Report on

TriCluster™ source array

For

Seismic Staffing LLC. has acquired the whole SeaSCAN product line and will continue to support this line to our clients

SeaScan

By

Continuum Resources

May 1999

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TriCluster™ is a patented marine seismic energy source technology offering significant benefits in a number of growing market areas: -

Time Lapse Seismic: 4D is emerging as a key technology to move seismic techniques from Exploration to Production. Over 100 4D projects are currently in progress, mostly in the marine environment, with more projects starting every month.

Vertical Seismic Profiling: New down-hole sensor technologies are creating new interest in VSP technologies to aid in detailed Reservoir Characterization.

High Resolution Imaging: 2D and 3D high resolution imaging is increasingly being applied to verify the near surface stability of the water bottom for expensive offshore construction, and to allow the planning of wells to avoid dangerous shallow water flows and near surface gas pockets.

Shallow Water Seismic: New seismic technologies, including remote storage and multimode recording electronics are allowing cost effective application of 2D and 3D in shallow water 'transition zone' areas that have previously been considered as 'no go areas' for traditional seismic methods.

In all these areas, Tricluster offers material cost and imaging benefits as shown below: -

	Time Lapse	VSP	High Resolution	Shallow Water
Symmetric source configuration eliminates survey to survey differences due to directionality.	Major value in difficult geologies	Increases reliability of well tie	Major increase in image quality	Minor increase in image quality
Compact form permits near point source performance to eliminate anisotropy artifacts from data.	Major value in difficult geologies	Increases reliability of well tie	Major increase in image quality	Minor increase in image quality
Array element spacing generates broad band signature	Adds value with shallow targets	Unlocks value of down-hole sensors	Major determinant of data quality	Minor increase in image quality
Rigid gun frame increases shot to shot signature stability.	Major value in difficult geologies	Increases reliability of well tie	Major increase in image quality	Minor increase in image quality
Rigid frame permits deployment from small flexible vessels (barges, tugs etc.)	Significant mobilization cost savings	Significant mobilization cost savings	Significant mobilization cost savings	Significant mobilization cost savings and access benefits
Integrated, portable form factor	Significant mobilization cost savings	Significant mobilization cost savings	Significant mobilization cost savings	Significant mobilization cost savings

Introduction

For over 10 years, SeaScan has developed the patented TriCluster™ airgun array into a proven and reliable marine seismic energy source suitable for many survey applications including conventional seismic acquisition (2D and 3D); high-resolution engineering seismic; VSP's; and reservoir monitoring applications. The TriCluster™ airgun array is a unique three-dimensional, scalable, heavy centered symmetrical marine seismic energy source suitable for use in all water depths. TriCluster™'s sequential gun timing and shock-mounted gun suspension offers the most repeatable, most symmetrical energy source on the market, in a rigid, easily transported and deployed frame mount. The unique three-dimensional source array endows TriCluster™ with many excellent attributes not present in a conventional tapered linear airgun array, and overcomes many of the undesirable features of linear arrays. Many of TriCluster™'s physical features are currently protected by issued U.S. Patents and Sea Scan have further features currently with U.S. patents pending.

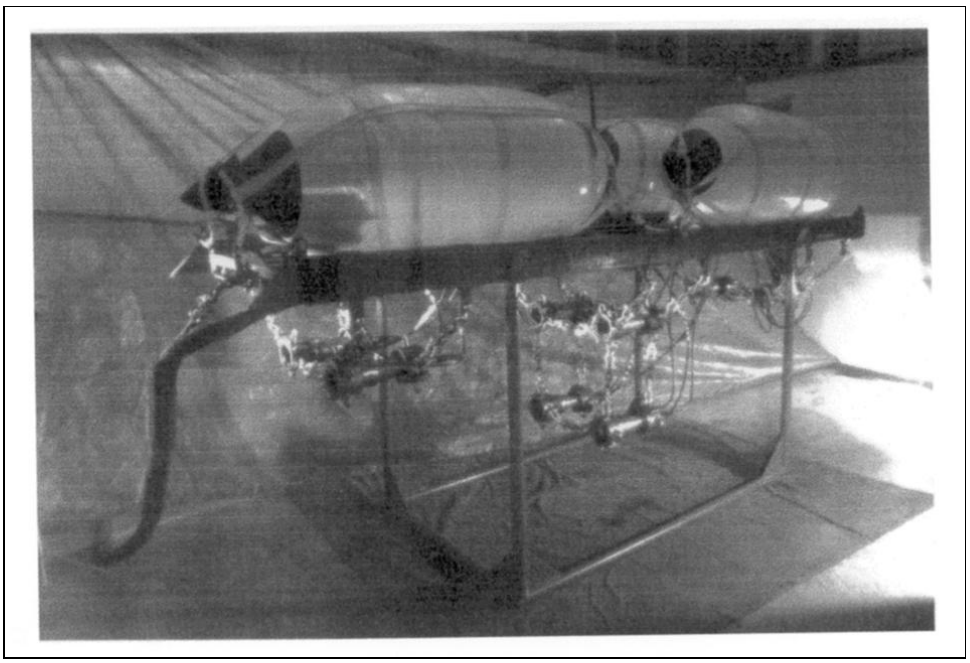

Figure 1 - Fully Configured 80 cubic inch Array with Tow Sled

Background

Most tuned airgun arrays in use today have been designed for towed streamer operations, with the design bias on optimization of the vertically downward and rearward-travelling energy in order to best record reflected energy into the streamer(s) towed behind the array. In this situation a tuned array is acceptable, but what happens when these arrays are used with bottom-referenced receivers? The asymmetry of the tapered, tuned array results in an asymmetric distribution of energy and significant variation of phase and amplitude with azimuth, thus introducing wavelet differences into a bottom-collected dataset based on sail-line direction alone. With the increasing interest in repeat 3-D surveys for reservoir monitoring where the primary focus of the experiment is to minimize known differences in recording equipment and technique to enhance the visibility of subtle differences in the reservoir, this symmetry offers important improvements over conventional arrays.

Features

The symmetry of the TriCluster™ array generates an output wavelet with a broad frequency spectrum that is identical for any pair of reciprocal azimuths, thus removing the immediate differences introduced to a dataset by a conventional tapered array. The symmetry of the array also generates an output wavelet that is the same for port or starboard evaluation at the same azimuth to the boat direction in a towed situation.

The multi-plane arrangement of the guns in the TriCluster™ array and the sequential firing of the gun planes yield a system with additional signature improvement over conventional towed source arrays. Firing the planes in sequence, the upper plane followed by the lower planes synchronized with the down-going wavefront, enables constructive interference of the down-going wavefront while the delay between the up-going wavefronts reduces the severity of the ghost notch, enabling a flatter, broader output spectrum. Firing times for the different levels can be adjusted to maximize the energy in the desired frequency range for the output far field wavelet. The proximity of the four guns in the center cluster further improves the array output through bubble interaction that reduces unwanted bubble noise.

In addition to the symmetry issues, the TriCluster™ gun suspension system offers additional signature repeatability and stability. Compared with a conventionally suspended airgun, where individual guns are free to swing and jump while towing and/or firing, the TriCluster™ system maintains proper gun positions with sprung shock mounts, enabling consistent and repeatable bubble interaction and hence consistent and repeatable array output. An added benefit of the suspension system is that it prevents collision of adjacent guns, and collision of guns and suspension equipment, thus extending the life of guns, hoses and control electronics. The rigidity of the TriCluster™ also removes any limiting minimum tow speed to maintain array characteristics. The removal of boat speed limitations from shotpoint intervals; means that TriCluster™ may be used as a static array for applications such as VSP shooting, where the source is suspended from a fixed point.

Physical Attributes

The TriCluster™ array consists of 8 identical airguns suspended within a rigid steel frame such that the guns form three distinct planes, as shown in the following figures. The frame is floated with four Norwegian buoys attached directly to the frame. Depth adjustment can be achieved by allowing a drop between the buoy attachments and the array frame.

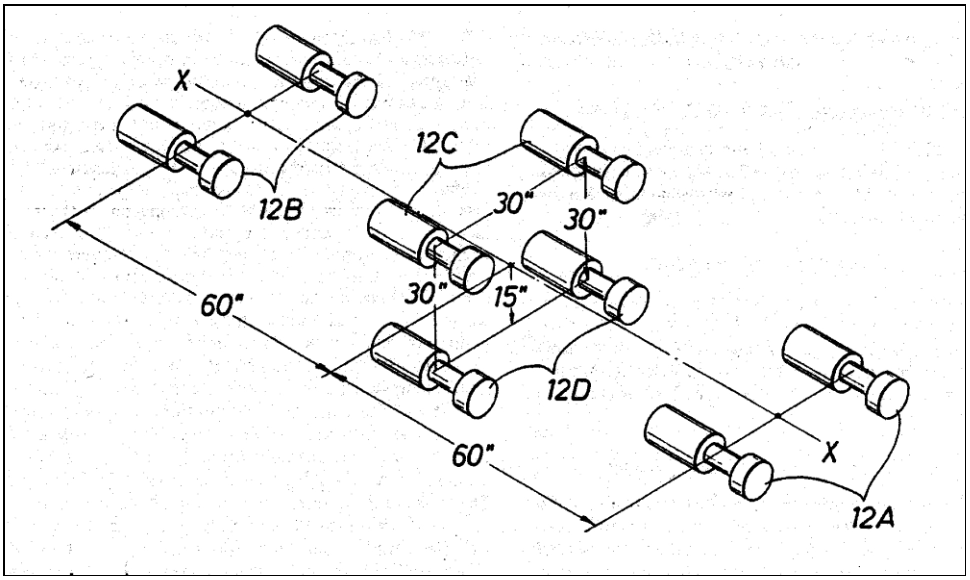

Figure 2 - Schematic of TriCluster™ Gun Arrangement

TriCluster™ is a scalable system, the total gun volume being adjusted by the substitution of guns with different volumes. At present the array can be fielded with total volumes of 80, 160, 320 and 560 cubic inches. In addition, for applications requiring higher signal energy levels, larger volumes are achievable by towing multiple sleds. For example two 560 cu. in. arrays towed to produce a volume of 1,120 cu. in.

