Improved seismic images through full-azimuth depth migration: updating the seismic geological model of an oil field in the pre-neogene base of the Pannonian Basin

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Introduction

A seismic survey was conducted in a production oil field located in Serbia, confined to the Pre-Neogene (Paleozoic) base of the Pannonian basin. It was assumed that additional significant unrecovered residual reserves still exist in this oil field, as well as additional similar undiscovered reservoirs. The further characterization of the existing reservoirs, and the identification and characterization of the new ones, required the implementation of advanced seismic imaging technology. Hence, a new project was designed composed of the following steps: Obtaining the highest possible seismic resolution in the area, and creating an updated, high-definition subsurface model that includes the structural complexities of the geological layers and the azimuthal anisotropic effects (e.g., fracture systems), especially within the target layers. This enables the identification and characterization of the target productive zones, making it possible to accurately design and plan the well placement.

A modern, full-azimuth seismic survey was performed with a fairly regular distribution of the source-receiver offsets and azimuths. The dominant fold (number of traces per shot) was about 120. The seismic sources consisted of groups of vibrators with a linear sweep signal, where the frequency range was 6 to 96 Hz and the time duration 15 seconds.

Emerson's EarthStudy 360 full-azimuth angle domain imaging system (Koren and Ravve, 2011) was chosen to facilitate the above-mentioned tasks. This is an advanced subsurface imaging system operating directly in the Local Angle Domain (LAD). The high-resolution images with the unique full-azimuth directional and reflection angle common image gathers obtained by this seismic migration technology make it possible to better define the structural subsurface model and furthermore, to detect fine interlayer fracture systems at the target areas. Both regional faults and low-amplitude sub-seismic faults (fracture indicators at these regions) were mapped. The main imaging characteristics were correlated with existing production wells in the area.

Background

The oilfield in this case study is one of the largest in the Republic of Serbia, accounting for 14% of all annual national production. It is located on the border of the micro-plate of Theissia and the Vardar zone, which are large structures at the base of the Pannonian basin. The structure complexity of the subsurface was confirmed by measurements performed in deep wells, where deeper Triassic sediment rocks of the Paleozoic age are replaced at greater depth by Jurassic-age formations. Neogene sediments overlapping the basin represent numerous dislocations.

The oil field is confined to a series of elevated blocks at the Paleozoic base, composed of crystalline schists of various compositions. The available cores indicate diagonal systems of open and closed fractures at the shale rocks, partially filled with calcite. The top of the fractured reservoirs has been regionally disturbed by erosion.

Industrial oil production in this field began in 1991. Natural depletion took place during the first five years. Reservoir pressure decreased by 50-60% and approached saturation pressure. Attempts to organize an in-situ waterflood did not bring the expected results due to the high heterogeneity of the reservoir and the block structure of the field. In recent years, hydraulic fracturing has been used, enabling increased production, possibly by involving previously untreated areas. The significant heterogeneity of the geological structure revealed during development of the field impacts not only well productivity, but also the success of the applied geological and technical measures.

Depth imaging technology

The previous seismic prospect in this area was based on conventional seismic imaging technology mainly obtained by iterative procedures using offset-domain pre-stack time and depth Kirchhoff migrations (PSTM and PSDM). In order to improve the accuracy and resolution of the available seismic images, a novel seismic imaging technology was selected: EarthStudy 360. This is a full-azimuth angle domain anisotropic seismic imaging system referred to in this article as Local Angle Domain (LAD) seismic

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imaging. Using this technology, we were able to better predict structural-tectonic inhomogeneities in the target geological environment, including fracture detection and characterization. The results were then used to design and place new production wells.

The LAD technology has been successfully used in many different subsurface geological regions worldwide for building subsurface geological models and generating and extracting high-resolution information about subsurface target areas. The rich information from all angles and azimuths ensures more reliable analysis with the highest seismic resolution, and significantly reduces uncertainty. This seismic imaging methodology is designed to enhance both structural continuities along sharp transition zones between the different geological layers, and discontinuous zones, indicating faults and small-scale anomalies of the elastic properties. It is particularly effective for identifying and characterizing fracture systems: intensity and orientation of the fracture nets, which are critical for optimizing drilling in order to deliver superior production rates.

