High-density 3D point receiver seismic acquisition and processing – a case study from the Sichuan Basin, China

Fusen Xiao¹, Jinli Yang¹, Bo Liang², Meng Zhang², Rong Li³*, Fang Li³, Hongping Xiao³, Xue Lei³, Qinglin Liu³ and Thomas Heesom⁴ present the planning, acquisition, processing and results from a full-azimuth high-density point-source, point-receiver broadband seismic survey over part of the Gongshanmiao structure in the Sichuan Basin, southwest China.

The benefits for subsurface imaging quality provided by full-azimuth high-density symmetrically sampled seismic data acquisition and processing are well documented (Vermeer, 2002). However, execution of such designs on a production scale has only recently been made economic and practical through the advent of new technologies including efficient, high-channel count recording systems and lower-cost compute power. This article presents a case study of a recent land seismic acquisition and processing project that illustrates one application and some of the benefits of these new technologies.

In early 2013 PetroChina Southwest Oil and Gasfield Company (SWOGC) successfully acquired a dense, symmetrically sampled dataset utilizing 45,000 digital point receivers and shallow-hole small-charge explosive sources. Advanced techniques were applied to effectively remove noise while preserving the seismic signal. The long-offset full-azimuth attributes of the dataset enabled identification and quantification of azimuthal anisotropy and the subsequent development of a suitable anisotropic velocity model for imaging. Compared to vintage datasets, the new survey delivered improved signal-to-noise ratio, better vertical and spatial resolution, and more precise imaging. It has helped to identify the spatial distribution of multiple fracture systems in a limestone reservoir unit and the development characteristics of reservoir sand channels, allowing better prediction of their thickness and spatial extent. This case study illustrates several of the improvements in imaging quality and interpretational reliability enabled by modern acquisition and processing technologies that are increasing the value of seismic data in supporting better well placement decisions and more effective field development and production management.

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Background
The Gongshanmiao structure in the central Sichuan Basin has a long history of hydrocarbon exploitation. The main oilfield in the Sichuan Province has been producing for more than 30 years. The producing horizons are Jurassic in age with a maximum depth of around 3500 m. They are considered to have significant potential to secure continued production from the field. SWOGC has three primary targets for imaging: the SXM formation is a tight sandstone reservoir in the Middle Jurassic; the LGS formation is a sand-shale inter-bed sequence in the Middle Jurassic; and the DAZ formation is a thin limestone inter-bedded reservoir in the Lower Jurassic. The prospect area is covered with small hills and lush vegetation, with forest in the mountainous areas and working rice fields in the lower regions. Surface topography comprises elevation variations of approximately 150 m, generally higher in the north east and lower in the southwest. The Xi River, 30 to 40 m wide, crosses the survey area in a northwest-southeast direction.

No new seismic data had been acquired in the area for ten years, although there are two legacy 3D seismic datasets, acquired in 1999 and 2003. Imaging quality potential from these datasets is limited by their sparse spatial sampling, short offsets, narrow-azimuth geometries and low fold. Imaging of the target layers suffers from blurred definition of fault planes, and structural details cannot be fully described and uniquely interpreted. Prestack inversion failed due to the low fold, short offsets and 20 m bin size of the vintage data, which lowers vertical and horizontal resolution and made it impossible to precisely describe the Jurassic target layers. Despite repeated processing and interpretation projects using the legacy narrow-azimuth seismic data, it was found that the boundaries and spatial distribution of the channel sands and the fractures in the carbonate layers could not
be interpreted accurately. SWOGC concluded that the legacy data was inadequate for locating wells in its future field development plans. To gain more insight into the characteristics of the reservoir formations and speed up its field development plans, the company initiated a new full-azimuth high-density point-source, point-receiver broadband seismic survey covering an area of approximately 180 km² located to the west of the main Gongshanniao structure.

Survey design
A detailed survey design study was undertaken focusing on improving imaging quality and reliability at the target horizons. The study included analysis of existing data and consideration of surface conditions and geological features in the prospect area. The survey was designed to obtain full azimuthal coverage of the key tight-sand target with as wide a broadband signature as possible. The full azimuth design allows capture of anisotropic information to enable geomechanical characterization of the reservoir in support of future well location planning.

