Sediment Classification Based on Repetitive Multibeam Bathymetry Surveys of an Offshore Disposal Site

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***Abstract* - A disposal site near Saint John, NB, Canada, has been surveyed at six-month intervals for the past three years with Simrad EM3000 multibeam bathymetry systems. Analysis of the bathymetry data from surveys in the autumn show accumulation of sediments over the site due to disposal activities in the summer and autumn; surveys in the spring show that the sediment has undergone transport and redistribution due to the effects of currents and waves over the winter months. Quantitative measures of sediment accumulation and erosion have been made and show definite changes in the nature and distribution of the disposal pile. Acoustic backscatter data collected simultaneously with four of these surveys were analyzed with the QTC MULTIVIEW™ software, which segmented the multibeam sonar images into six regions of homogeneous acoustic character. The Multiview process leading to the six classes is described. Seafloor grab samples and photographs were used to characterize these acoustic classes physically. The depths and the classes were interpolated onto the same grid to allow subtractions and comparisons. Interpolating classes was done with a categorical interpolation process. Comparisons among the sequence of maps of acoustic classes show the spreading of new spoils and consistent seasonal changes over large areas. Because high-frequency backscatter depends heavily on surface conditions, seasonal changes in the local hydrodynamic regime could be responsible for these changes in acoustic character.**

BLACK POINT OCEAN DISPOSAL SITE

Introduction

For over 40 years, the Black Point Ocean Disposal Site has been used as a disposal area for material dredged from shipping channels and around the wharves in Saint John Harbour, New Brunswick, Canada. The disposal site (Fig. 1), in an exposed location in the harbour approaches, is affected by strong currents induced by the outflow of the Saint John River, the high Bay of Fundy tides, and waves from winter storms. Previous studies indicate that disposal activities have resulted in a buildup of sediment at the disposal site, while a considerable portion of the dumped sediment has been transported away from the site.

In 1999 a joint research program was initiated between Environment Canada and the Geological Survey of Canada to define the zone of influence of the disposal activities; to assess the physical, chemical and biological impacts caused by disposal activities; and to evaluate the long-term use of the site. The study confirmed the buildup of material at the main disposal site and erosion of dredged material during the winter storms. The magnitude and direction of dredge spoil dispersion and the biological impacts of the dumping activities were investigated.

A geophysical survey in May 1999 collected data to provide information on the geological attributes of the disposal site and the geological and oceanographic processes effecting material placed in the offshore disposal sites [1]. Sediment samples were collected and over 200 bottom photographs were taken along transects through the survey area to provide information on the nature of seafloor materials.

Between April 2000 and September 2002 a series of six multibeam bathymetry surveys was performed to provide detailed bathymetric and backscatter information over the disposal site. Surveys were performed in the spring, before dredging had commenced, to determine the condition of the disposal site after the winter storms that frequent the area. Surveys were also performed in the fall, during or immediately after dredging to determine sediment accumulation from disposal activities [1]. The multibeam bathymetry survey in October 2000 was performed concurrently with dredging operations, which involved five small self-unloading barges and repeated trips to the Black Point disposal site. Current velocity data were collected over the disposal site with a RDI acoustic Doppler current meter and with InterOcean S4 current meters moored near the site [1,2].

