Land seismic super-crew unlocks the Ara carbonate play of the Southern Oman Salt Basin with wide azimuth survey

The Southern Oman Salt Basin 3D seismic survey being acquired by Petroleum Development Oman (PDO) is the largest, most densely populated wide-azimuth (WAZ) land seismic survey yet acquired, benefiting from the use of a land seismic super-crew. PDO geoscientists Robert Sambell, Said Al-Mahrooqi, Christopher Matheny, Said Al-Abri and Said Al-Yarubi describe what was involved in this breakthrough survey.

Phase I of the Southern Oman Salt Basin 3D seismic survey has been completed totalling 2700 km² and Phase II of 3500 km² is presently being acquired. Additional phases will continue. The survey design not only supports a true WAZ geometry but also provides good sampling. For phase I, an average productivity of 8000 vibrator points/day (VPs/day) providing 64,000,000 traces per day were being achieved in the final months and the total data acquired amounted to 120 Tbyte. With the introduction of simultaneous shooting for phase II, average productivity has been increased to 15,000 VPs/day providing 120,000,000 traces per day. A series of production records were set with the current best being 20,192 VPs/day, achieved on 30 November 2009. These are truly remarkable statistics which only a seismic super-crew can deliver.

The Southern Oman Salt Basin is situated in the south of the 100,000 km² block 6 operated by PDO (Figure 1). The play of interest in this study is the Ara carbonate play. As described by Al-Siyabi (2005), the first (unexpected) intrasalt discovery was in 1976 but the complexity of the play was such that the first phase of exploration was stopped in 1986. A second phase of exploration activity began in 1988 but again the complexity of the play frustrated this short-lived campaign. The third phase started in 1997 and continues to this day.

The Ara hydrocarbon system (Figure 2) spans the Precambrian/Cambrian boundary and as such represents one of the oldest hydrocarbon systems from which commercial hydrocarbons are being produced today. Some six cycles of carbonate-evaporite deposition have been recognized. Oil is produced from carbonate slabs (stringers) encased within salt from depths between 2500 m to 5000 m. While many discoveries have been made, traditional seismic data quality has not been good enough to accurately delineate the stringers and many wells have encountered surprises, both positive and negative: prognosed stringers might be absent, an unexpected stringer may be encountered, and the top salt pick may have an error of hundreds of metres distorting depth maps and degrading PSDM processing.

Figure 3 illustrates these problems on a typical vintage seismic section; the top and base salt reflectors are not adequately resolved, the stringer reflections are not convincingly focused, and to discriminate smeared noise events in the salt from real stringer events is problematic. Advanced techniques such as seismic inversion and quantitative interpretation were simply out of the question. Clearly the business required a major improvement in seismic data quality and the Southern Oman Salt Basin survey was the answer to this demand.

Challenge of land 3D acquisition
Seismic technology has made amazing progress since the introduction of digital technology 50 years ago. However, there is still one area of neglect—the ‘forgotten child’ of land 3D seismic data acquisition. To answer the question why, we need to go back to land 2D data. In a 2D world, the sampling and aperture requirements were straightforward and well understood and the technologies of the 1980s were perfectly adequate to satisfy these requirements. The standard design of the time – split-spread, shot-point between the receiver pegs, large orthogonal array to suppress cross-line shot-generated noise – was ideal, but not for 3D.

With the transition to 3D acquisition in the early 1980s, the thoroughness and discipline associated with 2D land design were lost due to the limitations of the new technology and budget considerations. With a maximum of 480 live channels available at the time group lengths of 50 m became the norm and the number of receiver lines were typically limited to four or six for normal in-line offsets. Compounding the problem, the source grid was so sparse that basically no domain was adequately sampled. Consequently data quality was compromised due to inadequate sampling and the lack of an effective orthogonal stack response to suppress cross-line shot-generated noise.

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patchwork of incompatible seismic surveys each designed for a specific target. This not only degraded the quality of the seismic interpretations that might span several surveys, it was also a very inefficient and costly way to acquire seismic data with re-shoots being more the rule than the exception.

Why PDO chose a 25 m receiver group interval is illustrated in Figure 4. A shot with a 25 m receiver interval is compared with one with 50 m receiver interval acquired at the same position. The serious aliasing and smearing problems of the 50 m receiver interval data is obvious. Advantage can no longer be made of the linear characteristics of the coherent noise modes during processing. One is forced to apply ‘brute force’ methods of noise suppression which run the danger of leaking noise through to the stack which may even have the appearance of coherent events.

Geophysical solution
Just as high-density, well sampled, WAZ data have provided breakthroughs in marine data quality, there is every reason to expect the same of land data. In fact, one could anticipate even greater improvements with land data because such additional complications as ground roll, repeated first arrivals, statics, and P5 conversions do not plague marine data.

With buried explosive sources in ‘low-noise’ areas, excellent results could still be achieved. After all, if there is little noise to suppress, then ignoring it may be acceptable. But for surface sources in general, with their high levels of source generated noise and explosive sources in ‘bad data quality’ areas, this strategy could not be expected to produce good data quality.

Over the intervening period, the number of channels on a typical crew has increased to perhaps 5000 at which point a choice has to be made between the number of receiver lines, receiver interval, and in-line offset. PDO in 2002 opted for finer receiver intervals going from 50 m to 25 m but that limited the number of geophone lines to four for deeper targets. Most of the industry stayed with the 50 m group interval, which still appears to be the norm. This configuration benefits from additional receiver lines, with eight or 10 deployed to create a wider azimuth (but certainly not a true WAZ) geometry. There is simply not enough equipment to support proper sampling, the required offsets, and a WAZ geometry at a reasonable cost and productivity.

In PDO, this led to small surveys being designed for very specific shallow or deep targets as can be seen from the vintage survey outlines of Figure 1. After 25 years of 3D acquisition, the seismic coverage in 2006 was a
The proper sampling of these phenomena with massive amounts of data may for the first time properly address these problems. The ‘New Generation Seismic’ initiative launched in 2007 aimed at a quantum leap in data quality for land seismic in South Oman and embodied the idea of a super-crew. The objectives were as follows:

- Significantly increase data density to the point of at least approximately satisfying sampling requirements.
- Vastly increase fold in support of the various processing steps and improved S/N.
- Acquire WAZ data to improve the cross-line stack response, support the proper imaging of the stringers which can have extreme dips, and provide improved multiple suppression. Whereas for marine data, WAZ geometries are often seen as primarily providing improved illumination, for land data, the noise suppression characteristics in the cross-line direction may actually be more important.
- Acquire large ‘carpet seismic’ programmes with uniform high quality acquisition parameters over huge areas focusing the whole geologic column, shallow and deep. Vintage surveys were often small ‘postage stamp’ surveys with dramatically differing character due to differing acquisition parameters having been targeted either at shallower (oil) or deeper (gas) targets.

Super-crew in action

To achieve these geophysical objectives, it was decided to mobilize 25,000 channels of 12 geophones per channel along with 16 vibrators. With this equipment, a true land WAZ survey providing a cross-line offset of 4 km with good productivity and competitive unit cost could be designed. The upgrade was done in stages and the parameters applied on completion of the upgrade were:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrumentation</td>
<td>SN428, VE464</td>
</tr>
<tr>
<td>Total channels</td>
<td>25,000</td>
</tr>
<tr>
<td>Geophones/channel</td>
<td>12</td>
</tr>
<tr>
<td>Size (phase I)</td>
<td>2700 km²</td>
</tr>
<tr>
<td>Live channels</td>
<td>8000</td>
</tr>
<tr>
<td>Fold</td>
<td>4000 (in 25 x 25 m bins)</td>
</tr>
<tr>
<td>In-line receiver interval</td>
<td>25 m</td>
</tr>
<tr>
<td>Receiver line spacing</td>
<td>200 m</td>
</tr>
<tr>
<td>VP grid</td>
<td>50 x 50 m (each location shot twice)</td>
</tr>
<tr>
<td>VPs/km²</td>
<td>800</td>
</tr>
<tr>
<td>Block width</td>
<td>21.5 km</td>
</tr>
</tbody>
</table>

Of course, in real life, compromises are still made. For example, a 25 x 25 m VP grid would certainly have been preferred with tighter geophone line spacing.

Costs and productivity

At PDO, the improvements in productivity obtained with the super-crew have actually reduced unit costs/km² compared to vintage surveys. There were a number of major operational improvements.

Night operations

Where safe, and this covers much of the Middle East, 24 hour operations are most important. These do of course require a thorough hazard analysis to identify and manage the additional operational hazards but, in the Middle East, there is a good safety track record. Basic measures such as only recording at night with a minimal crew of perhaps 30 personnel and restricting movement of line equipment to daylight hours when the full crew of perhaps 400 men may be working have successfully restricted exposure. With a manual of permitted operations (MOPO) in place, night operations only proceeded when considered safe and would be stopped in difficult terrain or poor weather conditions.