A dense point-source point-receiver design was selected, as fine point measurements increase spatial and temporal resolution (Egan, 2010) and enable higher signal fidelity than traditional array-based acquisition, which can limit wavelet bandwidth (Papworth, 2009). Dense point-receiver spacing delivers data in which many types of coherent noise are record-ed unaliased, and can be effectively removed in subsequent data processing while preserving signal integrity. Fine point-source spacing also benefits noise attenuation; the resulting high fold in the receiver domain is particularly advantageous for removing time-variant cultural noise. To sample the wavefield symmetrically for azimuthal processing, source line spacing was made equal to the receiver line spacing, with line spacing determined from analysis of existing data in the area.

The original source plan under consideration called for a sparse grid of relatively deep (>20 m) dynamite holes with large (>3 kg) charge sizes, as had traditionally been used in the area of operation. However, this plan of sparse, deep holes did not meet the desired bandwidth, productivity or sampling requirements of the survey. Local testing confirmed that smaller charges in shallower shot holes would lead to a broadening of the source bandwidth by boosting the high frequencies. A network of dense, shallow holes and smaller charge sizes would also allow for realization of the symmetrical sampling goal, which would increase trace density and would also be faster to drill, speeding up the programme while keeping costs down. The concern, however, was that shallow holes would lead to excessive surface-wave noise and would thus compromise data quality. To alleviate this concern, it was successfully demonstrated that by deploying finely-spaced point-receivers to record the noise unaliased, and utilizing advanced noise-attenuation processing routines on the resulting finely sampled data, the noise could be handled more than adequately. Ultimately, it was decided to use charges 0.5 to 1.5 kg in 6 m holes at 10 m point-shot spacing.

To ensure the capture of all high-frequency energy, a temporal sample rate of 1 ms was employed.

Figure 1 shows the square-patch acquisition template for the new survey in comparison with the 1999 design and Table 1 details the acquisition parameters for the new and two previous surveys. The final symmetrically sampled design featured 200 m source and receiver line spacing, 10 m source and receiver point interval, and up to 3600 m inline and crossline offsets. The resulting 25,920 live channel acquisition patch over 36 receiver lines led to the high trace density of 12,960,000 traces per km², which represented a new record for seismic acquisition in China. Combined with the full-azimuth sampling and increased offsets, this was expected to significantly improve the imaging quality and reliability compared to previous surveys.

Data acquisition
A total of 45,000 broadband geophone accelerometer point-receivers were deployed for data acquisition. The use of point-receivers enabled the very high trace counts required by the survey design while maintaining project cost and equipment logistical effort to a manageable level. This was achieved through the deployment of a fit-for-purpose point-receiver acquisition system – the first time this technology has been deployed in China. The cable-based system utilized point sensors integrated within the receiver line cable to minimize line-cable logistics. The use of point receivers eliminates the need to manage large quantities of geophone cable as is associated with the deployment of conventional geophone arrays, and the system’s low power consumption meant that up to 140 channels could be run off a single line box, keeping battery management to a minimum. Figure 2 shows some of the equipment used for the survey.

Acquisition commenced at the start of January 2013 and, with a desire to complete field operations before the Chinese New Year on 10 February, achieving fast implementation and sustained productivity was critical to success. A total of 54,000 shots were acquired over the period, with an average daily production of 2015 shotpoints, and peak production of 3372 shots in one day (Figure 3). This represented a new productivity record for explosive seismic acquisition in China and most likely globally. The acquisition system was capable of shooting in ‘super-spread’ mode, in which all deployed sensors are live and recording data. This enabled great flexibility for the shooting teams to operate over a wide area, contributing to the record-breaking productivity that was achieved. In addition, the system utilized built-in redundancy features including automatic data rerouting along fibre-optic cables that ensured the recording spread stayed active despite significant third-party interference.

