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Review

Approaches for Suppressing Seismic Bubble Pulse Reverberations

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ABSTRACT

Seismic data processing was carried out with the aimed of suppressing bubble pulse reverberations using different approaches on the acquired seismic dataset that are largely dominated by bubble pulses which conceal useful stratigraphic information. The outputs generated by the different approaches used to suppress the bubble pulses have to do with the underlying principles of each technique. The output of the spiking deconvolution strategy shows a generally higher frequency output compared to the input. The bubble pulses have been suppressed to a very large extent, although some remnants of the pulses can still be seen. The main pulse itself has been simplified from the initial high amplitude and complex pulse to a simpler one. The output of predictive deconvolution has roughly the same frequency content as the input. The output of the surface consistent deconvolution is similar to the output of the corresponding spiking and predictive deconvolution. The output of the trace subtraction method shows a surgically muted dataset. Only portions of the bubble pulses of the sea-bed reflection are removed and some part of the main pulse has been surgically removed as well. The output of the filter generation and application strategy shows a fully defined subsurface layering. The bubble pulses have been completely removed, the main pulse has been reduced to a simpler wavelet thereby improving the temporal resolution of the data. Apart from the multiples, the events left in the data are genuine geological reflections. The filter generation and application method has done better by eliminating the effect of the bubble pulse in the dataset, therefore this method deem suitable for removing the bubble pulse reverberations from the dataset.

Keywords: Bubble pulses, Deconvolution, Airgun, Seismic, Reverberation and Amplitude.

INTRODUCTION

In marine seismic operations; air guns are commonly used, these guns are pneumatic sources in which a chamber is charged with very high-pressure compressed air fed through a hose from a shipboard compressor. The air is released by electrical triggering, through vents into the water in form of a high-pressured bubble. An underwater bubble of gases at high pressure tends to alternately expand and contract. As long as the gas pressure exceeds the hydrostatic pressure of the surrounding water, the net force will accelerate the water outward. The net force decreases as the bubble expands and becomes zero when the bubble expansion reduces the gas pressure to the value of the hydrostatic pressure. At this point, the water has acquired its maximum outward velocity and so continues to move outward while decelerating because the net force is now directed inward. Eventually, the water comes to rest and the net inward force now causes a collapse of the bubble with a consequent sharp increase in gas pressure, in effect a new energy release and the process repeat itself (Telford et al., 1990). In this vein, the primary pulse generated by an air gun is followed by a train of bubble pulses that increase the overall length of the pulse. The seismic pulse is thereby unduly lengthened (Kearey et al., 2002). On seismic records, each oscillation effectively produces a new seismic record superimposed on the earlier record such that the resulting mixture is difficult to interpret. One way of suppressing the effect of bubble pulse in the field is to detonate the source near the water surface so that the gas bubble escapes into the air. The disadvantage of this method is that much energy is wasted and the downgoing seismic pulse is weakened. Arrays of guns of differing dimensions and, therefore, different bubble pulse periods can be combined to produce a high energy source in which primary pulses interfere constructively while bubble pulses interfere destructively (Kearey et al., 2002). Individual source bubble pulses can only be suppressed by the use of cages or wave shaping devices (Bowen, 1986). Water guns are used to avoid the bubble pulse problem in which a water jet is ejected into the surrounding rather than compressed air. The bubble pulse effects on seismic records are removed during processing. The acquired seismic dataset is largely dominated by bubble pulses that conceal useful stratigraphic information in the data, this work was aimed at suppressing bubble pulse reverberations using different approaches.

Basics of Deconvolution

The recorded seismogram can be modelled as a convolution of the earth's impulse response with the seismic wavelet. This wavelet has many components, including source signature, recording filter, surface reflections, and receiver-array response. The impulse response comprises primary reflections (reflectivity series) and all possible multiples (Yilmaz, 2001). Deconvolution is a process that counteracts this previous convolution action. It compresses the basic wavelet in the recorded seismogram, attenuates reverberations and short-period multiples, thus increases temporal resolution and yields a representation of subsurface reflectivity. The earth's impulse response is what would be recorded if the wavelet were just a spike. When an inverse filter is convolved with the seismic wavelet, this results in a spike. When applied to a seismogram, the inverse filter should yield the earth's impulse response. Considering the convolution operation in equation 1;

