Working With A Broader Dimensionality Of Seismic Data

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Seismic interpreters work with images reconstructed from hundreds of gigabytes or tens of terabytes of seismic data recorded at the surface of the earth. That reconstruction is carried out with a supplied velocity model(s), a seismic imaging algorithm (and associated imaging condition), and a decomposition method and procedure usually selected to meet exploration and development objectives. The reconstruction of the seismic image from data recorded at the surface is not unique and is highly dependent on the seismic acquisition, imaging velocities, and imaging algorithms. Fortunately, our ability to decompose the seismic data into highly sampled and organized domains provides us with a pathway to reduce the "non-uniqueness" of the seismic images and to "unlock" the full analysis capacity of surface recorded seismic data.

Today, a new generation of seismic imaging applications is in play to improve imaging quality for new and legacy acquisitions that sample both exploration and development fields. These imaging applications include two-way full wave solutions (e.g., Reverse Time Migration) and ray-based solutions (e.g., beam-steering solutions) designed to solve issues related to complex wave phenomena or to accelerate certain processes (e.g., velocity model building) related to the imaging process.

All seismic imaging applications decompose the recorded seismic data into organized subsets of data originating from a common physical or even non-physical location. These organized subsets of data are referred to as pre-stack gathers and are routinely used to analyze seismic data (e.g., velocity analysis, AVO/A analysis, noise suppression, etc.) prior to their use in forming a final image with stacking procedures. These organized subsets of data are varied and can include common reflection point image gathers, common focus point image gathers, common surface reflection point image gathers, distance image gathers, and others. These gathers can be sampled as a function of acquisition offset, subsurface angle, image distance, ray parameters (in the case of plane waves), and even azimuth.

How this decomposition is carried out is explicitly described by the migration operator and will dictate whether the gathers are suitable for use in velocity model updating procedures (e.g. tomography) and lithology determinations (e.g. AVA inversion) or whether the gathers are simply relegated to use for quality control purposes. The localization and resolution of the imaging operator and the domain used to carry out the decomposition can have a huge impact on the gather "integrity" returned by the imaging process and consequently on the interpretation carried out on the final image.

Geophysicists are well aware of the important role that seismic azimuth plays in the seismic imaging process, its impact on reducing velocity modeling and imaging uncertainty, and its ability to resolve issues related to velocity anisotropy and features like fracture orientation. Yet, most imaging operators are not constructed to recover this directional component from the recorded seismic wavefield. Motivations for its recovery and a method for its "in-situ" recovery are discussed below.

The Issue of Azimuth

In the last decade, the industry has made huge investments acquiring seismic datasets that are both rich and wide in azimuth. These data are needed as geoscientists seek better reservoir delineations and characterizations from seismic data. Benefits from these rich acquisitions have been acknowledged and documented, and include improved multiple suppression, improved noise suppression, and improved illumination of target areas.

While resultant seismic images incorporate many of the benefits of rich and wide azimuthal sampling, application of current technology and approaches are not sufficient to realize the full potential of these acquisitions or even the plethora of legacy and modern onshore acquisitions acquired with rich azimuthal sampling. Here, our underachievement can be attributed to our inability to uncover what we seek from seismic data, namely an "in-situ" recovery of acoustic and geometric images as a function of full (360 degrees) azimuth. It is the "in-situ" azimuth that provides the interpreter with valued information regarding subsurface illumination and stress directions.

Currently, most approaches for exploiting the rich directional sampling of the surface partition the recorded wavefield into a relatively small and manageable number of acquisition-azimuth sectors. These sectors are processed, imaged, and analyzed independently, and consequently place a huge burden on the geoscientists that need to carry

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out these projects, both in effort and time. Additionally, with the sectored approach, we are highly under-sampled in azimuth, ideally replacing 360 degrees of *continuous subsurface* azimuthal samples with a small number of *sectored surface* azimuthal samples. More importantly, since surface acquisition azimuth may have no correlation to subsurface azimuth (Figure 1), the sectoring process may destroy or at least reduce the subsurface directional resolution we are seeking to preserve.

