Full azimuth angle domain decomposition and imaging: A comprehensive solution for anisotropic velocity model determination and fracture detection
Zvi Koren, Paradigm

SUMMARY
A new subsurface angle domain seismic imaging system is presented for the generation and extraction of 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 (Koren et al 2007, Koren et al 2008). The complete set of information from both types of angle gathers leads to accurate, high-resolution, reliable velocity model determination and reservoir characterization. The 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. The 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. The reflection angle gathers are used for automatic picking of full-azimuth angle domain Residual Moveouts (RMO) which, together with the derived background directivities, provide a complete set of input data to isotropic/anisotropic tomography solutions. The full-azimuth angle-dependent amplitude variations are used for reliable and accurate AVAZ analysis and reservoir characterization. The proposed system is most effective for imaging and analysis below complex structures, such as sub-salt and sub-basalt, high-velocity carbonate rocks, shallow low-velocity gas pockets, and others. Additionally, it enables accurate azimuthal anisotropic imaging and analysis, providing optimal solutions for fracture detection and reservoir characterization.

INTRODUCTION
Faced with declining production in mature oil and gas fields, upstream energy companies are being forced to concentrate exploration efforts in areas of increasing operational and technical complexity. To conduct successful seismic programs in these conditions, substantial investments must be made to acquire wide and rich azimuth seismic data. While advances in seismic imaging and interpretation continue at a rapid pace, these solutions are still limited when extracting information about the subsurface geological model. Geophysicists ask a lot from their seismic data. For substructure (salt and basalt) reservoir exploration, complex wave phenomena distort the seismic image to the point where many iterations and repetitions of velocity model building and seismic migration are required before attempting a defensible interpretation.

In the deep water regions such as the Gulf of Mexico, this imaging problem is compounded by salt geometries that are highly irregular in shape in three dimensions. These salt bodies, in turn, may be overlain or truncated by shale sequences that give rise to different imaging problems that require additional velocity property (anisotropy) estimation and modeling procedures to secure more reliable seismic images.

For mature oil fields, geophysicists seek the maximum resolution from seismic data to uncover evidence of both structural and stratigraphic compartmentalization of reservoirs. Here, the preservation of the dynamic (amplitude) properties of seismic data is important for driving seismic inversion processes or attribute transformations that emphasize discontinuities or geometric boundaries of depositional features.

For fractured reservoirs, geophysicists often rely on directional sampling of the subsurface to create images that can be analyzed, compared, and differentiated to make inferences regarding fracture orientation and fracture density that define permeability zones and hydrocarbon migration pathways. These procedures are being refined as the industry gains more experience in exploring, developing, and producing gas from shale reservoirs from different basins around the world.

Seismic data can also play a useful role in understanding the distribution of hydrocarbons in heavy oil fields. Here, seismic methods and procedures suitable for shallow high angle imaging can be used to delineate, and in some cases, characterize these challenging reservoirs.

Unfortunately, when generating seismic images to address these exploration and development objectives, we frequently make assumptions regarding the compatibility of the seismic imaging methods with the seismic acquisition, or we make simplifications to the velocity description that under-parameterize the wave propagation model. These assumptions and simplifications are often accepted because time is limited, current technology is not fully understood, or alternative technologies are not available.

What is needed is a system that allows us to better qualify and even quantify the expenditures that we make in seismic acquisition and imaging to assist us in not only understanding the implications of our assumptions and simplifications, but also to help us assess where we can make changes that will have the greatest return on investment from our seismic programs. To achieve this objective, we need to give proper attention to the issue of subsurface angle domain decomposition, with an emphasis on azimuth.

In the past decade, the industry has made huge investments in planning and acquiring seismic acquisitions that are both rich and wide in azimuth.
These acquisitions are needed as geoscientists seek better reservoir definitions and hydrocarbon signatures from seismic data. Benefits from these rich acquisitions have been acknowledged and documented, and include improved multiple suppression, noise suppression and illumination of target areas. While the resulting seismic images incorporate many of the benefits of rich- and wide-azimuth sampling, the application of current technology and approaches does not appear sufficient to realize the full potential of these acquisitions.

