Results from the use of broad-band, sub-bottom seismic data with statistically based sediment classification techniques.

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Abstract

The QTC VIEW sediment classification system has been applied to shallow, high resolution seismic data recorded with the IKB-SEISTEC™ profiler from the navigable channel of the St. Lawrence estuary in Canada. A number of 10 minute sections of seismic data in water depths from 10-15 m were selected from profiles covering a the wide variety of bottom sediment types found in the channel. These data sets were used in n unsupervized classification scheme to differentiate the various sediments and seafloor morphologies. Five distinct classes (of sediments) were identified ranging from fine silt/clay to medium sand. However, it was found that shallow gas, in various forms has a controlling influence in some areas.

On a appliqué la methode QTC VIEW de classification des sédiments à des données sismiques de haute résolution recueillies avec un profileur IKB-SEISTEC dans le chenal navigable de l'estuaire du Saint Laurent (Canada). Parmi la grande variété de types de sediments qu'on trouve dans le chenal, on a choisi des sections de 10 minutes provenant de profondeurs situées entre 10 et 15 metres. On a utilisé ces données dans un plan declassification dirigé pour identifier les différents sédiments et les différentes morphologies du fond. On a identifié cinq classes de sediments, allant de vase/argile fine à sable moyen. Toutefois on a trouvé que des gas de différentes formes dans les sediments peu profonds ont une influence déterminante à certains endroits.

1. Introduction

Marine surveyors have been using echo sounders to classify the seabed for many years. Normally the echogram displays the time of arrival of the echo from the seafloor and presents depth as a mark placed on scaled paper. Inferences on the nature of the seabed can be made by observing the intensity of the seabed return as well as the changes in arrival time. This qualitative evaluation is possible because more information is present in the returning signal than that solely utilized by the echo sounder to indicate water depth. The echo received from the seafloor by an echo sounder is a measure of the acoustic properties combined with the acoustic backscatter characteristics of the sediment. Acoustic backscatter is controlled, in part, by the roughness of the seabed. If the surface of the seafloor is rough, then reflected energy will be return to the sounder transducer from wide angles. Since the distance travelled by off-axis energy is longer than the normal case, the received echo from a rough surface is longer in duration than for echoes reflected from a smooth surface. By applying signal processing techniques to sea floor echoes, accurate and repeatable acoustic classification of the seabed can be accomplished.

In the early 1970's, certain attributes such as echo amplitude and energy content were extracted from the bottom echo to provide real-time indications of acoustic reflectivity. In the 1980's, dedicated seabed classification was introduced which processed the seafloor echo envelope thereby generating values representing the acoustic response from specific seabed types.

The present generation of committed instruments uses high speed digital signal processors to extract many dominant features from the echo envelope in real-time providing greater accuracy and reliability in the discrimination of seabed types. One such commercially available instrument is the QTC VIEW which has recently been introduced for digital seafloor classification [1],[2].

In parallel with these improvements in processing sonar data, there has been advances in the techniques for sub-bottom profiling in shallow water. In 1987 a novel bi-static, broadband, seismic system was tested in the Mackenzie Delta area of the Canadian arctic where water depths less that 10 metres predominate [3]. Subsequent development of this technique lead to the introduction of the IKB SEISTEC™ in 1992 which has enabled high resolution profiling to be extended into water as shallow as 2 metres [4],[5]. In 1995, such a seismic system was used in a pre-dredging survey in the navigable channel, of the St. Lawrence between Montréal and Québec City in Canada. The raw seismic data was recorded in digital format on a DAT recorder so that various types of post-processing could be undertaken. The fact that good weather prevailed for the duration of this survey meant that the quality of the recorded data was very high and therefore ideal for further analysis.

