Moving towards full-sampling in land 3D acquisition

Marty Williams and Scott Hoenmans, Input/Output, explain the requirements for modern 3D seismic on land and anticipate the introduction of new operating technologies and methods to obtain fully sampled reflected seismic energy.

Geophysicists need seismic data to convey a reliable, geologically meaningful picture of the subsurface both at the prospect and geologic system levels. This requires that spatial sampling be sufficient to provide adequate resolution not only for identifying drillable targets, but also for characterizing depositional environments, intra- and inter-reservoir discontinuities, and other subtle features associated with finding and developing hydrocarbon reservoirs. To address these imaging needs onshore, sampling density needs to improve significantly by deploying more recording stations than is the current convention. To date, high station count surveys that fully sample reflected seismic energy have been cost prohibitive and difficult to implement. Fortunately, a new generation of cableless, single-station seismic recording systems will soon be commercialized which should provide geophysicists with a viable platform for acquiring high station count surveys and obtaining fully sampled data.

Spatial sampling

Spatial resolution is not just a matter of bin spacing. In the era of pre-stack migration and anisotropy analysis, all pre-stack domains need to be sampled. These criteria are rarely met in contemporary seismic acquisition since cost and recording system constraints force interpreters to cope with inferior resolution and unnecessarily noisy data that result from footprint, migration artifacts, AVO uncertainties, or unresolved anisotropy.

The solution for overcoming these modern interpretation limitations is to spatially sample the reflected seismic energy with increased station densities such that:

- Source and receiver intervals are equivalent in both the in-line and cross-line directions (an orthogonal geometry)
- Group intervals are small enough to avoid aliasing signal and organized noise
- The source effort is balanced with the receiver effort
- Sources and receivers are symmetric in response (Vermeer, 1990)
- Data are sampled in the offset, azimuth, and CMP domains so as to not introduce either gaps or aliasing of the reflections within these domains

Acquiring this ideal, fully sampled survey is a tall order. In one region we evaluated, it would have taken nearly 100,000 live stations. This would have exceeded any previous station count deployment for this development trend by more than an order of magnitude and satisfied only a portion of the ideal sampling criteria noted above. Conventional land acquisition systems would also have been technically challenged to acquire this quantity of data. Even if technically feasible, the acquisition cost would have been exorbitant.

The time is fast approaching, however, when this level of effort will become an economic necessity. Competition for resource access continues to increase worldwide. E&P operators are compelled to showcase environmentally-friendly seismic acquisition solutions with agencies like the Bureau of Land Management that control resource development activities on government lands in the US. They also must prove their sources of technological advantage when vying for production sharing agreements with sovereign host governments. As the pressures to secure and efficiently monetize resources mount, the winners will be those companies that have an edge in finding and developing subtle and more complex hydrocarbon reservoirs in increasingly difficult imaging environments.

Fortunately, the costs of acquiring high station count surveys should continue to decrease. On a per station basis, the up-front capital cost of equipment and the ongoing cost of field acquisition should fall as commercial deployments of cableless, single-station recording systems become more widespread. Supporting technologies in areas such as data storage, power systems, and LiDAR (light detection and ranging), as well as tighter, software-enabled integration among planning, surveying, and field acquisition workflows will drive further cycles of efficiency, especially as acquisition crews become more proficient in high station count operations.

We are rapidly approaching the point where acquisition technology and operational methods will support a step-change improvement in land imaging. By removing the constraints imposed by cable-based recording systems, geophysicists will be able to focus their land imaging programmes on full sampling of the entire seismic wavefield and to de-emphasize noise rejection sampling as the primary objective in land survey design.

Concept of full-sampling

A fully sampled 3D survey is acquired when every receiver location is both occupied and active out to a chosen offset radius around the source. The source locations would be offset from receiver locations by one half of a group interval in both the in-line and cross-line directions. Likewise, every source location would be used. By applying these full-sampling criteria, a perfect surface sampling would be achieved (Figure 1) resulting in a regularly-sampled stack array. In both offset and azimuth, the reflected seismic energy is well sampled (Figure 2). Such full-sampling is, of course, ideal. There will always be compromises as a consequence of conditions on the surface and the logistics of actual field operations. Until single-station cableless acquisition systems become commercially widespread, the costs and operational challenge of deploying large numbers of stations will remain prohibitive for at least the next couple of years.

Nonetheless, oil and gas companies are already beginning to plan land acquisition programmes that accommodate a step-change increase in station counts. For example, we recently designed a fully sampled survey for a major gas basin in North America. Given the recording template, the required number of stations to fully sample the reservoir horizons would have approached 100,000 receivers. Such a design would provide over 8000 unique fold (note that Figure 2 shows duplication of fold only because we chose to bin the data into 10° azimuths).

