horizons T2b and T2a, respectively. Reservoirs in both members are complex, fracture-cavernous and porous-cavernous, they spread along the area in a mosaic pattern and do not conform to structural factor (Kirichek et al., 2013).

In order to forecast zones of fracture-cavernous reservoirs in Triassic deposits, we generated and analyzed maps containing scattered waves amplitudes in the time intervals which correspond to productive horizons (Fig. 4).

After completion of works, well No. 15 was drilled at the field which penetrated identified bed with a fractured

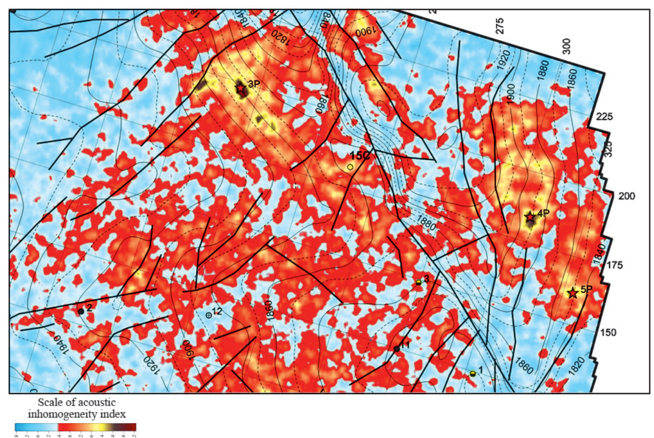

Fig. 4. Map of cumulative scattered waves amplitudes for horizon T2b

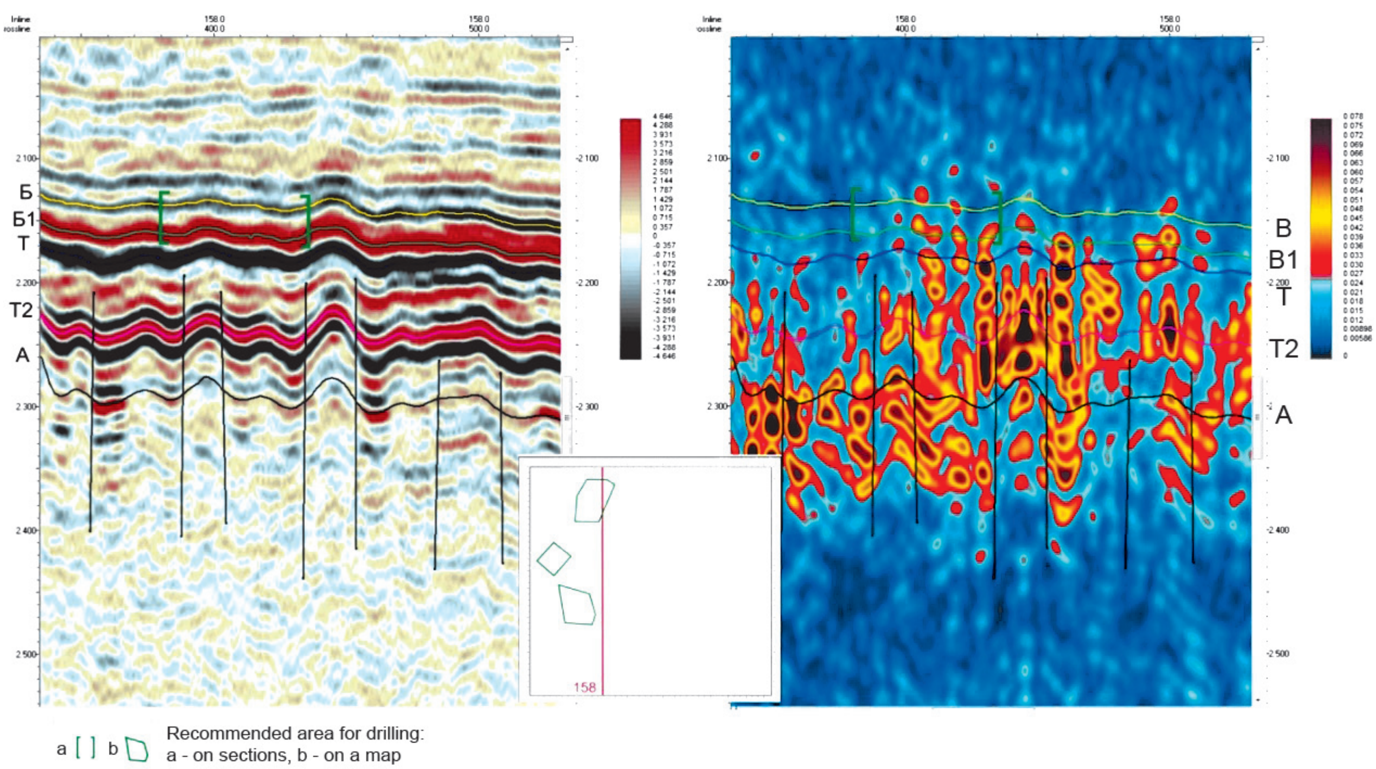

Fig. 3. Sections of reflected and scattered waves acquired after specialized data processing

reservoir in productive horizons: oil flow amounted to 124 m^3/day (Fig. 5).

Verification of this forecast which is based on scattered waves acquired with CSPD technology makes it possible to recommend this technology for mapping non-conventional complex reservoirs of fractured type.

