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Recent trends in offshore exploration: More data, less model

Summary

New marine acquisition techniques – such as wide- and multi-azimuth, over-under and dual-sensor – provide additional data that complement conventional narrow-azimuth towed streamer data. These new data help reduce uncertainties in velocity model building and ultimately lead to a more accurate image of the subsurface.

Introduction

It is a well known aspect of the general inverse theory that ill-posed problems need additional constraints to be resolved. These constraints often take the form of an *a priori* model from which the solution is required not to differ too much. This model represents an initial guess that must obviously be close to the exact solution if we want the correct answer. An alternative approach is to collect more independent data to reduce the under-determination of the system.

Imaging in complex geology where pre-stack depth migration is required to correctly reveal the subsurface structure is such an ill-posed problem. Common exploration targets include sub-salt, sub-basalt, and beneath gas plumes. The complex structures and the high velocity contrasts in these regimes combine to diffract seismic waves in all directions. The little energy that gets recorded by the relatively small streamer spread does not contain enough information to fully reconstruct the complex structures. In addition, noises (such as multiple reflections) further distort the already weak signals. Consequently, imaging in these complex geology regimes leaves a lot to interpretation.

To reduce under-determination more independent data must be collected. The industry started to gradually increase the streamer spread, reaching typically 9km in length and up to 1.3km in width. This comparatively small width was first addressed by acquiring surveys in multiple directions (see for example La Bella et al., 1998). Later techniques extended the width using additional source vessels (see for example Michell et al., 2006). An alternative approach is to acquire ocean-bottom seismic, which provides wide-azimuth as well as potentially multi-component data, but at a significantly higher cost.

It was also observed that due to attenuation and other high-frequency losses, target reflections often contain mostly low-frequency energy. Hence, enhancing the low-frequency content of seismic data provides higher signal-to-noise ratio. This can be readily achieved by towing sources and streamers deeper to benefit from the low-frequency boost of the ghost. However, the deep tow eliminates high-frequencies and a compromise has to be found to preserve resolution in the overburden.

Recent developments, such as dual-sensor streamer (Tenghamn et al., 2007) and 3D over-under (Kragh et al., 2009), gather more independent data and offer a no-compromise bandwidth extension on the receiver side. On the source side, over-under (Moldoveanu, 2000) and multi-level arrays (Cambois et al., 2009) also increase low-frequencies without loss of high-frequencies.

The methods listed above will be further developed and illustrated with various examples from around the world.

Increasing the spread

Longer offsets

The most efficient way to gather more independent data is simply to increase streamer length. The larger offsets offer the opportunity to undershoot some structures as illustrated by Figure 1. Streamers can now extend to 15km, as demonstrated recently in Indonesia with a Sercel Sentinel (Gratacos, 2010), but most 3D spreads are typically 8 to 9km long. The width however is much shorter and the widest spread on record reached a comparatively modest 1.3km (14 streamers 100m apart towed by Ramform Sovereign offshore Brazil in 2009). This discrepancy between in-line and cross-line lengths is acceptable for dip-strike features, but not for the more complex structures.

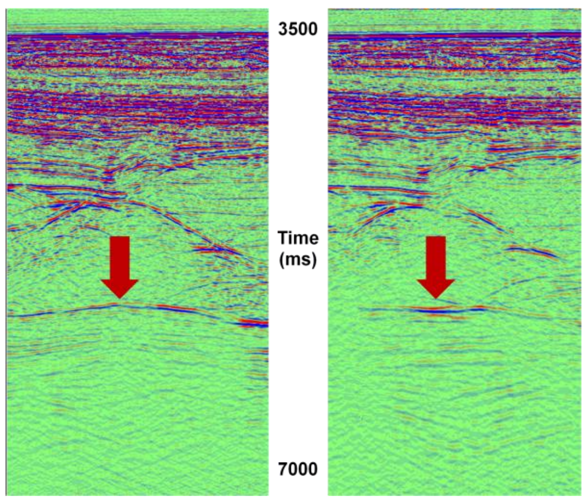

Figure 1: Pre-stack time migrated image of a salt structure in West Africa for near-offsets (left) and far-offsets (right). Large offsets undershoot the structure which explains the smaller pull-up for the base of salt (arrow) and the improved data quality subsalt. Note that residual NMO corrections cannot align the base of salt arrival times, demonstrating the need for pre-stack depth migration.

