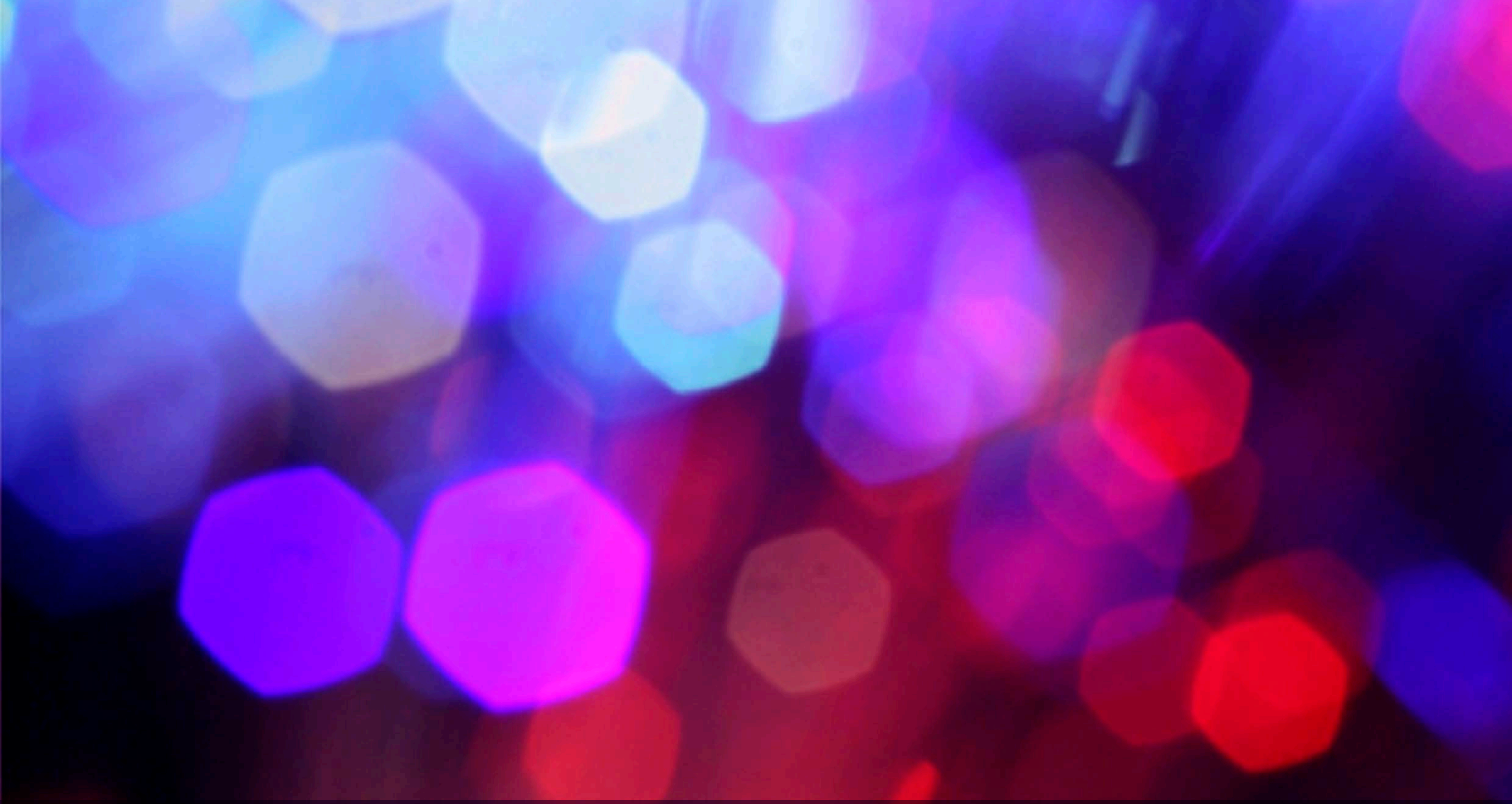

An illuminating exploration...