$$x(t) = w(t) * e(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where $x(t)$ is the recorded seismogram, $w(t)$ is the basic seismic wavelet, and $e(t)$ is the earth's impulse response. Note that the additive noise component of the recorded seismogram is neglected. The recovery of $e(t)$ when $x(t)$ and $w(t)$ is known represents a deconvolution operation. If a filter operator $f(t)$ were defined such that convolution of $f(t)$ with the known seismogram $x(t)$ gives an estimate of the earth's impulse response $e(t)$, then

$$e(t) = f(t) * x(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

Substituting equation (2) into equation (1) gives:

$$x(t) = w(t) * f(t) * x(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Eliminating $x(t)$ from both sides of the equation gives:

$$w(t) * f(t) = \delta(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

Where $\delta(t)$ is a spike function (a unit amplitude spike at zero time); that is, it represents the Kronecker delta function: The filter operator $f(t)$ is then given by:

$$f(t) = \delta(t) * \frac{1}{w(t)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

Thus provided the basic wavelet $w(t)$ is known, the filter operator $f(t)$ can be obtained as the mathematical inverse of the basic wavelet $w(t)$ from equation (5). This filter operator is the inverse filter needed to convert the seismogram to a series of spikes that defines the earth's impulse response as shown in equation (2).

The particular problem with deconvolving a seismic record is that the input waveform $w(t)$ is generally unknown, therefore the deterministic approach cannot be employed and the deconvolution operator has to be designed using statistical methods. This special approach to the deconvolution of seismic records is known as predictive deconvolution.

Bubble Pulses Suppression Techniques

- **Spiking Deconvolution**

The basis of spiking deconvolution is a case of Wiener filtering in seismic deconvolution whereby the desired output is a spike function. Spiking deconvolution is also known as whitening deconvolution because a spike has the amplitude spectrum of white noise. The application of this to the study was to compute the spiking deconvolution operator which is inverse of the wavelet in the seismic data. Since the wavelet consists of the main pulse and the bubble pulses, the spiking deconvolution operator would be the one that would compress the wavelet to a single spike at the location of the main pulse. This implies that once this operator is convolved with the whole dataset, it converts every occurrence of the noisy wavelet to a spike and subsequently, the subsurface layering would be fully defined. But the source waveform is not exactly known, and making the assumption that reflectivity is a random process, the characteristics of the wavelet was deduced from the autocorrelation of the seismogram as it is expected that the autocorrelations and the amplitude spectra of both the seismogram and the seismic wavelet are similar. The Spiking/Predictive Deconvolution tool was used to design and apply the spiking deconvolution operator. This tool designs and applies spiking or predictive deconvolution operators using the Wiener-Levinson, least square algorithm. The minimum phase spiking option was used for this operation to apply a traditional Wiener-Levinson spiking deconvolution.

The two most important parameters used here is the deconvolution operator length and the operator 'white noise' level. The former determines how much of the autocorrelation is used while the latter specifies the percentage of white noise to be added to the original spike response. This percentage of white noise is otherwise referred to as percent prewhitening. Prewhitening yields a band-limited output and it is used to ensure that numerical instability in solving for the deconvolution operator is avoided. The deconvolution operator length was first deduced from the autocorrelation output of the datasets. This operator length was designed to just include the part of the autocorrelation obtained from the datasets that most resembles the autocorrelation of the unknown seismic wavelet. That part is the first transient zone in the autocorrelation. The seismic wavelet in this case consists of the main pulse and the bubble pulses; therefore, the operator length was designed from the autocorrelation to include all the pulses. Parameter testing was carried out to know the appropriate deconvolution operator length and operator 'white noise' level, values of 200ms and 0.1% were chosen respectively. Figure 1.0 shows the dataset before and after the spiking deconvolution.

Predictive Deconvolution

Predictive deconvolution attempts to remove the effect of multiples by predicting their arrival times from knowledge of the arrival times of the relevant primary events. For this study, the primary event would be the first bubble pulse (not the main pulse) since it is actually the first bubble pulse that is been repeated as the subsequent bubble pulses. Like the spiking deconvolution, the Predictive Deconvolution tool was used. The minimum phase predictive option was used to apply a traditional Wiener-Levinson predictive deconvolution. In addition to the operator length and the operator 'white noise' level, another important parameter used for predictive deconvolution was the operator prediction distance. The operator prediction distance is the length of the prediction window, in milli second. It determines which part of the autocorrelation function will be untouched by the deconvolution. Both the operator prediction distance and the operator length were initially deduced from the autocorrelation of the dataset. Subsequent parameter testing shows that the most suitable values are operator prediction distance of 20ms and operator length of 190ms. The operator 'white noise' level of 0.1% was still used as determined. Figure 2.0 shows the dataset before and after the predictive deconvolution applied.