A total of 1.26 billion traces were recorded. With the 1 m/s sample interval, the total field dataset was 20 TB in size, which was more than 144 times that of the 1999 data volume. Figure 4 shows a raw shot record comparison between the
Figure 1 Acquisition template and offset-azimuth-fold coverage plots for the 1999 conventional narrow-azimuth survey (top) and the full-azimuth 2013 point-receiver survey (bottom).

<table>
<thead>
<tr>
<th>Acquisition vintage</th>
<th>1999</th>
<th>2003</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver lines in template</td>
<td>8</td>
<td>12</td>
<td>36</td>
</tr>
<tr>
<td>Live channels per line</td>
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<td>96</td>
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<tr>
<td>Total live channels</td>
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<td>500</td>
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<td>Analog group</td>
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</tr>
<tr>
<td>Source hole depth (m)</td>
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<td>15</td>
<td>6</td>
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<tr>
<td>Charge size (kg)</td>
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<td>3-5</td>
<td>0.5-1.5</td>
</tr>
<tr>
<td>Maximum inline offset (m)</td>
<td>1600</td>
<td>1920</td>
<td>3600</td>
</tr>
</tbody>
</table>

Table 1 Acquisition parameters for the 2013 point-receiver survey and two previous vintage datasets.
technology was an enabler for cost-effective acquisition of the dense dataset; the rapid development of high power, low-cost processing and disk arrays was equally as important to enable the processing at an acceptable price.

Special processes were applied to ensure adequate de-noising of the high-density point-receiver data. Conventionally, land seismic data is acquired by using receiver arrays and, in China, deep shot holes with large charge sizes. This in-field combination goes some way to attenuating noise; however, the approach is only partially successful. Poor spatial sampling and aliased noise modes can contaminate the signal making subsequent removal in processing difficult without compromising the underlying signal. Raw field data from point-receiver systems is inherently noisier than data from conventional systems due to the lack of any array-summation effect. In addition, geophone accelerometer sensors are more sensitive to high-frequency noise than velocity sensors. Therefore, point-receiver recording must be complemented by suitable noise processing. However, the powerful combination of point-measurement perturbation corrections and the ability to model and remove noise without affecting the underlying signal ultimately leads to a much cleaner dataset for input into imaging processes.

The third issue that had to be considered carefully was how to process the broadband full-azimuth data properly to retain the azimuthal information and to take full advantage of such a rich dataset to optimize future well placement.

The record high volumes of data acquired in this explosive-source survey made it comparable to a very large vibroseis survey. Huge disk capacity and computational capability were required to meet data storage and processing requirements. As much as the advancement of acquisition technology was an enabler for cost-effective acquisition of the dense dataset, the rapid development of high power, low-cost processing and disk arrays was equally as important to enable the processing at an acceptable price.

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The pre-stack imaging workflow shown in Figure 5 was designed based on the consideration of raw data attributes and statics, de-noising and full-azimuth, amplitude preservation requirements. It is full trace workflow, with all acquired
traces going through the workflow into the imaging step, itself a powerful noise attenuator. Full trace processing of such large datasets is only recently made feasible by the compute cost reduction described previously.

**Noise attenuation**

Correction for static effects is an important step to apply before addressing noise attenuation, especially considering the localized variations in elevation and near-surface effects in the prospect area. Point-receiver recording enables static corrections to be applied on a sensor-by-sensor basis. Because there is no in-field summation of data from multiple sensors, high-frequency information is not lost as would be the case with a geophone array planted over a varying terrain. The fine spatial sampling of the point receivers further enhances data resolution.

Reflection tomographic statics corrections based on first break picking is a mature and widely applied methodology. Due to the lack of noise suppression inherent in the use of infield receiver arrays, point-receiver raw traces appear noisier and may require more advanced methods for first-break picking. With appropriate preconditioning and data-adaptive picking workflows and parameters, it was possible to achieve very accurate first-break picks over the majority of the survey area. Automated data-adaptive
high-accuracy first-break picking and refraction tomography statics solutions successfully solved the most difficult statics challenges.