The importance of 24 hour operations lies in its support of WAZ geometries. By vibrating on the edge of the spread and repeating each vibrating point (VP), twice, the effective orthogonal offset can be doubled during processing by combining the two shots acquired at the same VP position into one ‘super-shot’. The night-time operation is only used to acquire the additional VPs, so in principle no additional movement of line equipment and associated labour is required for 24 hour operations. This also applies to additional repeating of shots. In recent PDO designs, VPs have been repeated three and four times (Figure 5). In this way, a narrower spread can be used on the ground. This enables longer receiver lines to facilitate simultaneous
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New recording equipment

Older recording equipment has certain disadvantages which impede productivity. One is the ‘salvo’ whereby the instrument has to stop recording after a certain quantity of data has been acquired to allow internal processing. Typically, this can lead to a 5% overhead during good production periods. Newer instrumentation removes this overhead with continuous recording. Another improvement is in the increased number of vibrator groups the modern vibrator controller can handle. Another improvement is in the increased number of vibrator groups the modern vibrator controller can handle. Previous models were limited to perhaps four vibrator groups but this limit has now been effectively removed with up to 32 groups now being the limit with the new PDO controllers.

Sweep length

Sweep lengths in the industry have generally shown a reduction over the past few decades. With high density recording, it is essential to ensure that time is not being wasted by unnecessarily long sweeps. With most noise being shot-generated with little random noise to suppress, long sweeps are difficult to defend theoretically and have not been supported by tests. In this survey, sweep lengths were brought down to six seconds without any observable degradation in final data quality.

Vibrator array

Two-vibrator arrays were used for many years in PDO but have now been phased out in favour of single vibrators. However, it should be noted that due to the denser VP grids, there is no reduction in energy being ‘put into the earth’. The marginal improvement observed at the shot level with 2 sources without sacrificing the WAZ orthogonal offset (see distance separated simultaneous sources below).

Block width

Land seismic is shot in blocks requiring ‘zippers’ between them to ensure a full-fold seamless data set. As all survey designers will have experienced, these ‘zippers’ represent waste and consequently reducing the number of blocks will reduce this overhead. Establishing the super-crew was done in steps and initially the South Oman Salt Basin survey was being acquired with 12,500 channels before the full 25,000 channels were mobilized. With 12,500 channels, a block width of 13 km was used, but with 25,000 channels, a block width of 26 km was possible (although only 21.5 km was actually needed to complete the survey). To a first approximation, assuming a survey width of about 47 km and an in-line offset of 6 km, the 12,500 channel scenario would require six blocks amounting to 3,120,000 VPs while the 25,000 channel scenario would only require two blocks amounting to 2,080,000 VPs (Figure 6). This is a massive 33% decrease in VPs. In effect, the additional channels are paying for themselves and more.

The ‘zipper’ also indirectly affects data quality. The ‘zipper’ width is determined by the maximum inline offset. So with conventional crews, there will always be pressure to minimize this offset to an absolute minimum to contain costs. This will usually lead to inline offsets smaller than desirable, and the cross-line offset will be kept to a minimum to allow the receiver lines to be as long as possible. As the overhead of the ‘zipper’ is significantly less for a super-crew, a larger offset will not be so problematic.

Figure 5 (a) By repeating VPs, ‘super-shots’ can be simulated during processing with double the width of the receiver spread on the ground. (b) By repeating VPs three times, a spread width three times the width of the actual receiver spread on the ground can be simulated.

Figure 6 (a) Acquiring a 2500 km2 survey with 12,500 channels would require six blocks. The ‘zippers’ of repeated VPs are indicated by the blue brick pattern. A total of 3,120,000 VPs is required. (b) Acquiring the same survey with 25,000 channels would require 2,080,000 VPs, a saving of 33%. See text for acquisition parameters.
SLIP-SWEEP RECORDING

SLIP-SWEEP recording (Rozemond, 1996) was developed by PDO in 1996 and is still being applied today, albeit rather conservatively. For a sweep time of \( T \) sec, the slip time (the delay to the start-time of the following sweep) is \( (T+1) \) sec. With all these measures implemented, VP and areal productivity have increased spectacularly.

OUTCOME

Figure 8 shows the increase in VPs/day as the various productivity measures were introduced. One day’s production with the super-crew is equivalent to seven days production three years ago. A record of 20,192 VPs/day was achieved on 30 November 2009.

IMPACT ON DATA QUALITY

The impact on data quality has been dramatic. This can be observed on preliminary results that still require optimization of processing parameters, particularly the velocity model which presently ignores azimuthal variations. Figures 9 and 10 illustrate these improvements. These figures display comparisons of (preliminary) ‘New Generation Seismic’ sections with vintage sections. Note that the vintage data had just been reprocessed by the same processing group that processed the new data eliminating the possibility of ‘apples and pears’ comparisons.

Figure 7 Two simultaneous VPs 13.5 km apart recorded into a 27 km receiver line.

Figure 8 Productivity in terms of VPs/day has increased dramatically as the various productivity measures were introduced. One day’s production with the super-crew is equivalent to seven days production three years ago. A record of 20,192 VPs/day was achieved on 30 November 2009.

The introduction of a third vibrator group with a separation distance of about 11 km is presently being investigated. Note that global recording is now possible whereby the whole geophone spread is kept live in anticipation of future research results allowing ‘blended’ processing of these two records as one (Berkhout, 2008).

DISTANCE SEPARATED SIMULTANEOUS SOURCES (DS3)

Distance separated simultaneous sources – DS3 (Bouska, 2009) have now been introduced for Phase II of the survey. By reducing the number of geophone lines to 14, geophone line length could be increased to 34 km. Two groups of six vibrators are now situated 17 km apart and vibrate with dynamic grouping of vibrators, that is, any vibrator in the first group can vibrate in synchronization with any vibrator from the second group. The principle is illustrated in Figure 7 where two synchronized shots 13.5 km apart are recorded in one receiver cable 27 km long. We believe this to be a very conservative application of DS3:

- To a certain depth, there will be no interference. Bouska (2009) suggests having a source separation of greater than twice the usable source to receiver offset to avoid ‘blended’ (Berkhout 2008) recording.
- Where ‘blending’ does take place, the enormous folds, presently over 5000 (25 x 25 m bins), prove very effective in suppressing the interfering noise.
- The main source of interference is a refraction arrival from the interfering shot which is susceptible to linear noise suppression techniques, should this prove necessary. For PDO data, these measures have not been necessary.

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- The main source of interference is a refraction arrival from the interfering shot which is susceptible to linear noise suppression techniques, should this prove necessary. For PDO data, these measures have not been necessary.
Reflecting on the data improvements:
- Preliminary testing has revealed the importance of fold. Figure 11 compares a portion of an original vintage section (fully displayed in Figure 9) with three azimuths from the new WAZ survey with equivalent fold. Although different in detail, these sections appear to have similar quality. It is only the new full-fold stack of Figure 9 that provides the breakthrough in quality implying that it is the improved noise suppression of the WAZ data rather than the improved illumination. However, the stringers can be steeply dipping and in these complex situations illumination can still be expected to provide further improvements.
- A particular surprise was the improved refraction static solution due to the better surface sampling where structural artefacts in the previous solution were removed. This is demonstrated in Figure 12 where the structural ‘high’ on the vintage data has been removed on the new data. This anomaly occurs beneath a fault continuing to surface where anomalous near surface layer velocities were properly modelled with the new data.
- Due to the fine sampling and high fold, the maximum offsets (the mute) could be significantly increased improving the stack response and multiple suppression.

The acquisition design no longer forces a compromise between deep or shallow data – the whole geologic section is now properly imaged.

The ‘carpet seismic’ approach delivers large areas of high quality data with uniform character leading ultimately to more reliable interpretations.

**Flexibility of a super-crew**

A super-crew offers enormous flexibility to tackle the full spectrum of geophysical challenges. A good example is a shallow field with top reservoir just 400 m below surface. Only with a super-crew could adequate sampling be supported with reasonable productivities. For this survey, the following high resolution parameters could be applied:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fold</td>
<td>4480 (in 25 x 25 m bins)</td>
</tr>
<tr>
<td>In-line receiver interval</td>
<td>12.5 m</td>
</tr>
<tr>
<td>Receiver line spacing</td>
<td>50 m</td>
</tr>
<tr>
<td>Geophones / channel</td>
<td>12</td>
</tr>
<tr>
<td>VP grid</td>
<td>12.5 x 50 m</td>
</tr>
<tr>
<td>VP distance (km²)</td>
<td>1600</td>
</tr>
<tr>
<td>Vibrator array</td>
<td>Single vibrator</td>
</tr>
</tbody>
</table>

Another application was to a shallow Shuaiba carbonate play with the depth of interest being about 1 km. New data for the first time resolves the clinoform trends which define the reservoirs with a clarity not previously seen. Figure 13 shows a section revealing six clinoforms that have been calibrated with the drill bit. For this play, a VP grid of 25 m in the cross-line direction and in-line receiver spacing of 12.5 m were required. The super-crew provides the flexibility to adapt acquisition parameters appropriately to all geological situations.