Outlining the granitic intrusion

Target of the survey is Oimasha field in Kazakhstan. The main oil-bearing capacity is associated with Mid Triassic deposits and granitic intrusion.

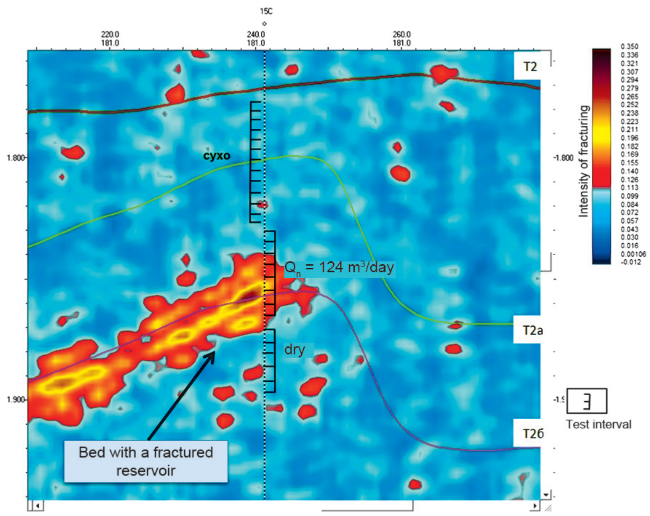

Fig. 5. Time section of scattered waves through well 15

Within the granitic intrusion, oil saturation is in the uplifted part of the granitic mass which cropped out on the day surface where weathered granites mainly developed. These weathered granites were situated at different depths from the surface of the granitic mass which was confirmed by testing and well drilling. Reservoirs are characterized by high heterogeneity and variability over the area and the section, therefore the formation reservoir has complex outlines.

This field was selected as a testing ground for comprehensive studies of the subsurface applying geological and geophysical methods. Detailed seismic exploration, high-precision gravity and magnetic surveys were carried out, but despite such a large scope of works completed, data on the structure of the reservoir within granitic intrusion was not acquired. Only a promising block was identified in the north-eastern part of the granitic intrusion. So it was decided to apply the CSPD method based on scattered waves.

Due to this method it was possible to not only map the top of granitic intrusion not visible on reflected waves (Fig. 6), but also, after interpretation, to identify zones with various potential in the granitic intrusion occurrence interval with fracture-cavernous type of the reservoir, which contains an oil accumulation.

By analyzing how intensity of scattered waves field changes along the section (Fig. 7), within the granitic intrusion interval it is necessary to point out that the

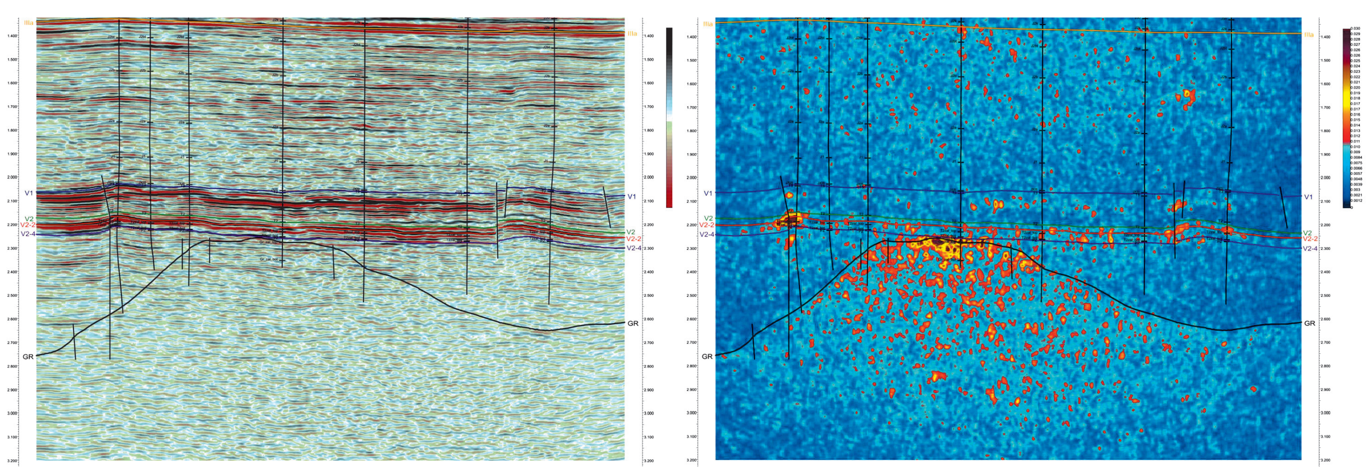

Fig. 6. Sections of reflected and scattered waves acquired after specialized data processing