The extension of image gathers to display azimuthal variations, especially in order to study azimuthal anisotropy effects caused by the existence of fractures, has become standard. The current approach divides the recorded wavefield into a relatively small and manageable number of acquisition-azimuth sectors, or surface offset (x,y) bins, which are processed, imaged and analyzed independently. This approach suffers from a number of shortcomings: Sectoring decisions (size and number) are often made subjectively, independent of subsurface structure; sectors are formed over relatively coarse azimuth ranges, compromising massive human resources; and sectors are formed based on surface acquisition azimuth, with no reference to “in situ” measurements of local reflecting surfaces. This process lacks accuracy, especially for long offsets, and does not properly use the entire recorded wavefield. Conventional azimuth sectors represent seismic images vs. surface source-receiver offsets and azimuths, rather than true angle domain information directly at the subsurface image points.

To recognize the full potential of rich and wide-azimuth seismic data, seismic imaging, characterization and interpretation technologies require a significant “upgrade” that can provide a more comprehensive decomposition of the seismic data, directly in the subsurface angle domain, from all azimuths in a continuous fashion.

We propose an innovative new technology that extracts unprecedented value from modern and legacy seismic data acquisitions, and is especially effective for wide and rich-azimuth and long offset, in both marine and land environments. The proposed system is designed to image, characterize, visualize and interpret the total seismic wavefield, and provide previously unattainable levels of subsurface knowledge.

The proposed system opens a new world of information to geoscientists. The system is designed to deliver to both depth imaging processing experts and interpretation specialists a complete set of data containing accurate subsurface velocity models, structural attributes, medium properties, and reservoir characteristics. The rich information from all angles and azimuths ensures more reliable analysis and significantly reduces uncertainty. This is a huge step towards a totally automated system, while allowing user intervention and QC at any stage in the workflow.

THEORY AND METHOD

Although the theory of angle domain imaging has been well established, its implementation, especially for large-scale 3D models or for high-resolution reservoir imaging, is still extremely challenging. A numerical implementation of true amplitude ray-based angle domain migration in real 3D complex geological areas, entitled Common Reflection Angle Migration (CRAM), has been introduced in recent years. Unlike conventional ray-based imaging methods, ray tracing is performed from the image points up to the surface where “diffracted” rays are traced in all directions (including turning rays), forming a system for mapping (binning) the recorded surface seismic data into reflection angle gathers.

Based on these developments, we propose a new and innovative seismic imaging system, in which imaged data events are decomposed in the Local Angle Domain (LAD), into two complementary full-azimuth angle gathers: Directional and Reflection. The combination of the two angle gathers, together with the ability to handle the full-azimuth information in a continuous manner, enables the generation and extraction of high-resolution information about subsurface angle dependent reflectivity in real 3D space. The complete set of information from both angle gather types expands our knowledge about both continuous structural surfaces and discontinuous objects, such as faults and small-scale fractures, leading to accurate, high-resolution, high-certainty, velocity model determination and reservoir characterization.

Directional gather-based imaging

Full-azimuth directional angle gathers decompose the scattered energy into dip/azimuth angle bins at all subsurface points. They contain information about both specular and diffraction energy. Specular energy is associated with reflection waves along continuous interfaces. Diffraction energy is considered to be scattered waves with non-specular directivity. It has been shown that diffraction energy contains information about local heterogeneities. The ability to decompose the specular and diffraction energy from the total scattered field is the core component of our proposed imaging system.