To recognize the full potential of rich and wide azimuth seismic data, imaging, characterization, and interpretation technologies require a significant "upgrade" that provide a more comprehensive treatment of azimuth.

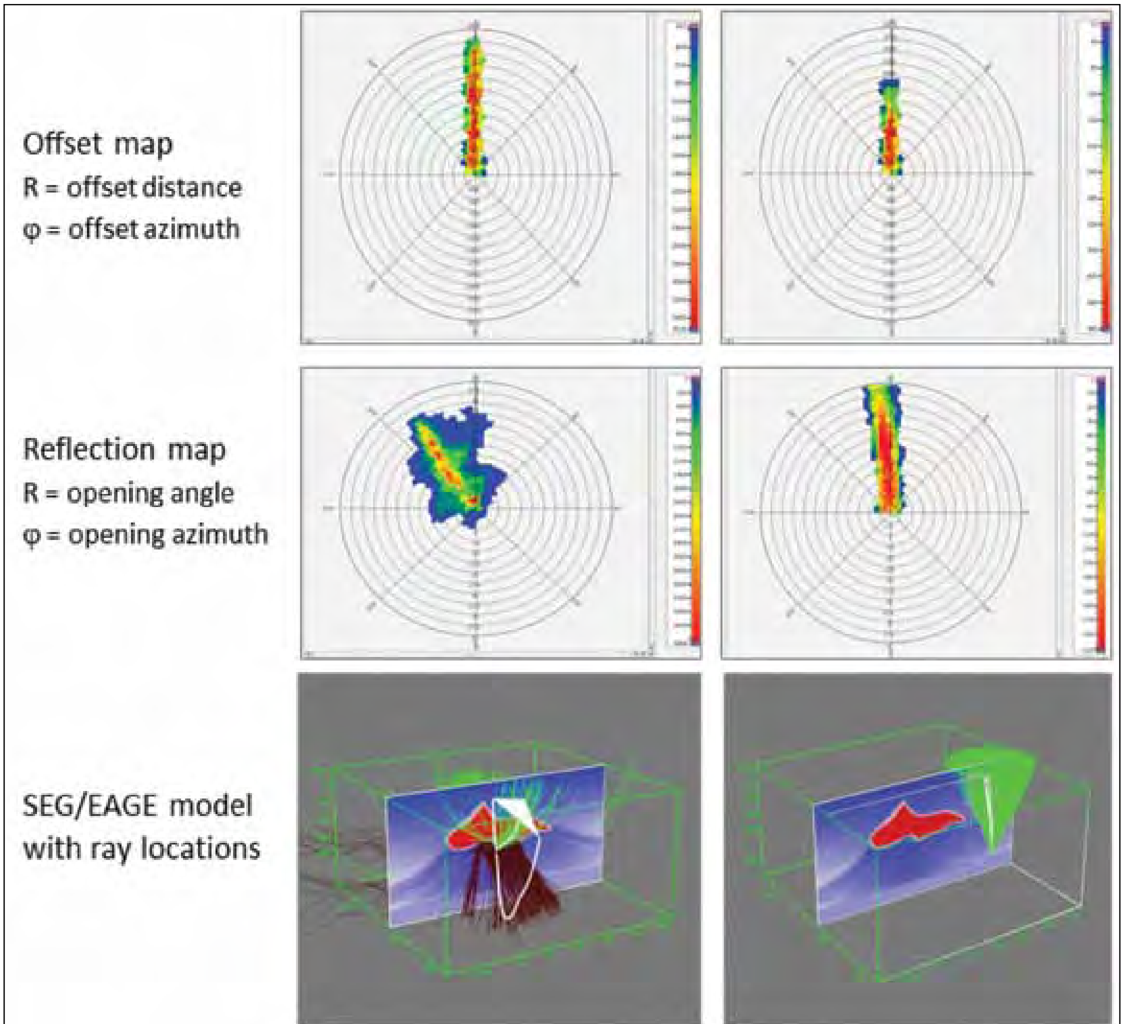

Figure 1: *Surface offset orientation (top) and corresponding subsurface reflector orientation (middle) for a simulation directly below the salt and away from the salt (bottom). This simple simulation illustrates the problem of sectoring as a procedure to deal with rich azimuth data.*

Decomposition of the Seismic Wavefield

What "upgrade" is required? Seismic imaging is inherently an averaging process where benefits from this averaging (e.g., signal to noise improvements) can easily be overtaken by the influence of azimuth on imaging velocity, traveltime, and amplitude. To compensate for these differences, we need to consider a procedure that decomposes the seismic wavefield into continuous full azimuth components as part of a depth imaging procedure, rather than a preconditioning step based on surface acquisition azimuth.

