Full-azimuth, high-density, 3D point-source/point-receiver seismic survey for shale gas exploration in a loess plateau: a case study from the Ordos basin, China

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The Ordos Basin, located in the central part of China, contains abundant oil and gas shale resources. This study took place in an area southwest of Yan’an City, Shaanxi province, and its main exploration targets were the Mesozoic Yanchang Formation, with a maximum depth of around 1500 m, and the Upper Paleozoic Benxi Formation, with a maximum depth of around 3550 m. The tectonic structure at the target levels is almost flat, with dips of only around one degree.

The objective of the survey was to identify ‘sweet spots’ in a heterogeneous gas shale reservoir beneath thick deposits of loess, which is sediment formed by the accumulation of wind-blown silt. Variations in the topography, thickness, and seismic velocity of the loess were identified as key factors that had led to inadequate imaging results from previous 2D exploration surveys in the area (Yao and Li, 2004). The new 3D survey, acquired by CNPC Sichuan Geophysical Company (SCGC) during 2013 using the WesternGeco UniQ integrated point-receiver land seismic system, delivered imaging results that improved the characterization of the gas shale.

Several features of the project area presented challenges for seismic exploration, many of which are typical of a loess plateau. The area is covered by unconsolidated loess with severe variations in thickness and velocity that can result in serious statics problems. The loess also causes dramatic signal absorption, leading to poor signal-to-noise ratio and potentially contributing to low resolution in the seismic data. As shown in Figure 1, surface conditions include rapid variations in topography that further complicate near-surface statics correction and can be the cause of various types of interference and noise. Survey logistics needed to account for heavily forested areas, hills and gulches. Also, more than 500 oil wells were pumping and some rigs were drilling during survey acquisition, representing additional sources of noise (Figure 2).

Figure 1 Elevation map of Yanchang Liuping 177 survey area. 2D crooked line 07YC111 is shown as the white line.
Legacy 2D surveys
An exploration technique previously commonly used in the area was to acquire 2D crooked-line high-resolution seismic data in the gulches. Advantages of acquisition in gulches include thinner and more consolidated loess with less variation in elevation and thickness, thus reducing signal absorption and statics challenges. However, there are several fundamental disadvantages of the 2D crooked-line technique. A 2D survey cannot properly image the geophysical and geological variations of the 3D subsurface, and irregular geometry breaks down implicit assumptions of many common-midpoint seismic processing techniques (Wu, 1996). While the technique provided reasonable images in some areas, crooked line acquisition and processing failed in others, particularly where the loess was thickest. Shaanxi Yanchang Petroleum therefore decided to test an alternative seismic technique to improve sweet-spot identification during shale gas exploration in this loess plateau area.

New 3D survey
During 2013, SCGC acquired a benchmark pilot 3D survey over an area of the southeastern Ordos basin where the loess is particularly thick. The new survey had a full fold coverage area of approximately 50 km². The southwestern part of legacy line 07YC111 diagonally crosses the area of the new pilot survey area. The loess becomes thicker from northeast to southwest along the gulch in which the line was acquired and, as shown in Figure 3, the 2D crooked line failed in the southwest part (left side of the seismic section) where the loess was thickest.

The Yanchang Liuping 177 Well Block survey was acquired using the WesternGeco UniQ integrated point-receiver land seismic system and point explosive sources. The survey geometry was designed to deliver full-azimuth data and high-density coverage, leading to high fold. Properly sampled point-receiver data can overcome wavelet distortion problems introduced when using conventional acquisition designs that sum individual geophone outputs in the field. It can also better address the severe ground roll issues encountered in this area. In addition, point receiver recording avoids statics errors within an array, which can be severe when heavy erosion leads to rapid changes in elevation. Furthermore, high-fold, well-sampled field data can be profitable for near surface model inversion to provide better statics solutions. High density 3D point-receiver acquisition has been verified both in theory and in many practical cases for its capacity to deliver high signal fidelity and fine spatial and temporal (Vermeer, 2002; van Baaren et al., 2012). Three such surveys have already been designed and executed successfully in China, for example Xiao et al., 2014.

Data acquisition
After careful analysis of existing data from legacy 2D surveys, and consideration of the unique loess plateau surface, Yanchang Petroleum approved the design of a high-density 3D...
seismic survey scheme aimed at providing a better image of the two target sets of gas-bearing shale.

