The Road to High-Density Seismic

Geophysicists work increasingly with complex reservoirs that often suffer from poor quality seismic data—sometimes so poor, the reservoirs eluded detection in older surveys. One example is the Wandoo field in offshore Western Australia. Here, an innovative method of acquiring seismic data has helped replace noise with visible structure and turned a challenging discovery into a commercial field.

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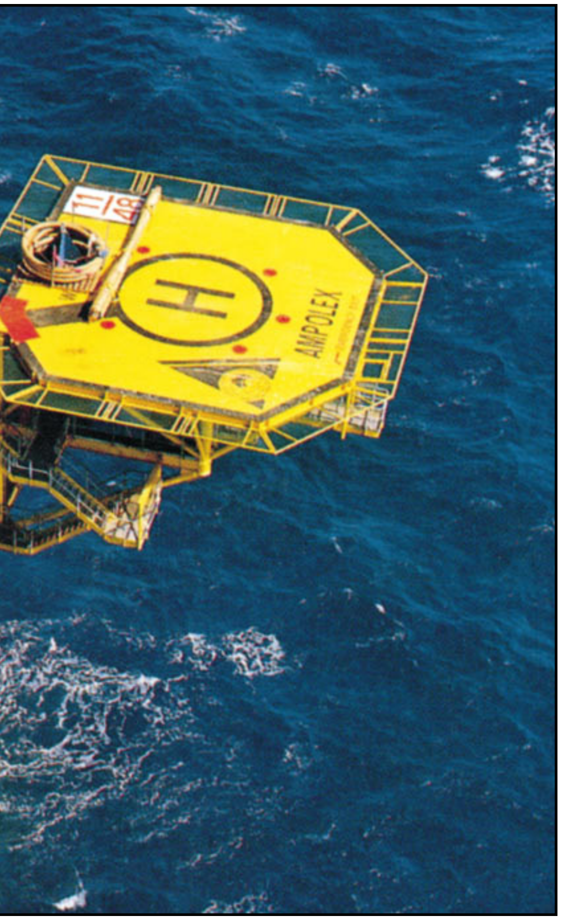
Designing a seismic acquisition scheme is like choosing equipment for a photo shoot. Both require proper illumination of a subject—one with light, the other with acoustic waves. Both are concerned with the focus of energy. And both strive to obtain the sharpest possible image.

Before a photo shoot, a photographer must choose the proper lens for the subject—macro lens, wide-angle, medium focal length or telephoto. The telephoto discerns distant objects but typically can't focus on those nearby. The macro lens makes the sharpest image of objects within a few inches, but can't see those far away.

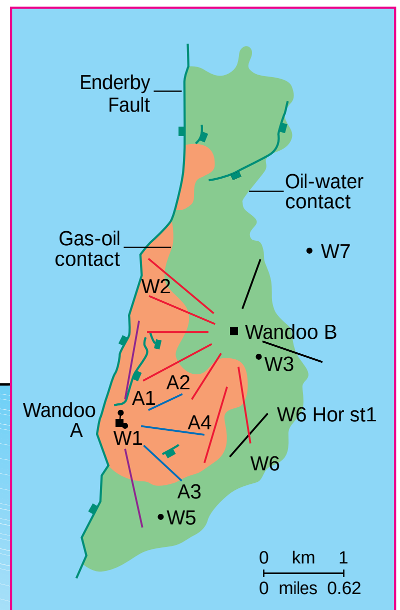
A seismic survey is designed to function like a telephoto lens. The "optical properties" of a seismic survey—the depth within the earth that the survey is tuned to see most clearly—are determined by two interlinked variables. Resolution is controlled by the bandwidth of the sources and receivers, mainly by the high-frequency content. Depth of investigation, and to some degree bandwidth, is controlled by the size of the sources and the acquisition geometry—the spacing of sources and receivers and, in a marine survey, the depth at which they are towed.

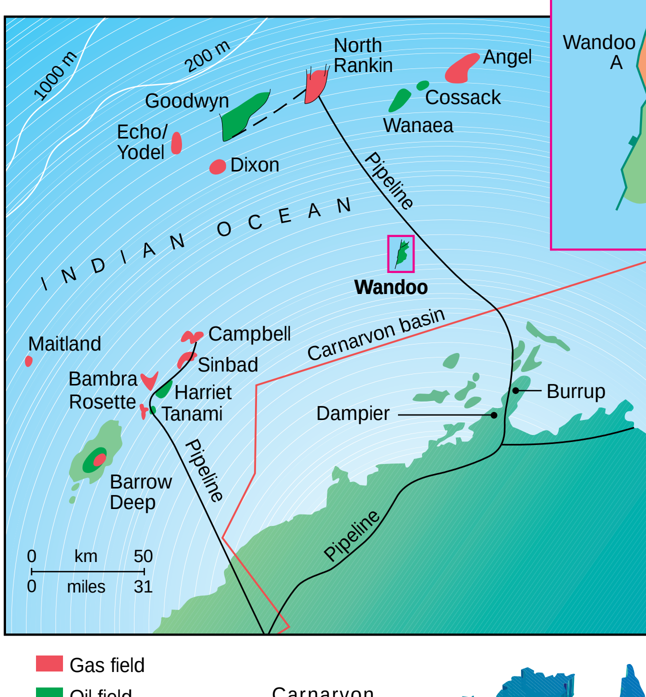
Most reservoirs are at least 1000 m deep [3280 ft] and so acquisition equipment and geometry are usually optimized to meet this demand. At the depth of a typical pay zone, the phenomenon of overlying rock layers attenuating higher frequencies—so-called earth losses—means that the recovered bandwidth is normally expected to be from 8 Hz to no higher than 60 or 70 Hz. Adapting survey equipment and geometry to investigate a shallower interval and higher frequencies is more complicated than simply twisting a different lens on the camera. It involves the equivalent of designing an entirely new lens.

