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Seabed classification of the Navy's exercise area in the northern North Sea

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English summary

The propagation of sound from ships, explosive charges and sonars is dependent on both topography and the geoacoustic properties of the seabed at low frequencies or in shallow waters. Information about the seabed is therefore of importance in military operations at sea. The Norwegian Defence Research Establishment (FFI) has for decades been doing hydrographical surveillance in prioritized areas. In connection with this work, FFI has also acquired acoustic single beam echosounder data and sediment samples from the seabed.

In this report we have studied single beam data in order to characterize and classify the seabed using commercial software. The area of interest is the Navy's exercise area in the northern North Sea dedicated for testing and evaluation of the new, Norwegian frigates. We have taken a 40 gravity cores and 37 grab samples to provide physical sediment samples from the seabed, which assists the interpretation of the acoustic data [1;2]. Seismic investigations have also been carried out [3].

To conclude, the seabed classification results are supported by the ground truths and seismic profiles of the upper layer of the seabed. Our study indicates that five sediment classes are enough to represent the seabed in the Navy's exercise area in northern North Sea. The dominant sediment types of the five classes found are

1) mainly silt with some clay
2) a mixture of clay, silt and sand
3) mainly sand, with a mixture of clay, silt and gravel
4) sand with varying amounts of gravel
5) mainly clay, with some silt and varying amounts of sand

A preliminary electronic bottom type map with the seabed classification results has been delivered the Navy. Additional data acquired in 2008 and processing of data from 2005 requires the bottom type map to be updated in agreement with the results presented in this report.

The report suggests further work regarding bottom sampling, video observations of the seabed, production of electronic maps of sediment velocity and density, and testing of other seabed classification tools.

Sammendrag

Utbredelsen av lyd fra skip, eksplosive ladninger og sonarer er avhengig av både topografi og havbunnens geoakustiske egenskaper ved lave frekvenser eller i grunne farvann. Informasjon om havbunnen er derfor viktig i militære operasjoner til sjøs. Forsvarets forskningsinstitutt (FFI) har gjennom tiår foretatt hydrografisk kartlegging i prioriterte områder. I forbindelse med dette arbeidet har FFI også logget akustiske data fra enkeltstråleekkolodd og tatt sedimentprøver av havbunnen.

I denne rapporten har FFI studert enkeltståledata for å karakterisere og klassifisere havbunnen ved hjelp av et kommersielt dataverktøy. Området av interesse er Forsvarets øvingsfelt i den nordlige delen av Nordsjøen, som er dedikert testing og evaluering av Norges nye fregatter. Omfattende kartlegging av havbunnen er gjennomført og FFI har tatt et stort antall kjerneprøver og grabbprøver for å skaffe fysiske sedimentprøver av havbunnen til hjelp i tolkningen av de akustiske dataene [1;2]. Seismiske undersøkelser er også foretatt [3].

Konklusjonen er at resultatene fra havbunnsklassifiseringen støttes av sedimentprøver fra havbunnen og seismiske profiler av det øverste laget. Vår studie indikerer at fem sedimentklasser er nok for å representere havbunnen i Forsvarets øvingsfelt i den nordlige delen av Nordsjøen. De fem dominerende sedimenttypene er:

1) Hovedsakelig silt med noe leir
2) En blanding av leir, silt og sand
3) Hovedsakelig sand, iblandet leir, silt og grus
4) Sand med varierende mengde grus
5) Hovedsakelig leir, med noe silt og varierende mengde sand

Et foreløpig elektronisk bunntypekart som viser klassifikasjonen av havbunnen i øvingsfeltet er levert Marinen. Ytterligere kartlegging av området i 2008 og prosessering av data fra 2005 krever at bunntypekartet oppdateres i samsvar med resultatene presentert i denne rapporten.

Rapporten foreslår videre arbeider innenfor bunnprøvetaking, videoobservasjoner av havbunnen, produksjon av elektroniske kart som viser sedimenthastighet og tetthet, og testing av andre verktøy for havbunnsklassifisering.

Contents

Preface

The work reported here is done under the FFI project Poseidon, which terminates December 2008.

1 Introduction

Information about the seabed is of importance in prediction of sonar performance in military operations at sea. The Norwegian Defence Research Establishment (FFI) has for decades been doing hydrographical surveillance in prioritized areas of the Barents Sea and off the coast of Norway. In connection with this work, FFI has acquired acoustic single beam echosounder data. In this report FFI has studied the backscattering from the single beam data in order to characterize and classify the seabed. The main objective with the work reported herein is to present a map showing the seabed with different sediment classes.

The area of interest in this report is the Navy's exercise area in the northern North Sea dedicated for testing and evaluation of the new, Norwegian frigates. The area is limited by the coordinates 59°30'N, 61°00'N, 002°30'E and the coast of Norway. The topography is varying with the North Sea Plateau in the west, the Norwegian Channel in the middle and the coast in the east as shown in Figure 1.1. Extensive surveying has been carried out during the years 2003 – 2008. During the surveys FFI has taken a large number of gravity cores and grab samples to provide physical sediment samples from the seabed, which assists the interpretation of the acoustic data. Commercial software has been used to process the acoustic data. The bottom samples collected and analyzed are reported in [1;2]. Seismic investigations of the exercise area is reported in [3]. The relevant main results from the referred reports are presented in this report.

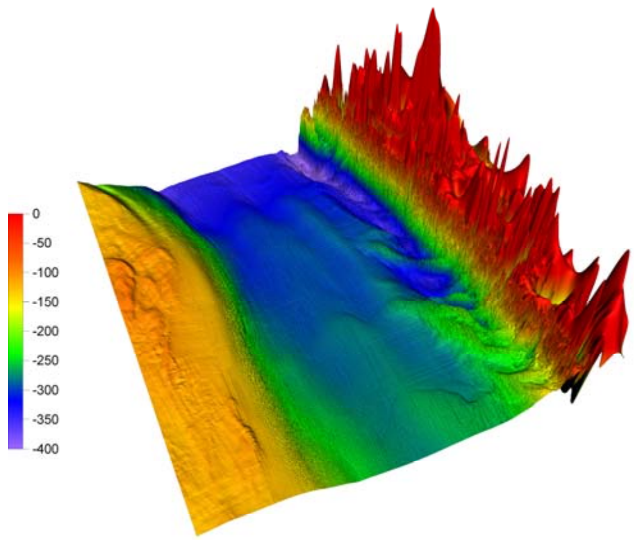

Figure 1.1 The topography in the Navy's exercise area in northern North Sea seen from southwest, with the North Sea Plateau in the west, the Norwegian Channel in the middle and the coast with the land topography in the east.