Duane Dopkin, Paradigm, US, points out how full azimuth decomposition, imaging and illumination enhances deepwater exploration.

Faced with replacing critical oil and gas reserves, energy companies are focusing exploration efforts in areas of challenging operational and technical complexity. To conduct successful seismic programmes in these areas, substantial investments are being made to acquire wide and rich azimuth seismic data. These rich azimuth acquisitions, in turn, are combined with the latest seismic imaging technologies (e.g. Reverse Time Migration) to improve prospecting and return on investment for these costly seismic programmes.

Geophysicists ask a lot from their seismic data. Subsurface structures (e.g. salt, basalt) can be the genesis of multiple wave types (e.g. converted waves, multiples) and complex wave phenomena which distort the seismic image to the point where many iterations of velocity model building and seismic migration are required before selecting defensible prospects and drilling targets. In the deepwater 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 may be overlain or truncated by shale sequences that give rise to additional imaging problems as they often introduce a ‘directional’ velocity dependency referred to as anisotropy. Proper lateral and depth positioning of reflected seismic events below these anisotropic generators require advanced velocity procedures to measure and model these parameters.

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 in deepwater regimes impacted by the geologic conditions described above. Benefits from these rich acquisitions have been acknowledged and documented, and

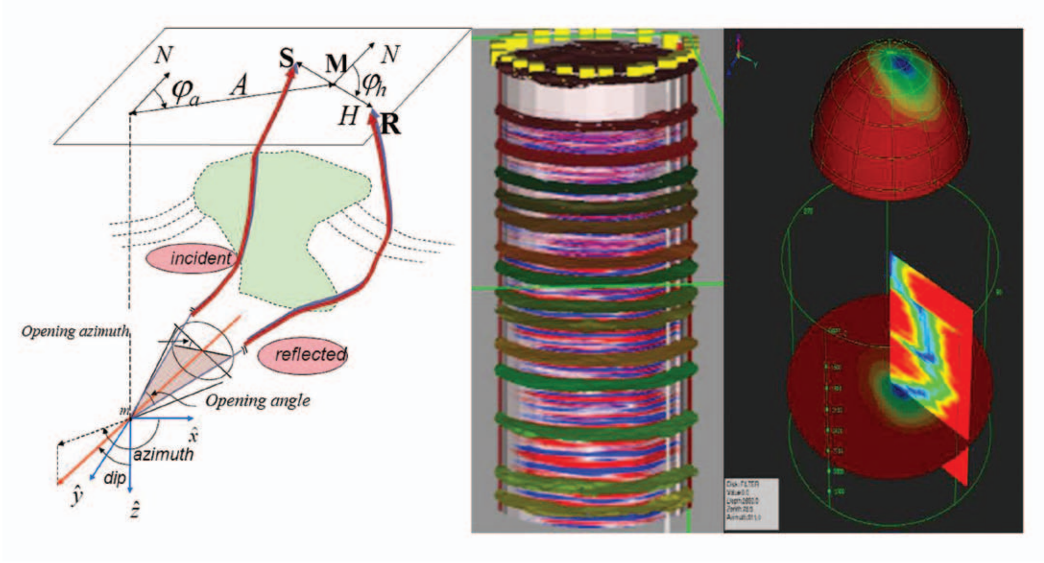

Figure 1. *Decomposition and imaging in the local angle domain. Ray tracing reference (left), full azimuth reflection angle gather (centre) and full azimuth directional angle gather (right).*

include improved multiple suppression, noise suppression and illumination of target areas. However, while the resulting seismic images inherit many of the benefits of rich and wide azimuth acquisitions, the application of current seismic imaging technology can fall short in exploiting the full potential of these acquisitions.