**The state of the art**

Other technologies currently available that support the super-crew philosophy are:
- V1 (Postel et al., 2008)
- HPVA (Postel et al., 2005)
- HVPS (Allen et al., 1998)
- ISS (Howe et al., 2008)
- Stakeless VP positioning

**Looking to the future**

- Cableless systems are presently limited to small, usually environmentally sensitive areas but these systems are evolving and can be expected to make the breakthrough in the coming years.
- The use of single geophones has been a discussion point for a decade but the industry has in general stayed with...
the conventional geophone string to provide cross-line noise protection. But with the maximum channel counts on modern systems now of the order of 100,000 and still increasing, adequate cross-line protection may now be within reach with single geophones. The combination of cableless systems and single geophones could be the solution to this dilemma.

The minimum vibrator group spacing in simultaneous source mode needs to be established. Smaller spacings would allow for additional vibrator clusters which would have a dramatic impact on productivity (Howe 2008).

Higher productivity will facilitate finer VP grids with the ‘holy grail’ in reach of a 25 x 25 m vibroseis grid spacing which would support legitimate common receiver processing.

The processing of land WAZ data is in its infancy but assuming continued progress, significant processing and interpretational benefits will follow. The snail plot (outward spiral in the offset-azimuth domain) of Figure 14 demonstrates that there is a strong azimuthal effect in the data as witnessed by the sinusoidal NMO behaviour. This is presently not being fully comprehended with the traces simply being stacked together after application of an azimuthally dependent RMO. The inclusion of anisotropy within the imaging process itself has shown real progress within the marine world and we look forward to transferring this technology to land. But once these issues are resolved, indications are that crisp high resolution data perhaps challenging the quality of good marine data should be possible.

The interpretation of WAZ data is also in its infancy. The shear mechanics of interpreting numerous sections, perhaps nine or more azimuth/offset pairs, is not yet resolved. And the parameterization of these interpretations into meaningful rock properties is a significant challenge. Much research remains to be done.

Conclusion
The impact of this work cannot be underestimated. Quite reasonable estimates of ‘return on investment’ from the expected...
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reserve additions would pay the cost of the South Oman Salt Basin survey a hundred times over, thanks to the proper structural definition of prospects and fields leading to greater production, lower development costs, and fewer dry wells.

A land seismic super-crew is the answer to:
- Marine style acquisition specs
- Proper sampling
- Massive folds
- High productivities
- Low unit costs

As the South Oman salt basin survey has illustrated, spectacular improvements in data quality are possible.

Constraints do apply however:
- A minimum programme size is required of perhaps 5000 km².
- Data quality should be intrinsically bad to justify the high density high fold data described here. Designs would need to be modified for good data quality areas with less emphasis on data density.
- The terrain should be 'easy' with gravel plain as encountered in much of the Sultanate of Oman being ideal.

The experience with a land super-crew would indicate that in problemmatic data quality areas, the taking of what are essentially unnecessary shortcuts with seismic acquisition specs to 'save pennies' is a dangerous strategy to follow. Only the surface of land WAZ technology has been scratched to date. Much work still needs to be done to realize the full potential of this technology.

Acknowledgements

We wish to thank the Ministry of Oil and Gas of the Sultanate of Oman for permission to publish this paper. We also acknowledge the efforts of PDO's two seismic acquisition contractors, Ardiseis (a CGGVeritas company) for establishing the first super-crew, and BGP for the first implementation of DS³ at PDO, and also PDO's in-house seismic processing contractor CGGVeritas. Stimulating discussions with Jack Bouska were also valuable.

References

Appendix B

A Dual-Sensor, Towed Marine Streamer: Its Viable Implementation and Initial Results
Rune Tenghamn*, Svein Vaage, Claes Borresen, PGS

Summary

In 1947, Roy Paslay, George Pavey and Pershing Wipff invented the towed marine streamer (Lawyer et al., 2001; Paslay et al., 1956). Since that time, there have been many improvements in streamer technology. However, one aspect of that technology has remained fixed during the intervening 60 years; the type of seismic detector has remained the hydrophone. As a consequence, every recorded and finally processed reflection wavelet from marine streamers has been accompanied by a ghost reflection from the ocean’s surface. And the resulting filter effect on the recorded data has restricted streamer towing depths to a range of about six to nine meters. In this paper, we report on the successful addition of particle velocity sensors to a new dual-sensor towed marine streamer, and the geophysical improvements and advantages that result.

Introduction

When a seismic reflection wave arrives from below a towed streamer, the resulting changes in hydrostatic pressure are sensed by the streamer’s hydrophones. That reflection wave continues to propagate up to the ocean’s surface where it is totally reflected back downward, but with opposite polarity. This ghost reflection’s pressure wave is again sensed by the hydrophones. The effect of this “ghosting” phenomenon is the introduction of a series of peaks and notches to the recorded data’s frequency spectrum, as illustrated in Figure 1. The first notch always occurs at zero Hertz. The second and subsequent notches occur at integral multiples of a frequency equal to the velocity of sound in water (approximately 1500 meters per second) divided by twice the streamer’s tow depth. Figure 1 assumes a tow depth of eight meters, introducing spectral notches at about 94 Hertz, 188 Hertz, and so forth. A deeper towing depth would be desirable as it would place the seismic sensors farther below weather induced surface wave noise. However, it would reduce the data’s potential bandwidth even further than illustrated if Figure 1.

It has long been understood that, by sensing and recording seismic data from co-located hydrophones and velocity sensors, and by properly combining their signals, ghost reflections can be cancelled. The resulting data’s bandwidth is significantly increased because the notches of Figure 1 are eliminated. This is possible because, while both types of sensors generate the same polarity signal in response to the initial, upward propagating reflection wave, they generate opposite polarity signals in response to the ghost reflection. When the two signals are properly summed, the ghost reflection cancels. Barr et al. (1989) took advantage of this opportunity in the first viable dual-sensor ocean-bottom cable system. Prior to that endeavor, numerous attempts were made to introduce velocity sensors into towed streamers (Pavey, Jr. et al., 1966; Berni, 1982, 1984, 1985a, 1985b, 1991; to name a few). However, to the authors’ knowledge, the work reported here represents the first such successful implementation in a towed marine streamer system.

The Problem

The primary obstacle to implementing particle velocity detectors in a towed marine streamer has always been the transverse mechanical vibrations that propagate along the streamer’s stress members. This noise is commonly referred to as strum noise. It propagates along the stress members at a velocity that typically ranges from 20 to 60 meters per second, and its amplitude is very large when compared to the noises sensed by the hydrophones. Modern hydrophones are designed to be acceleration cancelling, making them very insensitive to such mechanical vibrations (McDavid, 1976).

The frequency range of the tow noise sensed by particle velocity detectors in a towed streamer is typically restricted to between about 3 and 20 Hertz.

The Solution

Figures 2a and 2b contain traces recorded from a hydrophone and co-located velocity sensor station being towed at a depth of 13 meters. The low-frequency strum noise is quite apparent in the recorded velocity sensor signal. These two traces’ amplitude spectra are displayed in Figure 3.
The traces of Figure 2, along with all the other hydrophone and velocity sensor traces comprising the common-shot record, are transformed into the F-K domain. The hydrophone and velocity sensor signals are corrected for differences in sensor and recording channel impulse responses as well as transduction constants. The velocity sensor signal amplitudes are corrected for angle-of-incidence as described by Amundsen (1993).

The velocity sensor signals are low-cut filtered to eliminate the portion of their spectra that contain the high-amplitude strum noise, i.e. the frequencies below 20 Hertz. The result is illustrated in Figure 4. This missing, low-frequency portion of the velocity sensor’s spectrum is computed from that same portion of the hydrophone’s spectrum. Using z-transform notation, the hydrophone’s signal can be expressed as:

\[ H = (1 – z^n) \beta \]

where:
- \( z \) = frequency domain time-delay operator
- \( n \) = the ghost reflection delay time;

\( \beta \) = upward traveling wavefield; and
\((1 – z^n)\) accounts for the initial arrival of each wavelet from below, followed by the time-delayed ghost reflection from the ocean’s surface which has opposite polarity.

