Optimizing Well Productivity via Full-wave Seismic Imaging

A Success Case from the XinChang Unconventional Gas Field

Sichuan Province, China

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Executive Summary

Fractured reservoirs are becoming increasingly important sources of hydrocarbon production around the world. The drive to increase energy production is especially acute in China, given the country’s role as the ‘manufacturer for the world’ and its booming middle class. As the second largest energy company in China, Sinopec plays a key role in addressing the country’s energy supply challenges. Forty percent of Sinopec’s gas production is sourced from the Sichuan Province, where much of the production comes from low permeability, fractured reservoirs.

One of the larger fields in the Sichuan basin is XinChang, an asset targeted for a multi-year exploitation and step-out drilling program by the managers at Sinopec. Although seismic data existed for the field, it was believed to not be of the quality needed to image the deeper reservoir intervals nor to target fracture ‘sweet spots’ that correlated with the highest producing wells.

In 2003, geophysicists from Sinopec’s local operating company - Southwest Petroleum Branch (SWPB) - began to consider alternatives for improving seismic data quality at XinChang. Over the course of the next several years, SWPB undertook the largest full-wave imaging program on record with impressive results – both success rates and well productivity have shown dramatic improvements.

The Investment Mandate

China currently produces nearly 5 BCF of natural gas per day. Although supply and demand are roughly in balance today, as China continues to industrialize, demand for natural gas is expected to grow at more than 10% annually. As a result, China’s demand is expected to more than double to nearly 11 BCF/d by 2010. A number of measures are being taken to ensure that China’s demand needs can be met. Chinese-affiliated national oil companies are involved in several LNG-related deals throughout Asia and the Middle East and various pipeline projects are in the planning stages to import gas from Russia and Central Asia. However, pressure is also being brought to bear on the two main domestic producers – CNPC and Sinopec – to increase in-country production. Gas production is heavily emphasized, in part, because of increasing environmental pressures that are compelling China to reduce pollutants associated with its use of coal; the Chinese government has set a target to nearly doubling gas usage within the country’s energy mix to 5.3% in 2010 from approximately 3% today.

Sinopec supplies 15% of China’s natural gas, producing more than 700 MMCF/d. The company has had several exploration successes of late, reinforcing its position as China’s second largest gas producer. Sinopec recently announced that it would be committing nearly $5 billion
to develop the Puguang field in eastern Sichuan Province. With announced reserves of more than 12 TCF, Puguang is expected to double Sinopec’s reserves and production in the province, a region that already accounts for 40% of the company’s total production.

**Exploration & Production Context**

Discovered in 2000, the XinChang gas field lies in a foreland basin in the Sichuan Province of central China. XinChang lies below a topographically flat area roughly 50 km east of a north-south trending mountain range. The Western Sichuan Basin contains 2,000-6,000 meters of sediments that were deposited over the course of several geologic cycles. Source rock is mudstone of Upper Triassic age. Although the basin remained a depocenter throughout the Triassic, Jurassic, and Cretaceous periods, sea level regression caused the sediment facies to shift from a carbonate platform to continental clastics. The western portion of the Sichuan Province was later subject to significant tectonic deformation associated with the Himalayan uplift.

XinChang gas production comes from multiple pay zones that range in thickness from several meters to several tens of meters, and depths of 700 to 5,000 meters. The deeper, proximal gas reservoirs produce from the Upper Triassic while the shallower, distal gas reservoirs are of Jurassic-Cretaceous age. Porosity ranges from 2-5% in the deeper Triassic reservoirs. Permeability ranges from 0.07-0.2 millidarcies within the pay zones, classifying the reservoirs as tight and unconventional. The productivity of individual wells varies significantly, even within the same geologic horizon, due to variations in the intensity of naturally occurring fractures in the reservoir.

XinChang is one of the larger fields in the Western Sichuan Basin, an area that collectively produces 260 MMCF/d or roughly 5% of China’s total domestic production. The XinChang field itself currently produces 39 MMCF/d from four wells that are currently on-stream; a total of eight wells have been drilled in the field.