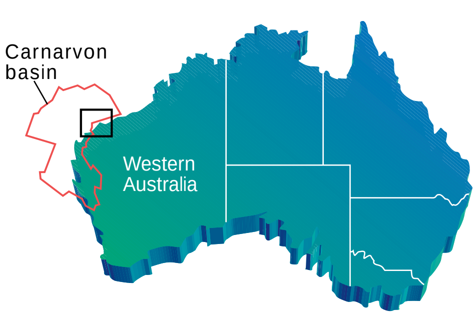
This was the requirement for surveying a field off the coast of Western Australia. Conventional seismic methods nearly over-



□*Wandoo A monopod, in 52 m [170 ft] of water, offshore Western Australia. All Wandoo production wells have been drilled from this platform. Work is underway to develop the Wandoo B production platform to accommodate eight horizontal wells. (Courtesy of Ampolex Limited.)*







□*Oil and gas fields in the northeastern flank of the Carnarvon basin, Western Australia (left). Detail of the Wandoo field (above) shows the existing Wandoo A wells and the planned Wandoo B wells.*

looked the Wandoo field, with 75 million barrels of reserves (*left*). Even when old 2D surveys were reprocessed with the latest techniques, they failed to clearly illuminate the sandstone play. Everything about the play kept it elusive. The oil leg is thin—22 m [72 ft]—placing it at the threshold of what can be resolved by relatively long-wavelength seismic energy.[1] It is shallow—600 m [1970 ft]—which made imaging it conventionally akin to photographing a sparrow just outside your window with an unwieldy 600-mm telephoto. High-angle faults riddle the zone, dispersing seismic energy. And, as icing on the cake, the unconsolidated pay sand is overlain by a layer of dense carbon-

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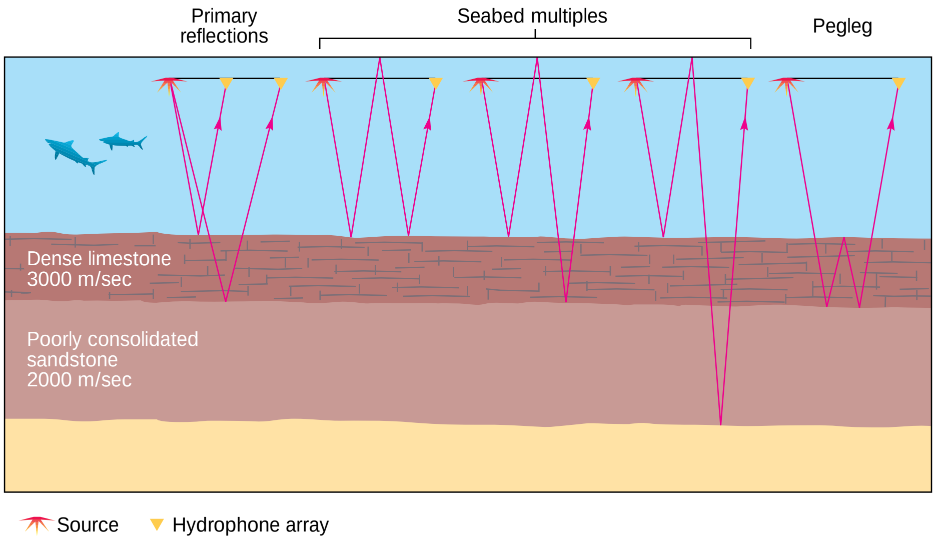
1. The shortest wavelength in a typical marine survey is usually no smaller than 30 m [100 ft]. The top and bottom of a feature that can be detected is typically no smaller than one-quarter wavelength, or, for a 30-m wavelength, about 7 m [23 ft]. Detectability means a feature can be seen, but can't be discerned clearly.



□*Types of multiples in a marine setting. In Wandoo, multiples tend to develop where a low-velocity layer overlays a high-velocity layer, such as at the interface of the sea and the limestone.*

ate that generates a signal processing nightmare called multiples (*above*).[2]

Today Ampolex Limited, the operator of the Wandoo field, produces 19,000 barrels of oil per day (BOPD) from an early production system with five horizontal wells. By 1997, Ampolex plans to drill approximately eight more wells to complete the development of the field. A key to this success is an innovative approach to 3D seismic acquisition.

What Makes Wandoo Work?

The Wandoo field, named after an Australian hardwood tree, lies 60 km [37 miles] offshore within a 40- by 100-km [25- by 62-mile] trend along the northeastern flank of the Carnarvon basin. As the preeminent basin in Western Australia, the Carnarvon covers 650,000 km^2 [250,000 square miles], an area about the size of Germany plus Italy, or slightly smaller than Texas. Thirty years of exploration in the basin have turned up 50 discoveries, holding 1.4 billion barrels of oil and 28 Tcf of gas. Drilling so far in the Carnarvon has achieved a 1-in-4 success ratio.[3]

Like the Permian Basin of West Texas, the Carnarvon comprises many smaller basins. The Wandoo area is heavily faulted and includes unconformities and sudden lithology changes significant enough to obscure standard seismic signals. The depositional environment grades from marine to shallow marine to fluvio-deltaic and nearshore shelf.

The Wandoo pay zone is interpreted as a shelf sandstone deposited in the Early Cretaceous during a brief regression within a transgression.[4] The reservoir contains high concentrations of electrically conductive glauconite, an iron-rich mica. Glauconite raises havoc with resistivity log interpretation, presenting one of the frustrations of low-resistivity pay (see "The Lowdown on Low-Resistivity Pay," *page 4*). The reservoir was characterized using core analysis, formation testing and nuclear magnetic resonance logs.[5] The Wandoo pay zone produces 19° API oil, the heaviest oil on production in Australia.

Interest in the Wandoo area stretches back to 1965, but for much of that time, the shallowness of the reservoir led it to be underrated.[6] The latest chapter opened in 1990, when Ampolex acquired acreage from a previous operator that saw little prospect for the region. Wandoo lies on the Enderby terraces, an Early Mesozoic complex listric fault trend.[7] In the Wandoo area, vintage 2D seismic data showed badly imaged fault blocks, and structure was not recognized at the Early Cretaceous level. Drilling in the region had turned up mainly dry holes and a few disappointing gas and oil shows.

The main barrier to understanding the field was poor seismic data, suffering from low fold and multiples. After careful analysis of subtle clues in the data, Ampolex, however, believed in the possibility of a shallow, Early Cretaceous play roughly mapped by the previous operator. After acquiring the acreage, Ampolex reprocessed the 2D data with modern techniques. This yielded a clearer picture that boosted optimism for the play.

