Source signature processing in deep water, Gulf of Mexico: comparison between deterministic deconvolution and phase conjugation

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Abstract
The Center for Marine Resources and Environmental Technology has been developing a new method to improve the resolution of high-resolution seismic profiling. To achieve this the source signature is recorded and the reflected data are sampled at a very high rate. In addition a certain amount of post processing is performed. During September 1999 a series of seismic profiles were acquired in the Gulf of Mexico using a 15 in^3 watergun towed at the surface and a short single-channel hydrophone array towed about 250 m below the surface. The profiles were digitized at a rate of 80000 samples per second; the length of each record was 4 s. Two different processes were applied to the data: deterministic deconvolution and phase conjugation. Both have the effect of compressing each reflected wavelet into a short pulse that is symmetrical about a central lobe. The ratio of compression obtained by applying deterministic deconvolution on the source signature pulse was about 300; it was about 160 when applying phase conjugation. This produced a resolution of about 6 cm by the deconvolution process and about 10 cm by using phase conjugation. The deconvolution process however is more subject to noise so the better result in this experiment was found to be provided by phase conjugation.

Key words *oversampling – source signature – deconvolution*

1. Introduction

In 1999, Shell reported nine of 20 pre-drill wells at its Ursa field in Mississippi Canyon Block 810 washed out due to Shallow Water Flows (SWF); Shell lost about $ 150 million. At present, conventional seismic surveying is not able to identify and characterize these kinds of hazards, because of the relatively low sand/shale contrasts in acoustic impedance. In order to be effective for identifying and characterizing SWF potential, the survey data must resolve layers less than a meter thick more than 700 m below the sea floor in more than a kilometer of water. This resolution has not been attempted previously using classical seismic systems.

For two years, the Center for Marine Resources and Environmental Technology (CMRET) has been working on developing a new method of high-resolution seismic profiling in order to satisfy this need. This method is based on very

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rapid sampling, also called «oversampling», and the recording of source signatures for use during processing. Both are crucial to achieving the required resolution.

Two types of signature processing are discussed herein: deterministic deconvolution and phase conjugation. The two processes are similar in that both remove the phase of the source signature from the complex spectrum of the seismogram. This «compresses» each reflected wavelet into a short pulse that is symmetrical about a central lobe. It is this compression that provides the increase in resolution. The comparison of the two source signature processes is illustrated using data from a CMRET deep-water research cruise.

For purposes herein, the measure of seismic resolution is taken to be the width of the dominant peak, or trough, of a processed seismic reflection. This is about one-half of the dominant signal period and corresponds closely to the minimum layer thickness (in two-way time) discernable on the output. For purposes herein, distance is determined from time using a speed of 1500 m/s, which is within a few percent of the propagation speed of the acoustic waves in sea water and in most unconsolidated sediments.

2. Deep-water cruise

2.1. *Study area*

During September 1999, seismic profiles were acquired over the continental slope of the northern Gulf of Mexico in water depths ranging from 300 to 1600 m. The cruise was in

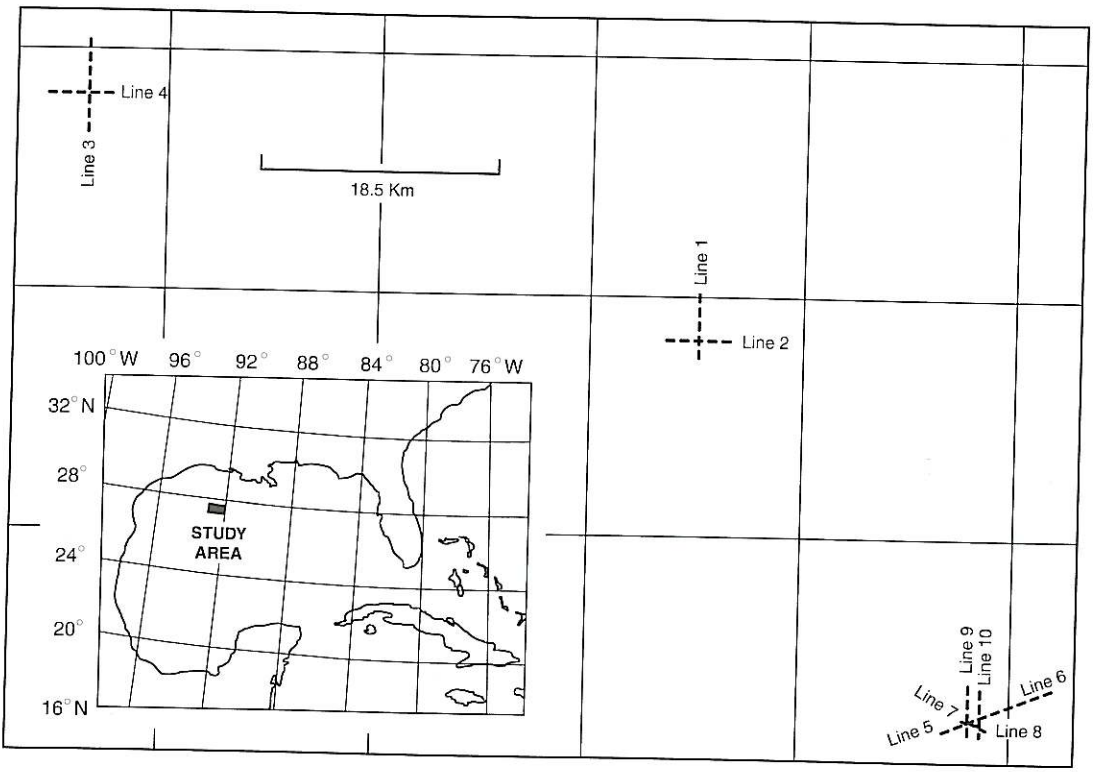

Fig. 1. Location of study area.

portions of the Garden Banks area (fig. 1) and duplicated conventional seismic profiles through wells where shallow flowing sands had been encountered. Twenty profiles were acquired, two profiles in opposite directions on each of ten tracks.