2 Geophysical description of the area

The Norwegian Channel is a trench in the continental shelf, running parallel to the coastline of Southern Norway from Jæren to Stad where it terminates on the continental margin. Several glaciation cycles during recent geological history have influenced the development of the Norwegian Channel and this is reflected in the sediment layer structure of the seabed. The exercise area covers about 23000 km^2 of the northern North Sea where the channel is approximately 300 m deep, with depth increasing slightly towards the north, and about 110 km wide. The water depth on the North Sea Plateau to the west is about 100 m [3].

FFI carried out geophysical surveys in the Navy's North Sea exercise area in September 2005 and February 2006, see Figure 2.1. Seismic equipment (twin airguns with single-channel streamer) and parametric sonar was used to map the sediment beds in the area. The sequence of unconsolidated sediment layers was found to have a total thickness of about 150 – 200 m in the central part of the channel and consists of several alternating layers of tills and marine or glaciomarine sediments, reflecting the glaciation history of the Quaternary period. A till consists of material eroded, transported and deposited by glacial ice, without the presence of water. Normal marine sediments are deposited by suspension fallout in an ocean or lake environment. Such sediments usually consist of fine particles (silt, clay) and frequently contain much biogenic material. Glaciomarine sediments are eroded and transported by ice, but deposited with water present, such as meltwater flooding from glaciers.

The seismo-acoustic data were interpreted based in part on published analyses of two shallow borehole cores on the Troll field, which have yielded detailed information about Quaternary layer structure, physical properties of sediments and depositional environment [4;5]. Two sedimentary formations which are found across most of the Norwegian Channel are of principal importance for seabed classification.

In the deep, flat part of the channel, the parametric sonar penetrated down to a hard, rough and irregular boundary which is interpreted as the top of a till (moraine) dating to the maximum of the last (Weichselian) glaciation. This formation is seismically and lithologically homogeneous with little internal layering. Borehole samples from the Troll site have a high sand fraction (about 30 %), a significant gravel fraction (about 3 %), low water content (less than 30 %) and relativley high shear strength [4;5]. The Weichselian till is significant because it connects with several large terminal moraines on the eastern side of the study area. The seafloor on these bathymetric features in Figure 2.2 is therefore expected to be composed of sandy sediments with a relatively stiff, muddy matrix and the presence of coarser pebbles and boulders.

A finely layered formation, roughly 15 – 40 m thick, consisting of marine and glaciomarine sediments covers the Weichselian till in the central, flat part of the Norwegian Channel and is also well developed in a wide trough outside the Korsfjorden inlet. These sediments have been deposited from the onset of the last deglaciation to the present [4-6]. The topmost, surficial layer is a homogenous, acoustically transparent unit, typically 4 – 9 m thick, which marks the transition to the marine depositional environment of the Holocene period (up to the present). At the Troll site, the surface layer consists of muddy (silty-clayey), normal marine sediments with low shear strength , high water content (60 – 70 %) and much biogenic material [4;5]. This unit is well represented in the set of gravity cores and grabs samples acquired by FFI (see Chapter 3 and [1;2]).

These two formations are part of the larger, Quaternay, unconsolidated sediment sequence which rests on a bed of westward-dipping layers of consolidated bedrock [7]. Crystalline, mainly igneous rocks of the Norwegian mainland are exposed at the seafloor to the east near the shoreline. The eastern flank of the channel has a complicated topography with ridges and valleys, some of which can be seen to be filled with softer sediments. To the west beyond 003º 30’ E, the terrain rises gently up to the North Sea Plateau (see Figure 2.2). From previous work in the northern part of the area [8;9], it is expected that seabed sediments on the slopes and plateau are predominantly sandy or gravelly.

The geological interfaces at the seabed were interpreted and digitized along the survey lines. The travel times were converted to depth in meters using approximate average sound speed (1550 m/s for the top Holocene layer). The resulting depth values were subsequently block averaged and interpolated to form a grid of Holocene clay/silt layer thickness. Figure 2.3 shows the resulting sediment thickness map. In most of the area, the seabed is covered by a few meters of marine clay/silt.

Figure 2.2 shows an outline of the largest seafloor features, including the narrow belt of outcropping crystalline rocks close to shore, the terminal moraines on the eastern side of the channel, and the onset of the slope up to the North Sea plateau.

In short, seismo-acoustic data combined with published sediment core analyses indicate that seabed sediments in the central part of the study area consist of mainly fine marine silts and clays. Coarser sand and gravel is expected on the North Sea plateau, while the slopes on the western side are believed to consist of mainly medium to fine-grained sand. To the east the sediment composition is more heterogeneous and predominantly sandy. Close to shore, the seabed is solid, crystalline rock with very little top sediments present, except as infills at the bottom of local depressions. The area is described in more detail in [3] with references to the research literature.

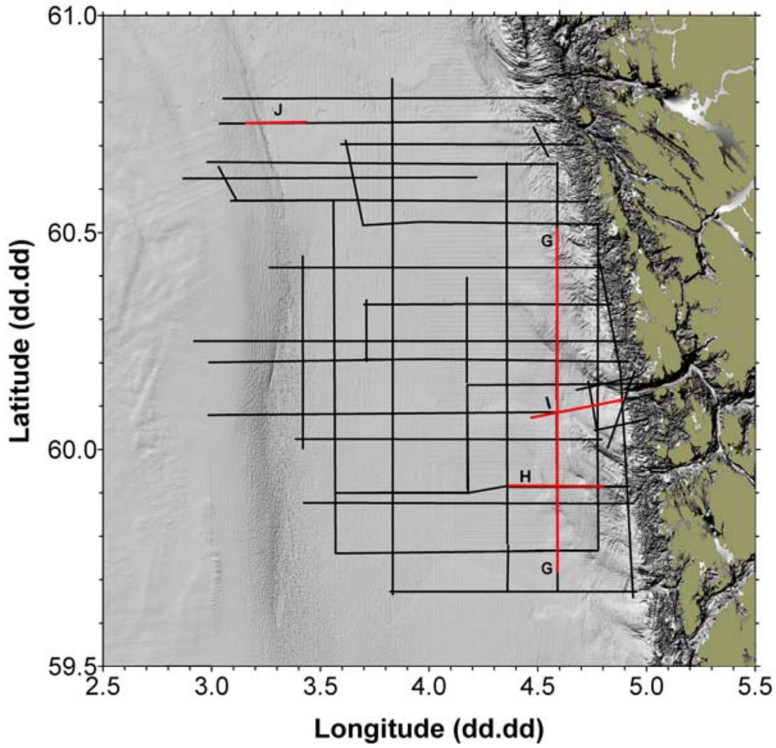

Figure 2.1 Map of survey lines from two geophysical surveys in 2005 and 2006. Transects corresponding to the parametric sonar profiles shown in Chapter 6 have been highlighted in red and labeled.

