Shooting Seismic Surveys in Circles

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1. Camara Alfaro J, Corcoran C, Davies K, Gonzalez Pineda F, Hill D, Hampson G, Howard M, Kapoor J, Moldoveanu N and Kragh E: "Reducing Exploration Risk," *Oilfield Review* 19, no. 1 (Spring 2007): 26–43.
2. Production in the seismic sense means production of seismic data. Therefore, productivity is the amount of time a seismic vessel spends recording useful data relative to the total time the vessel is in the survey area, usually expressed as a percentage.

Traditionally, marine seismic data are acquired by a seismic vessel sailing in a straight line over a target, then turning back to shoot another line parallel to the first. A new technique acquires seismic data in continuously linked circles with little or no nonproductive time. The results are high-quality data containing reflection information from all azimuths. Test results indicate that the technique will be useful for improving seismic imaging in several complex geological environments. The first full survey using the technique was acquired for Eni in 2008 on the Tulip project in the Bukat production-sharing contract block, offshore Indonesia.

Many of the world's most significant technical developments were envisioned long before they became commercial. For example, Leonardo da Vinci's 15th century designs probably played a part in the development of the helicopter and screw propeller. Within the E&P industry, recent developments by WesternGeco in 3D seismic imaging systems apply fundamental principles defined decades ago that had to await advances in technology to realize their potential. These developments have now enabled circular shooting—another idea from the past—to become a reality.

The seismic industry performed early trials of circular acquisition geometries in the 1980s. However, it was not until 2006 that WesternGeco realized that it could make a circular acquisition technique a practical option for 3D surveys.

Three-dimensional seismic surveys have probably done more than any other modern technology to increase the likelihood of exploration drilling success.[1] Subsurface imaging using 3D surveys has proved particularly successful for imaging clastic sediments; however, accurate imaging of sediments beneath hard seafloors, salt, basalt and carbonate layers remains a challenge, particularly in deep water.

In deep water, towed-streamer geometries are currently the only economically viable solutions for acquisition of large 3D seismic datasets. Conventional marine 3D surveys, acquired as a set of adjacent parallel straight lines, have proved their value as exploration tools in a wide variety of geological settings. These surveys image the subsurface with seismic raypaths that are aligned predominantly in one direction. Complex geology and highly refractive layers cause ray bending that can leave portions of the subsurface untouched when recording seismic waves traveling in just one direction. In such circumstances, conventional 3D data may provide ambiguous or misleading images, reducing confidence in exploration decisions and potentially introducing uncertainties and inaccuracies in models used for reservoir development.

Wide-azimuth (WAZ) seismic surveys provide data from raypaths traveling in a wide range of directions. The method has been shown to deliver better illumination of the subsurface, higher signal-to-noise ratio and improved seismic resolution in several complex geological environments, such as beneath large salt bodies with complex shapes. Until recently, in deep water, this improved method of imaging has required several seismic vessels working together.

This article reviews developments in towed-streamer WAZ acquisition and introduces Coil Shooting acquisition: a new technique that goes beyond WAZ to acquire a full range of azimuths

using a single vessel shooting continuously with a circular or curved path. We describe modeling and feasibility tests, which indicate that the technique has considerable potential for efficiently addressing imaging challenges in complex geological settings. Also presented are some details of the world's first full Coil Shooting project.

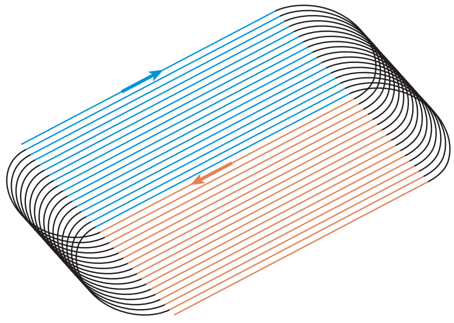
Wide-Azimuth Towed-Streamer Acquisition

Conventional marine 3D surveys acquire data from a vessel sailing in a series of adjacent parallel straight lines. The vessel is typically equipped with one or two airgun source arrays and 8 to 10 streamers. When the vessel reaches the edge of the defined survey area, it continues in a straight line for one-half the length of a streamer, then turns around in a wide arc to position itself for another straight line in the opposite direction, as if following the course of a simple racetrack (right).

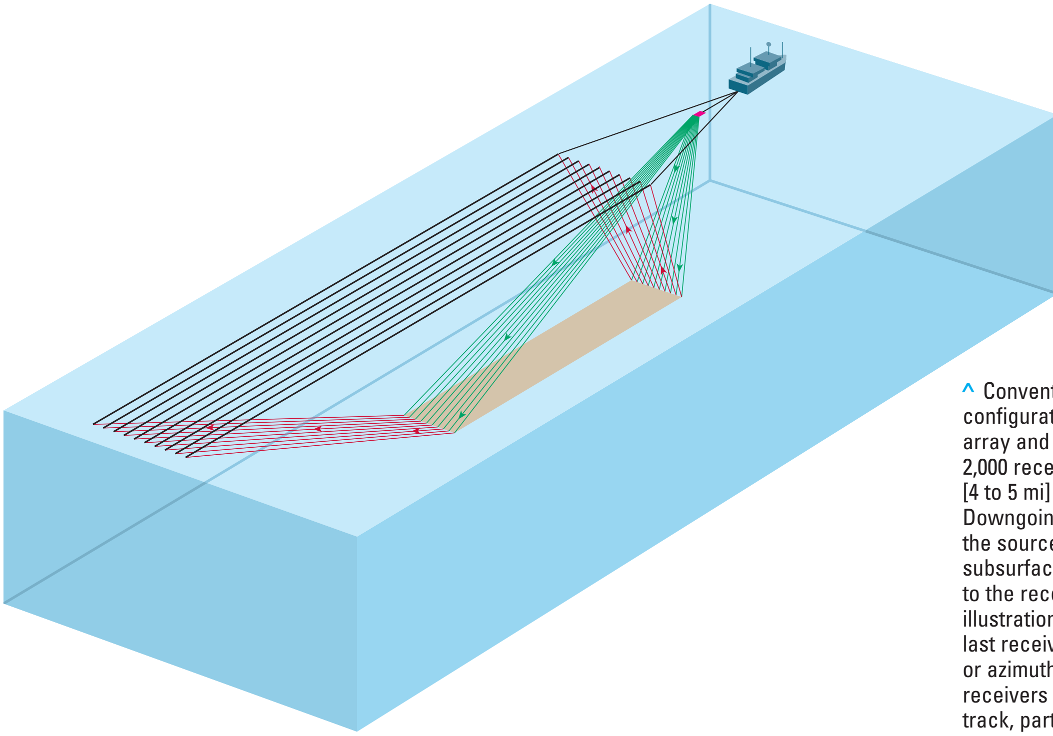
When the vessel gets back to the other edge of the survey area, it turns to follow another racetrack-like course displaced laterally from the first. This continues until coverage of that part of the survey area is completed.

Usually, no data are recorded while the vessel is turning because, in conventional acquisition systems, streamers do not maintain their lateral separation during turns, and the positions of receivers within the streamers cannot be accurately calculated. Additionally, turning may induce increased lateral drag on the streamers as they move through the water, resulting in increased levels of noise. Depending on survey dimensions, vessels can spend up to 50% of the time available for production on line changes, so line changes represent a significant period of nonproductive time (NPT).[2] This limitation can compromise data quality: to minimize NPT, and hence costs, some surveys are shot in the optimal direction for efficiency but not the best direction to achieve geophysical objectives.

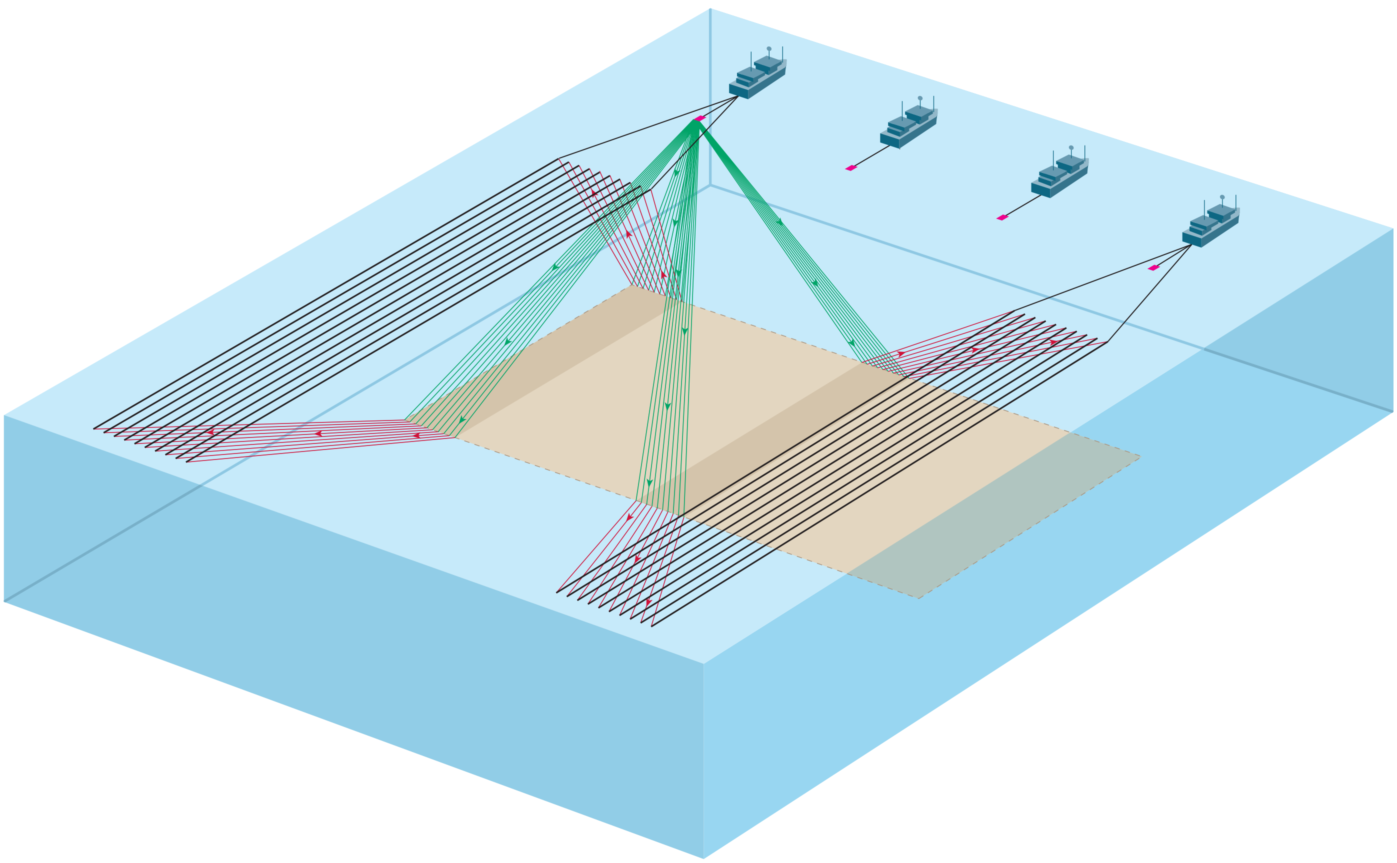
In conventional surveys, the direction, or azimuth, of a seismic ray traveling down from the source into the subsurface then up to a receiver



^ Typical conventional deepwater 3D acquisition configuration. The acquisition path follows a straight line (blue arrow) then turns 180° to acquire data in the opposite direction (orange arrow). No data are normally recorded during line turns (black).



