True 3D Seismic—Wide Azimuth Comes Of Age

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As wide azimuth (WAZ) becomes more widespread, its benefits are being seen in many different geological settings and areas worldwide. It is no longer considered an application solely beneficial for the Gulf of Mexico.

WAZ offers advantages for:

- complex overburdens, such as sub-salt, sub-basalt, and below unconformities;
- complex near-surface, such as rugose waterbottoms and land data with complicated topography; and
- fractured reservoirs.

Even in less complex areas, benefits can be seen. The step-change in the improvement of WAZ over narrow-azimuth (NAZ) data, in terms of improved illumination and imaging, better noise and multiple suppression, and the ability to derive high-fidelity velocity and anisotropic parameters, can be seen as analogous to the change from 2D to 3D seismic data.

Conventional NAZ marine acquisition provides dense sampling, but only of a very limited aperture of the wavefield. This means that the picture of the subsurface is influenced by the direction of shooting, and different images are obtained from surveys acquired in the dip and strike directions. With full-azimuth acquisition both these images, and those from all other azimuths, are combined to give the complete picture. Conventional land and OBS surveys generally sample the full range of azimuths, but sparsely and with limited crossline offsets, which results in noisy data. The trend of increasing the density of land acquisition, and the movement of marine acquisition to wider azimuths, means that land and marine acquisition are converging. The aim of both types of acquisition now is to obtain high-density, long-offset, full-azimuth datasets.

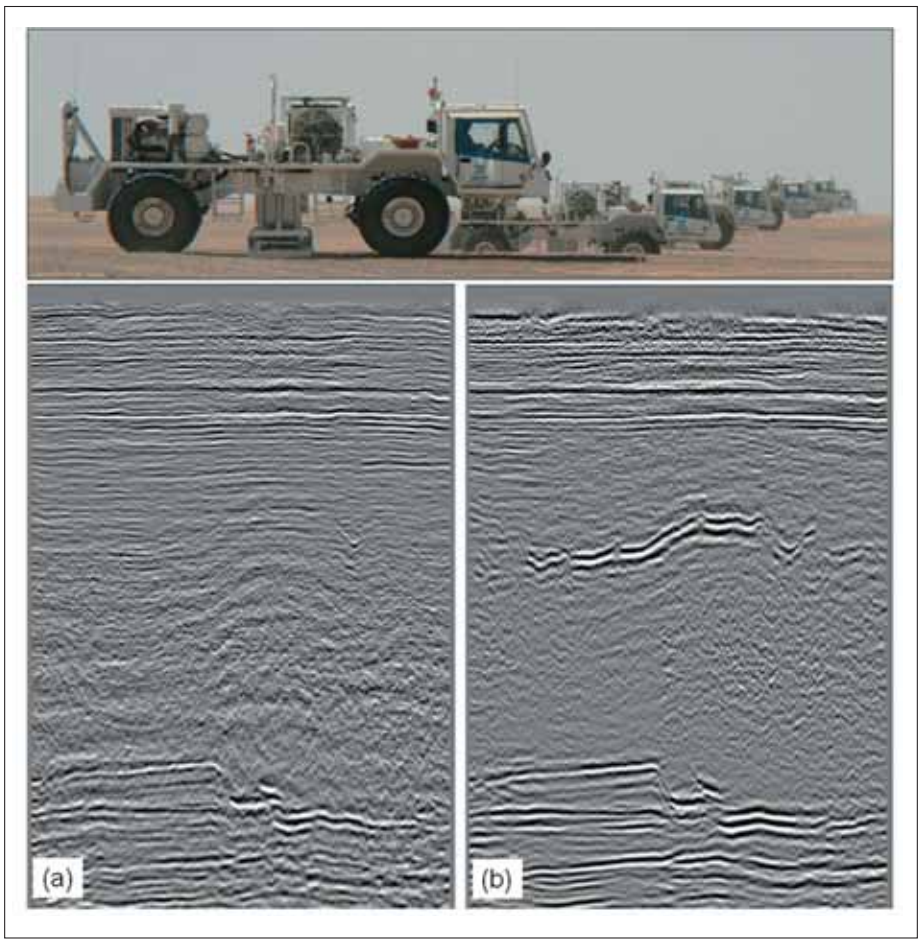

Fig. 1. High-productivity 40,000-channel super-crews enable efficient high-density WAZ. (a) Conventional narrow-azimuth data reprocessed in 2008 and (b) WAZ acquisition and processing showing significant improvement over conventional NAZ data. (from Wombell et al, EAGE Subsalt Imaging workshop, Cairo 2009).