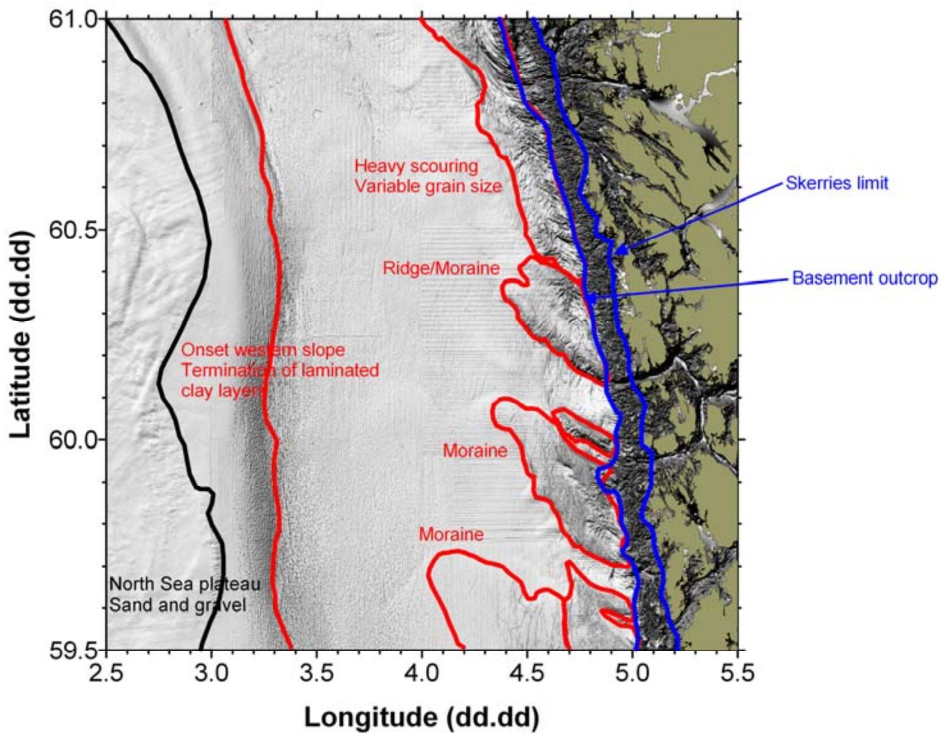

Figure 2.2 General features of the Navy's exercise area in the northern North Sea outlined on the basis of seismic, parametric sonar and multibeam bathymetry data acquired by FFI.

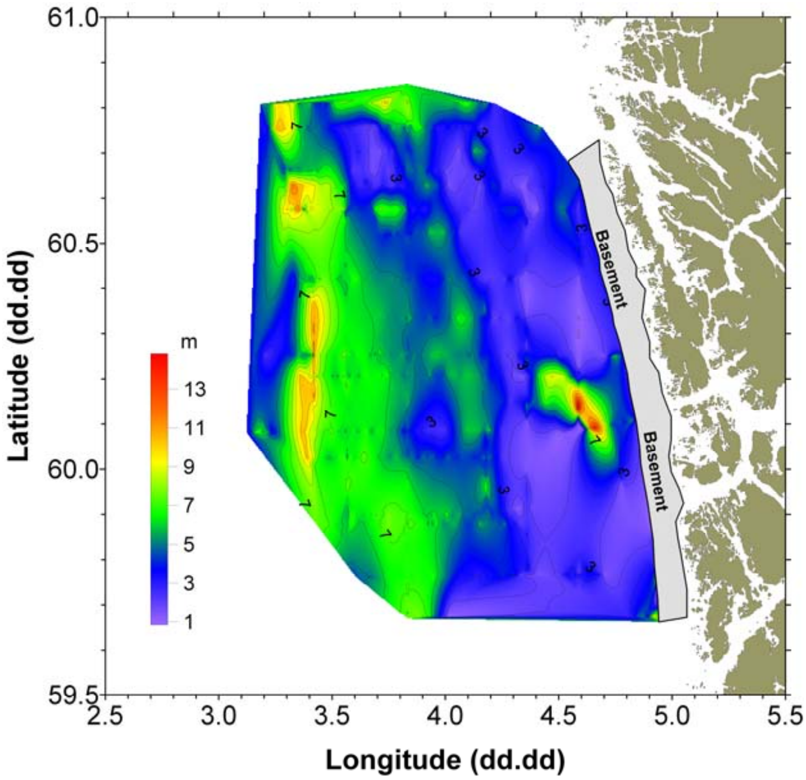

Figure 2.3 Estimated thickness of the top, surficial layer (Holocene) - silt/clay deposited in marine conditions after the last ice age. Two way travel times were converted to depths assuming an average sound speed of 1550 m/s. Contour interval: 1 meter.

3 Sediment samples from the seabed

FFI's research vessel M/S H U Sverdrup II has obtained both grab samples and gravity cores in the area of interest during the years 2004 – 2008. The 40 gravity cores were analyzed by the University of Bergen (UiB) in 2006, 2007 and 2008, and reported in [10-12]. In addition, five of the grab samples were analyzed with respect to grain size distribution by UiB. The 32 remaining grab samples were analyzed rudimentary by FFI onboard the research vessel, partly in collaboration with the Geological Survey of Norway (NGU). The 77 bottom samples obtained are described and interpreted in [1;2]. The relevant main results regarding the samples analyzed by UiB are summarized in this chapter. The grab samples analyzed rudimentary are omitted due to the subjective analysis method, though there is correlation between the two types of bottom samples [2].

