Applying full–azimuth angle domain pre-stack migration and AVAZ inversion to study fractures in carbonate reservoirs in the Russian Middle Volga region

Inozemtsev Alexander Nicolaevich,1 Stepanov Igor Viktorovich,2 Galkin Alexander Vasilyevich2 and Zvi Koren1* introduce full-azimuth angle domain imaging which in an onshore seismic exploration application resulted in a higher resolution and more informative depth image than conventional migration technology.

In onshore seismic exploration, standard migration technologies have traditionally been unable to provide sufficient detail and accuracy when imaging subsurface carbonate reservoirs. A new method was required to provide higher-quality depth images and reservoir characteristics, to both enable a more correct placement of exploration and production wells, and to improve production flow.

To address this issue a project was performed involving carbonate reservoirs in the Middle Volga region of Russia using a proprietary full-azimuth angle domain imaging system (Koren and Ravve, 2011), that includes tomography and anisotropic AVAZ inversion (Canning and Malkin, 2009). 3D seismic data from onshore surveys was first processed with careful amplitude preservation. The seismic dataset was characterized by an average fold of 90 with sparse full-azimuth distribution and a maximum offset of 3900 m. The maximum target depth was 4000 m.

Full-azimuth angle domain imaging
The full-azimuth angle domain seismic imaging system, called EarthStudy 360, used in this study is an effective technology for generating and extracting high-resolution information about subsurface angle dependent reflectivity. The system enables geophysicists to use all recorded seismic data in a continuous fashion directly in the subsurface local angle domain (LAD), resulting in two complementary, full-azimuth, common image angle gather systems: directional and reflection. The complete set of information from both types of angle gathers leads to accurate, high-resolution, reliable velocity model determination and reservoir characterization.

Directional angle decomposition enables the implementation of both specular and diffraction imaging in real 3D isotropic/anisotropic geological models, leading to simultaneous emphasis on both continuous structural surfaces and discontinuous objects, such as faults and small-scale fractures. Structural attributes at each subsurface point, e.g., dip, azimuth, and continuity, can be derived directly from the directional angle gathers.

Reflection angle gathers display the reflectivity as a function of the opening angle and opening azimuth. These gathers are most meaningful in the vicinity of actual local reflecting surfaces, where the reflection angles are measured with respect to the derived background specular direction. Reflection angle gathers are used for automatic picking of full-azimuth angle domain residual moveouts (RMO) which, together with derived background directivities, provide a complete set of input data to isotropic/anisotropic tomography solutions. The full-azimuth angle-dependent amplitude variations are naturally used for reliable and accurate AVAZ analysis and reservoir characterization.

The workflow in this study comprises a series of steps intended to provide a comprehensive characterization of the target reservoir:

1. 3D ray tracing to better understand subsurface angle domain illumination, taking into account velocity model anisotropy/heterogeneity and the seismic acquisition pattern of the data.
2. Derivation of initial anisotropic VTI velocity model parameters: $V_{vp}$, $V_{sv}$, $\theta$, and $\varepsilon$.
3. Generation of full-azimuth directional angle gathers, extraction of dip, azimuth and continuity (DAC), and performance of both specular weighted and diffraction weighted energy stacks to enhance the image quality of subsurface continuous and discontinuous objects, respectively.
4. Generation of full-azimuth reflection angle gathers in the specular direction, followed by automatic picking of...

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azimuthal dependent residual moveouts (RMO) \( M(\phi, \varphi) \) as a function of the phase opening angle \( \phi \) and azimuth \( \varphi \) at given subsurface horizon points \( m \), for anisotropic tomographic velocity model updating.

(5) Regeneration of the full-azimuth reflection angle gatherers and the automatic picking of azimuthal residual moveouts along target areas. The RMOs indicate \( \pi \)-periodic azimuthal variations that can be explained by the existence of aligned stress/fracture systems. The RMOs are used to obtain optimal azimuthal effective parameters; low NMO velocity direction \( \varphi_{\text{slow}} \), slow relative residual velocity \( \varphi_{\text{slow}} \), and \( \Delta \alpha = \alpha_{\text{full}} - \alpha_{\text{slow}} \) that indicates the azimuthal variation intensity. The azimuthal dependent RMO picks and their effective RMO parameters are then used to flatten the major horizons, allowing accurate AVOZ analysis.