"It was lousy quality data," said Malcolm Boardman, an Ampolex geophysicist on the project, "but gave us enough courage to drill." Wandoo-1 came on stream in May 1991, testing at up to 4500 barrels per day of 19° API oil, produced from a 22-meter oil column, which was overlain by a small gas cap.

The next step was a field-wide hydrographic site survey, a routine procedure to locate drilling rigs safely.[8] A site survey uses shallow penetrating 2D seismic to probe for seabed lithology and shallow gas pockets, which can result in a blowout or unstable support of the rig. It also uses side-scan sonar to investigate the seabed for obstructions such as rock outcrops and pipelines.

The seismic site survey tested the potential of high-resolution seismic methods. Although typically a low-tech procedure (minimal processing is performed, and source depth is often not rigorously monitored), the site survey contained enough high frequencies and depth penetration to present a picture of the shallow interval that was surprisingly clearer than that of the reprocessed 2D survey (*next page*).

The site survey demonstrated that the signal was there to record. However, it was clear that 2D techniques would be unable to resolve the complex structure adequately. Without full understanding of the location and displacement of the faults, potential reservoir compartmentalization would remain unquantified.

The Wandoo discovery had developed into an imaging problem and therefore required a 3D survey that could image the shallow zone and the complex pre-Cretaceous below.[9] Geco-Prakla was awarded the job after an extensive exercise of survey requirement specification, subsequent tender and bid analysis. "Geco-Prakla submitted a combination of the most technically comprehensive and sophisticated solution—and the cheapest," Boardman said.

Shallow, Mean and Nasty

At the simplest level, Wandoo has two characteristics that give geophysicists indigestion: a shallow target and a complex target. Shallowness alone is not a problem for most seismic methodologies. A shallow target can be imaged relatively easily if it is a simple layercake structure with reasonable acoustic contrast between layers. But lace those layers with many fractures, and make the acoustic contrast between layers huge—in this case, a velocity of 1500 m/sec for seawater overlaying 3000 m/sec in the limestone—then conventional methods can be hindered by multiples and ray bending.

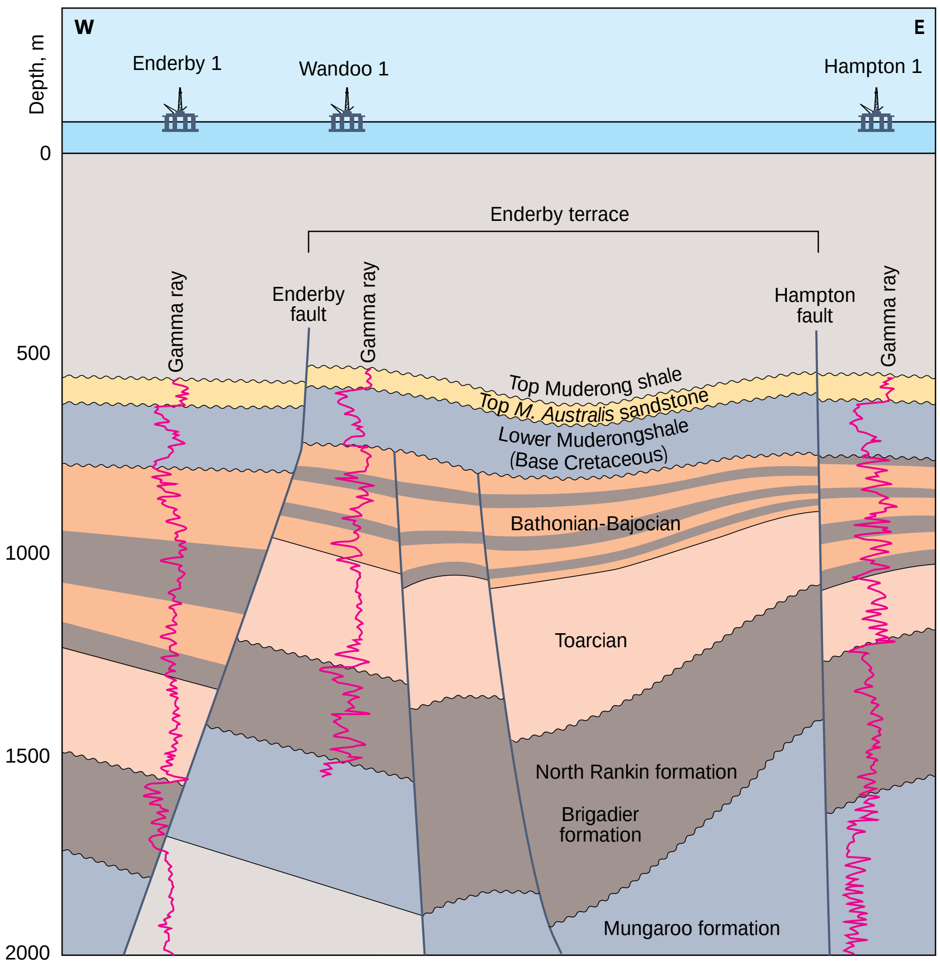
The foremost challenges of imaging Wandoo are:

- preserving sufficient frequency bandwidth to achieve the resolution needed to delineate the shallow producing horizon.
- mitigating the effect of multiples, generated by a large contrast in acoustic impedance between dense limestone outcropping at the seabed and far less dense underlying sands.
- visualizing structure beneath the major mid-Jurassic unconformity, associated with continental breakup.

A common link in all three challenges, to extend the photography analogy, is designing a lens that focuses close and does not generate unwanted reflection of light. In seismic terms, here is how each of these three challenges was met (see "How Wandoo Was Different," *next page*).

The first challenge, preserving bandwidth, required rethinking seismic technique. In conventional 3D seismic, frequencies above about 60 Hz contribute to higher resolution, but are attenuated during their passage to and from the reflector, and so are not recorded. The target is usually imaged with low frequencies, which are deep penetrating but result in a lower resolution. (The propagation properties of high and low frequencies explains why you can hear the low-frequency bass of the jazz combo next door, but not the high-frequency tenor saxophone.)

Preserving high frequencies meant first creating them. This was done four ways.



