Detecting Fractures with 3D3C Seismic to Reduce Risk and Optimize Production

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Abstract

The Xinchang field in western Sichuan Basin, China produces gas from fractures in tight sandstone reservoirs. An integrated field study was performed using full wave (full-azimuth multi-component) seismic data. The porosities in these reservoirs (2-4%) had little influence on production. The key to locating the best well locations included lithology discrimination and identification of the fractured areas.

The impedances of the sands and shales are very similar and can not be discriminated by the P wave data. However, the PS data in this full wave data has been very effective in identifying lithology. Shear wave splitting analysis has also indicated orientation and density of fracturing consistent with regional stress data, well results, core analysis, FMI and outcrop work. The integration of the results from the geologic, seismic and reservoir engineering data has led to selection of 16 new well locations and some early drilling success.

Introduction

Discovered in 2000, the XinChang gas field is one of the larger fields in the Western Sichuan Basin, an area that collectively produces 260 MMCF/d. XinChang currently produces 39 MMCF/d from four wells that are currently on-stream; a total of eight wells have been drilled in the field. Gas production comes from multiple pay zones within the Upper Triassic tight sandstones at depths of approximately 16,000 feet. Due to variations in the reservoir's naturally occurring fractures, productivity of individual wells varies significantly, even within the same geologic horizon.

Design

The geophysical challenges of the Sichuan basin and the objectives of management helped to frame the goals of the full-wave imaging project:

- ✓ Obtain high resolution images for the deeper reservoir targets
- ✓ Optimize images despite challenging near-surface conditions ranging from grassy plains to urban centers, and clastic slope deposits to carbonate outcrops
- ✓ Increase the signal-to-noise ratio and bandwidth of the entire dataset
- ✓ Eliminate background noise, especially from man-made sources in the survey area
- ✓ Characterize key properties in the reservoir intervals, including the distributions of lithology, sand thickness, porosity, gas saturation, and especially fractures
- ✓ Obtain higher quality data than legacy seismic datasets

In 2003, SWPB geoscientists assessed various geophysical alternatives that could deliver on these objectives. Using wave equation models, SWPB evaluated different survey parameters – including shot density, spread geometry, offset, and in-line and cross-line sensor separation (sampling density) – to deliver the requisite trace density and fold at a reasonable cost.

During the evaluation, SWPB geophysicists noted high levels of converted wave energy on the shot records of legacy datasets. In partnership with ION, SWPB modeled improvements that full-wave (multi-component) imaging techniques might provide and determined that recording converted wave energy could improve the bandwidth of the entire seismic dataset. Given an expectation that converted wave data could also add insights into lithology and fracture detection, SWPB geophysicists made the recommendation to acquire the survey using densely spaced, full-wave sensors.

By specifying 3C MEMS sensors, SWPB hoped to obtain broadband data with a significant low frequency component that would improve resolution and advanced geophysical analyses, including seismic inversion. By applying vector filtering to the 3C data, SWPB sought to attenuate ambient and near-surface noise as well as use the non-vertical shear components to enhance the bandwidth of the new P-wave data. They also believed the combination of P-wave and S-wave data would allow them to assess shear-wave splitting to ascertain fracture intensity and compare variations in lithology and fluid content within the reservoir intervals.

The topography of the field poses two survey design challenges. Most of the area is relatively flat with a surface layer that has been tilled for hundreds of years, which introduces challenges with attenuation of both frequencies and signal. The depth of the targeted acquisition objectives varies from 6,000 to 20,000 feet, with the primary zone of interest located at 16,000 feet. Illumination of the complex subsurface and the requirement to collect data in the deeper Triassic reservoirs required broadband, wide-azimuth, densely sampled data.

Imaging complex subsurface fractures wasn't the only challenge in Sichuan. Significant surface obstructions, both natural and man-made, cut across the landscape. The area is densely populated and several highways and railways as well as a network of pipelines and rivers exist throughout the survey area. As a result, careful consideration of the flexibility of the seismic acquisition system needed to be regarded to ensure the health, safety, and environmental (HSE) requirements of both seismic field workers and nearby residents.

In October 2004, SWPB commissioned BGP to commence acquisition using 6,000 VectorSeis® full-wave (3C) stations (18,000 channels) connected to an I/O System Four® acquisition platform. The field acquisition crew consisted of 1,466 people and 133 vehicles. The survey size, amount of data acquired, and magnitude of the operation make XinChang the largest full-wave program ever undertaken. BGP's attention to acquisition details – including quality control and HSE – set a best-practice standard that earned accolades from the E&P operator and that enabled them to deliver the highest quality data for processing.

