Applying full-azimuth angle domain imaging to study carbonate reefs at great depths

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Introduction

The main goal of the seismic surveys conducted in the target area in Kazakhstan was to image and detect a major Devonian carbonate barrier reef and to characterize the density and orientation of its main fracture zones.

This area is unique in that the carbonate layers occur at great depths, from 5700 to 8500 m, with a complex structure of overburden layers of interbedded clay, sandstone, salt and others (Table 1). These different lithology plays and morphology rocks create strong vertical and lateral velocity variations, resulting in a complex seismic wave phenomenon.

In addition, the target carbonate structures contain heterogeneous objects and require high-quality processing of the recorded data. Under such conditions, it is crucial to use full-azimuth, long-offset and dense (high fold) acquisition patterns. Advanced processing sequence tools and high-end depth migrations are required to handle both strong heterogeneity and azimuthal anisotropy effects.

Traditional Kirchhoff migrations, even the most accurate ones (wavefront reconstruction, beam), have not been able to provide the required image quality and level of detail required at the target zones (Figure 1). Conventional Kirchhoff migrations generate surface offset-azimuth/offset domain common image gathers (CIG). In this particularly complex area, the correlation between the surface offset-azimuths and the actual, *in situ*, subsurface slowness-azimuths (azimuth of the incidence/reflected ray pairs at the image points) is relatively poor, leading to significant errors in the estimation of fracture orientation. Additionally, Kirchhoff migrations do not account for multi-pathing (multi-wave path

Clay, sandstone, limestone
Marl, chalk, limestone
Clay interbedded with sandstone and siltstone
Limestone, marl
Clay, sandstone, siltstone, marl, coal
Clay, sandstone, siltstone
Salt and anhydrite with interbedded clastic inclusions
Siltstones, argillite, limestone
Organogenic limestone, dolomites

Table 1 Lithological description of the geological section from top to bottom.

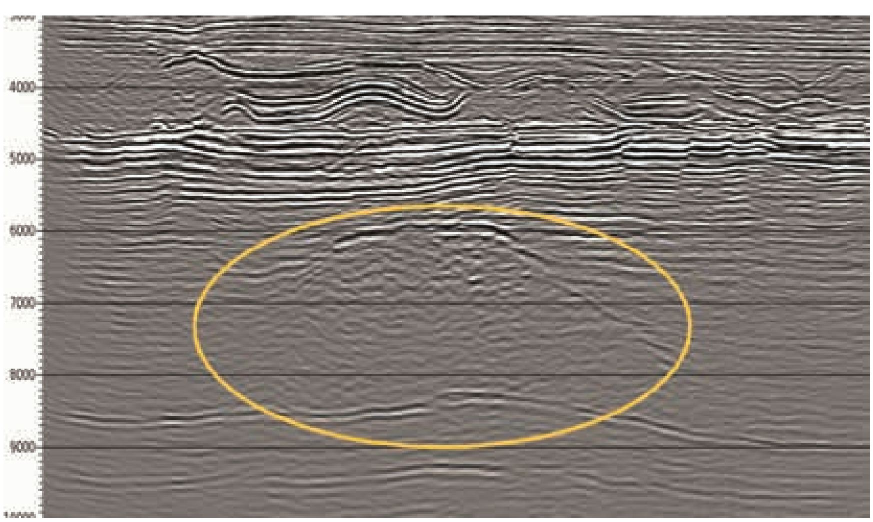

Figure 1 Final depth section after PSDM Kirchhoff.

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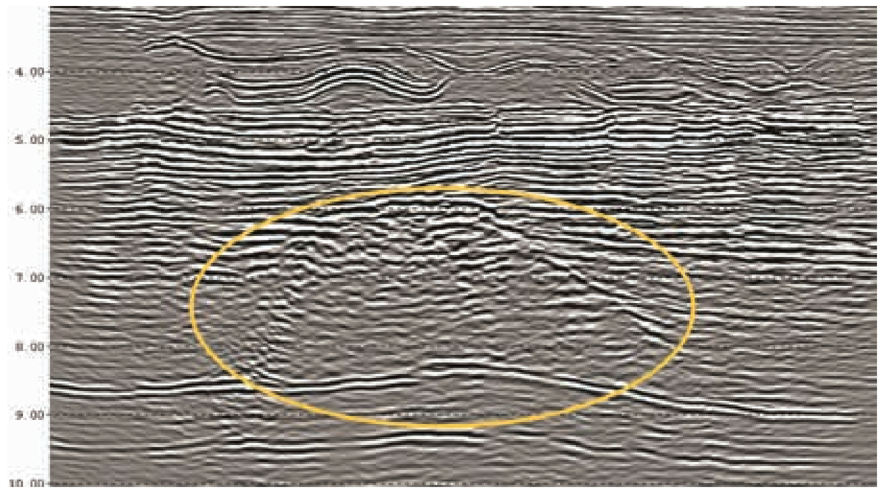


