# Full-wave seismic acquisition and processing: the onshore requirement

**C. Jason Criss, Cara Kiger, Pete Maxwell and Jim Musser of Input/Output explain the company's approach to full wave imaging and processing and why it is the technology of the future.**

Full-wave acquisition and processing is fast becoming the new revolution in seismic imaging, just as 3D seismic was a revolution in seismic imaging 20 years ago.

But why the need for full-wave imaging? As exploration and production efforts become more sophisticated, geoscientists are required to better define reservoir rock and fluid properties and fluid movements, and more accurately determine drilling locations to meet the challenges.

Present geophysical assumptions inherent in conventional 3D imaging limit our ability to image reservoirs and understand their contained fluids well enough to have maximum economic impact. These are assumptions of isotropy, frequency band limits, vertical emergent angle and the requirement for source-generated noise attenuation in the field. Because of these assumptions, 3D imaging as it is currently implemented has peaked in usefulness and is less able to deliver additional economic value. This directly affects our ability to find and develop new reserves at an acceptable risk. In addition to the impact on finding new reserves, currently producing fields are seriously suffering from the diminishing economic impact of current 3D technology.

Full-wave imaging has the potential to take the interpreter to the next level of improved reservoir characterization and imaging quality by delivering:

- Broader bandwidth, higher resolution images
- More accurate and reliable stack amplitudes and AVO
- Vp and Vs instead of only Vp
- Seismic frequencies down to 1-2 Hz, thus more closely matching well log information
- Symmetry in the recorded wave-field without the distortion imparted by current acquisition and processing practices
- Use of some of the seismic signal, traditionally considered to be noise, to contribute to the image and the interpretation (anisotropy, surface waves and mode contamination)

Delivery of these improvements means that interpreters can better define reservoir rock properties, reservoir fluid properties and movement, see through gas clouds to define drilling targets, determine fracture detection and orientation, and improve well placement for optimal hydrocarbon drainage.

To achieve the next level of required reservoir image quality, the industry needs to overcome the geophysical assumptions of conventional 3D imaging. A significant part of addressing current 3D technology limitations is adequate sampling of the full seismic wave-field. Full-wave imaging accomplishes this by:

- Faithfully recording the complete ground motion from all seismic signals, including source-generated noise
- Accurately measuring anisotropy whether in the P-wave mode or S-wave mode, and for both amplitude and velocity
- Obtaining an unaliased spatial sampling of the reservoir for a given dip, frequency and velocity
- Recording the full bandwidth of frequencies that the earth will return

To achieve the benefits of full-wave imaging, the industry first needed the enabling technologies of high vector fidelity, multicomponent digital receivers and high channel count systems that are reasonably easy to deploy and manage. Before development of these enabling technologies, poor vector fidelity and the cumbersome field operations made economic and technical success almost unobtainable.

## Full-wave requirements

Full-wave recording requires at least six considerations :

- High vector fidelity, multicomponent receivers to accurately preserve the relative amplitudes between components that enable successful vector oriented processing
- Point sources and single-point receivers to preserve anisotropy as faithfully as possible, especially for acquisition of long offsets at widely varying azimuths and for recording the full seismic signal bandwidth
- Faithfully recording and preserving the full bandwidth that the earth will return, with special consideration for low frequencies. Given the very deep targets now being explored where P-wave bandwidth is normally limited, given that converted-wave data are already band-limited and considering that high-resolution reservoir analysis using acoustic and elastic inversion normally requires a link between amplitude and velocity that normally does not exist in most seismic data, the low frequency component of the seismic signal is critical
- Wide-azimuth 3D survey designs to address the azimuthal component of anisotropy in amplitude and velocity
- Offsets allowing at least $45^0$ of reflection angle. This angle is beyond the point where the assumption of a two term

velocity is necessarily valid and is where the vertically oriented symmetry of anisotropy can become significant
- High enough channel count systems to enable wide-azimuth, long offset surveys with sufficient station densities to avoid spatially aliasing the target in P-wave or C-wave domains. This consideration does not require noise to be acquired in a spatially unaliased form nor to have the target vastly over-sampled to address source-generated noise

Of considerable importance in full-wave recording are the enabling technologies of the recording equipment - high-fidelity, three-component receivers and efficient, high channel count systems. Significantly improved operational efficiency due to incorporation of next-generation technologies in recording systems and single-point receivers brings improved operational efficiency (Tessman et al. 2004) that reduces acquisition cost and HSE exposure.

High-quality, single-point, three-component receivers such as VectorSeis (Figure 1) are a requirement for full-wave imaging and provide four significant benefits over conventional receiver arrays:
- Extremely accurate measurements of all ground motion - both for seismic signal and for noise
- No directional bias, making them ideal for recording azimuthal variations in seismic velocities (anisotropy)
- Freedom from intra-array statics, yielding recording of higher bandwidth, higher resolution seismic signals
- Easily deployed, better coupled, with lower weight and bulk for improved field operational efficiency and reduced HSE exposure

By measuring all ground motions on three orthogonal axes, high-quality digital receivers provide information to processing that describes apparent ground motion at the instant each sample was recorded. These sensors exhibit broad bandwidth, low distortion and tight sensitivity calibration, therefore, contributing to the overarching term, vector fidelity. New generation MEMS digital receivers (P. Maxwell *et al.* 2001) have these characteristics.