^ Conventional single-vessel streamer configuration. A vessel tows an airgun source array and 10 streamers, each containing about 2,000 receivers. Streamers are typically 6 to 8 km [4 to 5 mi] long and 100 m [328 ft] apart. Downgoing seismic rays (green) emanate from the source. They reflect at the seabed and at subsurface interfaces then travel upward (red) to the receivers where they are recorded. The illustration shows only raypaths to the first and last receivers in each streamer. The direction, or azimuth, between the seismic source and receivers is close to the direction of the vessel track, particularly for far offsets—the data recorded by receivers farthest from the source.



^ A four-vessel wide-azimuth acquisition configuration. Two recording vessels (*left and right*), both equipped with an airgun source array and 10 streamers, are joined by two source vessels (*center*). The source on the left-hand vessel is fired, and data are recorded by streamers on both recording vessels, providing two areas of subsurface coverage (dark tan). Sources are then fired in sequence by the other vessels, providing a wider area of subsurface coverage (light tan) and a broader range of source-receiver azimuths than can be achieved by a single vessel. Sail lines may be repeated with source vessels in different positions, providing different ranges of azimuths.

^ Image distortion. Refraction of light through the irregular surface of a glass causes parts of the spoon to be invisible or distorted. The image changes depending on the direction of view. Similarly, the azimuth of observation impacts the results of seismic imaging through geologic media with complex geometries.

will be close to the direction of the vessel track (previous page, top). Azimuths for far offsets will typically be within ±10° of the vessel track. Near offsets will have a higher range of azimuths because of the lateral displacement between the source and the front of the streamers.

Complex geology and highly refractive layers bend seismic rays so that portions of the subsurface may remain untouched by seismic waves, particularly when source-receiver geometries provide only a narrow range of azimuths. An analogy to this phenomenon, whereby the azimuth of observation impacts the results of imaging through media with complex geometries, can be made by viewing an object through textured glass (above). Viewing the glass from several different directions will enable the viewer to determine its contents more accurately. Similarly, acquiring seismic data with a broad range of azimuths has been shown to deliver more-accurate images of the subsurface in complex geological environments, such as those associated with salt bodies, by essentially "shining a light" on the formations from many directions.

Various towed-streamer acquisition geometries that increase the range of source-receiver azimuths have been tested in several locations, including the Nile Delta, the North Sea and, most prominently, the Gulf of Mexico. These surveys typically use three or four seismic vessels, each shooting in straight parallel lines (previous page, bottom).

Since 2001, the WAZ technique has been used in several surveys in which one or more recording vessels, following essentially the same racetrack-like course as for a conventional 3D survey, are joined by source vessels positioned in front of and/or behind the streamer spread, and offset laterally at various distances on each side of the spread. The technique typically provides an almost full range of azimuths at near offsets but only ±30° for far offsets.

In 2006, WesternGeco acquired a survey in which a WAZ geometry was deployed in two opposite sailing directions for each of three different orientations—effectively covering the subsurface six times. When combined, the resulting 3D dataset contained contributions from a complete range of azimuths for most offsets. This survey, acquired over the Shenzi field in the Gulf of Mexico, was the world's first rich-azimuth (RAZ) seismic survey.[3]

A 2007 study concluded that these types of surveys, combined with accurate velocity models and high-fidelity migration algorithms, could provide a step-change improvement in subsalt illumination, signal-to-noise ratio and attenuation of multiples, compared with conventional narrow-azimuth (NAZ) surveys.[4] The study found that wider crossline offsets led to better results, and that the best results were from data acquired over a complete 360° range of azimuths, as delivered by RAZ geometries.

The RAZ and WAZ towed-streamer geometries described above were all acquired as a series of adjacent straight lines. As with a conventional 3D survey, the time taken to turn the recording vessel between lines is usually nonproductive time. For multivessel operations and wide streamer spreads, this turning time is typically more than three hours per sail line, adding up to several weeks for a large survey. Another potential problem with parallel geometries is that they can leave undesirable acquisition artifacts in the data, such as stripes in the direction of sail lines that can be seen in the processed dataset.

Circular Acquisition

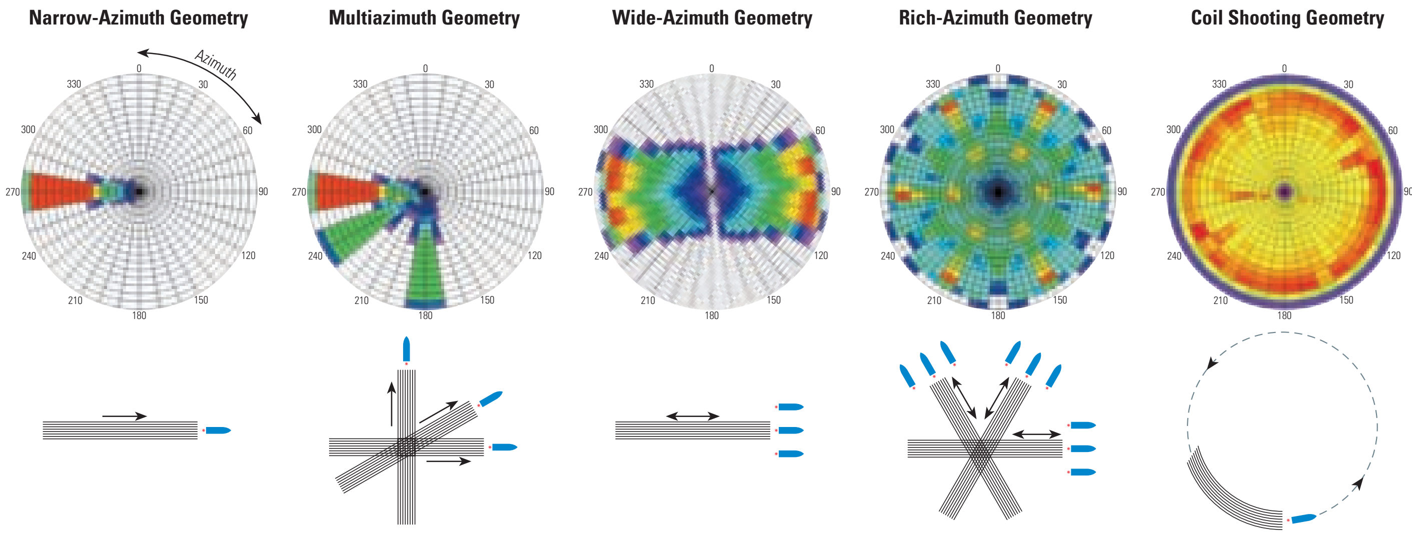
While acquiring the Shenzi seismic survey, WesternGeco and the operator—BHP Billiton—agreed that it might be worthwhile to continue firing sources and collecting data during line turns. The results of this experiment were extremely encouraging. The first stage of processing for these data, acquired using Q-Marine single-sensor technology, included an advanced noise-attenuation algorithm, which effectively addressed any increase in the levels of ambient noise to provide useful data at the edge of the survey area. In addition, acquisition productivity was increased through elimination of nonproductive time during line changes.

Because sail lines acquired during line changes approximate arcs of circles, they can be considered as a partial implementation of circular acquisition geometry. The success of continuous acquisition during the Shenzi RAZ survey convinced WesternGeco to investigate the possibility of employing circular geometry for wide-azimuth towed-streamer acquisition.

Like many fundamental seismic acquisition techniques, some potential benefits of circular geometry for marine acquisition have been known for many years. In the 1980s, it was proposed that sailing in concentric circles around salt domes would improve structural

3. Howard M, Harding C and Stoughton D: "Rich Azimuth Marine Seismic, A Cost Effective Approach to Better Subsalt Images," *First Break* 25, no. 3 (March 2007): 63–68.
4. Kapoor S, Moldoveanu N, Egan M, O'Briain M, Desta D, Atakishiyev I, Tomida M and Stewart L: "Subsalt Imaging: The RAZ–WAZ Experience," *The Leading Edge* 26, no. 11 (November 2007): 1414–1422.

Multiples are seismic energy that has bounced between more than one reflecting surface. A form of noise that can interfere with or obscure primary reflection events, multiples are suppressed by algorithms applied during processing.



^ Comparison of acquisition geometries (*bottom*) and azimuth-offset distribution plots in rose diagrams (*top*). The number of traces recorded for each offset-azimuth combination is color-coded in the rose diagrams. Offset corresponds to distance from the center of each circle. Azimuth corresponds to the angle within each circle. Colors range in order from purple and blue for a low number of traces, to green, yellow and red for a high number of traces. From left to right: Traditional marine surveys are acquired by one vessel in one azimuth and produce data with a narrow azimuth-offset distribution. Multiazimuth surveys are acquired by one vessel sailing in multiple directions and have azimuth-offset distributions clustered around the direction of the sail lines. Wide-azimuth surveys are acquired by several vessels, increasing the azimuth range for many offsets. Rich-azimuth surveys use several vessels shooting in several directions, combining the concepts of multiazimuth and wide-azimuth surveys to deliver contributions for most azimuth-offset combinations. The Coil Shooting single-vessel technique delivers a high number of contributions for a complete range of azimuths for all offsets.

imaging of the flanks of the domes and associated faulting.[5] Test surveys were acquired in the Gulf of Mexico and in the North Sea using concentric circle acquisition.[6] However, because the marine acquisition technology at that time did not allow proper implementation of the method, it was abandoned.