Figure 2 Final depth section after full-azimuth angle domain imaging.

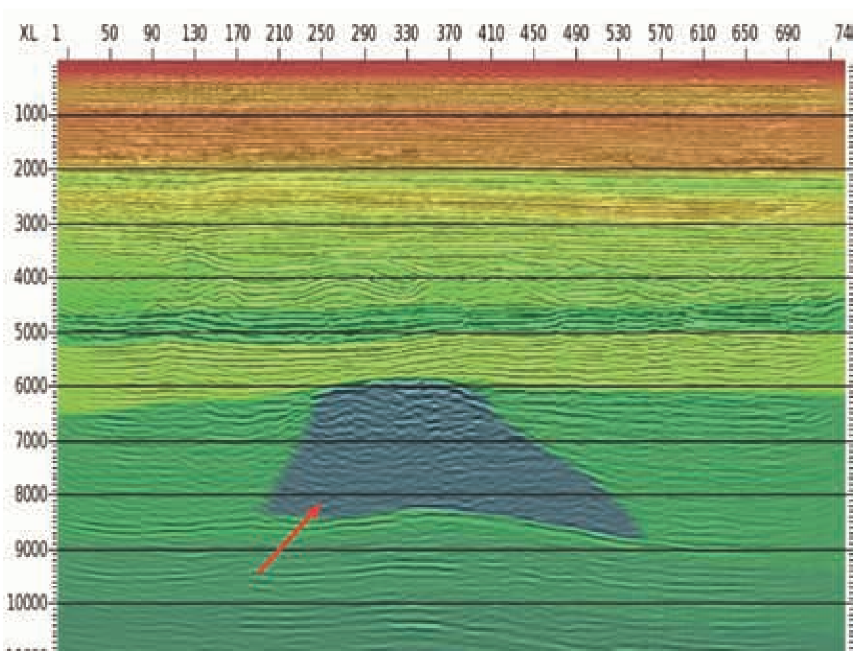


Figure 3 The final anisotropic DVM, obtained by studying the spectra of the horizontal interval velocities using refinement methods FastVel, Grid and Layer Tomography. The arrow shows the area corresponding to construction of the carbonate reef.

solutions between image points and surface source/receiver locations), which is essential when imaging in areas involving complex wave phenomena.

Kirchhoff beam migrations map surface beams with given directions backward to the subsurface. Since they account for the multi-pathing, they provide better results. However, they normally generate the same type of surface offset-azimuth/offset CIGs and therefore cannot be accurately used for azimuthal studies. They also cannot ensure sufficient subsurface illumination, especially at the complex target subsurface regions.

Solution

In order to obtain more reliable information about the deep structure of the carbonate reef and to estimate fracture distribution at different depth levels, the Paradigm EarthStudy 360 full-azimuth seismic imaging solution was applied (Koren and Ravve, 2011), including anisotropic imaging and azimuthally anisotropic inversion AVAZ (Canning and Malkin, 2009). This is the first time this technology was applied in this region.

The land 3D seismic data in this project consisted of a full-azimuth acquisition pattern, with a maximum length of offsets = 7000 m, and an average fold rate of about 100. A vibroseis group technology was used for the seismic sources.

The workflow for building and imaging the deep-velocity model (DVM) was based on the following main steps: Building a background azimuthally isotropic model (VTI with Thomsen parameters) followed by an iterative refinement of the top of the DVM using grid and model-based anisotropic tomography. Using the successive iterative approach, the final anisotropic DVM was used as input for the migration, resulting in higher resolution and more detail, especially in the target reef zone (Figure 3).