On the face of it, acquiring data with the full range of offsets and azimuths is not complicated. However, using old techniques would make this prohibitively expensive and time-consuming. New acquisition technology, in both land and marine, has made this a practical proposition.

The High-Density Revolution Onshore

High-channel-count recording systems and high-productivity vibroseis techniques have created a revolution in onshore 3D seismic productivity, enabling the move from sparse to high-density WAZ acquisition. This is being made possible by high-specification super-crews, which are recording data at up to 100 times the density of conventional land surveys, and at rates that are breaking records regularly. These efficiencies are being achieved by increasing the channel count to several thousand and conducting 24-hour operations. This increase in productivity has made high-density WAZ recording affordable. The new-generation land acquisition is in fact denser than current marine WAZ surveys by a factor of 10. This is important in the onshore environment to ensure adequate sampling of the seismic wavefield, including signal and coherent noise, so that the full benefits of WAZ techniques can be realised through the latest WAZ land processing.

Single-Vibrator Seismic

Using techniques such as V1 single-vibrator acquisition, developed by CGGVeritas, a step-change in source productivity has been achieved. V1 allows a large number of vibrators to act independently as separate seismic sources. This is done within a slip-sweep (overlapping sweeps) acquisition scheme, where long sweeps are used and wait times (slip times) between sweeps are as short as possible. For high-density surveys, this creates a huge increase in productivity and allows CGGVeritas crews to routinely record over 600 source points per hour.

V1 acquisition results in better image quality. Although less energy is emitted per shot point, the increase in the density of the source (and receiver) spread more than compensates. In addition to the increase in fold this creates, the denser geometry reduces acquisition footprint