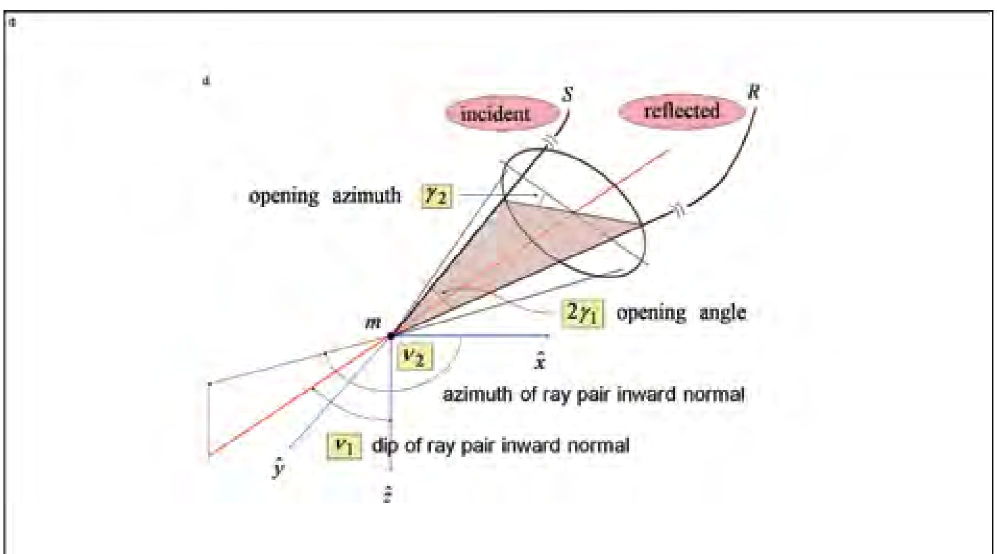

Figure 2: *Seismic mapping and decomposition in the local angle domain. Both full azimuth reflection and direction information are obtained.*

To achieve this decomposition and mapping of the seismic wavefield, a rich ray tracing procedure based on a bottom-up, exploding diffractor model is used. This engine traces rays in all angles and all directions to secure a uniform illumination of the subsurface and to properly map surface recorded data to subsurface image points. The ray tracing is performed in the "Local Angle Domain", a system that describes the interaction of the incident and reflected wavefields (Figure 2) with two independent systems of polar angles for mapping and decomposing the seismic wavefield into novel data structures needed to analyze and quantify some important properties of the subsurface.

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The resultant mapping and decomposition of the full wavefield in the local angle domain produces two types of full azimuth angle domain gathers. Full azimuth reflection angle gathers, described by the opening angle between the incident and reflected rays and the azimuth of the section between them, define a data structure that incorporates amplitude versus opening angle for the continuous azimuth spectrum. Full azimuth direction angle gathers, described by the zenith and orientation of the local reflecting surface, define a data structure that allow us to interact with both the specular and scattered energy from that local reflecting surface over the continuous in-situ azimuth spectrum.

Although full wavefield decomposition is appreciated as a desired outcome of the geophysical community, to date it has remained elusive as a production tool because of the billions of rays needed to reconstruct the wavefield at each image point. However, with this computation realized, the geophysicist has a new tool and new deliverables to study the subsurface.

With this decomposition procedure, we can secure a system that uses the entire wide and rich azimuth data in a continuous manner for generating and extracting high resolution information about subsurface angle dependent reflectivity, with simultaneous emphasis on continuous and discontinuous surfaces.