Weighting the specular energy provides improvements in the continuity of the reflectors. The specular energy also provides accurate information about the orientation (dip/azimuth) and the continuity of the local reflectors. By weighting diffraction energy, it is possible to emphasize geometrical features which are beyond the seismic resolution, such as small faults and even fractures.
Our approach consists of three main stages: Ray tracing, full-azimuth angle domain decomposition, and final imaging (weighted stacks). The ray tracing stage involves shooting a fan of rays from image points up to the surface. Ray attributes, such as traveltime, ray coordinates, slowness vectors, amplitude and phase factors, are stored for each ray. The full-azimuth angle domain decomposition stage involves a combination of ray pairs indicating incident and reflected/diffracted rays. Each ray pair maps a specific seismic data event recorded on the acquisition surface, into a four-dimensional local angle domain space in the subsurface - dip and azimuth of the ray pair normal, opening angle and opening azimuth. (Figure 1).

The four source-receiver surface coordinates (two for the source, two for the receiver) are defined according to their displacement vector and offset vector. Each vector is defined by its magnitude and azimuth, where the displacement magnitude is the horizontal distance between the source-receiver midpoint and the image location (also referred to as migration aperture distance). Note that theoretically each of the four surface parameters depends on all four LAD angles, and vice versa. There is, however (especially in moderately complex models) a stronger relationship between the directional angle gathers and the displacement vector, and between the opening angles and the offset vector.

**Velocity model accuracy**

Figure 2a shows the actual true velocity model of the SEG/EAGE salt model. Using directional angle decomposition, the energy as a function of the dip/azimuth angles at a given reflecting surface below the salt is shown in Figure 2b. The energy is displayed as a small spot concentrated in the vicinity of the actual directivity of the given reflector. Figure 2c shows the same velocity model when a 10% velocity error is applied in the region below the salt. The corresponding directional energy is shown in Figure 2d. It can clearly be seen that the energy is smeared (defocused) along the directional unit sphere, indicating the error in the velocity model and hence the directivity of the given reflector. This example suggests a procedure for quickly evaluating the integrity of the velocity model. Note that this directivity focusing analysis approach is considered as a complementary approach to the universally used velocity model error analysis, based on measuring residual moveouts along reflection angle gathers.

**Specular energy weighting**

Figure 3 shows an example of a cylindrical directional angle gather, where the specular energy (directivity-dependent Fresnel volume) is emphasized. The high amplitudes of the specular energy along the vertical axis indicate the directivity changes of the subsurface reflectors with depth.

Figures 4a and 5a show the imaging results of the inline and crossline sections, respectively, using traditional Kirchhoff-based migrations. Figures 4b and 5b show the markedly improved results obtained when using the specular energy shown in Figure 3 as the directional weighted stack operator.
Figure 6a shows the specular weighted energy stack at a given line, and Figures 6b, 6c and 6d show the same image with an overlay of the extracted structural attributes - dip, azimuth, and continuity.

Figure 6. Depth section along a given line with structural attribute overlay.

Figure 7 shows two depth migrated sections from 3D land data in Northwest Germany (owned by RWE- DEA AG and Wintershall AG) following the creation of directional angle gathers. The section on the left shows the direct stack of the directional angle gathers, and the section on the right shows the same section with specular energy weighted stack applied. The high energy values associated with the specular directions sharpen the image of the structure, and the improvement in the continuity of the structural information throughout the volume is clearly seen in the righthand section.

Figure 7. Depth migrated section from a 3D land survey in Northwest Germany.

Figure 8 shows an example of a directional angle gather in the vicinity of salt. Two areas of specular energy are clearly visible, indicating subsurface points in the vicinity of conflicting dips, such as pinchouts and unconformities. This shows that the common assumption that every image point is characterized by single directivity is somewhat naïve, and that we must also consider all the energetic directions.

Figure 8. Directional angle gather along pinchout. Two different specular directions at the same depth level. The vertical scale shows depth in meters.

Figure 9 shows an example of imaging in a complex basin in offshore Australia. Using directional angle decomposition and specular energy weighting, we were able to detect and image a structure that had previously been completely hidden (righthand image).

Figure 9. Imaging a "hidden" structure in offshore Australia. Kirchhoff depth image on the left, full-azimuth specular weighted image on the right.

Diffraction energy weighting

Figure 10 shows two depth slices from a fractured carbonate reservoir in the North Sea. Figure 10a demonstrates the resolution that can be obtained using a standard Kirchhoff migration. Figure 10b shows a high-resolution image of the same reservoir, emphasizing the fracture system and the channels, that was obtained by using a diffraction energy weighted stack.