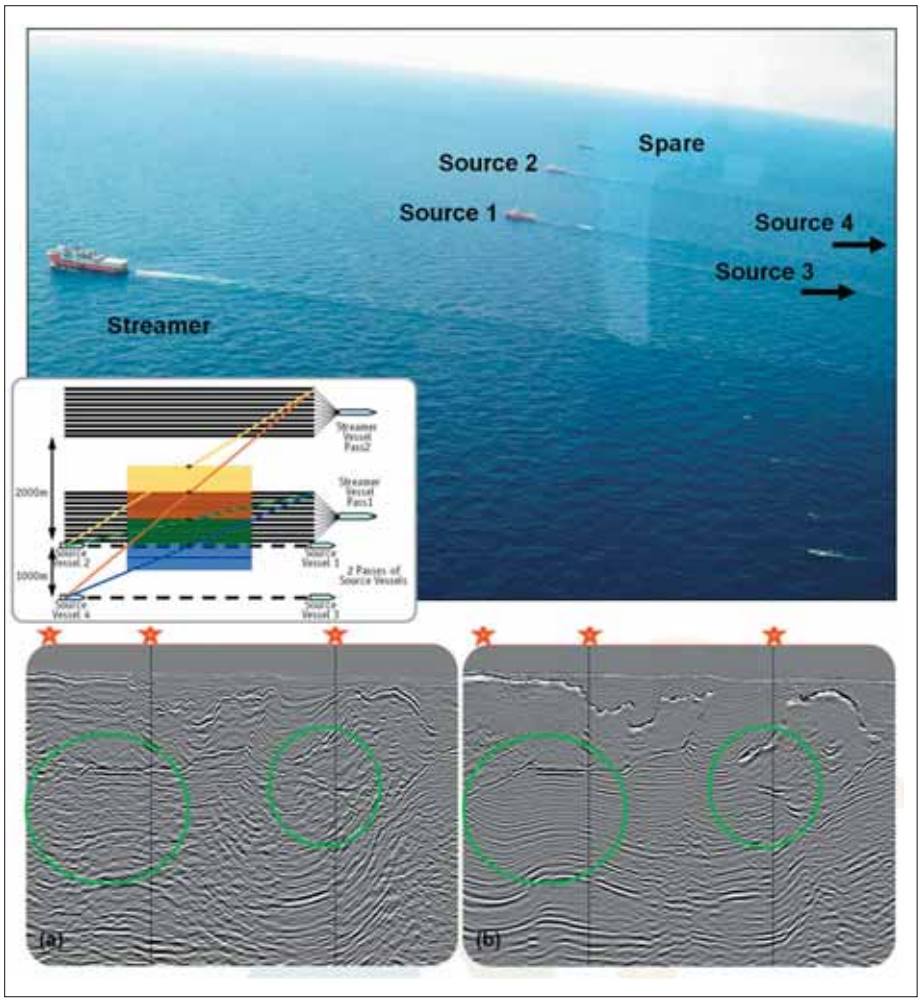

Fig. 2. WAZ acquisition in action on the Walker Ridge survey acquired in two passes, using a ten-streamer vessel and four source vessels. This data library survey covers some of the most significant recent finds in the Gulf of Mexico. The resulting data: (a) NAZ one-way wave equation migration and (b) WAZ one-way wave-equation migration which illuminates the pre-salt plays. Reprocessing with state-of-the-art TTI RTM will see further improvements.

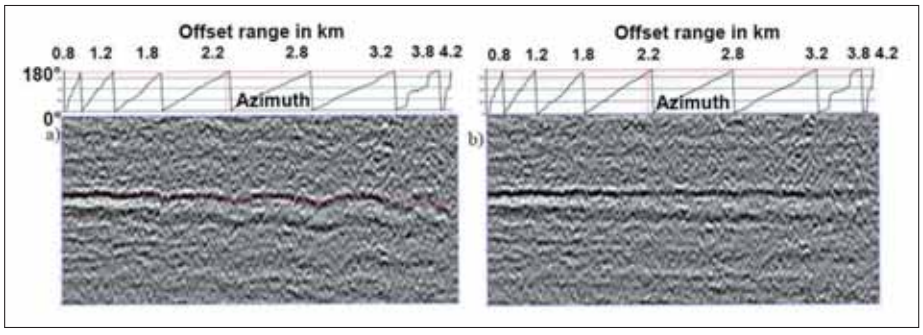

Fig. 3. CIG (common image gathers) sorted with increasing azimuth within each offset range (500 ms time window) (a) Before azimuthal residual moveout; and (b) After azimuthal residual moveout using a parabolic elliptical model. (From Lecerf et al EAGE 2009.)

noise. Slip-sweep shooting programmes with small slip times can result in harmonic noise contamination. To counter this, the noise is deterministically modelled using recorded ground force data and then subtracted from the record. This ensures V1 operations can achieve maximum production rates without compromising data quality.

The intrinsic isotropic point-source characteristics and increased shotpoint density make V1 data ideal for superior high-resolution imaging, and reservoir and fracture characterisation. With the elimination of the source array a range of effects are reduced, such as intra-array statics and residual normal moveout which cause signal attenuation. By adding the high-density WAZ benefits, V1 datasets provide optimum illumination (and energy recovery from the point-source), optimum multiple attenuation and valuable azimuthal information.

The substantially improved imaging provided by high-density WAZ data combined with true WAZ processing algorithms is illustrated in Figure 1. Figure 1a shows the image from a conventional NAZ survey reprocessed in 2008, and Figure 1b, the results from the new high-density WAZ data. There is a dramatic improvement in the signal-to-noise ratio of the new image due to the better sampling, which provides increased fold and stacking power, and the true 3D processing such as azimuthal residual moveout correction, which provides an improved signal-to-noise ratio and a better stack. Top salt is now significantly better defined, as are the sub-salt events.