**Figure 1** *VectorSeis digital receiver*

Because point receivers lack directional bias, they are uniquely suited for measuring the anisotropy of seismic signals both azimuthally and transversely. Figure 2 shows the significant and complex frequency and azimuth-dependent attenuation effects for a 12-sensor array and point source, assuming the seismic signal emergent angle is non-vertical. Higher frequencies experience greater attenuation effects, which makes the reliability of measuring anisotropy low. These signal frequency components are not recoverable; they are lost forever, reducing bandwidth and resolution of seismic images and impairing the accuracy of anisotropy measurements.

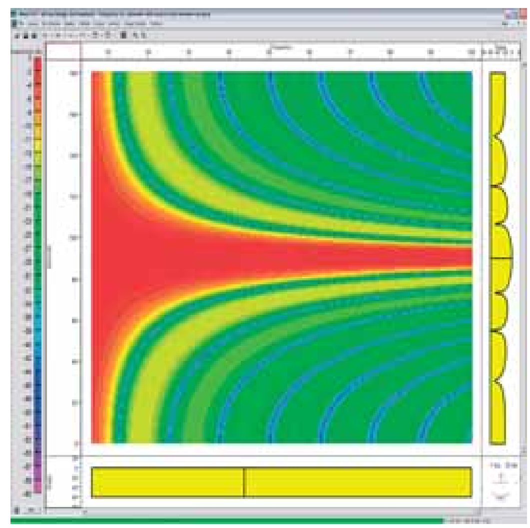

**Figure 2** *Azimuthal frequency attenuation effects for a 12-receiver array and point source. X-axis is frequency. Y-axis is azimuth. Colour scale is attenuation.*

Another advantage of point receivers is the recording of the full bandwidth of frequencies that the earth will return, including critical low frequencies. There are two advantages that point receivers have in recording the full seismic signal bandwidth - removing intra-array statics and preserving low frequencies when removing source-generated noise.

Receiver array statics are ubiquitous and function as high-cut filters on the returning seismic signals, reducing frequency content and image resolution. As little as a two to four millisecond static shift for individual receiver array elements causes noticeable high frequency attenuation (Figure 3a, 3b). Single-point receivers do not suffer from intra-array statics problems. In some areas, use of single-point receivers has been estimated to add 10-20 Hz at the high end of the signal bandwidth (Figure 4).

Use of single-point receivers raises concerns about signal to noise ratio in the presence of strong surface waves. Processing techniques such as vector filtering applied to full-wave data acquired by high-fidelity three-component

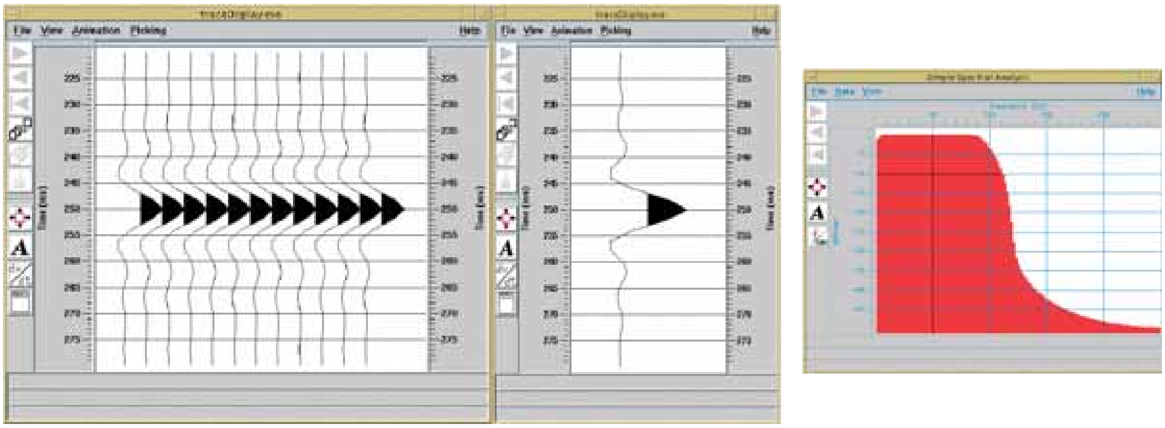

**Figure 3a** *Synthetic example of frequency attenuation effects from intra-receiver array statics - base case, no statics effects.*