Since the XinChang project acquired data using full-wave (3C) sensors, it was possible to apply several advanced processing techniques to extract maximum value from the data. Unlike a conventional geophone which records energy along a vertical axis, a 3C sensor contains three components: one vertical and two orthogonally paired horizontals. The two horizontal components record 'converted' wave (C-wave) energy, i.e., acoustic energy that has converted from a pressure wave (P-wave) on the downward-traveling wavefield to shear wave (S-wave) energy on the upcoming wavefield.

Data Processing

SWPB's goals of the converted wave processing stage were to:

- Obtain a high-resolution structural image that had compatible detail and frequency content when stretched to P-wave time
- Extract geophysical information such as shear impedance and Vp/Vs ratios that would be useful in characterizing reservoir lithology
- Map fracture patterns within and around the reservoir interval by assessing shear-wave splitting along the predominantly fast and slow velocity directions

The XinChang data were acquired with one of the horizontal accelerometers aligned with the receiver cable; consequently, the second horizontal accelerometer was aligned orthogonal to the cable direction. Horizontal rotation was performed to align one of the horizontal components with the source-receiver azimuth (Radial component) and the other orthogonal to the source receiver azimuth (Transverse component).

Azimuthal properties were preserved though the migration process. This allowed for more accurate shear wave splitting analysis and corrections. Under normal isotropic circumstances, rotating multicomponent data from in-line and cross-line to Radial and Transverse will isolate all of the usable energy onto the Radial component. After this, the Transverse can usually be discarded. As highlighted earlier, XinChang is affected by significant azimuthally varying anisotropy. After the initial rotation, a considerable amount of energy remains on the Transverse. For azimuthally anisotropic data and where shear-splitting is prevalent as in this case, a further series of rotations is required later in the processing workflow.

To deal with this effect, a method referred to as '2C Forward & Reverse Rotation' was applied to the data. This effectively removes the anisotropy – layer by layer – concentrating all of the energy onto the Radial component, thereby simulating an isotropic dataset. For each layer, this process yields detailed information with respect to fracture orientation (based on analysis of the fast/slow direction) and fracture magnitude (based on the fast/slow static).

Interpretation

Upon completion of the data processing, the Reservoir Solutions group integrated available well data, outcrop, and core analyses with the newly acquired seismic data to: better define the region's geologic and tectonic history; build structural and stratigraphic models for the area; map fracture patterns and intensity; and determine the best locations for future drilling.

The Sichuan Basin encountered some of the world's most dramatic subsidence rates during the Mesozoic, so burial of the reservoir to depths of 20,000 feet or more occurred relatively soon after deposition and before gas was generated in the surrounding and underlying source rocks. The resulting compaction reduced reservoir porosities to less than 4% and rendered the reservoir rocks almost totally impermeable. As a result, production is totally fracture-dependent in XinChang. The fracture network not only made gas charge possible under conditions of extreme overpressure, but also affords a major part of the gas storage capacity and the only mechanism by which gas stored in the matrix porosity can be accessed during production. The storage capacity of individual pools in the reservoir is dependent on interconnected fractures in fault zones, and the connections that damage zones around faults make with the naturally fractured sandstone reservoir beds. The most attractive exploitation targets are thin-bedded, brittle clastic rock types interconnected by faults across the entire reservoir interval.

The densely sampled, full-azimuth P-wave data provided higher frequencies than the legacy seismic data, providing an improved structural picture with excellent fault resolution. However, due to similar acoustic impedance from both the sands and shales, the lithology could not be determined from the P-wave alone.

As a result, converted (S-wave) data was needed to complete the reservoir characterization. Fortunately, the converted wave data was exceptional at discriminating lithology and delivered vital insights into risk reduction and drill-well target optimization during exploitation. The C-wave data also provided a means to target interbedded, sand-shale sequences and areas of optimal fracture intensity. Insights from similarity processing, curvature attributes, and shear-splitting analysis provided three independent fracture intensity measures which were integrated into discrete fracture network (DFN) models and fracture maps.