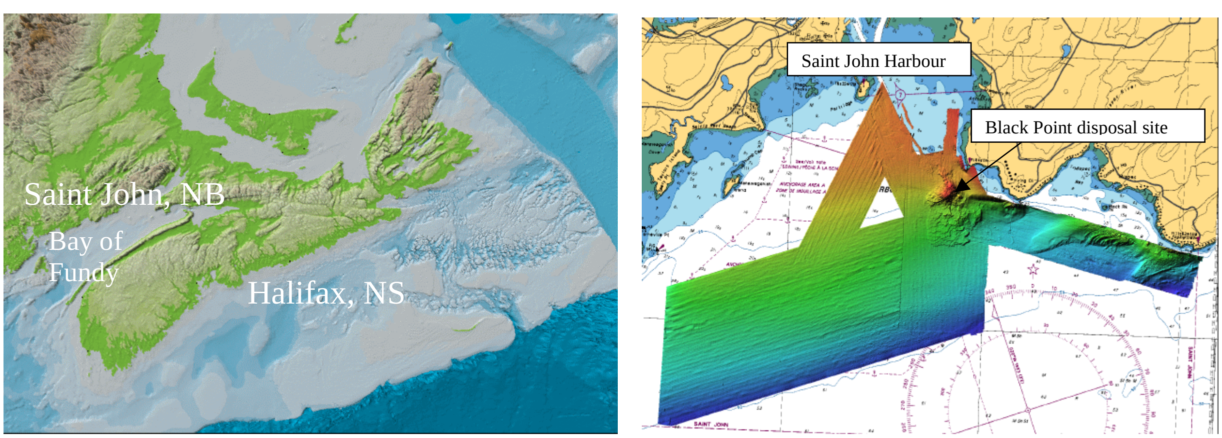

Fig. 1. Left: Location of Saint John, New Brunswick, on the east coast of Canada.
Right: The Black Point Ocean Disposal Site in the harbour approaches with shaded relief image generated from Simrad EM3000 multibeam bathymetry data collected in 1994, 1999, and 2000.

Geology

Fader et al. [3] mapped the seafloor in the area of Saint John Harbour as a silty sandy clay and clayey sandy silt grading locally to silty clayey sand (more that 20% sand). These modern fine-grained sediments overlay glacial debris (mainly till) and glaciomarine silt, and in turn occur over Triassic sandstone bedrock. In transgressed areas above the Pleistocene low stand of sea level (interpreted to occur at about 60 m present depth), the glacial deposits have been winnowed to produce a sand and gravel unit. Below the Pleistocene terrace, the glacial debris was modified by strong current action in the Bay of Fundy.

Oceanography

Twice daily, volumes of water in excess of 96 km^3 move in and out of the Fundy embayment [4]. The Atlantic Ocean tides increase in range as they propagate through the Gulf of Maine into the Bay of Fundy. Tides of 8 m are encountered near Saint John, and at the head of the Bay of Fundy the maximum range in elevation between high and low water is about 16 m. The abnormally high tides result from the near resonance between the semidiurnal tides and the natural oscillation of the water in the Bay of Fundy-Gulf of Maine system. Further amplification of tidal heights occurs in the upper Bay of Fundy where rapid narrowing and shoaling take place.

Wave-current meters were deployed at several locations near the Black Point disposal site, and the results used to assess near-bed wave-current processes. The field measurements were then used to develop and calibrate a 2-dimensional hydrodynamic tidal model. The results from the tidal model, as well as grain size and high-resolution bathymetry data, were input to the GSC sediment transport model SEDTRANS [5] to predict the potential frequency, magnitude, and direction of sediment transport at the deployment sites [6]. Results show that the seafloor in the area around the disposal site is very dynamic. Peak mean tidal currents reach 0.6 m/s and are generally to the east at peak flooding and to the west at peak ebbing. The sediment transport model predicted that fine sand sediment at the disposal site could be mobile throughout 54% of the tidal cycle. Clays and silts could be in transport for up to 70% of the tidal cycle. Model results also showed that transport rates in a one-year storm could be 1-2 orders of magnitude higher than tidal rates.

MULTIBEAM BATHYMETRY SURVEYS

The data analyzed in this work were collected with a Simrad EM3000 multibeam bathymetry system mounted in the Canadian Hydrographic Service survey launch *Plover*. The EM3000 system uses a 300 kHz transducer with 127 beams with a beamwidth of 1.5^o x 1.5^o. It provides a depth resolution of 1 cm with an accuracy of 5 cm RMS.

Lines were run using various spacing throughout the survey area to provide overlapping coverage of the seafloor. This technique provided redundant data throughout the survey area (about 200% coverage of the seafloor in depths greater than 20 m) and allowed greater emphasis to be placed on the inner beams during bathymetric processing, providing higher resolution data. Data were processed using a suite of software, to correct for tidal variations, and to remove spurious soundings and navigation data. Shaded colour relief images were generated and overlaid on geographically referenced bathymetry charts of the area as shown in Fig. 1. Depths ranged from 5 m in the north to 35 m in the south. This image shows that much of the seafloor in the western approaches to Saint John Harbour appears relatively smooth. A large accumulation of dumped material is evident at the Black Point disposal site.

Preliminary analysis of geophysical and multibeam bathymetry data from the disposal site has confirmed that material dumped at the site has failed and this process has formed a slump that extends about 1.5 km south of the disposal zone.

ACOUSTIC SEDIMENT CLASSIFICATION

QTC MULTIVIEW™ (Quester Tangent Corporation) was used to classify sediments in the area affected by dumping operations. Of the surveys described above, four data sets, from the spring and fall of 2000 and 2001, were classified. Fig. 2 shows the seven Multiview classification steps [7].