The general workflow for obtaining the new seismic prospect included the following stages:

Illumination study

An initial background structural model was constructed, consisting of four major reference horizons/layers: The pre-Neogene horizon base; the reflecting (bottom) horizon of the clinoform formation (N1); the reflecting (top) horizon of the clinoform formation (N5); and the reflecting (bottom) horizon of the Pliocene sediment zone (N6), which does not belong to the regional stratigraphic units.

3D ray tracing was then performed for the illumination study (Figure 1). The primary objective was to learn about the actual relationship between the parameters of the LAD migration (subsurface directional and reflection angles and azimuths) and the available seismic acquisition geometry (surface offsets and azimuths, and the extension of the migration aperture). Knowledge about available subsurface angles and azimuths plays a key role when deciding about the types of analysis that can be performed, in particular the sensitivity to anisotropic effects.

Following this step, we realized that the target area located in the submerged part of the pre-Neogene base is illuminated up to the range of an opening angle of 26-32°. This imposes certain restrictions on the entire subsequent processing graph.

LAD imaging and VTI model definition

The LAD migration was first performed using the background velocity model. The first stage of the migration involved estimating VTI (transverse isotropy with vertical axis of symmetry) parameters at the target sediment layers. Using the mis-ties between the depth of the interpreted horizons and the corresponding available well markers at those locations, we estimated the Thomsen **δ** parameters. The Thomsen **ε** parameters were estimated from the wide reflection angle seismic events along the full-azimuth reflection angle gathers. Note that in some parts, this information was not available and the **ε** parameters were approximated by extrapolation from the known areas and as factors of the **δ** parameters.

The LAD migration was then performed using the VTI model and iteratively refined using anisotropic tomography. At this stage the background velocity model did not yet contain any information about azimuthal anisotropy.

Overall, the average velocity in the upper formation (above the basin) is 1900 m/s. The top (OG N2) and bottom (OGN)

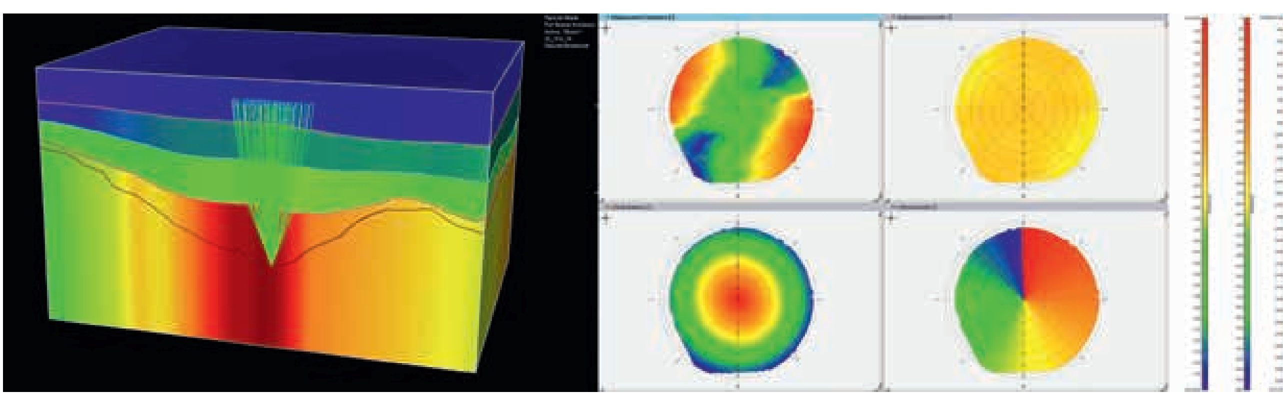

Figure 1 Ray tracing based on the background depth-velocity model in the submerged part of the pre-Neogene base.