Full Azimuth Angle Domain Image Gathers – Capturing New Data Dimensionalities and Data Structures

Local angle domain imaging carries many of the desirable properties of both full wave (multi-arrival) and ray based solutions, but additionally provides an ideal domain for the mapping and decomposition of the recorded wavefield to the two full azimuth data structures described above. The decomposition and mapping can be used to generate full-azimuth, angle-domain gathers at desired survey grid points or grid densities.

Figure 3a captures a full azimuth reflection angle gather. It is displayed as a cylinder and with transparency so that the full dimensionality of the amplitude versus opening angle versus azimuth can be appreciated. These full azimuth image gathers can provide a diagnostic quality control for existing velocity models, where moveout errors, velocity model parameterization (anisotropy) errors, or vertical fracturing can be easily evaluated. The moveouts can be measured by three dimensional automatic picking procedures and can be used to drive global tomography solutions accommodating all azimuths. The gathers can also be unwrapped and displayed (Figure 3b) in full angle and full

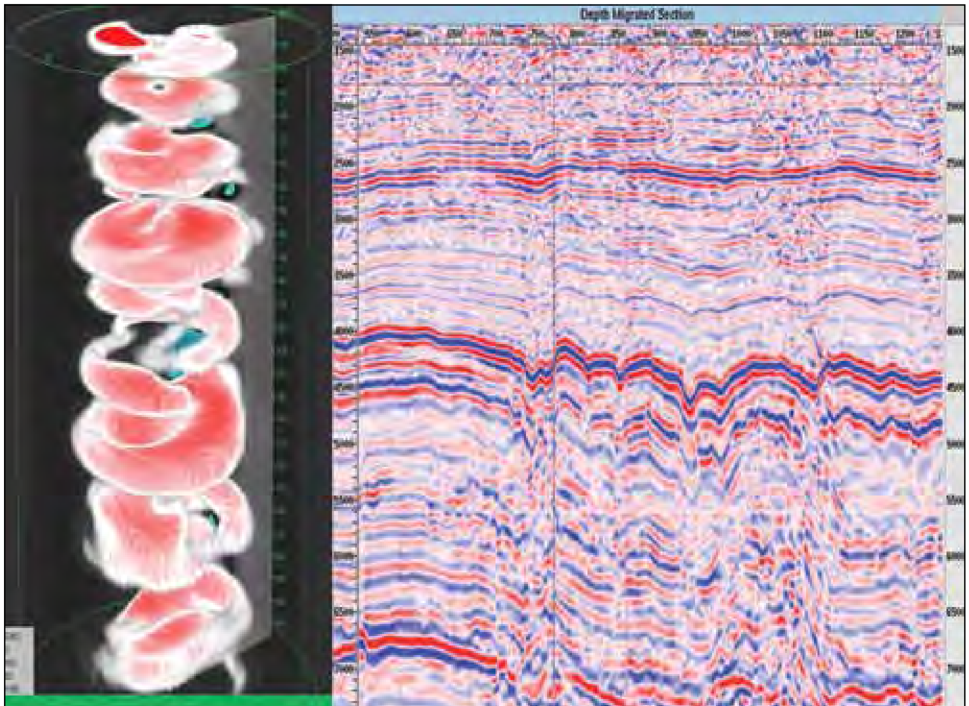

Figure 3a: Full azimuth reflection angle gather from a Barnett shale survey displayed in cylindrical view.