Figure 10. Two depth slices from a fractured carbonate reservoir in North Sea.

a) Image obtained using standard Kirchhoff migration

b) Image with high resolution features obtained using diffraction energy weighted stack.

Full-azimuth reflection angle gathers

True amplitude, full-azimuth 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. The reflection angle gathers are used for automatic picking of full-azimuth angle domain Residual Moveouts (RMO) which, together with the derived background directivities, provide a complete set of input data to isotropic/anisotropic tomography solutions. The full-azimuth angle-dependent amplitude variations are used for reliable and accurate AVAZ analysis and reservoir characterization.
An example of a 3D reflection angle gather in the area of the North Sea is shown in Figure 11. It is displayed as a cylinder (left) and with transparency (right), so that the full dimensionality of the amplitude versus opening angle and opening azimuth can be studied. These full-azimuth image gathers can provide diagnostic quality control for the accuracy of the velocity models, and enable the automatic detection of residual moveout (RMO) errors. The gathers can also be sampled in full-angle or full-azimuth sectors to better understand the influence of azimuth on the velocity model, and to better understand the behavior of seismic amplitude as a function of opening angle and azimuth.

Figure 12 shows 20 azimuthal sectors of reflection angle gathers that were extracted on-the-fly from the cylindrical gather shown in Figure 11 above. Figure 13 shows five extracted opening angle sectors (20, 30, 40, 50 and 60 degrees), each of which displays full-azimuth reflections. The azimuthally varying reflector indicates an azimuthal anisotropic effect, and is marked by a rectangle. In Figure 13a, the reflector is magnified and overlain by automatic RMO picks, which are used to flatten the event (Figure 13b).

Figure 14 shows the implementation of AVAZ inversion to the full-azimuth reflection angle gathers, using the study performed by Canning and Malkin (2009), to produce anisotropic attributes (from left to right): Normal incidence, gradient, anisotropic gradient, fracture orientation, and fracture density. Note the differences between the isotropic and anisotropic gradients. This illustrates the fact that these attributes measure different subsurface properties. The high fracture density values suggest the existence of fractures.

CONCLUSIONS

We have presented a novel imaging system for generating continuous, full-azimuth angle domain image gathers. Two complementary angle gathers, directional and reflection, deliver high-resolution information about the subsurface model. In particular, the new directional image gathers allow automatic extraction of geometrical attributes, such as dip, azimuth and specularity/continuity, and enable the generation of different types of images by weighting either specular or diffraction energy. It has been shown that several specular directions may coexist at the same image point, associated with conflicting dips (unconformities and pinchouts). Both continuous structure surfaces and discontinuous subscale small objects, such as channels and fractures, can be detected, even below complex geological structures. Full-azimuth reflection angle gathers provide information about full-azimuth residual moveouts, and therefore measure the accuracy of the background velocity model from all angles and azimuths. In particular, the full-azimuth RMO are used as indicators for the existence of azimuthal anisotropy effects due to fractures. Additionally, the true amplitude, full-azimuth reflection angle gathers serve as optimal data for amplitude analysis (AVAZ), and for the extraction...
of high-resolution elastic properties. The high accuracy, together with the greater amount of information available, provides more reliable results, reducing drilling uncertainty and risk.

Full-azimuth angle domain decomposition performed independently for every image point enables control and customization of the locality, direction, and scope of the area being studied, and the corresponding seismic data. The system may therefore be used locally as a target-oriented system for direct, high-resolution reservoir imaging, as well as globally for full-volume imaging of massive amounts of data.

By continuous and accurate representation of the azimuth component of seismic data directly in subsurface target locations, the proposed system goes far beyond seismic imaging to provide a 360-degree, full-angle solution for rich-azimuth seismic acquisitions. In the end, full-azimuth illumination provides a better ROI from rich- and wide-azimuth seismic acquisitions.

REFERENCES