1. Load raw data

The files logged on the survey launches were Simrad raw.all files. Multiview extracts the depth, seabed image, and position datagrams, plus some runtime parameters, from these files, and builds internal .sonar and .nav files.

2. Quality control

Just as it is important to set aside bad depth picks in bathymetric processing, careful quality control of the backscatter data is also essential. If the picked depth in a beam is unreasonable, the backscatter amplitude is unlikely to represent the bottom. Two cleaning processes are available in Multiview for identifying bad beams, which are then masked and thus set aside. The better process is to import from Caris HIPS™ the list of bad beams (with their ping numbers). Clearly, this is applicable only if HIPS was used for data cleaning. The quality of these surveys was found to be high, with less than one bad beam per ping. With high-

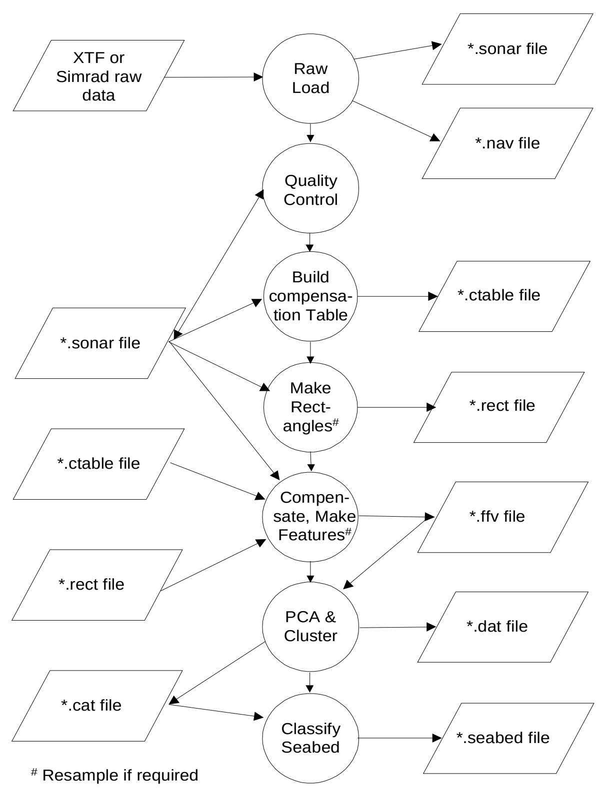

Fig. 2. The seven primary steps in QTC Multiview.

quality surveys a second technique is often sufficient, namely to identify bad beams based on depth differences from their neighbours. The second process was used in this work. A beam was masked if the square of its depth difference from the mean of its neighbours exceeded 150 times the standard deviation of depths in the same neighbourhood, with all depths in centimetres.

3. Compensation

Backscatter amplitudes depend on sediment type, grazing angle, and range. The dependence on the last two must be removed for useful classification. Simrad uses a two-part TVG to compensate for beam depression angle and range. Depression angle is only an approximation to grazing angle, however, and absorption is not fully considered – in short, there are a variety of effects that, if not controlled by further compensation, can cause artifacts in sediment classes. These artifacts usually appear as class borders parallel to the ship track, and are called range dependence (even though the main cause may be angular). Controlling this range dependence is perhaps the biggest challenge in developing a multibeam classification system.

Adaptive algorithms that make image brightness appear to be independent of range are in common use with side scan and multibeam images. They are not appropriate for preparing an image for classification because the amplitudes in a ping must not depend on its neighbours. Hellequin [8] achieves good results with compensation techniques based on backscatter theory. In contrast, the Multiview approach is phenomenological [9]. A large fraction of the data set is surveyed to populate tables organized with two independent variables: grazing angle and travel time, divided into bins typically 1° and 1 ms wide. Grazing angles are calculated by fitting tangent planes to depths in the neighbourhood of each beam footprint. Three compensation tables are populated, with the number of amplitudes in each angle-time bin, the sum of their amplitudes, and the sum of the amplitudes squared. In the compensation step, the tables are used to correct all amplitudes to zero mean and unit variance for the appropriate bin of grazing angle and range. Multiview does the compensation process in the background, without user action or additional steps.