The Q-Marine system, introduced in 2000, has overcome many of the challenges inherent in circular acquisition geometries, enabling its use for several new applications. Q-Fin steering devices precisely control the depth and lateral position of the streamers, making it possible to maintain constant streamer separation. Monowing multistreamer towing technology is highly effective at maintaining lateral streamer displacement while turning. Shaped like an aircraft wing, Monowing deflectors provide force perpendicular to the sailing direction to keep the wide streamer spread in position. Monowing deflectors are mounted close to the edge of the outer streamer. By contrast, conventional deflection devices are mounted outside the streamer spread, resulting in a much larger total equipment spread that necessitates a larger turn radius.

An acoustic network provides accurate positioning of the in-sea equipment. Large calibrated source arrays deliver deep-penetrating energy, and an advanced digital source controller provides a fully calibrated airgun source signature for every shot.

In the presence of strong cross-currents, towing streamers in a curve can increase noise levels in the raw field data. Q-Marine technology leverages advances in electronics and fiber-optic networks to provide high channel-count recording systems, enabling finely sampled single-sensor recording of both signal and noise in the seismic wavefield. Shell geophysicists documented the potential of the single-sensor method in the late 1980s, but limitations in hardware and processing capabilities at the time prevented full realization of its benefits.[7]

Adequately sampling streamer noise allows targeted signal-processing techniques to suppress it while preserving the integrity of the seismic signal. Part of the digital group forming (DGF) process, this effective noise removal allows acquisition of high-quality seismic data even in poor weather or when towing streamers through strong currents.[8]

Using circular geometry for towed-streamer acquisition offers benefits for both geophysical analysis and operational efficiency. The Coil Shooting technique acquires well-sampled, full-azimuth (FAZ) data, providing more complete illumination of the subsurface and benefiting noise reduction and multiple attenuation. It acquires short-offset data, something not possible with multivessel WAZ geometries. The method also delivers data sufficiently sampled in azimuth that the dataset can be split into different azimuth ranges for building anisotropic velocity models and analyzing fractures (above).[9]

The Coil Shooting technique involves a single vessel equipped with multiple streamers and a seismic source. The vessel sails along a pattern of overlapping circular or curved sail paths that cover the survey area, shooting and recording data continuously. This continuous mode of acquisition virtually eliminates NPT, so it is

5. French WS: "Circular Seismic Acquisition System," US Patent No. 4,486,863 (December 4, 1984).
6. Durrani JA, French WS and Comeaux LB: "New Directions for Marine 3-D Surveys," *Expanded Abstracts*, 57th Annual International SEG Meeting, New Orleans (October 11–13, 1987): 177–181.
7. Ongkiehong L and Huizer W: "Dynamic Range of the Seismic System," *First Break* 5, no. 12 (December 1987): 435–439.
8. Christie P, Nichols D, Özbek A, Curtis T, Larsen L, Strudley A, Davis R and Svendsen M: "Raising the Standards of Seismic Data Quality," *Oilfield Review* 13, no. 2 (Summer 2001): 16–31.
9. Woodward M, Nichols D, Zdraveva O, Whitfield P and Johns T: "A Decade of Tomography," *Geophysics* 73, no. 5 (September–October 2008): VE5–VE11.
10. Fold of coverage is the number of seismic traces that map to a defined area, typically 25 m by 25 m [82 ft by 82 ft].
11. Moldoveanu N: "Circular Geometry for Wide-Azimuth Towed-Streamer Acquisition," presented at the 70th EAGE Conference and Exhibition, Rome, June 9–12, 2008, paper G011.

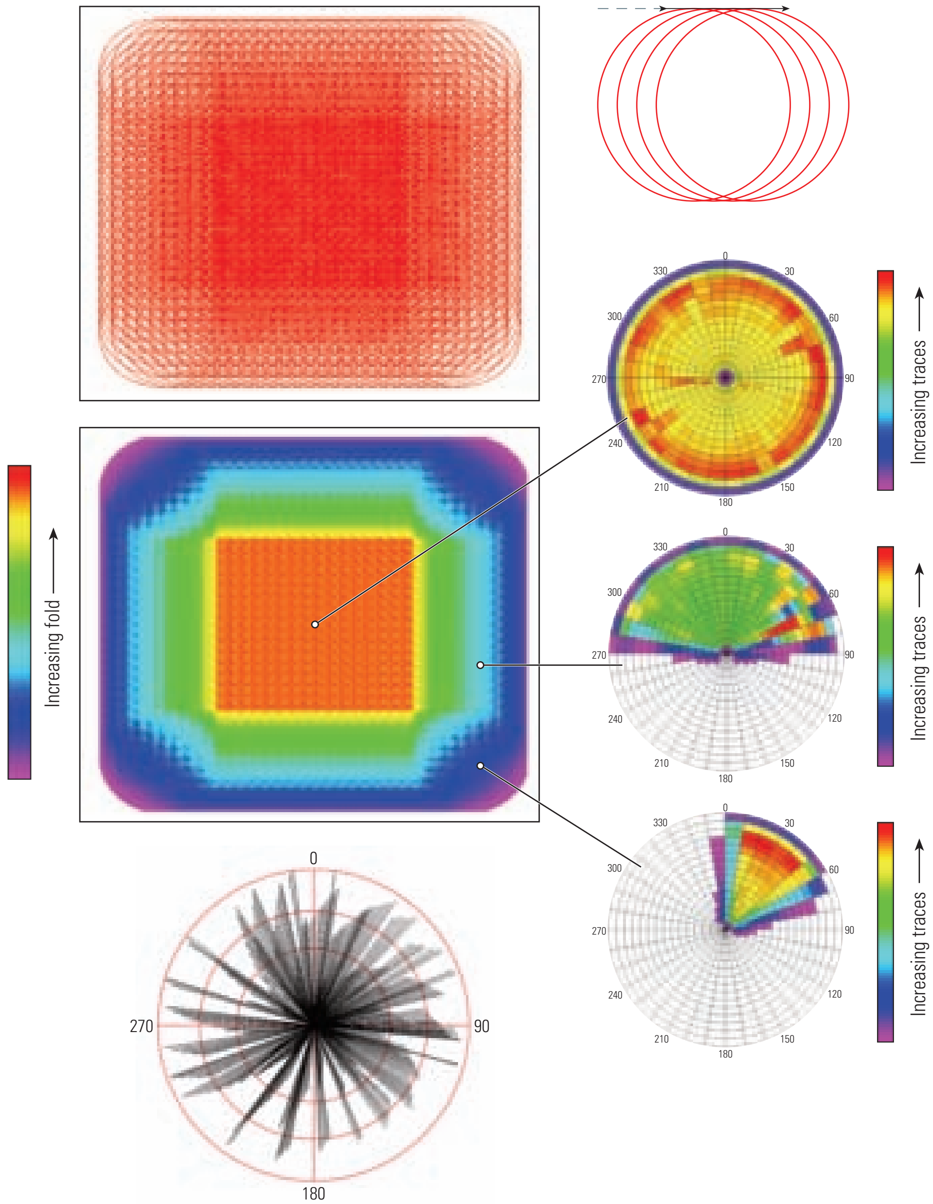
highly cost-effective for acquiring data with enhanced azimuthal contributions, particularly for appraisal and development projects, and for parts of the world where it is impractical to mobilize several vessels. For parallel geometries, vessels are typically productive about 45% of the time they are in a survey area. With circular geometry, this can double to 90% of available acquisition time. For parallel geometries, the last half-streamer length of each straight line acquires low fold of coverage in a “taper-off” mode.[10] This typically means that 3 km to 5 km [1.9 mi to 3.1 mi] of each straight line are of degraded quality. By contrast, the Coil Shooting method provides well-sampled data close to the edge of the whole survey area. Continuous line acquisition is also highly efficient for conventional 3D projects, in which shooting while turning provides valuable additional data for a relatively small additional effort.

Gulf of Mexico Feasibility Test

Based on the successful acquisition of data during line turns for the 2006 Shenzi survey, a Coil Shooting feasibility test was performed during 2007 in an area of the Gulf of Mexico previously covered by a parallel WAZ survey.[11] A primary objective of this first test was to determine whether it is feasible to sail using a circular geometry while maintaining constant streamer separation and accurately measuring receiver positions. Another objective was to provide an indication of any relationship between the curvature of streamers while towed in a circular trajectory and the levels of noise introduced. The test would also determine if Coil Shooting data could be processed and imaged, and give an early indication of the effectiveness of the method for delivering high-quality, full-azimuth data.

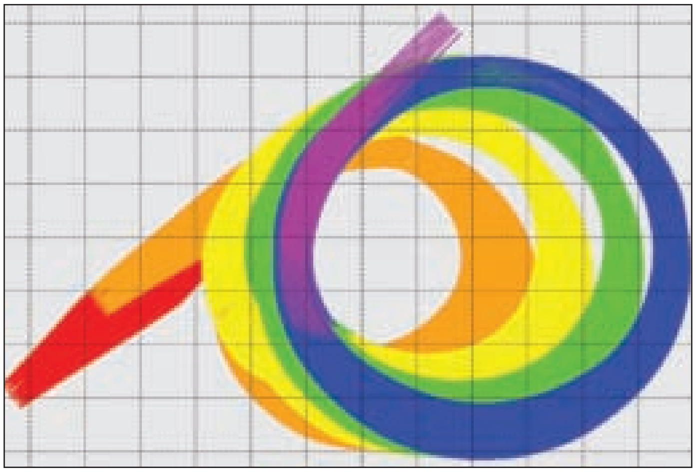
Prior to acquiring the test data, WesternGeco modeled the coverage, offset and azimuth distribution for circular geometry assuming a survey area of 42 km x 42 km [26 mi x 26 mi] and a vessel equipped with a single source and 10 streamers, each 7 km [4.4 mi] long separated by 120 m [394 ft]. This streamer configuration is typical of a WAZ acquisition geometry. The model assumed that data would be acquired by a vessel following a set of circles, separated from each other by a fixed distance in both x and y directions (right).