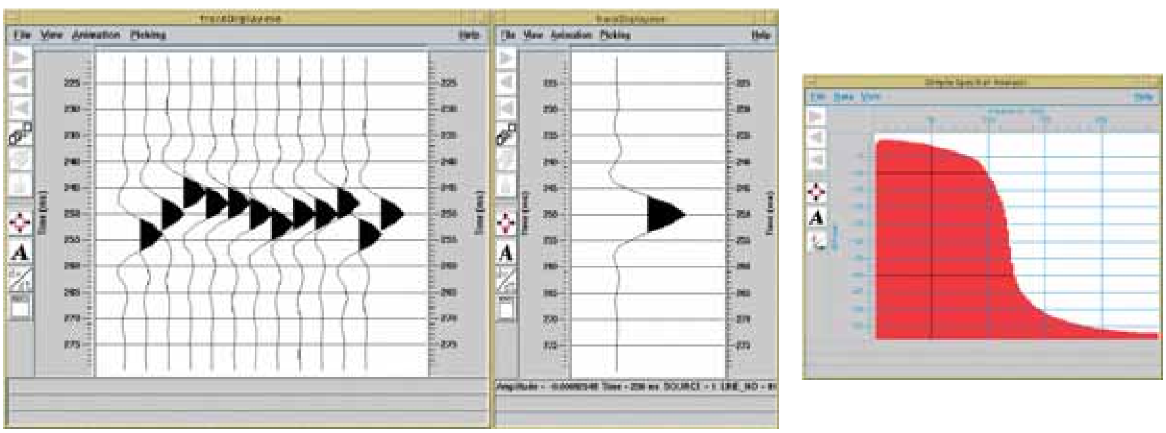

**Figure 3b** *Synthetic example of frequency attenuation effects from intra-array statics - + / - 4 ms intra-array static shifts.*

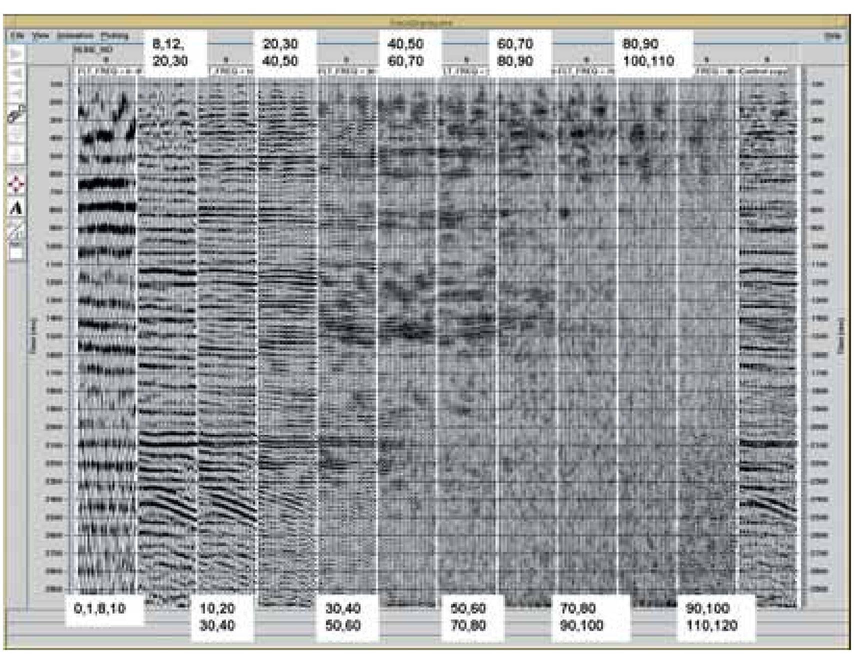


**Figure 4** *Frequency panel from VectorSeis data set displays broad bandwidth capabilities of VectorSeis digital, full-wave receivers.*

receivers have proved useful for suppressing or eliminating source-generated noise while preserving low frequency signal.

Recent advances in imaging improve our ability to preserve the full frequency bandwidth that the earth will give back. These techniques include vector processing techniques, coherent noise attenuation methods using vector filtering, separation of body waves onto their correct components and anisotropic processing.

## Vector filtering techniques/vector processing

Vector filtering is a coherent noise attenuation method that leverages digital, full-wave information. The method uses differences between noises and signals recorded on each of the three orthogonal receiver components to isolate and attenuate unwanted noise from individual components and seismic signals. An example of this type of noise attenuation is filtering of ground roll from the vertical trace (Figures 5a, 5b).

In the case of ground roll filtering, the vector filter method uses vertical and radial trace pairs. The vertical trace is assumed to have desirable signal and unwanted noise - in this case ground roll. The radial trace is assumed to be an independent estimate of ground roll without the vertical signal. Vector filtering uses a cross-correlation and inverse filter (filter to remove signal and keep noise) to isolate ground roll and then to simply subtract it from the vertical trace estimate. This is based on the assumption that ground roll is recorded on all components, while the desirable signal on the vertical component should be isolated to vertical-only ground motion. This method has several benefits when compared with other ground roll attenuation methods that isolate the ground roll noise in the F-K and other multi-trace domains.

The vector filter method is a trace-by-trace method that does not require adjacent trace information to isolate the noise. This has two very positive implications. There is no spatial mixing, meaning that any subtle azimuthally varying amplitude and time-shift information recorded by the data will not be mixed. The method does not require geometry information because it relies totally on the relationship between recorded ground motions at a single receiver station. This method responds identically to noise which is fully sampled as it does to noise which is spatially aliased. Benefits once thought to come only from deploying surface arrays can be better realized with single point receivers and proper application of vector filtering. The overarching requirement however, is high vector-fidelity recording.

As our experience with vector filtering methods has grown, not only has the process proved successful in removing ground roll from vertical traces, but it also successfully removes Love and Raleigh wave contamination from rotated horizontal data (Figures 6a, 6b). This application helped isolate converted wave signal from surface noise trains and has proven useful for converted-wave processing.