With the recent introduction of the QTC VIEW classification system, an opportunity existed to replay the seismic data from the St. Lawrence through this advanced system to evaluate its performance with broad-band seismic rather than higher frequency sonar echoes for which it was originally designed. In a recent experiment, the seismic data was replayed to simulate, as accurately as possible, actual survey conditions. The recovered analog seismic signal was applied to the normal input terminals of the QTC VIEW system and processed in data collection mode also in real time. The results of the application of the normal sonar seafloor classification routines to this seismic data set are discussed briefly in this paper. Initial results indicate that river floor sediments can be classified in real time by their seismic response using this technique.

2. Equipment

2.1 The high resolution profiling system

The sound source used in the IKB SEISTEC™ high resolution profiler is an electrodynamic "Boomer" with produces a single positive pressure pulse with a peak amplitude of 216 dB//1μPa@1m and a pulse duration ranging from 100 - 140 μs (Figure 1). Spectral analysis of the far field pulse reveals that useful energy is available from this source from 1 kHz - 12 kHz. Although Boomers have been used in geophysical surveying for many years, shallow water performance was limited by the traditional "eel" receiving array since target echoes and signals often coincided. The receiver used in this system comprises a short 25 cm line hydrophone mounted axially in a fixed reflecting cone with a 62 cm circular aperture. This *line-in-cone* receiver is supported in a surface towed catamaran along with the Boomer source. The advantage of this configuration over traditional methods for shallow water surveying is that the geometry of the source and receiver is fixed and the combined acoustic response of the source and receiver is consistant over a wide range of operational conditions.

The directional characteristics of the Boomer coupled with a near matching response of the receiver means that very consistent echoes can be received in target water depths ranging from 1 to 200 m. Figure 2 is an example of an echo response obtained from a relatively flat area of the seafloor in shallow water. The system impulse response consists of a small amplitude precursor (+ve pressure), followed by a negative excursion, a single positive and a second negative excursion. This characteristic shape is useful for determining the phase characteristics of reflecting horizons. The overall bandwidth of the system allows for a vertical resolution between reflecting layers of 25 cm; a feature has that has recently been exploited in discriminating shallow faults in San Francisco Bay [6].

The normal arrangement for data recording is shown in Figure 3. The signal from the *line-in-cone* receiver is amplified before transmission to the surface where it is made available for recording and analog processing prior to imaging on a grey scale recorder or direct digital recording. On playback, either the raw or processed analog signal together with a synchronizing pulse corresponding to "time zero", the Boomer firing instant, are recovered from the DAT recorder and made available for further conditioning, processing and analysis. In this experiment, the unprocessed (Raw) signal was recovered from the DAT and applied to the QTC VIEW input terminals without any additional analog signal conditioning. A synchronizing pulse was also recovered from the DAT recorder to simulate the transmitter excitation pulse.

2.2 The QTC VIEW

The QTC VIEW is a seabed classification system designed for use with echo sounders with operating frequencies up to 220 kHz. The system consists of hardware package whose input is normally connected directly to the sounder transducer terminals. An accompanying software package running on a Personal Computer analyzes, displays and stores the acoustic parameters. In operation, the system automatically tracks the bottom echo, digitizes the echo and analyzes the resulting waveforms using multiple trace statistics and multivariate analysis.