4. Place Rectangles

Rectangular patches are distributed over the unmasked regions of the backscatter image. The matrix of amplitudes in each patch leads to one data point in the final classification map. Usually the along-track pixel spacing exceeds the

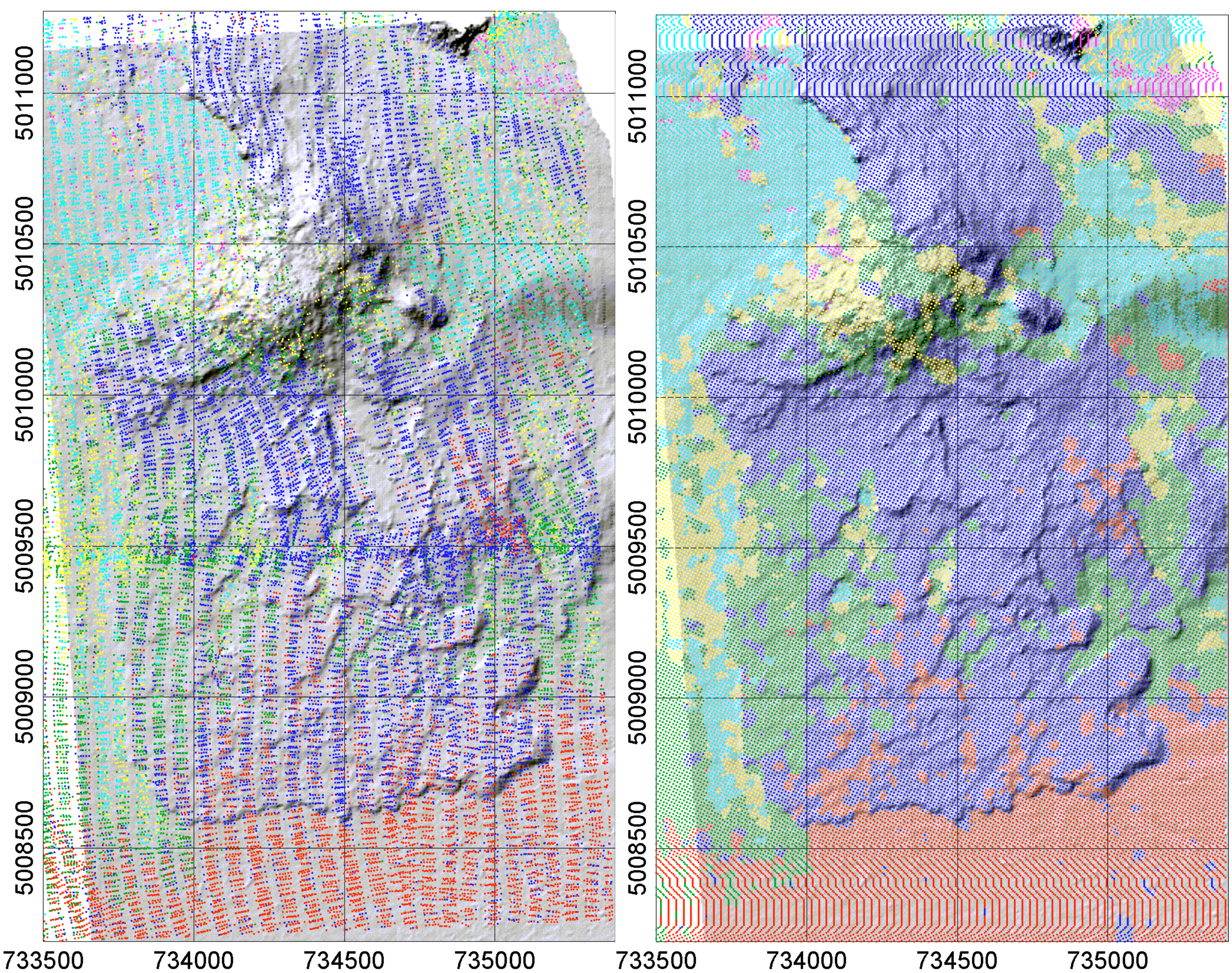

Fig. 3. Classification results from the backscatter images acquired in Apr 2000 overlaid on sun-illuminated bathymetry from the same survey. On the left are the six Multiview classes, obtained from line data and positioned along the survey lines. The right figure shows class markers interpolated to 5 m grid spacings. So that the bathymetry can be seen only every fifth point is plotted, which causes some Moiré patterns.

across-track, so one chooses rectangles with more pixels across- than along-track, so the corresponding bottom area is roughly square and at the desired spatial resolution. In this work, the rectangles were 129 x 17 pixels, that is, 129 across-track samples by 17 pings. In this survey, this was typically about 5 m x 12 m. In the shallow north part there were two or three patches to port and to starboard every 17 pings, with up to six or seven in the south.