Vector filtering techniques also show promise for removing other types of semi-coherent noise such as back-scattered noise produced by near-surface point refractors and discontinuities (geologic or topographic). Additionally, future areas of work include using the separated ground roll trains to invert for near surface structure and Vp/Vs velocity fields, a process that has had little success using current generation seismic data. The separation of Raleigh waves from Love waves from the body waves, the high-vector-fidelity recording of the vector motion of the ground roll and preservation

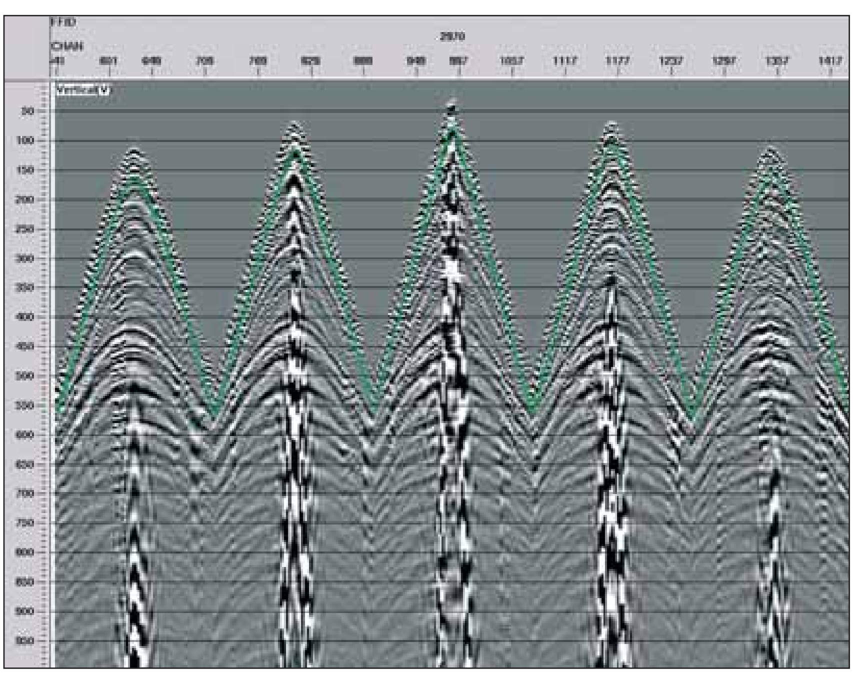


**Figure 5a** *Raw VectorSeis record contaminated with aliased ground roll. After Vector Filtering and signal processing (Figure 5b), aliased ground roll is successfully attenuated.*

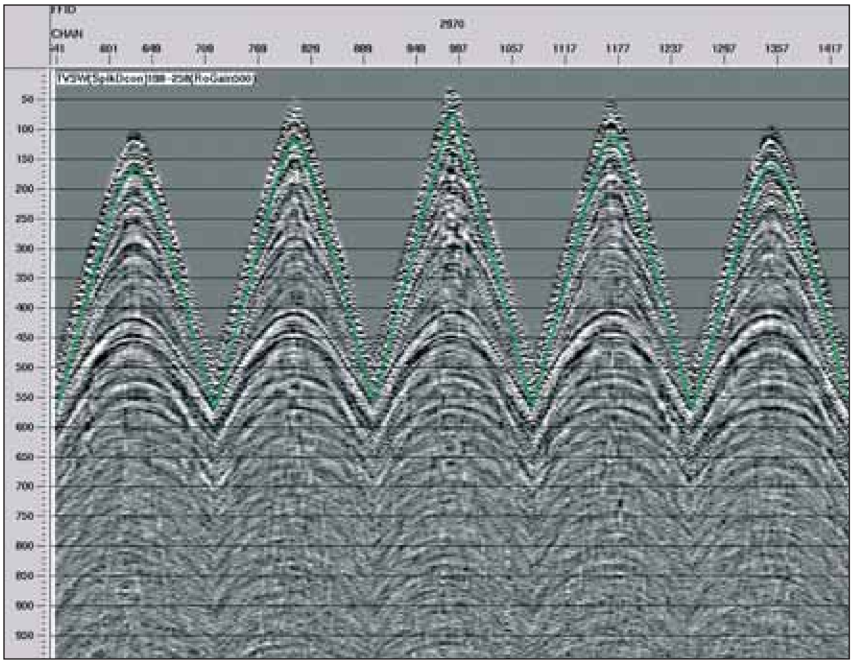

**Figure 5b** *Same VectorSeis record as in Figure 5a but with aliased ground roll successfully attenuated with Vector Filtering and signal processing.*

of ground roll bandwidth during recording and processing warrants another try at ground roll inversion.

Another aspect of vector acquisition and processing that has upside for improving seismic imaging for exploration and reservoir characterization is the possible ability to separate body waves onto their correct components. Remember the assumption in seismic acquisition of the vertical emergent angle for P-wave and S-wave rays. This assumption is one of the worst the industry has made to rationalize why a single component receiver is good enough for recording the compressional wave-field. Figures 7 and 8 demonstrate how bad an assumption a vertical emergent angle can be. These figures show significant contamination of modes from vertical component to horizontal component and vice-versa. The assumption, especially in faster-velocity near surface conditions, may have led to many failures in AVO interpretation and may be the main reasons for the disappointing results of AVO on land, except for the simplest Type III cases. At the very least, the problem of non-vertical emergent angle confuses interpretation of amplitude on migrated data. At worst, the non-vertical