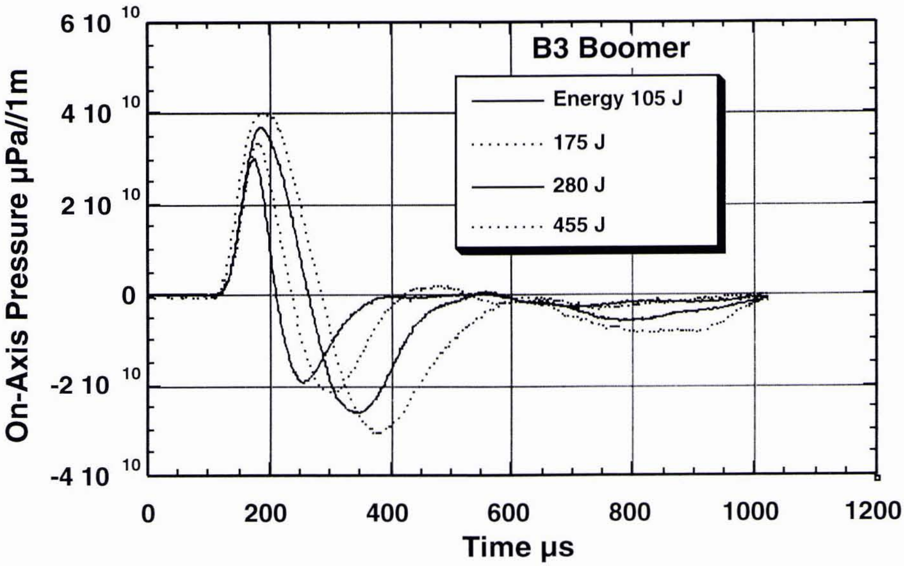

Figure 1. Output pressure signatures from B3 Boomer at different energy levels

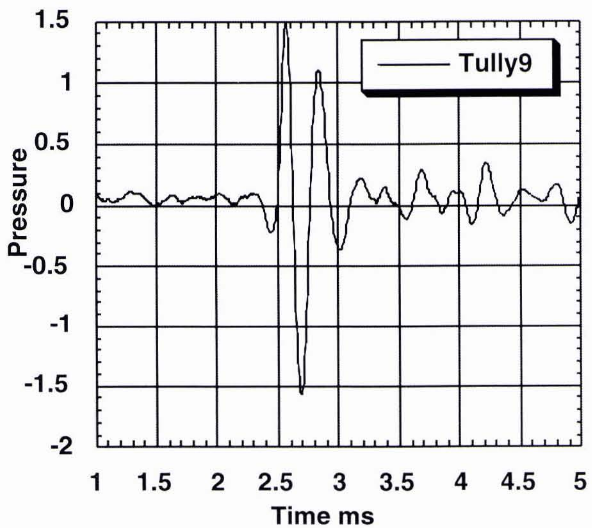

Figure 2. Typical seafloor echo from smooth surface (Inverted - positive pressure down)

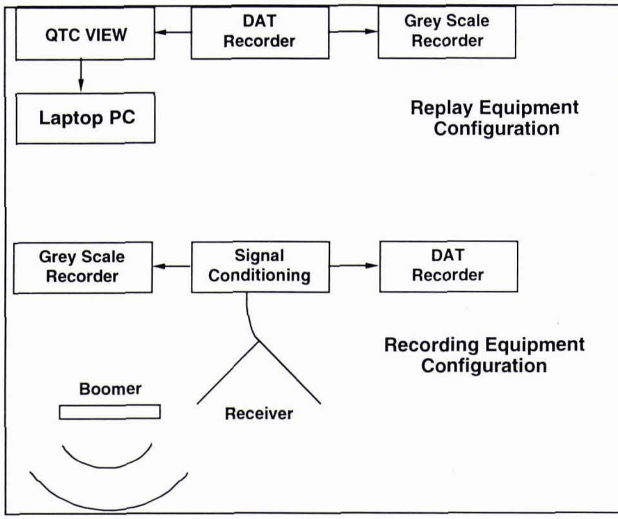

Figure 3. Schematic of recording and replay equipment configurations.

A sonar pulse impinging on a seabed is reflected and scattered at the seabed/water interface and the immediate sub-surface structure. The returned echo pulse contains components of the transmitted pulse (direct reflection) with the off-axis backscatter and volume reverberation superimposed. The shape of the returning signal is therefore influenced by the seabed roughness, the impedance contrast between the water and sediment and the volume reverberation of sound in the upper sediment layers. Thus, the combined response contains contributions from the physical properties of the water and seafloor material, the geometry of the sediment surface and the internal structure of the sediment all of which change considerable even over short distances in any dynamic environment. The bottom response, therefore, is highly variable and complex suggesting that a statistical analysis, applied to extracted parameters from multiple echoes, may be an appropriate method for differentiating and ultimately classifying sediments.