2.2. *Field and recording parameters*

A 15 in³ watergun source was towed on the surface and a short single-channel hydrophone array was towed about 250 m below the surface, both about 300 m behind the vessel (fig. 2). The objective was to record the outgoing source pulse isolated in time from returning reflections so that it could be used as the source signature during subsequent data processing. There was an interval of approximately 300 ms between the sea-floor reflection and the surface ghost which allowed 450 m of bottom sediment to be imaged before interference by ghost reflections was encountered.

The twenty profiles were acquired in 16-bit SEGY integer format. On the first profile, the source was fired at 5-s intervals with 3 s occupied by recording and 2 s being reserved for data storage and resetting. The firing interval was too short, however, as water-layer multiple energy from the preceding shot did not have time to dissipate. This was corrected on subsequent profiles by increasing the firing interval to 6 s, which allowed the record length to be increased to 4 s. The digitization rate was 80000 samples per second on all profiles. Traces in the first profile contain 240000 samples and the others contain 320000 samples.

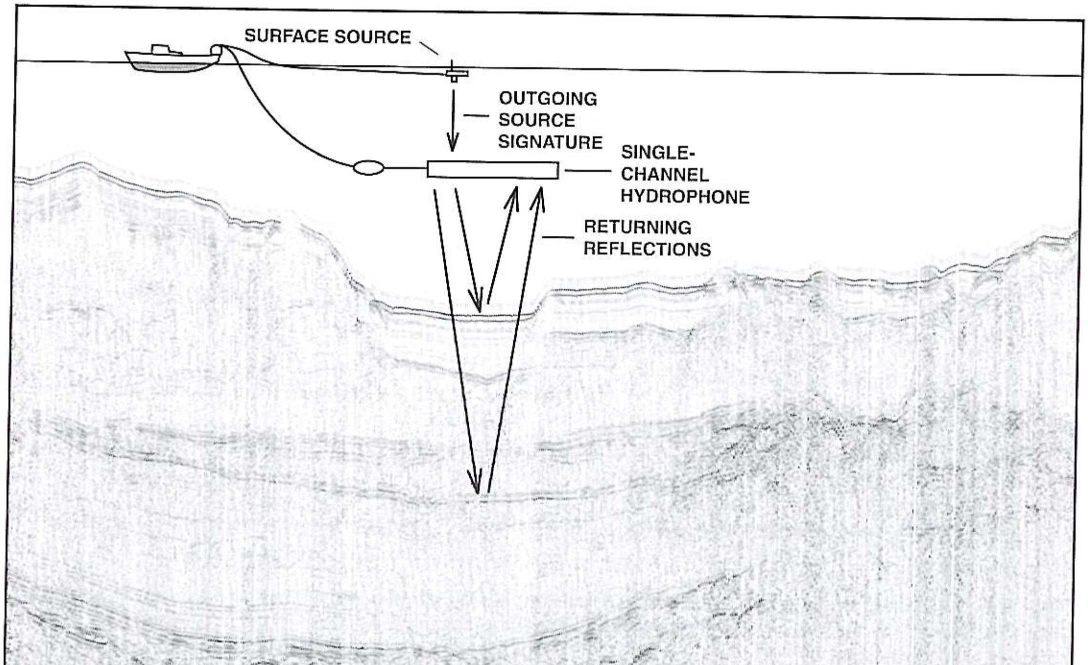

Fig. 2. Source/receiver geometry for recording far-field signatures in deep water.