What does this fold mean in terms of the image? To answer this question, one needs to consider the spatial domains where processing takes place. In this case, these include source, receiver, offset, azimuth, and CMP domains. It is the sampling in all of these domains that ultimately determine the quality of the final image. The shot and receiver domains are where most noise rejection, scaling, and wavelet shaping occur. While sampling is usually best in the shot and receiver domains, current seismic design practices introduce one inherent flaw in processing. Since these domains are well sampled in only the inline direction, scaling and noise rejection become directionally biased. If one is interested in analyzing the azimuthally-varying properties of the data (Jenner, 2002; Williams and Jenner, 2002) or wants to preserve amplitudes for an azimuthally-varying migration, access to fully sampled data becomes paramount.

The offset domain is closely linked to the azimuth domain for wide azimuth analyses. It is in these domains, along with the CMP domain, where most velocity and anisotropy analyses are performed. In addition, pre-stack migration is often applied in the offset-azimuth domain. As a result, full-sampling is critical for avoiding artifacts and footprint from offset-azimuth changes in data amplitude (Hill, 1999).

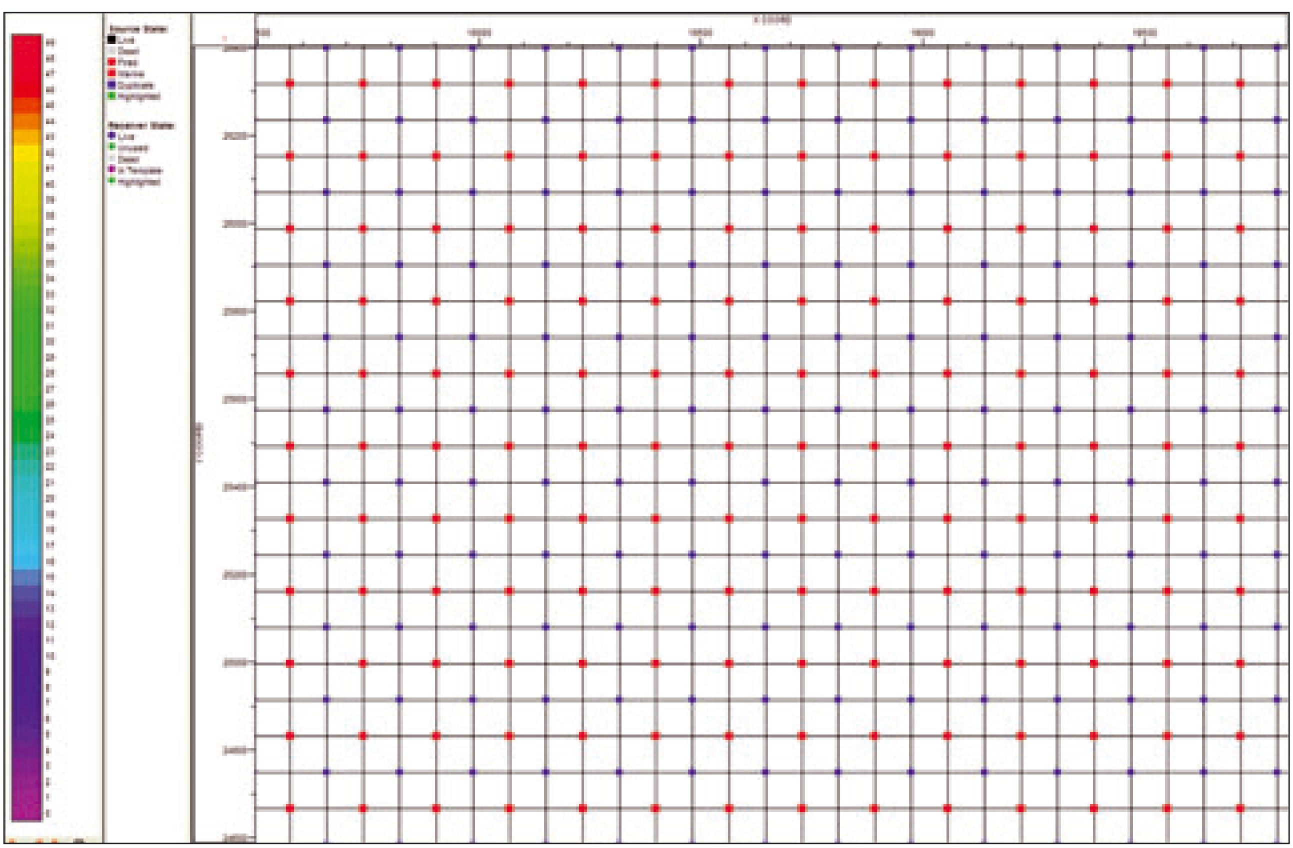

Figure 1 *Geometry of a full sampling survey. The blue circles represent receiver points and the red squares represent source points. The black lines illustrate the natural bin size of 25 m by 25 m.*