The seabed classification technique is comprised of the following processes: First a number of waveform shape descriptors are generated from each bottom echo. These are then reduced in number using a statistical analysis to determine those parameters which most usefully describe the echoes. These parameters are then used to classify logical groups of similar echoes into a dynamic, real time, 3 dimensional (colour) display.

The system can be applied in a supervised or unsupervised manner. Using a supervised classification technique, a series of sample echoes are collected from known seabed types. The information is compiled into a catalogue and used during subsequent real-time sea floor mapping. The system analyzes incoming echoes, chooses an acoustic class from the catalogue which most closely resembles the new echo, and provides an estimate of the confidence in the choice of class. It is the responsibility of the operator to relate the acoustic class to the physical nature of the seabed. An unsupervised approach utilizes a suite of tools which have been developed to analyze individual echo traces, extract the most useful information and logically group the total number of traces into a set of acoustic classes. The classification scheme is applied to the echoes with their associated geographic reference to classify sea floor sediments.

3. Geological Setting

The Gulf of St. Lawrence is the main drainage system for eastern Canada and the Great Lakes and an important shipping route for ocean going vessels. Between Montréal and Québec city, normal river flow conditions exist with the river flowing in a north-east direction. Although the river can be up to 5 km wide in places (Lac Saint-Pierre), for most of this region its width is normally less than 2 km. However, a relatively narrow navigable channel with a minimum depth of 12 m is maintained by dredging.

The 1995 seismic survey commenced at the port of Montréal where the river bed is composed mainly of glacial material or rock outcrop covered by a thin, mobile layer of silts and fine sand. From an acoustic viewpoint, the riverbed is "hard" and penetration using high resolution seismic profilers is limited to the surface mobile layer. However, further east the river sediments increase in thickness and are finer in composition. As one approaches Lac Saint-Pierre 80 km, north east of Montréal, the sediments are finer still with interbedded clays and silts being common. At the eastern part of Lac Saint-Pierre, less internal structure is seen in the upper sediment column indicating that fine to medium sands are present.

4. Data Reduction Methodology - Unsupervised Classification

The seismic data set replayed through the QTC VIEW consisted of 17 ten minute profiles selected from the original survey records. Each 10 minute section of data represents about 2.5 nautical miles and is composed from approximately 2000 individual echoes. The data were analyzed using unsupervised classification. Echo shape descriptors were generated from the entire data set. Each data record was reduced to three values representing the first three principal components of variance from the total data set.. All data were plotted and five distinctive acoustic classes associated with individual line sections were identified (Fig. 4).