□*Stratigraphy near Wandoo 1, based on reprocessed 2D seismic. This view enhanced the confidence of Ampolex that Wandoo 1 was located high in a separate fault block.*

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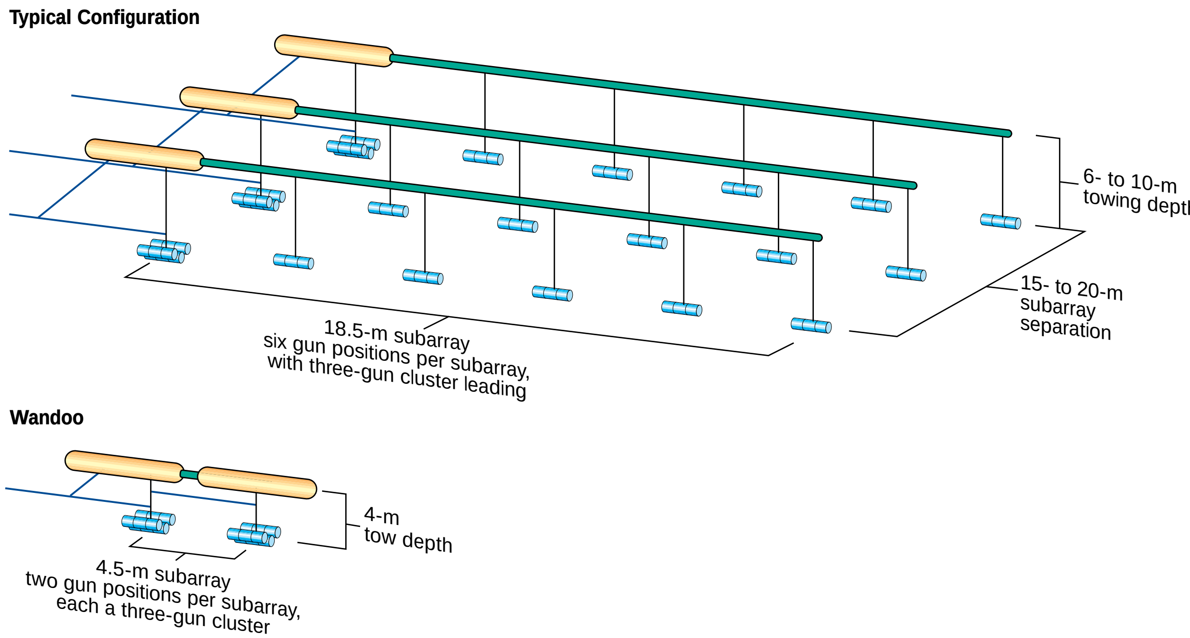
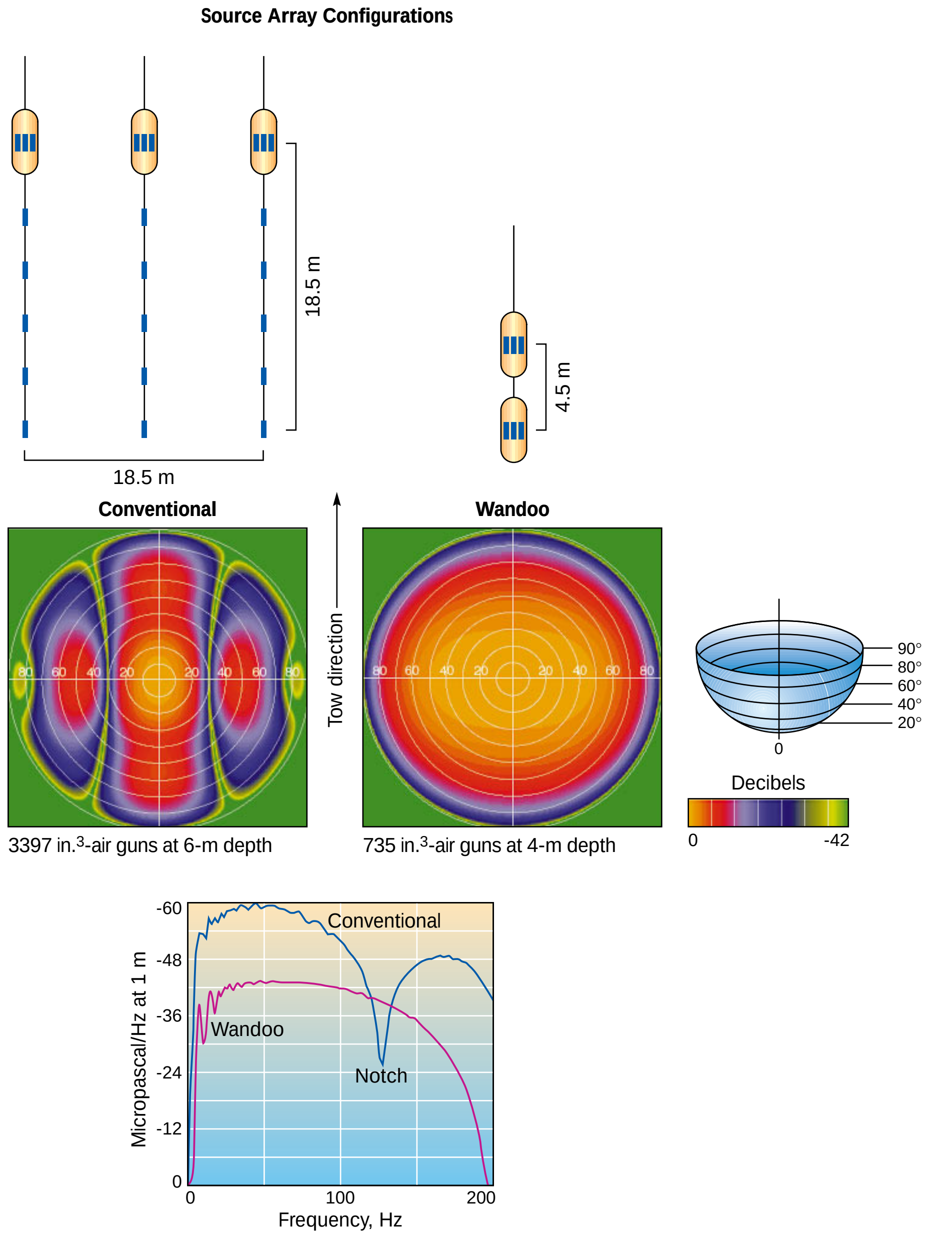
2. A multiple is seismic energy that has been reflected more than once, and persists through the arrival of desired signals. The Wandoo survey was affected mainly by short-path multiples, which arrive shortly after the primary event and obscure structural and stratigraphic detail. The effect is similar to hearing a public announcement in a large railway station, in which multiple echoes make the message unintelligible.
3. Williams P: "Oil and Gas Down Under: A Developing Frontier," *Euroil* 6, no. 4 (April 1995): III-XIV.
4. Boardman M and Delfos E: "Wandoo—A New Trend," *Proceedings of the Australian Petroleum Exploration Association Conference,* Sydney, Australia, March 20-23, 1994; also in *APEA Journal* 34, pt 1 (1994): 586-601.