All TriCluster™ arrays share a common frame mount, or Tow Sled, shown in
Figure 1 above. This Tow Sled is easily shipped in standard sea freight containers. The frame is light enough for airfreight, thus enabling global mobility and fast deployment worldwide. Deployment from the host vessel can be by crane or by custom-designed remote-operated frame and winch system, which also is designed to be quickly dismantled and assembled for shipping by container with the array itself.

Individual guns are suspended on spring-loaded shock mounts; thus all gun positions are fixed within the sled. This prevents damage through collisions of guns and equipment, and creates consistent, repeatable bubble interaction for maximum signature stability. Maintenance costs are further limited by reducing the number of gun types in the array to one, thus minimizing the quantity of spares required on board.

Figure 3 - TriCluster Deployment

Figure 4 - Multiple array sled deployment

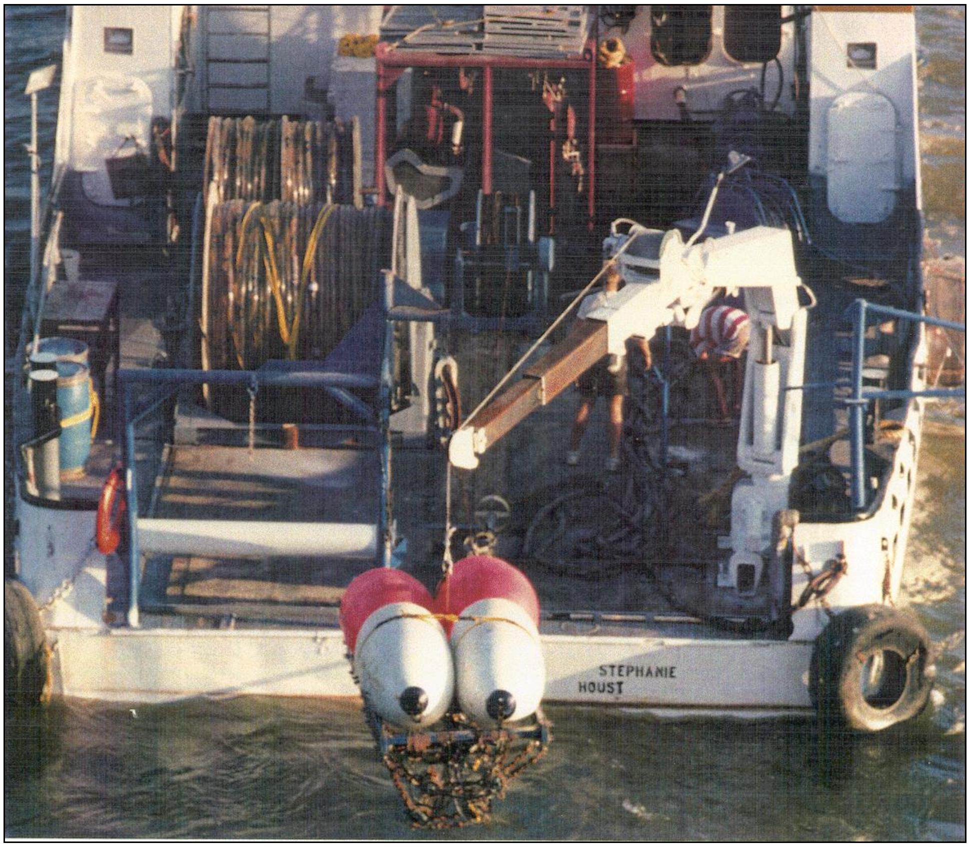

Figure 5 - TriCluster Deployment

Figure 6 - In water photograph of active 1100 cu. in dual sled in production

Gun Array Drop Out

A further advantage of the limited cluster configuration using a single gun type is the effect of gun dropouts on array performance. The TriCluster™ has a very limited number of dropout configurations. Most simple drop out configurations additionally produce a far field signature which would be considered acceptable by most standard criteria. The removal of a single gun (regardless of which gun) produces only 2 different drop out configurations (assuming all guns are fired at the same time).

Basic array configuration is:

- Two 2 gun clusters; single 4 gun cluster.

ONLY Basic drop out configurations are:

- Two 2 gun clusters, single 3 gun cluster.
- Single gun; 4 gun cluster; 2 gun cluster.

With most air gun arrays, the use of many gun sizes and different geometry means that there may be many different drop out configurations. These may occasionally number in the thousands for a particular array.

Extensive dropout modeling of the TriCluster™ array has been carried out and results are available through SeaScan.

Array Modeling

In order to demonstrate the advantage of the symmetry of the TriCluster™ array, signatures, power and phase spectra were generated for both TriCluster™ and a typical linear array. Far-field wavelets were generated for vertically traveling energy as well as for energy traveling at 30° from vertical at azimuths of 0° and 180° for the array centerline to illustrate the forward- and rearward-traveling wavelets.

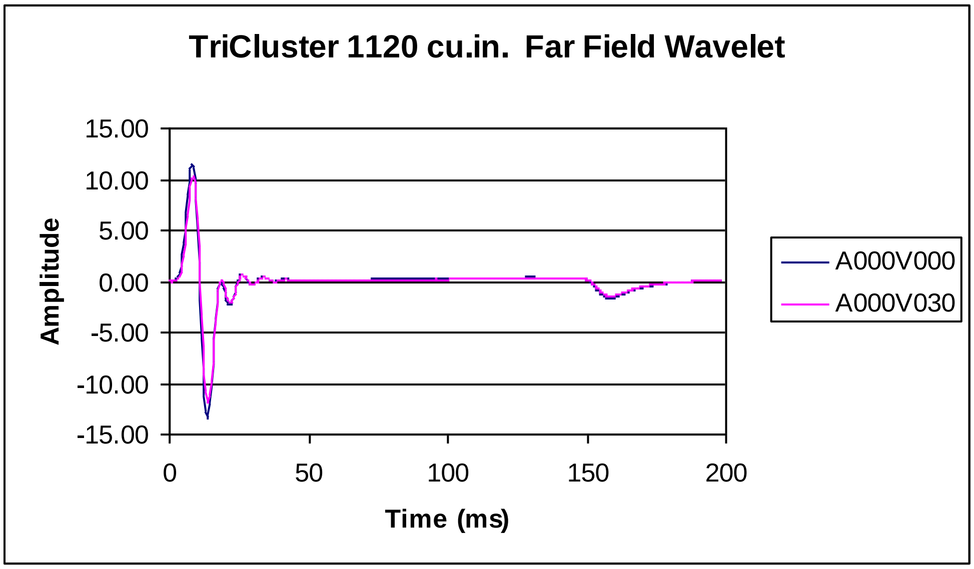

Figure 7 - TriCluster 1120 Far-Field Signatures

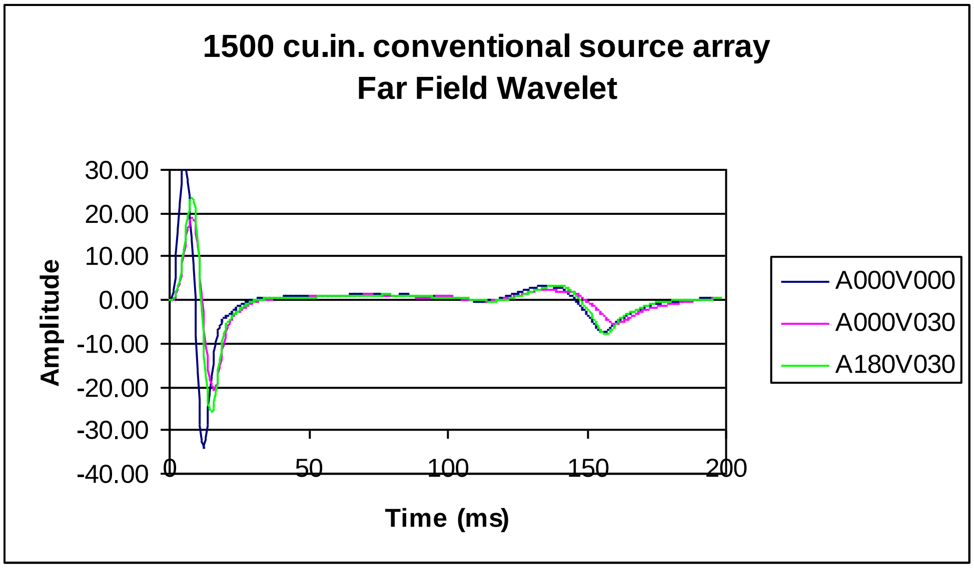

Figure 8 - 1500 Linear Far-Field Signatures

Figure 7 shows two far field signatures for the TriCluster source and Figure 8 shows three far-field signatures for a conventional array. The legend denotes the parameters for each array as follows: A000V000 shows the wavelet traveling vertically downward (0° from Vertical), A000V030 is the forward-traveling (Azimuth 0°) wavelet at 30° from Vertical, and A180V030 is the rearward-traveling (Azimuth 180°) wavelet at 30° from Vertical.