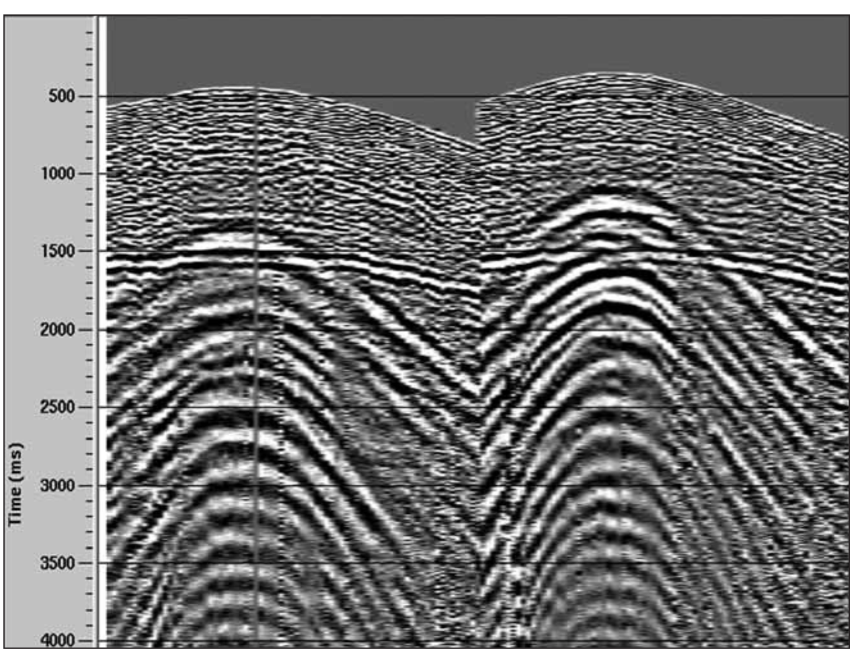


**Figure 6a** *Raw VectorSeis radial record contaminated with ground roll. Vector Filtering techniques can attenuate direction noise from radial components.*

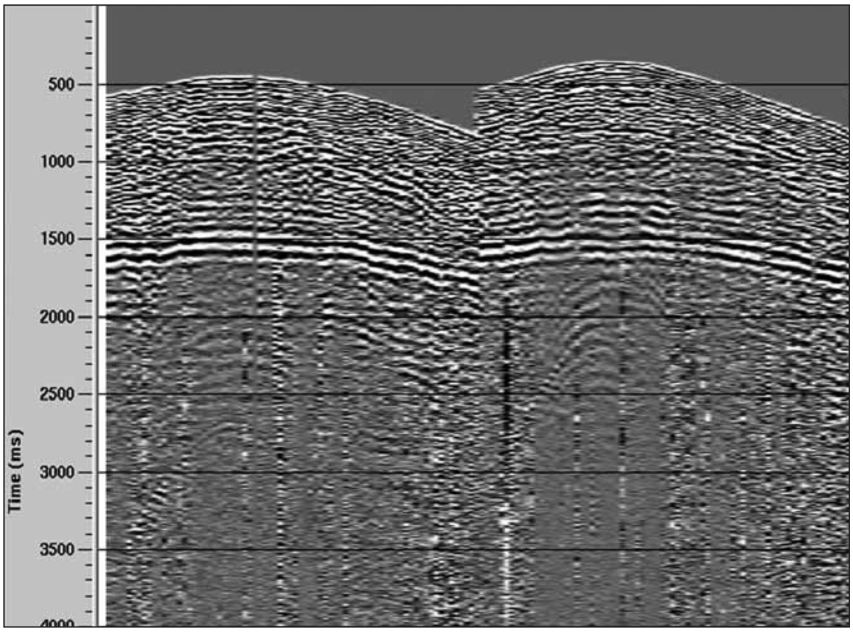


**Figure 6b** *VectorSeis radial record post Vector Filtering. Ground roll has been successfully attenuated, leaving a clean record for further processing.*

emergent angle can cause non-surface-consistent statics, which can affect reflector continuity. Statics also compromise recording and preserving the full bandwidth that the earth returns.

## Anisotropic processing

Anisotropy of the earth has long been considered a complication for seismic acquisition, processing and interpretation. As the industry is challenged to learn more from the earth using seismic data, we have made great strides in discovering that anisotropy is useful information rather that annoying noise that must be tolerated.

Fundamental to anisotropic processing is the requirement to process seismic data with expanded latitudes of freedom. Isotropic processing is restricted to analysis of the data spatially and with offset, while anisotropic processing requires the same spatial and offset information, as well as azimuthal and long offset information. The direction the seismic energy travelled from source to receiver is an important component of processing. This places requirements on the acquisition design and field operations to record well distributed and well sampled seismic data in both offset and azimuth.

