The effect of full-azimuth local angle domain (LAD) imaging on the study of terrigenous and carbonate reservoirs under complex in-situ conditions at an eastern Siberian field

Andrey Sorokin1, Lenar Shakirzyanov2, Alexander Inozemtsev3, Vadim Soloviev3 and Zvi Koren3 demonstrate anisotropy intensity and direction determinations in terrigenous and carbonate reservoirs, and improved acoustic impedance convergence calculated on a combination of advanced technology results and GIS data.

Introduction

The EarthStudy 360 full-azimuth local angle domain (LAD) imaging and analysis technology, developed by Paradigm, appeared on the geophysical services market in 2012. GazpromNeft NTC, a high-tech company that strives to incorporate the most advanced systems into its operations, did not let this opportunity pass by. A pilot project to test LAD imaging was undertaken in 2014. The study’s most significant findings were anisotropy intensity and direction determinations in terrigenous and carbonate reservoirs, and improved acoustic impedance convergence calculated on a combination of advanced technology results and GIS data. In 2015 GazpromNeft NTC used the technology to assess 3D full-azimuth angle domain survey data in an Eastern Siberian field.

Historically, Eastern Siberia has been one of the most difficult areas for seismic studies attempting to prospect for and predict reservoir properties. Complex relief and subsurface velocity heterogeneity in both vertical and lateral directions creates problems for seismic survey operations and for seismic data processing. The greatest challenges occur in depth processing, where specific complexities hinder the development of a depth/velocity model, beginning with near-surface formations and the top portion of the geologic profile.

Local lithological variations in the lateral direction, accompanied by the surface exposure of rocks of various ages and lithological characteristics (from carbonates to clays, salt-bearing strata, and sometimes trapped intrusions) make it necessary to develop complex velocity models and apply full-azimuth depth surveys which traditional approaches and migrations, based on the Kirchhoff integral, cannot provide. Cambrian, Jurassic and Quaternary rocks with P-wave velocities of 5000-5500 m/s, 3000-3500 m/s, and 900-1200 m/s, respectively, are exposed at the surface of the survey area.

Solution

In order to obtain more reliable information about the environmental depth structure and estimate of major hydrocarbon reservoir parameters, the EarthStudy 360 technology (Koren and

![Figure 1](image-url) a) The initial velocity-depth model obtained using the coherent inversion method. b) The final anisotropic VDM obtained using well tie tomography. The primary terrigenous reservoir is designated with a red arrow, and the carbonate reservoir is designated with a white arrow.

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Ravve, 2011) for obtaining and interpreting full-azimuth seismic images, including AVAZ anisotropic tomography and HTI anisotropic inversion (Canning and Malkin, 2009), was successfully introduced for the first time at an oil and gas field in this region. In addition, during depth processing a complex workflow was used to perform depth velocity model building using the built-in upper part of the interval velocities obtained by the refraction statics, followed by the application of Paradigm’s new well tie tomography.

Three-dimensional data was obtained based on a full-azimuth surface seismic survey with an active pattern length-to-width ratio of 2000 m and an average fold of 100. A group of vibration sources was used to excite elastic fluctuations.

The velocity-depth model utilized new methodologies, such as including a 3D velocity model in the near-surface portion of the velocity-depth model (VDM) derived using refracted wave data and VTI isotropy calculations, as well as iterative refinement of the VDM top portion and the complete model using model-based anisotropic tomography and well tie tomography. A conditional anisotropic VDM (Figure 1B) was developed using the serial iteration method, and was used to perform LAD imaging.

The migration process included the following steps:

1. 3D ray tracing to better understand subsurface angle domain illumination, taking into account velocity model anisotropy/heterogeneity and the seismic data acquisition pattern. Evaluation of major illumination parameters for depth boundaries in major reservoirs: fold, determining entry angles, azimuth, migration aperture, and the reliability of the parameters studied.

2. Migration and development of full-azimuth directional angle gathers, extraction of reflection surface dip, azimuth and continuity (DAC) cubes, obtaining weighted reflection and diffraction summation to improve the image quality of the specular component (information on continuous boundaries), and the diffraction component (information on heterogeneous objects – Figure 2).

3. Migration and development of full-azimuth reflection angle gathers using DAC cubes obtained in Step 2 to develop an amplitude cube for a specular component, evaluating residual kinematics (RMOz) parameters measured along seismic traces and adjusting gathers to obtain better images (Figures 3a and 3b).