Fold of coverage is highest over the target area in the middle of the survey and decreases towards the fringes. Azimuth-offset distribution across the modeled circular geometry survey was analyzed for three different areas, presented as “rose diagrams.” This analysis shows that the circular geometry provides full-azimuth distribution over the target area and a reducing range of azimuthal contributions in a fringe around the edges of the survey area.

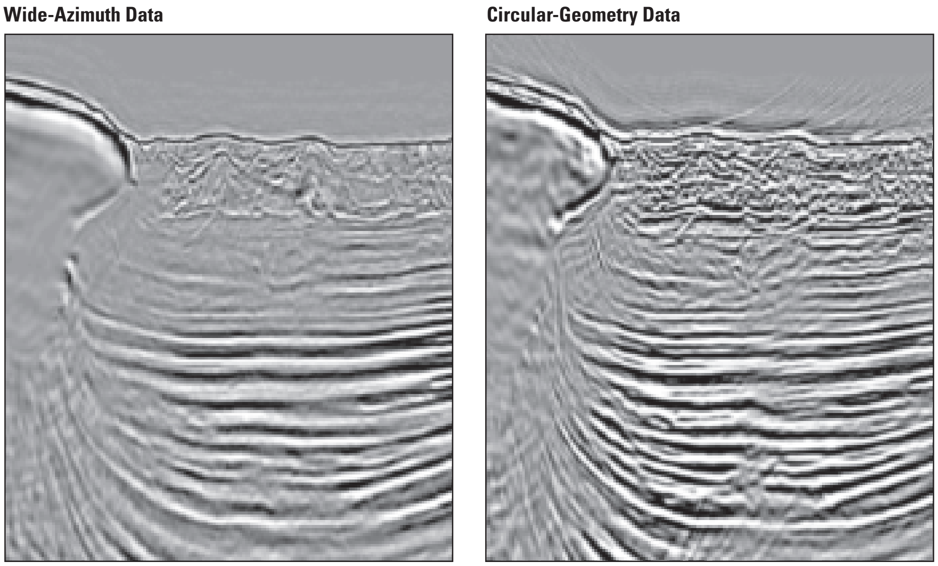


^ Azimuth and offset distribution for a Coil Shooting 3D survey. Data are acquired by a vessel sailing in a circular path (*top right*). When transit of one circle is complete, the vessel moves to a second circle separated by a fixed distance from the first, and this is repeated until the survey area is covered. The figure on the top left shows a grid of circles covering a survey area. The second diagram on the left is a coverage plot, displaying the trace density across the modeled survey area. This shows a high number of traces in the middle of the survey area (color-coded red), reducing to fewer traces at the edge of the area (green, blue and purple). On the right are rose diagrams indicating average azimuth-offset distribution for three parts of the survey area. Red indicates a high number, decreasing through yellow, green and purple. The area at the center of the survey has a complete range of azimuths and offsets. The area at the edge of the survey receives no azimuths between 90° and 270°. The region in the corner of the survey receives azimuths mostly from 0° to 90°. The bottom-left diagram is a “spider” plot illustrating the offset and azimuth of all traces within one typical 25-m x 25-m bin at the center of the survey area. Distance from the center of the circle corresponds to offset, and angle within the circle corresponds to azimuth.

Gulf of Mexico Coil Shooting Test



^ Acquisition geometry for the Gulf of Mexico Coil Shooting test. The plot shows areas containing traces from each of four circles acquired with different radii, colored orange, yellow, green and blue.



^ Comparison between E-Octopus 3D prestack depth migration of full-aperture, full-fold WAZ data (*left*) and circular-geometry test data (*right*). The Coil Shooting data exhibit some indications of improved imaging, such as the higher amplitude and better continuity of the salt overhang in the top-left area of the section.

For the purpose of comparison, analysis of the azimuth-offset distribution was also performed for a parallel WAZ geometry survey acquired with a four-vessel configuration. Near offsets are better recorded with circular geometry than with the parallel WAZ geometry because of the high lateral displacement between source and recording vessels in parallel geometries. Near offsets are needed to image shallow overburden, and fully sampled data, both in azimuth and offset domains, enable more effective application of processing algorithms that remove noise and improve resolution.

The high density of shot locations achieved through continuous acquisition results in higher total fold of coverage than could typically be achieved within the same number of days using a parallel WAZ geometry survey acquired with two source vessels and two recording vessels with the same streamer configuration. Well-sampled data with higher fold result in higher signal-to-noise ratio in the processed dataset.

Following the modeling exercise, a field test was performed to investigate the practicalities of acquiring data using the modeled circular geometry. Four overlapping circles with different radii were acquired in April 2007 by the seismic vessel *Western Regent* over an area covered by the E-Octopus project (left). E-Octopus is a WesternGeco multiclient program covering several hundred blocks in the Green Canyon and adjacent areas of the Gulf of Mexico. The project is designed to deliver more-precise base and edge of salt definition through the integration of magnetotelluric, gravity and Q-Marine WAZ seismic data.

The Coil Shooting acquisition test results proved that, using Q-Marine technology, it is feasible to sail along circles while maintaining constant streamer separation and achieving highly accurate receiver positioning. After the DGF process, ambient noise levels were acceptable for all the test data and comparable to those encountered in straight-line parts of the test.

The Coil Shooting test data were processed using the same sequence as applied to the parallel WAZ data, including single-sensor coherent noise attenuation, DGF at a 12.5-m [41-ft] group interval, shot-by-shot bubble removal and anomalous noise attenuation. Three-dimensional prestack depth migration was performed with the same velocity model used for parallel WAZ data. Despite low fold and limited migration aperture, the four-circle test data compare favorably with the full-aperture, full-fold parallel WAZ data (left).

Black Sea Test

The second field test of the Coil Shooting technique was in an area of the Black Sea known to have strong sea currents and subsurface imaging challenges related to complex geology. This test built on the success of the Gulf of Mexico test, which had already confirmed the feasibility of acquiring and processing seismic data with a circular geometry. The objective of the Black Sea test was to build experience and identify technological developments and procedures required to better support the method, particularly in terms of survey design, acquisition operations, quality control and data processing.

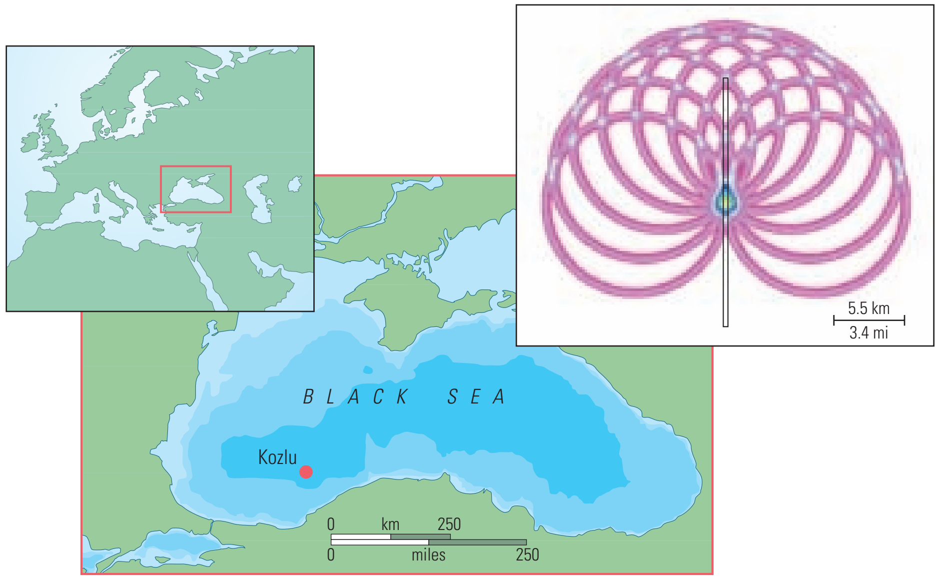
WesternGeco acquired a conventional NAZ 3D survey between September 2006 and January 2007 for Türkiye Petrolleri Anonim Ortaklığı (TPAO) in the Kozlu area of the Black Sea (next page, top).[12] The NAZ survey was acquired by the seismic vessel *Western Pride*, using Q-Marine technology. Water depth in the area ranges from

12. Palmer E, Bacon J, Toygar AR, Uygun S and Menlikli C: "A Complex, Deepwater Seismic Survey Produces High Quality Results," *World Oil* 229, no. 7 (July 2008): 89–93.