Multi-azimuth

A simple way to overcome the dip-strike limitation is to shoot the survey in multiple directions. These multi-azimuth (MAZ) surveys benefit from better illumination (Figure 2) but also from improved multiple attenuation (Figure 3) as explained by Widmaier et al. (2002). Keggin et al. (2006) showed that the superior image quality comes from the diversity of azimuthal information and not from the increased fold (Figure 4). The key to remove under-determination is to add new *independent* data and not just more redundant data.

The cost of a MAZ survey is of course proportional to the number of azimuths recorded. However, a 6-azimuth survey is much cheaper than 6-times the single azimuth cost. Obviously the mob/demob cost only applies once, but the line changes can be minimized following a carefully designed shooting plan. Also, azimuths can be chosen as a function of the swell, thereby reducing weather standby.

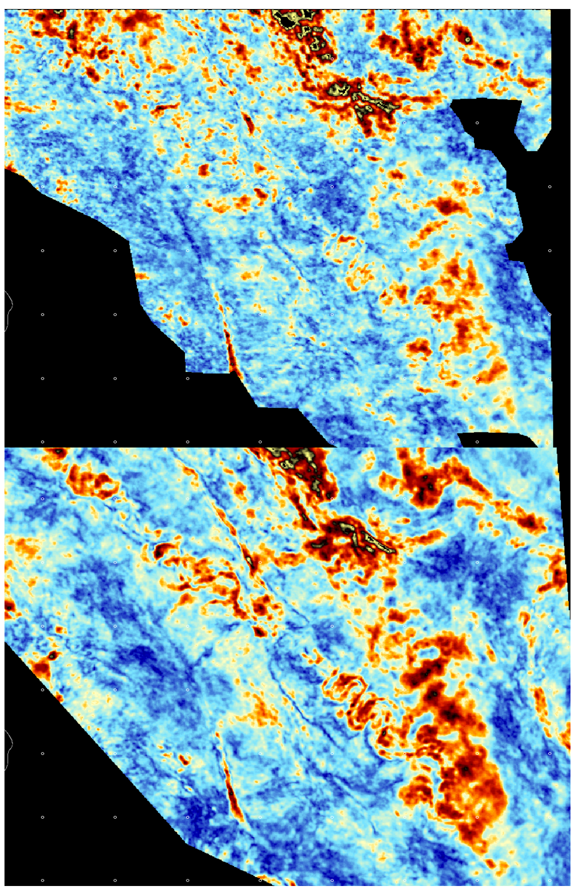

Figure 2: Seismic amplitude extract for a single azimuth (upper) and six azimuths (lower) from the Nile Delta, Egypt. From Keggin et al.

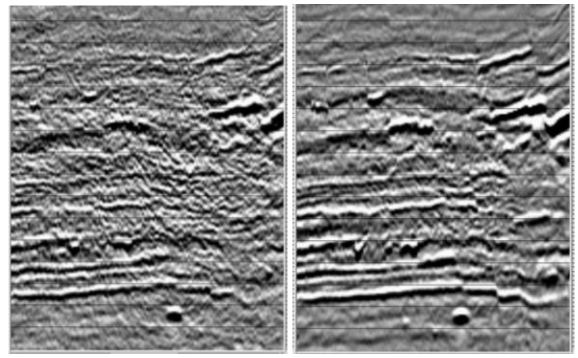

Figure 3: Seismic image for a single azimuth (left) and six azimuths (right) from the Nile Delta, Egypt. Diffracted multiples have been dramatically attenuated.