A primary point of focus of anisotropic processing is in velocity analysis. Traditional methods of seismic data velocity analysis use semblance plots and require data processors to pick RMS velocity trends by hand. For anisotropic velocities, this method has proven to be too inaccurate. The velocities must be analyzed in offset and azimuth but also with a spatial density on scale with the sampled bin grid size. This

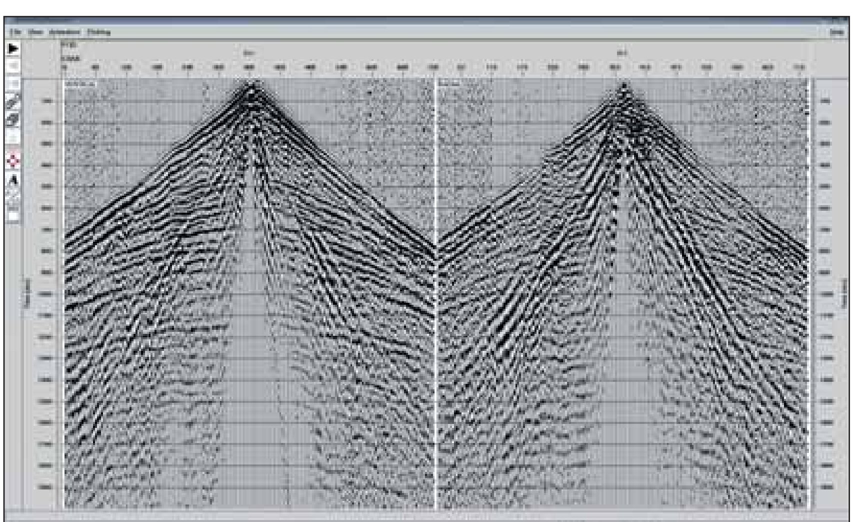

**Figure 7** *VectorSeis vertical record on the left and the radial component on the right. The radial component shows significant P-wave contamination from a non-vertical emergent angle for the P-wave ray. This mode contamination is almost an insurmountable noise problem for c-wave processing efforts. In contrast the vertical component is missing amplitude especially on the far offsets where emergent angles decrease. Without this energy all on one component, AVO analyses become unreliable.*

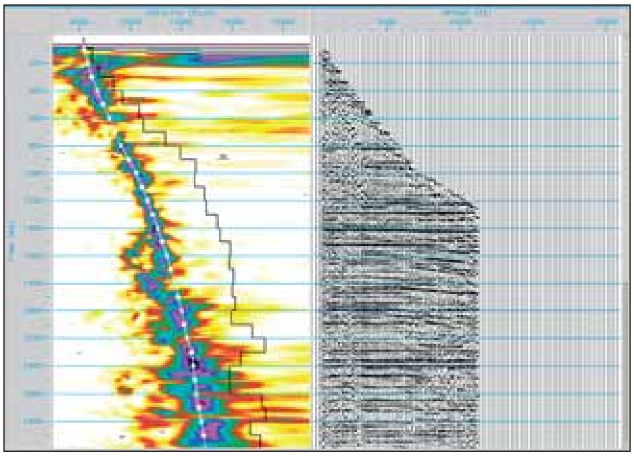

**Figure 8** *Conventionally-recorded geophone data showing converted wave contamination, manifested as slower velocity reflections. The contamination results from non-vertically emerging converted waves through a hard, fast near-surface layer. Vp/Vs ratios for the surface layer are assumed to be low. As a result, one might expect considerable P-wave energy to reside on the horizontal components.*

requirement can only be satisfied in a timely manner by using sophisticated computer algorithms. One method that accomplishes this is AZIM, pioneered by the AXIS processing division of GX Technologies (Williams and Jenner, 2002). It analyzes residual normal move-out on seismic gathers and uses a least squares approach to fit an elliptical velocity model to the azimuthal time estimates and a fourth-order curve to the long offset time distortion. This approach yields a very dense azimuthal velocity volume that can be used to correct for azimuthal velocity variation in seismic data. It has been shown to produce superior results in virtually all seismic processes that rely on accurate normal move-out corrections such as statics, stacking and migrations - virtually all processing steps benefit from better normal move out corrections.

In addition to clearer seismic images, the analyses produce densely-sampled velocity volumes that can be treated as data attributes. From these data, interpreters can extract directional information, interval velocities, gradients and more, all providing clues to the subsurface and its history (Jenner, 2002). This new source of information has proven necessary to understanding exploration in a variety of areas, including North Slope Alaska, Central US and in other areas of the world such as Egypt. We are measuring physical attributes of the earth with anisotropy measurements. The challenge will be to determine the relevance and application of those data. Each new area requires careful and systematic approaches to data acquisition, processing and interpretation to yield new benefits from anisotropic processing.

## Wide-azimuth, long offset survey designs

To meet the requirements of all the six considerations for full-wave seismic imaging, careful, robust survey design is critical. Of primary importance is acquisition of wide-azimuth, full-offset data. That means that seismic traces sampled in every direction represent the full range of offsets needed for accurately estimating seismic velocities at depths of geologic importance in the survey area. In a properly acquired wide-azimuth survey, the ratio between usable inline and crossline offsets sampled for each horizon of interest will be on the order of 1:1 (typically within the range of about 0.8:1 to 1.2:1). It is not sufficient that the maximum inline and crossline offsets are comparable. It is important that the range of offsets in each direction is also well sampled. Such characteristics are most easily acquired with survey designs having source lines orthogonal to receiver lines, comparable source and receiver line spacings, and nearly square source-centered active receiver patches. Figure 9 illustrates narrow- and wide-