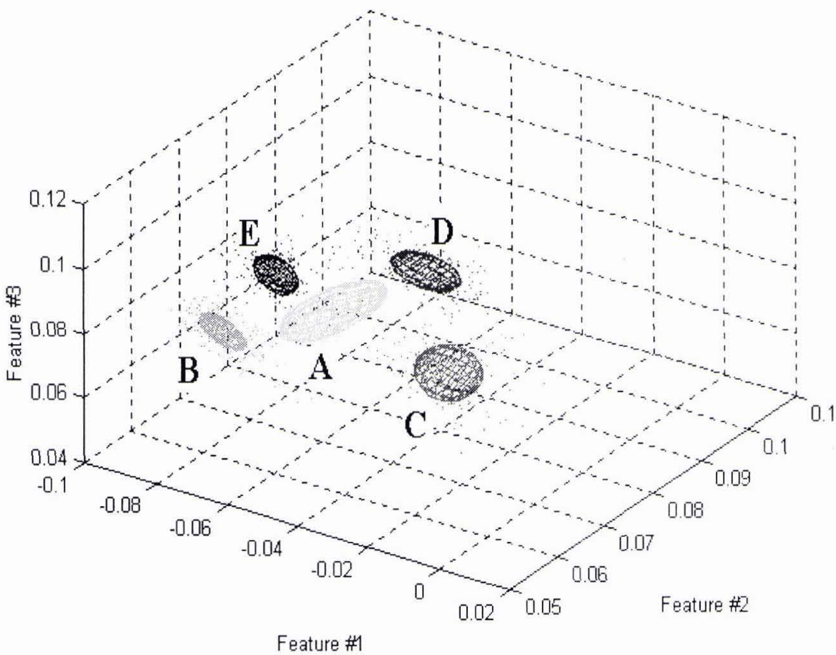

Figure 4. Plot of the three principal components from each data record. Clusters of points represent the five acoustic classes. Each ellipse is centered on the mean of each cluster and the wire mesh surface represents 1 standard deviation.

The original, unprocessed, hardcopy from the five profiles identified above were analyzed (Fig. 5). Five broad seismic facies were interpreted (Table 1). These data were compiled into a catalogue and used as the reference by which classify the seventeen original profiles of which two are discussed below.

Class	Description
A	Acoustically hard surface with much reverberant energy.
B	Rough surface topography - distributed gas curtain
C	Moderately rough surface with horizontal structure visibly all the way to surface
D	Very consistent section of softer sediments
E	Soft sediment with rippled surface

Table 1. Classification scheme used to describe the seismic data set.