Full-azimuth imaging provided a great deal of new information about the detailed structure of the large reef at depths of 6000 to 8500 m (Figures 1 and 2). It showed more precise tracing of the reef contour, and of the left and right sides of the reef structures. The left side is limited to a well-defined feathering fault. In the reef itself, a more complex internal structure was discovered using the full-azimuth image than with conventional migrations.

The reef can be divided into at least three tiers. The upper part (6000-7000 m) is the most promising. It shows fragments of different sizes, and small broken faults and cracks. This zone has the largest decompression carbonates and is therefore the most promising for the test wells. In the middle (7000-7500 m) and lower (7500-8500 m) tiers, the structure is still visible. The middle tier also contains decompressed faults and fractures, but to a lesser extent. A more consolidated carbonaceous stratum may be found in the lower tier.

The full-azimuth angle domain imaging workflow included the following steps:

1. 3D ray tracing using the background heterogeneous/anisotropic velocity model and the available acquisition pattern for a better understanding of illumination quality and angle distribution at the target layers. The illumination parameters are used to set the optimal parameters for the migration, such as migration aperture, maximum dip and maximum opening angle.
2. Generating full-azimuth directional (subsurface dip/azimuth) angle gathers. The specular energy along the directional gathers is used to generate three structural attribute volumes: dip, azimuth and specularity (indicating the continuity of the reflecting surfaces). Two different types of images are then created: specular weighted energy stack volumes for enhancing structural continuity, and diffraction energy stack volumes by weighing down the high amplitudes of the specular reflection events. The resulting image mainly contains scattering energy from edges, tips and other small discontinuous objects, referred to as seismic diffraction events.
3. Generating high quality, specular-energy oriented, full-azimuth reflection angle gathers. These gathers are optimal for both velocity model updating and for amplitude inversions.
4. Interactive azimuthally anisotropic, velocity vs. azimuth (VVAz) analysis, using the azimuthal residual moveouts

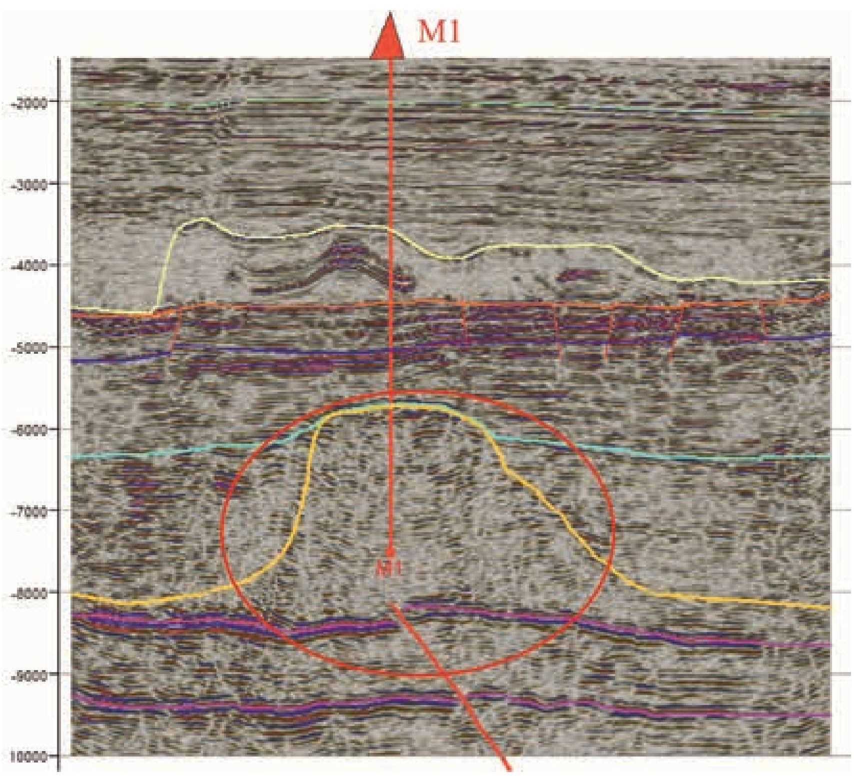


Figure 4a Cross-section depth of the cube after full-azimuth angle domain imaging. The red circle shows the area of the large barrier reef to a maximum of 2500 m in thickness and width on the order of 3500 m.