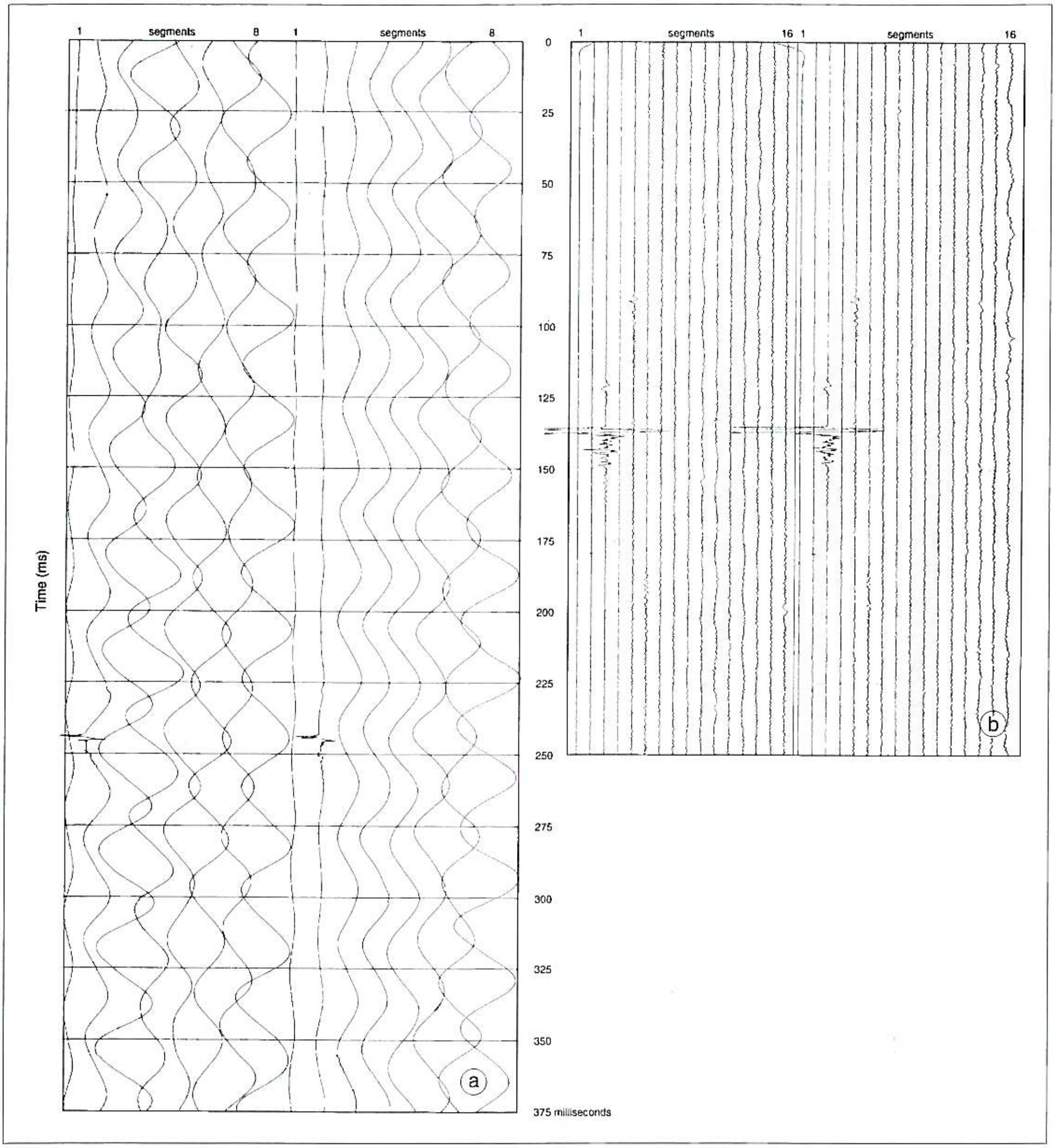

Fig. 3a,b. Field data: surface source, deep towed receiver, 80 000 samples per second: a) 3-s traces in 8 segments (note strumming); b) 4-s traces in 16 segments (low-cut filtered to remove strumming).

A format restriction is encountered when recording so many samples per trace because the number of samples per trace is written into the SEGY header as a two-byte integer, which cannot exceed about 32 000. This restriction was circumvented by dividing each trace into segments and writing it as a multi-channel record. Thus the 240 000-sample traces were written as 8-channel records of 30000 samples each (fig. 3a) and the 320000-sample traces as 16-channel records of 20000 samples each (fig. 3b). The segments were reassembled into a single trace for processing and the output separated into channels again.

A linear gain was applied, prior to digitizing, as a means of compensating for signal decay due to wavefront divergence. The first profile was recorded with no electronic filtering prior to the Analogue-to-Digital (A-D) convertor. Strumming of the deep-tow cable produced the strong 40 Hz signal visible in fig. 3a. In order to avoid clipping the strum signal, it was necessary to reduce the gain with the result that the seismic signal occupied only the low portion of the 16-bit dynamic range. In order that the gain to the seismic signal could be increased, the strum signal was attenuated on the other profiles by applying a 160 Hz (12 dB per octave) low-cut filter. Typical filtered field traces are illustrated in fig. 3b.

2.3. *Data processing*

Theoretical aspects of the data processing applied to the profiles are discussed by McGee (2000, this volume). The most obvious feature of each trace in fig. 3a,b is the offset from its null position by a slowly varying trend. These offsets were corrected during processing by use of a procedure known as «detrending». The detrending process is illustrated in fig. 4a-c. The input seismic trace containing a trend is shown in fig. 4a, the model of the trend in

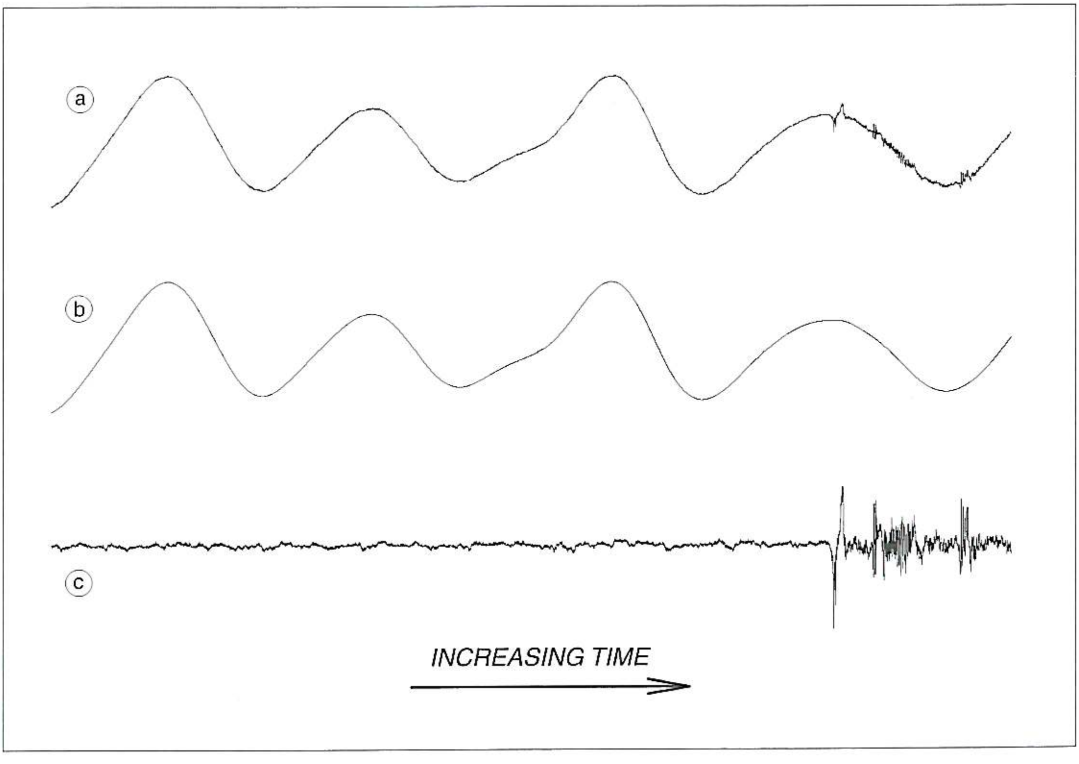

Fig. 4a-c. Illustration of the detrending process: a) input seismic trace containing a slowly varying trend; b) model of the trend; c) output trace at 2.5 times higher gain after subtraction of the trend model.