In the same manner, the velocity sensor’s signal can be expressed as:

\[ V = (1 + z^n) \beta \]

It can be seen from the above expressions that \( V \) can be expressed in terms of \( H \) as:

\[ V = [(1 + z^n) / (1 – z^n)] \cdot H \]

It is therefore possible to perform this computation of the velocity sensor’s spectrum for frequencies that do not result in zero values of \((1 – z^n)\). This calculated, low-frequency portion of the velocity sensor’s spectrum is merged with the rest, as shown in Figures 5 and 6.

Finally, the resulting velocity sensor trace is combined with the hydrophone trace. The combined trace’s amplitude spectrum is shown in Figure 7 where all spectral notches due to ghosting at the receivers have been eliminated. The notch at 125 Hertz is a result of ghosting at the source whose depth was 6 meters.
Field Test Results

The dual-sensor towed streamer was recently used to record test data in the North Sea. It was towed at a depth of 15 meters while a conventional streamer was towed at a depth of 8 meters. Figure 8 displays the stacked data from the conventional streamer. Figure 9 displays that from the dual-sensor streamer. The data from the hydrophones and velocity sensors have been combined as previously described. Therefore, these data contain no receiver ghosts. The section has been upward continued to a depth of 8 meters for comparison to Figure 8.

Figures 10 and 11 compare the data of Figures 8 and 9, respectively, bandpass filtered 80-100 Hz. As expected, the dual-sensor streamer data contain higher-frequency energy because the receiver ghost notch filter of Figure 1 has been removed. The conventional streamer data of Figure 8, however, have been high-cut filtered by the filter of Figure 1.

Conclusions

A dual-sensor, towed marine streamer system has been successfully implemented and tested. The seismic reflection data recorded from this streamer, when properly processed, is devoid of spectral notches that are caused by ghost reflections at the receivers. The system allows significantly increased flexibility in streamer towing depth allowing continued recording in rough seas, while increasing the potential bandwidth of the data.

Acknowledgments

The authors would like to thank PGS for permission to publish this work. We also thank the many contributors within PGS for their support of this project. A special thanks to Fred Barr who has contributed with his long experience in the field of multi-component technology.
Figure 8: Conventional streamer, 8-meters tow depth

Figure 9: Dual-sensor streamer, 15-meters tow depth, upward continued to 8-meters for comparison to Figure 8

Figure 10: Conventional streamer data, bandpass filtered 80-100 Hz

Figure 11: Dual-sensor data, bandpass filtered 80 – 100 Hz
EDITED REFERENCES
Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2007 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES
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Appendix C

A Wide Line Acquisition Case for Overthrust Nappe Structure of Kulong Mountain in Jiuquan Basin

He Yongqing* and Tang Donglei, BGP, CNPC, Tang Haizhong, Yumen oil field Branch Company, CNPC

Summary

It is difficult to acquire an interpretable seismic data from the overthrust nappe structure of the Kulong Mountain. Jiuquan basin in western China, the main reason is the static problem from the complicity of the topography and the near surface geology, ray distortion caused by the overthrust nappe and the weak reflection energy from the targets. But for the field acquisition, the side wave interference is the main reason of low S/N ratio. To overcome this difficulty, in 2001, we used wide line acquisition technique to suppress the side wave and accomplished huge success. Excellent data obtained prove the effectiveness for using the wide line acquisition technique in such complex area as Kulong Mountain, Jiuquan Basin.

Introduction

The overthrust nappe structure of the Kulong Mountain is located in the north margin of the Qilian mountain range. The elevation of the overthrust nappe mountain is high (2400-4200m), and the topography is rugged and fiercely cut (see figure 1), with rapid-changing surface structure (exposured base rock with high velocity, loose gravel deposit on gully, significant thickness of alluvial gravel in mountain front) and the varied subsurface structure (overthrust nappe structure, steep-dip formation or steep thrust fault), etc. All those factors affect the seismic data quality severely. As a consequence, the seismic profile acquired in the 80s of the last century couldn’t meet the requirement for a satisfactory geological interpretation. In 2001, we used the wide line acquisition method to acquire line A and this method suppressed the side wave interference, so eventually we obviously were able to improve the seismic data quality.

The analysis of scattered noise

In Kulong mountain area, in general the relative elevation difference is about 200m; the maximum change can be as high as 400m. According to the data statistics of elevation, the largest elevation difference between adjacent channels is 101.1m (see figure 1). Along line A, the exposed formation on the surface are: Ordovician iron-bearing quartzose sandstone, Jurassic conglomerate, Carboniferous coal and sandstone (alternately layered), Permian alternate sandstone, conglomerate and organic rocks (shale and mudstone), Silurian red-yellow sandstone and amaranth shale, and the Quaternary conglomerate, etc. Therefore all kinds of noise, for example, surface waves and refracted waves, are very strong. But the side scattered waves and the scattered noise caused by other factors have the most influence on data quality.

The side scattered wave originated from the huge elevation changes in steep cliffs of displacement and the faulted plane, some even over 200m. Thus the interface between the cliff of displacement and the air is a strong wave impedance interface, and seismic wave is reflected and recorded as side scattered noise from all directions with different apparent velocities. It is the most difficult wave to suppress in the field operation and subsequent data processing.

Besides the scattered noise caused by other factors apart from the noise generated by steep cliffs of displacement, the shallow lithological interface and the anomalous geology body are the second emission sources resulting in secondary scattered noise.

None of aforementioned scattered noise can be separated from the useful reflection in the frequency domain, wave number domain, or in the apparent velocity domain. The high velocity of the secondary noise is almost the same with those of the reflection waves, therefore complicating the seismic records and reducing S/N ratio severely. It is very difficult to eliminate such a noise in data processing.

The wide line acquisition method

On the base of the model built using old seismic data and considering the scattered noise in the working area, we designed a wide line geometry (shown on figure 2) where in the center there are four receiver lines, each has 280 channels; and shot points are positioned at two sides (marked by a star).

The designed parameters are as follows:
- The geometry configuration: 4 receiving lines * 280 channels * 2 shots
- The number of channels: 1120
- Group interval: 30m
- Shot interval: 30m
- Receiver line interval: 60m
- Minimum shot-receiver line spacing in X-line: 30m
- Maximum shot-receiver line spacing in X-line: 210m
- Minimum offset: 33.54m
- Maximum offset: 8387.63m
- The spread pattern of In-line: 30-15-8385m.

The logistics and the safety management are the key elements when operating in such a complicated area as the Kulong Mountain. In addition, the vile weather and the hard drilling conditions brought more difficulties to our field work. But in the end, we overcame all difficulties and safely acquired the high-quality field data.

In order to improve the seismic data quality as much as possible, we adopted a particular strategy during different processing stages: we established a intermediate reference datum and selected a reasonable replacement velocity for the field statics, and during subsequent data processing, we have done the first arrival residual statics, surface consistent statics, the non-surface consistent statics for the static corrections, and applied linear noise suppression, abnormal amplitude suppression and the random noise suppression in the shot-point domain, the receiver domain and the common offset domain. We also arrayed single shots laterally to eliminate the scattered noise.

The fact that the data we collected this time is so much better than before proves that the wide line acquisition can suppress the side-scattered wave effectively and successfully, and the more there are the receiver and shot lines, the better the data.

After residual statics and the special processing in aforementioned domains, we can get a final section. In order to show the effect of the wide line acquisition, we chose two sections for the comparison. Figure 3 is the final section of Line A recorded by conventional 2D survey (single shot and single line), figure 4 shows the final section of the same line (Line A), but recorded with wide line technique. From figure 3, we can see that the data collected in main mountain body (on the left of the section) is poor, but on figure 4, the data in main mountain body is improved much, even the overthrust nappe section and the underlying targets layer are also very clear.
Conclusions

In the complex Kulong mountain area, the overthrust nappe structure developed abundantly and the main noises are the side-scattered wave with other scattered noise, so the wide line acquisition is the best technique to suppress noise and improve the seismic data quality.