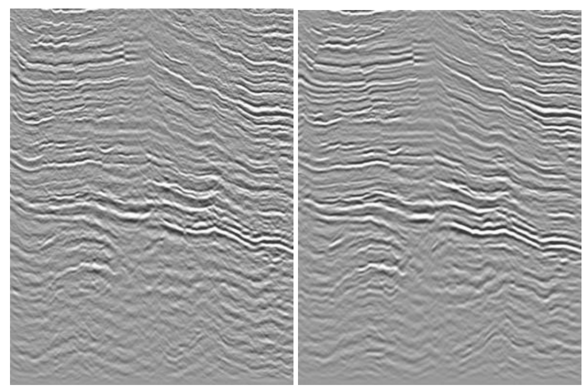

Figure 4: 60-fold single azimuth image (left) compared to 60-fold multi-azimuth image (right). The improved quality, especially in the deep, shows that the superiority of MAZ surveys is not due to increased fold but to azimuthal diversity. From Keggin et al.

Wide-azimuth

Another approach to increase the cross-line width is to decouple sources and receivers. This requires the use of at least one seismic recording vessel and two source vessels. The survey is acquired via several passes, gradually offsetting the source vessels laterally. Other designs involve more than one recording vessel. These wide-azimuth (WAZ) surveys show improved illumination and multiple attenuation (Figure 5).

MAZ and WAZ surveys give the same imaging benefits and the main geophysical differences are in offset and azimuth sampling. Cost is obviously a differentiating factor with MAZ being more efficient for mid-size surveys (ca. 1,000km^2) and WAZ for large exploration surveys (ca. 10,000km^2) where line turns are a minor issue. Note also that WAZ is the preferred solution in areas where a border cannot be crossed.

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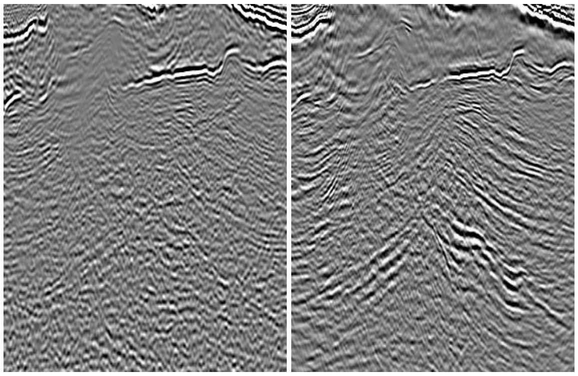

Figure 5: Narrow-azimuth survey (left) compared to wide-azimuth survey (right) in the Gulf of Mexico. From Michell et al.

Other approaches

Howard (2004) combined the WAZ and MAZ concepts in a hybrid method called RAZ, for rich-azimuth survey. The survey was originally designed for the Shenzi field in the Gulf of Mexico and included shooting during line turns. Moldoveanu pushed this idea further in 2008 proposing to shoot in circles, thus generating a wide range of azimuths (through a combination of MAZ and streamer bending) using only one 3D vessel. However, this method requires a lot of circles to obtain a regular offset-azimuth distribution, which makes it economical for small size surveys only.

Ocean bottom surveys are another way to decouple sources and receivers and obtain a wide range of azimuths. The cost, however, is generally much higher than for equivalent MAZ or WAZ surveys, especially in deep water. This method is therefore limited to congested areas inaccessible to streamers, and for the special case of gas chimneys where converted-waves are the only way to image the subsurface.

Enhancing low-frequencies

The bandwidth of towed-streamer marine data is ultimately limited by the ghost. The up- and down-going wave interferences are destructive for some frequencies, but constructive for other frequencies. The deeper the tow, the lower the first notched frequency, but also the lower the boosted frequency. For example, a 25m tow produces a notch at 30Hz and a 6dB amplitude boost at 15Hz. Since subsalt imaging benefits from low-frequency content, it seems logical to tow the streamers as deep as possible. However, the lack of high-frequencies limits the shallow resolution, which results in an inaccurate picking of the top-salt and therefore an inaccurate velocity model. Ideally we should deghost marine streamer data to benefit from the full bandwidth. This can be achieved by two methods: over-under (Brink and Svendsen, 1987) and dual-sensor streamer (Tenghamn et al., 2007).