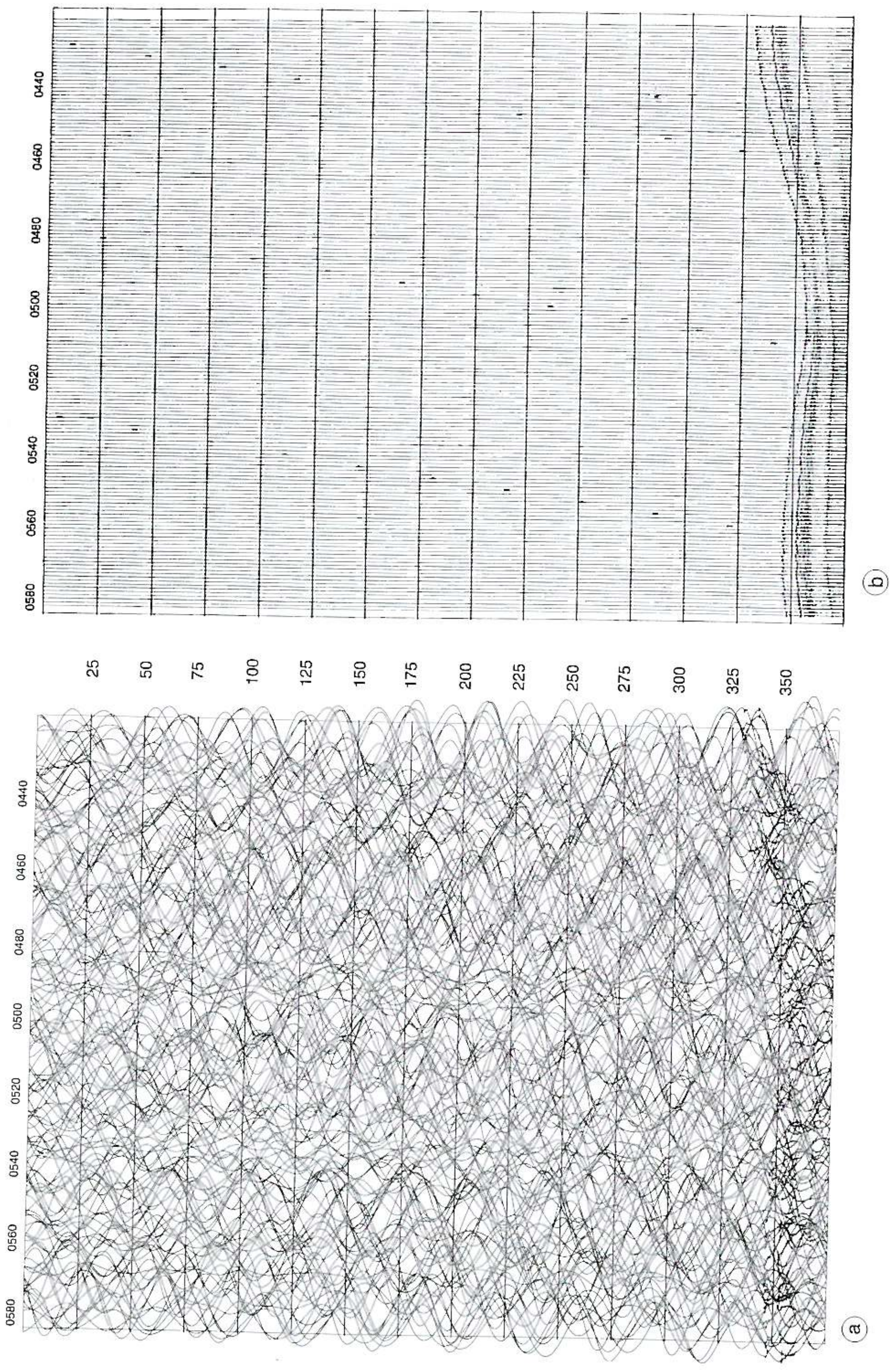

Fig. 5a,b. Example of the detrending process applied to a series of traces: a) input; b) output.

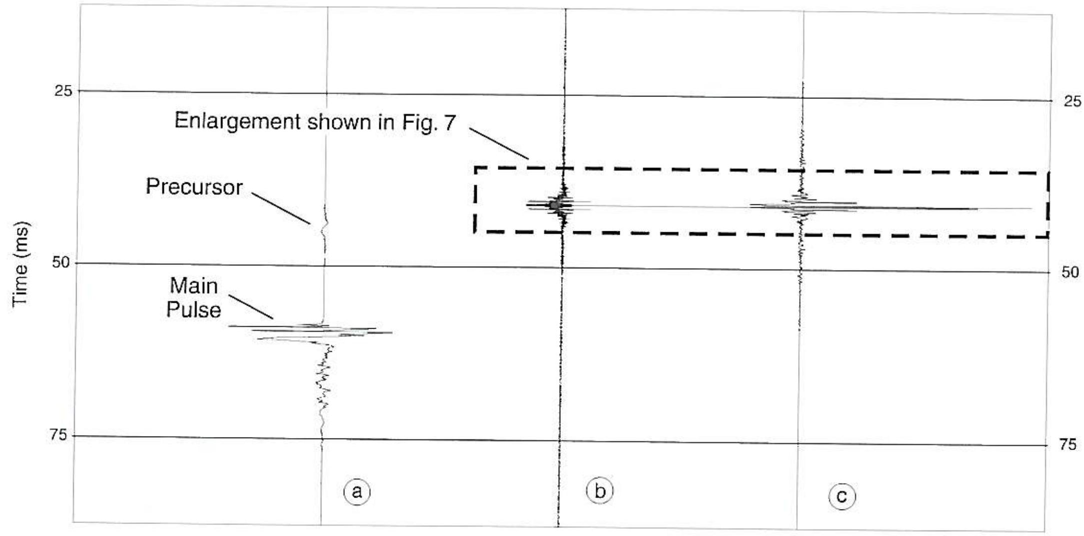

Fig. 6a-c. 15 in³ watergun source signature before and after processing: a) raw signature received at the deep-towed hydrophone; b) source signature deterministically deconvolved to itself; c) source signature phase conjugated by itself.