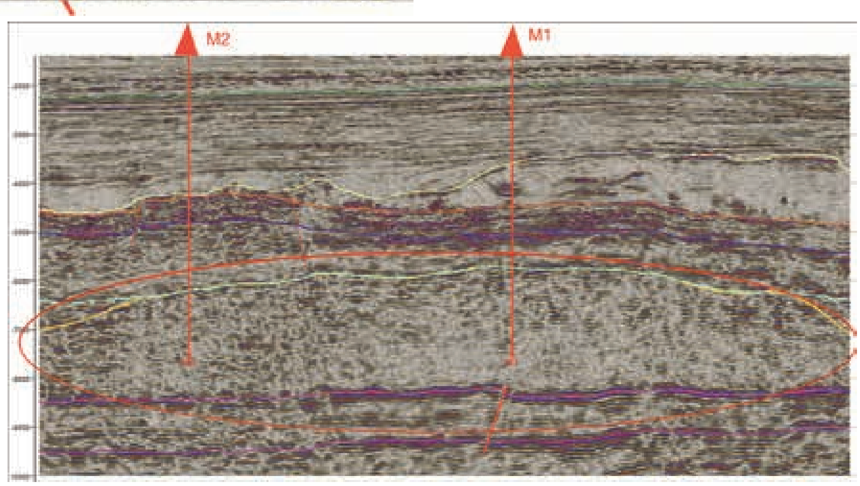


Figure 4b Longitudinal section of a cube depth migration after full-azimuth angle domain imaging. The red oval shows a large area of the barrier reef to a maximum of 2500 m in thickness and a length of more than 10,000 m.

measured (picked or analysed) along the full-azimuth reflection angle gathers. The output contains local (layer) azimuthal anisotropic intensity (different from Delta2 and Delta1 of Tsvankin orthorhombic parameters) and the orientation of the local high velocity.

5. Amplitude vs. azimuth (AVAz) preprocessing and analysis, to further refine the azimuthal anisotropic attributes.
6. A comprehensive quantitative and qualitative interpretation of the results in order to provide a prognosis of improved properties in the main reservoir.

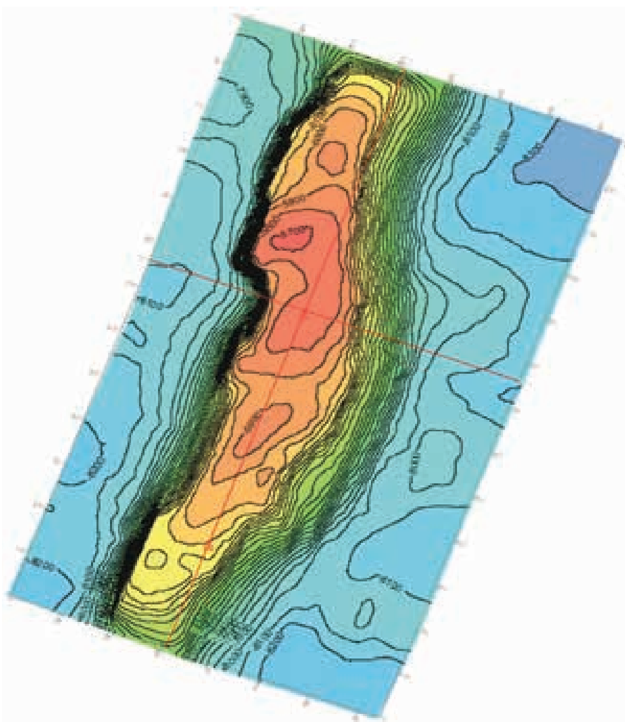


Figure 5 The final structural map of the top reef constructed from the amplitude cube.

Analysis of geological results

Figures 4a, 4b and 5 present the final results of full-azimuth angle domain imaging, processing, analysis, characterization and interpretation of the structural carbonate reef summarized, including a drilling path recommendation.

Main results of the structural interpretation

A visual comparison (Figures 1 and 2) revealed a higher quality image in the parameters of the dynamic expression of the seismic horizons, increasing the degree of traceability and detailed reflections from the target horizons and reef structure. There was also less migration noise and a more accurate focus, helping to more clearly resolve a complex interference zone. This in turn provided a more accurate representation of the object as a whole and solved two important problems – clarifying the position of the top and bottom of the carbonate reef, and providing a geological interpretation of the wavefield and of potential reservoir structures.