While advances in seismic imaging continue at a rapid pace, most of the solutions are limited in their ability to properly deal with the rich azimuthal sampling of data recorded at the surface. What is needed is a solution that allows us to better qualify and even quantify the expenditures that we make in seismic acquisition and imaging. The solution should assist us not only in understanding the implications of our assumptions and simplifications in dealing with wide and rich azimuthal data, but also help us assess where we can make changes that will have the most impact on our seismic programmes.

To achieve this objective, we need to give proper attention to the issue of mapping rich azimuthal data recorded at the surface to image points in the subsurface. Recognising the full potential of rich and wide azimuth seismic data acquired in deepwater exploration areas requires a significant 'upgrade' to our seismic imaging, characterisation and interpretation technologies. Much like a camera equipped for continuous recording at all angles and directions, this upgrade would provide a comprehensive decomposition of the recorded seismic data into physical domains that recover and preserve subsurface illumination in all orientations and angles in a continuous manner. If successful, we will introduce new seismic data representations that allow us to better understand subsurface illumination, to better qualify seismic images, to reduce the non-uniqueness of the seismic method, and to better describe the critical parameters of the velocity model.

Limitations of azimuthal sectoring

Much like the benefits of capturing images from a continuously revolving and pivoting camera, the benefits of sampling the subsurface with continuous azimuth are well understood. Azimuthal sampling of seismic data allows us to better detect and measure velocity anisotropy, to identify and separate different wave types, to predict lithology from more meaningful seismic signatures, to detect stress orientations and intensity, and to understand the dependency of seismic acquisition on image quality (illumination). However, unlike the camera analogy, capturing seismic data at every subsurface point in all angles and directions (azimuths) is much more problematic. Computational and operational barriers often limit the solution to surface acquisition interpolation schemes followed by course acquisition sampling of surface azimuths (sectoring) rather than the desired decomposition and imaging of seismic data to continuous subsurface azimuthal datasets.

Although intuitively attractive, the surface sectoring approach has severe drawbacks. Sector decisions (size and number) are often taken independently without consideration given to the subsurface. Instead, decisions are often taken out of convenience to accommodate project deadlines and application limitations of dealing with multi azimuthal data. More importantly, sectors formed over a range of surface azimuths lack the resolution and accuracy to properly use the entire recorded wavefield to uncover the information and data listed in the previous paragraph. This is particularly true when long offsets are involved. Finally, while easy to create, sectored datasets are processed independently and subsequently must be analysed and interpreted. Extracting a holistic interpretation from the analysis of these independent datasets is not straightforward.

To resolve these issues, we introduce a new seismic decomposition procedure that replaces images constructed from sectored source to receiver offsets and azimuth with data structures and images constructed from in-situ angle and azimuth data at any or all subsurface image points. The rich information from all angles and azimuths ensures more reliable analysis and significantly reduces reflector position uncertainty. The solution is designed to deliver a complete set of data containing accurate subsurface velocity models, structural attributes, medium properties, and reservoir characteristics.

A new seismic perspective

All seismic imaging methods decompose seismic data into organised domains of subsurface data that provide the pathway for other data analysis procedures including velocity analysis, AVO(A), and other seismic characterisation solutions. These organised data domains (pre-stack gathers) can take many different forms with vertical sampling in time or depth, and spatial sampling in surface offset or subsurface angle. There are other representations of pre-stack gathers depending on the seismic imaging technology being used. However, other than forming gathers with the sectoring approach described above, all of these pre-stack gathers carry no directional (azimuth) integrity and are limited in their capacity to extract subsurface attributes with azimuthal dependency.