A total of 45,000 broadband geophone accelerometer point-receivers were deployed. More than half a billion traces were recorded, and at its 2 m/s sample interval the total field dataset was almost 6 TB in size. Acquisition of the programmed 28,564 shots began on 28 October 2013 and was completed in only 38 days. Despite the difficult terrain of this loess plateau, average daily production was 921 shots and the maximum daily production was 1878 shots. Point-receiver/point source acquisition significantly reduced project cost compared to a conventional survey, where each source would typically have required 6-8 holes with a large charge at 50-100 m source intervals and two strings of 12 geophones per 25 m receiver point.

**Data processing**

The two main challenges were to address the survey area’s serious statics challenges and the high levels of various types of noise, examples of which can be seen in the example raw shots shown in Figure 4. Each receiver spread commonly included several hundreds of metres of elevation variation, along with thick layers of loess with very low seismic velocity. The data exhibited strong ground roll and scattering surface waves, and the extreme statics within a spread introduced complex behavior in this otherwise coherent noise. More than 500 producing wells, several active drilling operations, and other sources of noise presented further challenges in extracting the weak signal that had been absorbed and attenuated by the loess. Furthermore, the geological characterization objectives, especially in terms of inversion processes such as amplitude versus azimuth (AVAZ) and amplitude versus offset (AVO) analysis, required high-fidelity seismic data with full-azimuth and amplitude-preserving processing.

A tailored processing scheme was applied to the high-density point-receiver data. The basic strategy was to start with statics correction to align coherent noise and
The first breaks were often weak and contaminated, they were successfully identified using the converging picker method. Based on the high-accuracy first break picks, refraction tomography was applied to solve the statics problem. Field near-surface investigation was used to constrain the weathering layer velocity. Various parameters were tested, including the number of layers, offset ranges, and smoothing distance. Residual statics based on reflection signal were applied to solve shorter wavelength statics. Rough noise attenuation was first applied to increase the robustness of the residual statics method. The statics results were evaluated in terms of the statics solution itself plus comparisons of shots and stack sections with and without statics applied. As a result of these corrections, first breaks, ground roll and hyperbolic events all become much more coherent. Figure 5 shows example shot gathers before and after static correction. Figure 6 shows an example stack before and after correction.

**Statics solution**
The top two priorities for solving the statics problems were firstly to make sure the first breaks were picked as accurately as possible, and secondly to ensure refraction statics methods and parameters were thoroughly tested and optimized. Point-receiver acquisition enables detailed identification of changes in first breaks from channel to channel and thus provides opportunities for more accurate picks than with traditional geophone array data. In addition, the high-density acquisition design ensured high shot and receiver fold, which can reduce the negative impact of occasional bad picks to inversion algorithms, and make the results more robust and noise-proof.

For this project, an automatic first break picking method called ‘converging picker’ was used for first-pass picking. The converging picker generates a near-surface model by iteratively reducing differences between the model and the traces. The final model is used to guide and constrain first break picking. This method is stable and relatively insensitive to noise so does not require much data conditioning. An initial spatially variant velocity model needs to be provided when using this picking method. After that, a second pass re-pick application is conducted under the guidance of the first-pass picks. Although the first breaks were often weak and contaminated, they were successfully identified using the converging picker method.

Based on the high-accuracy first break picks, refraction tomography was applied to solve the statics problem. Field near-surface investigation was used to constrain the weathering layer velocity. Various parameters were tested, including the number of layers, offset ranges, and smoothing distance. Residual statics based on reflection signal were applied to solve shorter wavelength statics. Rough noise attenuation was first applied to increase the robustness of the residual statics method. The statics results were evaluated in terms of the statics solution itself plus comparisons of shots and stack sections with and without statics applied. As a result of these corrections, first breaks, ground roll and hyperbolic events all become much more coherent. Figure 5 shows example shot gathers before and after static correction. Figure 6 shows an example stack before and after correction.