The dataset exhibited strong variations in amplitude between different shots and traces because of varying surface conditions, source energy variations and environmental noise. To protect signals from being influenced by amplitude variations, surface consistent amplitude compensation was applied prior to noise processing, and then backed-off on the clean dataset.

Compared to conventional seismic shot records, the point-receiver data featured more traces, richer noise types and stronger noise energy. Three state-of-the-art routines were applied to tackle the ambient, coherent and scattered noise types within the dataset. These techniques are described as non-uniform, and have been designed to work successfully on data acquired with irregular acquisition geometries. This overcomes the restrictions of conventional multi-channel filtering, such as FK filters, which assume regularly spaced data and can result in residual artefacts if the regularity requirements are not met. The new algorithms also positively impact field operations because they enable offsetting rules to be made more flexible. Receiver lines can ‘contour’ around obstacles without having to conform to restrictive offsetting rules that limit options and tie-up equipment.

In addition to conventional methods such as the editing of large amplitudes in multiple domains, a novel technique called non-uniform environmental noise suppression (NU ENS) was successfully applied to the data to address ambient noise. NU ENS uses a diversity principle and frequency separation of signal and noise to model ‘random’ environmental noise, which can then be adaptively subtracted without affecting the underlying signal. The main coherent noise types encountered in the survey were direct and scattered surface wave noise. Non-uniform coherent noise suppression (NU CNS) uses local coherent noise modelling via an FX least-squared minimization technique, and this was applied effectively. Both of these techniques benefit from being relatively insensitive to the low signal-to-noise ratio of the raw traces.

To better suppress remaining scattered surface waves, an interferometry-based method was applied after NU CNS. The estimation of the scattered groundroll noise – using a routine called model-driven interferometry (MDI) – is an extension of conventional interferometry that is based on the cross-correlation and summation of wavefields observed at a pair of receiver locations. The result of this process is an estimate of the wavefield (i.e., noise model) at one receiver as if a source had been placed at the other. If a source is also placed at the other receiver location then the noise estimate can be subtracted from the measured data.

In many land geometries, the co-location of sources and receivers is rare due to economic and logistical reasons, and hence the conventional interferometry approach cannot be used. MDI solves the problem of non-co-located sources and receivers by modelling the wavefield arriving at the source location (equivalent to providing the co-located receiver information), and using this to perform the cross-correlation and summation with the seismic data observed by the associated receivers. This is a practical breakthrough making the technique applicable to real-world seismic acquisition where, typically, a receiver is surrounded by several shots in a 3D seismic land survey. The massive trace count and dense symmetric sampling of the 2013 dataset significantly aided the application of MDI. Comparison of data before and after de-noising is shown in Figure 6.

Imaging
To take full advantage of the long-offset full-azimuth attributes of the dataset for complex structural imaging and azimuthal anisotropy description, offset vector tile (OVT)
transverse isotropy (VTI) anisotropy was observed on the image gathers, especially over the interval 500-1500 m/s two-way time (twt). Building the best possible velocity model so as to obtain optimum reservoir imaging was therefore a key processing requirement. In the pre-anisotropy-corrected velocity field, it was observed that the data could be moveout-corrected quite flatly either with a short spread velocity that ties the VSP velocity at wells, within around 27 degrees incident angle – or the velocity had to be biased toward the higher end, up to 10%, to best flatten both near and far offset data with take-off angles up to 45 degrees. Based on this, a well-constrained spatially and vertically variant anisotropic velocity field was built. In addition to enabling a high-quality imaging result, the same well-consistent low frequency velocity model was directly used in subsequent inversion.

