Land seismic in difficult terrain and complex geology: a case study from the Jungar Basin, northwest China

Huantong Lv1, Xianmin Li1, Zaichao Jiang1, Long Zhang1, Lixin Xiao1, Jian Wu1, Yan Liang2, Bo Liang2, Meng Zhang2, Rong Li3, Fang Li3, Sherman Yang3, Peter van Baaren4, Thomas Heesom4 and Hongping Xiao4 describe how a high-density, point-source, point-receiver approach can address statics and noise challenges of rough mountain thrust-zone topography and deliver high-quality imaging results.

High-density, single-component, point-receiver land acquisition geometries are increasingly displacing ‘conventional’ acquisition designs that are based on long-standing practices of sparse sampling, low channel counts and an analog approach to noise attenuation via multi-sensor arrays. Over the past decade, dense point-receiver – often complemented by point vibroseis or dynamite source – geometries have been proven in diverse locations including Australia, the Middle East, North and South America, Russia and China. Two case histories from China have recently been published that demonstrate the success of the approach in solving geological challenges encountered in the exploration and development phases of challenging oilfield environments in the Sichuan Basin (Xiao et al., 2014) and the Ordos Basin (Wang et al., 2014).

This article describes the acquisition and processing of a high-quality land seismic dataset in part of the south rim of the Jungar Basin, northwest China. The geology of the area is complex due to a compressional environment that has led to extensive folding, thrust faulting, and over-thrust faulting. In addition to complexities in the subsurface, surface conditions are dominated by rough mountain thrust-zone topography, presenting further challenges to accurate seismic imaging.

Until recently, heavy dynamite charges, grouped sources and large receiver arrays have been considered optimal for seismic acquisition in the area. A 40 km² 3D pilot survey, acquired in 2013, has demonstrated the potential improvements that can be provided by an alternative approach with a high-density point-source, point-receiver geometry.

Imaging challenges

The oil and gas exploration history of the south rim of the Jungar Basin extends back more than 60 years, and the Horgos anticline has been a particular focus of interest. As shown in Figure 1, the Horgos anticline has a strike direction approximately east-west and is located in the lower wall of a major strike-slip fault. The dipping layers outcrop at the surface with a near 60 degree dip angle, and the core of the anticline is highly faulted.

2D seismic lines have been acquired in the area since the 1980s. A 3D survey was acquired by PetroChina Xinjiang Oilfield Company (XOC) in 2001, and after several rounds of reprocessing the dataset provided significant improvement to subsurface imaging quality compared to the vintage 2D results. In 2003 a well was drilled into the Paleogene E1-2z target zone sand body that produced commercial volumes of hydrocarbons. However, due to the challenges of high pressure, high temperature (HPHT) reservoir conditions and engineering issues, this well was abandoned. In the following years, three more wells were drilled along the strike direction of the anticline, but they all missed the reservoir and none of them produced. It became clear that the reservoir was probably more complicated than initially thought, and was likely to be highly compartmentalised as a result of extensive faulting.

In an attempt to improve imaging quality and reduce drilling risks, in 2013 XOC decided to acquire a 40 km² pilot 3D survey using the WesternGeco UniQ integrated point-receiver land seismic system. Figure 2 shows the topography of the survey area, which includes steep slopes, a sharp ridge, and elevations ranging from around 600 to 1500 m. The anticline is represented at the surface by steeply dipping (up to 60 degrees) outcrops of hard Quaternary rocks, while other parts of the survey area exhibit weathering-related features including ditches, rivers, thick layers of loess, and large piles of loose gravel, all of which pose challenges
to seismic acquisition (Figure 3). The near-surface loess and gravel layers can cause seismic energy be absorbed, thus inhibiting propagation and illumination of the deep subsurface. Significant localized variations in the thickness and velocity of weathered surface layers can result in serious statics challenges. The loess and gravel can also act as energy diffractors, and in some parts of the survey area they generate strong guided waves that mask the low-amplitude reflection events.

2001 legacy 3D survey

The 2001 3D survey attempted to address the challenges presented by the surface conditions through the use of deep holes and heavy charge dynamite sources. Most sources were deployed at depths in excess of 15 m in the hope of penetrating beyond the weathering layer. Charge size was generally between 16 and 21 kg. In the loess areas, several source holes were grouped together to increase the intensity of the source energy.

To attenuate groundroll energy and ambient noise, 30 receivers in three strings were grouped and summed in the field. Such large geophone arrays ignore variations in statics and coupling between the many individual receivers. This not only restricts the ability to resolve short period statics and preserve high-frequency signal, but can also compromise true amplitude recovery after noise attenuation. A further drawback of the 2001 survey is that it did not adequately sample the 3D wavefield. Acquisition parameters included an 80-m shot interval and 40-m receiver group interval, resulting in a dataset in which

2013 survey design

To avoid repeating the undesirable array-induced effects of the 2001 survey, a point-sampling approach was chosen for

Figure 1 Legacy seismic section through the Horgos anticline.