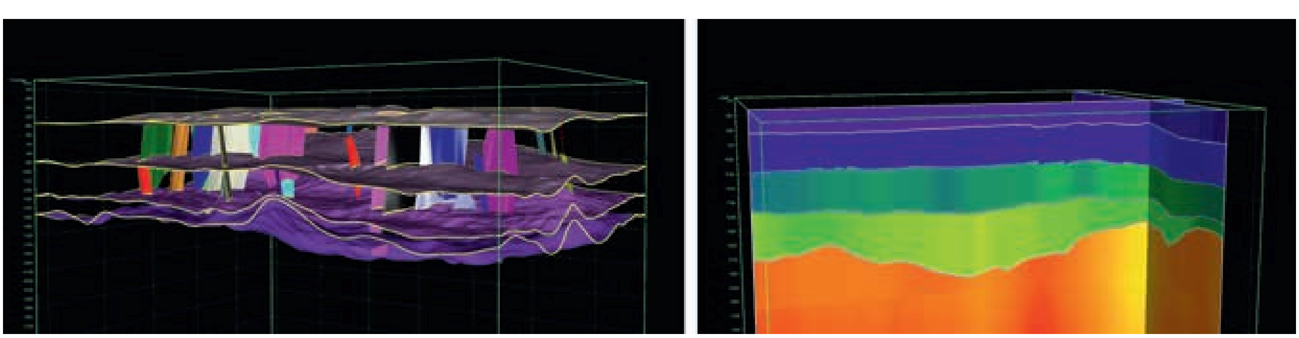

Figure 2 Structural-tectonic skeleton for DVM with the inclusion of transverse faults (left) and without faults (right).

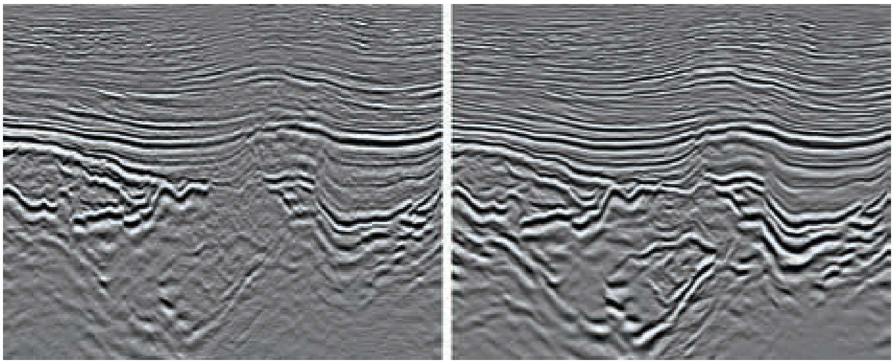

Figure 3 Comparison of final images. Inline section. Left – Kirchhoff, right – LAD.

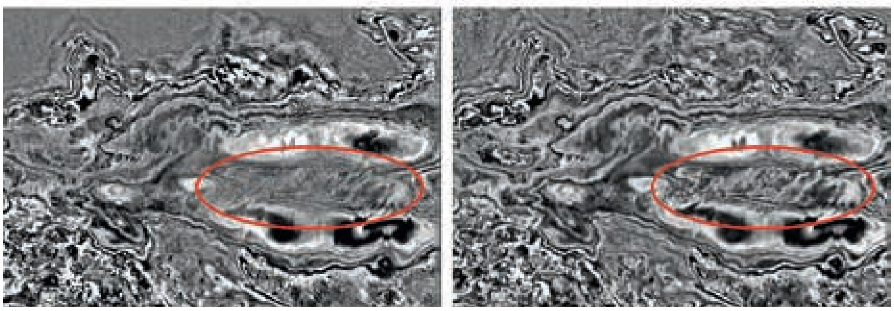

Figure 4 Comparison of final images. Deep slice. Left – Kirchhoff, right – LAD. The red oval is the central part of the oil field.

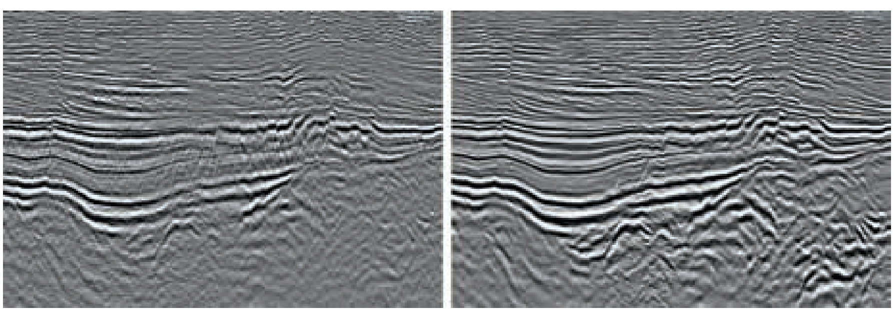

Figure 5 Comparison of the final images. Inline section. Left – Kirchhoff, right – LAD.