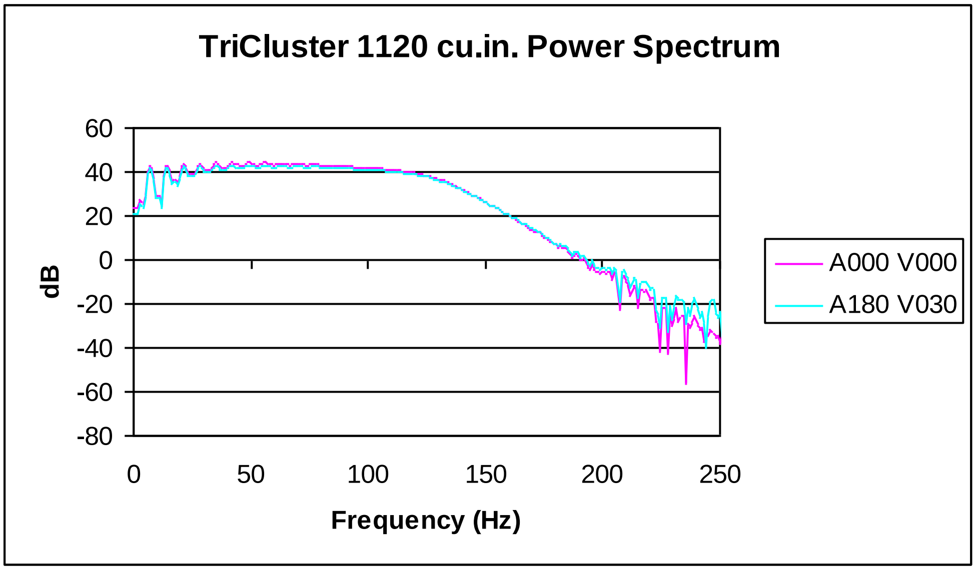

Figure 9 - TriCluster 1120 Power Spectra

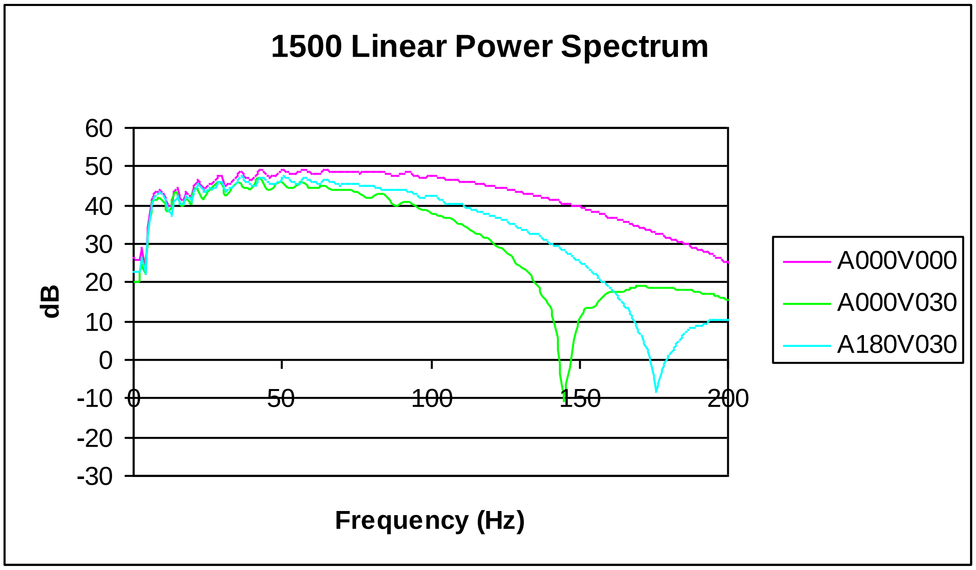

Figure 10 – 1500 Linear Array Power Spectra

In Figure 9 it is clearly shown that the TriCluster™ array is virtually a point source and generates near-identical output regardless of azimuth. Figure 10, however, shows the bias of the tuned linear array to generating a broadband vertically traveling wavelet, but the differential timing of the guns when viewed from 30° not only introduces notches to the spectra, but these notches are variable with azimuth, thus introducing the undesirable differences described above.

It is in the phase spectra shown in Figure 11 and Figure 12 that the asymmetry of the linear array can be shown to be the least desirable. The TriCluster™ array diagnostics in Figure 11 again shows virtually no difference with angle from vertical, and both the forward- and rearward-traveling wavelets are identical in terms of phase. Figure 12 shows the dramatic difference between the phase spectra of the non-vertical wavelets which would have the potential to introduce undesirable differences between data acquired on adjacent sail-lines based on array orientation alone. This is in addition to the variation of array output caused by changes in bubble interaction through flexing of the array or variations in separation, etc., that cannot be easily modeled.

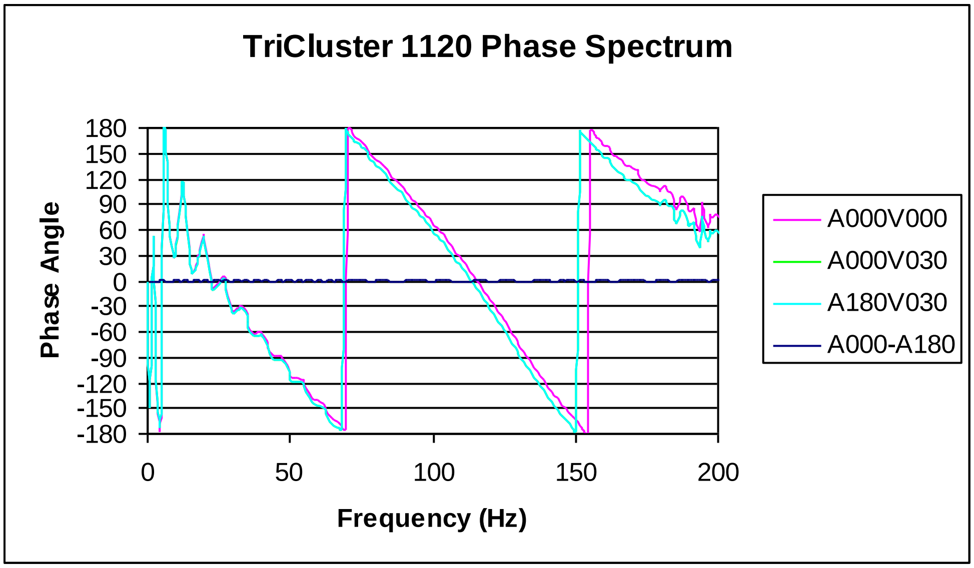

Figure 11 - TriCluster 1120 Phase Spectra

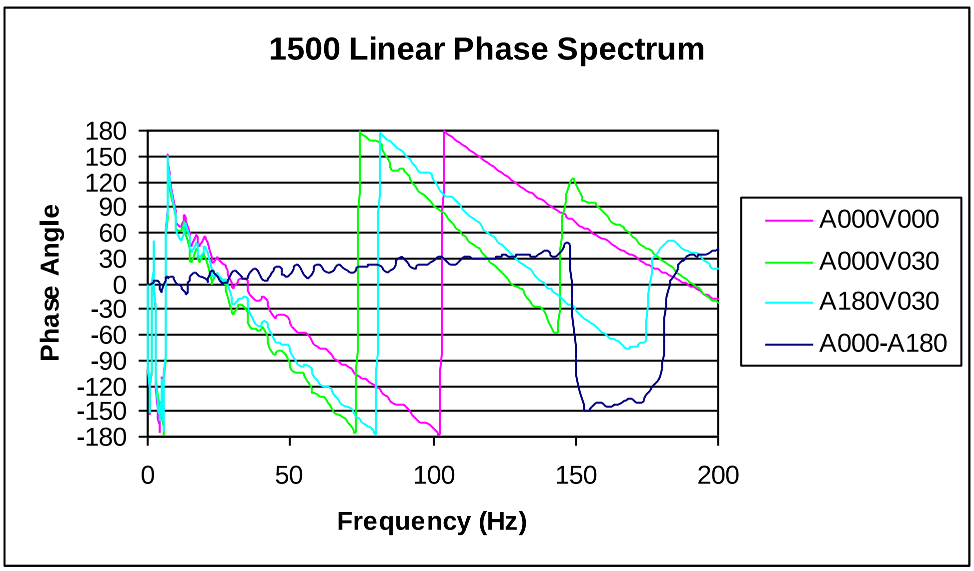

Figure 12 - 1500 Linear Phase Spectra

Additionally the symmetry of the TriCluster source means that there is no difference between the forward propagating wavelet and the backward propagating wavelet. The boat direction is irrelevant to the directionality of the source signature. Boat direction can play a significant part in introducing variations in the effective wavelet from a conventional source array. Figure 13 shows the difference between the source signature at an angle of 30^{o} from vertical, forwards and backwards from the source (but still in a vertical plane parallel to the boat track.