The grab samples and gravity cores analyzed by the University of Bergen are classified according to modified versions of Folks classification systems [13;14]. Only subsamples taken from the top layer of the cores are interpreted, with mean core depths ranging from 5.5 cm to 24.5 cm. The classification is based on the mass percentage of gravel, sand, silt and clay as defined in Table 3.1. The classification results for all except one sample are plotted in Figure 3.1. The samples consist mainly of fine sediments. Only 11 out of 44 samples have more than 2 % gravel, and of these only one has more than 30 % gravel. The sand content of the 11 samples are however above 40 %. Of the remaining 33 samples, 22 have less than 10 % sand. The dominance of fine sediments in the cores is partly due to the fact that gravity cores are difficult to obtain from coarser sediment seabeds, and that the major part of the grab samples are not analyzed with respect to grain size.

Sediment types	**Grain size (mm)**
Clay	< 0.002
Silt	0.002 – 0.063
Sand	0.063 – 2.0
Gravel	> 2.0

Table 3.1 The definitions of clay, silt, sand and gravel used in this report. Mud contains both silt and clay.

A geographical representation of the classification results is shown in Figure 3.2. The abbreviations and description of the sediment classes are tabulated in Appendix A. Figure 3.3 – Figure 3.5 show the amounts of gravel, sand, silt&clay and clay in the bottom samples, where the symbol heights equal the percentages. The top layer subsamples from the Norwegian Channel are mainly classified as silt (Z) and mud (M), where mud (M) is mixture of the sediment types silt and clay. The soft seabed in the trench is as expected from Chapter 2. It is however worth mentioning that only one of the bottom samples taken in the trench is classified as clay (C) – namely the sample north of the northern moraine. The three gravity cores obtained in the Norwegian Channel beneath the North Sea Plateau are classified as sandy silt (sZ). On the North Sea Plateau, sand and gravel was found in the bottom samples, however lesser gravel than expected (refer Chapter 2). The part of the plateau surveyed is mainly sandy. In fact, one of the grab samples is classified as pure sand (S). The surprisingly low amounts of gravel in the northern part of the plateau may not be representative for the remaining plateau.

Sand and gravel was also found on the two moraines. Here the amount of gravel is larger than expected (refer Chapter 2). Along the coast north of the two moraines the grab samples are classified from clay (C) to gravelly, muddy sand (gmS). The three samples obtained from Korsfjorden are classified as clay (C), sandy clay (sC) and mud (M). Hence, the fiord has very soft bottom. Arranging the subsamples taken from the top layer of the cores and the five grab samples analyzed for grain size distribution into four groups, an appropriate division becomes:

1) Clay, mud, silt (C, M, Z)
2) Sandy clay, sandy mud and sandy silt (sC, sM, sZ)
3) Silty sand and sand (zS, S)
4) Sediments with at least 2 % gravel (gsM, gmS, gS, sG)

The geographical representation of the grouping is shown in Figure 3.6.

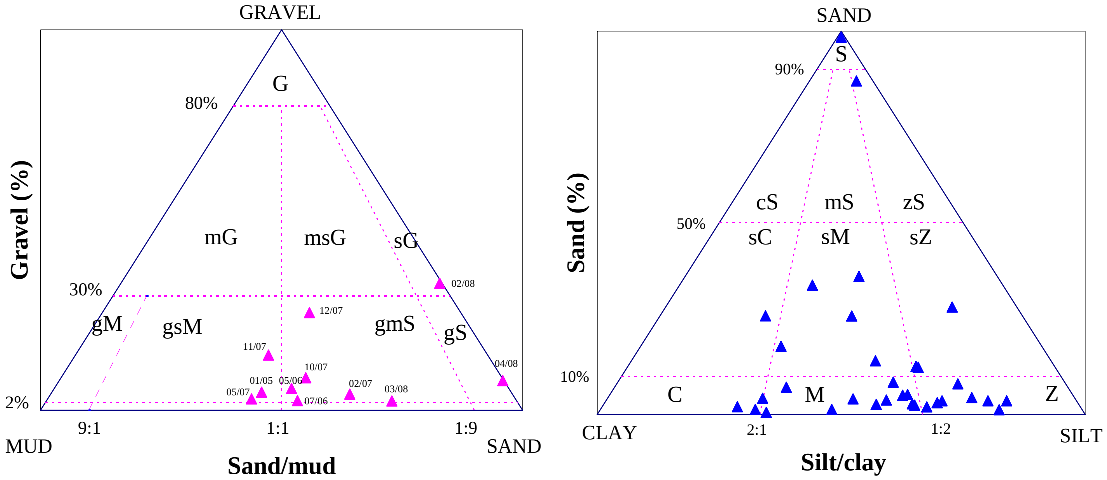

Figure 3.1 Classification of 39 gravity cores and five grab samples in modified versions of Folks classification systems. The left panel shows the samples with more than 2 % gravel (eight cores and three grabs, at least 40 % sand), where mud is including silt and clay. The right panel shows the samples with less than 2 % gravel (31 cores and two grabs). The abbreviations are found in Appendix A.