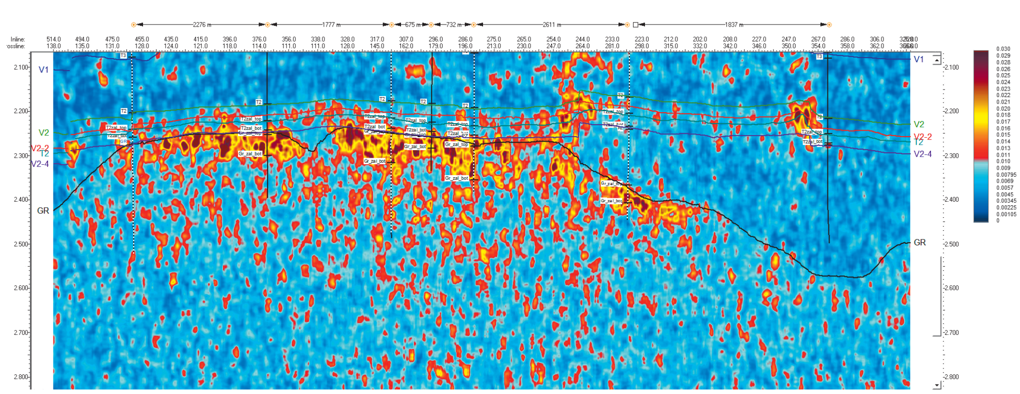

Fig. 7. Time section of scattered waves through wells. Identification of healed faults and faults with open fracturing

field's intensity falls abruptly along with depth which may indicate deterioration of reservoir properties. All drilling data, well testing results and core studies indicate that interval of rocks with good reservoir properties was not more than 100-150 meters (Anokhina et al., 2014).

Identification of healed faults and faults with open fracturing

Faults represent main sources of fracturing, therefore it is crucially important to generate a complete picture of fault tectonics for the surveyed field. It can be acquired by joint interpretation of reflectors cube, diffractors cube and instantaneous and geometrical attributes cube. Deep faults and expansion zones form conductive channels – the ways for hydrocarbons to migrate and enter previously formed traps (Anokhina, Demidova et al., 2017). Appearance of faults in the scattered waves field is associated with fracture zones confined to such areas. Separation of the faults into conductive and healed ones is an important task which is quite hard to solve according to reflected waves without involving the scattered components.

Specialized processing of seismic exploration data was carried out at Yuxi field in the north-east of China. Results of this work allowed to separate mapped faults into permeable and healed ones (Fig. 8). On the section of reflected waves (Fig. 8, left) it is impossible to understand which faults will be conductive. And only by involving the scattered component (Fig. 8, left), we can see that faults in the western part of the field are healed (Fig. 9), and good flow rates should not be expected in wells there.

Since faults are the main sources of fracturing, it is crucially important to generate a complete picture of fault tectonics for the surveyed field, which can be acquired by joint interpretation of reflectors cube and diffractors cube. In addition, such interpretation allows to separate the faults into fluid-permeable and non-permeable. There also appears a chance to map permeable faults without vertical shifts, identification of which on reflected waves sections causes much doubt.

Identification of zones dangerous for drilling

Let us examine a case of similar operations conducted at a field in the eastern part of Angara-Lena oil and gas-bearing area of Lena-Tunguska Oil & Gas Province.

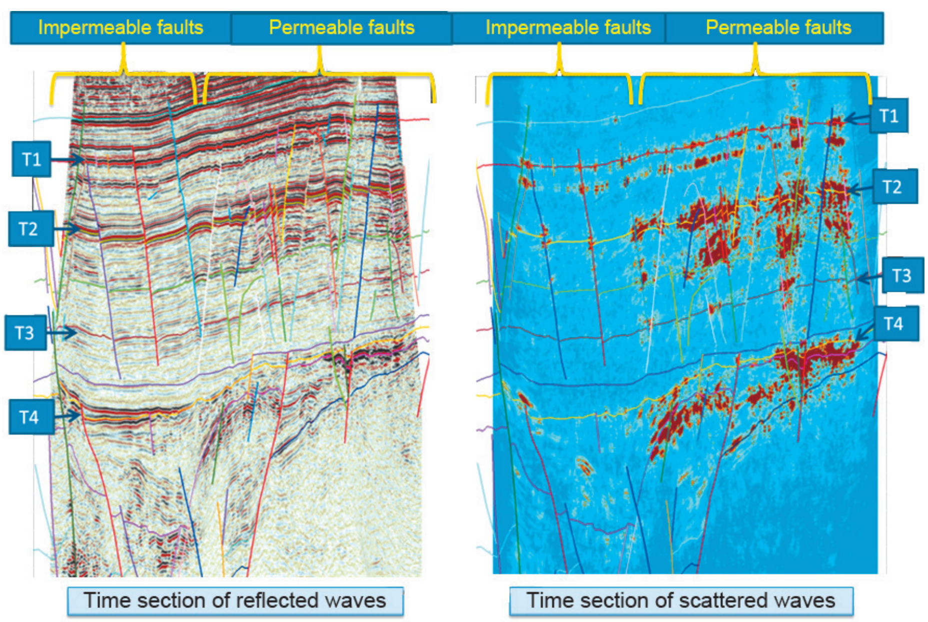

Fig. 8. Sections of reflected and scattered waves acquired after specialized data processing