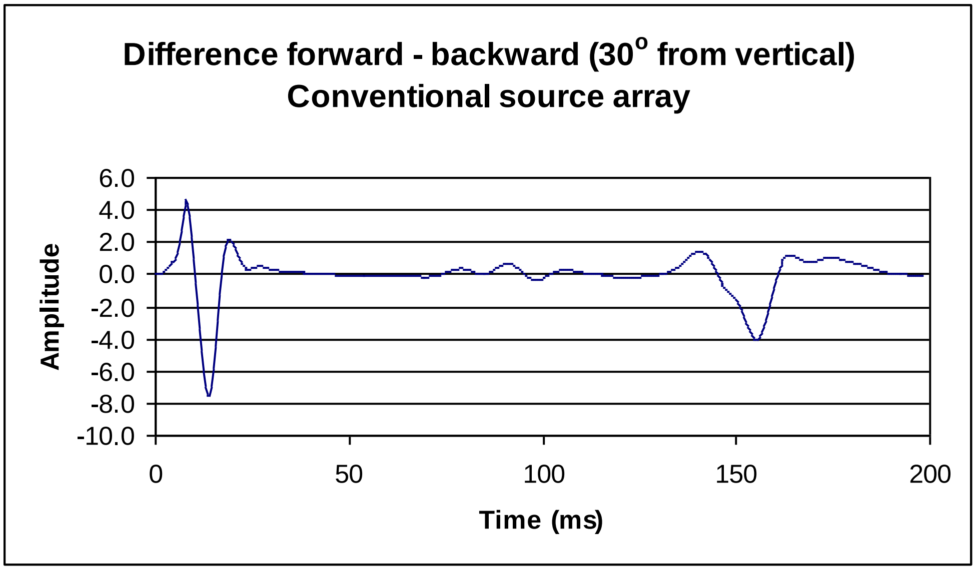

Figure 13 - Directionality of Conventional Source Array

Note that there is significant amplitude in the difference trace shown in Figure 13. This means that for repeated seismic experiments, differences due to source directionality could easily overwhelm the differences that are sought in the reflected energy from the subsurface. Peak difference in the directionality of the array at 30^{o} from vertical is approximately 6 Barm. The peak output of the array (vertically) is only 24 Barm, so the effective change is approximately 25%. At steeper angles from vertical the difference between the forward and backward far field signatures will be even greater.

Typical reflection amplitude changes due to change in fluids in the reservoir are generally estimated to be between 10 and 20%, which means that conventional source array directionality may be bigger than the variations which are sought.

The uniform directionality of the TriCluster array will significantly improve the ability to examine true 4D or reservoir monitoring effects.

Seismic Acquisition Examples

There follow a series of data examples showing the practical benefits of the TriCluster™ array in real seismic acquisition data. The following four displays are hydrophone data and spectra from the Teal South Phase 1 4-D project in the Gulf of Mexico. A TriCluster™ 1120 cubic inch source was used and data recorded into a 24-receiver sea-bottom 4-component array. In order to display a significant number of traces in a familiar display, the data has been regrouped into a common receiver gather for the purposes of this illustration.