The target reservoir is a Famennian (Upper Devonian) carbonate complex (Figures 4a and 4b). The top of the reservoir consists of clay sediments of the lower and medium tiers (Coal and Artinskian age) and Kungurian salt-bearing strata. Overlying coal sediments are represented by bottom-slope and basin facies. In the lithological plan recommended for drilling, the structure is a large barrier carbonate paleo reef. The edges of the platform and the slopes of the structure showed improved reservoir properties owing to intense fracturing.

The second problem was solved using the amplitudes and specular component data, allowing a confident determination of the morphology of the carbonate body and trace horizons associated with the base (presumably Average Devonian) and top carbonate reservoir. The top carbonate reservoir in the regional plan rises in a north-northeasterly direction, and then gradually sinks (Figures 4b, 4b and 5). The top reservoir is composed of overlying argillites of Lower Carboniferous age, which are ubiquitous in this part of the study area. The reef was found to have a non-uniform inner structure, including elements of layering.

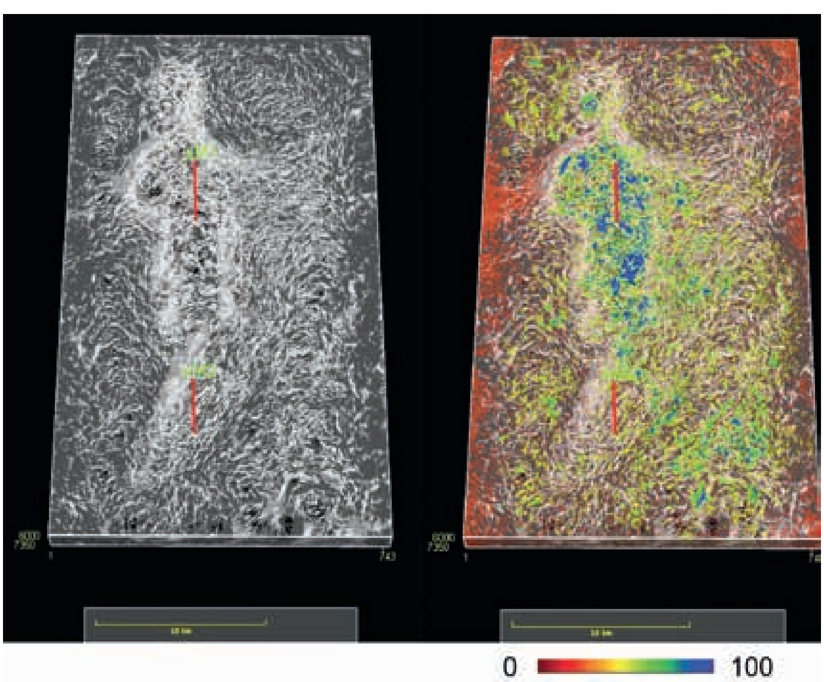


Figure 6 Comprehensive analysis of the attribute cubes and properties in the 3D volume. Left: curvature. Right: intensity of isotropic HTI (in %) + curvature.