fig. 4b, the output in fig. 4c after subtraction of the model from the input. Figure 5a,b shows wiggle-trace plots that illustrate the application of detrending to a sequence of traces: a) input and b) output.

After detrending, the source signature was used both to deconvolve and to phase conjugate the data before correction for spherical divergence was made. Figure 6a shows watergun source raw signature; fig. 6b the signature deconvolved to itself and fig. 6c the signature phase conjugated by itself. The wavelets are normalized to unit energy across the interval shown and plotted in relative, not true, time. The outgoing source signature begins with a small precursor at 40 ms and develops into a complicated, high-amplitude pulse near 60 ms before decaying to insignificance beyond 80 ms. The deconvolved and phase conjugated signatures are symmetrical about a time near the onset of the precursor. The symmetry is more obvious in fig. 7a,b where the plots of the processed wavelets are enlarged: a) deconvolved and b) phase conjugated. In can be seen that secondary peaks are located about 0.5 ms on each side of the dominant peak.

Most of the energy in the source signature is distributed over about 20 ms. For the processed signatures, the same energy is compressed into their central peaks. The width of the peak of the deconvolved wavelet is 0.060 ms, that is a compression ratio of more than 300. The width of the phase conjugated peak is 0.156 ms, that is a compression ratio of about 130. It is oversampling that allows the compression to be so great. If the sampling rate were smaller, the amount of compression would be less.

The widths of the central peaks are an indication of the best resolution that can be accomplished without increasing the sampling rate. At the speed of sound in sea water (1500 m/s), the deconvolved peak is about 4.5 cm wide. Thus signature deconvolution provided resolution about 2.5 times better than the phase conjugation process. Deconvolution is notoriously susceptible to noise, however, so phase conjugation is often preferred, in practice, even though it provides somewhat lower resolution.

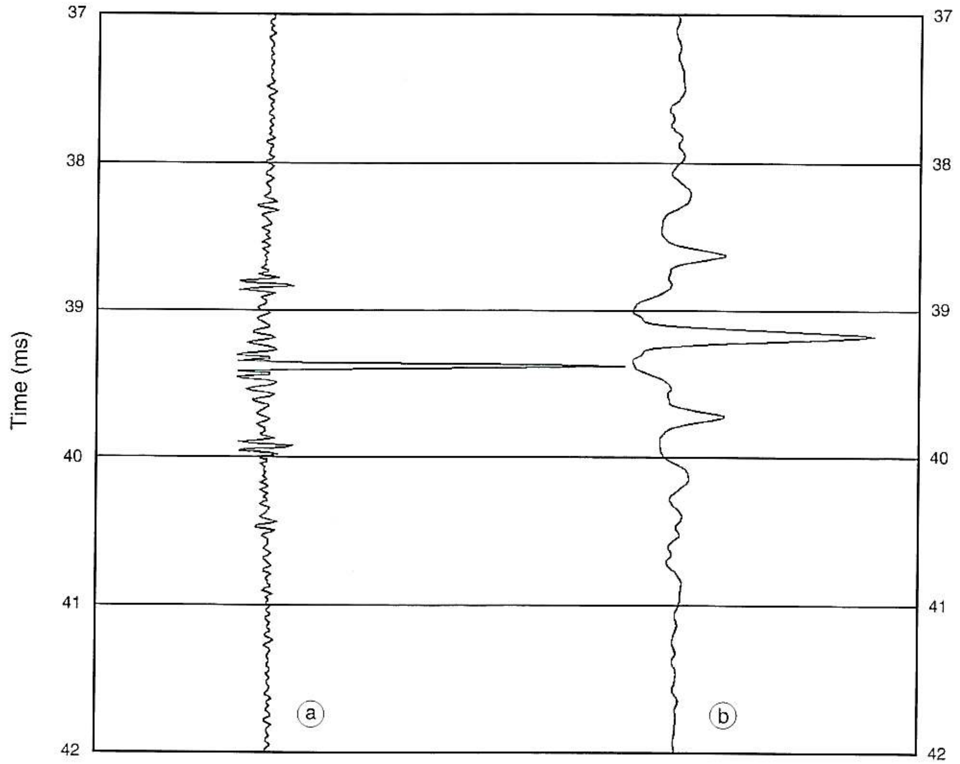

Fig. 7a,b. Enlargement of processed wavelets in fig. 6a-c: a) deterministic deconvolution; b) phase conjugation.

2.4. *Processed results*

Figure 8a,b shows a sequence of traces with no frequency filtering prior to the A-D convertor and after signature processing and spherical divergence corrections. The output of deterministic deconvolution is shown in fig. 8a and that of phase conjugation in fig. 8b. Coherent reflections are seen as much as 70 ms (53 m) below the sea floor (BTSF). Details within the outlined areas are shown in fig. 9a,b and fig. 10a,b.

Figure 9a,b corresponds to the area outlined in the left-hand portion of fig. 8a,b, fig. 9a being the output of deterministic deconvolution and fig. 9b being that of phase conjugation. In each, the uppermost reflection is from the sea floor. In fig. 9a, it comprises an oscillatory pulse with little consistent detail.