References


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Appendix D

Modeling the impact of wide-azimuth acquisition on subsalt imaging

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ABSTRACT

Wide-azimuth towed streamer (WATS) acquisition improves the subsalt seismic image by suppressing multiples, improves the results of 3D surface-related-multiple elimination (SRME) processing, and provides more uniform seismic illumination of subsalt targets. A simple model shows that the additional suppression of multiples in the case of WATS acquisition is the result of a natural weighting of the traces going into the stack due to the areal nature of the acquisition. This simple model also shows that the extent of the additional multiple suppression is strongly dependent on the acquisition effort. A sparse acquisition effort will result in little additional multiple suppression. The use of 3D SRME processing is shown to be more accurate in predicting multiples, given input data with multiple azimuths, compared to making similar predictions from narrow-azimuth data. Three-dimensional SRME has the potential to reduce the residual multiples to the same extent as WATS acquisition with a higher acquisition effort. A complex model demonstrates that WATS acquisition does reduce the multiple-generated noise in subsalt images, but 3D SRME processing further reduces the residual multiple noise. The use of 3D SRME may reduce the multiples more than that achieved by increasing the cable half-aperture in the WATS acquisition effort. Finally, ray trace modeling is used to investigate the effect of WATS acquisition on subsurface illumination for subsalt imaging. We show that narrow-azimuth acquisition produces irregularities in subsalt illumination perpendicular to the acquisition direction which are a potential cause of migration noise. WATS acquisition results in higher and more uniform subsalt illumination and, hence, improves the subsalt image by reducing subsalt migration noise.

INTRODUCTION

Imaging beneath complex salt structures in the Gulf of Mexico is a difficult task because of the distorting effect of the overlying salt bodies. It has been observed that different acquisition directions yielded different subsalt images (VerWest et al., 2001; Michell et al., 2004) when traditional narrow-azimuth acquisition techniques are used. An example of this is shown in Figure 1 (VerWest et al., 2001). This has led to the planning and execution of multiazimuth seismic surveys (Howard and Moldoveanu, 2006; Keggin et al., 2006). However, when the distorting geometries of the overburden are very complex, no simple set of azimuths may yield a satisfactory result. This has led to the planning and execution of wide-azimuth surveys in the form of wide-azimuth towed streamer (WATS) acquisition and ocean-bottom node acquisition (Michell et al., 2006). The survey design proposed by Howard and Moldoveanu (2006) advocated a mix of multi-azimuth and wide-azimuth geometries to gain the advantages of both acquisition methods. In these WATS acquisition designs, all azimuths are acquired in a uniform manner. The WATS survey designs were developed through the use of detailed 3D finite-difference modeling (Regone, 2006a, b). The multiazimuth results led one to believe that the WATS acquisition would improve the subsalt images by improving illumination. A somewhat surprising result that came out of the modeling was the degree to which multiples were reduced. Because no random noise was introduced in the seismic models, this noise in the images came entirely from the multiples present in the modeled data. Although this was observed in the modeling results and it was demonstrated that the extent of the multiple suppression varied as a function of patch width and sail-line spacing, the mechanism that was causing the improved multiple suppression was not clear. The emphasis of the modeling was the use of realistic complex models and planned acquisition layouts.

In this paper, we use several model data sets to understand the impact of WATS acquisition and to separate that impact into multiple-suppression effects and illumination effects. The multiple-reduction effects will be further broken down into the contribution from WATS acquisition and the contribution from SRME processing. To accomplish this, both simple and complex models will be used. The simple
models are useful because they produce results that are easy to understand. The complex models are useful because they more accurately represent the subsurface, and they show that the effects seen in the simple models carry through to the more complex cases. The first section of this paper shows the mechanism by which WATS acquisition suppresses multiples, and how that effect varies as one varies the acquisition effort. The second section explores the role of SRME processing compared to WATS acquisition in suppressing multiples. This is done with a simple model and a more complex model taken from an actual deepwater Gulf of Mexico scenario. The last section explores the effect of WATS acquisition on subsurface illumination using ray tracing and a complex salt model.

**BEHAVIOR OF MULTIPLES IN WATS ACQUISITION**

Although WATS acquisition geometries can produce significantly higher-fold data that can result in higher suppression of random noise, this is not the main focus of WATS acquisition. Higher-fold and hence the same higher suppression of random noise could be achieved by increasing the fold in narrow-azimuth acquisition. The more important effect of WATS acquisition involves the behavior of coherent noise such as multiples.

To understand the behavior of multiples in WATS acquisition, a simple 1D model was constructed and analyzed. The parameters for the model are given in Table 1. The acquisition layout for the model is shown in Figure 2. It is a towed-streamer layout with an arbitrarily wide set of cables. The width of the cables is specified by the cable half-aperture, i.e., the distance from the source to the farthest cable. The cables are 100 m apart, and the receivers are located every 100 m along each cable. The cables are 8000 m long, and the source is at the front of the middle cable. The target primary was given an amplitude that was 14 dB lower than the water-bottom and the top-of-salt primaries and 20 dB lower than the water-bottom, top-of-salt peg-leg multiple. This is typical of the problems faced in imaging subsalt reflectors in the Gulf of Mexico.

The common-midpoint (CMP) gathers for this model were created assuming various shot spacings, sail-line spacings, and cable half-apertures. The first results are for 100 m shot spacing and 100 m sail-line spacing. This is a denser sail-line spacing than that currently being used for WATS acquisition and will be used as a baseline to which other variations can be compared. The corresponding gather for a single cable in line with the source is shown in Figure 3 with normal moveout (NMO) applied with the primary velocities. This is the idealized result for a narrow-azimuth acquisition. The resulting offset spacing is 200 m, and the horizontal axis that is labeled Trace number corresponds to 41 traces with offsets from 0 to 8000 m, incremented by 200 m. The data were modeled with a zero-phase wavelet with a trapezoid frequency spectrum 0-10-25-40 Hz. As can be seen in Figure 3, the multiples are aliased in the farther offsets.

![Figure 2. Acquisition layout for the model data. The receiver area is filled with receivers on a 100 x 100 m grid of length 8000 m and of variable width indicated by the half-aperture. The narrow-azimuth, single-cable result corresponds to a cable half-aperture of 0 km.](image)

![Figure 3. Gather for an 8000 m single cable from the simple model described in the text with NMO applied using primary velocities. The offset range is 0–8000 m with 200 m between traces.](image)
Figures 4 and 5 show similar gathers for the WATS case of cable half-apertures of 2000 and 4000 m sorted by increasing absolute offset. The gather in Figure 4 with the cable half-aperture of 2000 m contains 861 traces from 0 to 8246 m. However, the horizontal axis no longer represents a linear increase in offset. Because of the spatial distribution of receivers, there are more far offsets than near offsets. The gather in Figure 5 with the cable half-aperture of 4000 m contains 1681 traces from 0 to 8944 m. In both cases, the density of traces around a given offset increases linearly with offset instead of remaining constant as is the case for the single cable shown in Figure 3. This is true up to the offset which equals the cable half-aperture. Up to that point, the horizontal axis represents approximately the offset squared. The moveout of the events has not changed, but this effective change-of-variable results in an apparent change of shape for the multiple from that of approximately a parabola to that of a straight line when plotted as a function of trace number rather than offset.

This change of shape and offset distribution has significant impact when stacking the data. This has been observed in the past, and a method of reducing fold was proposed to save processing costs and improve multiple suppression (Yang, 1989). While fold reduction can result in sampling in offset squared instead of offset, it will also frequently result in aliasing of the multiples. WATS acquisition with a sufficiently high acquisition effort results in offset-squared sampling for the near offsets naturally and, because of the higher offset density at larger offsets, reduces the multiple-aliasing problem. An alternative to fold reduction is offset weighting. By weighting the traces by offset, a similar effect can be accomplished for the near offsets. However, if the far offsets are aliased, offset weighting will result in more noise in the stack from the aliased far-offset traces.

The gathers shown in Figures 3–5 are CMP gathers at a single location, but they are also the common-imaging gathers (CIGs) that would result from a Kirchhoff prestack migration. When stacked to form an image trace, the result is significantly different for the three gathers. To demonstrate this, we stacked the gathers for the narrow case (0 km) and for WATS cable half-apertures of 1 to 6 km, incremented by 1 km. These results are shown in Figure 6. In Figure 6, the left plot shows the stacked result over the window from 3.5 to 5.5 s for both multiples (arrows) and the primary (circle). The right plot shows the result for the multiples only. This was used to measure the suppression of the multiples by the stacking process. Because the primary events are flat, they constructively interfere in the stacking process. For the case of narrow acquisition (0 km), the parabolic shape of the multiples results in partial constructive interference for near offsets, resulting in a near-offset remnant of the multiple related to the zero slope at zero offset (a Fresnel zone artifact). For intermediate offsets, the multiples destructively interfere. For the far offsets, the multiples are aliased and little cancellation of the multiple occurs. It is important to note that the strongest multiple is now similar in amplitude to the target primary for the narrow case. This means that the stack process has suppressed the multiples by about 20 dB. For wide-azimuth acquisition, there is almost complete destructive interference of the multiple over the entire offset range. The higher trace offset density eliminates the aliasing problem at far offsets, and
the nonzero slope at near offsets ensures the cancellation of the multiples in that range. There is an “end-point” artifact that occurs at zero offset. However, this is much smaller in amplitude than the near-offset Fresnel-zone artifact that occurs for narrow-azimuth acquisition. Figure 7 shows the suppression of the rms amplitude of the residual multiples compared to the narrow-azimuth result as a function of cable half-aperture. It shows that there is significant additional suppression of the multiple for a cable half-aperture of 2–4 km by WATS acquisition. Past that, there is diminished benefit because, no matter how much the cable half-aperture is increased, the end-point artifact remains unchanged.