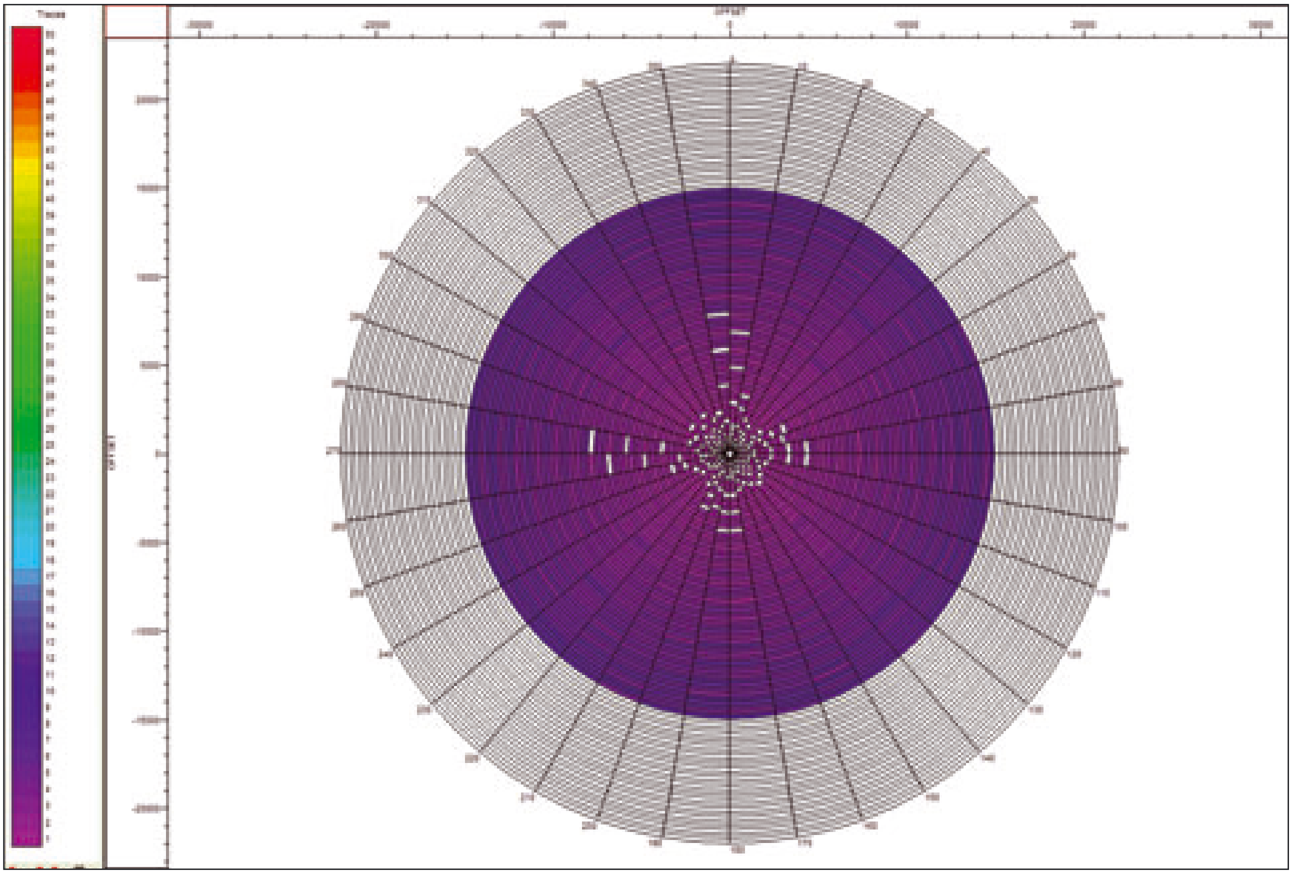

Figure 2 *Rose diagram of a natural bin contained within a full sampling survey. The diagram is defined by 10° azimuth sectors and approximately 100 m offset sectors with a maximum offset of approximately 5000 m.*

When working with wide azimuth data, there are processes and attributes that depend on having a full complement of offsets for a given azimuth. Similarly, for many geologic environments, the offset domain needs to be split into well-populated azimuths to avoid loss of resolution and mixing of amplitudes (Williams and Jenner 2002).

Ultimately, what is desirable is a CMP that is evenly sampled in offset for any given choice of azimuth sector width. With even the best current acquisition technologies and methods, the combination of conventional azimuth and offset sampling is insufficient to provide azimuth sectors of any reasonable resolution. Significant and often detrimental interpolation is therefore required to migrate in the azimuth sectors.