4. Interactive HTI analysis and recording of HTI isotropy effects. Kinematic (VV Az) inversion and use of RMOz corrections accompanied by obtaining cubes and maps of HTI isotropy parameters (Delta2 is HTI isotropy intensity, HTI axis is the HTI direction of the axis of symmetry, Alpha is RMO in the direction lateral to the axis of symmetry).

5. AVAz pre-processing and analysis.

6. Amplitude AVAz inversion for calculating cubes and maps of AVAz parameters: Anisotropic gradient, HTI isotropy intensity related to a variety of stresses and rock fractures, and HTI direction of the axis of symmetry.

7. Integrated quantitative and qualitative interpretation of results in order to predict improved major reservoir properties.

An example of a reflection gather and an inline section before and after RMOz corrections is shown in Figure 3. The increased dynamic resolution of reflections after RMOz corrections is noted in the interval of the primary terrigenous reservoir in Vendian rocks.

Figure 2 Diffraction component cube analysis. In a cross-section of diffraction component 2b, an aspect-stabilized system of annular geological bodies is visible in carbonate deposits. 2a) Specular component section. Presumably, these are sinkholes with a diameter of a few dozen to 300 m. A photo of a sinkhole formed at the surface is shown in Figure 2c.
more accurate transition zones are observed; when used together, they help to obtain unambiguous resolutions for complex interference zones (marked with ovals).

This, in turn, gives a more accurate understanding of the image as a whole, and provides new, geologically important details, to clarify the basement boundary and positions of the roof and floor of terrigenous Vendian deposits, as well as more details about the prospective carbonate stratum and clarifying structural correlation.

Comparative cross-sections of amplitudes and final images obtained using Kirchhoff and LAD imaging are shown in Figures 6 and 7.

**Evaluation of data quality, images, attributes and properties**

An evaluation of the quality of the data obtained using LAD imaging was conducted based on a comparison of images with the Kirchhoff migration and based on various attributes for both migrations. Comparative inline sections of amplitude cubes are shown in Figures 4 and 5 for final images produced using the Kirchhoff migration and LAD migration.

The visual comparison reveals higher image quality in terms of the seismic horizon continuity, an increase in the traceability level and reflection detail from the target reservoirs and the basement (designated with arrows). Reduced migration noise and
The qualitative enhancement of information is even more critical, as the LAD technology uses completely azimuthal information and correctly interpolates traces during the migration. In particular, the effect of the lower ‘closure’ zones related to the lack of long offsets may be seen in the top portion of the seismic section in Figures 6 and 7. Moreover, new minor discontinuities are visible in LAD results for this zone, in addition to the overall increased traceability.

Quantitative evaluations of quality improvements for the signal-to-noise ratio (SNR) show that it almost doubled in value: from 6 (Kirchhoff) to 11.5 (LAD).

**Comparison**

**Evaluation of quality and sensitivity in the coherence cube, and in dip, azimuth, continuity (DAC) attributes**

A coherence cube is an additional tool for indirectly measuring the degree of heterogeneity (or boundary roughness) in the subsurface. It can provide valuable information about faults, cracks and other heterogeneities.

Figure 8 shows a comparison of maps extracted from coherence cubes calculated using Kirchhoff and LAD migrations.

A comparison of coherence maps for the different migrations shows signs of individual faults, visible in maps based on a Kirchhoff cube. However, there are also visible unresolved heterogeneity clusters. A higher-resolution image in a slice of the LAD-based coherence cube clearly shows large and small faults, their combination and fractal hierarchy, as well as mega-cracks or clusters, and individual lineations of other heterogeneities.

Dip, azimuth, and continuity (DAC) are important attributes that enable us to determine and qualify, at each point, the directivity of the Normal vector to the subsurface reflecting surfaces. The continuity attribute provides a concrete understanding of reflection boundary continuity in the first Fresnel Zone, or the absence of such borders (in this case, there is heterogeneity there, represented by previously diffracted waves). This information is extracted automatically from seismic data by evaluating these attributes’ values. There is one fundamental difference, however: This information is extracted from stack data in the Kirchhoff migration, whereas in the LAD migration it is extracted from directional gathers (based on the use of a beam of rays tracing at each point). To this end, DAC information extraction from LAD data is a direct method, while DAC extraction from Kirchhoff calculated by summation is an indirect method. Therefore, DAC information should be considered more accurate and reliable in the case of LAD migrations. This difference is like that between prestack and poststack migrations in terms of image quality and reliability.

