Making Seismic Data More Relevant in Shale Resource Plays with Full-azimuth Imaging and Characterization

A Paradigm Geoscience Data Service

Unconventional plays have proven to be sources of huge opportunity for oil and gas companies and the global oil and gas economy. Shale formations in North America (e.g. Eagle Ford, Bakken, Barnett, Woodford, Montney and Haynesville) have achieved high visibility as technology plays through the successful application of multiple fracture stimulations, borehole micro-imaging, micro-seismic data, geosteered horizontals, 3D sonic scanning, and new completion strategies. These successes are being carried over to emerging shale plays, creating new opportunities for the industry to improve recovery and mitigate the cost and risk associated with drilling activities.

While the technology advances to date in these plays have largely been focused around the wellbore, with measureable improvements in well completion processes, fracking and directional drilling, seismic data can also play a significant role in characterizing these reservoirs as part of the field development process.

Shale plays are generally heterogeneous in property (elastic, geomechanical) distribution and stress. Determining stress or fracture intensity and orientation from the seismic method is a desirable outcome for drilling engineers, but a challenging one for geophysicists, particularly at significant depths and in the presence of complex overburdens.

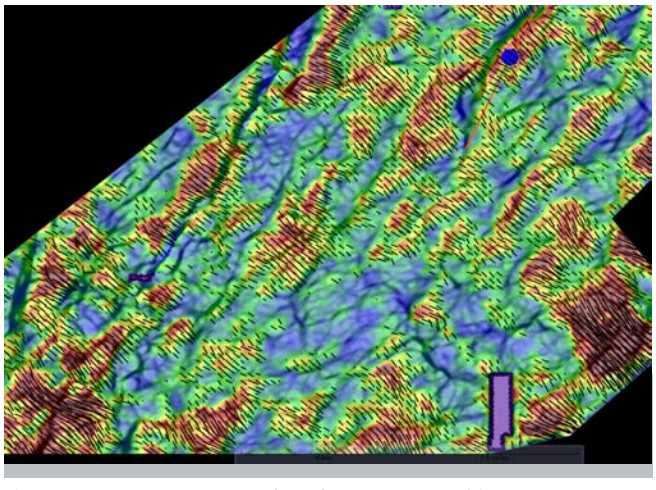
To make seismic data more relevant in shale plays, Paradigm has developed and refined a patented, full-azimuth decomposition and depth imaging procedure, EarthStudy 360®, to characterize stress and natural fractures. The system recovers in-situ full azimuth and angle domain reflectivity at seismic image depth points for subsequent fracture/stress (anisotropic) analysis.

> This is a radical departure from conventional procedures that use surface regularization and sectoring procedures that under-sample the data. With this new approach, stress or fracture anisotropy of 1% can be detected in a systematic manner and provide a powerful supplement to the conventional poststack attributes used to characterize and grade the reservoir.
> *North American Operator*

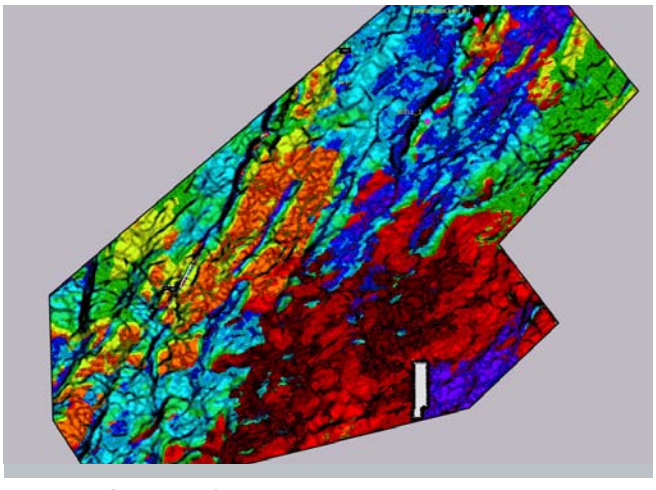
In addition to stress and fracture determination, this depth imaging procedure can differentiate between imaging of **continuous** (specular) and **discontinuous** (diffraction) energy. The diffraction images capture small faults often masked in conventional imaging by the stacking process. These faults can have a substantial impact on production in unconventional reservoirs.