While acquiring fully sampled data may represent the ideal vision for land imaging, what is a reasonable expectation for acquiring an 'almost fully sampled' survey? What trade-offs and compromises are required? And, how can one control the cost? For the North American example referenced previously, data have historically been acquired with 1500 to 3000 geophone channels using a nearly wide azimuth patch (Figure 3). This station count and acquisition design delivers approximately 30-40 fold (Figure 4). In some basins and for some prospects, this fold may be sufficient. In this case, however, the basin has a complex tectonic and diagenetic history. Although the subsurface has little structural relief, azimuthally-varying anisotropy is common. This anisotropy is spatially variable and relatively strong (upwards of 7% in P-wave velocity variability). The rocks are fast. Near-surface velocities start at 3000 m per second and increase to 4500 m per second at the reservoir, which lies at an average depth of 3500 m.

As a further complication, many areas on the surface are hard. The weathered layer is limited. Vp/Vs ratios at the surface vary from near three to less than two. Signal to noise can be low because of ground roll, scattered surface waves, and P-wave contamination by converted waves (Figure 5 shows a 9x9 macro-bin stacked into offsets after azimuthal velocity correction. Each offset is 30 fold or greater). Maximum frequencies recovered from the data are rarely above 70 Hz, with the dominant frequency being near 20 Hertz.

Although several 3D seismic programmes have taken place in the basin (typically using Vibroseis sources), the data are fairly low fold and band limited. While the azi-

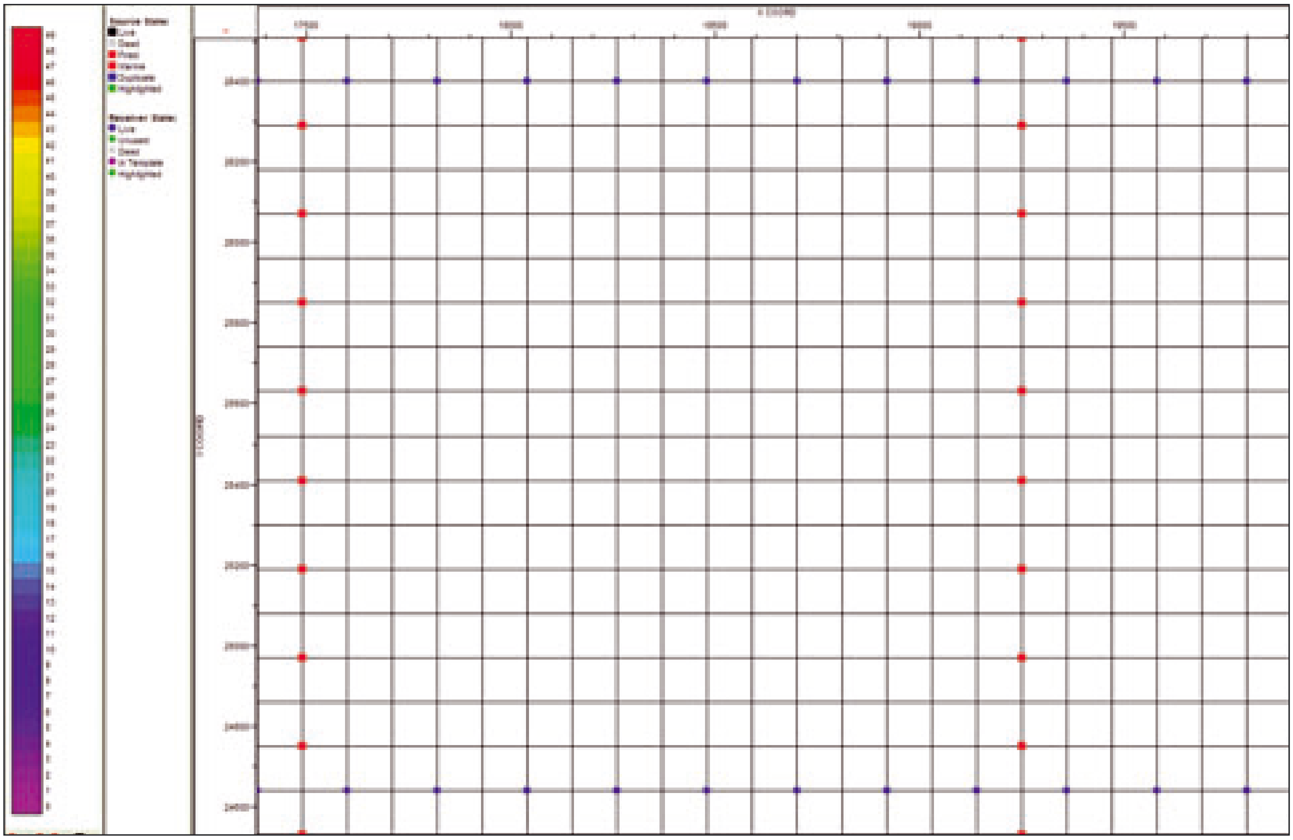

Figure 3 *Geometry of a traditional orthogonal survey. The blue circles represent receiver points and the red squares represent source points. The black lines illustrate the natural bin size of 37.5 m by 37.5 m.*

muthal distribution is fair, signal-to-noise problems often result in unreliable anisotropy analysis. As a consequence, severe time shifts resulting from the velocity anisotropy - up to and greater than a wavelength - are present in uncorrected data. The practical method of solving this problem has been to decimate the data to narrow the azimuth distribution and limit the offset. Unfortunately, this process also lowers the fold. Without decimation, the uncorrected anisotropy, stacking-velocity errors, and unresolved AVO leave amplitude and phase footprints in the data, making the data difficult to interpret, particularly when interpreting attributes.