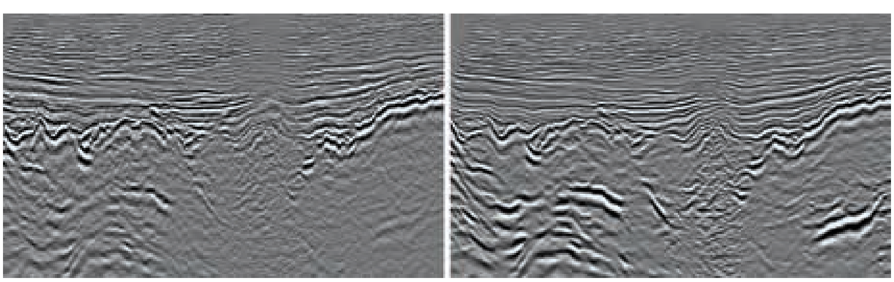

Figure 6 Comparison of the final images. Crossline section. Left – Kirchhoff, right – LAD.

of the clinoform formation are characterized by velocities of about 2800 m/s and 3400 m/s, respectively. Layers at the top of the Paleozoic basement are characterized by interval velocity values on the order of 4300 m/s and more. The average value of $\boldsymbol{\delta}$ for the formation (layer) N6 was 0.02, for formations corresponding to the top and base of the clinoform complex, 0.01 and 0.07, respectively, and for the formation corresponding to the top of the Paleozoic basement, 0.08. As mentioned, due to the lack of wide opening angles we assume in many areas that $\boldsymbol{\varepsilon} = \boldsymbol{\delta}$. The values of $\boldsymbol{\varepsilon}$ were later refined to improve the image focusing.

Inclusion of faults

The next stage consisted of adding the existing faults automatically extracted from the migrated seismic cube. The model below includes 31 traversed faults (Figure 2). Note that the creation of a structural model which includes tectonic disturbances is the most time-consuming task in the overall process.

LAD Imaging

Using the refined VTI model with the interpreted faults, a LAD migration was performed. The improvement in the quality of the LAD images compared to the Kirchhoff migration images is clearly seen in Figures 3-6. The enhanced images with the improved signal-to-noise ratio make it possible to enhance the interpretation and better track structural continuities and geological boundaries. In addition, the LAD migration was able to suppress signal interferences (including internal multiples) during the migration process. Figures 3 and 4 show comparisons of final images obtained using the Kirchhoff and LAD migrations. In Figures 5 and 6 we see better defined closed formations. Moreover, on the LAD imaging result, it is also possible to identify new

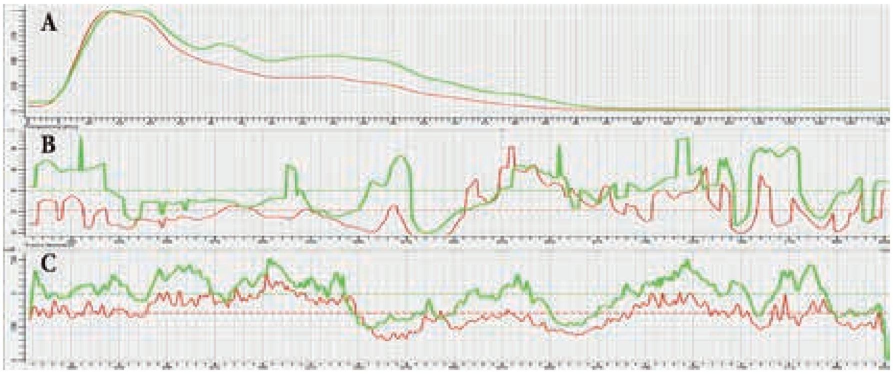

Figure 7 Quality control along the target inline: A - amplitude spectra, B - vertical resolution in Hz, C - signal-to-interference ratio. The Kirchhoff migration is in red, the LAD migration is in green. The dotted lines are mean values.