In fig. 9b, however, the sea floor reflection is seen to comprise two positive pulses about 0.30 ms apart, the first being weaker than the second. Thus phase conjugation reveals that the sea floor consists of a 23 cm-thick layer of softer sediment overlying a second, firmer layer of sediment. Such detail is not obvious on the deterministic deconvolution output. Results obtained from both processes indicate that the second, firmer layer is very homogeneous and about 6 ms (4.5 m) thick. Both processes show that the second layer overlies a third layer whose lower boundary is indistinct. The phase conjugated output is clearer, however, in showing that the interface between the second and third layers is complex, the reflections from it being a weak negative followed 0.15 ms (11 cm) later by two stronger reflections, the first being positive and the second being negative, separated by 0.1 ms (7.5 cm) which is about the limit

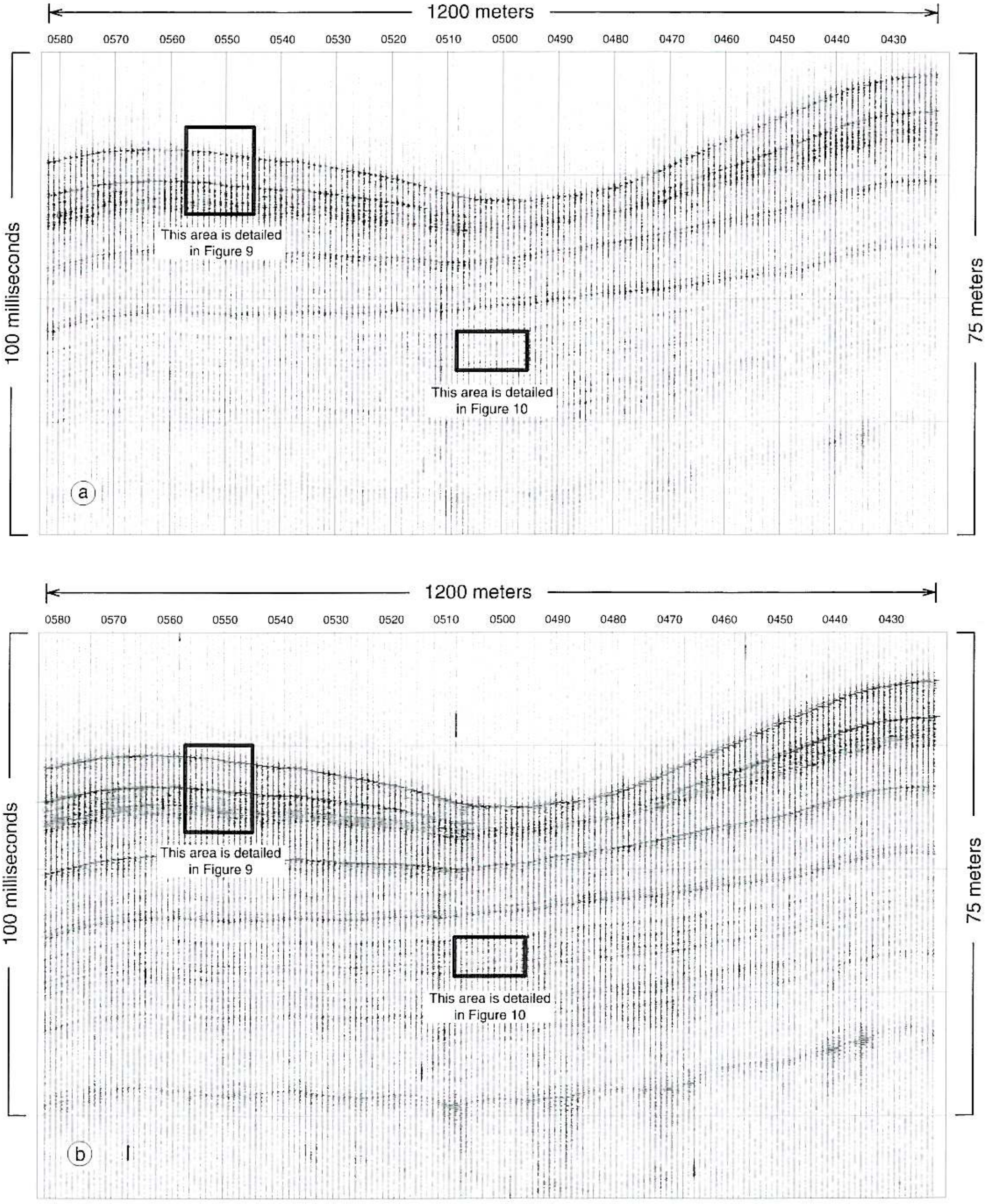

Fig. 8a,b. Deep-water (1300 m) profile after signature processing and spherical divergence corrections with no frequency filtering prior to the A-D convertor: a) deterministic deconvolution; b) phase conjugation.