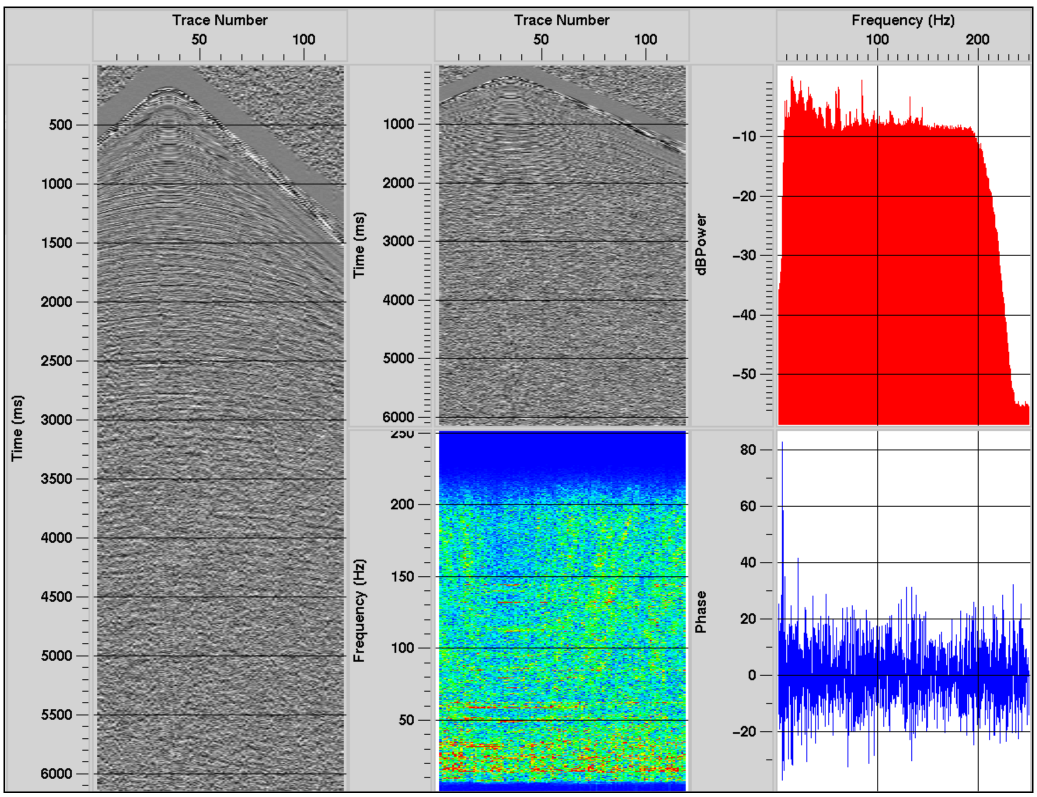

Figure 14 – Complete Receiver Gather Analysis

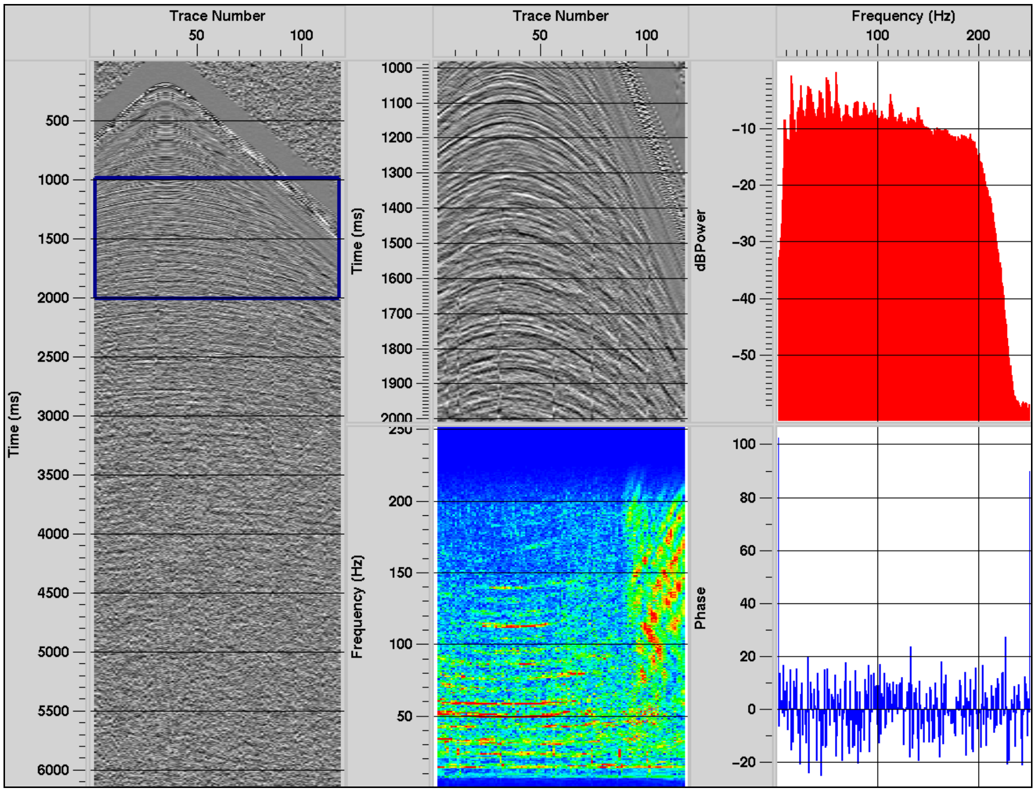

Figure 15 – Window 1000 – 2000 ms Analysis

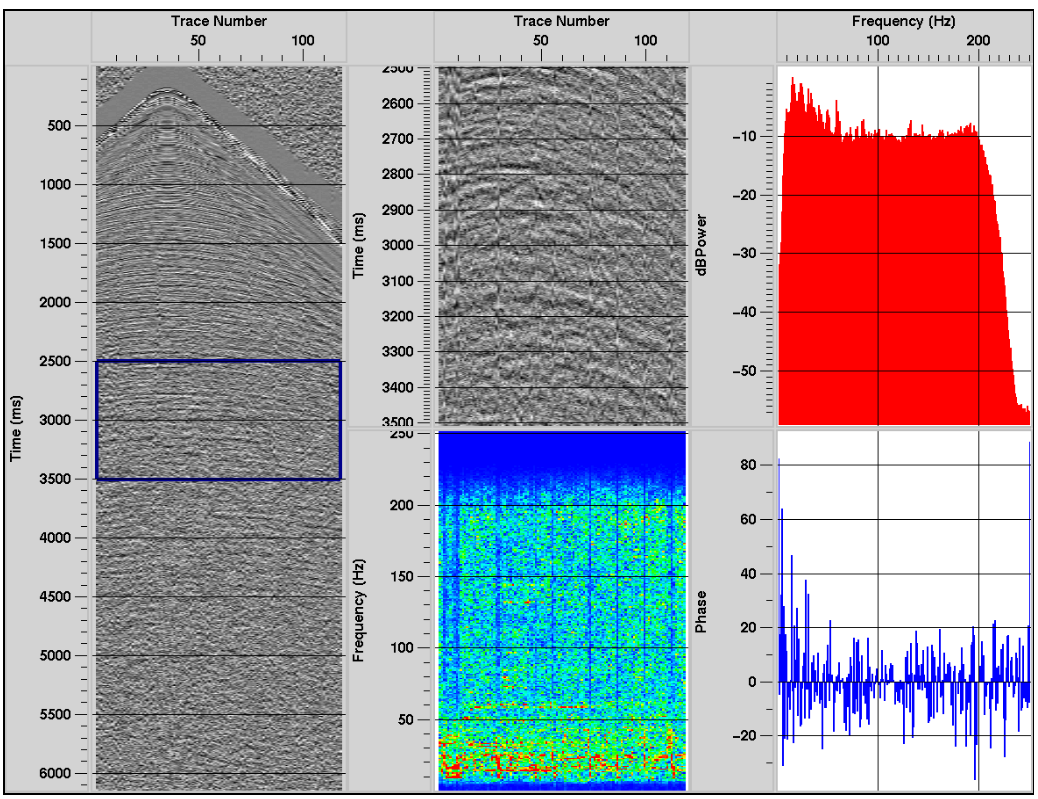

Figure 16 – Window 2500 – 3500 ms Analysis

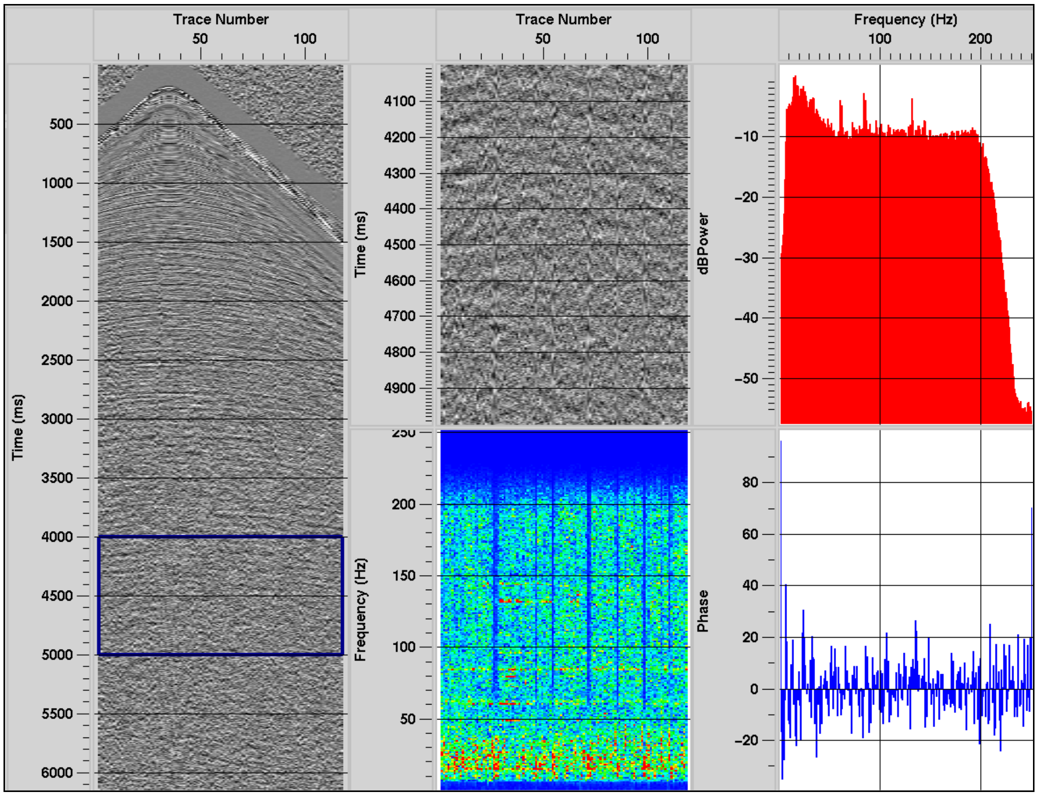

Figure 17 – Window 4000 – 5000 ms Analysis

The figures above show the broadband nature of the TriCluster™ signature in real data examples. An additional feature claimed by SeaScan as unique to TriCluster™ is the improved penetration of high frequency signal over conventional arrays. The figures clearly show that at all the time levels investigated there is indeed energy present up to 200 Hz., with minimal attenuation of the higher frequencies with increasing time.

Note that the spectral analysis in Figure 17 shows strong signal to 200 Hz., and is limited only by the anti-alias filter which has been applied to the data set (2 ms sample rate). This analysis window is taken from deep in the record (below 4 seconds) and suggests that the source generated significant energy at very high frequencies.

The value of the high frequency content is perhaps shown most dramatically in Figure 18 and Figure 19. Figure 18 shows a Tricluster shot record as recorded, and Figure 19 shows the same record after with frequency limits normally associated with conventional seismic source arrays.

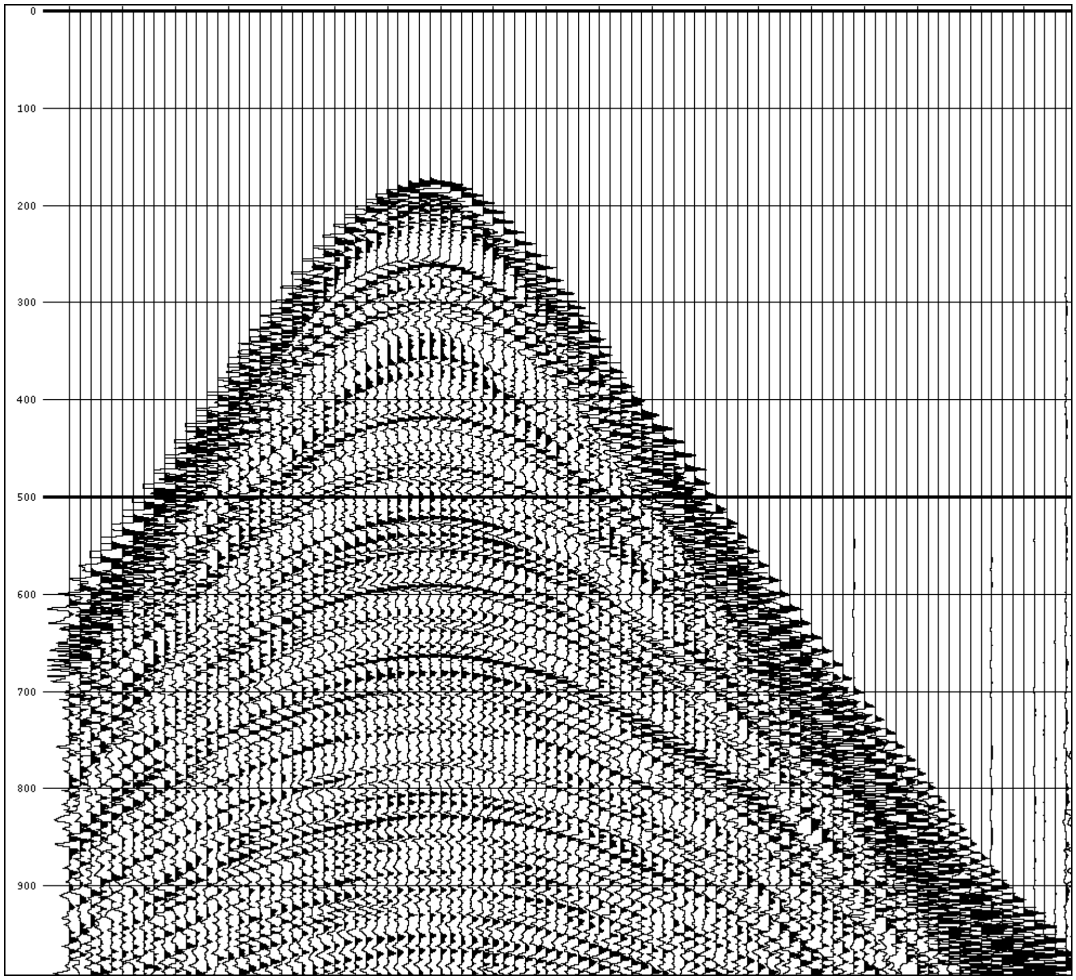

Figure 18 - TriCluster data

Figure 18 shows the raw (unfiltered) data collected using a Tricluster source. Note the high frequency content of the reflectors and associated resolution of the data.

Figure 19 shows the same data having been resampled to 4 ms. with appropriate (90Hz) anti-alias filter. The figure illustrates the loss of resolution which would be associated with a lower frequency source, or lower effective bandwidth.