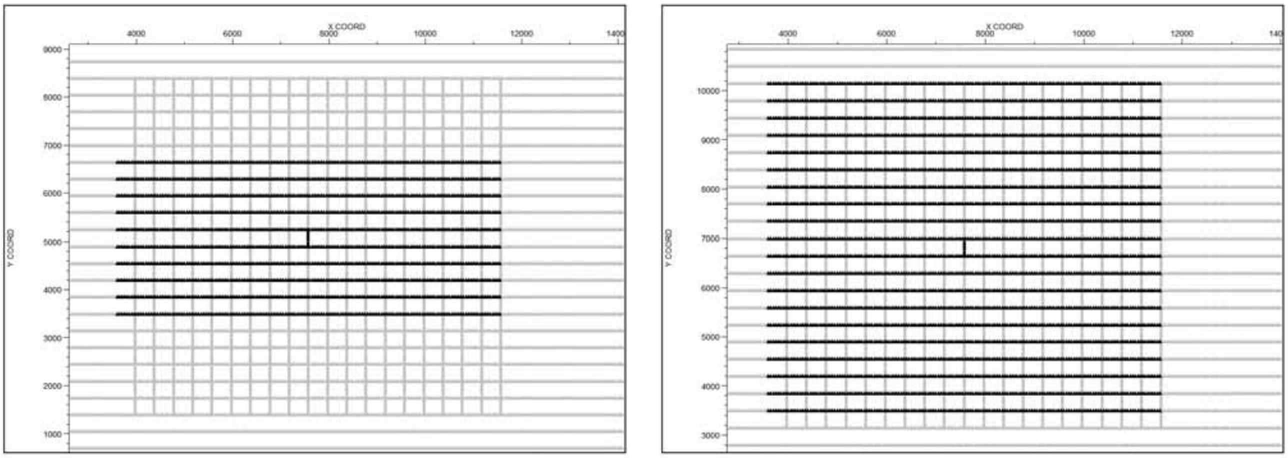


**Figure 9** *Narrow-azimuth survey design (left) with an inline to crossline offset ratio of about 2:1 is compared to a well-sampled wide-azimuth survey design (right) with an inline to crossline offset ratio of about 1.2:1.*

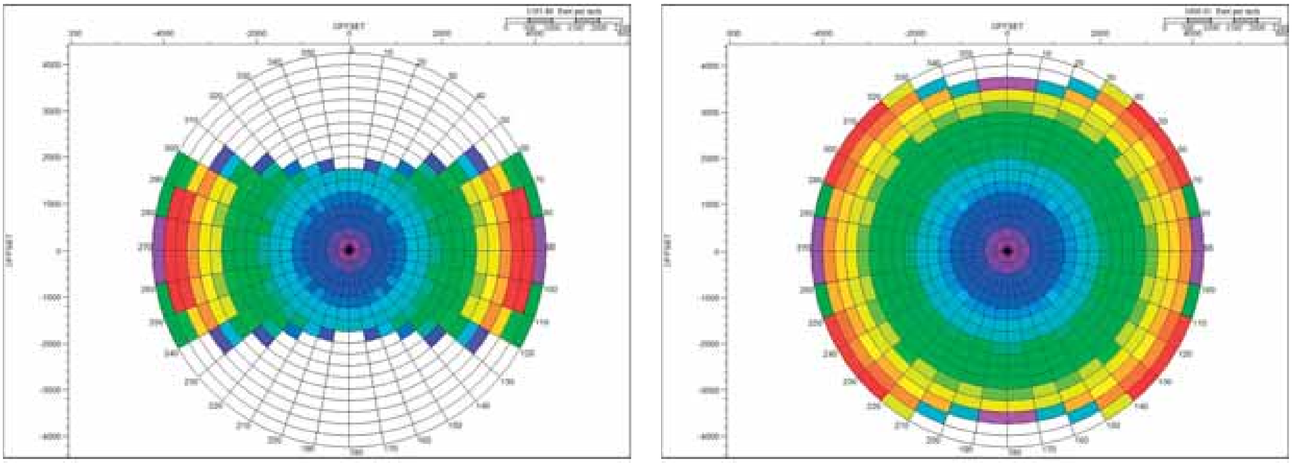

**Figure 10** *Offset-azimuth rose plots for narrow-azimuth (left) and wide-azimuth (right) survey designs. Radial wedges represent azimuthal sections (clockwise with north at the top) and concentric rings represent offset increasing from the center outward. In both designs, inline offsets (east-west) are very well sampled. Crossline offsets are also very well sampled in the wide-azimuth design, but poorly sampled in the narrow-azimuth design.*

azimuth recording patterns. Figure 10 shows the statistical distribution of offsets and azimuths for the same two designs. The narrow-azimuth design fails to capture long offset data in the crossline direction. The wide-azimuth design collects uniform offset distribution in every azimuth.

As a general rule in full-wave acquisition, the long offsets acquired in all directions should be on the order of twice the depth of the horizon of interest. This will allow more accurate estimation of the complete velocity field and better characterization of the amplitude variations with offset. The long offsets also provide the data for analyzing the apparent transversely anisotropic portion of the anisotropy. The caveat here is that if the transverse isotropy is not corrected for in processing, the data beyond an offset to depth ratio of one can be almost worthless.

For robust full-wave seismic acquisition, spatial sampling is also very important. Nyquist anti-aliasing spatial sampling criteria are usually used to predict the required subsurface sampling interval (bin size) for properly imaging the subsurface horizons based on seismic velocity, frequency content and signal dip. This constrains the surface spacing for both source and receiver stations. However, S-waves and converted (PS) waves (generated by P-wave sources, converted to S-waves at the reflecting horizon and recorded with multicomponent receivers) propagate at substantially slower velocities than P-waves, generally requiring finer spatial sampling.