The Wider Perspective Offshore

Although more operational than purely geophysical, similar advances have been made in marine acquisition. State-of-the-art steered streamer technology, such as the Sercel Nautilus system, has improved the ability to control and regularise multiple streamers. A new generation of planning, navigation, communication and quality control tools have been developed to deal with the complexities involved in coordinating several vessels in a large-scale WAZ towed-streamer operation. These systems use state-of-the-art navigation and communication networks designed specifically for real-time monitoring, and control of source and streamer vessels for WAZ projects. Ship-to-ship communications are a critical component of a WAZ survey. The transmission of radio signals over long distances, over water, with multiple sources of interference and occasional non-line-of-site conditions, is a challenge. New systems meet this challenge. For example, on the Southern Green Canyon WATS (WAZ towed-streamer) survey, CGGVeritas achieved zero technical downtime due to communications failures.

Several thousands of square kilometres of both proprietary and data library WAZ projects have now been acquired in various configurations. Most of these involve combinations of one or more multi-streamer vessels, and between two and four additional source vessels. Where fewer vessels are used, it is necessary to make multiple passes over the same area to record the range of crossline offsets required. This requires accurate source repositioning, which is enabled by the state-of-the-art navigation software. Modelling and simulation tools have been developed to provide the ideal combination of speed of acquisition with effective illumination and data quality for all situations.

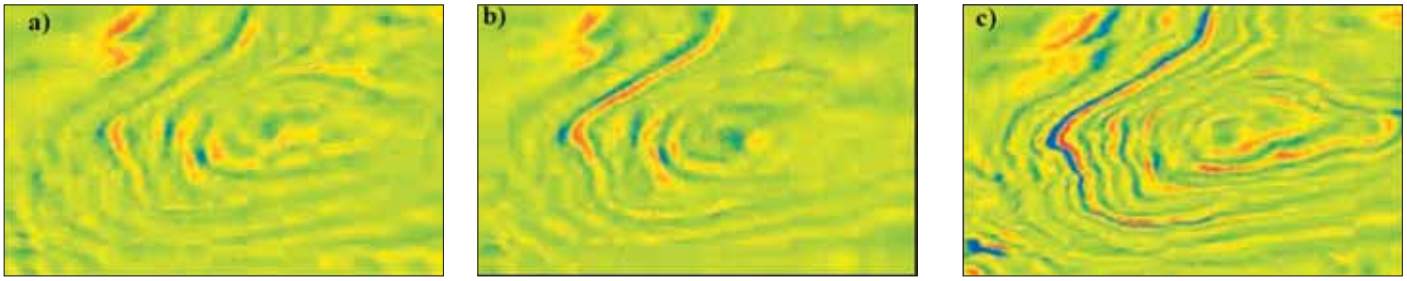

Fig. 4. Time slices of the far-offset stack (full azimuth). (a) Before azimuthal residual moveout; (b) After azimuthal residual moveout using independent velocity analysis within six azimuth sectors; and (c) After azimuthal residual moveout using true 3D azimuthal velocity analysis. From Lecerf et al EAGE 2009.