Legacy seismic datasets exist for the field and have historically been considered to be adequate. However, management at Sinopec’s local operating company (Southwest Petroleum Branch - SWPB) wanted to obtain higher quality data to optimize an exploitation and step-out drilling program for the deep Triassic reservoirs as part of its five-year plan. 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 that range from grassy plains to urban centers, and clastic slope deposits to carbonate outcrops to pebbled river beds
• 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

Early Full-wave Assessments
In 2003, SWPB geoscientists began to assess various geophysical alternatives that could deliver on these objectives. Using wave equation models, SWPB assessed different survey parameters – including spread geometry, offset, in-line and cross-line sensor separation (sampling density), and shot density – that would be needed 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 (Figure 6). In partnership with ION survey planners, SWPB modeled the improvements that full-wave (multi-component) imaging techniques might provide. SWPB geophysicists 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 shoot their next survey using densely spaced, full-wave sensors.
By specifying 3C VectorSeis® sensors, SWPB hoped to obtain broadband data with a significant low frequency component that would improve resolution and advanced geophysical analyses, including seismic inversion. In addition, by applying techniques such as 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 that would be acquired. 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 to compare variations in lithology and fluid content within the reservoir intervals.

In 2004, SWPB committed to what was then the largest full-wave land acquisition project on record.

**Designing a Densely-Sampled, Full-wave Survey**

The topography of the XinChang field poses two distinctly different survey design challenges. Most of the area is characterized by a relatively flat surface topography with a surface layer that has been tilled for hundreds of years, which introduces challenges with attenuation of both frequencies and signal. In the eastern edge of the survey area, some outcrops are exposed due to regional tectonic influences.

The depth of the targeted acquisition objectives varies from 2,000 to 6,000 meters, with the particular zone of interest located at 5,000 meters. Illumination of the complex subsurface and the requirement to collect data in the deeper Triassic reservoirs required broadband, wide-azimuth, densely sampled data. The XinChang survey was designed with these requirements in mind.

The conventional bin size formula created an estimate for surface sampling density:

\[
\text{bin} = \text{vel} / 4f \sin(dip)
\]

In consideration of geophysical objectives and economic constraints, the decision was made by SWPB to set the bin interval at 25 meters. This allowed unaliased P-wave data to 80 Hz to be recorded despite assumed bedding dips as great as 36 degrees. However, since a 25 meter bin implies a 50 meter group interval, and long offsets as great as 8000 meters were needed, a wide-azimuth shooting template of 24 lines x 264 stations was selected.

The survey was designed with a ‘swath-type’ geometry. At the center, the source was set in an in-line direction; on the edges, the sources were placed in a cross-line direction. When rolled in the cross-line direction, the 12 line x 264 station template formed a virtual template of 24 x 264 stations, yielding a surface pattern categorized as a ‘brick-type’ layout. Figure 8 shows the fundamental shooting template that was used. When rolled, the template forms a virtual patch of 24 lines x 264 stations.
Figures 9 and 10 illustrate the final design and resulting fold as the survey was shot in the field.

Since the primary target for the converted wave imaging was relatively deep, no special offset requirements were generated. In general, issues such as sampling and aperture were all constrained by the P-wave requirements at XinChang.

Imaging the 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.

Figure 9. Final survey design. Source points (dynamite) in blue; receivers in red. Total surface expression of 705 km²; receiver area of 527 km².

Figure 10. Final survey fold. Average of 32 fold in the 340 km² reservoir study area. 66 fold in the full-azimuth, fully migrated area at the heart of the survey.

Figure 11. Acquisition challenges surrounding XinChang.
Data Acquisition

In October 2004, SWPB commissioned the seismic contractor BGP to commence acquisition at XinChang. BGP deployed 6,000 VectorSeis full-wave (3C) stations (18,000 channels) connected to an I/O System Four® acquisition platform set for 1 ms sampling and 7 second records.

A 10 kg dynamite source was used with an average burial depth of 14 meters. 10,408 shots were taken into 35,341 receiver points. The field acquisition crew consisted of 1,466 people and 133 vehicles. The survey size, amount of data acquired, and magnitude of the acquisition operation make XinChang the largest full-wave program ever undertaken.