Comparative examples for estimating the continuity (smoothness) parameter of reflection boundaries for Kirchhoff and LAD migrations are shown in Figures 9a and 9b.

The Kirchhoff continuity map displays primarily border continuity, individual faults, and fuzzy shapes found in other
that were ‘overlooked’ previously become visible when the
colourmap is rotated.

By comparing dip boundary maps (Figure 10), we may
estimate potential increases in dip angle estimation accuracy (and
heterogeneities. The LAD continuity map, on the other hand,
shows that a presumably continuous field of reflection borders
is broken down into a series of additional faults, lineaments and
annular objects. More complex relationships between new objects

Figure 9 a) Data quality comparison at continuity
map level. Target horizon. b) Data quality comparison
at continuity map level with colourmap rotation.

Figure 10 Data quality and accuracy comparison at
dip map level. Target horizon.
object sensitivity) if this parameter is evaluated directly using LAD directional gathers as input.

The colourmap is identical for both. Average estimates for maximum dip angles of boundaries (or objects) are no more than 3 degrees for the dip map obtained using a Kirchhoff cube. The maximum angle for the dip map obtained using LAD imaging is 9 degrees. To put it differently, the accuracy of measurements and respectively, dip parameter sensitivity, increase by a factor of three when using LAD imaging.

A similar picture can be observed when estimating the azimuth parameter (Figure 11). A chaotic azimuth profile picture is observed during Kirchhoff migration owing to lower-quality

Figure 11 Data quality comparison at the dip azimuth attribute map level. Target horizon.

Figure 12 LAD. Integrated analysis of attribute and property cubes in a volume. Curvature + dip + azimuth, target reservoir interval. A complex relief of a horizon terrigenous subsurface is visible for this combination of attributes in 3D space relative to fault, mega-crack, and other heterogeneity zones. The overall picture looks like a 3D photo.

Figure 13 Colour-coded and vector map (left) of HTI anisotropy intensity (higher value – warm tone) compared to a map of reflection boundary dip angles for the terrigenous reservoir roof. Note that HTI isotropy intensity and direction are controlled by a system of faults and mega-discontinuities as well as the configuration of domed uplifts (structures) that could cause stress variations. A domed structure with maximum stress at the edges and minimum stress at the dome is circled.

Figure 14 a) A fragment of an HTI anisotropy direction and intensity map for the colour-coded and vector options. Higher values of HTI intensity are designated with warm colours. Well 2 has the highest productivity. Well 5 demonstrates some oil-bearing capacity, and Well 4 is dry. b) A fragment of an HTI anisotropy direction and intensity map for the colour-coded and vector options. The northeast part of the surveyed area is considered the most promising in terms of production drilling. Higher values of HTI intensity are designated with warm colours. Well 3 is dry.
obtained by summation and ensure a high convergence between the seismic data and well information. The overall result of using LAD migration technology was an increase in the signal-to-noise ratio to 11.5, almost double that of a respective value of 6 for the Kirchhoff migration.

The modelling of elastic parameters based on LAD data occurred with higher correlation coefficients, indicating that a wavefield for full-azimuth depth migration was restored more correctly. There was a marked reduction in the degree of fault impact on geological body contours and the overall trend towards reducing uncertainties along faults in LAD-based maps, where reservoir sand continuity was higher. Based on the results of these efforts, the optimum locations for both appraisal and production wells scheduled for drilling were confirmed, and recommendations were made for drilling two exploration wells and one research well.

In summary, LAD imaging combines all the key approaches for studying a fault/crack system: traditional interpretation of faults, analysis of structural attributes, dissipated waves, and anisotropic properties of the environment. Pilot use of this technology under various seismic/geological conditions is of great interest to the development of seismic data processing. The two-fold increase in signal-to-noise ratio using LAD technology enabled us to obtain pervasive improvements in sensitivity at each interpretation stage. Correlation in the target interval increased to 0.9, mis-ties in structure building were reduced to 3-5%, and more reliable tracing of discontinuities and correlation of reflection reservoirs was achieved. Use of RMOZ and AVAZ inversions provided novel information about HTI anisotropy intensity and direction. This was subsequently used to develop a hypothesis of the present tectonic picture and relevant oil-bearing capacity.

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