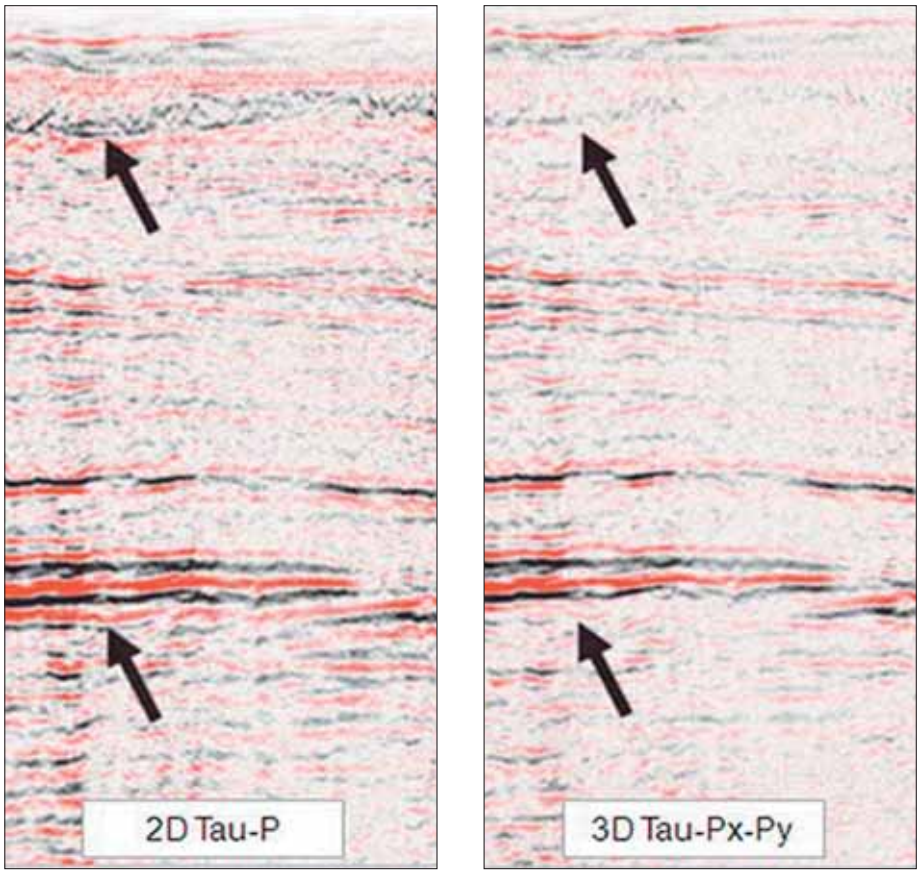

Fig. 5. Converted wave (PS) stacks from an OBC survey after processing through a 2D Tau-p versus a 3D Tau-Px-Py deconvolution demultiple sequence. The 3D Tau-Px-Py result exhibits improved deconvolution demultiple and increased signal-to-noise ratio.

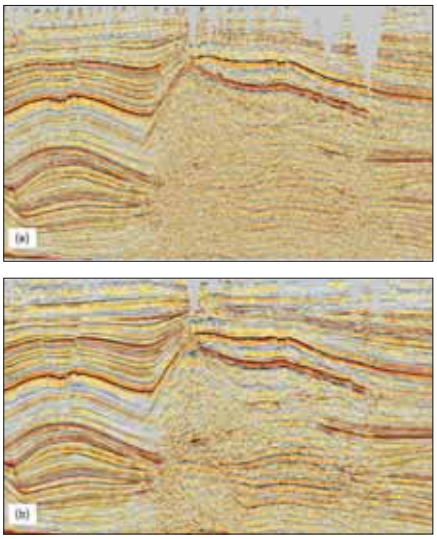

Fig. 6. WAZ interpolation uses a multi-dimensional operator to optimise sparse and irregular seismic datasets for imaging and pre-stack analysis. The algorithm uses up to five interpolation dimensions to infill large gaps, increase fold and regularise offset-azimuth distribution. This minimises migration artefacts relating to the geometry, and creates regularly populated pre-stack gathers which preserve AVO and AVAZ characteristics for reservoir and fracture characterisation.

Figure 2 shows the acquisition of the Walker Ridge WAZ data library survey, which covers 460 Gulf of Mexico lease blocks, and was acquired using four source vessels and a high-capacity ten-streamer vessel. The flexibility of the acquisition configuration allowed targeted high-density recording over two recent Lower Tertiary discoveries. Results from the survey in the targeted sub-salt bedding are particularly impressive, the improvements being well illustrated by comparing the NAZ and WAZ images. Data library surveys are a cost-effective way for oil companies to reduce the cost of WAZ data but still enjoy the benefits.

Alternatives to WAZ

Multi-azimuth recording can be a convenient way to get additional azimuthal information as it uses a single vessel. It provides very good sampling along the discrete azimuths recorded, but it essentially delivers separate NAZ datasets which are generally not combined into a single volume until after migration. Even if merged pre-migration this does not provide sufficient sampling to fully benefit from the new generation of true 3D WAZ processing algorithms. It is currently used in a more targeted way, for specific development objectives, rather than for large-scale WAZ exploration.