   Regression is a retreat of the sea from the land, brought about by a fall in sea level, uplift of land, or both. Transgression is the opposite: the spread of the sea over the land, brought about by a rise in sea level, subsidence of land, or both.
5. Delfos E and Boardman M: "Wandoo—A New Trend," *APEA Journal* 34, pt 1 (1994): 586-601.
6. Ampolex 1994 Annual Report: 20.
7. A terrace, in this context, is a local shelf or step-like flattening in otherwise uniformly dipping strata.
8. A hydrographic survey is usually a low-fold, analog seismic survey for soil engineering purposes.
9. For an introduction to seismic imaging: Farmer P, Gray S, Hodgkiss G, Pieprzak A, Ratcliff D, Whitcombe D and Whitmore D: "Structural Imaging: Toward a Sharper Subsurface View," *Oilfield Review* 5, no. 1 (January 1993): 32-41.

□*Comparison of a typical configuration (top) and high-resolution air gun arrays.*



How Wandoo Was Different			
Technique	**Typical Survey**	**Wandoo**	**Main Benefit**
Streamer separation	75 to 150 m [246 to 492 ft]	25 m [82 ft]	Improves ability to resolve steeply dipping, shallow reflectors by preserving high-frequency content in energy diffracted by them
In-line group interval	12.5 to 25 m [41 to 82 ft]	6.25 m [21 ft]	
In-line offset	150 to 300 m [492 to 984 ft]	43 m [141 ft]	Improves near-trace coverage
Source bandwidth	8 to 90 Hz	30 to 150 Hz	Greater bandwidth preserves high-frequency content
Shot-point interval	25 m	12.5 m	Increases signal-to-noise ratio with higher fold
Air gun array	20 to 40 guns arranged in a swath 20 m [66 ft] wide and 18 m [60 ft] long, fired in alternating groups.	6 guns in 2 in-line rows 4.5 m [15 ft] apart and 4.5 m long, functioning as a single point source.	Compact array provides a more uniform wavefront with broader band width, maintaining high fold at shallow depths
Air gun displacement	4000 in.^{3}	735 in.^{3}	Preserves high frequencies
Towing depth	6 to 10 m [20 to 33 ft]	4 m [13 ft]	



How a shallow, point-source air gun array preserves high-frequency content. Polar plots (middle) compare the relative intensity versus direction of a modeled outgoing seismic wave at 100 Hz, for conventionally deployed and Wandoo air guns. Amplitude (blue is low, red high) is shown for an angle of incidence of the wavefield, in which 0° is vertical and 90° is horizontal. Differences in the wavefield are caused mainly by the dimensions of the air gun array and the water depth at which the guns are deployed. If the plots were modeled for 40 Hz, the conventional air guns would show nearly the same response as the Wandoo plot at 100 Hz. In the source amplitude plot (bottom) the notch in the curve for the conventional airgun array results from tow depth. Air guns are normally towed at a depth of 6 m [20 ft] or more, which improves both low-frequency content and operational ease. However, when energy from the source is reflected back from the sea surface, destructive interference causes notches in the frequency plot to appear at progressively lower frequencies with deeper tow. At Wandoo, the shallow tow ensured this notching was pushed beyond the useful frequency spectrum.

First, air guns were gathered into a tightly spaced array to act as a point source (*previous page, top*). The length of the gun arrays had to be reduced to match the overall shorter, denser sampling of the hydrophones. Concentrating the guns as a point source resulted in a more uniform wavefront (*above*). This contributed to producing a clean, high-frequency signature.

Second, guns were tuned to achieve a high "peak-bubble ratio," an indicator of how sharp a source signature is in the time domain. Air guns emit a high-pressure burst of air. The resulting bubbles expand and contract as they rise in the water, sending secondary acoustic pulses that can be difficult to eliminate during processing. In a well-tuned array, firing of the guns is timed to stagger the bubble oscillation periods. This produces a destructive interference of the secondary pulses. In effect, they cancel each other to produce a single, clean peak—one peak when the bubbles expand, another when they contract—that preserves the high-frequency content.

Third, the sources were towed at a shallow depth—4 m rather than the usual 6 to 10 m. Surprisingly, the sources were not susceptible to excessive operational problems, despite their shallow depth.

A fourth element to increase high-frequency content was rewiring conventional streamers for a shorter group interval, which is the distance between the centers of groups of hydrophones. A group is a number of hydrophones that feeds a single channel. By shortening the group length from 16 m to 10 m [53 to 33 ft], and the group interval from 12.5 m to 6.25 m, geophysicists were able to avoid destructive interference of wavefronts reflecting off shallow targets at higher angles and with higher frequencies than desired (*next page*).[10]