**Noise attenuation solution**
The shot records showed few clear signals even after statics correction and mild noise attenuation; however, a test stack with automatic gain control (AGC) showed very clear events due to the high fold and reduction in strong amplitude noise resulting from the AGC. This confirmed that a good signal existed but was very weak and contaminated by noise. AGC was not an option for the production processing sequence because it is not an amplitude preserving process. After considering the near surface conditions, subsurface geology, data quality, noise characteristics and point-receiver acquisition features, a fit-for-purpose noise attenuation sequence was devised and applied. This included multi-domain anomalous
amplitude noise attenuation (AAA), non-uniform coherent noise suppression (NUCNS), surface-consistent amplitude compensation and deconvolution, and offset vector tile (OVT) domain residual coherent noise attenuation.

Noise characterized by anomalous amplitudes was removed by transforming the seismic data into the frequency domain and then applying a spatial median filter. AAA is applied in a user-defined spatial-temporal window, and frequency bands with amplitudes that deviate from the median amplitude by a specified threshold are either scaled or replaced with an interpolated band using neighbouring traces. Multi-domain, shot, detector, and CMP domain AAA was applied aimed at suppressing ambient noise – especially the well production noise. Well production noise is typically narrow-band/single-frequency, and is randomly spaced in the CMP domain hence easier to discriminate by amplitude within the specified number of traces. The strong near-offset scattering noise, which was mainly within 1000 m offset range, was also attenuated by AAA in the CMP domain. Data within the 2000 m offset range was selected and randomly sorted. By doing this, the scattering

Figure 5 Shot gathers before (top) and after (below) tomographic statics.

Figure 6 Stack with elevation statics (left) and with tomography statics plus residual statics (right).
noise became randomly distributed, enabling AAA to remove it as it was then characterized as having anomalous amplitude.

The NUCNS process computes an estimate of shot-generated coherent noise that interferes with reflected signals in non-uniform seismic data. The coherent noise often originates at the near-surface in the form of dispersive surface waves and strong trapped modes that have the same apparent velocity as the refracted energy. Compared with conventional multi-channel processes such as FK filtering, NUCNS overcomes the assumption of regular geometry. Coherent noise is locally estimated at each trace location for two specified ranges of low apparent velocities. For each trace, the estimation procedure uses surrounding traces to determine the content of coherent noise via a frequency dependent least-squares estimate. The cross-spread and CMP domain noise-attenuation sequence significantly improved signal-to-noise-ratio in the stack.

Strong signal absorption in the thick loess layer resulted in significant spatial variation in the seismic wavelet. A conventional surface-consistent deconvolution approach could be adversely affected by the large amounts of noise. Simple solvers, which are usually performed using a least square or a rough approximation method, are biased by high-amplitude

![Figure 7 CMP gather with autocorrelation (top) and stack (middle) before (left) and after (right) robust surface consistent deconvolution (RSCD). Bottom panel shows a frequency spectrum comparison between 900 ms and 2500 ms on the stack before (red) and after (blue) RSCD.](image-url)
common-azimuth and common-offset gathers. The structural features in the OVT domain are almost flat, and thus some coherent noise with high dip could be separated through application of curvelet transform in a specified scale and dip range. Figure 8 shows example stack data before and after noise attenuation.

Migration plays an important role in noise attenuation, and is particularly beneficial in a full azimuth, high-density, high-fold dataset such as the new Yanchang Liuping 177 3D pilot survey. With the strong amplitude noise removed and wavelet consistency improved, prestack time migration (PSTM) and subsequent stack further improved the coherent signal and the 3D subsurface image.

Imaging results
Crooked-line data acquired in gulches achieved reasonable imaging results in areas of thin loess in this part of the Ordos Basin, but failed increasingly with thickening loess layers. As presented at the start of this article, the southwestern part
Data Processing

(left side of section) of 2D crooked line 07YC111 shows poor imaging of the target horizons. As shown in Figure 9, the new 3D dataset, acquired with the UniQ integrated point-receiver land seismic system and processed through a tailored amplitude-preserving noise attenuation scheme, delivered significantly better results.

Conclusion
Previous seismic exploration in this loess plateau area achieved limited success, due mainly to serious statics challenges and low signal-to-noise-ratio. This pilot case study has shown that 3D acquisition with a full-azimuth, high-density, high-fold geometry, combined with integrated statics and noise attenuation solutions, can dramatically improve the subsurface image in areas with challenges such as those found in this part of the Ordos Basin. Point-source/point-receiver acquisition also reduced survey cost relative to a conventional 3D survey.

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