Although there are many ways to decompose recorded seismic data, ray-tracing procedures provide a vehicle to simulate the subsurface 'camera'. However, unlike traditional ray tracing procedures that are carried out from the acquisition surface, we need a rich ray tracing engine that can be initiated from any or every image point in the subsurface. This rich ray tracing 'shoots' rays in all angles and all directions so that we can 'capture and preserve' seismic data in an azimuthally continuous manner. It is carried out in a special reference system, referred to as the Local Angle Domain (LAD). By carrying out the ray tracing in this domain, we can decompose seismic data into two independent but complementary sets of full azimuth gathers. The first set of gathers (reflection) contains a continuous (360°) sampling of reflectivity (amplitude) information as a function of reflection (opening) angle. These gathers provide the data structure to detect and measure velocity anisotropy, to predict lithology, to detect stress directions, and to update velocity models. The second set of gathers (directional) contains a continuous azimuthal sampling of the total scattered energy as a function of the dip and azimuth of local reflecting surface. Since the total scattered energy contains both continuous (specular) and discontinuous (diffracted) energy, we are able to easily differentiate and create images that emphasise these two components (Figure 1).

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 characterisation.

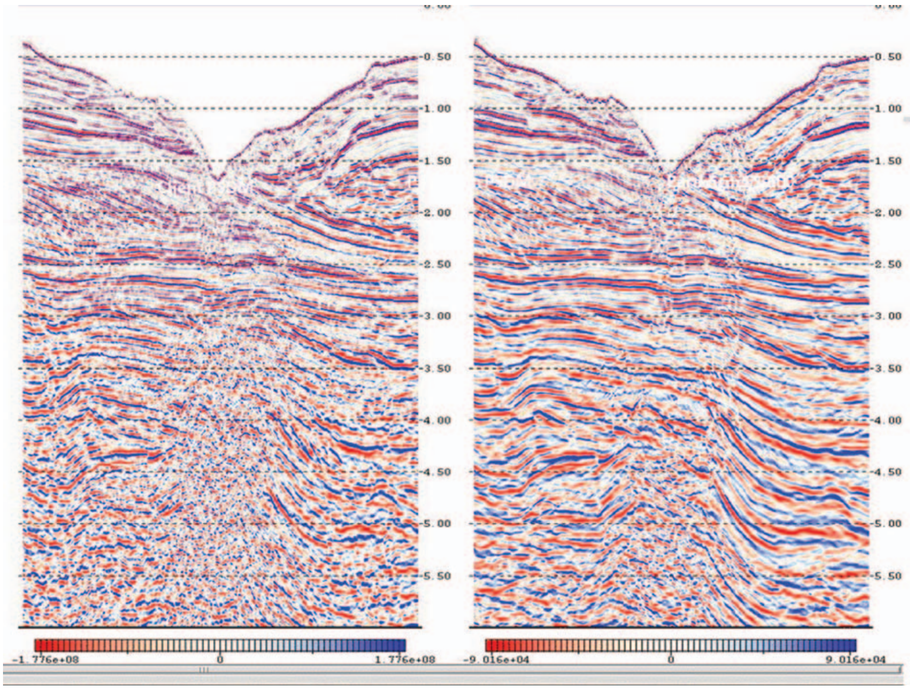

Figure 2. *Comparison of conventional seismic depth image (left) and seismic depth image generated with full azimuth decomposition, imaging and specular weighting.*