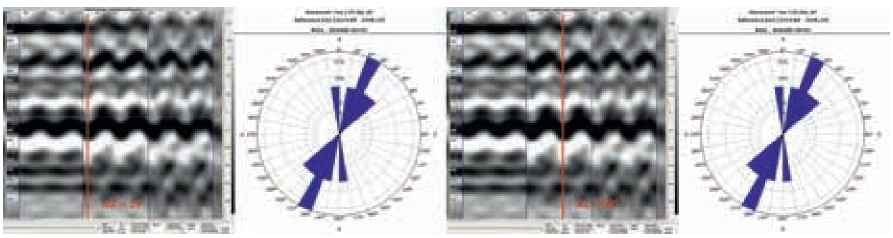

Figure 8 Full-azimuth reflection angle migrated events (sorting: fixed range of angle of expansion - all azimuths) and rose-diagram FMI (borehole studies).

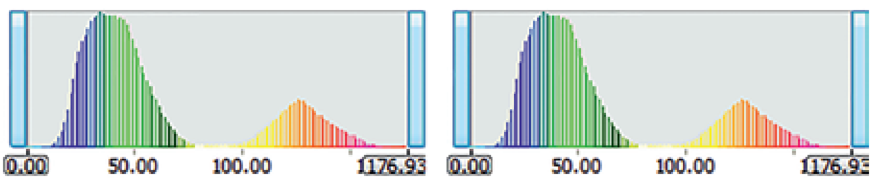

Figure 9 Histograms of the anisotropic attribute values: A- AVAZ - Anisotropy Orientation; B-VVAZ - Anisotropic Slow Azimuth.

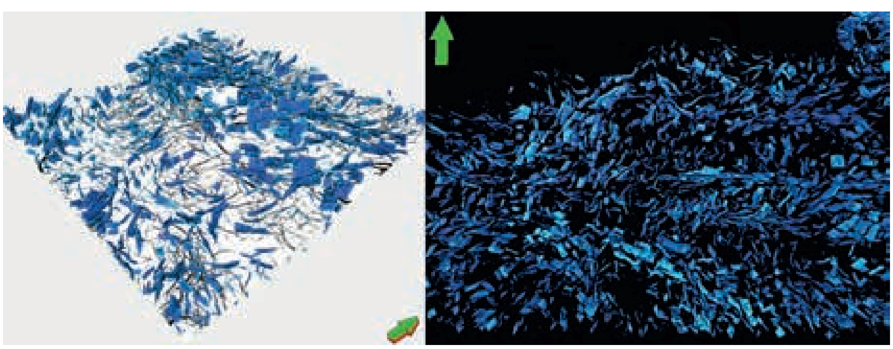

Figure 10 Horizon section (Tconst) and zone of distribution of incoherent events, isolated in transparency (opacity) mode over the fragment of the seismic data cube.

small faults, which could not be seen before. Figure 6 compares the cross sections of the final amplitude cubes obtained by the Kirchhoff migration and LAD imaging technology.

For quality control, a quantitative evaluation of amplitude spectra, vertical resolution and signal-to-interference ratio in the target area was carried out (Figure 7). Based on the results of the assessment, it can be concluded that for all of the parameters mentioned above, the results of the LAD migration significantly exceed the quality of the conventional Kirchhoff migration.

Fracture detection and characterization

The full-azimuth directional and reflection angle image gathers provide unique information about the existence of small-scale fracture systems. Operating on the directional image gathers makes it possible to explicitly enhance the low-amplitude signals diffracted from the aligned fractured objects, which are normally (using conventional imaging methods) masked by the high-amplitude signals of the reflection events. Thus, by designing dedicated diffraction-based weighted stack filters, we were able to see the signatures of the fracture systems which could not be seen before.

Additionally, the full-azimuth reflection angle gathers indirectly provided information about the orientation and intensity of the observed fractures. This type of analysis combines both kinematic information (azimuthal residual moveouts) and dynamic information (azimuthal variations of the reflecting amplitudes). The kinematic approach is normally referred to as the so-called velocity vs. angle and azimuth (VVAZ) and the dynamic to amplitude vs. angle and azimuth (AVAZ) (Canning and Malkin, 2009). Figure 8 shows two examples where the azimuthal variations of the residual moveouts and the amplitudes are correlated with well measurements.