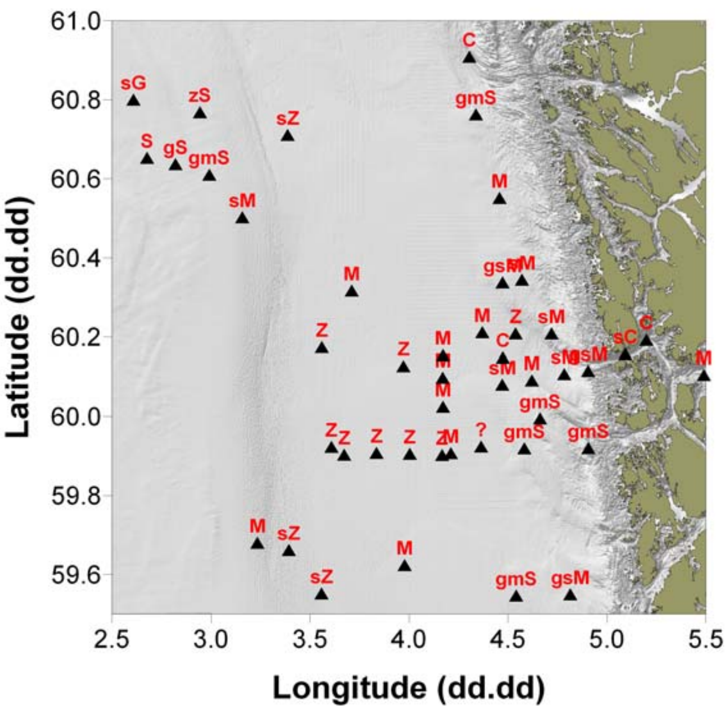

Figure 3.2 Geographical representation of the classification results of 39 cores and five grab samples analyzed by the University of Bergen. Only the top subsample of each core is plotted. The samples from the trench contain mainly silt and mud. Closer to shore and on the North Sea Plateau sand and gravel are found in the bottom samples. The question mark is sample 08/06 which perhaps may be classified as sandy mud [2].

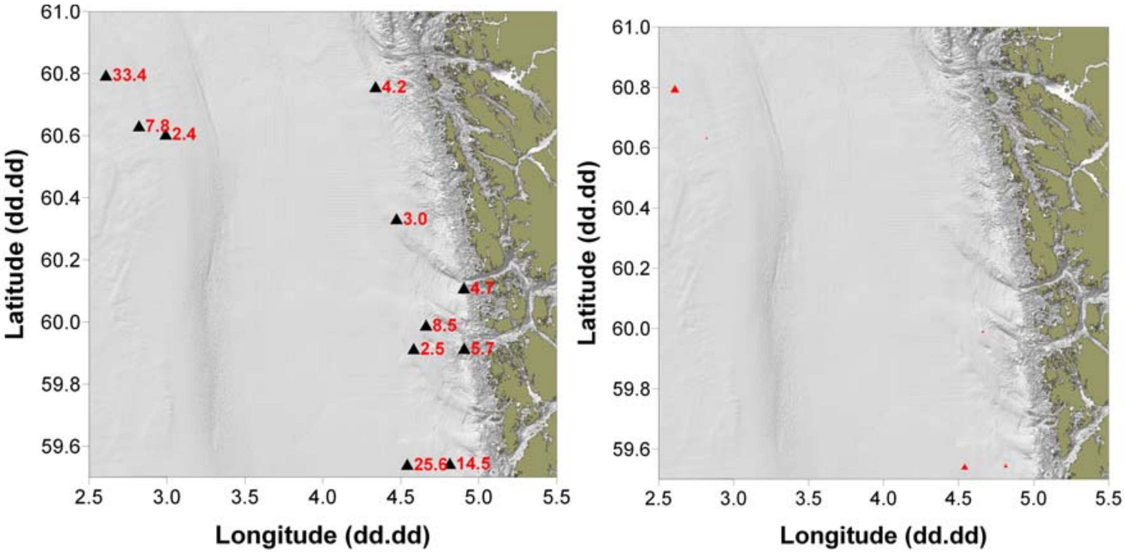

Figure 3.3 The amount of gravel in the samples analyzed by UiB. The remaining samples not shown have less than 0.5 % gravel. Right: The symbol heights are scaled according to percent gravel.

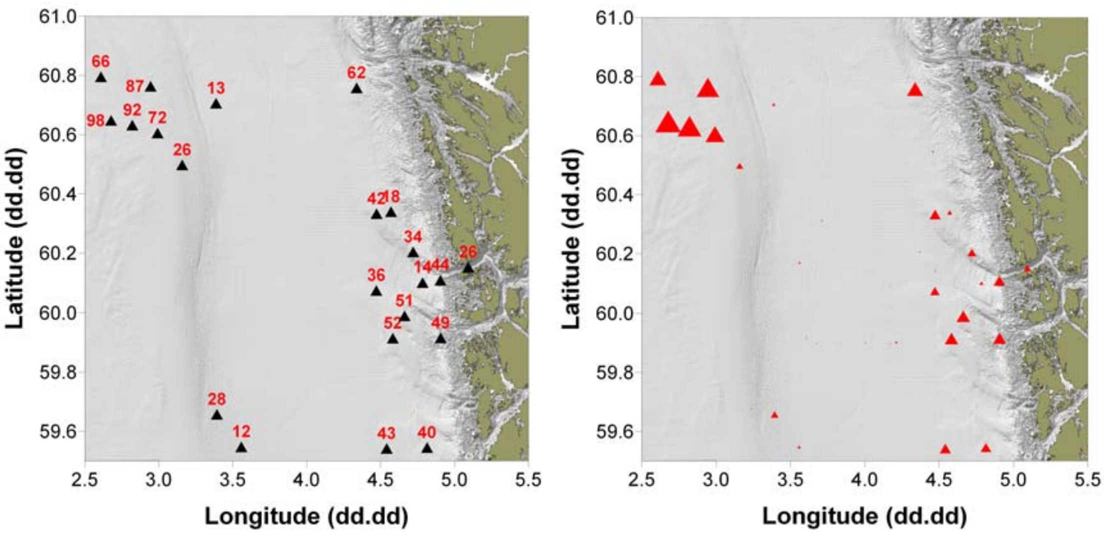

Figure 3.4 The amount of sand in the samples analyzed by UiB. Left: Only samples with more than 10 % sand are shown. Right: The symbol heights are scaled according to percent sand (max 98.4 %), all the samples are shown.