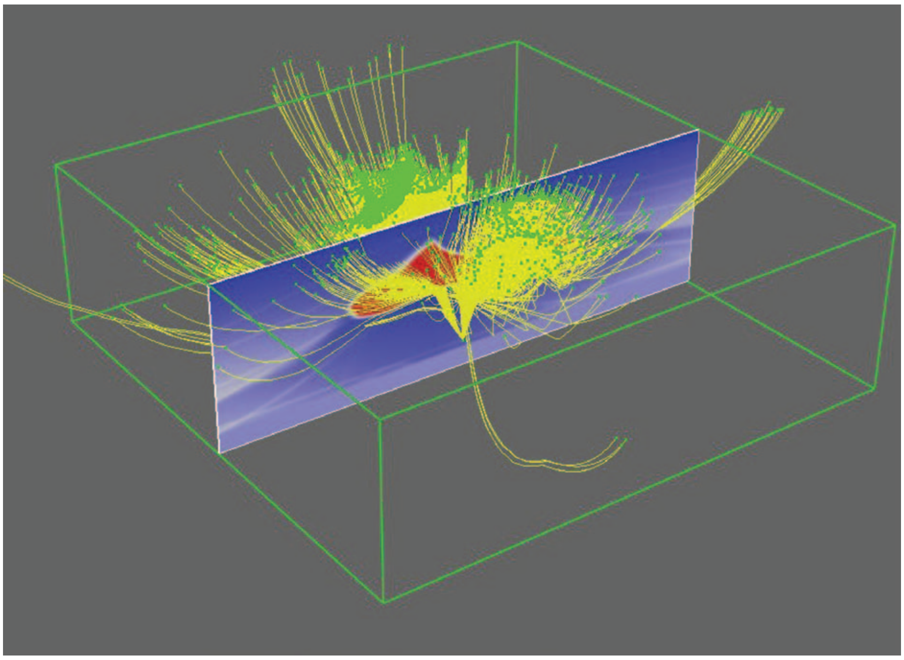

Figure 3. *Point-diffraction ray tracing from a subsalt reflection image point. See text for expanded explanation.*

Enhancing deep reflectors

Full azimuth directional angle gathers represent a seismic decomposition of the total scattered energy wavefield into dip/azimuth angle bins at all subsurface points. These gathers contain information about both specular and diffraction energy. Specular energy is associated with reflectors from continuous interfaces. Diffraction energy is associated with non-specular directivity originating from local heterogeneities such as channels and fractures. The ability to decompose the specular and diffraction energy from the total scattered field allows for the creation of enhanced feature images from the fully recorded wavefield.

In the deep waters of the Gulf of Mexico, for example, the interpretation of subsalt reflectors is often challenging because of wave interference (e.g. multiples, converted waves), attenuation, ambiguities in velocity model definition, and complex wave phenomena. To compensate, we can use the