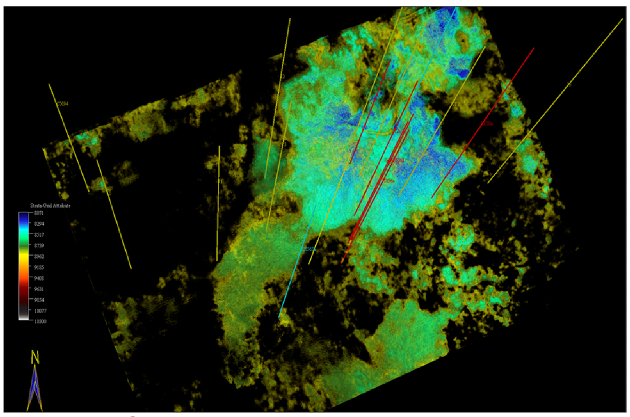

Figure 1. Shear impedance used to identify location of the source rock in the XinChang survey area.

As mentioned earlier, fractures play the most important role for storage of the gas and consequently, location of the best fractured zones is the most important item in the risk reduction portfolio. The C-wave data provided a means to target interbedded, sand-shale sequences and areas of optimal fracture intensity (Figure 2). Insights from similarity processing, curvature attributes, and shear-splitting analysis provided three independent fracture intensity measurements which were integrated into discrete fracture network (DFN) models and fracture maps. Fracture orientation was determined from the shear wave splitting analysis of the fast direction and is much more accurately determined from the polarity reversal of the data. Fracture density was determined from the $\mathbf{V}_{fast} - \mathbf{V}_{slow}$ analysis. Shear wave splitting analysis and the lithologic and source rock interpretation from the converted wave data were critical to the well location selections. The integration of interpretations from all disciplines – seismic, core, well log, outcrop analysis, well production data – enabled a full risking of the drill-well prospects being considered and a re-prioritization of the list.

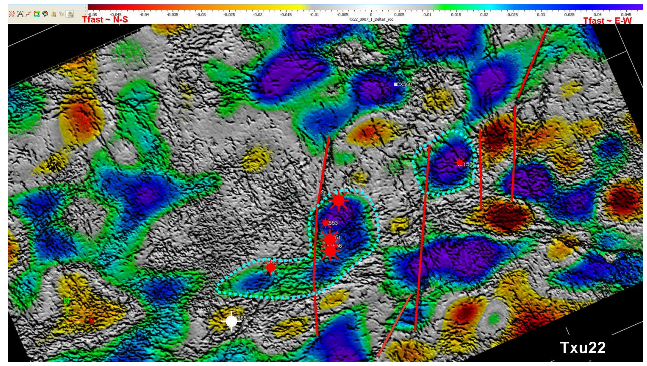

Figure 2. This slide shows a combination of attributes including similarity, fracture orientation and density from shear splitting and small faulting. The size of the well symbols shows the relative production from these wells.

Results

The use of full-wave data integrated with geological and production information enabled describing the lateral extent of the reservoirs, predicting the effective fracture distribution, and identifying and quantifying natural gas reserves in the Xinchang gas field. Beginning in 2006, the results from these efforts were used to select new exploratory well locations. By the end of 2008, eighteen wells had been designed and five out of the six completed new wells had production rates of up to 18.4 MMCF per day. Overall, the drilling success rate in the Xinchang area has been increased from 35% to greater than 80%. Encouraged by the effectiveness of the Xinchang 3D3C seismic exploration project, a new 3D3C project was designed in the Hexingchang-Gaomiaozi area east of Xinchang. The new 500 km^2 seismic survey was completed in early 2009. That data is currently being processed. The new acquisition parameters were designed to further improve azimuthal coverage and increase the fold to 128. Additional exploration benefits from this new full-wave project are expected.

Conclusions

The reservoirs of the Upper Triassic Xujiahe Formation of the western Sichuan Basin have some of the lowest porosities and permeabilities in the world. Due to the depth of the reservoir, low porosity and permeability, very high velocities, and highly over-pressured reservoirs, conventional seismic exploration technologies for petroleum reservoirs are not sufficient to image the fractures zones necessary for production, therefore resulting in high exploration drilling risk. Full-wave seismic data significantly reduced risk and improved the success in exploring the deep fractured tight gas reservoirs of Xinchang. Through in-depth research and continuous improvement, 3D3C technology will play a more important role in tight reservoir prediction, gas-bearing recognition, fluid property determination, and fracture detection.

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