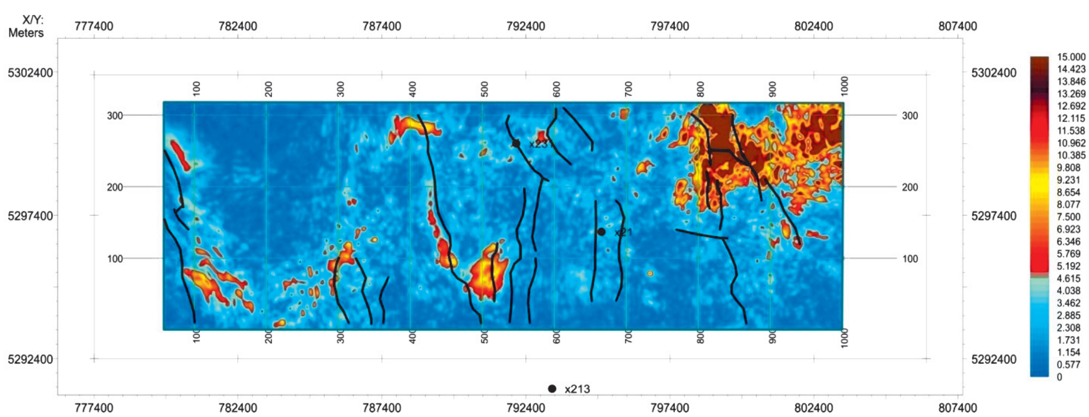

Fig. 9. Map of cumulative scattered waves amplitudes for horizon T3

Main potential oil and gas-bearing objects in this region are sandy horizons within pre-salt Terrigenous sequence. Previous exploration in the surveyed region shows that drilling of prospecting and exploratory wells in thick salt beds above oil and gas accumulations is often complicated and even becomes impossible due to natural brine shows.

Five deep wells have been drilled in the survey area. Drilling of wells A and B was suspended in the upper part of Usolye suite in Lower Cambrian deposits. The wells were abandoned due to an accident associated with salt brine (rapa) inflow in Christophorov and Balykhtin horizons. Complications during drilling also occurred in overlying intervals of the geologic section (Bilchirsky horizon) in wells D and A. Wells D, F and G penetrated a productive interval of Vendian deposits at more than 2000 m depth.

The interpretation process for the entire survey area included correlation and connection of key reflector horizons. Their connection was conducted as per Vertical Seismic Profiling and Logging data acquired in wells located in the survey area and in direct proximity (Fig. 10).

Forecast over scattered waves in the zones which may present hazards during drilling due to presence of fracturing and emergence of various complications associated with presence of areas with abnormal high formation pressure, is based on the same principles as forecast for reservoirs of fractured and cavernous types.

An example is a resultant map containing total amplitudes of scattered waves in the Bilchirsky horizon which overlaps a productive interval (Fig. 11). The map shows the wells in which salt brine or gas shows were encountered caused by abnormally high formation pressure. Scattered waves' amplitude anomalies singled out on the map may be identified with spreading of fractured-cavernous reservoir in dolomites. Filling of the reservoir may vary: either formation water with high salinity (rapa) or hydrocarbons. For example, gas shows were encountered in well A in Bilchirsky horizon. Identified zones are likely to have abnormally high formation pressure.

Near well G the scattered waves anomaly is much smaller, and passing through this interval during drilling in this well did not cause any difficulties.