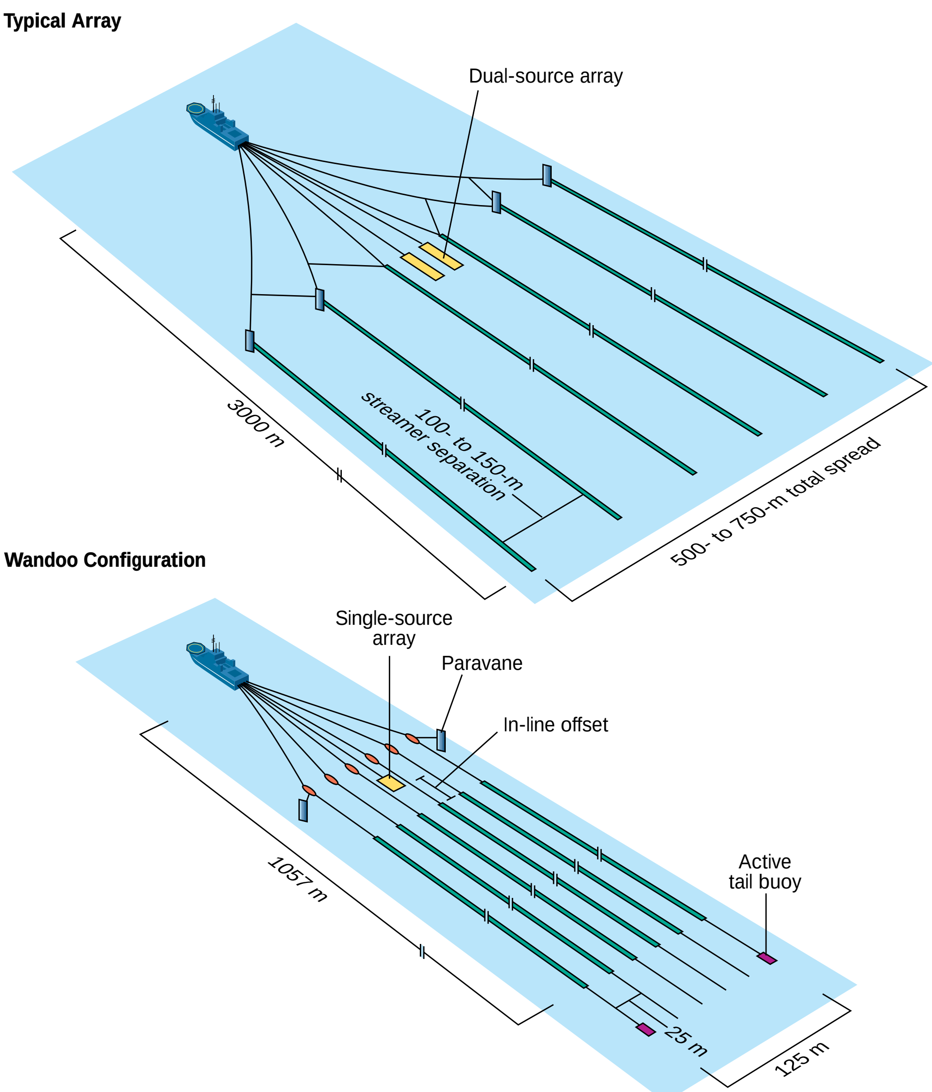
A secondary contributor to high-frequency content was a smaller total gun displacement. Displacement is the volume of air released by the guns, which affects the frequency content and depth penetration of the signal. The smaller the displacement, the higher the frequency and the shallower the penetration. Despite a displacement five times smaller than usual, data were acquired to 3 sec, or to a depth of about 3750 m [12,300 ft]. (In seismic speak, depth of penetration is measured by recording time. Three seconds is about half the usual time.) The final step that boosted high-frequency content took place during processing, and consisted of adjustment in arrival times to account for the effect of tides. Tidal fluctuations can influence resolution by changing the vertical distance between the source-receiver spread and the reflector.

Use of smaller gun displacement also contributed to solving the second two challenges, coping with multiples and the effect of the breakup unconformity. Smaller gun displacement helped cut noise generated by multiples by producing a smaller signal in the first place. “We didn’t want a big, loud signal,” said Malcolm Boardman. “That would induce too many reverberations, and the earth would just ring like a bell.”

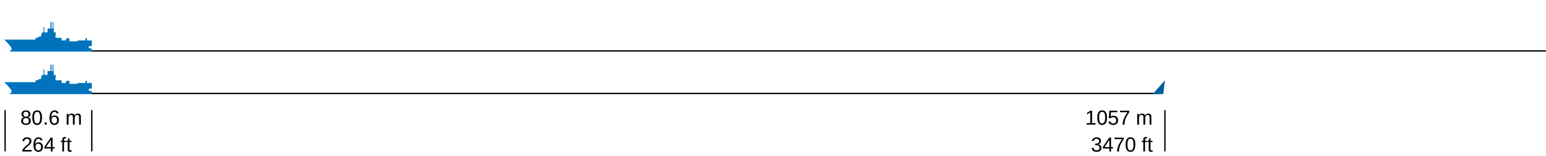
But the main tool to pare down the effect of multiples and the unconformity was to increase fold. Fold is a measure of the multiplicity of source-receiver pairs that probe a given point in the earth. The higher the fold, the more traces are added together to enhance the coherent signal while reducing the amplitude of random noise. Normal sampling is 30-fold coverage over an area of 6.25 x 25 m. Wandoo was 20-fold over an area 3.125 x 12.5 m [10 x 41 ft]. This means that in Wandoo, within 39 m² [420 ft²], the same reflection point in the subsurface was sampled by 20 source-receiver pairs—almost triple what is normally done.

Increasing fold in this survey related directly to sampling density, which is determined by the number of receivers and by the number of times the source is fired per square kilometer. In this case, it was fired about four times more frequently than is typical.[11] To date, the Wandoo survey is the densest in the industry, at about 16 times the typical value. This density was made possible by the redesign of the acquisition geometry to allow sampling at a high rate while still remaining economically viable (*left and below*). Using six streamers, instead of three or four, was a key to keeping the technique economic.

A challenge of high-density sampling is achieving accurate positioning information, which means measuring and recording the spread—the arrangement of hydrophones in relation to the source, in both in-line and crossline directions. Accurate positioning was crucial because of the tight geometry of the spread and the use of in-sea elements as short as 7 m. Typical positioning precision of 10 m could not be tolerated.