5. Feature generation and PCA

Statistical features [7] are generated from the 129 x 17 backscatter amplitudes in each rectangular patch of each line of the survey. The feature algorithms are based on published methods for seabed discrimination in images [references in 7]. To be included in Multiview, each family of features had to been shown to provide useful discrimination in some, at least, circumstances. A large number of features, 127, can be used because principal components analysis (PCA), in the next processing step, will select those combinations of features best suited to particular data sets. To do so, features from several lines, often from entire surveys, are merged before PCA. Repeatedly it has been found that, of the variance of the entire data set, a large fraction, often more than 90%, was captured in the first three principal components. Only the first three components are kept and used for classification, in which they are called Q1, Q2, and Q3.

6. Clustering

Classification of the sea bottom that gave rise to these features is done in the space of the three Q values. Starting with all records assigned to the same class, a variant of the k-means clustering method segments them into clusters, which become the acoustic classes. Each record, originating from the amplitudes in a rectangle, is assigned to the closest class centre in Q space in a process that is iterative and stable. Each cluster represents an acoustically distinct region of the bottom.

In most clustering methods, Euclidean distances are used to determine closeness in Q space. In acoustic classification, natural clusters are rarely spherical, however, so Multiview measures distances in units of cluster standard deviation along the line between the record and the centre, the Mahalanobis distance. Using this metric requires that the k-means iteration run inside another loop, called k-stats, that determines the cluster statistics. Another term in the metric used in Multiview for clustering is the population of the cluster from the previous iteration of k-stats. Clustering in Multiview can be described as a maximum-likelihood Bayesian approach based on an underlying Gaussian multi-modal model. More background on these approaches to QTC clustering may be found in [10,11].

QTC clustering starts with all records in one cluster. The user decides which cluster to split, in which direction, and when to stop splitting, guided by statistical indicators of how well the clusters match the underlying Gaussian model. Each split was chosen to minimize this statistical score at that step. Splitting was stopped at six classes, because further splits reduced this score only marginally compared to previous splits.

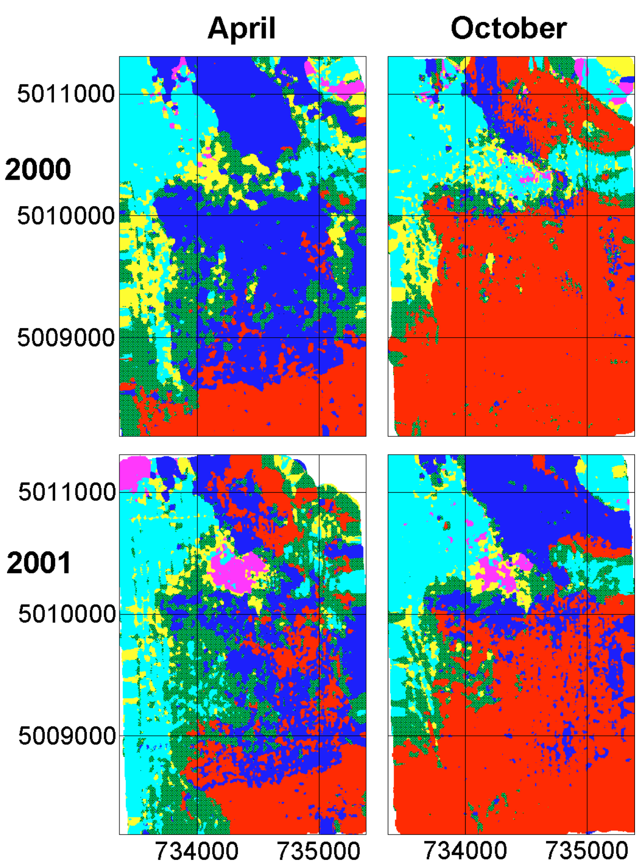

Fig. 4. Maps of classes assigned by QTC Multiview based on acoustic diversity. An unsupervised process gave the six classes for 2000 and the catalogue used to classify the 2001 backscatter images, so class numbers and colours are consistent across all four surveys. Positions are UTM, NAD 83, zone 19.

7. Classify Seabed

The main use of this step is classifying new data with a catalogue that was built in the clustering step.