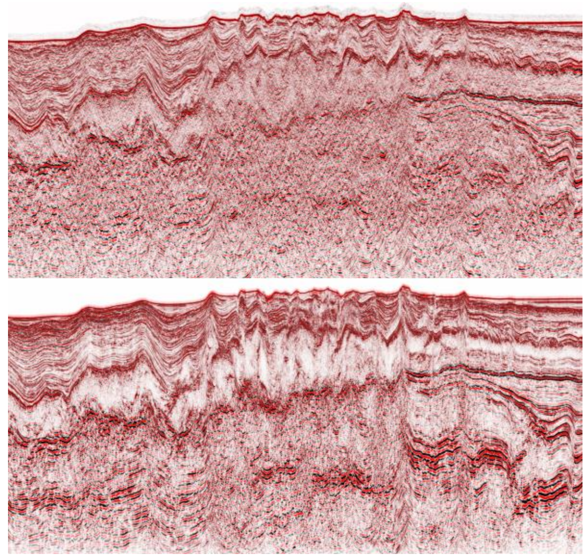

Figure 6: Conventional streamer (top) and 25m towed dual-sensor streamer (bottom) offshore Cyprus. The additional low frequencies provide an improved image below the Messinian without compromising shallow resolution. From Lie and Semb (2009).

Figure 6 illustrates the benefits enhanced low-frequencies can bring to imaging beneath an attenuating overburden, in this case the complex anhydrite and channel fill in the Messinian. It is a 2D example with a dual-sensor streamer, but the technology also works well in 3D (Figure 7). Over-under has generally been limited to 2D due to the complexity and the inefficiency of towing two 3D spreads one on top of the other. Kragh et al. have showed in 2009 that the *under* spread could use less and sparser streamers, making over-under more efficient in 3D.

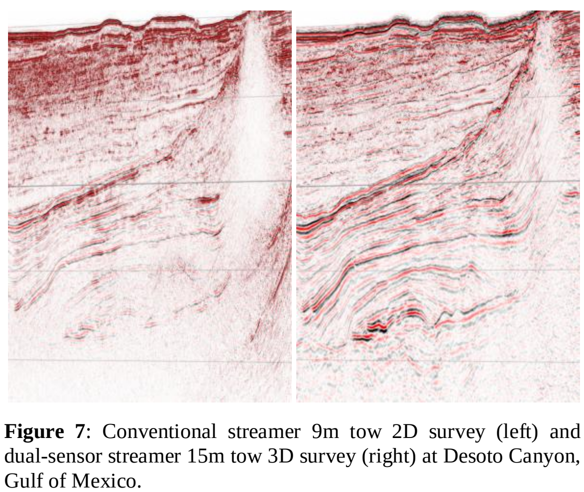

Figure 7: Conventional streamer 9m tow 2D survey (left) and dual-sensor streamer 15m tow 3D survey (right) at Desoto Canyon, Gulf of Mexico.

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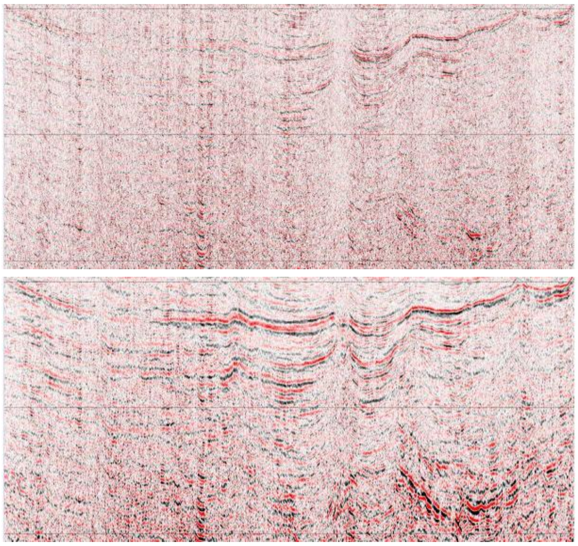

Figure 8: The enhanced low-frequencies provided by a dual-sensor streamer and a multi-level source (lower) result in a much clearer image than with conventional source and streamer (upper). From Cambois et al.