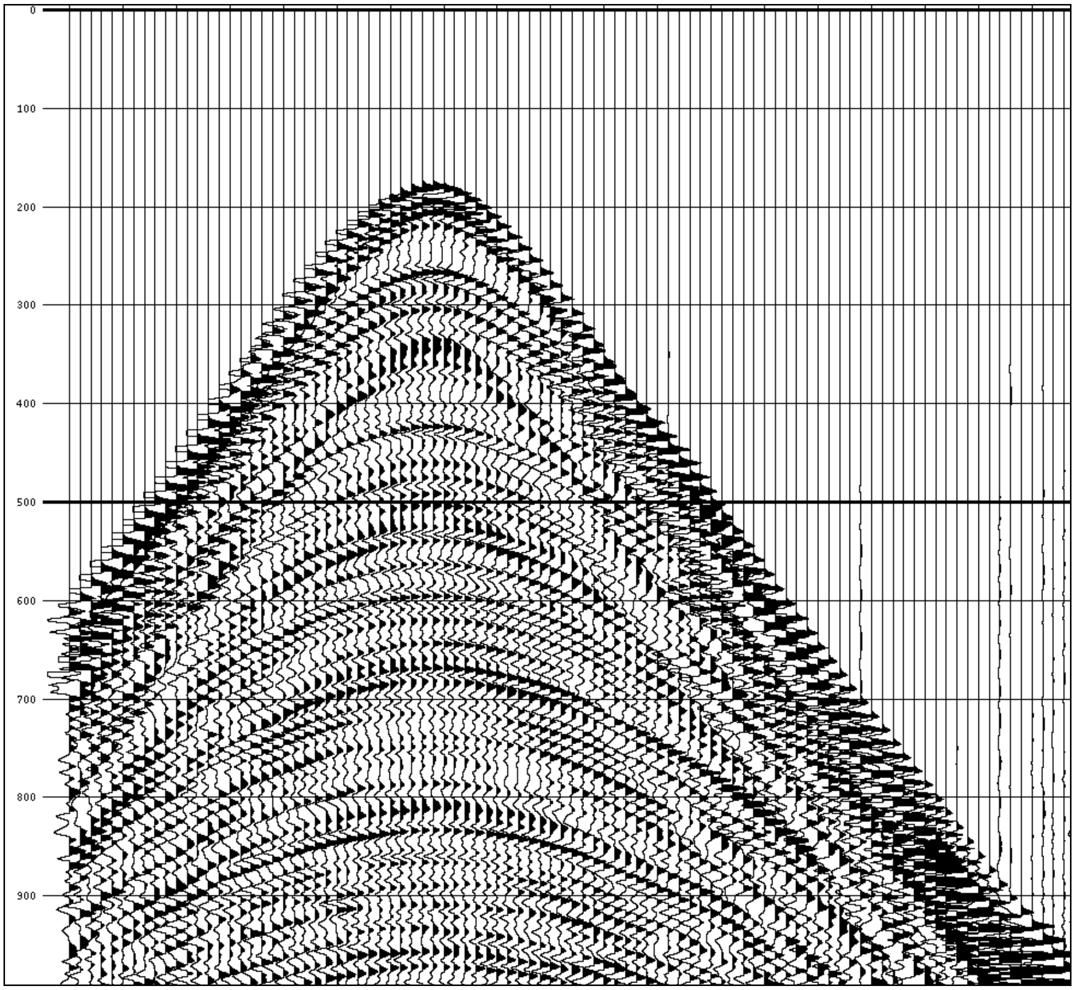

Figure 19 - Conventional data (simulated)

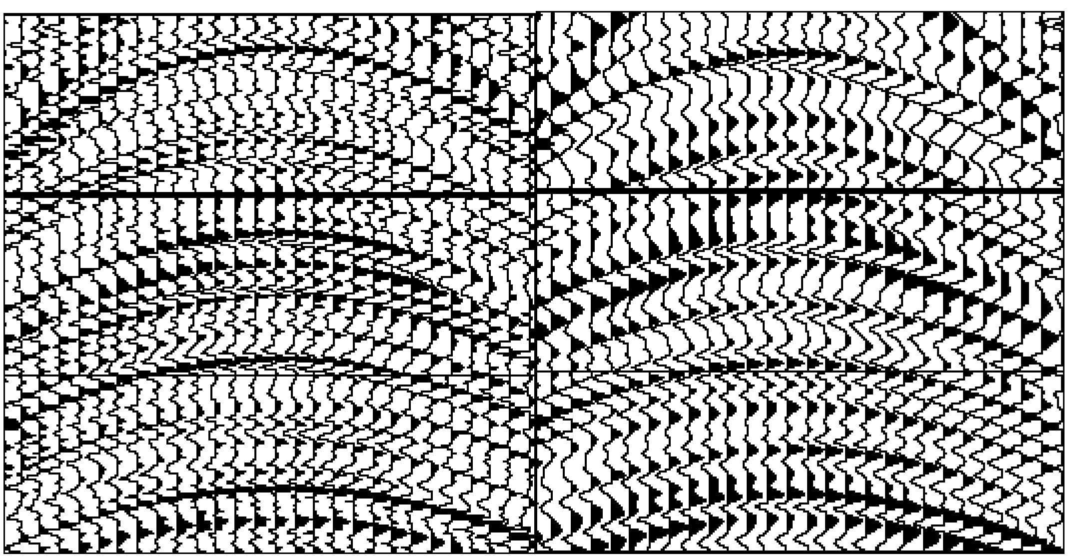

Figure 20 - Zoom comparison of TriCluster / simulated conventional data

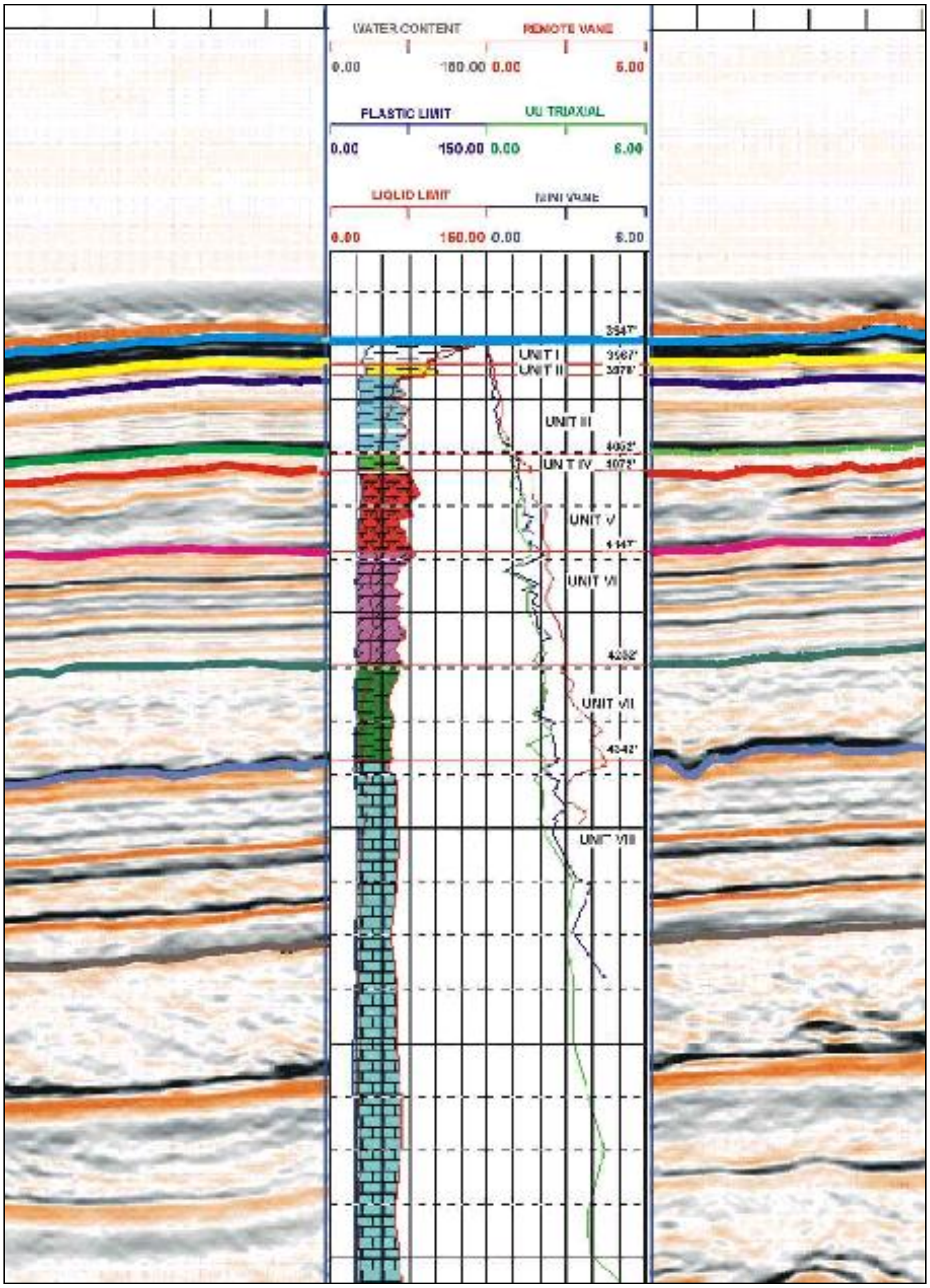

Figure 21 - Engineering TriCluster™ Data Example with Soil Log

Figure 21 shows an example of the high resolution TriCluster data tied to a well synthetic for engineering applications. The broad bandwidth of the data makes ties to other data types considerably easier and more accurate.