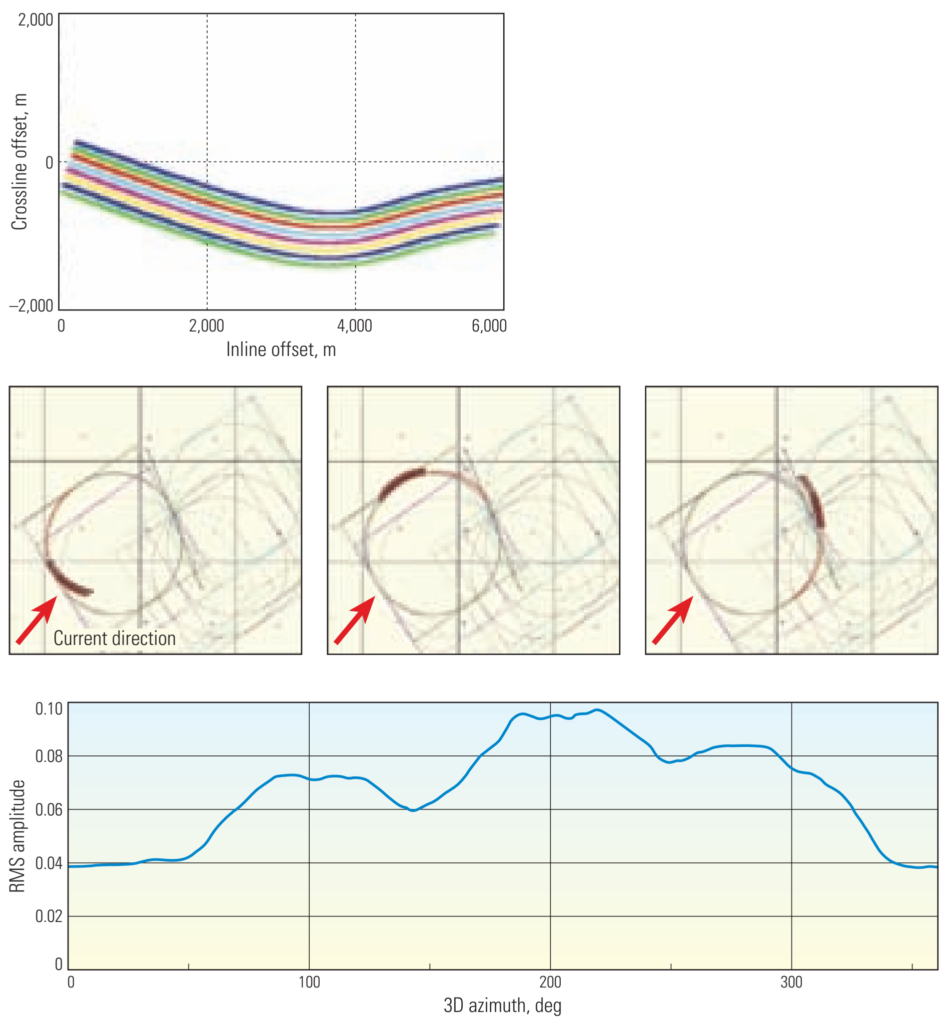
1,100 to 2,200 m [3,600 to 7,200 ft]. The target for this exploration seismic survey included potential reservoirs related to a complex sequence of limestone reefs and shales at depths of 3,500 to 4,000 m [11,500 to 13,100 ft], overlying volcanic structures. Parts of the target strata have low acoustic impedance contrast with rocks above and below, so create only weak reflections. The overburden includes layers of gas hydrates, which can inhibit transmission of seismic energy. The seabed is rugose, and complex near-seabed geology results in strong diffractions. In some areas, the target is masked by strong water-bottom multiple energy, including multiples of the diffractions generated near the seabed.

The Q-Marine data, combined with an advanced processing sequence to address the strong multiples and other noise, delivered a high-quality seismic image. Experience gained in acquiring and processing this dataset suggested that the geological and geophysical challenges of the area would benefit from an enhanced-azimuth seismic imaging approach such as the Coil Shooting technique.

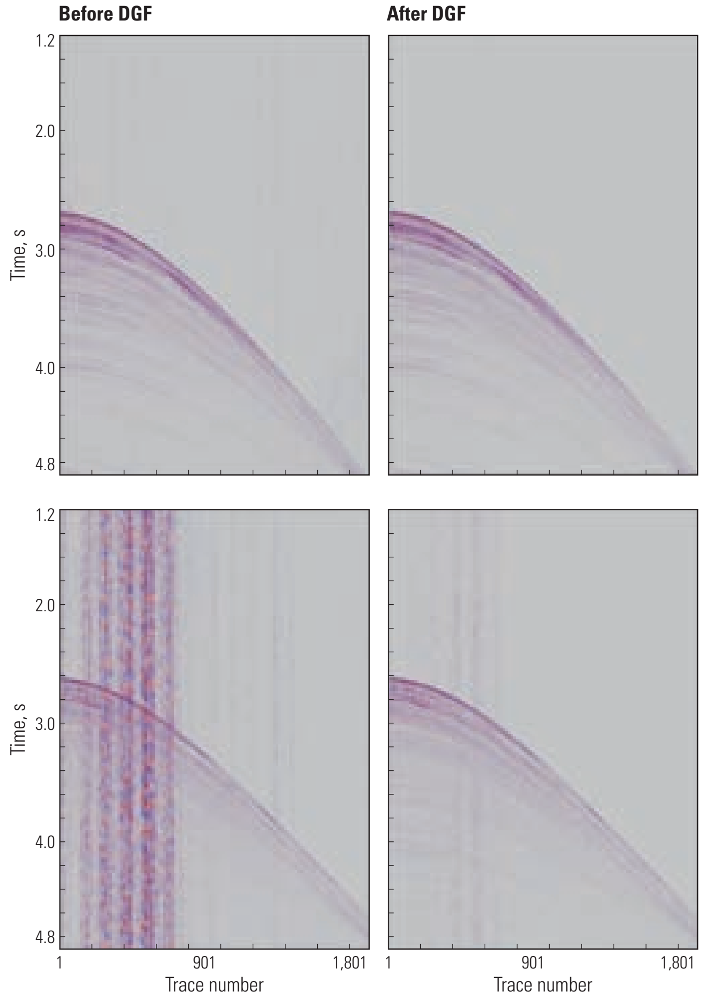
During acquisition of the NAZ survey, strong localized currents were encountered; these were thought to be related to the undulating seabed. These currents tested the Q-Marine streamer-steering system and also provided another learning opportunity for the subsequent Coil Shooting test. The currents were strong enough to cause the spread of eight streamers, each 6 km long, to bend and deflect, sometimes increasing feather angle by more than 15° within the space of 6 km (right). Despite these strong currents, the streamer array remained parallel and under good control throughout the survey.



^ Location and design of the Kozlu Coil Shooting test. The Kozlu survey area is in Turkish waters in the southwestern part of the Black Sea. The test data were acquired as a set of nine intersecting circles in a "half-dahlia" pattern (*top right*).



> The effects of strong currents in the Kozlu area. The illustration at top left shows the shape of the eight streamers for one example location of the 2006/2007 Kozlu NAZ 3D survey. A crossline offset of zero represents the direction of sailing. Localized currents caused significant bending and deflection, or feathering, of the streamer spread from the direction of sailing. The same currents were observed during the 2007 Coil Shooting test. The middle figures display streamer positions in three parts of one acquired circle. Current direction is shown by the red arrows. When shooting perpendicular to the current direction (*left and right*), streamers are deflected. When shooting parallel to the current direction (*center*), streamers follow the course of the vessel around the circle. The graph (*bottom*) plots noise in the field data against the azimuth of the vessel. Noise is measured as the root-mean-square (RMS) amplitude of data between 0.5 and 2 s two-way time, which is earlier than the first reflections. The graph indicates that the direction of towing clearly impacts noise levels in the streamers.



^ Kozlu field data. At top left is a shot record with low levels of noise. At bottom left is a shot record showing high levels of noise. The first curved line below 2.6 s on the near (left-hand) trace is the water-bottom reflection. In a perfectly noise-free environment, amplitudes above this would be zero. On the right are the same two shot records after digital group forming (DGF), which greatly attenuates the noise. Further noise reduction is achieved during subsequent processing stages.

TPAO agreed to have WesternGeco perform a Coil Shooting test survey over its acreage. Vessel commitments meant that only a four-day time slot was available for acquisition of the test data volume. A suitable survey design had to be derived that would allow efficient acquisition of a fit-for-purpose dataset in this short time frame. To meet the objectives of the test, the dataset was required to have full-azimuth and close to full-fold coverage over a geographical area sufficiently large to enable generation of a 3D-migrated image suitable for analysis and comparison with data from the NAZ survey.

The geometry modeled for the previous Gulf of Mexico test involved a series of circles that translated laterally by a fixed distance. This design is not efficient for a small test area. An innovative solution was required to quickly achieve coverage of a small, full-azimuth, high-fold area. One proposal was for the vessel to follow the pattern of the edges of the petals of a flower such as a dahlia. The design ultimately selected for the Black Sea test was a "half-dahlia," comprising nine circular coils rotated about a fixed point. This was expected to deliver a 2-km x 5-km [1.3-mi x 3.1-mi] area of adequate coverage within the allocated time frame.

The Kozlu Coil Shooting test data were acquired within three days during December 2007 by the seismic vessel *Western Monarch*. As with data from the Gulf of Mexico test and later Coil Shooting projects, levels of noise in the field data were observed to fluctuate considerably within each of the nine circles acquired (above). Experience to date indicates that towing a streamer in a curved trajectory will increase average noise levels relative to shooting in a straight line. A lesson learned from the Kozlu test, and supported by other Coil Shooting projects, is that current direction has a significant impact on how and when noise levels increase.

During acquisition of the Kozlu test dataset, the dominant current was flowing in an approximately northeasterly direction. When towed along part of a circle perpendicular to this current, streamers were observed to feather to the northeast. When towed with or against the current, streamers remained close to the track of the vessel. Plotting average noise levels in all the acquired test data against source-receiver azimuth—approximately the towing direction—shows clearly that noise levels are highest when towing perpendicular to the current.

Q-Marine field data are recorded with single sensors at 3.125-m [10.25-ft] intervals along each streamer. This spacing is sufficiently small to sample most noise, enabling it to be recognized and removed by data-adaptive algorithms applied within the DGF process. Shots with low levels of ambient noise are free of noise after the DGF process. For shots with higher levels of ambient noise, some residual noise may remain after DGF, but this is attenuated during subsequent processing.

The Coil Shooting test data were processed using a sequence comparable to that applied to the previously acquired NAZ data, including prestack time migration. A new technology, 3D general surface multiple prediction (3D GSMP), was applied to the test data volume.[13] This method is effective for attenuating multiples, while preserving the integrity of primary energy. The technique is useful in areas of complex geology, such as rugose surfaces and crossline dip, where the geophysical assumptions of many other demultiple techniques break down. Unlike many other algorithms, 3D GSMP can be applied to multiazimuthal data, as generated by Coil Shooting acquisition.