Surface Consistent Deconvolution

The goal of surface consistent deconvolution is to decompose seismic data into their individual components. Surface consistent deconvolution is based on the concept that a seismic wavelet can be broken down into its source, receiver, offset, and Common Depth Point (CDP) components. This approach was tested on the data. The Surface Consistent Deconvolution tool was used. This tool uses any combination of source, receiver, offset, and CDP components for power spectrum calculation and deconvolution. Both the spiking and the predictive option of the surface consistent deconvolution tool were used. The spiking option applies Wiener-Levinson spiking deconvolution for each selected component while the predictive option applies Wiener-Levinson predictive deconvolution. The same parameters used in spiking deconvolution and predictive deconvolution were also used here. The components used to design the deconvolution operators were the SHOT and the CDP; these two components were also used in the application. Figure 3.0: show the dataset before and after predictive surface consistent deconvolution.

Trace Subtraction

Visual inspection of the data showed that the bubble pulses are consistent across the survey line. This was conveniently corroborated by the output of the autocorrelation of the flattened version of the dataset. The idea is that, since the bubble pulses are consistent, then one could just stack a few traces from the flattened version of the dataset, subtract the bubble pulse portion of that stacked trace from every other trace, then this should leave the whole dataset with the bubble pulses free. This was attempted, but the output was just like the stacked trace. This implies that the amplitude of the stacked trace was much more than the amplitude of each of the traces. However, the amplitude of the stacked trace