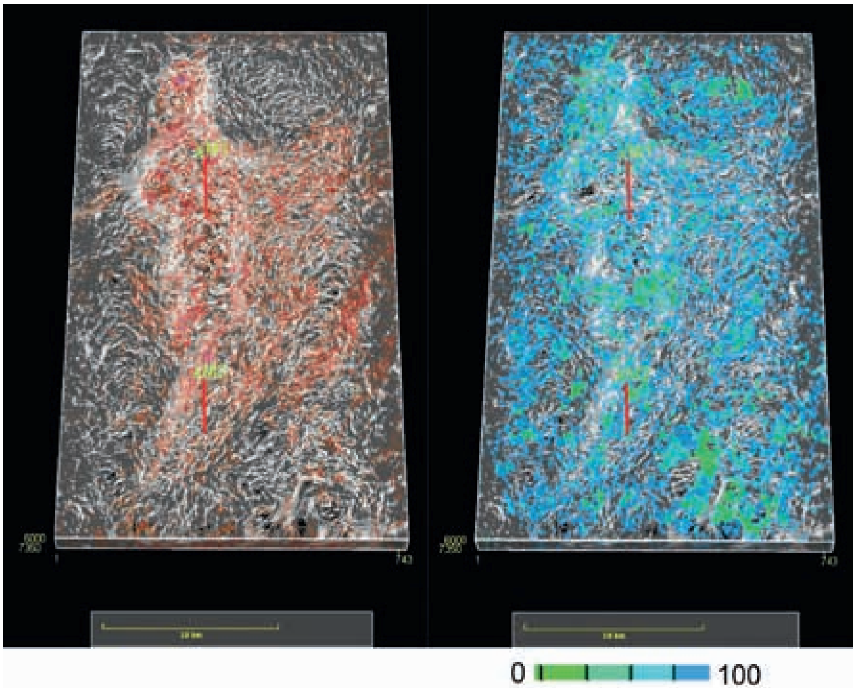


Figure 7 Comprehensive analysis of the attribute and property cubes in bulk. Left: The density of cracks + curvature; right: direction fracture + curvature. The reef body in space is expressed in great detail; it is possible to lay the project well with a high measure of accuracy. The colours are shown in the dominant azimuthal direction of the fractures.

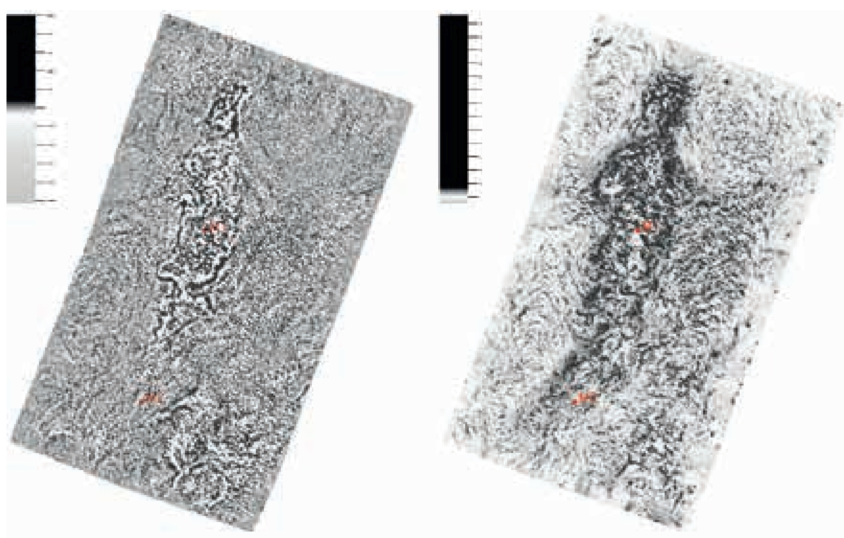


Figure 8 Use of a scattered component to clarify irregularity zones. Left: depth slice of scattered cube at depth H = 6000 m, right: slice shows curvature attribute (MajorPrincipalCurvature_Curvate) at the same depth.