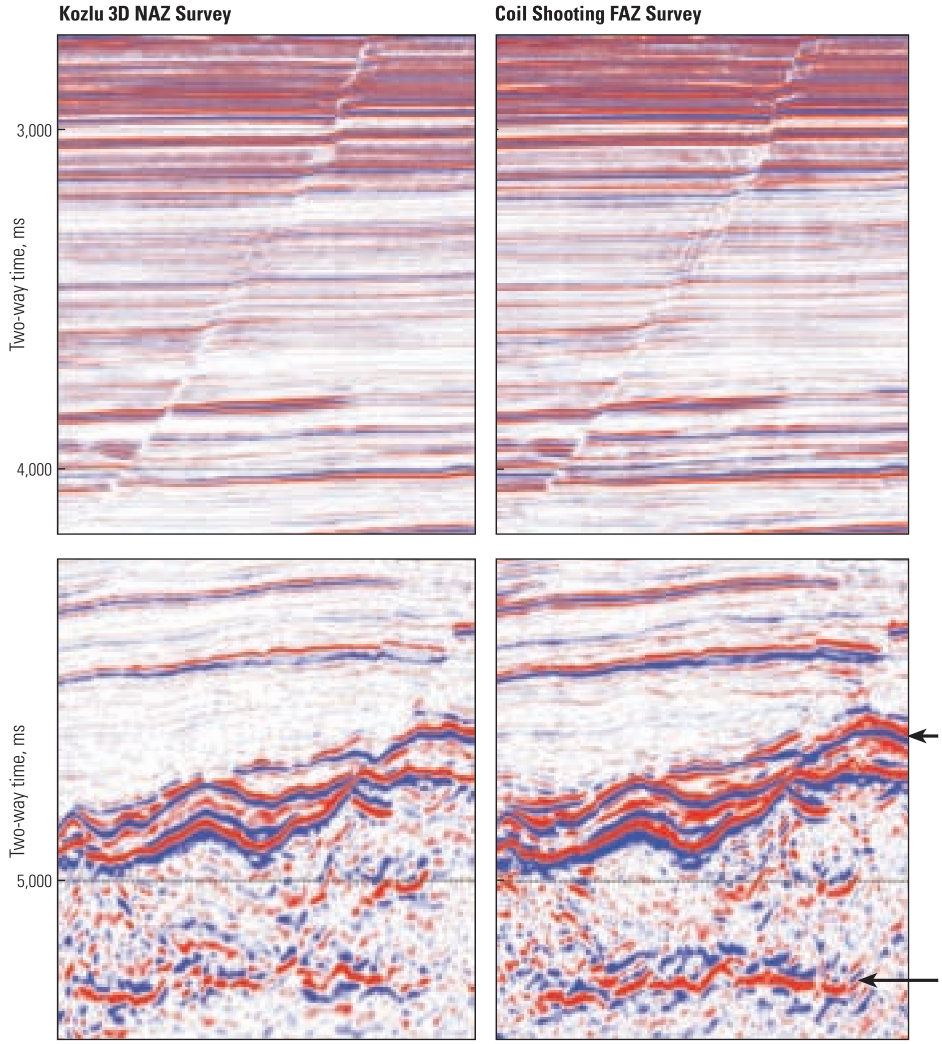
The Kozlu Coil Shooting test achieved its objectives. The innovative survey design enabled a fit-for-purpose dataset to be acquired within the allotted time. It also provided valuable knowledge about the effects of ocean currents on noise levels. The test dataset was small and may not include sufficient migration aperture to accurately image all reflection events. Nevertheless, the processed results compare favorably with the previous NAZ survey (next page, top). The Coil Shooting data show more continuity at the top and bottom of the carbonate reef target and improved fault resolution in several parts of the section. The results indicate that full-azimuth acquisition will improve the quality and reliability of seismic imaging in the area.

Full Deployment in Indonesia

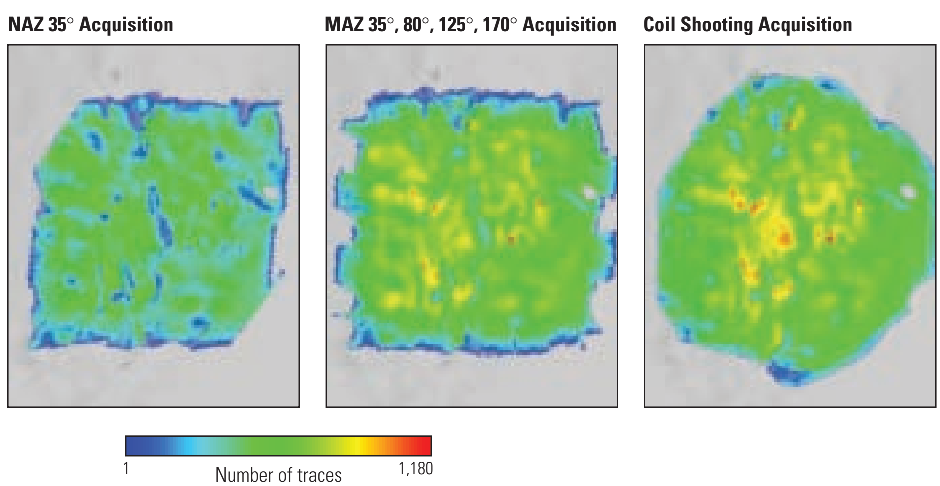
In October 2007, WesternGeco presented the Coil Shooting technique at the Milan headquarters of the E&P division of Eni, a company with experience in several projects involving wide- and multiazimuth imaging and with a history of designing and applying innovative marine acquisition techniques. The Eni E&P geophysical team immediately recognized the benefits of the technology and worked to identify a suitable location where the technique could be expected to resolve imaging challenges better than other techniques. Eventually the company chose the Tulip structure in its Bukat production-sharing contract block, offshore Indonesia.

The Tulip field has complex geology, and the target has low P-wave impedance, so only weak seismic reflectivity. By contrast, the water bottom is strongly reflective, and there is a bottom-simulating reflector (BSR) across the whole survey area.[14] Parts of the existing 2D seismic data exhibit up to six reverberations of water-bottom and BSR-related multiples, which contaminate the weak primary reflections. The seafloor topography is highly undulating, with ridges and canyons. Anomalies close to the seabed create diffractions that propagate through the section. In addition, a gas hydrate BSR in the overburden attenuates P-wave energy, obscuring the geology below.

A team of Eni and WesternGeco geophysicists evaluated possible towed-streamer acquisition configurations using a structural model of the Tulip field based on existing information, including bathymetry, 2D seismic data and a 3D velocity-depth model. The team compared the subsurface illumination, in terms of incidence angles and azimuth, that would result from a Coil Shooting geometry; conventional NAZ surveys, considering four different shooting directions; and multiazimuth (MAZ) acquisition, which is the combination of several NAZ surveys shot in different directions (right). Multivessel WAZ and RAZ options were not considered because it was important to record near offsets to image the undulating seabed.



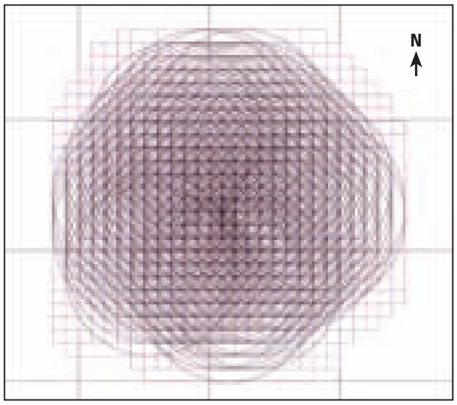
^ Comparison between NAZ 3D survey (*left*) and Coil Shooting test results (*right*). The top comparison shows better imaging of faults in the shallow section of the Coil Shooting data. The bottom comparison displays improved continuity and more detail at the top and base of the reservoir (black arrows) in the Coil Shooting data.



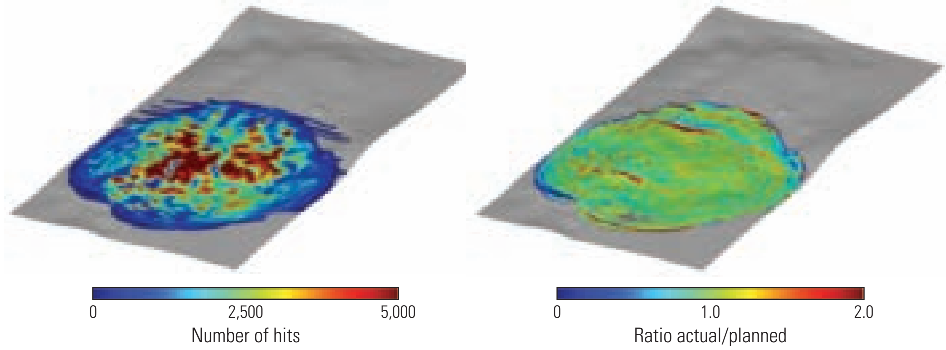
^ Presurvey illumination tests for the Tulip project. NORSAR-3D software was used to predict the illumination of a subsurface target. The colors represent the number of traces mapping to each part of the target horizon, ranging from blue (low) to red (high). Areas of the target are poorly illuminated with conventional narrow-azimuth acquisition (*left*). Multiazimuth acquisition in four directions (*middle*) provides much better illumination but requires four times the acquisition effort of the conventional geometry. Coil Shooting acquisition (*right*) illuminates the target effectively and is more efficient to acquire.

13. Moore I and Dragoset B: "General Surface Multiple Prediction: A Flexible 3D SRME Algorithm," *First Break* 26 (September 2008): 89–100.
14. A bottom-simulating reflector (BSR) is a seismic reflection often seen in seismic sections from deepwater areas. Studies indicate that it is primarily due to the acoustic impedance contrast in areas where free gas is trapped at the base of a gas hydrate stability zone.

Tulip Survey Plan



^ Planned source positions for the Tulip survey. The survey plan required the vessel to sail along 145 circles covering the survey area.