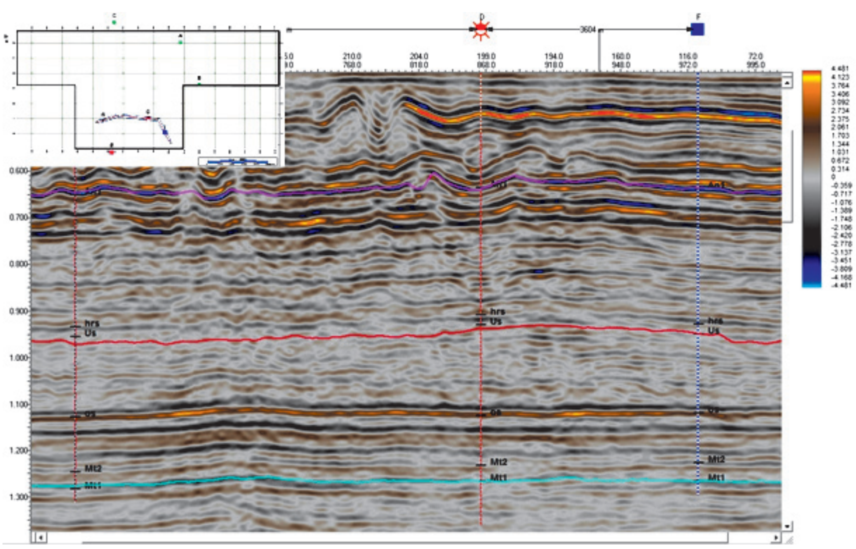

Fig. 10. Vertical slice of reflected wave cube passing through wells D, G and F

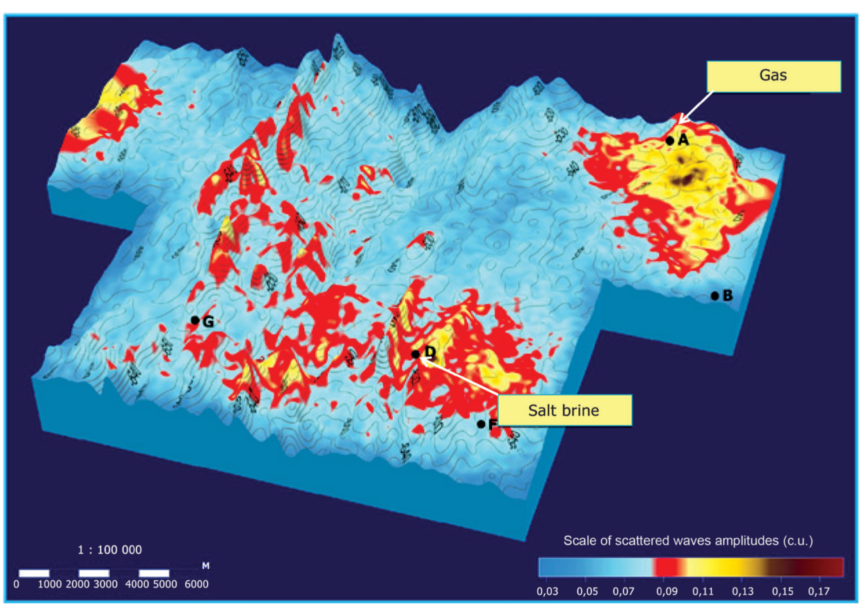

Fig. 11. Map of cumulative scattered waves amplitudes for Bilchirsky horizon

So, seismic surveys with scattered waves allowed to identify rather vast fracturing zones in the survey area associated with abnormally high formation pressure, as well as with areas of splitting along faults, which present interest during designing and selection of a technology for deep drilling.

Interpretation resulted in a map showing fracture zones in Lower Cambrian deposits (Fig. 12). Application of specialized processing which separates the full wavefield into reflected and scattered components, allows to identify fracture zones, in particular in intra-salt formations of Lower Cambrian dolomites filled with high-salinity formation waters.

Special value of using the scattered waves' component is in the forecast of abnormally high formation pressure before start of drilling. Such data is extremely important during designing of the well and selection of its configuration. It enables to conduct drilling in an optimum technological mode avoiding emergencies (Anokhina et al., 2016).

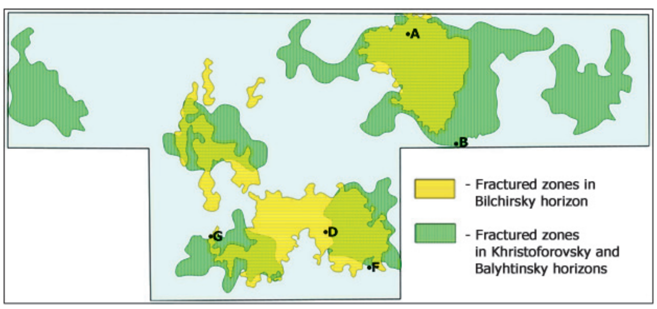

Fig. 12. Predictive map for fracturing zones in Lower Cambrian deposits

Horizontal drilling geo-steering

In recent times, a question often arises concerning the need to develop fields with fractured type of reservoir confined to Carbonate deposits, followed by drilling of horizontal holes. Therefore correct identification of fracture zones is a very important task because these very zones are confined to tectonic faults which provide good reservoir properties and consequently high flow rates. In order to identify such zones, in addition to establishment of kinematic and dynamic characteristics of reflected waves, it is necessary to involve completely new technologies and forecasting techniques, such as:

- scattered waves which allow to identify intervals with increased fracturing and cavernosity of productive formations, destruction zones and other objects (the CSPD method);
- micro-seismic monitoring data which enables to identify peculiarities of the reservoir which contains hydrocarbon deposits (the MSPRM method).

Both methods accomplish the task of mapping the open fracturing zones.

Let us study an example of a field with regionally oil and gas-bearing Upper Jurassic sub-sequence (Bazhenov – Upper Abalaksky). Reservoirs in formations $Ю_1$ (Upper Abalaksky sub-suite) and $Ю_0$ (Bazhenov – Lower Tutlemeisky sub-suite) have a rather complicated development character caused by both micro-lamination and foliation of rocks, as well as by tectonically stressed zones (disjunctive fault zones, destruction, stretching and compression zones) and hydro-thermal processes (desalination and dissolution). Type of the reservoirs is porous/cavernous/fractured.

A 3D survey was conducted in the area which was processed according to CSPD method, followed by multistage hydraulic fracturing along with micro-seismic monitoring. This allowed to conduct comprehensive interpretation of already available scattered waves cubes and new micro-seismic data.

Multistage hydraulic fracturing was carried out in the horizontal hole accompanied by micro-seismic monitoring. According to well tests, the last three ports yielded oil inflow. On the scattered wave section they fall into the zone of higher values, which indicates presence of fracturing. Main micro-seismic events recorded during hydraulic fracturing are also localized near these ports (Fig. 13).