Full-Azimuth Imaging and Characterization Services for the Eagle Ford Shale

- **Velocity Model Building Services**
  - » Background anisotropic (VTI) velocity model building using full-azimuth data
  - » Shale lithozone anisotropy (HTI or orthorhombic) velocity model building
  - » Precision depthing with well marker mistie tomography
  - » Integration of geophysical (velocity) model and geologic model (optional)



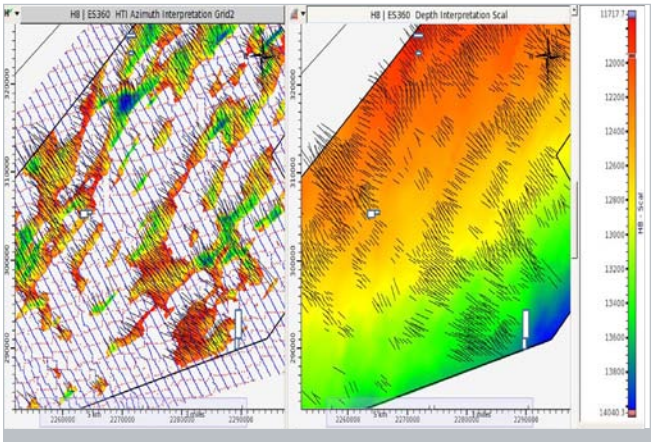
▲ Fracture and stress vectors from full-azimuth AVA(Z) inversion superimposed on curvature seismic attribute. *Data courtesy of Seitel.*



▲ Seismic facies classification based on trace shape with seismic curvature. *Data courtesy of Seitel.*

Paradigm®

- **Seismic Imaging Services**
  - » Full-azimuth imaging in the local angle domain with and without specular imaging to emphasize continuous reflectors
  - » Full-azimuth diffraction imaging in the local angle domain to recover fractures that are irretrievably lost with traditional seismic imaging procedures
- **Seismic Fracture Characterization Services**
  - » Full-azimuth velocity (VVAZ) and full-azimuth amplitude (AVAZ) inversion
  - » HTI or orthorhombic fracture determination (effective or interval parameters)
- **Shale Reservoir Property Characterization**
  - » Full gather inversions for P-wave impedance, S-wave impedance, density, Lambda-Rho, Mu-Rho, Poisson's Ratio, Vp/Vs
  - » Ductile and brittleness calculations
  - » TOC from seismic data
- **Shale Interpretation Services**
  - » Fault framework determination, from diffraction imaging to fault likelihood to fault framework
  - » Analysis of shale properties – vector maps, rose diagrams, correlation with FMI data
  - » Sweet spot identification through co-visualization of deliverables with geobody detections
    - ◦ Seismic images – specular, diffraction
    - ◦ Fracture attributes – fracture intensity and density
    - ◦ Shale properties – TOC, brittleness, ductile
  - » 3D visualization and analysis of full-azimuth gathers
- **Additional Services**
  - » Real time geosteering through petrophysical or geomechanical property model



▲ Fracture/stress maps from full-azimuth RMO inversion (left: acquisition surface geometry, right: depth map). *Data courtesy of Seitel.*

  - » Microseismic data analysis, including fracture stimulation path modeling
  - » Assembly and analysis of stimulation data, model data (DFN), and property data
  - » Recommended well plans based on minimum stress directions

Paradigm Unconventionals Service Advantages

- The industry's only true in-situ full-azimuth imaging system that reconstructs prestack seismic data that emulates the sampling of a formation (like a dipole sonic)
- Avoids the approximations and detrimental averaging of azimuthal sectoring approaches
- A rich set of interpretation deliverables suitable for geophysicists, geologists, and drilling engineers
- Two independent methods for fracture/stress determination for validation, confirmation, or preferential selection
- All operations are carried out in depth, with well markers included in the velocity model building process
- Preferential imaging (specular and diffraction) for emphasizing specific shale lithozone features

Seismic Deliverables from EarthStudy 360

Shale projects can vary significantly in terms of acquisition, data quality, lithozone resolution, and objectives. EarthStudy 360 can produce the following full set of deliverables (in practice, the deliverables are limited to project objectives and operator requirements):

Full-Azimuth Inversion		Image Generation	
HIT or Orhorhombic/ Effective or Interval			
Full-azimuth AVAZ Inversion	Full-azimuth RMO Inversion	Image Creation	Prestack Data
Maps and/or volumes	Maps and/or volumes		
Axis of symmetry (minimum Hrz. stress)	Axis of symmetry (minimum Hrz. stress)	Angle stacks	Full-azimuth reflection angle gathers
Normal incidence	Major velocity	Azimuth stacks	Full-azimuth directional angle gathers
Isotropic gradient	Minor velocity	Beam forming stacks	Illumination angle gathers
Anisotropic gradient	Anisotropic strength	Specular stacks	
Fracture density		Diffraction stacks	
Anisotropic intensity reliability			