In the examples presented up to this point, the sail-line and shot spacing has been fixed at 100 m. Practical issues such as cost and acquisition time make it necessary to use lower acquisition efforts. For example, the WATS acquisition for BP’s Mad Dog survey used a 150 m shot interval and a 250 m sail-line interval. Other survey designs have been proposed and are now being acquired that involve 500 m sail-line intervals to further reduce costs. This simple model has demonstrated that the wide-azimuth acquisition can significantly suppress multiples in the data. It also gives us a mechanism to explore the trade-offs which result from reducing the acquisition effort.

In all the following examples, the cable half-aperture has been fixed at 4 km. Figure 8 shows gathers resulting from a 250 m sail-line spacing using 100 and 250 m shot spacings. The number of traces in these gathers has dropped to 700 and 280, respectively. One can see that as the number of traces drops, the multiple reflections appear more irregular due to increasingly sparser sampling. This irregularity disrupts the destructive interference that occurs in the stacking process and is responsible for the suppression of the multiple in the stack. Similarly, Figure 9 shows gathers resulting from a 500 m sail-line spacing using 100 and 250 m shot spacings with 350 and 155 traces, respectively. Figure 10 shows the resulting stacks for a sail-line spacing of 250 m and shot spacings of 100, 250, and 500 m compared to the narrow-azimuth result. Similarly, Figure 11 shows the same results for a 500 m sail-line spacing. Figure 12 shows the rms of the residual multiples relative to the rms of the residual multiples in the narrow-acquisition case. It can be clearly seen that a reduction of the acquisition effort by increasing the sail-line spacing or the shot spacing reduces the effectiveness of the multiple suppression by the WATS acquisition. As the sail-line spacing and shot spac-
ing are increased, there are variations as to exactly what offsets contribute to each CMP or CIG bin. These variations create changes in the destructive interference of the multiples. Figure 12 shows the result for only one bin. The other bins would have slightly different results, and the spread of those results is approximately ±1 dB from the points plotted. Because the combinations of offsets which contribute to a particular bin are related to the shot spacing and receiver spacing, the variations in multiple suppression will have a regular, repetitive pattern in the inline and crossline directions and can result in an acquisition-related footprint in the data.

Because the destructive interference of the multiples depends on the frequency content of the wavelet, these results will change as a function of the wavelet bandwidth. If lower frequencies are considered, the destructive interference will decrease. A greater multiple suppression for the sparser sail-line and shot spacings. However, it is best and most practical to keep the shot spacing as close to 100 m as possible. The multiple-suppression resulting from WATS acquisition occurs because of the uniform spatial distribution of the receivers. For this reason, multi-azimuth narrow-acquisition such as that proposed by Keggin et al. (2006) will not yield a similar suppression of the multiple-generated noise. The method proposed by Howard and Moldoveanu (2006) uses a combination of multi-azimuth and wide-azimuth acquisition, so it would yield some of the multiple-suppression properties described in this paper depending on the width of the wide-azimuth component. The modeling in this paper was done using NMO and stack. However, common-offset Kirchhoff migration would give the same results because the model is 1D. The behavior of the multiples in common-shot depth migration is different. The multiples in the image gather will again be linear after migration, but the slope is upward instead of downward from the zero-offset point. Thus, a similar suppression of the multiples will still occur after stack when using common-shot depth migration.

ROLE OF 3D SRME IN WATS ACQUISITION

In the previous section, we have shown that WATS acquisition suppresses multiples better than traditional narrow-azimuth acquisition. In processing of narrow-azimuth data, the process of 3D SRME has been heavily relied upon to suppress multiples (Berkhout and Verschuur, 1997; Lin et al., 2005). Where then does 3D SRME fit in the processing of WATS data? Has it been made obsolete?

To answer this question we have considered two tests. The first again involves a simple model. The model is shown in Figure 13. The model has one dipping reflector and a point diffractor. A multi-azimuth synthetic data set was generated from this model. One azimuth used offsets only in the direction indicated in Figure 13 as 0° azimuth, which is the strike direction of the dipping reflector. The other three directions contained offsets modeled with azimuths of 45°, 90°, and 135° with respect to the strike direction. First, the multiples were predicted using 3D SRME processing for this model for the shot position indicated in Figure 13 using only the 0° azimuth data, which corresponds to using narrow-azimuth data that was shot parallel to the strike of the structure. The prediction of multiples for the two lines indicated in Figure 13 is shown in Figure 14. Also shown in Figure 14 is the true position of the multiples (indicated by a dashed green line) for this model. In the center of each line, the timing of the predicted multiples is fairly accurate; but farther from the shot, one can see that the timing of the predicted multiples is in error. The 3D SRME prediction process was then repeated using all four

![Figure 10. Stacked traces for 250 m sail-line spacing. The numbers along the bottom of each figure indicate the shot spacing; the reference single-cable, narrow-azimuth result is labeled Ref.](https://pubs.geoscienceworld.org/books/chapter-pdf/3783883/9781560802853_backmatter.pdf)

![Figure 11. Stacked traces for 500 m sail-line spacing. The numbers along the bottom of each figure indicate the shot spacing; the reference single-cable, narrow-azimuth result is labeled Ref.](https://pubs.geoscienceworld.org/books/chapter-pdf/3783883/9781560802853_backmatter.pdf)

![Figure 12. Plot of the rms reduction of the multiple traces relative to the single-cable, narrow-azimuth acquisition result for various sail-line and shot spacings.](https://pubs.geoscienceworld.org/books/chapter-pdf/3783883/9781560802853_backmatter.pdf)
azimuths; the result is shown in Figure 15. Now it can be seen that the timing of the multiple predictions is much more accurate. This is not surprising because the 3D SRME process involves convolving the input with itself for all possible source/receiver positions. These positions include positions which are away from the line between the source and receiver position. Narrow-azimuth acquisition does not include this information, and such data needs to be created by extrapolation. When acquisition with additional azimuths is included, the extrapolation problem is turned into an interpolation problem, which is more accurate given the additional information. Thus, using multi-azimuth or WATS data as input to the 3D SRME process will result in more accurate multiple predictions and more effective multiple suppression because both schemes increase the azimuthal information in the data. The major difference for 3D SRME processing between multi-azimuth and WATS acquisition is that WATS acquisition would typically have a denser azimuthal coverage due to the uniform spatial distribution of the receivers.

To further demonstrate the role of 3D SRME, a test was performed on data from the simple model in the previous section. The data used was the gather for 4 km WATS acquisition with 500 m sail-line spacing and a 500 m shot interval. The stack of this gather is the 500 m result shown in Figure 11. This 4 km WATS gather has 81 fold, whereas the narrow-acquisition gather with 100 m shot spacing shown in Figure 3 has 41 fold. Even though the WATS gather has twice as many traces, they are spread over a wide range of azimuths and have much coarser inline offset spacing. This results in a very irregular appearance of the gather. In this case, the WATS acquisition did not result in a reduction of the multiple energy in the stacked trace. In fact, the rms of the multiples was 2.4 dB higher than in the narrow-azimuth-acquisition case and was the lowest point shown in Figure 12. The SRME process was used to suppress the multiples for both of these cases. In the case of the narrow-azimuth single cable, SRME processing gave a very good result. In the case of the WATS acquisition, 3D SRME processing was used to predict and remove the multiples. Both the narrow-azimuth and WATS cases were then stacked, and the results are shown in Figure 16. The SRME results are very similar for the narrow-azimuth and WATS cases. This is because of the fact that it was a 1D model, and the extrapolations required for 3D SRME processing are simple. In each case, the rms
level of the multiples was reduced about 9 dB compared to that of the narrow-azimuth case without SRME processing. The WATS result with SRME reduced the rms level of the multiples by more than 11 dB compared to the WATS results without SRME. This level of multiple suppression was achieved using WATS acquisition alone only for the higher acquisition effort such as 100 m shot intervals and 250 m, or closer, sail-line intervals. This test demonstrates that 3D SRME processing has the potential to attenuate multiples in WATS data when the acquisition has become so sparse that it alone cannot be relied upon to reduce the multiples.