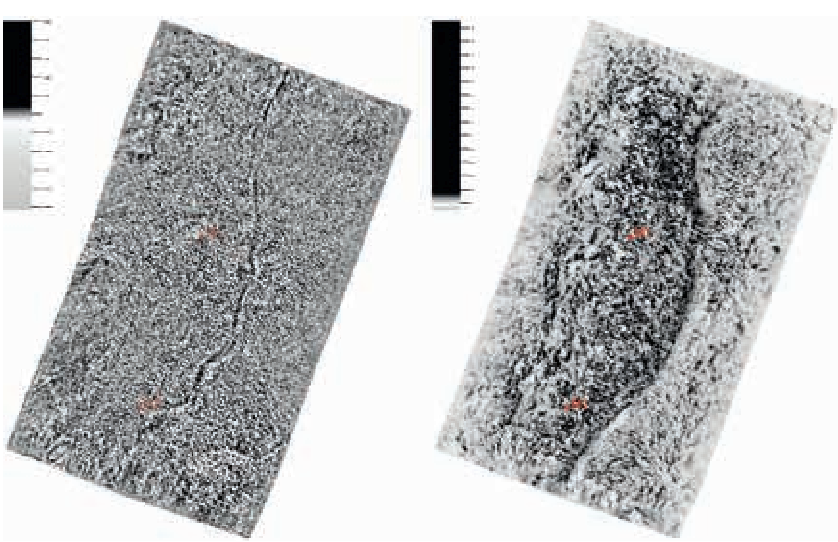
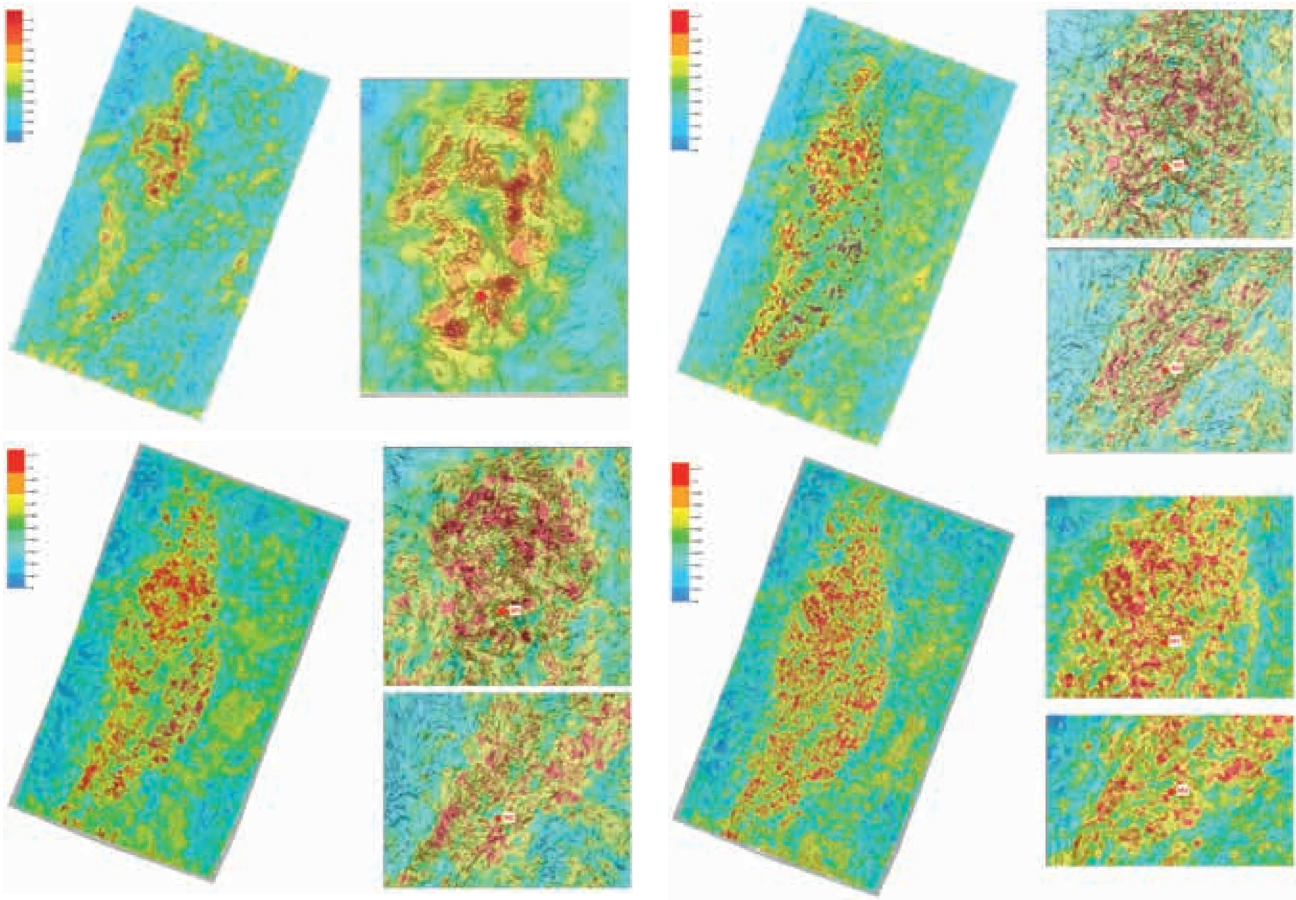


Figure 9 Use of a scattered component to clarify irregularity zones. Left: A deep cut of H = 7600 m; right: A depth slice curvature attribute (MajorPrincipalCurvature_Curvate). A joint analysis of the scattered components and volumetric curvature at this depth highlights sharp heterogeneity, limiting the eastern board of the carbonate platform.