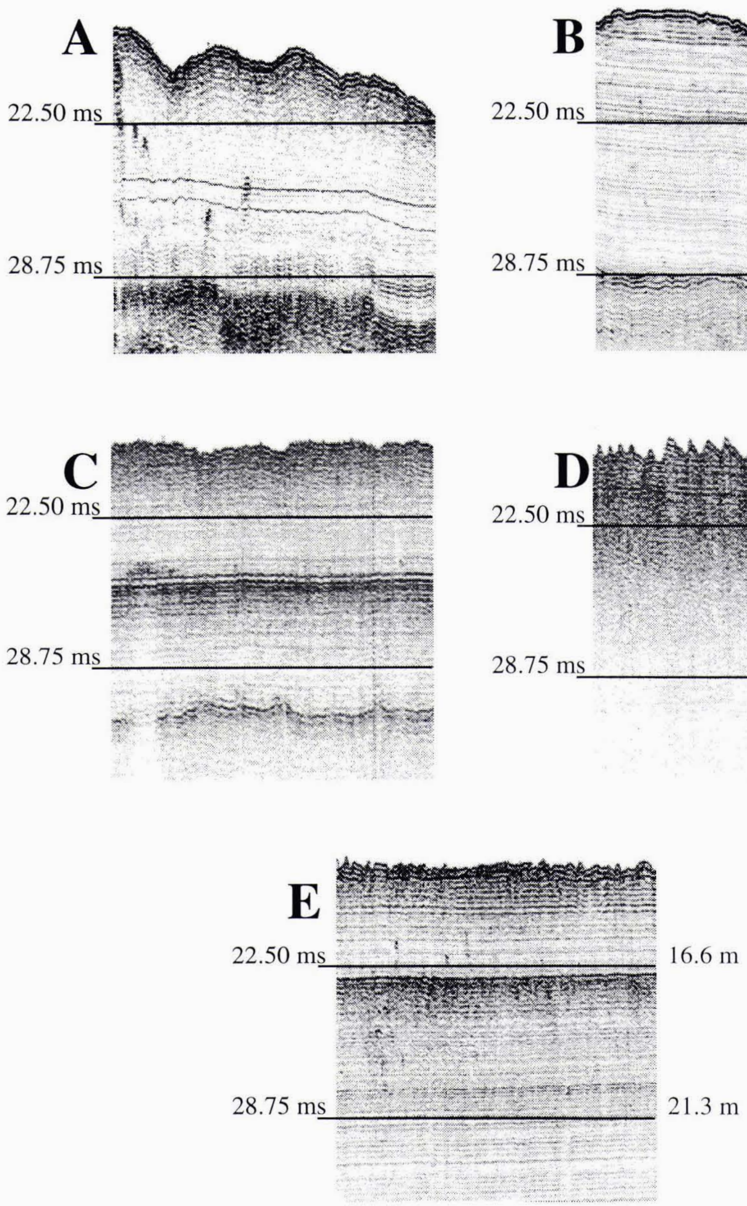

Figure 5. Seismic profiles from the five reference sections. The left hand scale is two-way travel time from the sea surface in milliseconds. The right scale on section E is distance in meters calculated with a sound speed of 1460 m.sec-1. Note the gas enhanced reflectors at 18.5 m in Panel C and at 17m in Panel B

5. Results

Initially, each of the five reference profiles were processed using the catalogue developed from the five reference profiles. As expected each of the sections were classified as having an acoustic signature similar to that class in the catalogue. One exception occurs where profile "A" contains a small number of echoes similar to that of Class "B". This is explained by recognising that each cluster of points from the reference profile has a relatively tight scatter but outliers may overlap with other classes.

When the reference catalogue processed profiles other than those used to generate the catalogue, the results are variable. Figure 6 is a ten minute section of data with the classification shown as a bar of various shades of grey representing the classification.

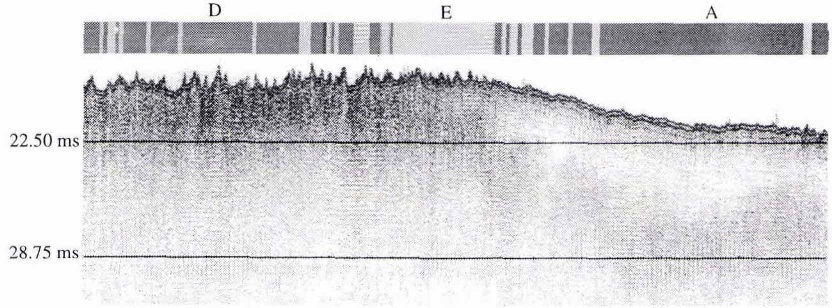

Figure 6. Seismic profile representing a ten minute section of data processed by the reference catalogue. The scale on the left is the two-way travel time to the sea surface. The bar at the top shows a shade of grey representing a class for the seabed directly below. Letters at the top of the bar indicate the class associated with the shade of grey below it.

The profile shows two distinct surface reflectors. To the left the section exhibits a high relief surface that is virtually free from reverberation. A gas curtain with associated 'gas brightening' has masked most subsurface structure and appears to be more defuse at the center of the section [7]. There is a distinct difference in the acoustic character of the bottom echo over the latter part of this section where the seabed has less relief and more immediate reverberation possibly indicating a coarse surficial sediment. This portion of the profile shows less gas near the surface and weak parallel reflectors are visible to approximately 3 ms of the seabed. The lack of a gas curtain to the right of the section also suggests coarser sediments.

The section was identified as having an acoustic response similar to class D initially followed by class E near the center and class A towards the end. The correlation between the first part of this profile and class D as seen in Figure 5 appears weak. There is a stronger correlation between the center portion of this profile and class E which shows slight relief on the surface of the seabed with little reverberation possibly indicating less dense material and gas brightening at depth. There is a high correlation with the latter portion of the section and class A which exhibits some reverberation at the sea bed surface and weak parallel reflectors. The class A reference section exhibits gas enhanced reflectors at depth.

Figure 7 is ten minute section of data exhibiting a more varied acoustic response. The section can be characterized in terms of surface scatter effects and a gas curtain at specific depths below surface.