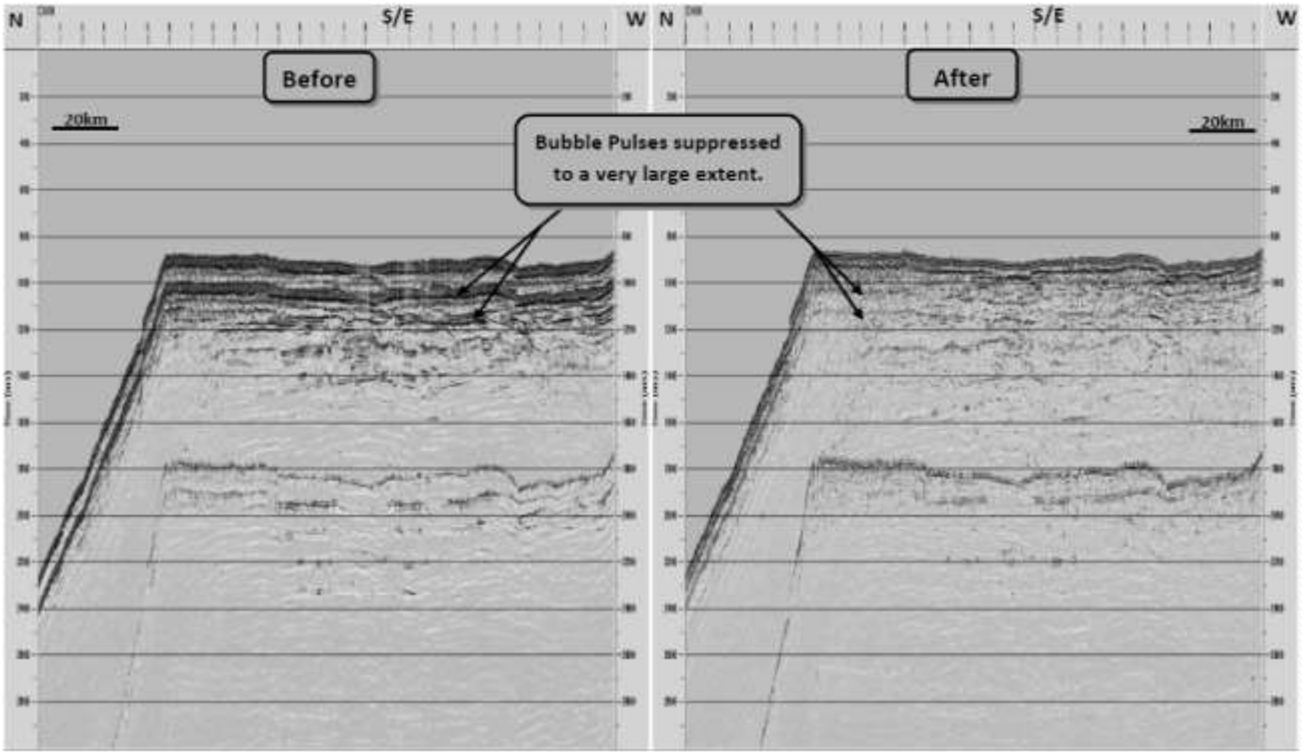

Figure 1. Before and after the application of spiking deconvolution

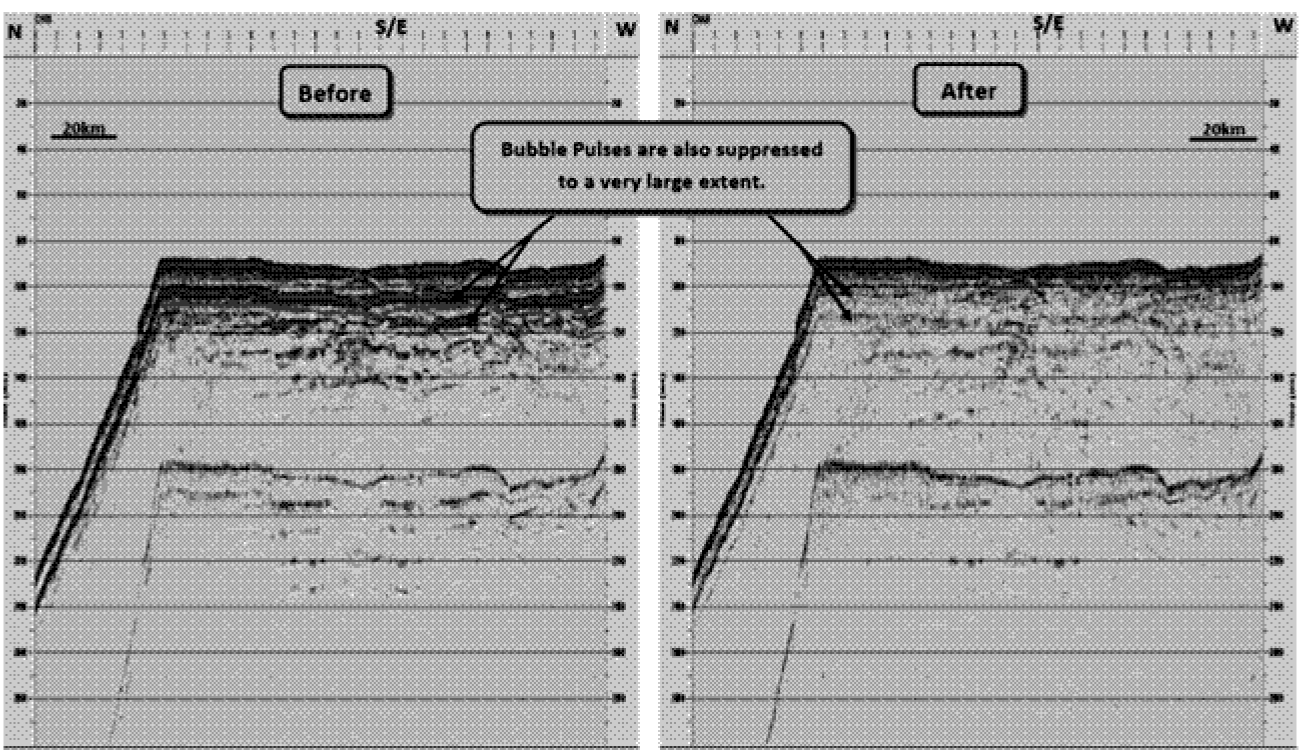

Figure 2. Before and after the