Designing the fully sampled survey

Being cognizant of current cost and operational capabilities, we have developed an approach to overcome many of the sampling problems which involves designing a survey that is nearly fully sampled and that employs full-wave acquisition technology and methods (Criss et al., 2005). For the proposed North American gas basin 3D pilot programme, the survey design anticipates approximately 20,000 live stations (Figures 6 and 7 compared to Figures 1 and 2). To balance the tradeoff between station count and cost:

- The receivers were decimated by line intervals from 50-100 m.
- The group interval will be recorded at 50 m versus the traditional 75 m or greater
- The shots were decimated from a uniform grid of 50 m to a uniform grid of 100 m.

These design parameters imply that, in the shot domain, the trace spacing will be 50 m while, in the receiver domain, the trace spacing will be 100 m. Ground roll will be aliased in both domains, but the signal will not be aliased. The change from 75 m in previous surveys to 50 m in this survey will provide additional spatial resolution with a 25 m bin, helping to resolve narrow alluvial valleys that separate the depositional environments into sand-prone intervals and inter-valley coastal plane facies. While the sandstones in the valleys are not extensive stand-alone targets, identifying their presence or absence is a predictor for where the stacked sandstone sequences may lie.

Given that the source will be single-hole dynamite and the receiver will be a single multicomponent sensor, the data will be symmetrically sampled except for the fact that the source and receiver are not on the same plane. Symmetrical