The technique of acquiring precessing circles (or coils), patented by Tensor and first used in the mid-1980s, has also been examined. This is an efficient acquisition technique for small surveys, as it requires only one vessel and there is no downtime for line turns. However, continuous recording also means that there are no natural time-slots for scheduled maintenance, and larger surveys are more efficiently recorded using parallel WAZ patterns.

Towing streamers in a turn creates additional noise and, even with the superior noise performance of solid streamers, circular geometries lead to higher noise than conventionally towed streamers. In addition, although circular geometries do deliver a broad range of azimuths and offsets, there tend to be only a limited selection of azimuths in any individual processing bin. In order to obtain the required consistency of distribution of azimuths and offsets in processing bins, advanced multi-dimensional interpolation may be required.

Ocean-Bottom data

WAZ seismic surveying using seabed recording has been performed for many years, and with the development of true 3D WAZ processing algorithms its full potential is being recognised. Seabed surveys have mainly been used as a solution to specific geological problems such as gas clouds, or in areas where waters are too shallow, too congested, or too sensitive for streamer acquisition. Now, other benefits such as improved illumination, noise and multiple suppression, and fracture estimation have been highlighted. Ocean bottom data has the additional benefit of being multi-component and so able to offer the enhanced processing options of 4C data.

The opportunities of processing in extra dimensions

The acquisition of all this additional data has created new opportunities and challenges for processing. Processing of the early multi-azimuth orthogonal and circle shoot 3D data in the 1980s was hampered by the low levels of memory and disk space available on the computers of the day. Indeed, those early surveys were processed using fewer resources than available on a modern mobile phone. Today's super-computers are easily able to handle the terabytes of data produced daily by a modern high-density land crew. Understanding how to unleash the full potential of all the extra information available is another issue. New multi-dimensional algorithms have been derived to deal with the additional complexities of such things as azimuthal anisotropy and to take advantage of the true 3D nature of the data.

WAZ acquisition provides better azimuthal illumination of structures for a more accurate image. Additionally, analysing azimuthal variations of the seismic response may offer information on fracture orientation. To meet both objectives, we need to ensure that the WAZ character of the data is preserved throughout the processing sequence so that we get the full benefit of true 3D algorithms. We now have the opportunity to go beyond our NAZ data with its 2D gathers and assumptions, and apply true 3D algorithms to true 3D gathers, to achieve even better noise and multiple attenuation pre-stack, and so provide better velocity models and better images.

Enhanced multiple attenuation can be achieved by such techniques as true 3D SRME (surface-related multiple elimination) for deep water. By respecting the true offsets and azimuths from WAZ data, this allows the modelling of complex multiples from out-of-plane reflectors and diffracted multiples from rugose seafloors. Wave-equation SRME algorithms also allow this method to be applied to OBS data.

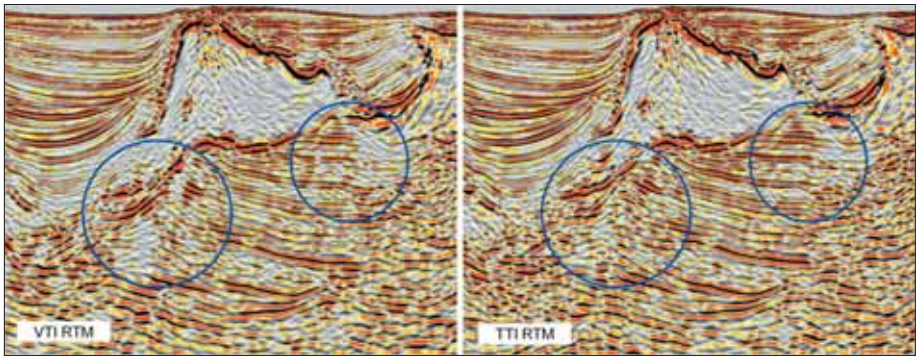

Fig. 7. Inclusion of TTI anisotropic effects obtained from WAZ information has greatly improved the imaging of complex structures wherever dipping sediments are present. Sub-salt images beneath the mini-basins are more coherent and focused on TTI RTM results than those from VTI RTM.