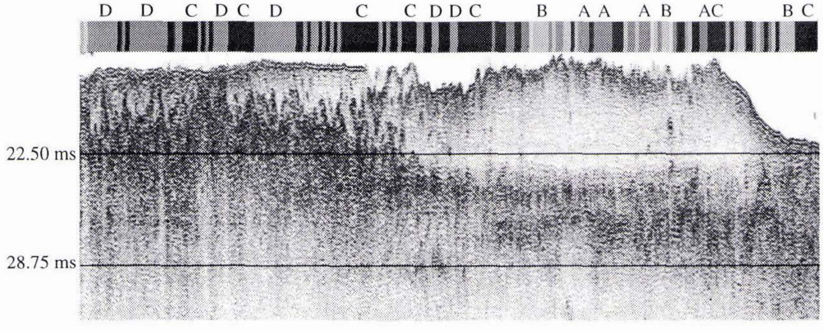

Figure 7. Seismic profile representing a ten minute section of data processed by the reference catalogue. The scale on the left is the two-way travel time to the sea surface. The bar at the top shows a shade of grey representing a class for the seabed directly below. Letters at the top of the bar indicate the class associated with the shade of grey below it.

The left side of the profile in Figure 7 has a relatively flat seabed with little surface reverberation suggesting a soft material. There is little shot to shot coherency except towards the end of the initial portion where surface reverberation may indicate a coarsening of the sea bed material. Gas appears to be diffuse in the near surface and increases at 2-3 ms below the sea floor. The highly undulating appearance of the deeper gas reflector, may represent off-axis response from gas charged sediments. The character of the sea floor changes just before the center of the section by exhibiting higher bathymetric relief and increased surface scatter. Weak parallel reflectors are observed in the sub-surface and gas near the base of the section masks any deeper structure.

The classification along this section consists of acoustic responses similar to classes A through D. In a broad sense the initial portion of the section contains class D and the latter portion contains classes A and B. Class C is represented throughout the section but is predominant near the center. There is a reasonable correlation between class D and the first portion of the section. Both exhibit weak surface reflectors and defuse gas. The correlation with class C is less clear and may be related to increased surface scatter effects. Classes A and B occur in the latter portion of the section with Class A exhibiting mixed correlation with very similar surface reverberation and weak parallel reflectors at depth, yet poor shot to shot coherency. At the very end of the section, class B correlated well with the reference section showing high reverberation at the surface and good shot to shot coherency of the immediate bottom echo.

6. Summary and Conclusions

The purpose of the experiment was to evaluate the application of statistical based seabed classification techniques to sub-bottom profile data. The *line-in-cone* receiver and fixed geometry of the SEISTEC profiler provides certain advantages in consistency of data to allow detailed statistical treatment of sub-bottom seismic data to proceed. The results indicate a certain level of repeatability with the data set in that the five original reference sections were identified and classified properly when reprocessed independently of the reference catalogue.

The success in the classification of other processed sections independant of the reference profiles was variable. For seabeds with minimal shot to shot echo coherency at the seabed, the success was limited whereas other seabeds exhibiting strong coherent surface reflectors were classified correctly. The success rate could probably have been improved by more closely constraining the time window being used for processing and analysis. In addition, the selection of a ten minute section as a data window may have contributed to added biases and uncertainties. In some cases, there was a degree of variability along these reference sections which would have influenced the choice of useful acoustic parameters and limit accurate classification.

Since the analysed seismic signal is influenced by sub-seabed structure as well as the physical properties and surface geometry of the seafloor, we must conclude that where the sub-bottom characteristics change significantly, we can expect errors in classification. Shallow gas, which appears in the seismic sections in various forms:- as defuse reflectors, brightened reflectors or coherent layers at various depths, demands special consideration. Not only are the gas charged sediments highly variable in terms of their acoustic reflection characteristics but gas enhanced reflectors produce echoes with very high amplitudes relative to normal sub-bottom reflectors. These high amplitude yet delayed reflectors could dominate the classification process particularly in the softer sediments where gas often accumulates. We must therefore consider using shorter windows at various depths when future seismic data is being processed in this manner.

7. References

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