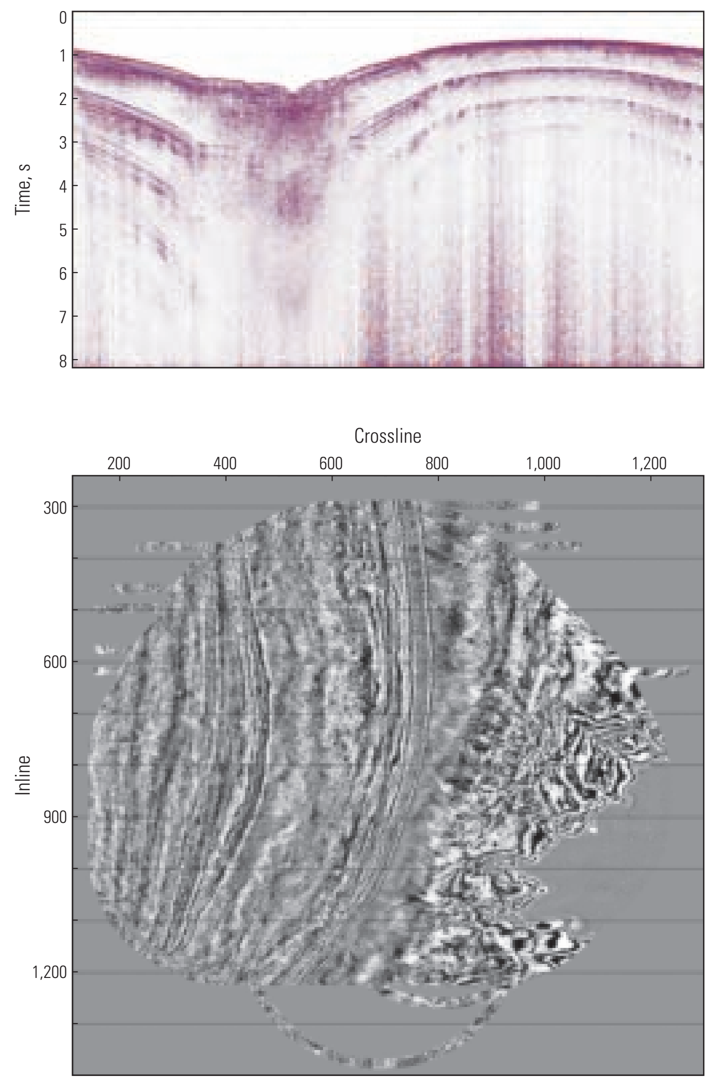


^ Onboard quality control of illumination. As data were acquired over the Tulip field, actual source and receiver positions were used to model illumination of the subsurface target horizon using NORSAR-3D software. The left plot shows the number of traces mapping to the horizon at each part of the survey area, ranging from blue (low) to red (high). The plot on the right displays the ratio of actual to planned coverage. A value of 1 (green) means that coverage matches the survey plan. Red indicates higher coverage than planned. Areas in dark blue signify lower coverage than planned. Based on this, some additional "infill" data were acquired over areas of low coverage within the main survey area and away from the edge, where variable fold is to be expected.

The study concluded that a Coil Shooting survey would provide the best illumination of the targets. As a result, Eni Indonesia, on behalf of the Bukat Joint Venture, awarded WesternGeco the world's first commercial full-azimuth towed-streamer survey using the technique. The seismic vessel *Geco Topaz* acquired the 563-km^2 [220-mi^2] survey during August and September 2008, equipped with eight streamers, each 6 km long, separated by 100 m (above).

Because of ocean currents and other factors, acquisition cannot exactly match planned source and receiver positions, so the actual subsurface coverage was monitored as the survey progressed. The presurvey evaluation used the commercial NORSAR-3D modeling package to evaluate illumination of the subsurface target from planned acquisition geometries.[15] The same package was used onboard *Geco Topaz* during acquisition to model the illumination based on actual source and receiver positions (above right). Comparison of the predicted illumination from planned versus actual positions highlighted gaps in coverage requiring additional data, known as "infill lines," to be acquired.

The field data exhibit low levels of noise, building confidence that acquiring data while towing streamers in a circular trajectory does not compromise data quality (right). The Tulip field Coil Shooting survey was completed in 49 days. By comparison, a three-azimuth MAZ survey was predicted to require 60 days, and a four-azimuth survey 75 days (next page, top).



^ Onboard quality-control (QC) displays for the Tulip survey. The example "pie bin" stack section (*top*), produced during acquisition of one circle, is continuous: if rolled on a cylinder, the start and end of the section will match. The time slice at 2 s (*bottom*) was extracted from the 3D QC stack volume built onboard during acquisition. This display was made after about 90% of the programmed circles were acquired.

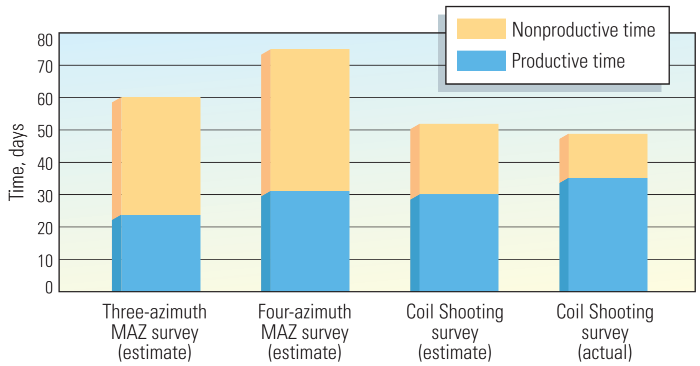
15. NORSAR-3D is a product of NORSAR.
16. Houbiers M, Arntsen B, Thompson M, Hager E, Brown G and Hill D: "Full Azimuth Seismic Modelling at Heidrun," presented at the PETEX conference, London, November 25–27, 2008.

Norway Survey Design Study and Test

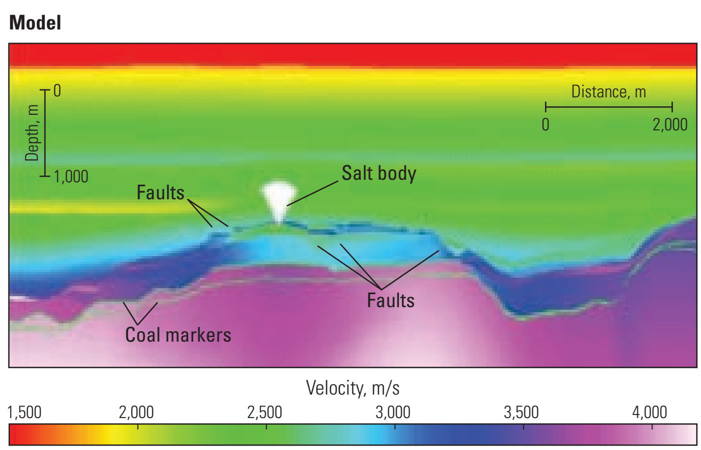
StatoilHydro included the Coil Shooting option in a simulation study performed during 2008 that investigated whether a full- or wide-azimuth acquisition geometry could resolve seismic imaging challenges at its Heidrun field, located in 350-m [1,150-ft] water depth in the Norwegian Sea, 100 km [62 mi] from the coast of Norway.[16] Heidrun came on stream in 1995, and production in 2006 was estimated at 3 million m^3 [106 MMcf] of gas and 22,260 m^3 [140,000 bbl] of oil per day.

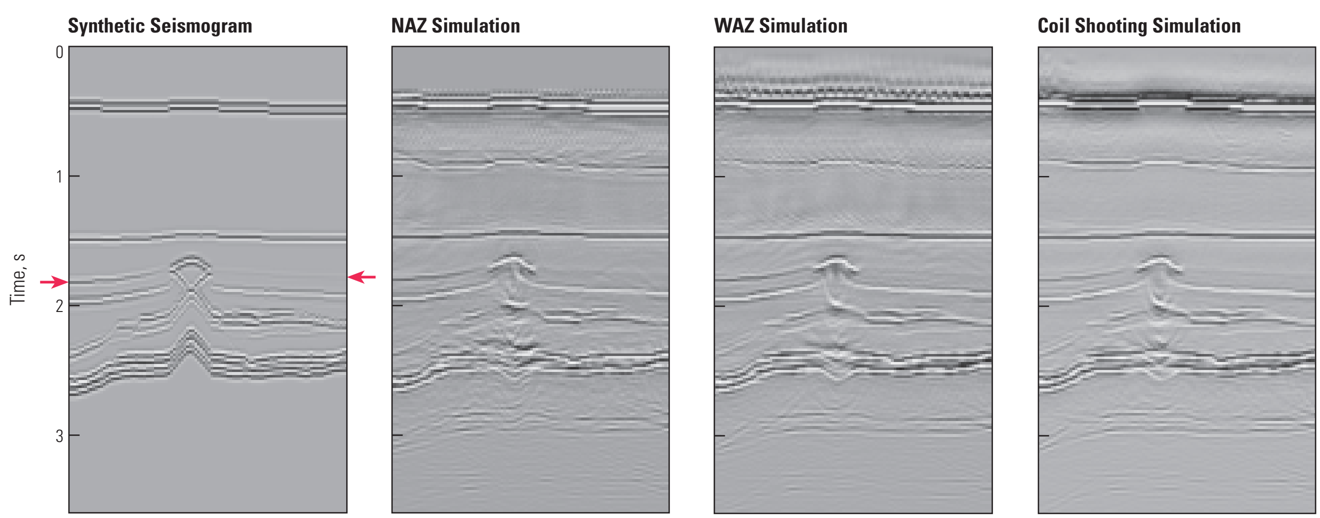
The reservoir consists of sandstones of Early and Middle Jurassic age at about 2,300-m [7,500-ft] depth below the Base Cretaceous Unconformity (BCU). The reservoir is heavily faulted, and parts of the field are not fully understood because of imaging problems. In particular, a dome-shaped feature in one area causes a highly disturbed image. One explanation for this dome is that it is formed by a salt diapir sourced by Triassic salt. Another imaging problem is that, in some areas of the field, faults and dip directions below the BCU are unclear and conflicting. Despite several vintages of seismic data, it has not been possible to obtain a clear seismic image of these complex areas. An ocean-bottom seismometer (OBS) survey provided better attenuation of multiples caused by strong impedance variations around the dome than was achieved by conventional towed-streamer surveys. The geometry of an OBS survey provides data from a full range of azimuths but at a significantly higher cost than a towed-streamer survey.