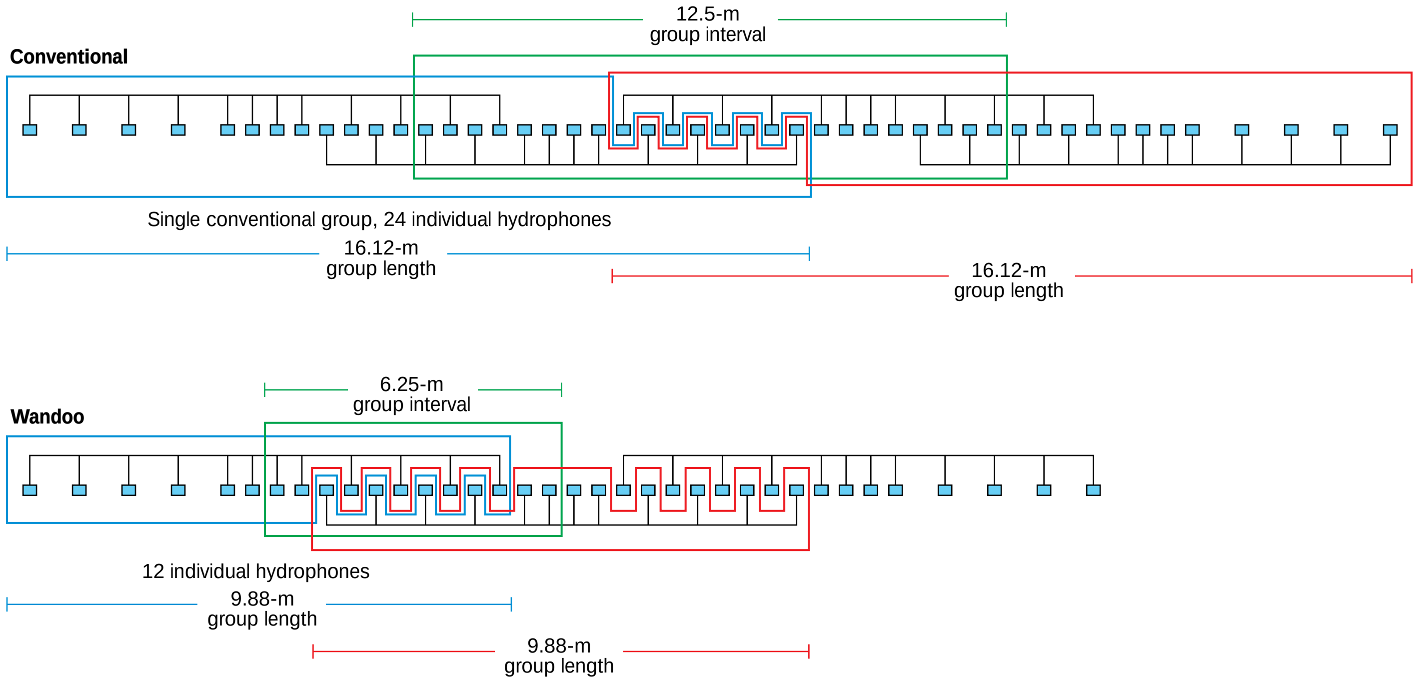


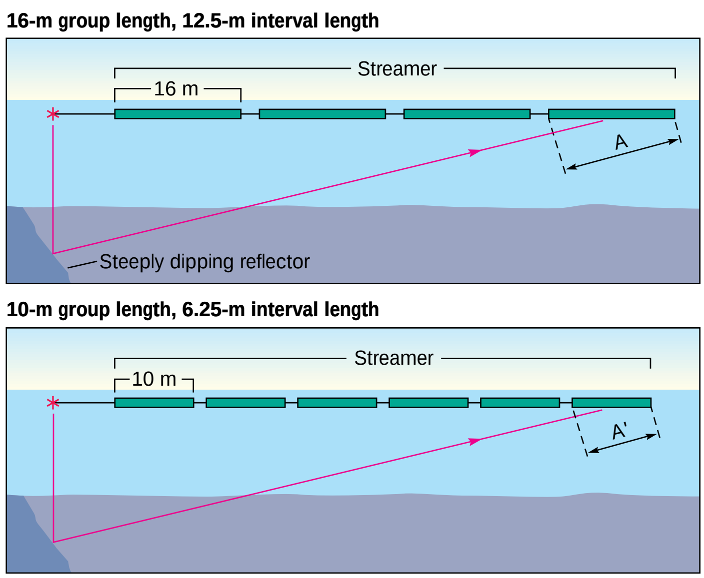
☐*The Wandoo survey spread compared with a conventional spread (above). Streamers in the Wandoo survey (below) were 1057 m [3470 ft] long, about one-third the typical streamer length.*



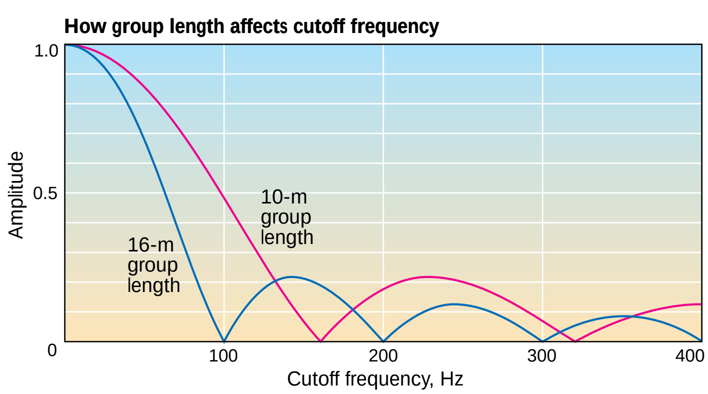
10. For a discussion of destructive interference of seismic signals:
Waters KH: *Reflection Seismology* (2nd ed). New York, New York, USA: John Wiley and Sons, 1981.

11. In a typical survey, a pair of source arrays is fired in alternating sequence about every 10 sec, with the vessel moving at about 4.5 knots [8.3 km/hr; 5.2 miles/hr]. This means a shot is fired about every 25 meters. In the Wandoo survey, the vessel slowed to 4 knots [7.4 km/hr; 4.6 miles/hr] and a single-source array was fired every 6 sec, at about the recycling threshold of the system with the required 3-sec record. This resulted in a shot every 12.5 m.





Anatomy of a group length and group interval in a hydrophone array (above), and how group length and interval affect frequency content of signals from shallow reflectors (left and below). Hydrophones (above) are grouped to form a manageable number of channels and to cancel out sources of noise. Group length is selected to reduce the amplitude of returning energy at frequencies and in-coming angles that are inadequately sampled. Group interval—the distance between the centers of neighboring groups—is selected to sample returning energy that is adequately sampled for imaging of subsurface structures. For simplicity, the schematic (left) shows groups that do not overlap. In this view A and A' represent the time lag for a wave to propagate along the length of a hydrophone group. Wave periods greater than A or A' are cut off. A shorter group length (A') means a shorter time lag and the retention of short-period (high-frequency) wave data.