Figures 10a, b, c and d show composite images of depth slices and fragments, curvature cubes (MajorPrincipalCurvature_Curvate), and fracture intensity (Anisotropic_Intensity) at depths of (respectively): 5800 m, 7000 m, 7200 m and 7400 m. By comparing these figures, it can be concluded that Anisotropic_Intensity distribution (Fracture Density) in a carbonate body changes both vertically and laterally. This is important information when selecting a drilling point and the test intervals in the borehole. Attribute MajorPrincipalCurvature_Curvate, for its part, clearly delineates reef building at all depths.

Based on these results, we recommended an initial exploration well at a depth of 7000 m to explore subsalt sediments, and the establishment of reserves in the Devonian part of the section in a more elevated part of the top reservoir.

The goal of exploration well M-1 was to identify the presence of carbonates of the Devonian age with good reservoir properties and profitable hydrocarbon reserves. The well should be drilled in the carbonate paleo reef of Upper Devonian Age.

Attribute and property analysis, and prediction of fractured zones in the reef structure

An integrated interpretation of the results was made after analysing the amplitude of various cubes and slices. Initially, a joint analysis was made of amplitude cubes and cubes of attributes DAC, HTI isotropic intensity and direction (after AVAz inversion), coherence and curvature.

The most effective joint analysis of the cubes was the intensity and direction of HTI isotropic and volumetric curvature. Examples are shown in Figure 6.

With this combination of attributes, the complex pattern of mega-cracks in the reef is clearly visible, together with their relation to the maximum and average values of HTI intensity associated with the density of meso-fractures developed in the reef. The red vertical lines indicate the projected wells.

In another combination of attributes (Figure 7) we can clearly see the zoning density distribution of meso-cracks and their relationship with mega-cracks. The trend direction of the fractures is in the range of 80-100 degrees azimuth sector of the north.

A joint analysis of the scattered components and volumetric curvature (Figure 8) shows that two independent attributes demonstrate approximately the same zones of maximum development of mega-cracks, increasing the reliability of the prediction.

Analysing the two different approaches to identifying irregularities of various types, it can be said that the image from the diffraction component gives more subtle and unique information about the faults and reef contours than the surface curvature attribute. This is because the diffraction component is extracted directly from the full-azimuth directional gathers, and is therefore a direct indication of irregularities. Information about the curvature of surfaces is an indirect indicator of irregularities already extracted from the stacked cube.

The new details extracted from these attributes about the distribution of fractures and their direction in the depth domain, as well as information from the diffraction component and curvature attributes, were also used in the integrated interpretation to improve the reliability of the prediction when choosing the locations of new wells M-1 and M-2.

Conclusions

As mentioned above, in well M-1 we assume hydrocarbon production flow from the upper Devonian carbonate sediments. The top of the carbonates (Famennian age) must be opened at a depth of 5800 m. Based on interpreting the seismic and petrophysical estimation in the adjacent territory, several zones are revealed with different reservoir porosity in the range of 2% to 10%. The area with the best prospects is around the M-1 well, where the target reservoirs are carbonates of Upper Devonian age. The detailed three-dimensional seismic survey reveals a carbonate structure in a favourable position for trapped hydrocarbons.

In this project, the Paradigm EarthStudy 360 technology was applied to ultra-deep and complex geological sections for the first time in the CIS region. The wide-azimuth 3D survey performed using this technology significantly improved the resolution of the depth image and provided new information about the known reef complex in the south of the Caspian Sea, which is located at great depths. A structural plan of the reef roof was traced. A feasibility prediction of hydrocarbon resources, and a detailed study of the internal structure, both vertically and laterally, were made. We were able to confidently predict prospective areas for drilling, and for spacing to test newly drilled wells.

The use of RMOZ and AVAZ inversion yielded important data about the intensity and direction of HTI anisotropy and fractures, which is important when drilling vertical and directional wells. The new information obtained for this field can significantly reduce the risk of drilling less productive wells, and reduce material costs for field development.

Acknowledgments

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