The second test involves two-way acoustic model data based on a 2D input model from the deepwater Gulf of Mexico. This model is complex in 2D and has been extended in the perpendicular direction to generate a 3D model. The model data were provided by Chevron USA. The model data were generated on a fine grid and then decimated to correspond to proposed acquisition geometries for the imaging and 3D SRME tests. Data were generated from this model for the narrow-azimuth and WATS acquisition geometries with 2 and 6 km cable half-apertures. The imaging geometry used was 75 m shot spacing for the narrow-azimuth test and 150 m shot spacing for the WATS test with a 250 m sail-line spacing for both. The cables were 8 km long with receivers every 50 m. The narrow-azimuth test had a maximum crossline offset of 500 m, and the WATS tests had a maximum crossline offset of 4 km. Figure 17 shows the velocity model overlain on the migrated seismic data with no free-surface multiples. The model data also allowed us to form two orientations of the acquisition: one with the cables oriented along the section in Figure 17 (dip) and one with the cables perpendicular to the section in Figure 17 (strike). Figure 18 shows the migrated image using narrow-azimuth dip acquisition, and Figure 19 shows the migrated image using narrow-azimuth strike acquisition. Whereas there is considerable multiple noise beneath the salt bodies, which comes from free-surface multiples, when compared to the narrow-azimuth acquisition results in Figures 17 and 18. The observed reduction of the multiple noise and the improvement in the image was greater for the strike acquisition because the narrow-azimuth strike acquisition image was poorer than that from the dip acquisition. The simple model in the previous section showed that one should expect improved multiple suppression of about 10 dB in data from the 4 km WATS acquisition compared to that of the narrow-azimuth acquisition (see Figure 12).

The input data sets were then processed with 3D SRME to determine the relative improvement from that process compared to that of the WATS acquisition. The results for narrow-azimuth dip and strike acquisition are shown in Figures 21 and 22, respectively. The 3D SRME process produced a significant improvement in the image for the dip acquisition but failed beneath the deeper salt body for the strike acquisition. The improvement for the dip acquisition resulted from the fact that the model was invariant in the orthogonal direction, and the extrapolations required for 3D SRME processing produced a good result. For the strike acquisition, the orthogonal direction (which has limited offset sampling by the acquisition) is highly variable and, thus, the extrapolation is difficult. The 4 km WATS dip acquisition result with 3D SRME is shown in Figure 23. It can be seen that this result is an improvement over the 4 km WATS result without 3D SRME in Figure 20 and over the narrow-azimuth dip acquisition result with 3D SRME in Figure 21. It is also a significant improvement over the narrow-azimuth strike acquisition result with 3D SRME in Figure 22. Thus, although WATS acquisition shows the improvement for the dip acquisition resulted from the fact that the model was invariant in the orthogonal direction, and the extrapolations required for 3D SRME processing produced a good result. For the strike acquisition, the orthogonal direction (which has limited offset sampling by the acquisition) is highly variable and, thus, the extrapolation is difficult. The 4 km WATS dip acquisition result with 3D SRME is shown in Figure 23. It can be seen that this result is an improvement over the 4 km WATS result without 3D SRME in Figure 20 and over the narrow-azimuth dip acquisition result with 3D SRME in Figure 21. It is also a significant improvement over the narrow-azimuth strike acquisition result with 3D SRME in Figure 22. Thus, although WATS acquisition shows

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Figure 17. Velocity model for synthetic data overlain on the depth image produced from a 4 km WATS input data set with no free-surface multiples.

Figure 18. Depth image for narrow-azimuth dip acquisition.

Figure 19. Depth image for narrow-azimuth strike acquisition.
Improved imaging related to its suppression of multiples, 3D SRME processing further improves the result. The improvement in the image resulting from the WATS acquisition and the 3D SRME process appears to be more significant for the reflectors which strike parallel to the acquisition direction. For components of the structure which are dip to the acquisition direction, the 3D SRME process applied to narrow-azimuth data produced a good result although this too was improved by the WATS acquisition. Because complex 3D subsurface geology has a combination of dip and strike components with respect to the acquisition direction, the use of WATS acquisition and 3D SRME together will be necessary to obtain the best images of the subsurface. In some cases, the use of 3D SRME processing may provide more improvement in the image than an increase in the WATS acquisition cable half-aperture for significantly less cost. Models such as those used here, or 3D models such as those used by Regone (2006a, b), are useful tools for evaluating those situations.

Although this last model looks more realistic and clearly demonstrates the role of WATS acquisition and 3D SRME in improving the image, it does not illustrate why the WATS acquisition suppressed the multiples. This is an example of a model which is complex enough to be credible but does not explain in a simple way the underlying mechanism. By using both simple and complex models, we have shown the impact of WATS acquisition and 3D SRME processing on the subsalt seismic image and the underlying mechanisms.

ILLUMINATION MODELING OF WATS ACQUISITION

We used a different form of modeling to investigate the impact of WATS on subsurface illumination. This was based on ray tracing. The velocity model used was the full sediment-salt velocity model for a portion of the Walker Ridge area of the deepwater Gulf of Mexico. A 3D view of the velocity model is shown in Figure 24. Also shown in Figure 24 is a constant-depth target horizon at 8800 m, which is approximately the depth of interest for exploration targets in this area. This is an area of moderate salt complexity, and good subsalt images are obtained using single-arrival Kirchhoff depth migration. Hence, multiple-arrival ray-based modeling should give some insight into the imaging and illumination. The illumination of this target horizon was modeled by ray tracing based on acquisition...
in the E-W direction with a narrow-azimuth acquisition with a cable half-aperture of 450 m, then with a multiazimuth acquisition with cable half-aperture of 450 m using E-W and N-S acquisition, and finally with E-W WATS acquisition with cable half-aperture of 4 km. In each case, the maximum inline offset was 7420 m. The ray tracing included amplitude effects by means of approximate wavefront curvature calculations. The modeled data were then used to calculate the number of ray hits and the illumination amplitude on the target horizon. The illumination amplitude result for the narrow-azimuth acquisition is shown in Figure 25. The higher amplitude area in the lower right corner corresponds to the region where there is no salt in the overburden. All of the results were normalized to give the same response in this area so that one could evaluate the relative response in the subsalt areas. The thing to note about this result is the horizontal streaking in the subsalt area which corresponds to the acquisition direction and is not seen in the extra-salt areas. The result for a multiazimuth acquisition using two directions, E-W and N-S, is shown in Figure 26. This has produced a more connected illumination beneath the salt, but there is still an overprint of the two acquisition directions on the illumination. The result for a 4 km WATS acquisition is shown in Figure 27. One can see that the increased cable half-aperture has eliminated the acquisition-related striping in the subsalt area, and high- and low-amplitude features coalesce into more continuous features, which can be correlated to structural features in the top and base of salt. These high- and low-amplitude features will always exist because the salt acts as a lens that focuses or defocuses the acoustic energy. The WATS acquisition has produced two important changes in these results. The first is that the overall illumination is increased compared to that of the narrow-azimuth or multi-azimuth acquisition. However, another important effect is that the acquisition-related striping in the illumination has been significantly reduced. The discontinuous illumination in the narrow-azimuth result can produce migration noise in the subsalt region related to the discontinuity of the reflection information. The reduction of this discontinuous nature of the illumination by the WATS acquisition may result in less migration swing noise and, hence, improved subsalt images.

Figure 24. A 3D view of the velocity model used in illumination study along with the target horizon at 8800 m depth. The colors displayed on the target horizon represent the illumination amplitudes from the modeling for 4 km WATS acquisition.

Figure 25. Illumination amplitude map on target horizon for narrow-azimuth acquisition with a cable half-aperture of 450 m. The E-W acquisition direction was horizontal relative to this map.

Figure 26. Illumination amplitude map on target horizon for multi-azimuth acquisition with two azimuths, E-W and N-S.

Figure 27. Illumination amplitude map on target horizon for 4 km cable half-aperture WATS acquisition. The E-W acquisition direction was horizontal relative to this map.
CONCLUSIONS

We have demonstrated the potential impact of WATS acquisition on subsalt imaging using a series of seismic models. WATS acquisition improves the seismic image by suppressing multiples, improves the results of 3D SRME and provides more uniform seismic illumination of subsurface targets.

First, we used a simple model to show that the additional suppression of multiples in the case of WATS acquisition is the result of a natural weighting of the traces going into the stack because of the areal nature of the acquisition. The extent of the multiple suppression is strongly dependent on the acquisition effort. A sparse acquisition effort will result in little additional multiple suppression. The 3D SRME process is more accurate in predicting multiples given input data with multiple azimuths compared to making similar predictions with narrow-azimuth data. The 3D SRME process has the potential to reduce the residual multiples to the same extent as WATS acquisition would with a higher acquisition effort.