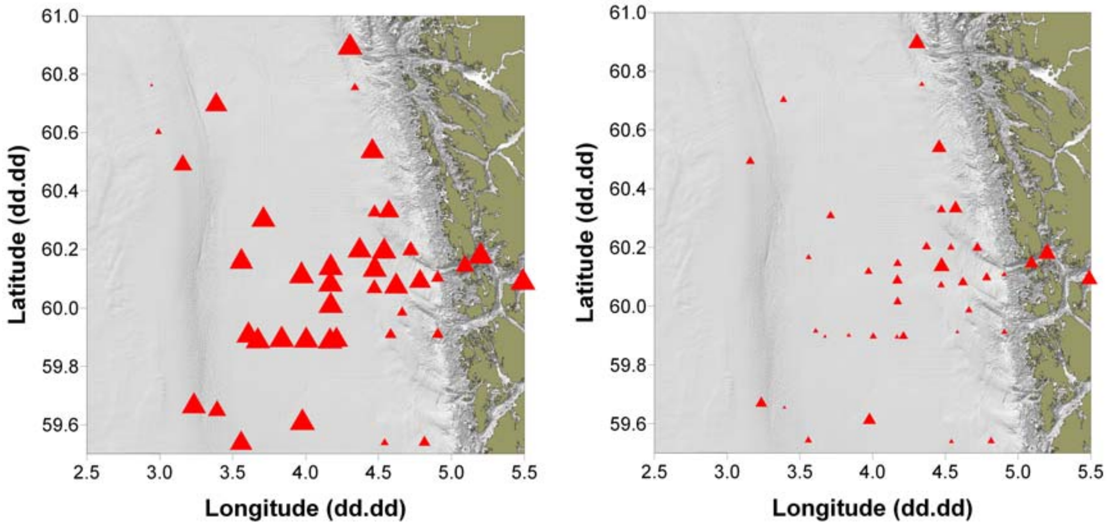

Figure 3.5 The amount of both clay and silt (left) and clay only (right) in the samples analyzed by UiB. The symbol heights are scaled according to percent clay and silt (max 99.4 %) and clay only (max 70.3 %), all the samples are shown.

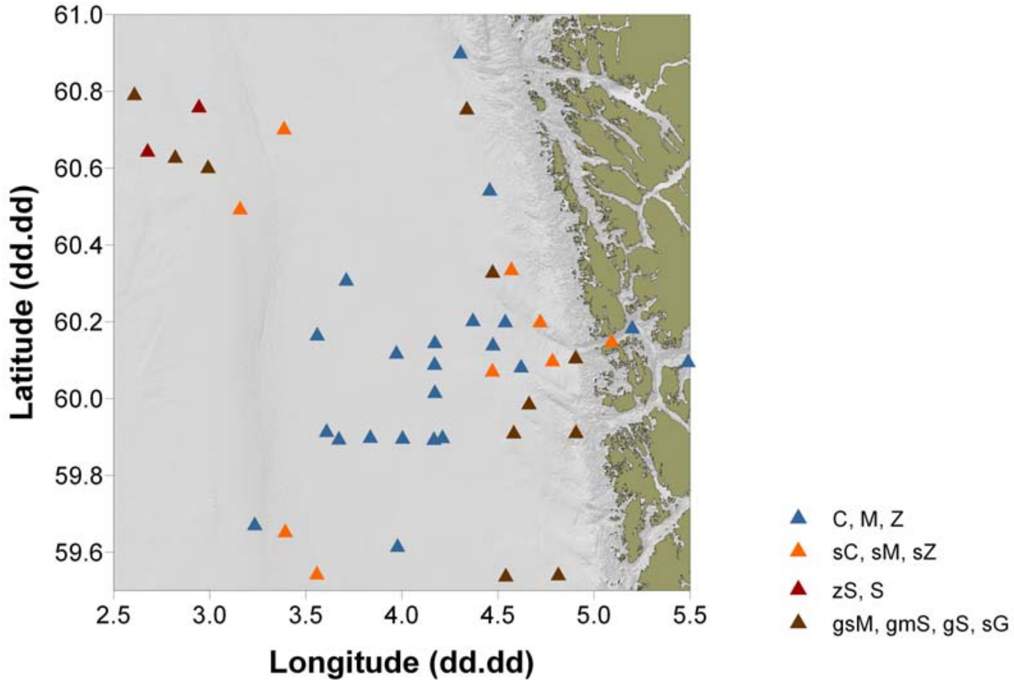

Figure 3.6 Grouping of the 39 gravity cores and five grab samples based on the classification results. The brown triangles contain more than 2 % gravel.

4 Single beam backscatter data

The single beam echosounder data was acquired using first an EA 500 and later an EA 600 from Kongsberg Maritime. Until the spring of 2007 the frequencies available were 12 kHz, 18 kHz and 38 kHz. In spring 2007 a 200 kHz single beam echosounder was installed onboard the research vessel and replaced the 18 kHz.

The surveys of interest in this report are listed in Table 4.1. The following information about each survey are tabulated: date of start and stop of survey, the number of raw data files recorded, the number of megabytes the files add up to, the frequencies used to acquire single beam data and any comments. Figure 4.1 shows the surveyed area and the survey numbers. Only data from the 38 kHz echosounder are processed in this report. During several surveys in 2005, the navigation dropped out during the data acquisition. The raw files from the surveys 09/05, 14/05 and 15/05 were fixed later on, using navigation data from other sources. Regarding 17/06, single beam data were not acquired during the second half of the survey. Two surveys (04/05 and 05/05) were mainly inshore and only data outside the coast are included in this report. Data from 21/08 are not processed due to lack of time and termination of the FFI project Poseidon.

Unfortunately the single beam data were acquired using two pulse lengths, namely 0.512 ms and 1.024 ms. This complicates the processing. The varying transmit power was not a problem.

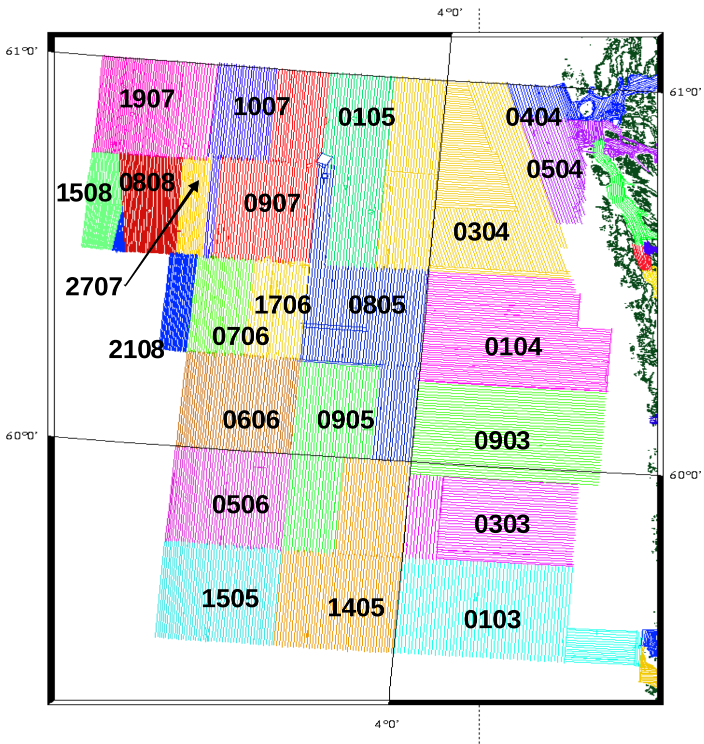

Figure 4.1 The map is showing the data acquired by FFI between 1998 and 2007 in the area of interest outside Bergen.