The agreement between the VVAZ and AVAZ approaches may be seen in Figure 9, where the VVAZ-based Anisotropic Slow Azimuth and AVAZ-based Anisotropy Orientation are clearly correlated.

The availability of well data enabled a comparison between the information on the identified fracture and the predicted one. The initial information was provided by borehole methods that allow studying the anisotropy of the physical properties of rocks: borehole microscanners (or ‘microimages’) and VAL (wave

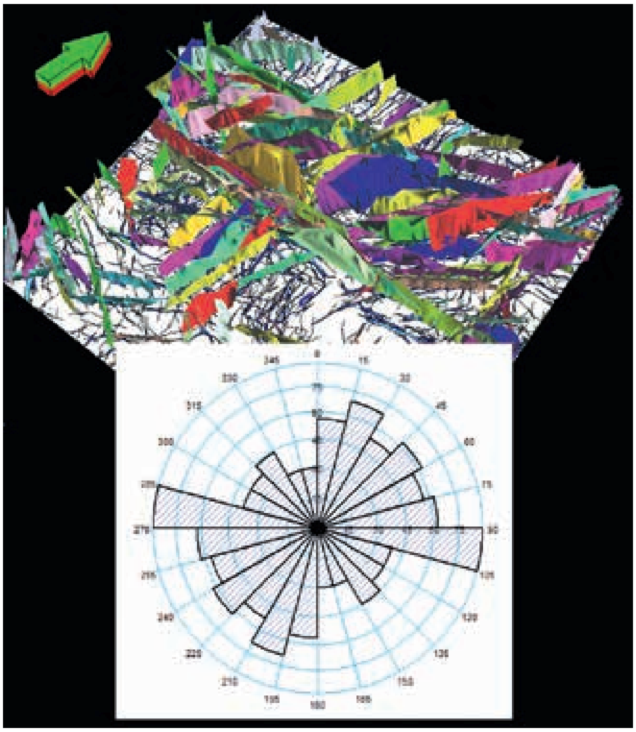

Figure 11 Diagram obtained after the 'automatic extraction of faults' and visualization of extracted objects.

acoustic logging) performed in six wells of the deposit in the study (Polivakho et al., 2018).

Before beginning the horizon interpretation, and in order to establish the key directions of the tectonic disturbances, the familiar method of working in transparency (opacity) mode using the Ant Tracking attribute was applied (Olneva et al., 2017). Figure 10 shows the horizontal slice (Tconst) and distribution zones of incoherent events, extracted in transparency mode from the fragment of the seismic data cube.

The next step was an 'automatic fracture extraction' procedure, through which a diagram of the key identified directions (stereonet) was created (Figure 11). By testing various options and working with different designed filters, a diagram was obtained that did not contradict the data in the azimuths indicated by the histograms.

Vector maps

Next, we constructed vector maps that regionally indicate the local orientation and intensity magnitudes of the fracture systems. As a reference, we used the vector map obtained from the Coherence Cube operating on the final (post-stack) migrated image. Figure 12 shows a comparison between the Coherence-based map and the rich details obtained from the VVAZ/AVAZ vector map at the target area.