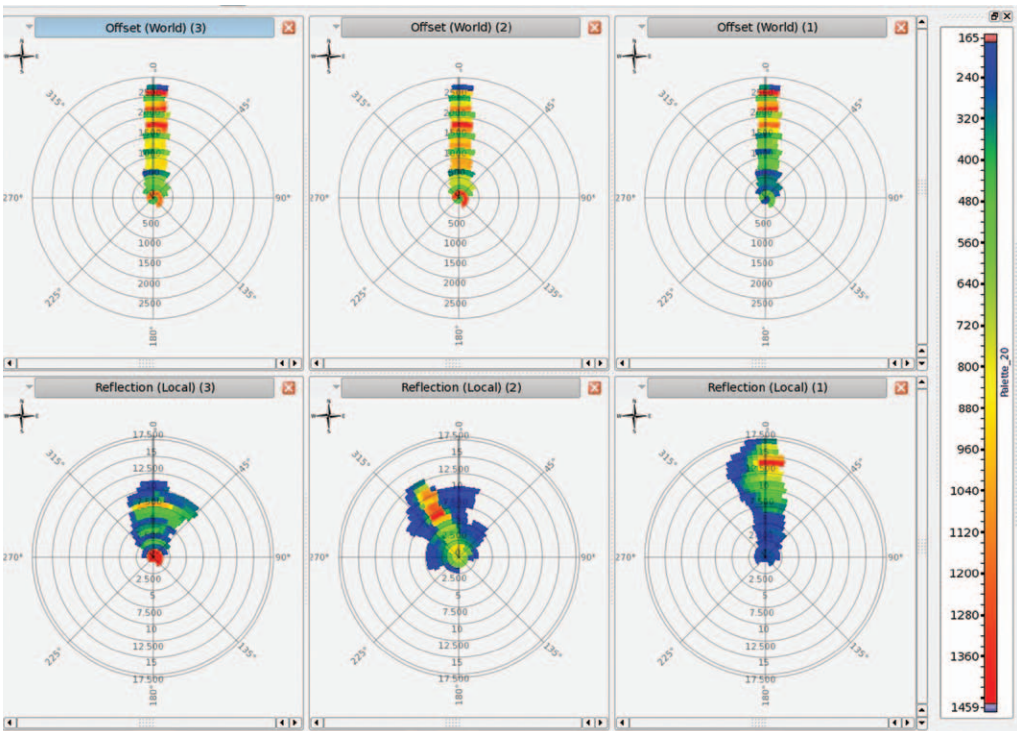

Figure 4. *Rose diagrams of ray-pair illumination intensity captured at acquisition surface (top) and subsurface image points (bottom). See text for expanded explanation.*

energy values computed from the full azimuth directional angle gathers as weighting factors in the creation of the final image. The high 'energy' values associated with the specular directions sharpens the image of the deeper reflectors (Figure 2) at the expense of the scattered or non-specular energy in the data. Additionally, the focusing of the specular energy we observe in the directional gathers serves as an indicator of velocity model error and accuracy. This full azimuth subsurface decomposition of the recorded wavefield into directional gathers provides the means to more precisely unite the fields of seismic imaging and interpretation in areas of complex wave phenomena.

Resolving anisotropic ambiguities

Modelling anisotropic velocity behaviour in deepwater exploration basins is critical for a more accurate lateral and depth positioning of reflected events beneath the anisotropic generating formations as well as for the creation of more interpretable seismic images. Full azimuth reflection angle gathers allow geoscientists to visualise the influence of anisotropy on the moveout of reflection amplitudes sampled continuously over all azimuths. The analysis of anisotropic behaviour can be visualised in three dimensions so that the sources of anisotropy can be better understood and the strength of anisotropy better appreciated. When coupled with the information and data contained in the full azimuth directional angle gathers, geoscientists are better able to differentiate between different types (e.g. VTI and TTI) of anisotropy.

Resolving illumination ambiguities

Subsurface illumination analysis is a widely used technique in deepwater exploration areas to better understand the dependency of the seismic image on the seismic acquisition and velocity model description. When used properly, it can deliver information about imaging reliability, help define optimum imaging parameters, enhance acquisition geometry, and validate prospects selected on the basis of amplitude or amplitude continuity.

Illumination analysis is routinely carried out with ray tracing procedures. Here, the rich 'bottom-up' ray tracing procedure described earlier is used to secure a uniform illumination of the subsurface and establish a mapping of subsurface angle parameters to surface geometry parameters. The result of this ray tracing procedure is a rich set of illumination factors (angle dependent) and physical ray parameters (e.g. geometric spreading, reliability factors) that are essential for quality control of imaging results, especially below complex structures such as salt bodies. Figure 3 shows an example of point-diffraction rays traced from a subsalt reflection point, where only a subset of the rays arrive to the surface within the given aperture (green rays).

The full benefit of this type of illumination can be appreciated by the generation and evaluation of illumination Rose diagrams. Figure 4 (top) shows the ray-pair illumination intensity from three subsurface image points arriving at the surface from different distances and azimuths. The narrow azimuth acquisition geometry is clearly noted. Figure 4 (bottom), on the other hand shows the same ray-pair illumination intensity, this time at the subsurface, as a function of opening angle and azimuth. Note the poor correlation of orientation at crossline 325, reflecting a large translation in azimuth as rays pass from the surface through the salt. This provides a strong visual argument against using surface azimuthal sectoring as a procedure to deal with wide azimuthal data.

Conclusions

Full azimuth decomposition, imaging, and illumination provide deepwater exploration professionals an additional and powerful tool to evaluate subsurface complexities. The full power of the solution is realised in its ability to decompose the recorded seismic wavefield into the physically meaningful domains of reflection angle and reflection dips over a full and continuous range of azimuths. The solution is a well needed complement to a portfolio of existing deepwater seismic imaging technologies that collectively remove imaging uncertainty and improve the non-uniqueness of the seismic experiment.

References

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