EarthStudy 360 Delivers New Information about Fractures in Carbonate Reservoirs

The Challenge
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.

The Paradigm Solution
A project was performed in carbonate reservoirs in the Middle Volga region of Russia using the Paradigm EarthStudy 360® full-azimuth angle domain imaging system (Koren and Ravve, 2011), including 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.

The workflow included:
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 velocity model parameters (VTI).
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, using residual moveouts (RMO) measured along the gathers for anisotropic tomographic velocity model updating.
5. Re-generation of the full-azimuth reflection angle gathers, followed by azimuthal (HTI) residual moveout analysis and inversion to obtain optimal HTI effective parameters: Azimuth of axial HTI symmetry; HTI anisotropy intensity (Delta2); and relative residual velocity along fractures (Alpha).
6. Performance of amplitude AVAZ inversion to obtain volumes of AVAZ attributes: Anisotropic and isotropic gradients, and volumes of fracture density and fracture orientation.

The Method
A comparison was made between the quality of the seismic depth image obtained using the EarthStudy 360 Imager and that of a Kirchhoff migration. The depth velocity model, migration aperture and other parameters in both cases were the same.

Figure 1 shows two seismic images after applying the different migrations. The image on the left (EarthStudy 360) shows greater detail in the vertical and lateral directions, and improved depth image quality, including complex reef constructions and faults. There are
also signs of a global fault in the center of the reef complex. With the Kirchhoff migration, only separate and indistinct signs are discernible.

Directional angle gathers were created, and dip, azimuth and continuity (DAC) of the subsurface reflectors were automatically extracted. This information is very important for geologists, as it provides quantitative knowledge about the dip and azimuth of the geological interfaces at each local subsurface point. The results were much more precise than those obtained using standard techniques performed over post-stack data, normally obtained by computing different structural attributes. This information is also essential when performing migrations that consider TTI anisotropy.

Full-azimuth reflection angle gathers were generated using the background velocity model shown in Figure 3 below. The results showed both kinematic and dynamic azimuthal variations. HTI anisotropic 3D reflection angle gathers were analyzed. The curves of amplitude variations obtained along the carbonate reef reflectors showed considerable azimuthal changes, indicating the existence of fractures or preferred stress orientation.

Figure 4 shows a clear correlation between the seismic image and the AVAZ inverted attributes: Fracture density and HTI axis of symmetry along a near vertical fault within the reef. The azimuth of the HTI axis of symmetry is oriented at an azimuthal range of 110-140°.

Fig. 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° dips.

Fig. 4. The results of AVAZ inversion at the vertical section level, along the reef.

Fig. 3. An example of the input data for the analysis of HTI anisotropic 3D reflection gathers.
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.

Using EarthStudy 360, a diffraction weighted stack was obtained from directional gathers by filtering specular energy in Fresnel’s first zone and conserving only the energy of the diffracted reflections. This was done by means of a special processor in the Paradigm GeoDepth® Velocity Navigator module.

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, 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.

Interesting information was obtained when comparing the results received using EarthStudy 360 at the amplitude map level. The depth slice in the reef after EarthStudy 360 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.
The 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: At left – a fracture density map (the yellow-red color indicates increased fracture density) with a vector image imposed on it that shows the direction of minimum horizontal stress and stress intensity. At right – a map of azimuthal orientation of the minimum horizontal stress direction. The vector direction coincides with the fracture direction in a range of 37-55°.

The evidence showed that the use of EarthStudy 360 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.

Based on that information, a new well was drilled, and for the first time in this region, oil was found in the Paleozoic zone. In addition, a large oil inflow was received from a Devonian reef.

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References

“The volumes and maps obtained using the EarthStudy 360 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.”