Figure 2 Satellite image of the topography of the Horgos anticline block.
the 2013 acquisition, applied both to the sources and the receivers. Analysis of the phase velocity of the groundroll in representative locations indicated that its slowest value was about 500 m/s at 20 Hz. To ensure unaliased recording of the groundroll, both the source interval and receiver interval were set at 10 m. This dense sampling, coupled with a desire for longer offsets and a wider azimuth acquisition template, necessitated a live recording patch of nearly 29,000 channels. Cost-effective acquisition of such high-end parameters is beyond the capabilities of most seismic acquisition systems, but was easily achieved with a fit-for-purpose deployment of the UniQ point-receiver system.

The rough topography and large areas of hard-to-access farmland in the survey area meant that vibroseis trucks were not a viable source option, so dynamite was used for the 2013 acquisition. Industry studies and experiments have illustrated that, with smaller charge sizes, a larger proportion of the source energy is transformed into body waves and less groundroll is generated. Studies have also shown that, as charge size increases, signal bandwidth decreases. For the new survey, the general guideline was to use relatively shallow (6–10 m) holes and small (3–6 kg) charge sizes, although these parameters were allowed to vary slightly across different parts of the survey area.

Acquisition parameters for the 2001 and 2013 surveys are compared in Table-1. Figure 4 shows the nominal acquisition templates and rose diagrams indicating offset and azimuth distribution. To summarize: the 2013 acquisition

<table>
<thead>
<tr>
<th>Acquisition year</th>
<th>2001</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver lines in template</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>Live channels per line</td>
<td>270</td>
<td>1,200</td>
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<td>Total live channels</td>
<td>2,160</td>
<td>28,800</td>
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<tr>
<td>Receiver line interval (m)</td>
<td>160</td>
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<tr>
<td>Receiver interval (m)</td>
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<tr>
<td>Receivers per km²</td>
<td>156</td>
<td>500</td>
</tr>
<tr>
<td>Source line interval (m)</td>
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<td>200</td>
</tr>
<tr>
<td>Source interval (m)</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Source points per km²</td>
<td>35</td>
<td>500</td>
</tr>
<tr>
<td>Bin size (m)</td>
<td>20 x 40</td>
<td>5 x 5</td>
</tr>
<tr>
<td>Nominal fold</td>
<td>15 x 4</td>
<td>30 x 12</td>
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<tr>
<td>Receiver station type</td>
<td>3 strings of 10 geophones in analog group</td>
<td>digital point-receiver</td>
</tr>
<tr>
<td>Source hole depth (m)</td>
<td>21 @ 16–18 kg x 1 hole 15 @ 9 kg x 2 holes 12 @ 6 kg x 3 holes 6 @ 3 kg x 7 holes</td>
<td>6–10</td>
</tr>
<tr>
<td>Charge size (kg)</td>
<td>16–21</td>
<td>3–6</td>
</tr>
<tr>
<td>Maximum inline offset (m)</td>
<td>5,380</td>
<td>5,995</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>0.16</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 1 Acquisition parameters of the legacy 2001 3D survey and the 2013 point-receiver 3D survey.
used point-receivers and sources, smaller charge sizes, shallower hole depths, and smaller source and receiver intervals. It delivered higher trace density and fold, longer offsets, and a wider range of azimuths. The survey was acquired in June and July 2013. A total of 50,460 shots were recorded, at an average rate of 1660 shots per day.

**Analysis of raw shot data**

Despite the smaller charge size and shallower hole depth, the 2013 point-source, point-receiver field data were of good quality. Figure 5 shows a raw shot from the new dataset and one from the 2001 survey at approximately the same location. The older data looks superficially cleaner and has less background noise as a result of the in-field summation of a 30-receiver array. The raw point-receiver shot record has no noise attenuation. However, its fine spatial sampling ensures that several types of coherent noise, including the low wave-number groundroll energy, is recorded unaliased, enabling it to be effectively removed during data conditioning using data-adaptive techniques.

Figure 6 shows example raw shot records from parts of the survey area with different surface conditions. Data from around the top of the anticline, where hard rock outcrops (shots 5 and 8), exhibit clearer reflection events and relatively weaker groundroll energy. However, variations in topography have resulted in scattering. Topography is smoother in the south and north ends of the survey area (shots 2 and 14), and Gobi and gravel covers the surface. In these areas, reflection events are weaker and guided wave energy is stronger, with more obvious dispersion due to the thick weathered layer. All of the raw shot records show clear statics variations and strong background noise, which are typical characteristics of data from such rough mountain thrust-zone areas. The key challenges for data processing included effective noise attenuation, accurate statics correction, appropriate velocity model building and high-fidelity imaging.
Statics correction

As shown in Figure 6, first breaks in the raw shot records exhibit significant statics variations. Solving these statics accurately is not only critical for preserving signal during stack, but is also an essential prerequisite for multi-channel noise attenuation. Point-receiver recording enables static corrections to be applied on a sensor-by-sensor basis, thus avoiding degradation of the seismic signal that can result from intra-array perturbations in conventional data.