During the course of acquisition, BGP was able to make use of several features of VectorSeis and System Four to overcome the acquisition challenges in the XinChang area:

VectorSeis enabled the acquisition crew to:
- Deploy a single-point sensor versus an array of six or more geophones, to enhance the productivity of the crew during deployment and retrieval (which occurred nightly for the entire spread, as mandated by local regulatory authorities) and minimize environmental impact (due to less ‘footprint’ and cabling vs. a geophone array) in agriculturally intensive areas
- Ignore the tilt of the receiver plant, to enhance productivity generally and to enable deployment without burial within the paved urban zones inside the survey area
- Achieve superior coupling across diverse surface conditions, ranging from sand to clay to pebbles to river bottom

System Four enabled the acquisition crew to:
- Handle the high data requirements from 18,000 separate channels recording at 1 ms sampling
- Use the intuitive Windows-based interface to rapidly spot line-faults
- Manage spread troubleshooting, repair, and maintenance operations in a streamlined manner, despite the large number of personnel assigned to the crew

BGP acquired the data over the 527 km² survey area in 132 days. The company’s attention to acquisition details - including quality control and HSE - set a best-practice standard that earned them accolades from the E&P operator and that enabled them to deliver the highest quality data to the data processors.
Data Processing

Since the XinChang project acquired data using full-wave (3C) VectorSeis sensors, it was possible to apply several advanced processing techniques to extract maximum value from the data. Unlike a conventional geophone which records energy only along a vertical axis, VectorSeis 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.

Noise Removal and P-wave Processing

In the case of XinChang, the P-wave data was processed in a fairly conventional manner. The area suffers from significant ambient and man-made noise, as well as ground roll. The noise was removed through proprietary adaptive subtraction techniques that are not the focus of this paper. After the application of a standard, amplitude-preserving PreSTM method, high-resolution images like that shown in Figure 14 were developed. In addition to the images themselves, the P-wave processing helped to determine the appropriate Vp/Vs ratios that were subsequently used in several attribute volumes for interpretation purposes.

C-Wave Processing Objectives

As laid out by SWPB, the 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

Figure 14. Typical P-wave data from full-wave survey.

Courtesy: SWPB and GX Technology
Processing the C-Waves: Horizontal Rotation

At XinChang, the data were acquired in the field with one of the horizontal accelerometers aligned with the receiver cable; 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). Rotation from H1/H2 to Radial/Transverse is an appropriate and necessary step for an isotropic, flat-layered sub-surface. After rotation, all of the reflected energy should be concentrated onto the Radial component, while the Transverse component should consist only of random noise only. For azimuthally anisotropic data (Figure 15) and where shear-splitting is prevalent as is the case at XinChang (Figure 16), a further series of rotations is required later in the processing workflow.

Figure 15. Radial C-wave azimuth sector gathers. Difference in $V_{\text{fast}}$ and $V_{\text{slow}}$ is evidence of azimuthal anisotropy.

Figure 16. Transverse C-wave azimuth sector gathers (before corrections). Unstacked (left) polarity flips indicate shear splitting. Stack of gathers (right).
The processing workflow for both the P-wave and S-wave data, and how it fed into subsequent reservoir analyses, is shown in Figure 17.

Processing the C-Waves: Azimuthal Static Corrections & Polarity Reversals

High resolution C-wave migration volumes were created by combining the Radial and Transverse volumes using the following methods:

**Transverse component:**
1. Polarity reversal semblance analysis was performed on the Transverse volume
2. Based on (1), polarities were flipped so all azimuth sectors became "in phase"
3. Transverse data was stacked and a pilot trace volume created
4. The pilot volume was cross-correlated with this individual azimuth stack to derive residual transverse AZ statics (1000-6000 ms window)
5. Statics from (4) were applied to produce a final Transverse volume.

**For the Radial component:**
1. Individual radial azimuth stacks were cross-correlated with the final Transverse stack volume from above (using a 1000-6000 ms window) to derive the regional azimuth statics
2. Regional azimuth statics from (i) were applied
3. Data from (ii) were stacked to form a new pilot
4. Data from (iii) were cross-correlated with the pilot form (500 ms window) to derive a time-variable, residual-azimuth static
5. Statics from (iv) were applied to produce a final Radial volume.
**Shear wave splitting**

Under normal isotropic circumstances, rotating multi-component 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.

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 (Figure 18).

For any one layer, the following steps were applied:

i. Perform polarity reversal semblance scans to determine fast and slow azimuths
ii. Rotate the Radial & Transverse from azimuth sector orientation to fast & slow directions
iii. Apply statics to align slow direction with fast direction
iv. Rotate data from (iii) back to Radial & Transverse directions
v. Strip off corrected Radial layer, then repeat steps (i)-(v) for the next layer.