Results

Figure 8 is a comparison of the vintage pre-stack time migration section and the new point-receiver VTI pre-stack time migrated (PSTM) section. Figure 9 is a comparison of the frequency bandwidth delivered by the new and vintage data-sets. Signal-to-noise ratio, vertical and horizontal resolution, and imaging precision are all greatly improved in the point-receiver dataset. The new image provides a more accurate description of the plane of the major fault in the centre of the section. The data is positioned more accurately and the domain sorting and regularization was employed prior to migration. Conceptually, the OVT domain is the extension of the cross-spread domain, where each OVT dataset is a subset of each cross-spread gather. One cross-spread array is a gather of traces selected from a certain source line and a certain receiver line. Splitting each cross-spread gather by dividing along source lines and receiver lines results in each OVT, where the size of the OVT is determined by source and receiver line distance. The number of OVT tiles is equal to the nominal fold and each OVT has its own offset and azimuth.

Average offset and azimuth of each OVT tile is calculated before migration to represent the average offset and azimuth of the OVT gather. This method is more advanced than data separation by fixing offset range and ignoring azimuth. Sorting into gathers by azimuth is not then necessary after migration in the OVT domain and OVT gathers can be used for azimuth analysis directly (Stein, 2010). Moreover, OVT gathers can also be sorted to ‘spiral’ gathers by offset and azimuth (Figure 7). Minor variations in the event shown in the gather represent azimuthal characteristics of the fractured DAZ carbonate reservoir. This azimuthal anisotropic information was directly extracted to represent fracture direction and density distribution, which was used in subsequent rock property inversion and fracture prediction.

Due to the existence of layers in the overburden and the data having sufficiently long offsets, clear evidence of vertical
Recent trends in seismic acquisition technological developments aimed at increasing broadband data have mostly focused more on vertical resolution (i.e. temporal frequency bandwidth) than spatial resolution. However, improving spatial resolution is of increasing importance, especially for the exploration and development of unconventional resources such as tight oil, tight gas and shale gas. Details of spatial variations in geological, geophysical, and rock physical parameters such as the distribution of sweet spots and fractures, as well as local anisotropy-related in-situ stress, provide valuable information to support well completions engineering and efforts to increase production such as optimizing horizontal well placement and hydraulic fracturing design.

Developments in extracting and visualising attributes of seismic datasets are helping to reveal ever-more detailed information. Figure 10 shows coherence sections of the vintage PSTM data and the new point-receiver VTI PSTM, demonstrating dramatic improvement in fracture corridor imaging. In Figure 11, this fracture development zone has been validated by a horizontal well. At the time of writing, the dataset is undergoing pre-stack inversion and initial results are encouraging. Figure 12 shows provisional results of lithology classification based on acoustic impedance and Vp/Vs properties inverted from simultaneous AVO inversion. Shale, wet and hydrocarbon bearing sand are colour-coded by black, blue and orange respectively for multi-level fluvial braided channels and isolated channels within a shallow contact relationship is clearer. Additionally, the new image shows the spatial distribution of multiple fracture systems and helps to recognize development characteristics of the sand channels allowing better prediction of their thickness and spatial extent.

Figure 8 Comparison of pre-stack time migrated data. Legacy 1999 & 2003 combined data with 2012 processing (top); 2013 point-receiver data with anisotropic PSTM (bottom).
Figure 9 Frequency spectra of data over window 800-1500m/s twt. Red: 1993 & 2003 data with 2012 reprocessing, post-stack time migration. Green: 2013 point receiver post-stack time migration. Blue: 2013 point-receiver data VTI PSTM.

Figure 10 Coherence slice comparison. Left: 2013 VTI PSTM point-receiver data; Right: Legacy 1999 and 2003 combined data with 2012 PSTM processing.
target formation. Further analysis is also being performed that incorporates anisotropy determined from the new seismic dataset into a geomechanical model.

Conclusions
High trace density onshore surface seismic 3D surveys have become economically feasible through recent technological developments and increasingly cost-effective data acquisition and processing capabilities. This case study from the middle Sichuan Basin in southwest China demonstrates some of the benefits of these new technologies. Combined with full-azimuth point-source, point-receiver acquisition geometries and broadband source, recording and processing techniques, high-density 3D surveys can economically deliver significant improvements in the quality and reliability of subsurface imaging. These improvements are increasing the value of high-resolution (both temporally and spatially) seismic data in supporting better well placement decisions and more effective field development and production.

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References