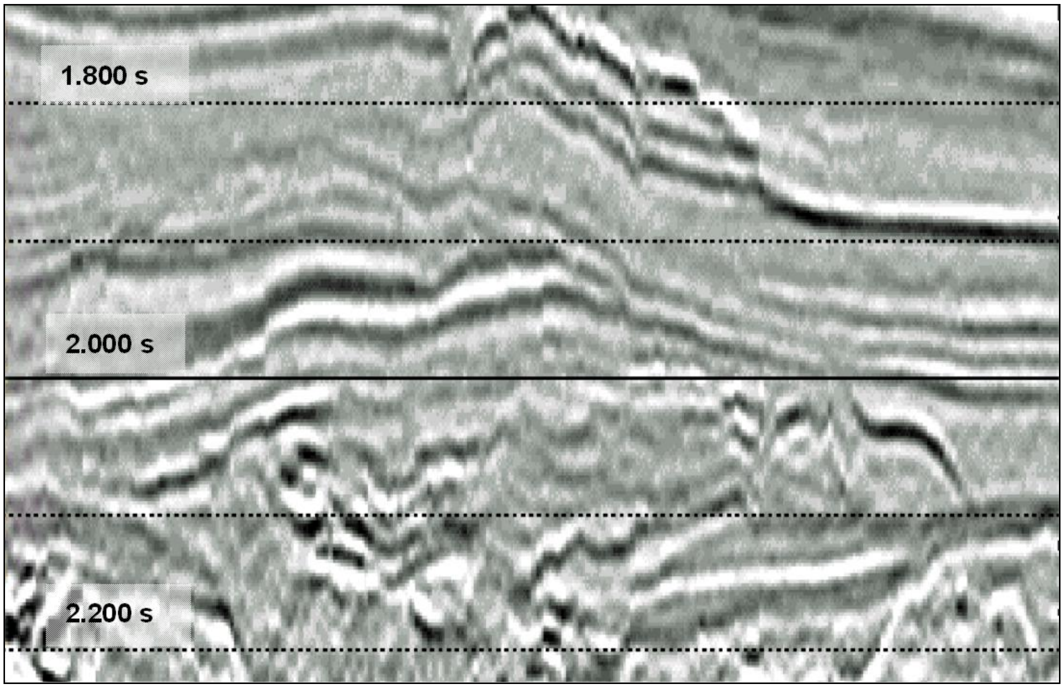

Figure 22 – Conventional Exploration Level 3-D Data

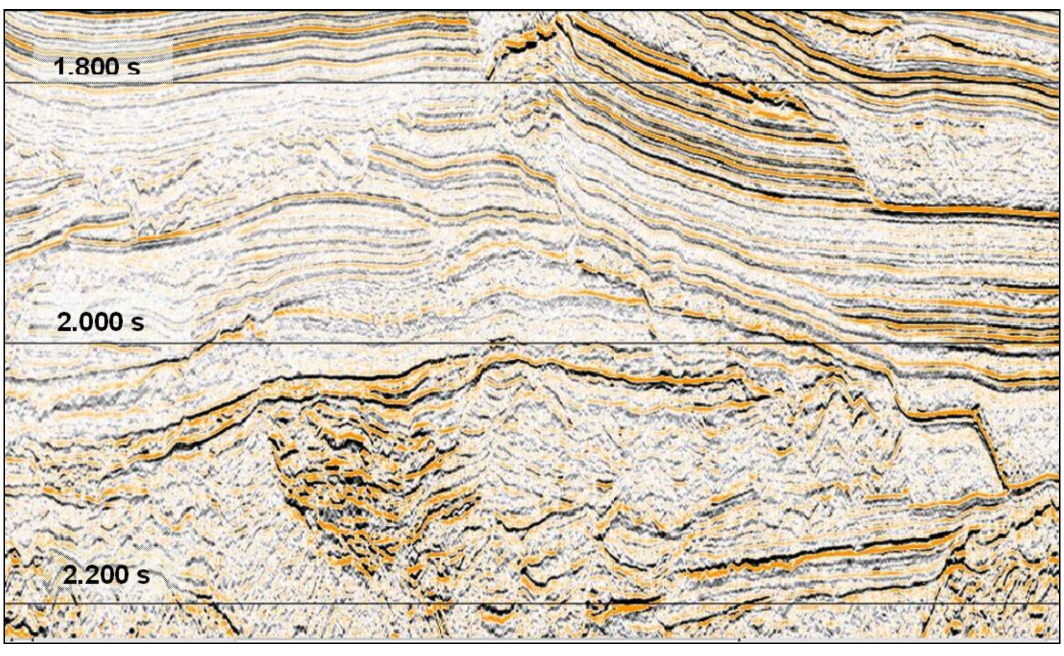

Figure 23 - Short Offset TriCluster™ High Resolution 3-D Data

Figures 24 through 29 show a comparison of conventional seismic data with the result achieved with a TriCluster source. Even in the poor quality reproduction supplied here the improved frequency content and penetration of the TriCluster data is obvious.