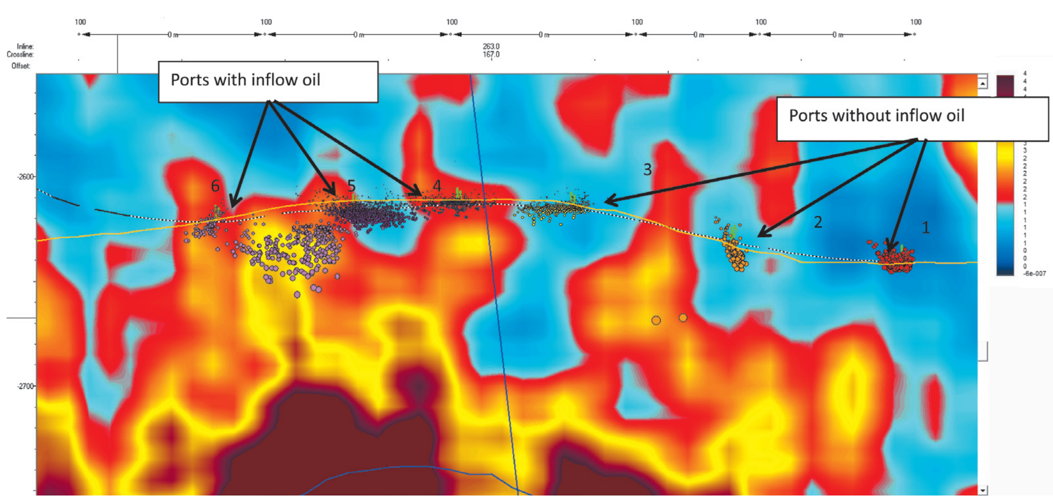

Fig. 13. Fragment of a time section for scattered waves cube projecting the micro-seismic events cloud

Specialized processing of seismic data according to CSPD technology allows to identify areas with natural open fracturing and zone with "unhealed" faults. Micro-seismic emission emerges in the zones of "currently-living" faults and in the areas with open natural fracturing. Such zones are encountered during passive micro-seismic monitoring applying the MSPRM technique. Joint interpretation of data integrated from these methods allows to reliably forecast the location of zones with open fractures and draining in space, since anomalies of scattered waves field with high amplitudes and cloud of micro-seismic events have the same nature. Management of formation stimulation results during hydraulic fracturing allows to acquire data on the directions of fracking areas development during acid fracturing near the development of a productive formation, and thus to upgrade the field development system and to increase forecasting accuracy for reservoir spreading zones confined to fracturing zones, and efficiency of prospecting drilling (Anokhina et al., 2016).

In addition to the CSPD and MSPRM technologies, Research Institute of Applied Informatics and Mathematical Geophysics of Immanuel Kant Baltic Federal University has elaborated and implements a new approach to medium visualization, based on application of inter-dependent visualization of paired images (IVP IC). The method based on such approach is called Vector Pair Reverse Time Migration (VPRTM).

The state of image processing is a key factor for the RTM method. Conventional RTM-images have original artefacts because this method is based on wave equation. In order to overcome such obstacles, image regularization is accomplished on the basis of seismic data filtering in an extended domain of image common point parameters (Vector Dimension Common Image Gathers).

The present paper provides the VPRTM development results, in particular, using an example of finding ultra-weak diffractors against strong reflections on a field in West Siberia. Reflection or scattering of acoustic wave on an obstacle at any time may be seen as interaction of two inter-connected vectors: incident wave particle velocity vector and reflected or scattered wave generation vector. We suggested an accurate statistical analysis of amplitudes and phases of inter-connected vectors for all time samples and sources, and elaborated the conditions for imaging the inter-connected vector pairs, which allows a new outlook on visualization of acoustic media (Erokhin et al., 2017). Fig. 14 shows an example of reflected waves section, with a "smile" object singled out.

Solutions to a direct and associated challenge are based on first-order equations. This allows to work at each point of space in the first arrivals zone with pairs of inter-connected vectors which depend on time and sources. Filtering of inter-connected vector pairs in amplitude and phase domains establishes a tolerable set of pairs. Application of this set of vector pairs allows to generate images of the medium which are more descriptive that conventional RTM images (Fig. 15).

It is clearly visible on the time section for reflected waves MULTI BackRTM that traceability of reflectors improves significantly despite a loss of high frequencies in the section. In case of scattered waves we can