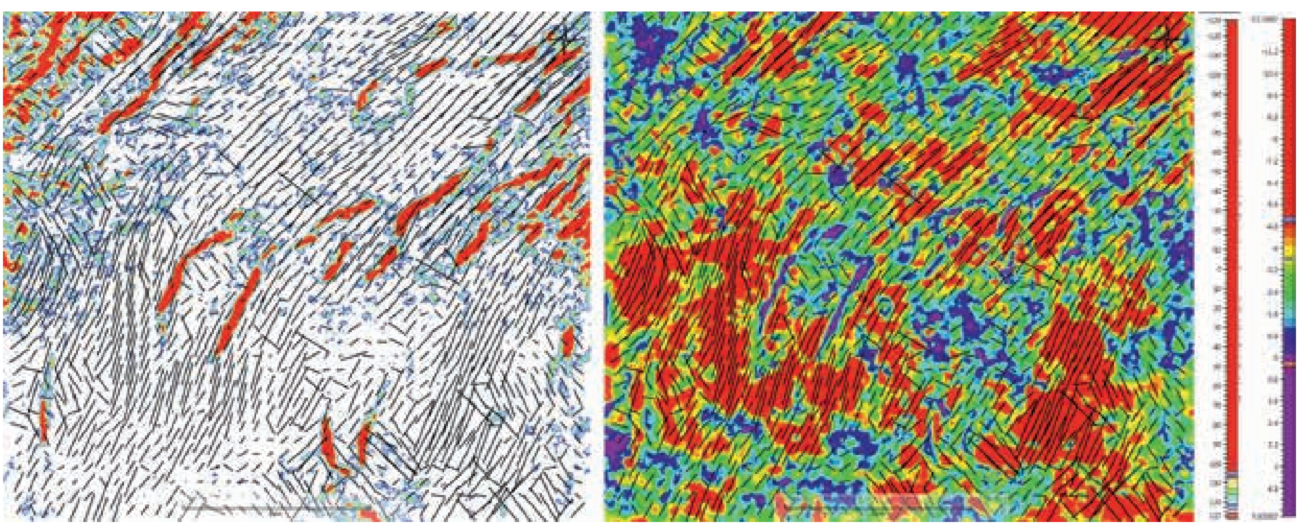

Figure 12 Fragments of a vector map combined with a horizontal slice in the Coherence Cube (A) and the corresponding slice obtained by the VVAZ/AVAZ analysis (B).

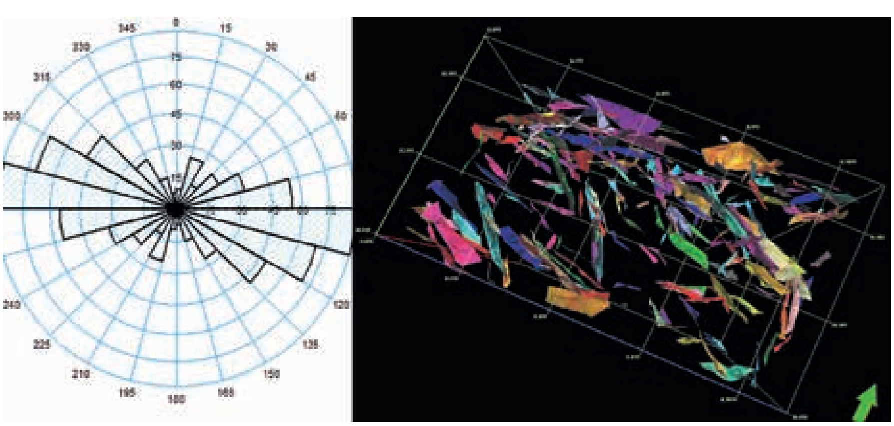

Figure 13 Automatically extracted fault planes and a rose diagram showing the key direction.