(6) Performance of azimuthal dependent amplitude inversion (AVAZ) to obtain volumes of AVAZ attributes: Anisotropic gradients, volumes of stress/fracture density and stress/fracture orientation.

**Figure 1** A comparison of the results of EarthStudy 360 vs. Kirchhoff.

**Figure 2** Dip (left) and azimuth (right) volumes automatically extracted from directional angle gathers – it is possible to see that the complex reef is characterized by 50\(^o\) dips.
Integrated interpretation was performed by combining volumes of seismic amplitudes and fracture density. This combination enabled a direct assessment of which parts of the reef contained fractures. It was ascertained that the main fracture density anomalies were concentrated in the structure of the reef, and were distributed non-uniformly in the reef layers.

Interesting information was obtained when comparing the results received using the new system at the amplitude map level. The depth slice in the reef after full-azimuth angle domain imaging shows higher lateral resolution and detail than the Kirchhoff depth slice. In this same area, geologists have detected a barrier paleo-reef (the modern Great Barrier Reef in Australia, shown in an aerial photograph). The modern reef has a similar paleo-reef structure consisting of many connected (or unconnected) segments, and it is located along a major fault. We may confidently assume that the paleo-reef and the modern reef had the same origin, which further contributes to our understanding of the reef mechanism.

A diffraction weighted stack was then obtained from directional gathers by filtering specular energy in Fresnel’s first zone and conserving only the energy of the diffracted reflections. The seismic volume of the diffraction weighted stack has a much higher resolution of discontinuous features than the traditional Coherence Cube, as the coherence attribute is calculated along post-stack data (averaging), and the diffraction weighted stack is performed on pre-stack directional angle gathers. The quality of the slice extracted from a discontinuous cube is far better than the lateral resolution quality of the slice obtained using the Coherence Cube (Figure 7), and many more details relating to fractures of different sizes are visible. It is even possible to see a local ring-shaped object (reef) similar to the objects in a modern barrier reef.

Results

The most important results obtained in this project were the identification of fracture density and fracture azimuthal orientation within the target carbonate reef. Figure 8 shows fragments of two such maps in that area: on the left, a fracture density map (the yellow-red colour indicates increased
Figure 4 The results of AVAZ inversion at the vertical section level, along the reef.

Figure 5 Integrated interpretation of AVAZ inversion results: a reef complex and separate reef are circled.

Figure 6 Amplitude slices following Kirchhoff and EarthStudy 360 migrations. For comparison, a fragment of the Great Barrier Reef is shown.
fracture density) with a vector image imposed on it that shows the fracture orientation and intensity; on the right, a map of azimuthal orientation of fractures. The vector direction coincides with the fracture direction in a range of 37–55°.

The evidence showed that the use of full-azimuth angle domain imaging in onshore seismic exploration resulted in a higher resolution and more informative depth image than any traditional migration technology. The data provided more information about structural attributes such as dip and azimuth of the subsurface reflectors, and about reservoir properties characterized by fracture density and their azimuthal orientation. Furthermore, the seismic volume of the diffraction weighted stack had a much higher resolution of discontinuous features than that obtained using the traditional Coherence Cube technology. Together, this new information enabled a more certain identification of reef objects in carbonate thicknesses, and a reliable estimation of the distribution and orientation of fractures.

The volumes and maps obtained using this full-azimuth imaging technology provide essential information for drilling and for improving production flow, as they give a full description of the subsurface parameters, including information about the distribution of large faults and fracture properties. This information ensures optimal horizontal drilling as well as the correct placement of exploration wells.

References
The workshop will explore the need to develop national workforces in emerging hydrocarbon provinces and focus on the challenges, methods and tools for the development of local E&P skills in the 21st Century.

Two sessions followed by a forum discussion are planned with invited speakers from NOC’s, IOC’s, academia and institutes. The first session focuses on “Challenges: How to build local capability content”; the second on “Solutions, tools and methods”. Between these two sessions there will be round table discussions.

Three 1 hour breaks are planned for demonstrations of learning tools and posters and with ample opportunity to share knowledge and experience. The day will be closed with a networking reception.

For further details, to submit a poster or to register please go to www.eage.org.

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