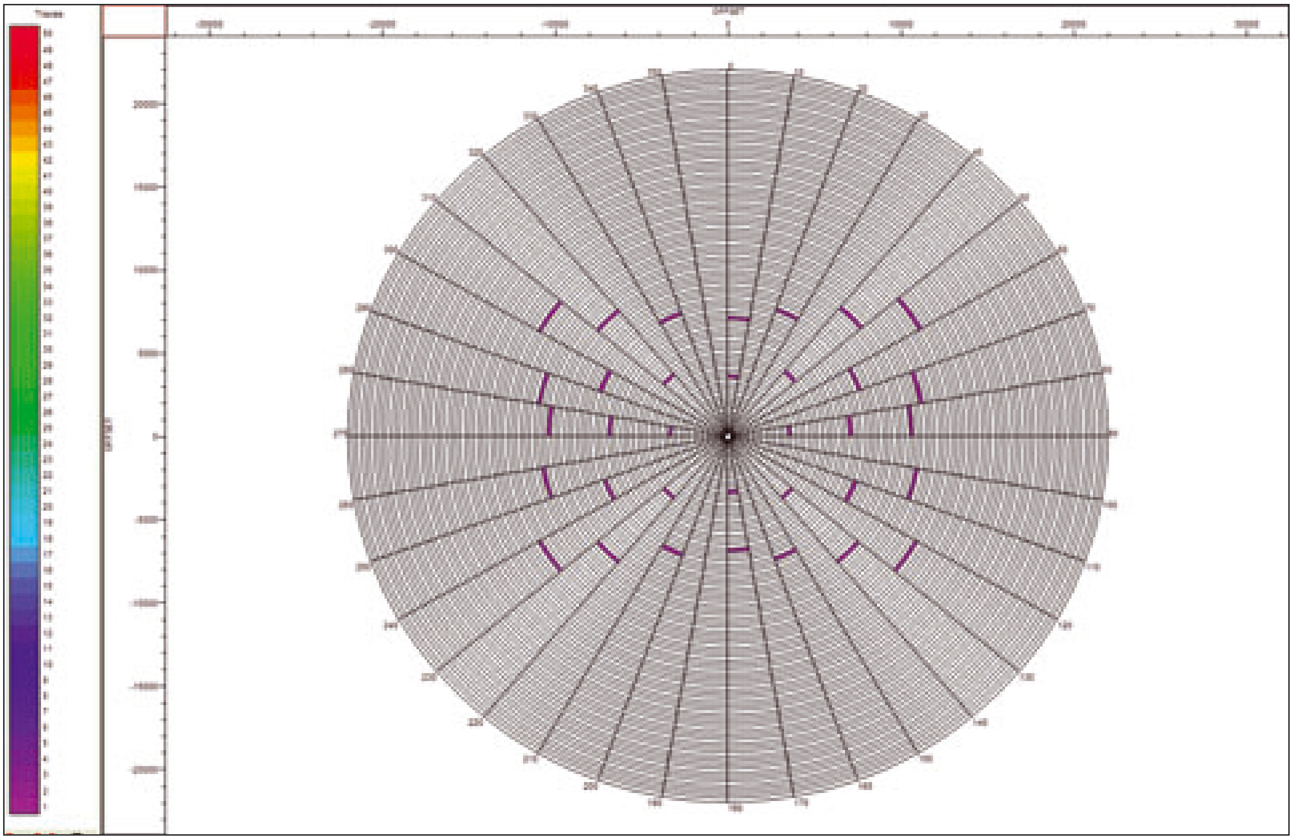

Figure 4 *Rose diagram of a natural bin contained within a traditional orthogonal survey. The diagram is defined by 10° azimuth sectors and approximately 100 m offset sectors with a maximum offset of approximately 5000 m.*

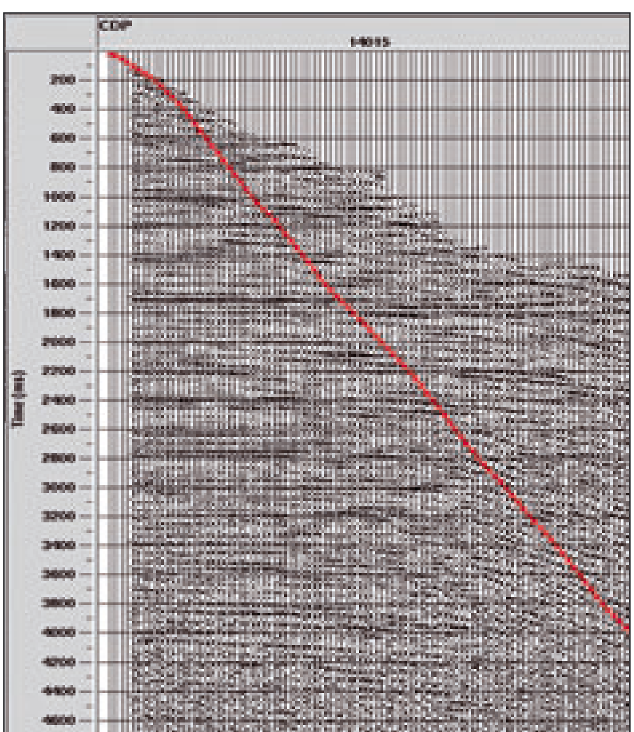

Figure 5 *9x9 macro-bin stack of a common midpoint gather. The far offsets are contaminated with what is suspected to be converted wave energy. The acquisition surface is outcropping sedimentary rock with a low Vp/Vs ratio. At the far offsets, surface particle motion is not vertical. Ground roll is not present because of the macro-bin stacking.*

sampling is critical in this case because the data are going to be analyzed for azimuthal properties that relate to faults, fractures, and localized velocity gradients. Non-symmetric arrays and differing arrays between source and receiver positions are detrimental to any azimuthal imaging of P-wave data and could be fatal to converted wave imaging. Symmetry preservation will be enabled by using high vector fidelity, 3C full-wave sensors rather than geophones.

This survey is designed to account conventionally for symmetry and excellent sampling in the traditional sense of shot, receiver, and CMP. In the offset domain, there will be gaps that require interpolation; however, the amount of interpolation will depend on the azimuth sectors chosen. If the sectors are chosen properly, there will be sufficient azimuthal sampling and resolution without the detrimental effects of over-interpolation.

For this survey, a requirement was set that 10° sectors be fully populated with no more than five contiguous missing offsets within the sector. With this constraint, the objective is barely met with only one fold per offset/azimuth bin and little duplication. If three contiguous CMPs are summed, there are almost no holes in the offset domain. To fill the gaps on 10° sectors using this acquisition design, one would need to replace the removed sources and receivers, a move that would increase acquisition costs due to the additional equipment and source effort requirements. The offset-azimuth sampling under this additional effort would yield duplicate traces in the bins that may be wasted under the 10° azimuth requirement. Another option would be to fill in the receivers in the design back to fully sampled. However, this removes the balance between source and receiver effort while doubling or quadrupling the amount of needed receiver equipment.

The economical solution is to widen the azimuth sectors. This has the effect of filling in missing offset-azimuth cells and of duplicating traces in some bins, which may lead to unnecessary duplicate offsets. Presently, we do not have an estimate for the limits on the azimuth sectors; however, we do know from processing azimuthal data in the pre-migration domain that large sectors give poor results when fitting an elliptical solution to velocities and AVO. There lies the trade-off - sector width versus the width of missing offsets, which translates to cost versus obtaining a vastly improved image. In contrast, the other land acquisition decisions are focused on azimuthal symmetry, recording the vector wavefield, and operational efficiency.