Unsupervised Classification

Statistical methods are used for acoustic sediment classification because inversion of models of high-frequency backscatter is possible only in specialized situations. Given a full geophysical description of the bottom, as well as knowledge of the sonar, the echo time series can be calculated. However, the reverse does not give unique results. One therefore either uses prior descriptions of the sea bottom to do supervised classification based on similarities between echo characteristics, or segments the survey area into regions of similar acoustic character, which is called unsupervised classification. QTC Multiview, while capable of both operations, was designed primarily for unsupervised classification. When a data set is classified in this way, Multiview gives not just class assignments but also a catalogue containing the parameters needed to classify other data sets consistently. In this case, the surveys done in 2000 were classified unsupervised and the resulting catalogue was used to classify the data recorded in 2001. This process yielded six classes across all four surveys, consistently segmented by acoustic character.

Sediment Classification of the Black Point Area

The six classes based on acoustic diversity, from the Apr 2000 survey, are shown in Fig. 3. Multiview classifies line-by-line, using information such as slant range and grazing angle for compensation and other purposes. The number of classified data points to port and to starboard varies with depth, because depth controls the number of across-track samples and thus how many rectangular patches can be placed on that part of the image. The backscatter amplitudes in each patch lead, through the seven steps described above, to a single classified point. In this work, there were usually

TABLE 1

VOLUME COMPARISONS

Volume change from bathymetry	
Apr 00 – Oct 00	-0.32
Oct 00 – Apr 01	-0.19
Apr 01 – Oct 01	+0.29
Recorded dumping	
Oct 00 – Apr 01	0.27
Apr 01 – Jul 01	0
Aug 01 – Nov 01	0.27

Units are millions of cubic metres.

between three and seven points each side, with a gap directly under the ship because pixels are more widely spaced there.

To compare classification maps among the four surveys, the classified points had to be put onto the same grid. This was done with an interpolation routine for categorical data that selects all the classified points within a search radius, optionally weights them based on distance, and assigns the most common class to that grid point. These results are shown in the right-hand plot of Fig. 3

Gridded class assignments for the four surveys classified here: April 2000, Oct 2000, April 2001, and Oct-Nov 2001 are shown in Fig. 4. The consistency between the spring surveys and between the autumn surveys is striking, while classes in the northwest quadrant are similar in all four surveys.

Two EM 3000 transducers were used in these surveys, specifically #113 in 2000 and #106 in 2001. Multiview segregates data and files according to serial number. This clearly is required for compensation, because identical calibrations cannot be assumed. Could images from the two heads be classified together? Two answer this, the two data sets, 2000 and 2001, were classified separately, following parallel unsupervised classification paths. In addition, as described above, the 2001 data was classified with the catalogue from unsupervised classification of the 2000 survey. The two classification maps were virtually identical. This shows that Multiview is robust to the minor deviations in pulse length, beamwidth, and the like that presumably exist between these two sonar heads.

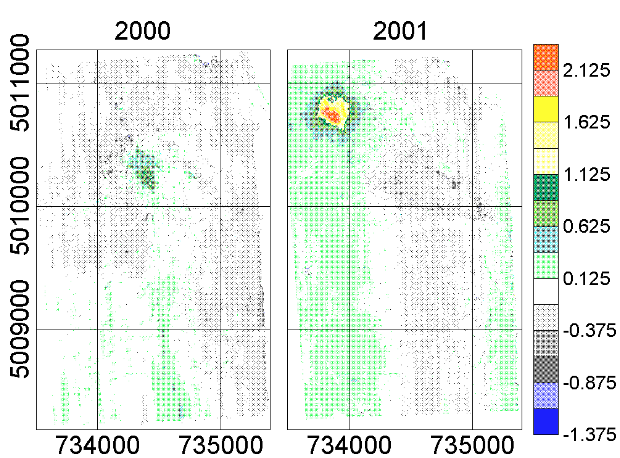

Fig. 5. Shaded contour plots of the depths in October of each year minus those of that April, corrected for mean systematic error. The separation between contours is 0.25 m.

TABLE 2

BOTTOM PHOTOGRAPHS IN AREAS OF THE SIX CLASSES

#	Colour	Description
1	Red	Silt, some pebbles
2	Green	Silt (low visibility)
3	Blue	Silt, some pebbles, few small rocks
4	Cyan	Silt, plentiful pebbles
5	Yellow	Silt (low visibility)
6	Magenta	No photographs in any Class 6 area

RESULTS

Changes in Bathymetry

The depth data allow changes in seabed volume between surveys to be estimated. Of primary interest are the changes during the disposal season and comparisons to volumes dumped. Before subtracting, depths were interpolated to the same 5 m grid as the classes and systematic errors due to vertical datums or other issues associated with the large tidal range were removed. Subtractions and integrations over the area shown in these figures then gave the estimates of volume changes in Table 1. It is noteworthy that in the summer of 2000 there was a net loss of sediment in spite of dumping.