A complex model was used to demonstrate that WATS acquisition does reduce the multiple-generated noise in subsalt images, but 3D SRME processing further reduces the residual multiple noise and improves the images. The use of 3D SRME processing may reduce the multiples more than would an increase of the cable half-aperture in the WATS acquisition effort. Thus, the use of 3D SRME processing may allow one to obtain equivalent image quality with a reduced WATS acquisition effort for exploration. However, for development where the cost of higher quality images is justified, wider and/or denser WATS acquisition plus 3D SRME processing may be necessary.

Finally, we used ray trace modeling to investigate the effect of WATS acquisition on subsurface illumination for subsalt imaging. The WATS acquisition results in higher illumination levels subsalt. However, another important effect is that the illumination from WATS acquisition is more uniform; and irregularities in illumination, present in narrow-azimuth acquisition and a potential cause of migration noise, are significantly reduced.

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B028

Improved Marine 4D Repeatability Using an Automated Vessel, Source and Receiver Positioning System

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SUMMARY

A new automated and integrated, vessel, source, and receiver control system has been developed to improve the accuracy and repeatability of 4D surveys. The new control system replaces operator intervention with automated updates to vessel, source, and streamer steering devices from positioning information from all in-sea equipment. This has lead to a step change in the accuracy of source repeatability (2.5-m repeat accuracy for 95% of shotpoints), and has also improved the ability to repeat receiver positions.
Introduction
Source and receiver repeatability is one of the most critical aspects for time-lapse seismic acquisition. In this paper, we describe a new automated marine field positioning system for achieving improved source and receiver repeatability. The system has gone through several stages of testing, and the most important repeatability test results are given. The test results have since been confirmed through several successful 4D surveys in the North Sea during the 2007 season, and also during wide-azimuth surveys in the Gulf of Mexico.

Integrated vessel, source, and streamer steering
A new integrated steering controller, called Q-Pilot, has been developed. Q-Pilot will automatically steer the vessel, the sources, and the streamers to achieve the best possible 4D position match. The combined control system, source steering, and streamer steering is called dynamic spread control (DSC). In the development of the system, three important features were identified: 1) Automation – it is not possible for an operator to accurately predict the behavior of the towed spread and the vessel in a changing current environment. 2) Independent source steering – very tight specifications on source position repeatability are not possible to achieve even with optimal and automated vessel steering. Controlling the source position independently is a vital ingredient and this means that the vessel may be steered to position the front end, which improves the receiver repeatability. 3) Planning and QC – Planning the 4D survey acquisition is more involved and requires more care than planning a regular exploration 3D survey. Hence, dedicated software was developed to provide an optimized navigation plan (NavPlan) for each 4D monitor survey. These three key items formed the basis for defining the system requirements.

The NavPlan contains the desired source and receiver positions. NavPlan positions are simply subtracted from the measured real-time positions from the navigation system and run through independent controllers for the streamer steering devices, winches (for source steering), and vessel. In addition, several feed-forward controllers are used to improve the system performance.

The vessel controller can be set up in several different ways. The basis for the vessel steering is the track point. Figure 1 shows an example where the track point is set up to be the streamer front ends. The vessel is moved to starboard because the current is pushing the entire spread to port.

At the same time, the winches control the sources so that both the streamer front ends and the sources are positioned correctly.

Accuracy of source positioning
In a recent test in the North Sea, we performed source repeatability tests by matching to a predefined NavPlan. The plan called for matching a dual source configuration to a non-straight line, thus increasing the difficulty of achieving the necessary accuracy compared to straight preplot line shooting. The test result showed source positioning error to be less than...
2.5 m for 95% of the shotpoints (Figure 2). This level of accuracy is an order of magnitude better than some conventionally acquired 3D surveys.

In another test in the Gulf of Mexico, in an area with stronger and more rapidly varying ocean currents, the same excellent source repeatability results were achieved. This test was done during a wide-azimuth survey, where two streamer vessels were equipped with identical spreads and exposed to the same environmental conditions. One streamer vessel (dark blue) had the DSC system installed and the other streamer vessel (dark red) was manually steered. In this way, a true apple-to-apple comparison was achieved. The vessel with the DSC system achieved 4-m error or less relative to the preplot for 95% of the observations, while the manually steered vessel achieved 14-m error or less. The results were consistent for the duration of the test, which lasted for a few weeks. Also seen on the graph is that the source positioning results for the source vessels is somewhere between the two streamer vessels. A source vessel is not towing a large seismic spread and is much easier to maneuver than a streamer vessel. However, not even the easy-to-control source vessels can match the performance of the DSC-controlled vessel.

**Accuracy of receiver positioning**

As described in the previous paragraphs, the DSC system can, for all practical purposes, eliminate source positioning errors. This level of source repeatability is important for 4D binning. During the same North Sea test that was mentioned previously, we also tested the ability of the system to repeat receiver positions accurately.

A baseline test line was acquired first without any active streamer steering. This test line is shown in dark blue in Figure 4. It had a streamer feather that varied from almost -6° to +3° – i.e., a variation of 9° over the entire line. For the shotpoint range shown in the graph, the
variation is 4°. Once the baseline was established, three different attempts were made to repeat the baseline streamer feather (green, red, and cyan lines).

The left part of Figure 4 shows the streamer feather relative to the straight line preplot, calculated from the P1/90 navigation data. A very good feather match is obtained for the range of shotpoints shown. The right part of Figure 4 shows the estimated streamer feather calculated from the measured ocean current as dotted lines. The solid green and blue lines on the right graph are the same as the left graph, i.e., the streamer feather calculated from the navigation data while the red and cyan lines are omitted for clarity. A linear relationship is assumed – i.e., streamer feather is estimated as the angle between the measured vessel speed and the crossline component of the measured ocean current. This simple principle is illustrated in Figure 5, where Φ is the estimated streamer feather. The estimate can be quite noisy, so in Figure 4, the estimate is filtered before plotting.

As shown in the right part of Figure 4, the estimated feather appears to be reasonably good when compared to the true measured streamer feather from the baseline line (dark blue). Also, the green shows that, in this case, the currents were too strong for the streamer steering to be able to compensate. During this line, the streamers are steered with maximum available force towards the baseline line for the entire line, but because the streamer steering devices are only able to compensate for roughly 3° of streamer feather, a good feather match is never obtained. For the other two lines it is further observed that the natural feather (assuming that the estimated feather from the current meter data is a reasonable approximation to natural feather) is quite different from the baseline line. No attempts were made to match the tidal cycles on these test lines and, with careful planning of line start times in regions where the currents are mainly tidal driven, it should be possible to achieve very good results with this system.

**Benefits for survey efficiency and design**

Having shown that source repeatability error can be reduced to almost zero, we can now envisage more efficient survey designs. While the system has been designed to benefit 4D...
applications, there are other situations where source repeatability is important, e.g., wide-azimuth surveys. The recent implementation of wide-azimuth towed-streamer surveys, mainly in the Gulf of Mexico, has led to acquisition of surveys with a much higher density of traces. This presents challenges to data processing in terms of cost and efficiency. However, the survey designs call for repeating shotpoint positions many times. If these shots can be repeated to sufficient accuracy, then they can be merged to form supershots with a dramatic reduction in data processing time and cost.

In 4D applications, the need for combined source and receiver repeatability has been demonstrated: see, for example, Calvert (2005) and Smit et al. (2005). Reducing the source repeat positioning errors to almost zero allows control of the final repeatability solely by the receiver repeat positioning errors. Goto et al. (2004) demonstrated the use of streamer steering to improve receiver repeatability and other attempts to improve repeatability include the use of streamer overlap, although the latter reduces the survey efficiency by deploying more in-sea equipment (streamers and associated devices). Of course, there is no reason why both streamer steering and overlap cannot be used simultaneously.

The use of an automated vessel, source, and streamer steering facility improves the repeatability of the 4D survey, which feeds through into ultimately more efficient surveys. The additional level of control also allows the possibility of acquiring “antiparallel” surveys (adjacent swaths are acquired in opposite azimuths), which have superior geophysical attributes in terms of azimuth sampling (Vermeer, 2002). An added benefit to acquiring 4D surveys in “antiparallel” mode is that higher streamer feather differences can be tolerated before the combined source and receiver position errors fall outside 4D repeatability specifications.

Conclusions
We have documented a new automated and integrated vessel, source, and streamer positioning system called dynamic spread control that can be used in 4D applications to improve significantly the accuracy of repeat surveys. The DSC system is able to provide accurate feather match for lines with dynamically changing feather, provided that the current strength is less than the operating capability of the streamer steering devices. The DSC system produces a step change in source position accuracy. A major part of this improvement comes from the automation, thus removing the need for frequent operator intervention.

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