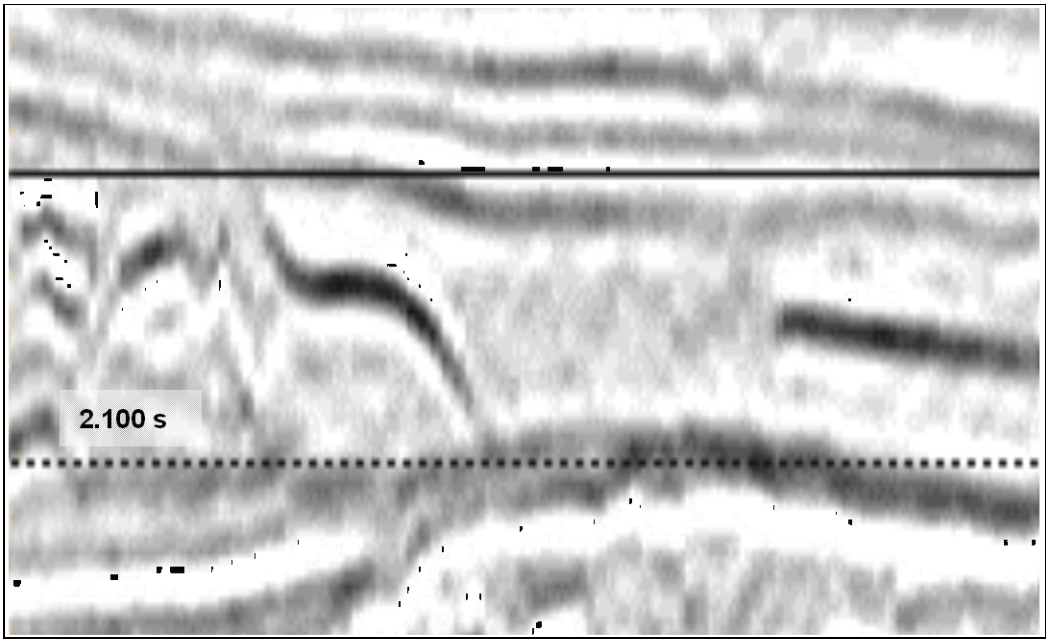

Figure 24 – Conventional Exploration Level 3-D Data

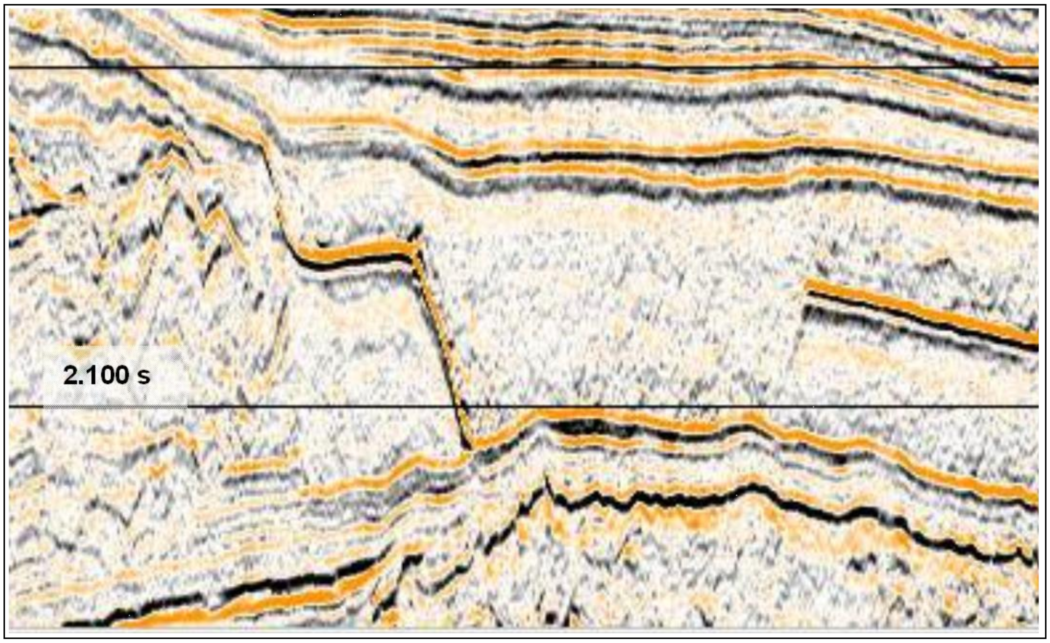

Figure 25 - Short Offset TriCluster™ High Resolution 3-D Data

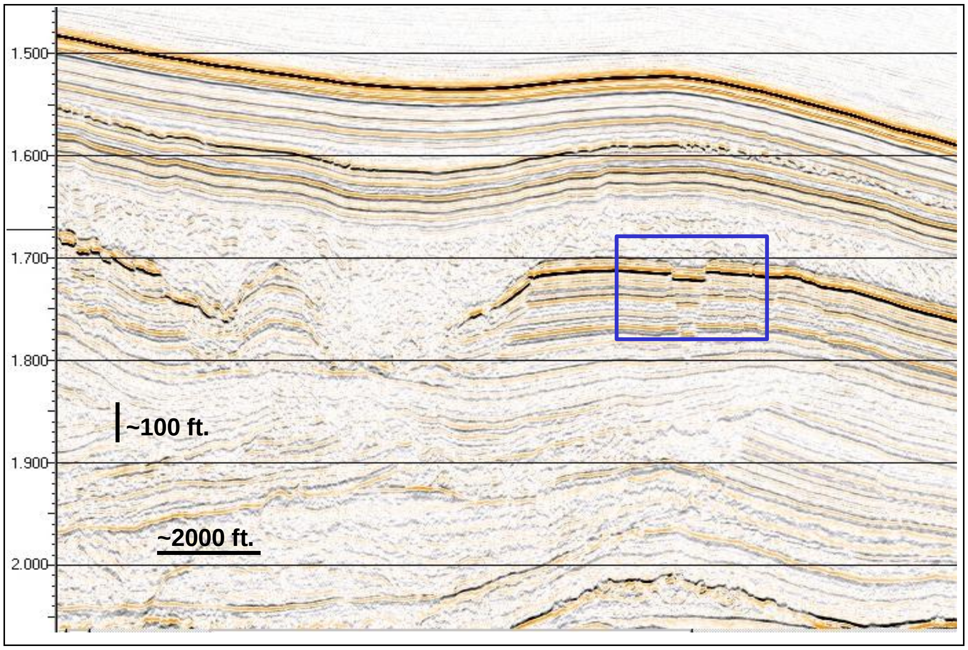

Figure 26 - High Resolution 3-D Seismic Section – TriCluster Source

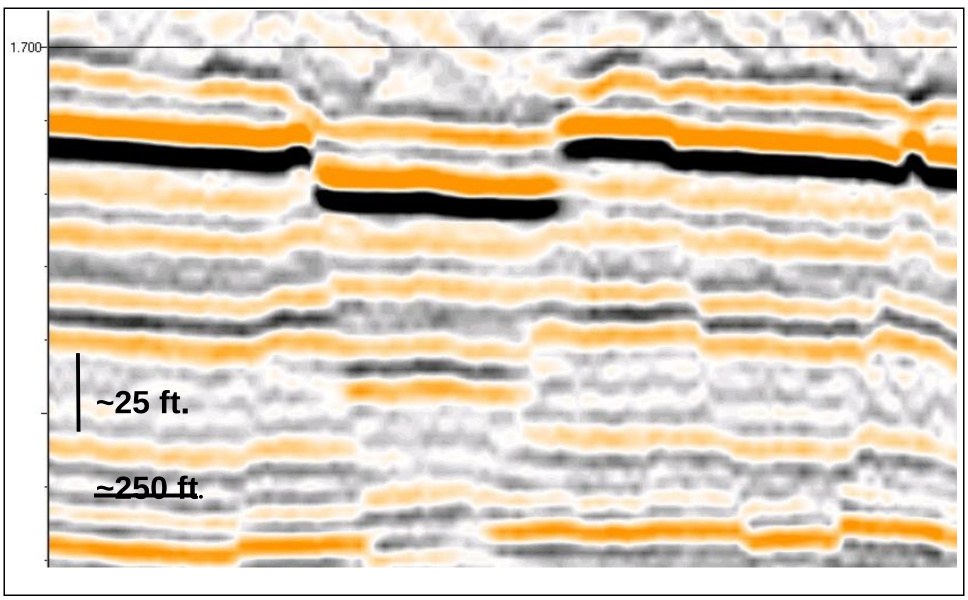

Figure 27 - Detail of Figure 26

Figures 26 and 27 give a scaled example of the penetration and resolution potential at exploration target depths in the region of 1.7 seconds TWT.

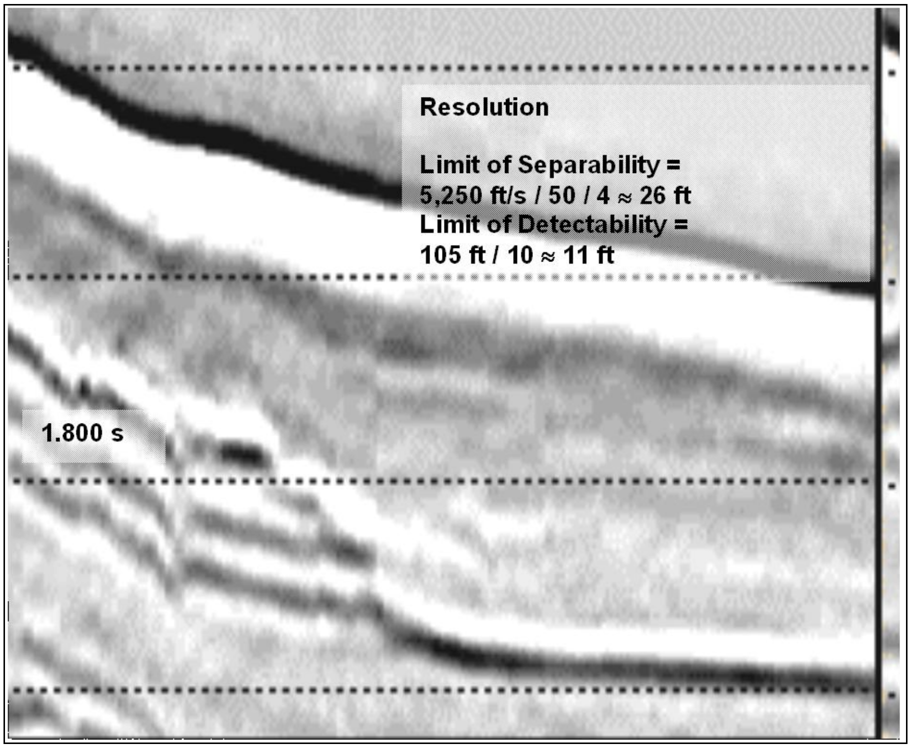

Figure 28 - Conventional Exploration Level 3D Data

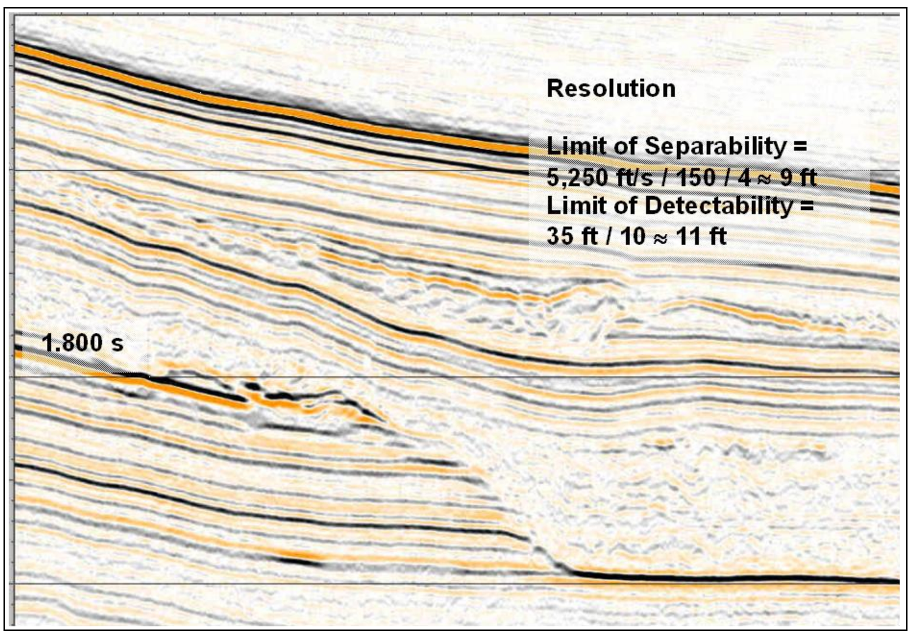

Figure 29 - Short Offset TriCluster™ High Resolution 3-D Data

Figures 28 and 29 show the comparative resolution improvement resulting from the broader bandwidth of the TriCluster array over conventional seismic acquired with a linear airgun array.

Intellectual Property Portfolio

SeaScan has pursued an aggressive patent philosophy, and believe that there is considerable value in licensing or trading the intellectual property that has been established. Some of the relevant patents are cited here:

Patent 4,956,822

This fundamental and broad based patent covers any air gun array, towed at shallow depth, with multiple guns which are mounted in a frame arranged so that the guns are weighted towards the center.

The patent also covers an arrangement of guns into 2 vertical planes

Patent 5,469,404

This patent covers specific sequential firing of guns on 3 levels.

For shallow array deployment, the patent also covers sequential firing of guns on any number of levels.

A number of other patents are currently under application or consideration, some of these are of particular value for 4D applications

Patent approved to be issued (June 1999)

This patent covers using TriCluster arrays (or others) when the usage is from a fixed platform rather than towed from a moving vessel. This is of particular importance for repeated 3D surveys for time lapse (4D) seismic work..

Trademark "TriCluster"

Thorough it's wide use of the name "TriCluster " SeaScan has clearly established a trademark in the industry. Registration of this trademark is currently underway and should be approved by end of June 1999.

Summary

TriCluster™ is a patented marine seismic energy source technology offering significant benefits in a number of growing market areas such as: -

- Time Lapse Seismic (4D and 4C).
- Vertical Seismic Profiling.
- High Resolution Imaging.
- Transition Zone and Shallow Water Seismic.

In all these areas, Tricluster offers material cost and imaging benefits and has a proven track record. . The patented array design is engineered to survive and yields less damage to guns due to the rigidity of gun suspension. Low maintenance is enhanced even more by use of a single gun type which reduces the spares requirement.

Technically, not only is the TriCluster array more repeatable than conventional source arrays it also has the following advantages:

- Better directionality
- Better repeatability
- Consistent gun interaction
- Independence of Tow Speed or Direction

Reference

Earl H. Doyle, "*The integration of deepwater geohazard evaluations and geotechnical studies*" (1998) Offshore Technology Conference.

Charles D. Winkler, "*High Resolution Seismic of a late Pleistocene Submarine Fan Ponded by Salt-Withdrawal Mini-Basin on the Gulf of Mexico Continental Slope*" (1996) Offshore Technology Conference.