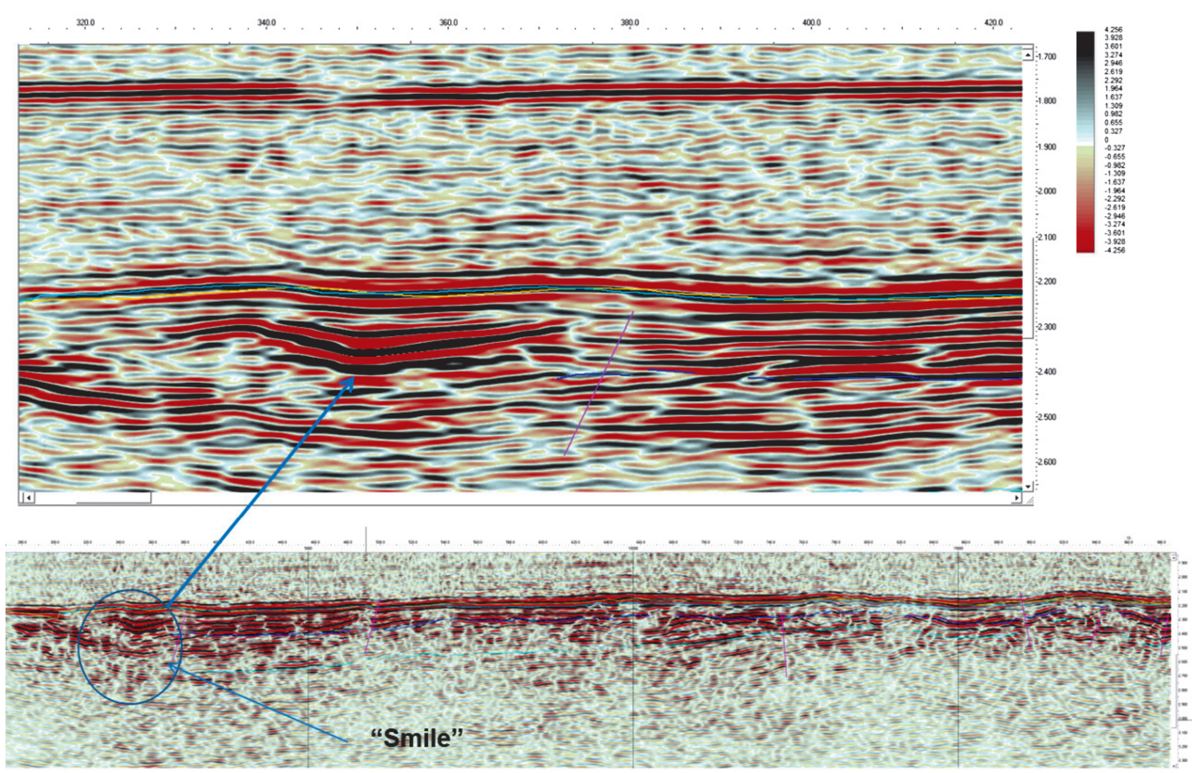

Fig. 14. Vertical slice of reflected waves cube with "Smile" object singled out

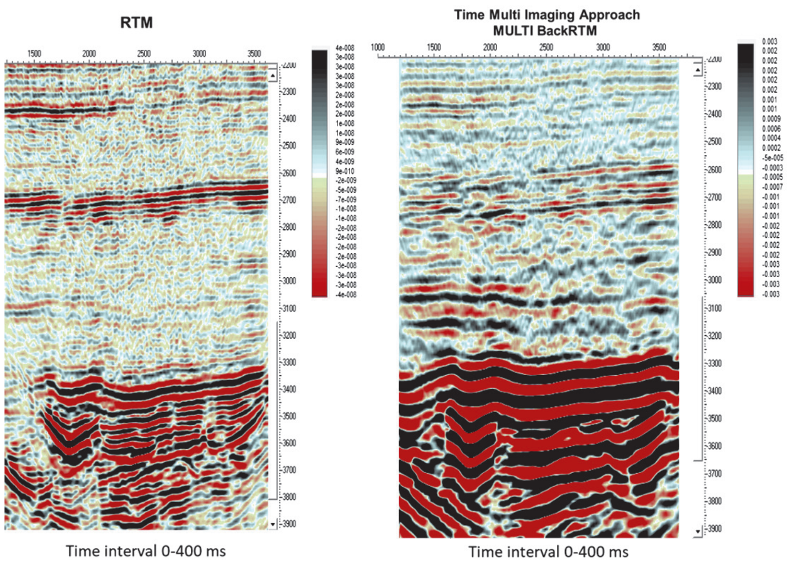

Fig. 15. Example of time sections RTM and MULTI BackRTM

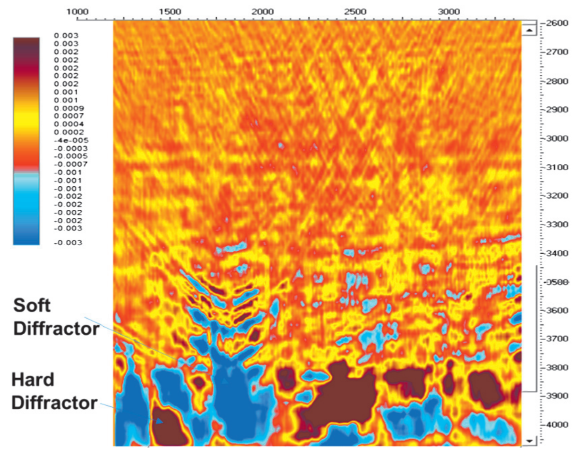

Fig. 16. Time section DIFFRACTOR BackRTM

differentiate decompaction zones – soft diffractor, and compaction zones – hard diffractor (Fig. 16).

The VPRTM method with background diffraction demonstrates high sensitivity to velocity fluctuations. The method has a potential for analysis in AVO, Dip, Frequency, Impedance, Reflectivity and Diffractivity procedures.

Figures 17-19 show examples of VPRTM sections: attributes Impedance, DIP and Fluid Factor.