application of predictive deconvolution

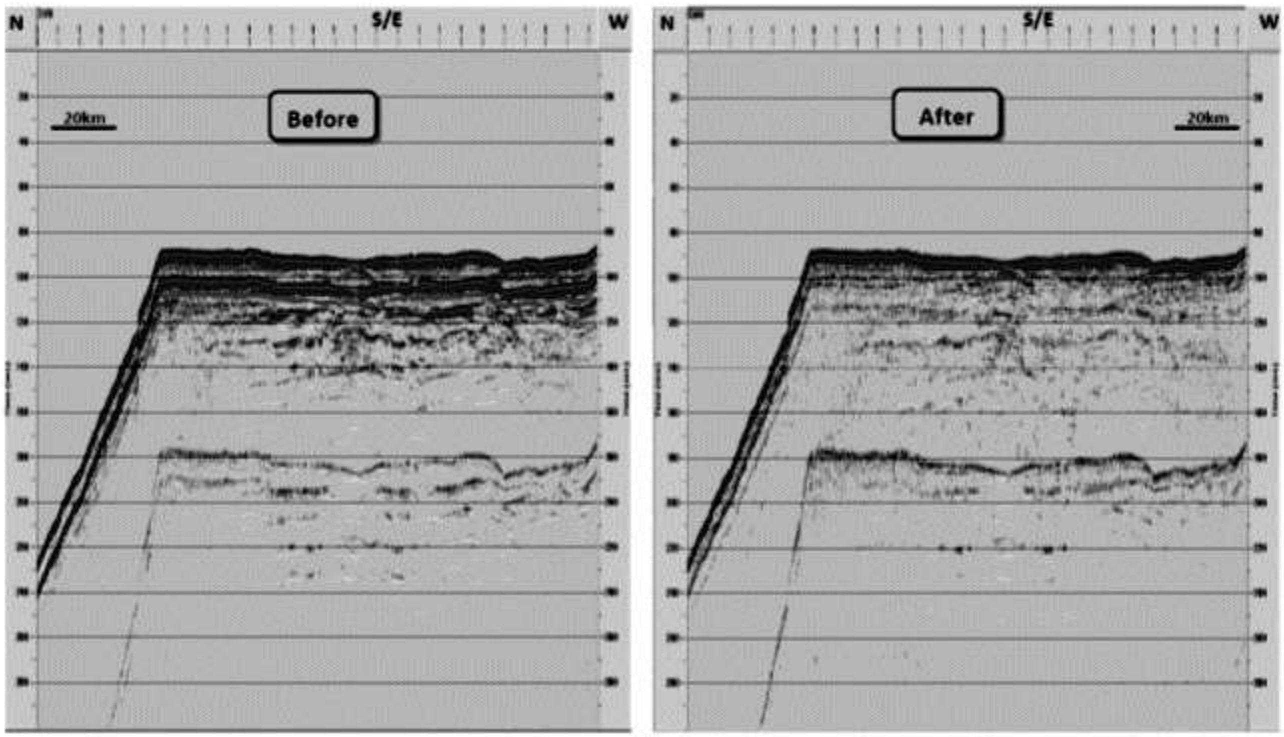

Figure 3. Before and after the application of the predictive option of surface consistent deconvolution