Geoscientists generated a 3D geologic model, covering a rectangular area of about 200 km^2 [78 mi^2] to a depth of 3,800 m [12,500 ft], to represent the field (left and below). It included an overburden with weak lateral velocity variation, a faulted reservoir section and a section below the reservoir. The faults included in the reservoir section represent the two main fault systems in the field, crossing each other at

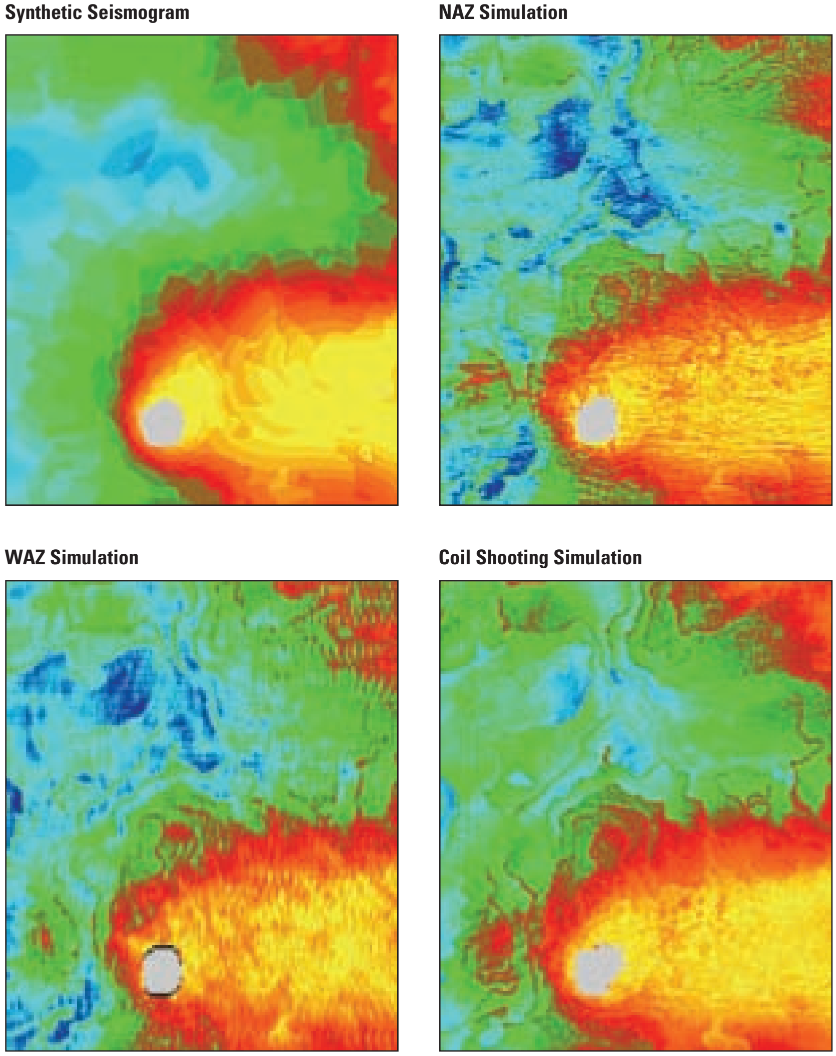


^ Comparison of acquisition duration for three single-vessel geometries considered for the Tulip survey. The Coil Shooting survey (*right*) was completed more quickly than was predicted, and more quickly than estimates for MAZ surveys using either a three- or four-azimuth parallel-line geometry.





^ Heidrun modeling results. The depth-velocity model (*top*) displays the faulted reservoir, coal markers and a small salt body. In the lower panels, the synthetic seismogram (*far left*) shows the 1D zero-offset reflectivity convolved with the wavelet for the middle part of the model. It represents the simplest seismic response. Note the pull-up of events below the salt body, caused by the high P-wave velocity in the salt. This pull-up disappears when the section is converted to depth. The red arrows mark the horizon used for the amplitude analysis shown in the figure on the next page. The simulated NAZ data (*middle left*) exhibit distortion in reservoir reflections under the salt body. The WAZ (*middle right*) and Coil Shooting data (*right*) have better continuity and better imaging of steeply dipping events. Sea-surface multiples are included in all three simulations.



^ Heidrun modeled horizon amplitudes. Amplitudes were extracted by autotracking the amplitude peak on the horizon marked by the red arrows on the previous figure. Amplitudes in the simulated Coil Shooting data (*bottom right*) match amplitudes of the synthetic seismic section (*top left*) better than do the NAZ (*top right*) and WAZ (*bottom left*) geometries.

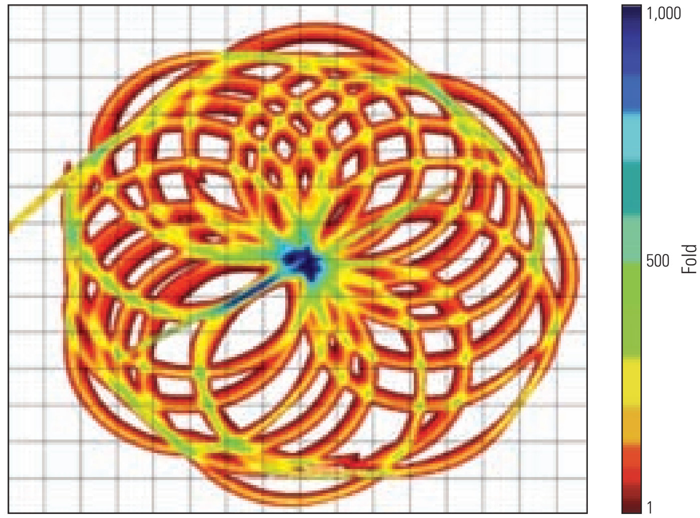
an angle of about 45°. Apart from two faults with lower average dip, all faults had an average dip between 40° and 60°. Below the reservoir, two thin coal markers were included, one of which is the base of the reservoir. A small salt body was included at the location of the dome. Each layer and faulted subdivision of the structural model were allocated densities and P-wave velocities based on a depth-migration model from 3D seismic data and well data.

Three types of acquisition geometries were simulated: conventional NAZ; a WAZ four-vessel configuration; and a Coil Shooting survey, using about 170 coils to provide a full 360° range of azimuths over the modeled area. Modeling was performed using a one-way wave-equation migration approach that included simulation of seabed multiples. Geoscientists evaluated simulated results for each of the acquisition geometries, comparing modeled vertical sections and also maps of peak amplitude extracted from one of the horizons in the overburden (above).

Compared with the WAZ and Coil Shooting results, the NAZ design exhibited more noise, especially around steep faults and in areas where the seabed has small bumps. The NAZ results also have artifacts below the salt that were more anomalous. The NAZ configuration showed conflicting dips resulting from contamination by energy from multiples. The seabed multiple and multiples of the coal markers were better attenuated in the WAZ and Coil Shooting designs than in the NAZ design. A steep flank of the structure, visible in the WAZ and Coil Shooting designs, was invisible in the NAZ geometry. This flank was also invisible when modeling was performed without multiples. Artifacts related to the acquisition footprint can be seen in the shallow part of the WAZ data, and to a lesser extent in the NAZ design. The Coil Shooting results exhibit less acquisition footprint.

The Coil Shooting geometry showed more consistent amplitudes along the analyzed horizon than the NAZ or WAZ designs, and these amplitudes were comparable to the expected values of the reflection coefficient at that horizon. The study concluded that a survey design with an increased range of azimuths and a higher fold of coverage would enable imaging of steeply dipping flanks that are invisible in a NAZ design. Such a survey would also deliver fewer artifacts, better noise suppression and better multiple attenuation. The study indicated that a Coil Shooting design would also provide more consistent and accurate amplitudes.

To validate the conclusions of the modeling exercise, StatoilHydro acquired a Coil Shooting test dataset over the field. The seismic vessel *Western Monarch* acquired the data during a four-day period in September 2008. Survey design approximated the dahlia pattern, with 18 coils intersecting over the target area (right). The coils are slightly irregular in order to avoid surface obstructions in the area, including a tension leg platform and two loading buoys. One straight line was also acquired to provide some azimuths that were missing because of the obstructions. The test survey geometry was designed to provide approximately 3 km x 3 km of full-azimuth, high-fold data, plus sufficient surrounding aperture to provide 3D migrated images that could be compared with previous seismic surveys and the modeling results. At the time of writing, the data were being processed in preparation for this analysis.

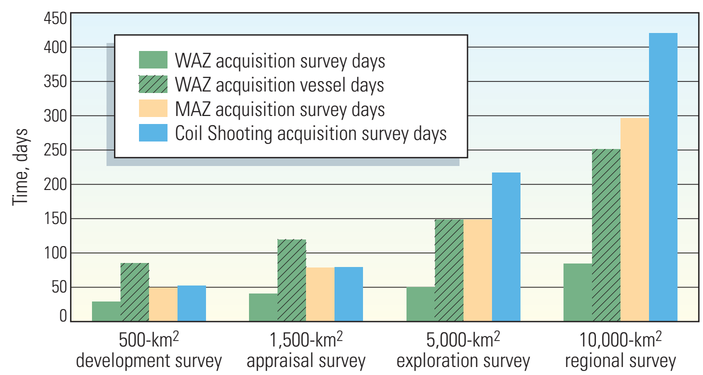


^ Heidrun acquisition geometry. The test data were acquired as 18 intersecting coils plus one straight line oriented at a heading of approximately 60°. The number of traces (fold) mapping within 25- x 25-m bins is color-coded. Fold rises where circles intersect and is highest in the center of the survey.

Worldwide Potential

Wide- and rich-azimuth seismic techniques have been proven to deliver superior subsurface images and better attenuation of coherent noise and multiples relative to conventional narrow-azimuth acquisition. Experience gained since trials starting in 2006, including the first commercial deployment in 2008, indicates that the Coil Shooting technique is a highly efficient and effective method of acquiring data with a 360° range of azimuths across the full offset-range over a survey area. A key benefit of the technique is that it requires only one vessel, negating the need for deployment of additional source and streamer vessels. This is particularly attractive for acquiring small to medium-sized 3D datasets, or for projects in remote areas, where it may not be practical to mobilize several seismic vessels at the same time.

For very large surveys, deploying multiple vessels may be a more effective option, because every shot is recorded by a large number of streamers (bottom right). WesternGeco multivessel surveys in the Gulf of Mexico typically deploy a total of 20 streamers, compared with 10 streamers expected for typical Coil Shooting projects. In practice, few surveys are likely to be large enough to warrant deploying several vessels, and these will normally be practical only in highly active areas such as the Gulf of Mexico.



^ Estimate of acquisition duration for surveys of various sizes. This chart compares the predicted time required to acquire different sizes of survey using three techniques: the Coil Shooting method, a three-azimuth single-vessel MAZ geometry and a multivessel parallel WAZ geometry. Estimates for the WAZ geometry assume two recording vessels and two source vessels. The predicted time to complete the survey is shown for all three geometries. For the WAZ survey, the chart also shows "vessel days," in which the time is increased by a factor of three—a rough indicator of the increased cost incurred though deploying multiple vessels.

Compared with a single-vessel three-azimuth MAZ survey, for the same sailing distance, Coil Shooting technology delivers more shots, a larger imaged area and better sampling of offset and azimuth. The Coil Shooting technique provides a cost-effective solution for better illumination and improved seismic imaging in complex geological environments around the world. —JK