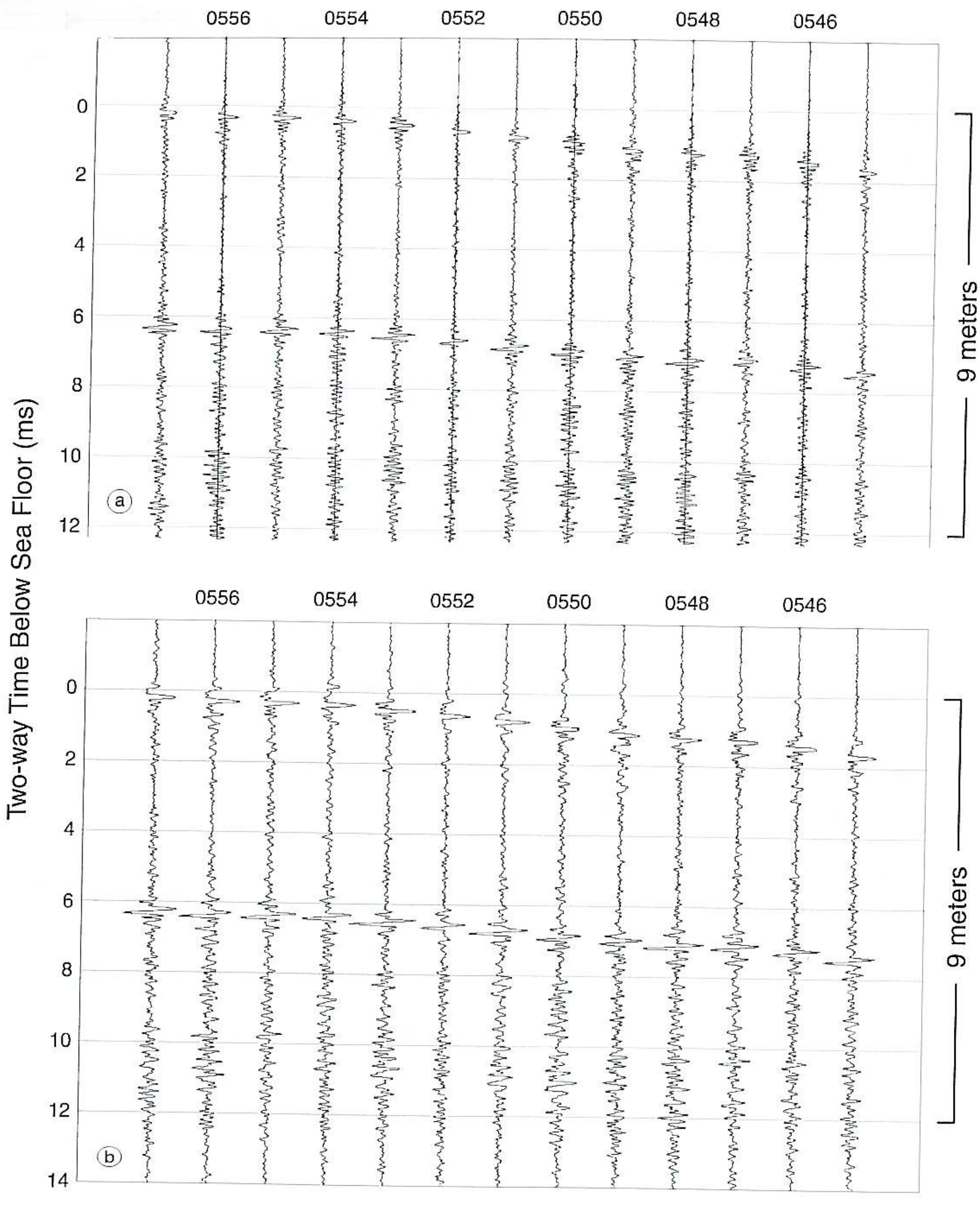

Fig. 9a,b. Details in areas outlined in the left-hand portion of fig. 8a,b; a) deterministic deconvolution: b) phase conjugation.

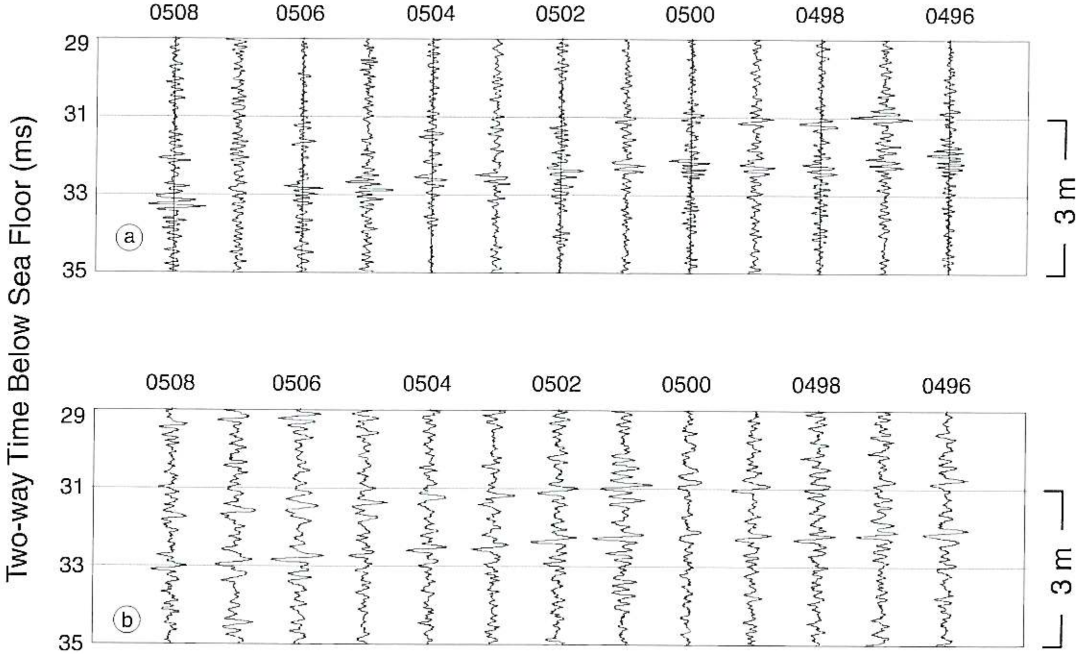

Fig. 10a,b. Details in areas outlined in the central portion of fig. 8a,b: a) deterministic deconvolution: b) phase conjugation.

of resolution. Results obtained using either process indicate that the lower portion of the third layer comprises a region of numerous reflections which may correspond to a sequence of layers too thin to be resolved.