3000 m
1.9 miles

Positioning software was adapted to accommodate the tight geometry. Moreover, the limit was pushed using conventional positioning technology: the satellite-based global positioning system, laser ranging, acoustic networks and land-based radio ranging. As a result, the spread was positioned to within 5 m [16 ft] and at times to within 2 m [7 ft], contributing to the accuracy of the final product.

Where does Wandoo Lead?

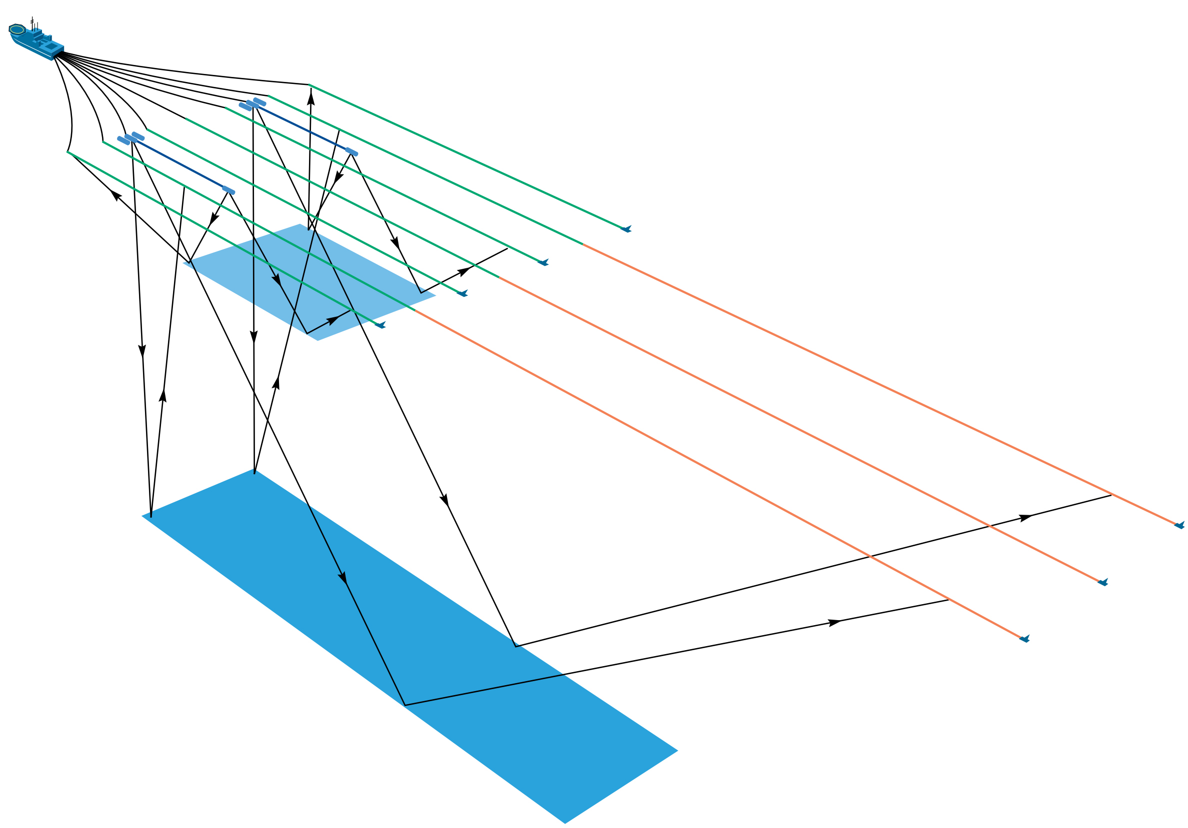
In Wandoo, the most valuable contribution of high-density seismic was precision drilling that hit the target the first time in appraisal and development wells. In drilling each of five wells, Ampolex was able to land precisely in the pay zone, and keep the well trajectory within 2 m vertically for a 1000-m [0.6-mile] horizontal section. Ampolex was able to predict where the well was stratigraphically on the first try. None of the development wells had to be plugged off and redrilled. "Good seismic meant that we had no surprises and therefore, no added drilling expenses," Boardman said.

For Ampolex, a key lesson was how to tune acquisition parameters for optimal results. "Any target shallower than 1200 meters [4000 ft] would profit from some of these parameters, such as closer streamer spacing," Boardman said. "Our work in Wandoo has made us think about the possibilities of tuning regular 3D surveys."

For Geco-Prakla, an additional benefit was the opportunity to develop a shallow-looking 3D survey, leading to evolution of what is called multi-3D: simultaneous use of interleaved short and long streamers, with conventional penetration and high-resolution sources, and simultaneously acquiring high- and normal-resolution data to image targets at multiple depths (*below*). It is like a camera that uses two lenses simultaneously, a macro and a telephoto.

The multi-3D approach now under development is seen to provide three key benefits. First, it can be used for detection of shallow gas, replacing the lesser quality 2D seismic component of the site survey. Second, it provides high-resolution imaging of shallow traps and secondary targets that might be missed by a conventional survey. And third, multi-3D can provide high-resolution, interpretable images of the near surface to build a detailed velocity model, needed to model ray behavior and convert data from the time domain to depth. An improved near-surface velocity model improves the entire seismic section, since most velocity problems are compounded by shallow velocity errors. It would also reduce the risk of artifacts at depth resulting from near-surface velocity anomalies, such as river channels, which do not show up properly on surveys of conventional resolution. These artifacts are often disappointing drilling targets.

As 3D seismic continues to mature and diversify into new niches, multi-3D may fill an expanding need for high-density, high-resolution data. The lessons learned in Wandoo may help multi-3D pioneers get the most from this latest evolutionary step. —JK



□*A dual-purpose thin paintbrush and thick paintbrush. The multi-3D acquisition scheme can provide high-resolution images of a shallow target while simultaneously imaging a deeper target. The small shaded area depicts the zone investigated by the short streamer traces, and the large shaded area is that area investigated by the long streamer traces.*