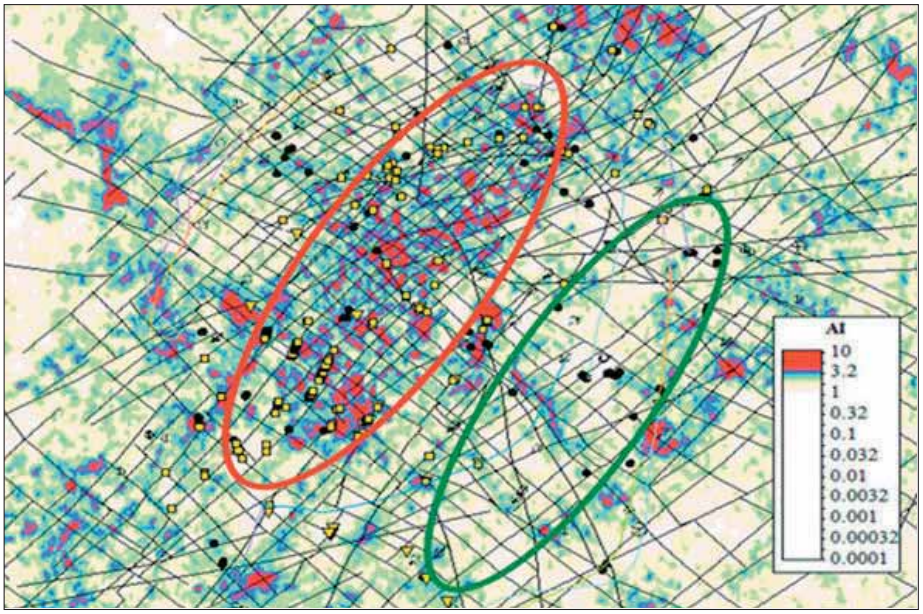

Fig. 8. The normalised azimuthal amplitude anisotropy intensity map is shown above with overlay of interpreted faults (black). Well data is shown with the mud-loss points (yellow) indicative of permeable fracture zones. Outlined in red is the known conductive fracture corridor which correlates with high anisotropy intensity values and in green an area of low fracture intensity.

Wherever there are dip-moveout or azimuthal effects, velocity will vary with azimuth. Use of true 3D azimuthal velocity analyses provides better correction than azimuth sectored velocity analyses, producing flatter gathers and, hence, better signal-to-noise ratios and better stacks, particularly at far offsets, as shown in figures 3 and 4. Velocity analyses that simultaneously take into account all azimuths are less sensitive to noise than independent 2D analyses within azimuth sectors. This is especially beneficial for velocity picking in low signal-to-noise land data.

True 3D radon parabolic transforms allow more reliable discrimination of primaries and multiples. Anisotropic multiples are not well modelled by either 2D radon de-multiple or azimuth sectored 2D radon. By using a true 3D radon transform these effects are explicitly included in the modelling and can be effectively subtracted from the data, as shown by Hugonnet et al (2009).

Similarly, true 3D Tau-px-py transforms provide a better representation of the data than 2D Tau-p transforms, and therefore provide better noise attenuation and deconvolution de-multiple, as demonstrated by the OBC data shown in Figure 5.

Although the use of 2D algorithms on WAZ data can be improved by azimuth sectoring, this still only provides multiple 2D gathers. The full benefits of WAZ data are only achieved by using true 3D transforms and algorithms on true 3D gathers. When divided into azimuth sectors, data tends to suffer from reduced fold and

poor signal-to-noise, and processing is limited by the 2D assumptions of the NAZ algorithms applied within each sector. True 3D algorithms and gathers do not suffer from this reduced fold and, as the azimuthal and offset information is incorporated into the algorithm, require us to make fewer assumptions.