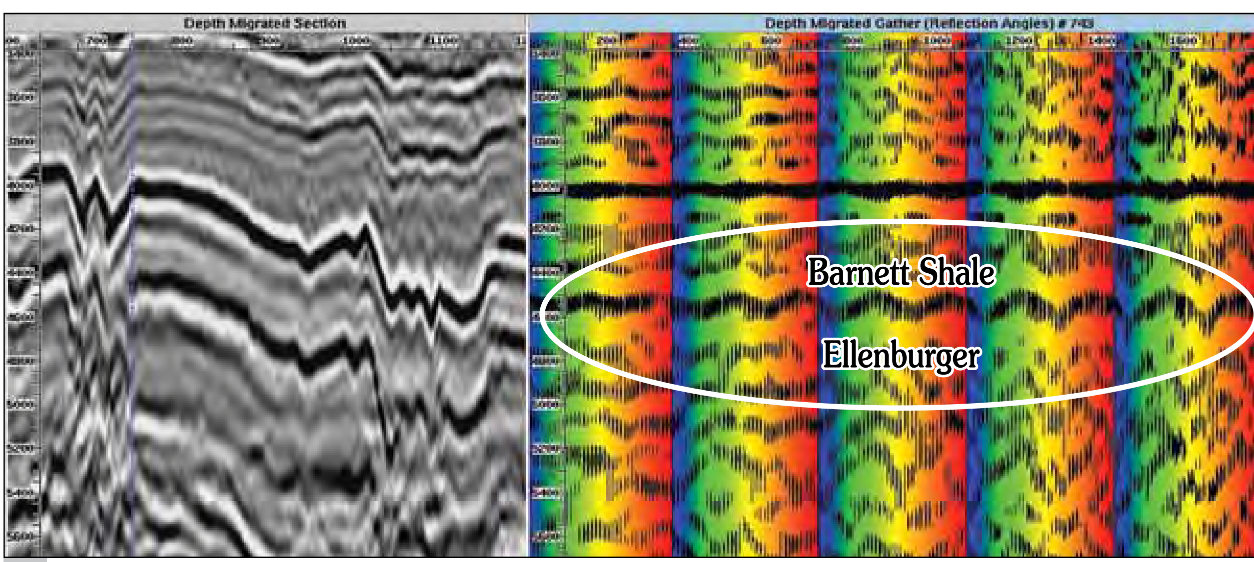

Figure 3b: *Same full azimuthal reflection angle gather from the Barnett shale survey displayed in a two dimensional view (unwrapped)*

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azimuth sections to better understand the influence of azimuth on the velocities and to better understand the behavior of seismic amplitude as a function of opening angle and azimuth. They can also be used as inputs to full azimuth AVA inversion solutions and are ideal for the detection of naturally occurring vertical fractures. Note the important distinction that the extraction of angle and/or azimuthal sectors is a post imaging decision and operation performed on the full azimuth gather rather than an arbitrary pre- imaging selection and operation with all of the problems and limitations associated with acquisition sectoring.

Figure 4 captures a full azimuth direction angle gather. Like the reflection gather, it is displayed in cylindrical form for a better appreciation of the full directionality of the energy associated with the total wavefield reflected/diffracted at each image point. To emphasize the full azimuthal decomposition, a unit sphere is displayed above the cylindrical angle gather that includes both the specular and scattered energy originating from a common image gather depth point. Additionally, an opaque azimuth sector is shown so that the dip energies of the local reflecting surfaces can be analyzed along this direction. The location of the high energy spot on the unit sphere indicates that the image point is located in the vicinity of the actual reflecting surface. The orientation of the local reflecting surface is defined by the dip and azimuth indicated by the maximum energy value.

The system's ability to use directional measurements to separate the specular energy from the total wavefield, allows the geoscientist to extract subsurface information with simultaneous emphasis on continuous surfaces and discontinuous objects. Extraction of the high energy values associated with the specular directions sharpens the image of the structure, while extractions of diffuse (scattered) energy allow the geoscientist to detect discontinuous objects like faults and small-scale fractures.

The full azimuth reflection and direction angle gathers carry information about the subsurface that is normally lost in imaging procedures. They can be used to perform necessary azimuthal corrections prior to stacking or AVA procedures, and they can also be used with the creativity of the asset geoscientists to generate deliverables that reveal signatures not previously seen in subsurface images.

A New Seismic Imaging Perspective and Era

Seismic data contains multi-dimensional information that is often lost in conventional imaging algorithms and procedures by integrating (summing) over the azimuthal component. The information that can be obtained from a rich decomposition of the seismic wavefield is tremendous. It opens up the door to a new approach that is applicable to both regional and target-oriented investigations. For wide and rich azimuth acquisitions, the emphasis in directional measurement is on the in-situ local reflecting surfaces rather than the acquisition surface. The decomposition creates the opportunity to generate new visualization perspectives of the subsurface and new ways for geoscientists to interact with the total seismic wavefield. Finally, the decomposition of seismic data to full azimuth and full angle gathers, suggests a procedure for both qualifying and quantifying previous velocity models and imaging efforts.