To acquire fully sampled data with a reasonable operational cost, the oil and gas company plans to deploy an early version of the recently announced FireFly cableless land acquisition system from I/O. Surveying will take place in real time using the latest GPS and LiDAR navigation tools. Because of expected mode contamination (most likely caused by low Vp/Vs at the surface), data will be recorded using 3C VectorSeis full-wave sensors. By recording 3C multicomponent data, processors will have an opportunity to remove converted waves from the vertical component of the receiver and, if the converted wave data are ultimately processed, to similarly remove P-wave energy from the horizontal components.

Conclusion

The next generation of land imaging will centre upon fully sampling reflected seismic energy. This will require

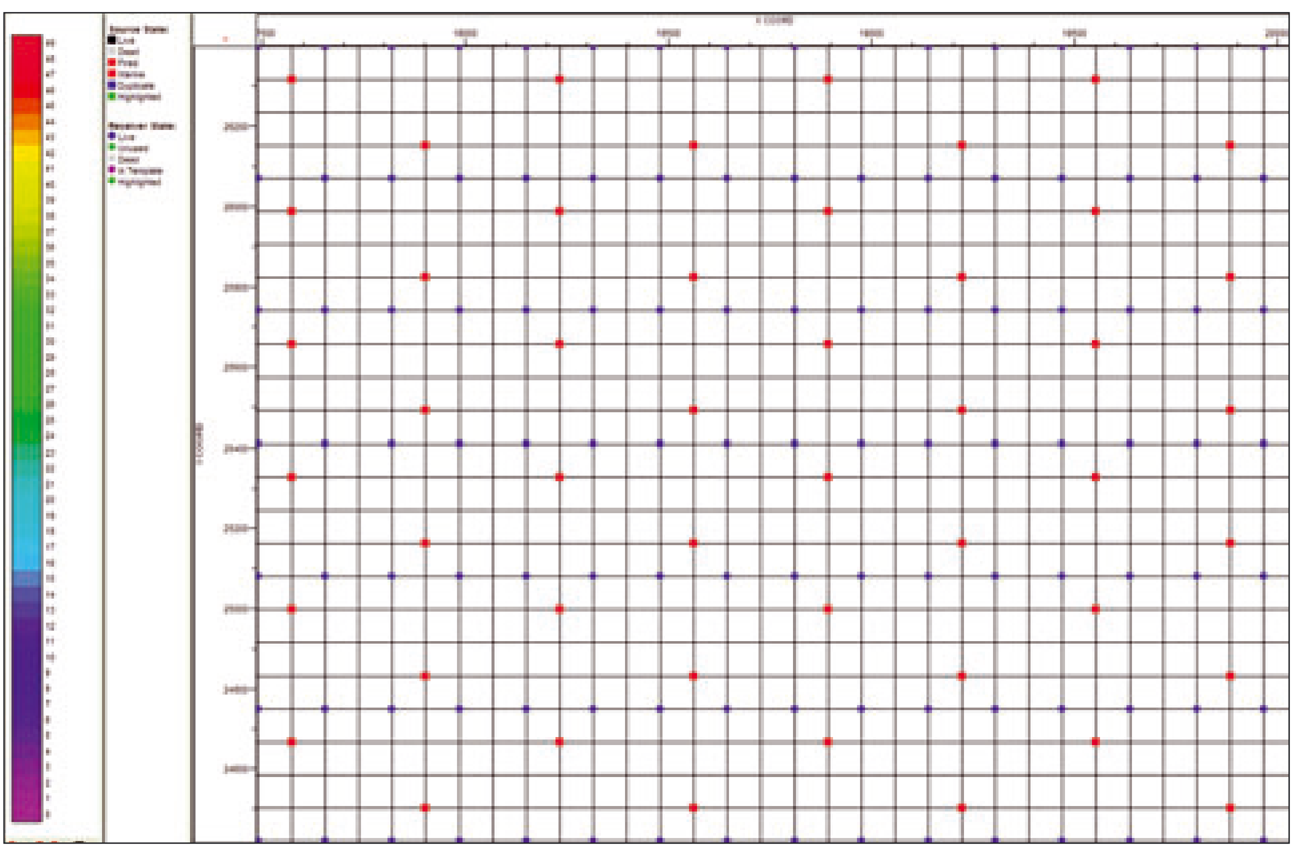

Figure 6 *Geometry of a reduced full sampling survey. The blue circles represent receiver points and the red squares represent source points. The black lines illustrate the natural bin size of 25 m by 25 m.*

