

Imaging increases the surface seismic data relevance in unconventional plays

A new imaging system uniformly illuminates the subsurface.

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he unconventional gas shale plays represent sources of huge opportunity for oil and gas companies and the global oil and gas economy. Established gas plays in shale formations in North America (e.g., Barnett, Woodford, Marcellus, and Haynesville) have achieved high visibility as technology plays through successful application of fracture stimulations, microseismic data, geosteered horizontals, and new completion strategies to characterize this distinctive class of unconventional plays. These successes can be carried over to emerging shale plays, creating new opportunities for the oil and gas industry to improve the hydrocarbon recovery factor and mitigate the cost and risk associated with drilling activities.

Surface seismic data can also play a substantive role in gas shale plays. More recently, rich- and wide-azimuth seismic surveys are being acquired to enhance the total value of these shale assets through improved imaging quality, resolution, and new deliverables including representations of fracture or stress orientation and intensity. While it is clear that the industry has made tremendous strides in sampling the surface with these rich seismic acquisitions, the same claim cannot be made with regard to the sampling of the subsurface. Indeed, to accommodate the rich azimuths in legacy and modern onshore and offshore acquisitions, the industry has come to rely on acquisition sectoring



Figure 1. This image shows a full-azimuth reflection gather. The third figure (far right) shows an anisotropic reflection surface with residual moveout behavior attributed to HTI anisotropy. (Images courtesy of Paradigm)

of the recorded seismic data and the subsequent independent processing and imaging of these sectors (usually eight). Unfortunately, the subsurface directional data, resolution, and image integrity that needs to be preserved is compromised and biased by the limitations of the sectoring approach. As a consequence, the return on investment for these rich seismic acquisitions is compromised.

To overcome these limitations and to increase the relevance of surface seismic data in improving estimated ultimate recovery in gas shale fields, a fundamentally different imaging approach is required to provide geoscientists and



Figure 2. An unwrapped full-azimuth reflection angle gather shows the moveout behavior of the highlighted event immediately below the gas shale formation.



Figure 3. In this constant angle full-azimuth gather, each gather is an input to the residual moveout inversion for HTI parameters.

engineers with new data and perspectives that can impact their exploration and production programs. To this end, a new technology, full-azimuth decomposition and imaging, designed to sample the subsurface in every direction in a continuous manner, is proposed for application to gas shale reservoirs to secure a better understanding of subsurface stress directions and intensity. The result: new data images that provide a novel way for interpreters to interact with seismic data and to characterize the shale plays with more confidence and with more information.

Anisotropy, subsurface directional resolution

Subsurface deformations can induce stresses or fractures with orientations and directions that are potentially detected by the seismic method. These properties may be directly correlated to sweet spots and provide useful information for reservoir engineers in the frac design process and for drilling engineers in the directional drilling process.

Stress and vertical fracture orienta-

tion are sources of azimuthal anisotropy of the HTI type (transverse isotropy with horizontal axis of symmetry) and can be recovered by seismic velocity and amplitude versus angle (AVA) inversion methods. In HTI media, the fast velocity is associated with the direction of maximum stress (parallel with the open fracture orientation), and the slow velocity is along the minimum stress direction (perpendicular to the open fracture orientation).

Sectoring of surface source-receiver azimuthal data is a popular way of recovering these directional properties. Unfortunately, there are a number of conditions imposed by the sectoring process that limit its ability to uncover these properties successfully. They include:

• *Sector integrity:* Sectoring or acquisition segmenting is based on sourcereceiver azimuth rather than *in situ* orientations of local reflecting surfaces. The two may not correlate, particularly when the overburden is complex. Geoscientists should make measurements (and consequently, construct deliverables) derived from *in situ* subsurface properties that map properly to surface parameters.

- *Sector resolution:* Both directional and spatial resolution (sampling) are compromised with the sectoring method. Directional sampling is frequently limited to eight sectors, and spatial resolution can be lost in pursuit of the necessary fold (azimuth and offset) to create sectored gathers with measurable qualities.
- *Project effort:* Sectored project turnaround time is needlessly increased by the number of independent datasets created by the sectoring process.

Full-azimuth decomposition, imaging

To rectify all of these limitations, a new imaging system has been developed based on decomposition of seismic data in the local angle domain (Koren et. al. 2008), a reference framework that implements Snell's law in three dimensions with a rich ray-tracing procedure that uniformly illuminates the subsurface from all possible directions and all possible reflection angles. Unlike conventional ray-based imaging methods, the ray tracing is performed from the image point up to the surface, forming a system for mapping the recorded surface seismic data to each image point. The result is a reflection angle gather based in depth, fully sampled in all directions (azimuths). These "3-D cylindrical" gathers provide a new seismic data structure that, when viewed with visualization systems, shows the influence of fast and slow velocity directions on reflected events due to vertical fractures or differential stress (Figure 1).

Figure 2 shows the same gather in a two-dimensional display format, where azimuths and reflection angles are unwrapped. Note the periodic moveout behavior of the reflected event beneath the Barnett Shale, a classic signature of anisotropic stress. Because the amplitudes and residual velocities (moveout) are continuously sampled over all directions (azimuths), new seismic inversion schemes can be implemented to determine of stress orientation and intensity. This full-azimuth sampling provides the highest directional resolution while preserving and even potentially increasing the spatial and temporal resolution of inversion results.

Stress orientation, intensity

Figure 3 highlights the same reflected event with a constant opening angle and 180° of azimuthal data. This data allows a new method to be described (Ravve, et. al. 2009) to compute effective anisotropic parameters (e.g., major and minor velocity, azimuth of the axis of symmetry) of the HTI type from residual moveouts sampled as a function of reflection angle and azimuth. These parameters can be extracted as a regular grid along interpreted horizons and used to construct stress orientation and intensity maps (Figure 4).

The full azimuth gathers also can define a new AVA inversion procedure (Canning, et. al., 2009) that incorporates continuous amplitude measurements sampled over all azimuths. Like the residual moveout inversion described above, this inversion procedure generates reservoir properties (e.g., anisotropic gradient, fracture orientation, fracture density) that can be visualized as volumes or maps.

Because both of these inversion procedures are carried out on full-azimuth angle domain image gathers, the results are more stable than conventional methods. Furthermore, the directional resolution of the measurements made on the gas shale formation has been increased substantially, and two independent schemes have been created (one based on residual moveout, the other based on amplitude) to make stress orientation and intensity determinations.

Making seismic data relevant

By performing an *in situ* full-azimuth decomposition of the seismic wavefield, it is possible to observe seismic signatures and extract diagnostic properties that are unbiased and uncompromised by the acquisition sectoring process and procedures. It is believed that this new imaging system will make seismic data more relevant in gas shale plays by increasing the hydrocarbon recovery factor, lowering finding and development costs, and directly impacting stimulation programs.



Figure 4. On the left is stress orientation and intensity from full-azimuth residual moveout inversion. The image on the right shows stress orientation and intensity versus angle inversion.

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