Survey	Date start	Date end	# files	# MB	Comments	f (kHz)	τ (ms)	P (W)
01/03	3/2-03	20/2-03	44	5.2		12, 38	0.512	2000
03/03	20/2-03	28/2-03	29	4.1		12, 38	0.512	2000
09/03	11/3-03	18/3-03	36	5.1		12, 38	0.512	2000
01/04	10/2-04	20/2-04	37	4.5		38	1.024	1000
03/04	20/2-04	31/3-04	121	6.2		38	1.024	1000
04/04	23/2-04	3/3-04	44	0.7	Included off-coast lines	38	1.024	1000
05/04	28/2-04	16/3-04	39	1.9	Included off-coast lines	38	1.024	1000
01/05	24/2-05	3/3-05	78	5.9	Noisy period	38	0.512	1200
08/05	27/8-05	7/9-05	227	9.5	Partly loss of GPS 2/9 and 4/9	12, 38	0.512	800
09/05	25/9-05	7/10-05	175	7.6	Fixed files	12, 38	0.512	800
14/05	17/11-05	7/12-05	287	12.2	Fixed files	12, 38	0.512	800
15/05	28/11-05	11/12-05	204	8.4	Fixed files	12, 38	0.512	800
05/06	18/2-06	25/2-06	74	4.5		12, 38	1.024	2000
06/06	28/2-06	10/3-06	92	4.6		12, 38	1.024	2000
07/06	12/3-06	16/3-06	40	2.2		12, 38	1.024	2000
17/06	3/9-06	?	7	0.31	Only 3/9 and 4/9	12, 38	1.024	1200
09/07	6/2-07	18/2-07	96	3.0		12, 38	1.024	2000
10/07	20/2-07	8/3-07	47	1.6		12, 38	1.024	2000
19/07	20/8 -07	29/8-07	130	10.6		38, 200	0.512	1200
27/07	11/11-07	22/11-07	196	17.7		12, 38, 200	0.512	1600
08/08	18/2-08	16/3-08	111	9.8		12, 38, 200	1.024	2000
15/08	26/3-08	3/4-08	57	5.0		12, 38, 200	1.024	2000

Table 4.1 The EA 600/500 data processed for this report. P is transmit power, τ is pulse length and f is frequency.

5 Processing of backscatter data

This chapter describes the data handling of the raw files from the echosounder to the production of classification maps. The process is as follow:

1) Conversion of raw data
2) Bottom picking
3) Computing feature vectors of all the data
4) Creating a catalogue based on selected or all the feature vectors
5) Classifying the entire area with same pulse length
6) Gridding and plotting
7) Production of AML (additional military layer)

5.1 Conversion between data formats

The software tool EchoView from Sonardata, Australia [15] was used to convert raw single beam data to separate sonar and navigation files (*.sonar and *.nav) ready to import into the seabed classification software QTC Impact. The exported time series were Sv – volume backscattering strength. The format of the data files is unknown. At first EchoView version 3.50 was used, later all the data was reprocessed in version 4.20, even later version 4.40 was used.

The transceiver settings changed during the years of interest. The pulse length alternated between 0.512 ms and 1.024 ms. The transmit power varied between 800 W and 2000 W. Wrong type of transducer was selected in the EA600 software during the years 2003 – 2005. This did not influence the raw data logged, but three of the calibration values stored in the data files became erroneous and had to be corrected by manual calibration in EchoView. These were 1) two-way beam angle, 2) transducer gain and 3) 3 dB beam width, see Table 5.1. The correct two-way beam angle is -20.6 dB rel 1 Steradian. The correct transducer gain is 26.5 dB if pulse length 1.024 ms and 26.0 dB if pulse length 0.512 ms. However, when processing the data from 2003-2006, transducer gain equal to 26.5 dB was used independently of the actual pulse length. Fortunately no visible differences were observed, and the data was not reprocessed. The correct minor- and major-axis 3 dB angles are both 7.10°. In some of the surveys the sound speed was constantly set to 1500 m/s, in others the sound speed was as measured during the survey. The calibration in EchoView normalized the data files, except for pulse lengths. When using version 4.40 the pulse length had to be set to 0.511 ms and 1.023 ms in the calibration procedure in order to force the exported files to be compatible with earlier processed data in the seabed classification software. This did not influence the actual data.

Parameter	**Setting**
Absorption coefficient (dB/m)	As in first ping
Sound speed (m/s)	As in first ping
Transmitted power (W)	As in first ping
Two-way beam angle (dB rel 1 Steradian)	-20.6
Transducer gain (dB)	26.5 (0.512 ms and 1.024 ms in 2003-2006) 26.0 (0.512 ms in 2007 and later)
Sa correction (dB)	As in first ping
Transmitted pulse length (ms)	As in first ping (before version 4.4) 0.511 or 1.023 (version 4.4)
Frequency (kHz)	As in first ping (38 kHz)
Minor-axis 3 dB angle	7.10
Major-axis 3 dB angle	7.10

Table 5.1 Calibration values as set in EchoView.

The size of the exported *.sonar files was user selected. New files were generated when reaching the file size or passing midnight. Unfortunately, the earlier versions of EchoView used (version

3.30 and version 4.20) had problems with memory handling and only a limited amount of data was possible to convert in one operation to QTC format, before the program had to be restarted. Hence the conversion process took much more time than necessary. It is possible to pick the bottom in EchoView, but the author did not succeed in importing this bottom line from EchoView to QTC Impact.