Refraction tomographic statics correction based on first break picking is a mature and robust methodology that has been shown to address complex statics problems in mountainous and loess areas of China (Wang et al., 2014). Due to the nature of point-receiver recording, ambient noise levels in the raw data are generally higher than in conventional data, which can make first-break picking more challenging. Preliminary preconditioning was therefore applied to the data to assist iterative, data-adaptive picking workflows, which provided high-quality first break picks over the majority of the survey area. Figure 7 compares stacked data after preliminary preconditioning with and without refraction tomography statics correction. This shows that, using the high-quality first break picks, most statics problems were resolved and the stack image was significantly improved.

Noise attenuation

Noise in the dataset can be categorized into three main types: groundroll, guided wave and ambient. In the south and north parts of the survey area, away from the top of the Horgos anticline, the groundroll exhibited obvious dispersion, i.e. different frequencies travelling at different phase velocities. Around the top of the anticline, the groundroll was less dispersive but scattering was relatively more serious. An algorithm called non-uniform coherent noise suppression was applied in the cross-spread domain to address the groundroll.

Guided wave noise is, in essence, refraction energy that travels multiple times in the surface column above a refractor. In the Gobi and loess areas, where the weathering layer was thickest, guided waves were especially strong. In general this energy has linear moveout and travels at an apparent velocity close to the refractor’s velocity, which can make it difficult to differentiate from reflections. Processing exploited its linearity through application of a
radial transform algorithm to model and suppress the guided wave energy.

Ambient noise included quasi-random wide spectrum background noise and external sources of band-limited interference such as water well drilling activity. An algorithm called non-uniform environmental noise suppression was applied to address the ambient noise. Figure 8 compares relative amplitude processed (RAP) stack sections with and without the cascaded noise attenuation flow.

**Imaging**

As evident on the legacy migration and the new stack sections, the Horgos anticline area has a complex subsurface structure, and as a result the velocity field was also expected to be complex. Song (2014) has demonstrated a successful strategy in a survey from northwest China of combining an initial shallow velocity model based on diving wave
In the deeper section, where dips are lower, the structure of reflections from Jurassic coal-bearing strata is much clearer than was achieved with the legacy data. The high-quality illumination of the deeper data was a pleasant surprise when considering the relatively small dynamite charges and shallow holes used for acquiring the new dataset. Figure 12 compares example sections from the 2001 and 2013 datasets.

The maximum offset at which good DWT picks could be made on the data was around 5500 m, which in this case equated to an effective penetration depth of about 1.5 km below the surface; close, to the typical ‘rule of thumb’ of a quarter of the maximum offset. Confident in the accuracy of the top 1.5 km, the deeper section was clipped to a maximum of 4000 m/s, and that model was used as a starting point for prestack depth migration, RMO picking, and iterations of cell-based tomography to update the deep part of the model.

Considering the steep dip of the subsurface structure, an isotropic or vertical transverse isotropic (VTI) model was unlikely to be effective, so a tilted transverse isotropic (TTI) model was assumed from the start. Figure 10 shows Vp for the final model overlaid on the resulting depth section. In order to compare the new data with the legacy data, the depth model was also converted into the time domain and prestack time migration (PSTM) was applied.

**Results**

Figure 11 compares the PSTM results of the legacy 2001 data with the equivalent migration of the new 2013 survey, in which overall data quality can be seen to have been significantly improved. Imaging of the target zone is clearer, faults are sharper, and signal to noise ratio (S/N) is greatly improved throughout the section.
after 0-8 Hz bandpass filtering. The results confirm that the new survey successfully delivered the low frequencies required for illuminating deep targets.

Figure 13 shows an example of the legacy prestack depth migration (PSDM) compared to the results of PSDM of the 2013 dataset using the TTI velocity field. Compared to the PSTM results, the new data provides further improvement, particularly in fault imaging and S/N.

**Conclusion**

Seismic datasets recorded in mountain thrust-zone areas of China commonly suffer from severe statics and noise problems. Until recently, heavy charges, deep holes, source groups, and large geophone arrays have been considered the best way of addressing these challenges. This case history from the Horgos anticline area of the Jungar Basin demonstrates that a high-density, point-source, point-receiver approach using small charges and shallow holes can provide a cost-effective alternative that delivers superior results. Applying statics correction to individual point receivers avoids degradation of the seismic signals that can result from variations between geophones in a conventional array. High fold and fine spatial sampling ensure that several types of noise can be effectively removed without compromising signal quality. Fine spatial sampling of cmp bins in both inline and crossline directions, when combined with well-designed approaches to processing and velocity model building, enables accurate imaging of steep dips and resolution of complex subsurface geological structures.

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**References**