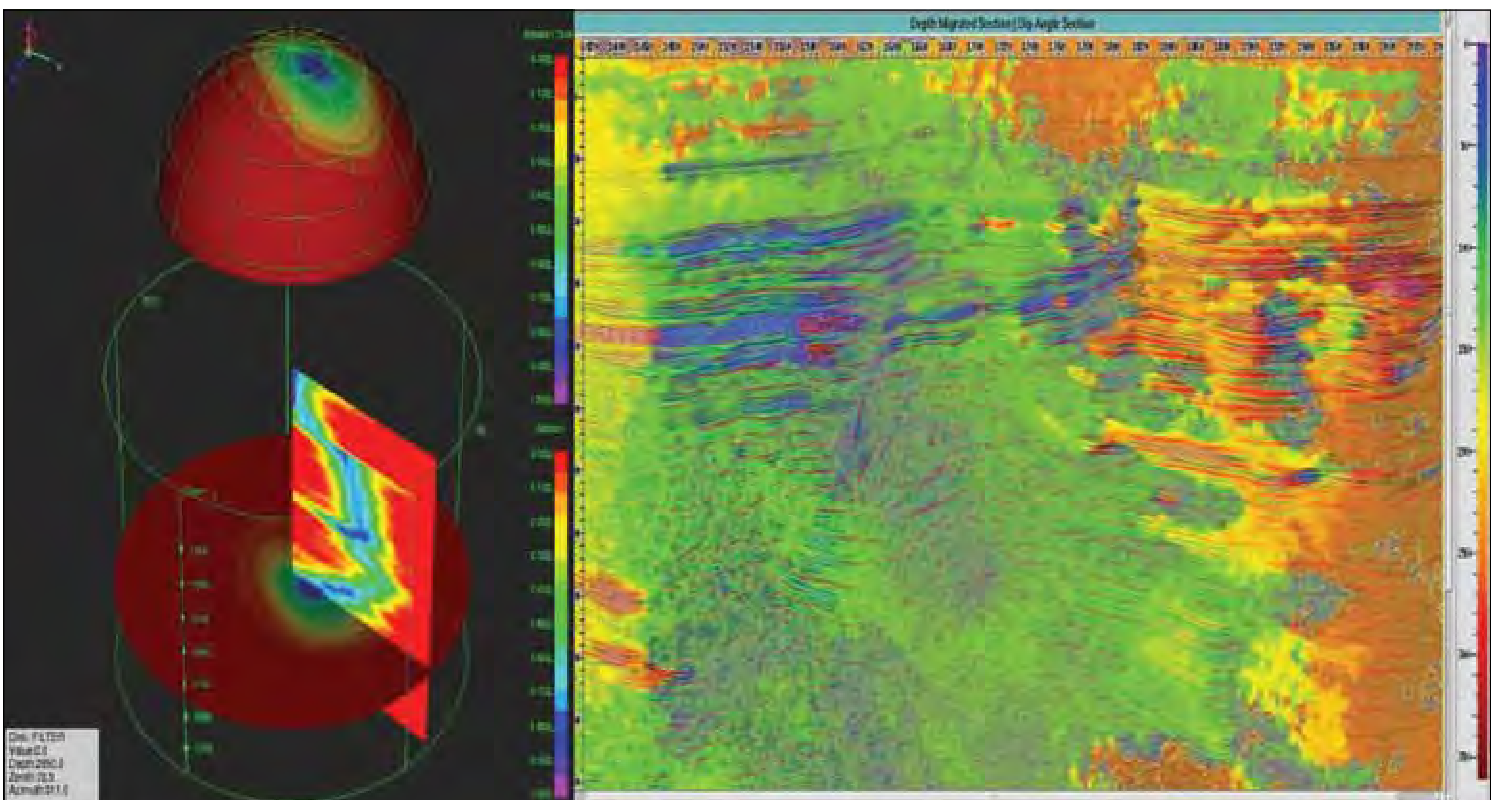

***Figure 4**: Full azimuth directional angle gather with structural attribute extraction.*