Over-under can also be used to remove the source ghost, further enhancing the data low-frequency content. An alternative approach is to tow the sub-arrays at different depths and shoot them in sequence to build a constructive down-going wave at the expense of the up-going wave (the source ghost). This beam steering technique, called multi-level source reduces the energy of the ghost and increases the data low-frequency content (Figure 8).

Benefits for velocity model building

In addition to the imaging benefits described above, these new acquisition techniques can also improve the velocity model building part of the process. For example, Van der Burg et al. (2010) demonstrated that a multi-azimuth tomography can provide a much higher-resolution velocity model than a single-azimuth tomography (Figure 9). The increased low-frequency content also reduces the need for well constraints during inversion (Figure 10). Inversion can be either full-waveform (Kelly et al., 2010) or stratigraphic (Özdemir, 2009; whose title clearly inspired this one!).

Conclusions

Recent developments in marine acquisition provide new independent data that dramatically improve imaging of complex structures. The spread extension in the cross-line direction (via MAZ or WAZ) gives better illumination and multiple attenuation, while additional low-frequencies increase seismic wave penetration. The velocity model building also benefits from these new acquisition techniques, thereby improving image quality.

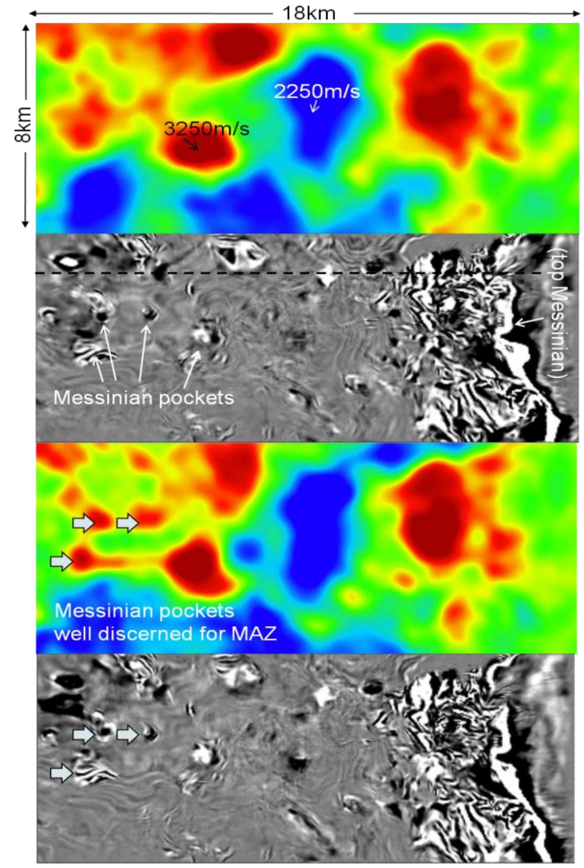

Figure 9: Depth slices for velocity and seismic just below top-Messinian for single-azimuth (upper) and multi-azimuth (lower) tomographic inversion. Note the anhydrate pockets (arrows).

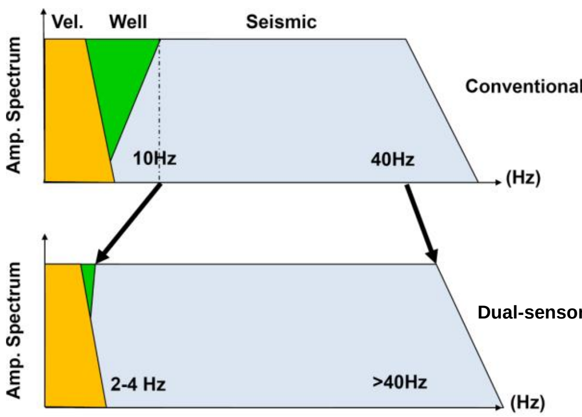

Figure 10: Theoretical amplitude spectra for conventional and dual-sensor data. The increased bandwidth toward low-frequencies without high-frequency losses reduces the need for well constraints during inversion. From Reiser and Ribeiro (2010).

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