Maps of these bathymetric differences show the sites of major disposal activity in the two summers. Fig. 5 shows contour plots of height differences between spring and autumn surveys for 2000 and 2001. Remnant systematic error can be seen, indicating the challenge of full tidal correction with a range of up to 8 m. The centres of dumping activities in the two years were about 0.7 km apart.

Physical Descriptions of the Acoustic Classes

Physical attributes of the acoustic classes were

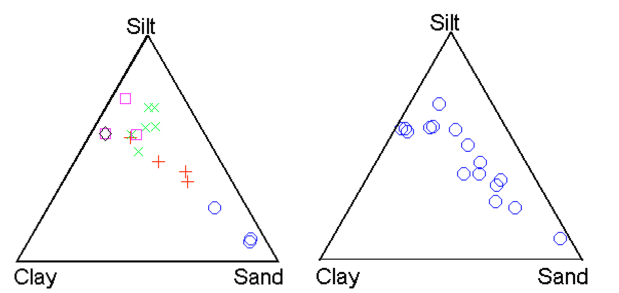

Fig. 6. Grain sizes in 34 grab samples. Samples from acoustic classes 1, 2, 4, 5, 6 on left as o, +, x, □, ◊ respectively; from class 3 on right.

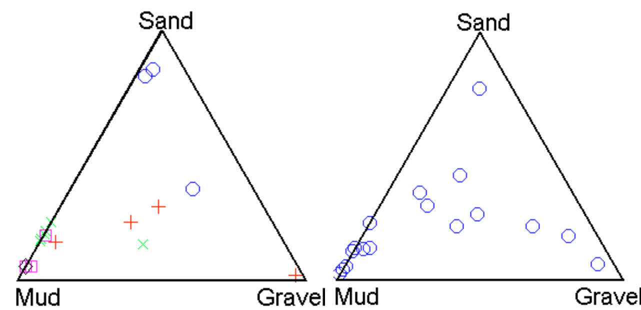

Fig. 7. Coarse grain sizes in 34 grab samples. Samples from acoustic classes 1, 2, 4, 5, 6 on left as o, +, x, □, ◊ respectively; from class 3 on right.

determined by examining seafloor photographs taken 75 cm above the bottom and from grain-size data. Table 2 summarizes the photographic observations. Suspended sediment reduced visibility in some photographs.

Grain sizes were measured from grab samples obtained with a vanVeen sampler. By using extra weights and lowering gently, the sediment was retrieved with little disruption. The grain-size results, as fractions of sand, silt, and clay, are shown in Fig. 6, for each acoustic class. Class assignments are the class at the location of the grab in the April 2000 class map. Each of classes 1, 2, 4, and 5 can be associated with a region of this ternary diagram. (No statement can be made about class 6 as there is only one sample.) Class 3, though, as shown in the right-hand plot, includes a wide silt to sand spectrum.

The same data, based on the same grab samples, are plotted as fractions of mud, sand, and gravel in Fig. 7.

There is a correlation between distribution of grain sizes and acoustic classes 1, 2, 4, 5. These classes trend, in numerical order, from coarse material to fine, with, perhaps, some overlap between classes 4 and 5. Acoustic class 3 shows no correlation with material size as captured in the vanVeen grab sample. By relying on PCA, the Multiview process emphasizes diversity based on seabed acoustic components that exhibit the most variability. In this area, grain size can account for most but not all of the classes, so one can infer that the seabed diversity is driven by sediment particle size. Other seabed features, such as bedform, porosity, and the presence of organic material, can also influence the backscatter and thus affect the assignments of points to classes.

Changes in Sediment Classes

After each summer, Class 4 (cyan) expanded notably around each disposal centre. The expansion is more obvious in 2000 because the centre of dumping activity that year was in a region of Classes 2, 5, and 1, while in 2001 it was mostly Class 4 even in April. These expansions can be seen clearly in Fig. 8. To make this figure for each year, the gridded class assignments for each survey were searched to find the locations that were Class 4 in October and which class each location was in April. All these points are plotted, coloured according to the April class that was transformed to Class 4 during the summer.