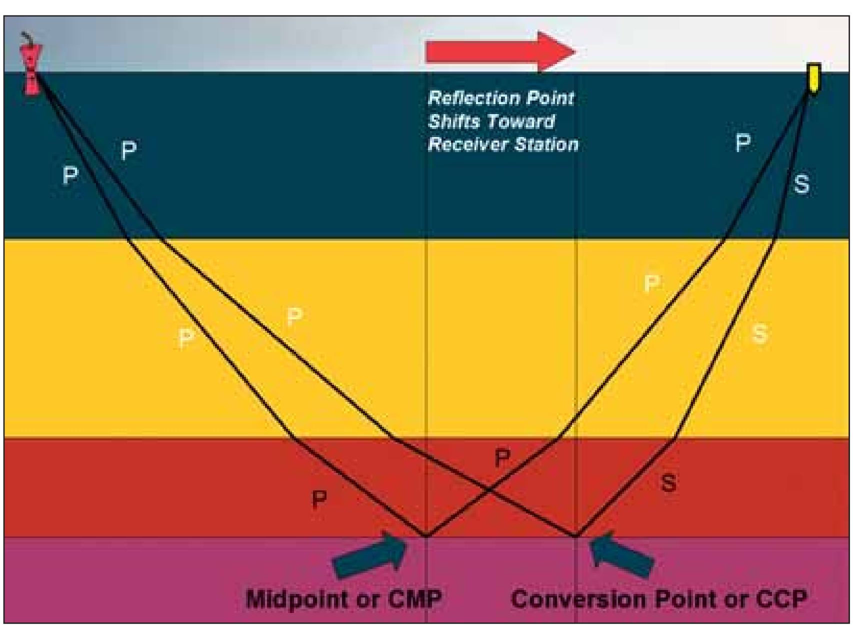


**Figure 11** *P-wave reflection data are recorded with a P-wave source and vertically-oriented P-wave receivers. In flat-lying layers, the P-wave reflection point is midway between the source and receiver. PS-wave reflection data are recorded with a P-wave source and horizontally-oriented S-wave receivers. Since the up-going reflected PS wave travels at the slower S-wave velocities, Snell's Law dictates that the reflection point for PS waves is shifted toward the receiver station.*

In a true full-wave seismic acquisition design, all components are acquired simultaneously, so the slower S-wave velocities should generally be used to compute the subsurface bin size and surface station spacings for imaging, meaning that the P-wave data will generally be over-sampled. Figure 11 illustrates the asymmetry of PS reflection data. Because of this shift of PS reflection points toward receivers and the fact that S-waves travel disproportionately slower in shallow unconsolidated sediments, it is very important in full-wave survey designs for receiver line spacings to be kept relatively small, especially for shallow reflection horizons.

In conventional acquisition systems, geophone arrays are used to attenuate ground roll noise, or the data must be recorded with small station spacings without aliasing so the noise can be removed in processing. Because vector filtering techniques for ground roll removal are applied as single-trace, post-acquisition processes and are totally independent of acquisition geometry, ground roll noise aliasing is eliminated as a survey design criteria. It is not necessary to design surveys for the spatial aliasing condition of ground roll, nor are receiver arrays required to physically filter ground roll.

## High capacity, high channel count systems

Full-wave acquisition techniques for improved P and S-wave images require high capacity, high channel count systems that can efficiently acquire, transfer and record large amounts of data (Mougenot, 2004). Full-wave survey designs with adequate wide-azimuth sampling at target depths require a large number of deployed receiver stations. With three-component digital receivers, we can very quickly get to 10,000+ channels equivalent that require longer listen times because S-wave velocities are slower than P-wave velocities.

Large spreads and active receiver patches must be managed to minimize power consumption and to monitor and record a variety of QC parameters in real time. Coupled with these demanding data handling, efficiency and QC requirements is the need for lightweight, easily deployed equipment robust enough to operate reliably in harsh field environments.

Modern recording systems such as Input/Output's System Four address these full-wave imaging requirements. Fibre-optic cross lines capable of high data transmission rates; fast, reliable network telemetry architectures and power delivery systems that self-heal in redundant deployment enable cost effective full-wave acquisition. Parallel network architectures coupled with buffering and handshaking protocols ensure that there is a path for seismic data to get back to the recorder, even when severe cable disruption occurs. Network architecture and communications enable operators to quickly locate and repair cable faults. Power and telemetry redundancies enable acquisition to continue during field repairs.

Acquisition QC is performed by recording system capabilities such as SourceAware™ which ensures that active receiver template quality statistics match or exceed user defined thresholds and which can interrupt acquisition when critical poor quality conditions are detected. Finally, large RAID systems that are part of modern central recording systems allow routine data management activities such as taping and plotting in the recording truck to proceed without impacting the pace of operations.

## Conclusions

Over the last 50 years, seismic imaging advances have come in several technology waves, each resulting in improved exploration success and better hydrocarbon reservoir characterizations from clearer seismic images. The latest advance, full-wave imaging and the technologies that make it possible, deliver high quality seismic images to oil companies and operational benefits to contractors today. With high-fidelity, three-component single-point receivers and wide-azimuth surveys with proper receiver spatial densities, full-wave imaging delivers improved resolution, more efficient noise suppression and higher quality seismic images that ultimately improve our geological and geophysical understanding and development of oil and gas reservoirs.

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