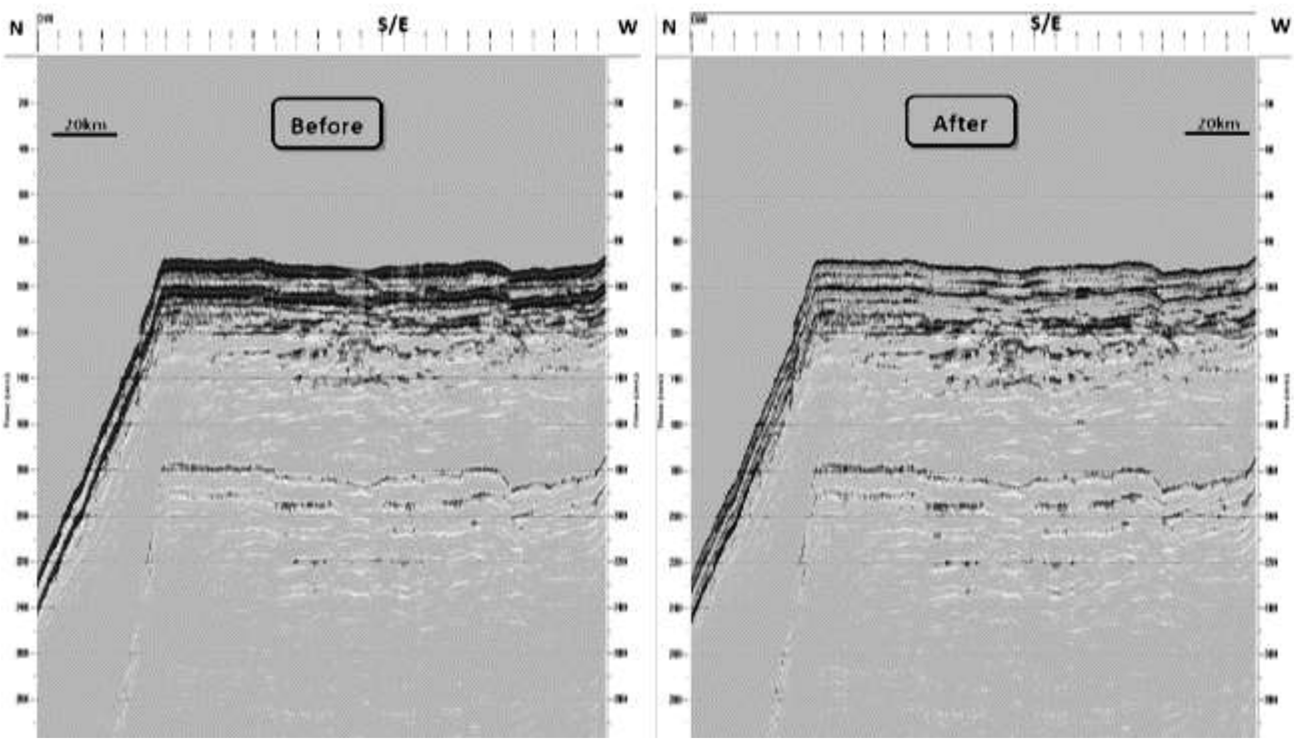

Figure 4. Before and after the bubble pulses have been removed through trace subtraction

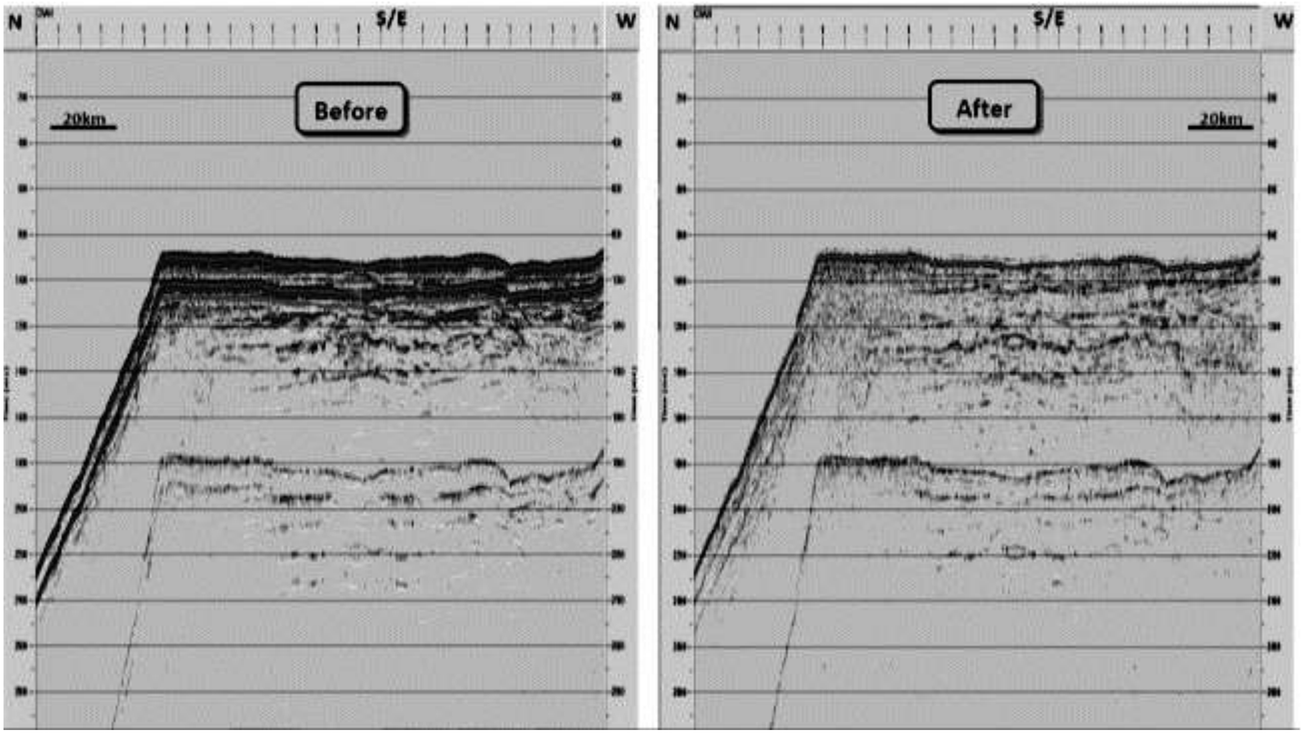

Figure 5. Before and after the application of an inverse filter operator

was scaled down, but it was difficult scaling it down to the amplitude range of the dataset. In order to execute this concept, a typical trace from the dataset was used instead of the stacked trace. This trace was muted in such a manner as to remove every other event except the bubble pulses. This was done by using a top mute to remove the sea-bed reflection, a bottom mute to remove all other reflections after the last bubble pulse, and then a surgical mute to remove the bit of reflections between the bubble pulses. These operations left the trace with only the first and the second bubble pulse remaining. This resulting trace is what would be subtracted from every other trace in the dataset. This resulting trace was then reproduced to exactly the same number of traces as contained in the dataset using the 'Reproduce Traces' tool in ProMAX^{TM}. This then gave a separate dataset containing only bubble pulses; this dataset would then be subtracted from the flattened version of the actual data. Figure 4.0: shows the dataset before and after the bubble pulses have been removed through trace subtraction.