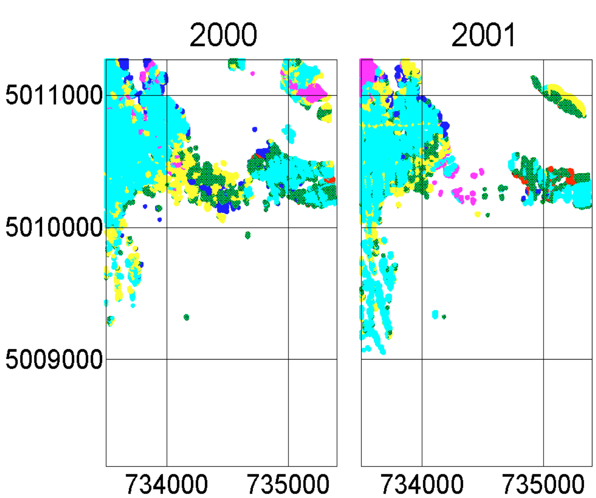

Fig. 8. Maps of sediments that became Class 4 (cyan) in the October surveys. Class colours are as given in Table 2.

Detailed examination of spring digital terrain models near the dump site before dumping in 2000 reveals ridges and valleys of old spoil material. In the same area the acoustic classes were mixtures of classes 2, 5, and 1, arranged in a similar manner. After the season's dumping, the valleys were, in general, filled with new material, and the acoustic class in the area was predominantly class 4.

The most striking changes in Fig. 4 are the consistent spring-autumn changes. The slump is classed acoustically primarily as Class 3 in the spring and Class 1 in the autumn. Each summer, particularly in 2000, and in similar patterns, large areas converted from Class 3 to Class 1. Acoustic character can change as sediments migrate and as the seabed conditions change because of biological action or hydrodynamics. Causes for the changes found here cannot be assigned clearly because the ground truth data are limited and were taken only in the spring.

DISCUSSION

At 300 kHz, the sonar frequency of the EM3000, the backscatter depends primarily on surface conditions, both impedance and roughness. Dredged sediment generally has a reflective and rough surface after dumping, making it distinct acoustically from natural fine-grained seabed. In this work, we did not find a distinct class corresponding to new spoils. However, the Black Point dump site has been active since 1958, so new spoils are dumped atop old spoils. According to the transport model, all the fine-grained sediments are mobile during much of each tidal cycle. One would therefore expect that the surface roughness of freshly dumped material would soon conform to the roughness of material dumped in previous years, and thus that new material would not retain distinctive acoustic character for more than a few days. In these results, newly dumped material appears as an enlargement of class 4, rather than as a separate class, consistent with this model.

The seasonal class changes may be due to a mobile veneer of fine sediments over the slump. Another possible explanation is seabed changes, which are more likely to be caused hydrodynamically than biologically, given the absence of biological observations in the photographs. Either explanation would be driven by seasonal currents and by wave action.

Compensating backscatter amplitudes for range and angular effects is crucial to classifying seabeds without range-dependent artifacts. The classes taken directly from Multiview, such as in Fig. 3 left, are almost free of range dependence, showing that this compensation technique is effective. Furthermore, there is quite good agreement between classes obtained on east-west lines and on north-south lines where they cross. Classes at track crossings should always agree if the seabed is isotropic. However, where currents have built ripples or waves, the images often depend on the horizontal angle between the sonar beams and the crests. Currents in this area are primarily east-west, so some dependence of class on sonar viewing angle was to be expected.

CONCLUSIONS

QTC MULTIVIEW™ was used to classify the sediments on and near a dump site based on acoustic diversity. Backscatter amplitudes from four data sets collected by two Simrad EM3000 multibeam systems were classified, with survey dates six months apart. The Multiview classes were reasonably consistent seasonally, yet showed interesting changes that seem to depend on seasonal hydrodynamic regimes. During the dumping season, sediment classes at the major disposal locations changed consistently with the history and hydrodynamic conditions of the dump site. This showed that EM3000 survey data are sufficiently reproducible that comparisons between repetitive surveys can give useful and practical results and that Multiview can be used to track changes in sediment classification.

Distinct sonar heads were used in the two survey years. Classes from the surveys with the second head were almost identical whether classified with the Multiview catalogue from the first head or independently.

Categorical interpolation, that is, interpolation with class numbers as distinct from continuous variables, is both useful and effective. Interpolated acoustic classes, such as in Fig. 3 right, can be compared among surveys to assess seasonal or other changes.

Seasonal surveys of this area were done in 2002 and are continuing. Analyses of these new data may well provide confirmation and insight into the seasonal changes reported here.

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