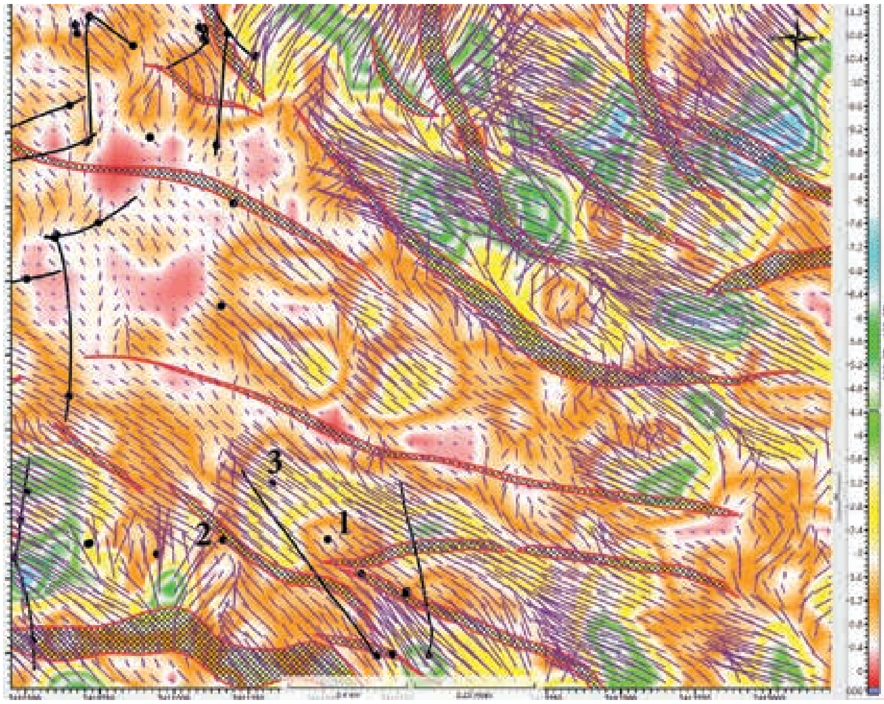

Figure 14 Fragment of the vector map in the time interval, comparable to the productive interval, combined with the Anisotropic Gradient attribute.

Testing these interpretative small faults/fractures allowed them to be applied to a more complex interval of studies in the near-surface part of the Paleozoic sediments. Their azimuthal direction of 110-120^{o} was confirmed (Figure 13) by the results of automatic fault extraction, corresponding to a maximum on the histogram in anisotropic attributes (azimuth at 30^{o}).

Figure 14 shows an extremely coherent vector map along the bottom horizon of the clinoform formation. Depending on the intensity and direction of the anisotropy, different combinations of aligned vectors are indicated.

Well placement

Based on the resulting vector maps, two production wells were drilled in the southeastern block of the field. Well 1 was placed in the fractured zone in the pre-Neogene base. This well, which has been in operation since October 2017, is characterized by an above average inflow, with no need to intensify its production.

Well 2 was also located in a concentrated fracture system zone. It has been in operation since December 2017, and for half a year it yielded more than 10 tons/day without hydraulic fracturing. Later, hydraulic fracturing was applied to enhance productivity.

Based on the results of the two wells, it was decided to plan both exploratory and production wells in new blocks. Well 3 was located in the southwestern part of the field. An analysis of GIS and petrophysical core data revealed several factors that play a key role in both the choice of development intervals and the planning of new wells.

A joint analysis of the results of the extraction and petrophysical interpretation showed the presence of natural fracturing zones, and the resultant critically stressed fractures. The latter is due to the stress-strain state of the rock, its mineral-component composition and its structural features. Therefore, for example, the weathering crusts, usually lying at the top of the reservoir, mostly consist of fragments of underlying metamorphic schists, the fractures of which are filled with clay from the sedimentary rocks covering them.

The combination of special well analysis methods, such as wellbore microscanners and broadband acoustic logging, enabled us to pinpoint the most promising intervals of natural fracturing. These were later modelled in the inter-well space based on correlation with a seismic attribute such as anisotropic gradient.

Another important factor was the presence of zones of increased capacity, usually associated with breccias from the foundation rocks. Even though the effective porosity of these rocks is much lower than their total porosity, the increased values of the latter were considered important criteria when selecting optimal development ranges. Similar zones were distributed in the inter-well space based on their correlation with the seismic amplitude attribute.

The combination of intervals with high-capacity properties and intervals of natural fracturing is the most promising result from the point of view of high flow rate and long life of the productive well. This is one of the main criteria when choosing new well locations.

Conclusion

This case study demonstrates the power of a novel seismic imaging technology, EarthStudy 360, that maximizes information about the complex subsurface structural geological model and the fine details required for identifying and characterizing small-scale aligned objects, such as fracture systems, which are essential for high productivity.

The result of the study is a detailed structural-tectonic model based on a high-quality seismic image, in which a key regional stress direction is established, and the main directions of the fracture-fractured network are determined.

The detailed interpretation includes a depth analysis of field development data, such as hydro-survey materials, pressure measurements in wells, water salinity, etc. The main practicable result of the full-azimuth studies is substantiation of the criteria for the effective placement of production and exploratory wells, including optimization of the direction of the horizontal wells. The application of full-azimuth depth migration to obtain a high-quality seismic image was positively evaluated by experts from NIS NAFTAGAS (Serbia) and received support for future replication.

In addition, using the results of the LAD technology, three new wells were drilled in 2018. All of the wells were drilled into fractured reservoirs. According to the latest test results, two wells are oil saturated and one is water saturated.

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