- **Filter Application and Generation.**

The basis of this strategy was to obtain a filter operator that would be convolved with the dataset to suppress the bubble pulses present in the data. In order to simplify this approach, a representative trace of the whole dataset was obtained; this trace will subsequently be referred to as the observed trace. This trace was obtained such that it contains all the events that are coherent across the dataset, and such coherent events are mainly the sea floor reflection and the bubble pulses. The observed trace was obtained by stacking a large number of traces from the flattened version of the dataset. Prior to the stacking, top and bottom mute has been applied to the data at 730ms to remove the direct arrival and the sea-bed multiple reflections thereby leaving the observed trace to be made up of mainly the sea floor reflection and the bubble pulses. An operator is therefore sought, such that when this operator is convolved with the observed trace, it suppresses the bubble pulse, leaving the trace with only the sea floor reflection. This operator was generated from the observed trace, applied on the observed trace to see if the output resembles the reference trace, once satisfied, the operator was then applied on the whole dataset. Figure 5.0 shows datasets before and after the application of an inverse filter operator and bandpass filtering.

RESULTS AND DISCUSSION

The outputs generated by the different approaches used to suppress the bubble pulse have to do with the

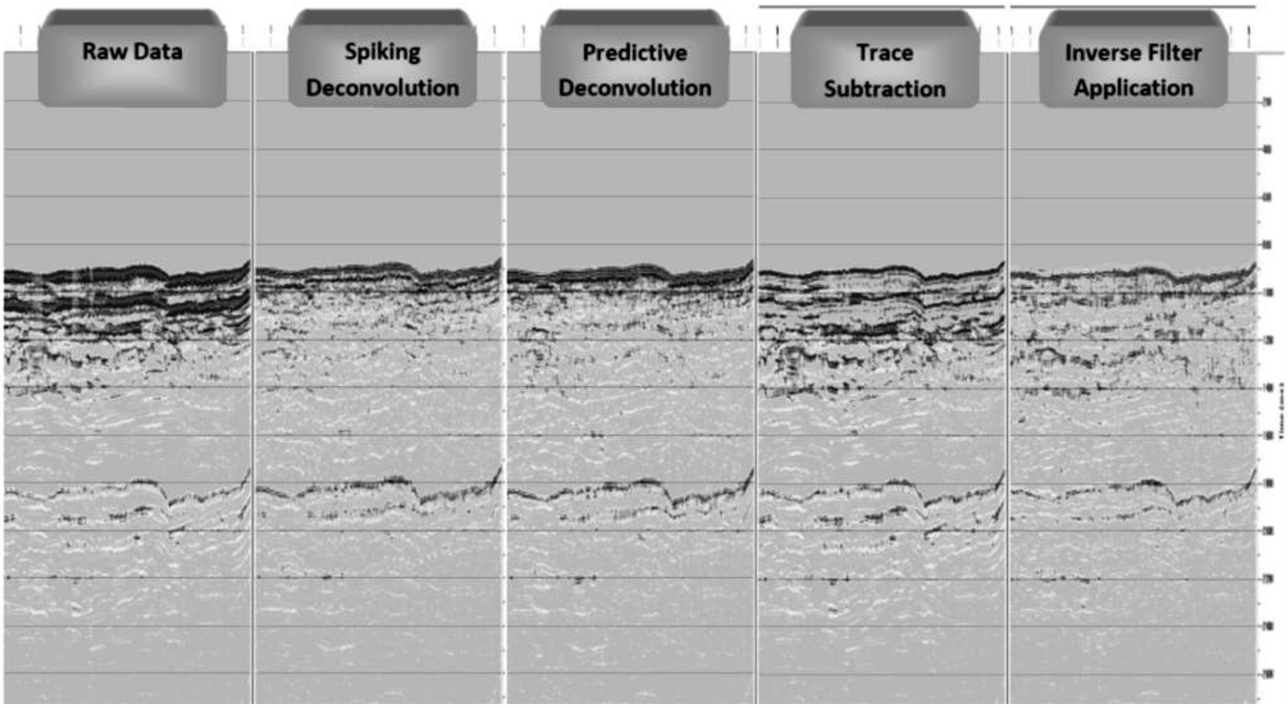

Figure 6. Comparison the outputs of the various techniques used

underlying principles of each strategy. The output of the spiking deconvolution strategy as displayed in Figure 1.0 shows a generally higher frequency output compared to the input. The bubble pulses have been suppressed to a very large extent, although some remnants of the pulses can still be seen as identified on the figure. The left-over of the bubble pulse is much more along the continental slope of the data. The main pulse itself has been simplified from the initial high amplitude and complex pulse to a simpler one. The output of predictive deconvolution as shown in Figure 2.0 has roughly the same frequency content as the input. Here, the bubble pulses have also been suppressed to a very large extent with some left-over pulses still visible. The amount of the first bubble pulse left after the application of this process is much more than that of the second bubble pulse especially along the continental slope. The main pulse remains unchanged; the implication of this is that all the genuine reflections will present a complex nature of the main pulse thereby making it difficult to interpret the finest details of the sequence stratigraphy of the data. The output of the surface consistent deconvolution is similar to the output of the corresponding spiking and predictive deconvolution. The output of the trace subtraction method (Figure 4.0) shows a surgically muted dataset. Only portions of the bubble pulses of the sea-bed reflection are removed and some part of the main pulse has been surgically removed as well. A good proportion of the second bubble pulse is quite evident in the data. Apart from the 300ms window (900ms to 1200ms) where the sea-bed reflection and its bubble pulses are located, every other part of the data remains unchanged. The output of the filter generation and application strategy (Figure 5.0) shows a fully defined subsurface layering. The bubble pulses have been completely removed, the main pulse has been reduced to a simpler wavelet thereby improving the temporal resolution of the data. Apart from the multiples, the events left in the data are genuine geological reflections.