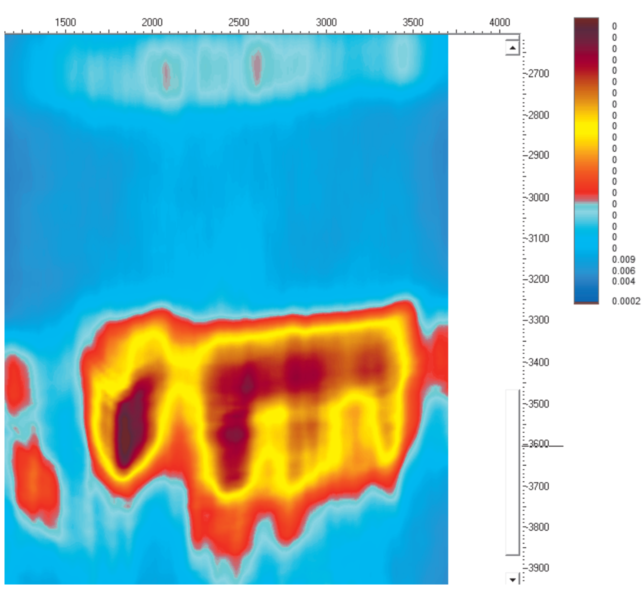

Fig. 17. VPRTM: Impedance

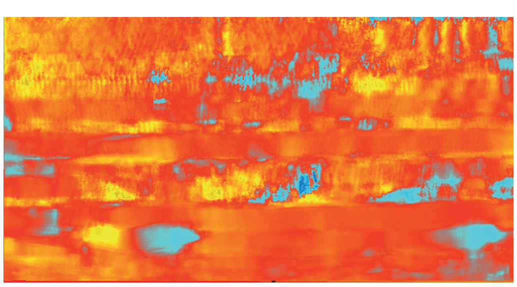

Fig. 18. VPRTM: DIP+-25OC

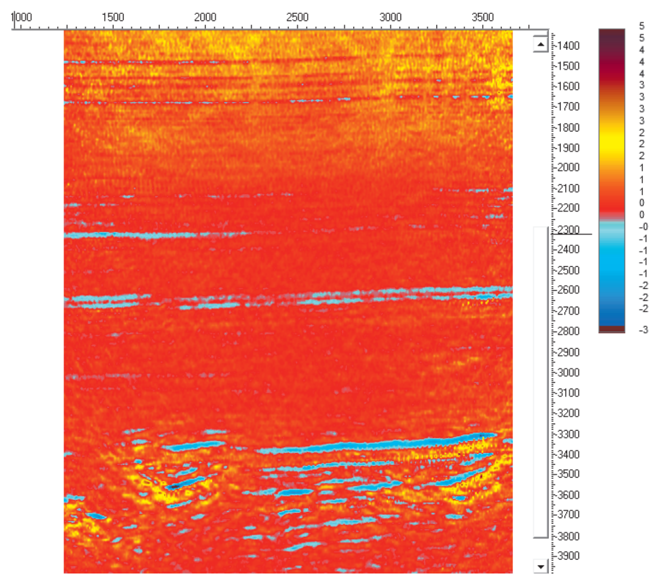

Fig. 19. VPRTM AVO: Fluid Factor

Processing data acquired as per the VPRTM method for a field in West Siberia is given on Figure 20. Oil-bearing capacity of the field is associated with Bazhenov suite deposits (green line) and the basement (red line). It is visible that the strongest scattering zones are situated in the top part of the basement. Drilling in these zones yielded oil flow rates substantially greater than in Bazhenov suite.

Conclusions

1. A single mathematical approach has been developed to solving the tasks of active and passive seismic acquisition. This approach is based on reverse geophysical tasks theory.

2. CSPD method has been developed for discovering a scattered seismic component. The method has been verified on model and actual data. It demonstrated high accuracy for ultra-weak scatterers.

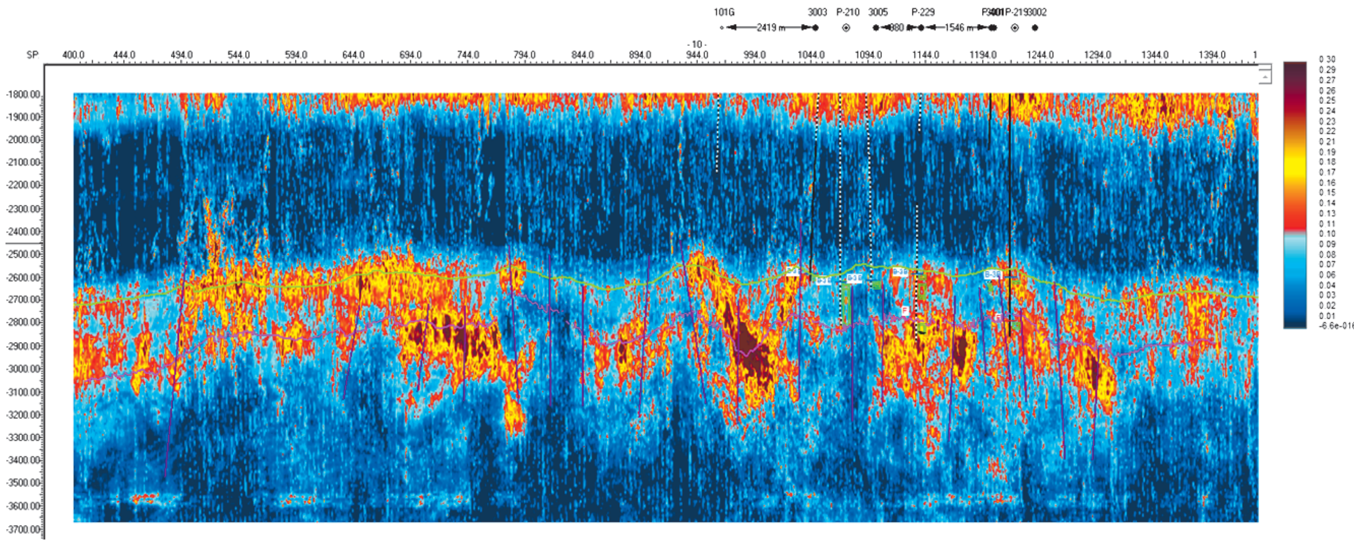

Fig. 20. Diffractor after VPRTM

3. A new method has been offered and implemented for reverse time vector pairs migration (VPRTM). It is effective for both generation of diffraction images as well as for AVO, velocity tomography, impedance, angles, etc.

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