Figure 10a,b shows details within the area outlined in the central part of fig. 8a,b. The output of phase conjugation reveals a layer whose upper boundary is a positive pulse at 31.7 ms (24 m) BTSF on the left-hand side of the fig. 10b. The layer is about 1.3 ms (1 m) thick and its lower boundary is marked by a negative reflection. These reflection polarities are consistent with the layer being a sand unit within a formation of silt or soft clay. Deterministic deconvolution does not resolve the layer nearly as well. Thus fig. 9a,b and fig. 10a,b demonstrate that the phase conjugation process provides better results than does the deterministic deconvolution process, at least in the case of these data.

Figure 11a,b shows details of traces, fig. 11a being processed traces with no frequency filtering prior to the A-D convertor and fig. 11b being processed traces with a 160 Hz low-cut filter applied prior to the A-D convertor. In fig. 11a, the reflection from the sea floor is seen to comprise two positive pulses separated by 0.30 ms, that translates to a sea-floor consisting of a 23 cm-thick layer of softer sediment. Such resolution is not achieved when a 160 Hz low-cut filter is applied prior to A-D conversion. Indeed, in fig. 11b, the reflection from the sea-floor is also made by two positive pulses, the first weaker than the second but the delay between them is about 0.54 ms, and represents a layer about 41 cm thick. Thus, fig. 11a,b shows that acquisition with no low-cut frequency filter prior to application of the A-D convertor results in better resolution than acquisition with filtering.

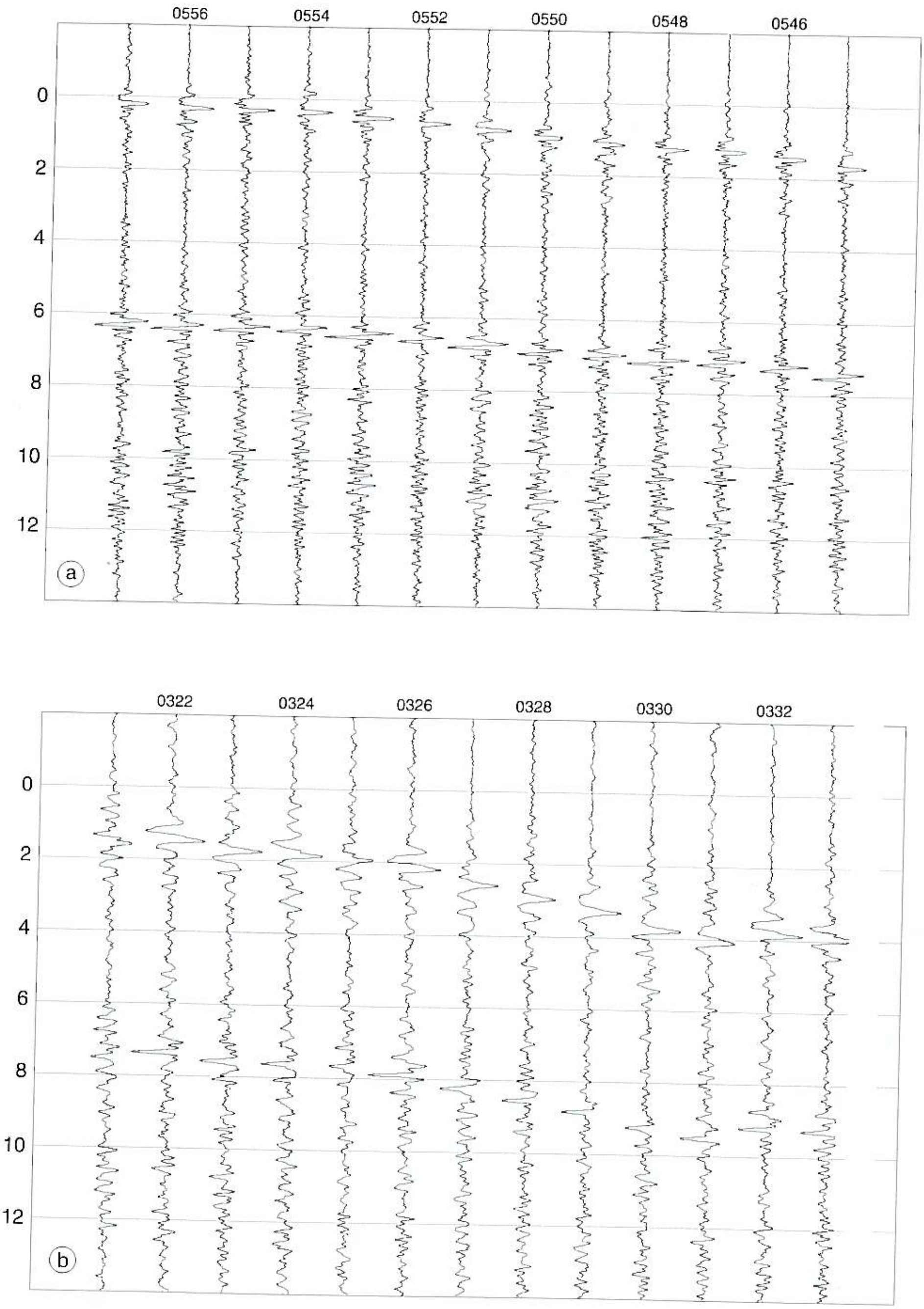

Fig. 11a,b. Details of traces: a) phase conjugated with no frequency filter prior to the A-D convertor; b) phase conjugated with a 160 Hz low-cut filter prior to the A-D convertor.

3. Conclusions

During the last two years, the CMRET has conducted several cruises to test and improve a high-resolution seismic system. Processed results from the September 1999 CMRET research cruise in deep water show that oversampling and recording a source signature in the field can result in improved resolution in processed data. At present, the system can resolve layers on the order of ten centimeters thickness in water depths of 1600 m.

Although deterministic deconvolution is potentially a better source signature process in terms of resolution, it is more sensitive to noise than phase conjugation and data processed by phase conjugation exhibit more details. Moreover, with a high-resolution, broadband system, it has been demonstrated that adding a low-cut filter prior to the A-D convertor reduces resolution.

REFERENCES

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