In order to appraise the outputs of all the strategies tested in this work, the outputs have been placed side-by-side against the raw data in Figure 6.0. Predictive deconvolution did not improve the resolution of the data; the resolution is unaffected. It actually did suppress some of the bubble pulses, but this method was downplayed for two major reasons. The first is that the basis of the application of this method defies the aim of the work. The first bubble pulse was the primary event that was used to predict the arrival times of the subsequent pulses, it is therefore expected that this first bubble pulse would still be left after the method has been applied. The other reason is that the main pulse has been left unaffected. The main pulse is complex and of high amplitude, the details of the sequence stratigraphy of the vicinity of the main pulse would not be visible unless the main pulse is simplified.

The trace subtraction method has only tackled some 250ms window (850 ms to 1100 ms) of the data. The idea of this method was to totally remove the bubble pulses, but this method has some shortcomings. It could well be said that the bubble pulses are consistent across the traces, but the fact remains that they are not located at exactly the same positions across the traces. Slight variations in the speed of the acquisition vessel have inflicted some variations on the bubble pulse period. If the bubble pulses were to be located at the same position, then this method would have removed them completely. A good part of the second bubble pulse has been left untouched and it looks as if the integrity of the main pulse has been compromised.

Even if this method had removed the bubble pulse completely, then an explanation has to be given to explain why the actual geological reflections that are supposed to be occupying the positions of the bubble pulses are missing. All the points mentioned in this argument make this method grossly unsuitable for the purpose of this work. The temporal resolution of the data is quite improved in the spiking deconvolution and inverse filter application outputs compared to the others. This is quite understandable if the underlying principle of these strategies is considered. The spiking deconvolution compresses every occurrence of the wavelet into a spike. The inverse filter application on the other hand applies the inverse filter operator to the data such that every occurrence of the bubble-pulse ridden wavelet would be replaced by the wavelet in Figure 2.0. But the spiking deconvolution was not fundamentally targeted at the bubble pulses as it was designed to just compress the wavelet to a spike. Although the deconvolution operator length was designed to include the main pulse and the bubble pulses, the bubble pulses were not substantially suppressed.

The filter generation and application strategy did the job perfectly as the subsurface layering was fully defined after the application. This method interestingly suppresses the bubble pulses completely and it is quite satisfying that some genuine geological reflections that are coherent across the traces remain after this process. From previous studies, it has always been a concern that processes designed to remove bubble pulses from continental shelf data may also remove primary reflections that are approximately parallel to the sea floor, but this is not the case after applying this method. This approach also simplified the main pulse which invariably improved the temporal resolution of the data greatly. The filter generation and application method has undoubtedly achieved the aim of this work by eliminating the effect of the bubble pulse in the data. This method is therefore selected as the best approach in removing the bubble pulse reverberations from the dataset.

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