For each layer, this process yields detailed information with respect to both fracture orientation (based on analysis of the fast/slow direction) and fracture magnitude (based on the fast/slow static).

![Figure 18. Transverse C-wave azimuth sector gathers (after corrections). Compare to Figure 16.](image-url)
Integrated Reservoir Interpretation

Upon completion of the data processing portion of the project, the Reservoir Solutions group from GXT was engaged by SWPB to integrate all 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.

As an initial step, structural experts from GXT visited the field to measure in-situ fracture orientations within outcrops of the Triassic reservoir formations. GXT geoscientists used this data, existing core data, and borehole breakout data to validate the orientation of the anisotropy determined from shear-splitting in the converted wave seismic data. In addition, well log data was analyzed to determine which seismic attributes provided the best lithologic discriminations and reservoir characterization indicators (e.g., porosity).

The very dry gas in XinChang is produced from fracture-dominated, Triassic fluvial-deltaic sands that were deposited along the western edge of Sichuan Basin. The structural framework of the field was established by relatively gentle deformation of the Longmenshan thrust belt in early Jurassic time and the reactivation of basement faults during several subsequent tectonic episodes. Today, the Sichuan Basin is strongly influenced by the uplift of the Tibetan Plateau, with a very strong east-west maximum horizontal stress, potentially opening preferential, east-west-trending fracture systems.

The Sichuan Basin was characterized by some of the world’s most dramatic subsidence rates during the Mesozoic, so that burial of the reservoir to depths of 6,000 meters 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% on average and rendered the reservoir rocks almost totally impermeable. As a result, production is consequently 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; this gave 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 wave alone (Figure 20).
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, consequently, delivered vital insights into risk reduction and drill-well target optimization during exploitation and also provided a means to target the interbedded, sand-shale sequences and the 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 21. The full-wave advantage in lithology determination. Shear impedance directly derived from C-wave data. The brightly colored blue-green areas correspond to organic-rich Triassic shales that overlie the reservoir interval and that correlate with the most productive wells.

Figure 22. The full-wave advantage in lithology determination. Shear impedance co-rendered with similarity (K_max curvature). Fractured, interbedded sandstones (green) juxtaposed against the organic-rich shales (purple) are the most productive reservoirs in this horizon.
Structural features, stratigraphic plays, and fracture trends that were interpreted from the densely sampled, full-wave seismic data were used to determine locations for new prospects in the survey area. 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 23. The full-wave advantage in fracture determination. Shear impedance with co-rendered similarity indicates fracture intensity and helps optimize well placement.

Figure 24. The full-wave advantage in fluid determination. Full-wave helps characterize gas saturation distribution. Courtesy: SWPB
Early Results from the Drilling Program
Based on the preliminary results from the full-wave acquisition program, Sinopec's SWPB affiliate already had enough insight to begin modifying its drilling program. Since the completion of acquisition in 2005, two additional wells have been drilled at XinChang, both completed as producers.

In addition, as processing and reservoir analysis efforts have progressed, SWPB geoscientists have had even more insights into the primary drivers of well productivity, including sand thickness, reservoir gas saturation, and fracture intensity within the immediate vicinity of the wellbore. As their insights have improved, so too has well placement. The most recent well completed at XinChang is now the most productive well in the entire Sichuan Province. This single well nearly doubled production from XinChang and was heralded by the Chinese media, who proclaimed that “world-class seismic technology has given new life to this area.” Two additional wells are currently being drilled and an additional twelve well locations have been identified from the integrated, full-wave imaging and reservoir analysis project.

Epilogue
Based on the success of this project, executives from SWPB, Sinopec, and ION have signed long-term cooperation agreements involving full-wave seismic imaging. The scope includes:

- Identifying fields within China that would benefit from full-wave imaging techniques
- Moving additional full-wave equipment to the region
- Naming ION's GX Technology group the preferred provider of full-wave imaging and reservoir analysis services.

Discussions are also underway regarding international cooperation in order to help advance Sinopec’s goal of securing advantaged access to hydrocarbon resources based on its differentiated application of next-generation seismic imaging technology.

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