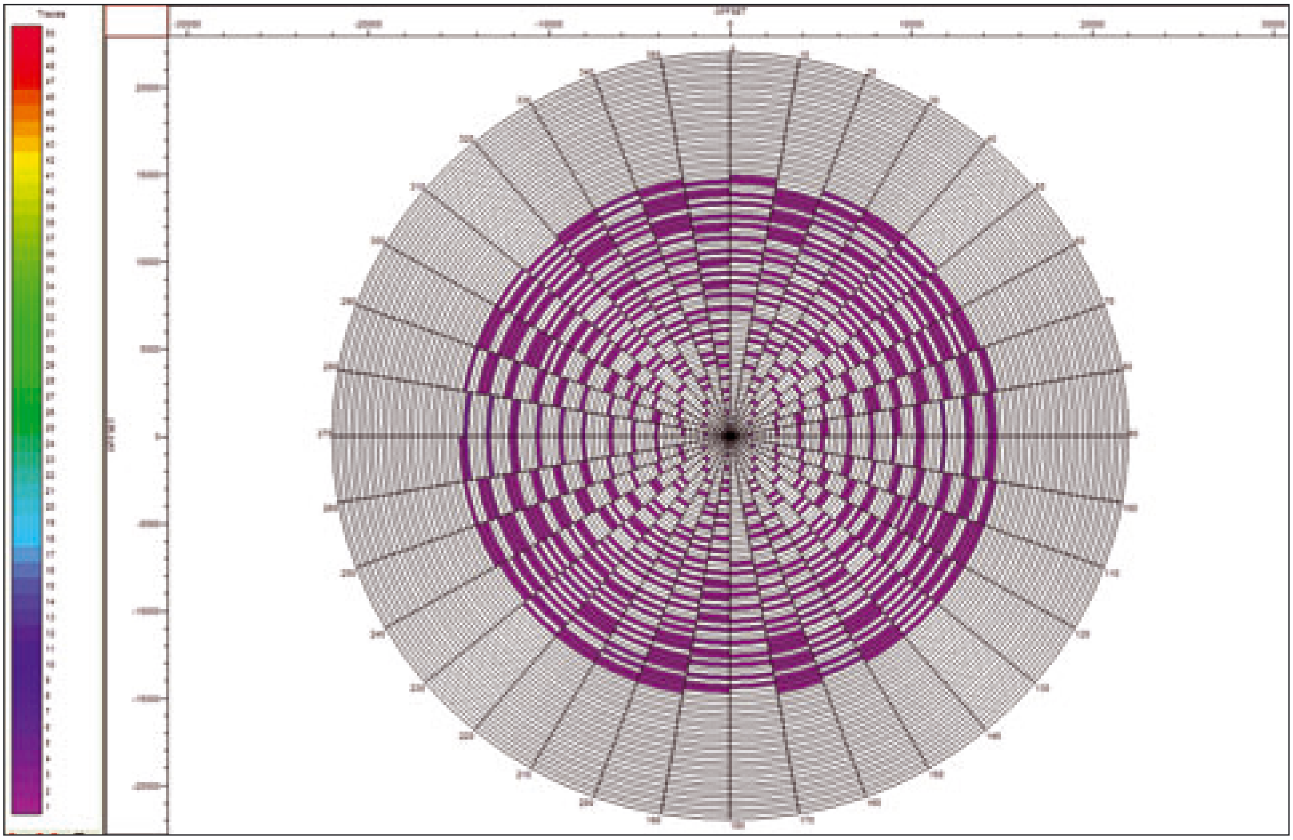

Figure 7 *Rose diagram of a natural bin contained within a reduced full sampling survey. The diagram is defined by 10° azimuth sectors and approximately 100m offset sectors with a maximum offset of approximately 5000 m.*

high station count acquisition systems and an entirely new set of operating technologies and methods. Imaging objectives will move away from overcoming the detrimental effects of under-sampling and towards fully sampling the entire seismic wavefield. While survey design decisions will continue to balance the ideal sample interval, azimuth sector width, and offset sampling with cost and operational considerations, these trade-offs will now result in a very different level of imaging. Increasing fold, and having a more effective stack array as a result of a more fully sampled survey, will mitigate most issues of noise, footprint, and pre-stack migration artifacts, allowing resources to be expended on the more value-adding activity of characterizing the properties of a well-imaged reservoir.

References

Jenner, E. [2002] Azimuthal, AVO: Methodology and data examples. *The Leading Edge*, **21**, 8, 782 - 786.

Vermeer, G. [1990] *Seismic Wavefield Sampling, Geophysical Reference 4*. Society of Exploration Geophysicists

Williams, M. and Jenner, E. [2002] Interpreting seismic data in the presence of azimuthal anisotropy; or azimuthal anisotropy in the presence of the seismic interpretation. *The Leading Edge*, **21**, 8, 771 - 774.

Hill, S., Shultz, M., and Brewer, J. [1999] Acquisition footprint and fold-of-stack plots. *The Leading Edge*, **18**, 6, 686 - 695.

Criss, J., Kiger, C., Maxwell, P., and Jim Musser, J. [2005] Full-wave seismic acquisition and processing: the onshore requirement. *First Break*, **23**, 2, 53-61.