To further improve on the benefits of WAZ acquisition, and to fill in any remaining gaps in offset or azimuth, multi-dimensional state-of-the-art Fourier interpolation and regularisation algorithms are now available (Trad, EAGE 2008), which can create an ideal dataset from any reasonably sampled data. Figure 6 shows an example of the use of REVIVE 5D interpolation developed by CGGVeritas to interpolate and regularise onshore data.

WAZ data also provides significant advantages for imaging. Although imaging algorithms have been 3D for some time, we now have the opportunity to perform true 3D velocity model building, with the picking of events and azimuthally variable residual moveout (RMO) on a 3D surface and porting this information into the velocity tomographic inversion. The additional azimuthal information allows more accurate derivation of TTI (tilted transverse isotropy) anisotropic parameters, vital in areas where dipping sediments exhibit anisotropy, to create accurate velocity models for the latest TTI imaging algorithms. TTI reverse time migration (RTM) can be performed on WAZ data to provide well-focused images beneath complex overburdens (Zhang & Zhang, 2008 and Huang et al, 2009). Figure 7 shows the benefit of including this information. TTI RTM reliably produces better images than those from either isotropic or VTI (vertical transverse isotropy) RTM.

Reservoir characterisation

The true 3D approach to processing greatly benefits reservoir characterisation, as it inherently preserves the azimuthal signature and provides better velocities and seismic attributes. The better offset-azimuth diversity provides a much better dataset for fracture characterisation. Often there is a direct relationship between the magnitude of azimuthal anisotropy, fracture intensity and permeability. This can be used to derive seismic-based fracture intensity estimates across fields. It is a unique and valuable resource for well planning and production management in naturally fractured reservoirs. Fracture analysis is also extremely useful in the study of tight gas shales, where natural and induced fractures are essential for economic gas production.

Figure 8 shows a normalised azimuthal amplitude anisotropy map from a WAZ OBC dataset, acquired over a carbonate reservoir undergoing secondary recovery by water-flood. A seismic fracture characterisation project was undertaken to map highly permeable fault zones and fracture corridors for well planning and reservoir management. A detailed study of the seismic and fracture data available from the wells found a good correlation between seismic azimuthal anisotropy, fracture intensity and permeability. Both the P and PS data from the multi-component OBC survey were used to generate maps of seismic attribute anisotropy to highlight zones of high fracture intensity and permeability for well planning. The use of WAZ multi-component data has helped to reduce the uncertainty in the interpretation by providing independent estimates of seismic fracture intensity from the P and PS data for comparison.

WAZ Worldwide

WAZ data has shown proven benefits in many areas around the world, and is becoming more common. WAZ marine surveys are being recorded offshore West Africa, and feasibility studies are being carried out for surveys in the North Sea and other areas, including the Far East and Brazil. WAZ land surveys are being performed from the Middle East to the Canadian Arctic.

WAZ is no longer seen as a niche application for use only in deep water and sub-salt, but is now seen as widely applicable. WAZ surveying is appropriate for any area of complex structural geology, or where velocity contrasts are significant. For example:

- Areas where salt causes imaging problems, such as the central and southern North Sea in the UK and the Aptian salt basin of the west coast of Africa, as well as the Gulf of Mexico;
- Areas of complex structural geology, such as overthrust belts, especially where high-velocity strata have been thrust over younger, lower-velocity rocks, e.g. the American and Canadian Rocky Mountains and the Tien Shan Basin of China;
- Basins where deep sedimentary geology is overlain by basalts, which are notoriously difficult to penetrate by conventional seismic methods, e.g. onshore and offshore India and the Faroe-Shetland Basin in the North Atlantic;
- Areas below carbonates and fractured carbonate reservoirs;
- Imaging of fractured granite basements such as offshore Vietnam; and
- Kazakhstan's pre-Caspian basin, home to Kashagan, the world's largest oil discovery in the last 35 years.

Marine acquisition is becoming wider, land acquisition is becoming denser, and processing is becoming truly multi-dimensional. Acquisition technology advances continue to increase the efficiency with which WAZ data can be acquired. The superior imaging provided by WAZ data offers the opportunity to open up new plays, reduce drilling costs, and characterise difficult reservoirs.

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