5.2 Classification software QTC Impact

QTC Impact versions 3.40 and 3.50 from Quester Tangent Corporation, Canada were used to process the single beam echosounder data and classify the seabed [16]. Exported data files from EchoView covering maximum 24 hours of data acquisition were imported into QTC. The restriction of 24 hours is because the navigation files contain time, but no date. The restriction of 16 files made earlier by QTC was not an issue in our case. Version 3.50 of QTC Impact has the option to import raw data directly from our Kongsberg Maritime echosounder, which will make the processing of the data easier. If using this option however, the full feature vectors (FFV's) are not compatible with FFV's computed from the data going through EchoView. Due to the amount of FFV's already computed, we did not change the processing line. All the surveys with pulse length 0.512 ms were processed together and similarly for all the surveys with pulse length 1.024 ms.

The bottom pick algorithm in QTC Impact was used to pick the bottom. At first, the operation *Bottom picks of all traces* was carried out (default). However, for many of the logging days the number of rejected picks was surprisingly large. Hence, the operation *Pick only traces above a certain signal strength threshold* was selected and the threshold was set as low as possible, usually 1 %. When suspicious or clearly incorrect bottom picks were shown in the depth statistic, the threshold was increased. The number of picked traces equals all traces subtracted the number of unpicked traces. The number of traces processed further however, equals picked traces minus traces with no picks (rejected traces). These traces are called raw waveform data which has bottom picks.

raw waveform data = # all traces - # unpicked traces - # traces with no picks (rejected)

The depth statistics window shows a histogram of # raw waveform data with bottom picks within each depth interval. Any outliers are visible in this window.

After the bottom picking, the FFV's were computed and merged with the navigation data. Five pings are averaged to make one FFV. In order to compensate for the changes in the footprint with respect to depth, a reference depth is set. The reference depth compensates for the changes in the acoustic signal due to changing water depth. In our processing a reference depth of 300 m was used, and only data between approximately 100 m and 600 m were processed. This gives a ratio of six between maximum and minimum depth, which is acceptable if the acoustic diversity of the seabed is large, according to [17]. In the FFV editor it is possible to validate the FFV's and unselect suspicious data. Figure 5.1 shows the bathymetry editor along a survey line where several depressions are observed. These are not removed before classification.

The next step is to create a catalogue to build a reference set for seabed classification. FFV's from one survey or from several surveys are merged (if the pulse length is the same). At first the FFV's are analyzed by Principal Component Analysis (PCA) to identify the three most important features (Q-values) to describe the seabed variability. Next, the data are clustered into classes manually or automatically. In this report only automatic clustering has been used. The range of classes and the number of iterations per class is user selected. A score value is computed for each iteration and class. The class with the minimum score value is highlighted. However, from experience the minimum is often the highest number of classes. In our case the process of auto-clustering is time-consuming if all the data are used in the auto-clustering. One of the two datasets we have takes about a week of processing on the computer with 10 iterations and 4 – 8 classes.

The seabed classification process is the last step in QTC Impact. The FFV's are classified based on a catalogue made from one survey or from several surveys. The classification output is exported to *.seabed files in ASCII format.

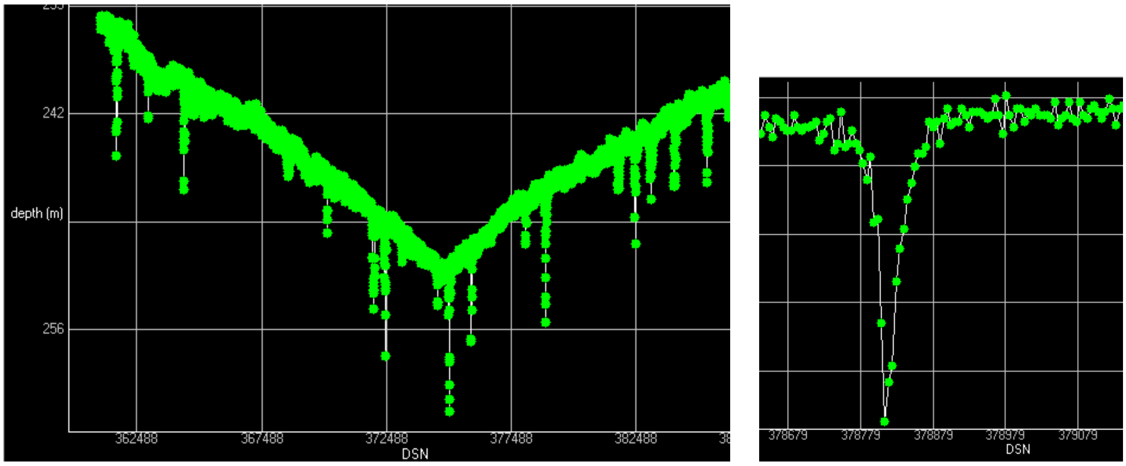

Figure 5.1 The bathymetry editor in QTC Impact showing the bathymetry along a survey line. To the right is one of the depressions (pockmarks) enlarged. The depressions are not removed before classification.

5.3 Post-Processing

The post-processing is possible to do using QTC Clams, which is a tool for mining classification data [18]. The data are loaded into QTC Clams and the data source unit is set to decimal degrees. Node spacing and search radius are set to meters. The search size limits the number of nearest neighbours to be used in the interpolation algorithm. The search radius gives the maximum searching distance (in meters) in the area surrounding each query point. Scaled mapping is selected. Output files are for instance plots in *.jpg-format or data files in *.grd-format ready to import into other software. However, the *.grd-files are rectangular and areas with no data are also designated a value.

The software tool Surfer version 8 from Golden software was usually used to plot the classified data. It is possible to read *.seabed files directly into Surfer (column 3, 4 and 11) and plot the classification results. Due to the large amount of data, the relevant columns were instead decimated using the software tool GMT and the command *blockmedian*, before export to Surfer. *Blockmedian* uses a median filter on blocks of data to reduce the amount and remove fine scale variations. In Surfer the data was plotted with color codes on a shaded relief map of the bathymetry or on a surface map.

6 Seabed classification analyses and results

6.1 Classification results

The single beam data acquired with different pulse lengths need to be processed separately. When all the data with pulse length 1.024 ms is used to make a catalogue, the classification results are as shown in Figure 6.1. Figure 6.2 shows the classification result for pulse length 0.512 ms when all the data are used to make the catalogue for the classification. If using only some of the data to make the catalogue, the resulting classification plot may change. The number of classes are in both figures set to five, but this is not necessary the value giving the lowest score. Generally we have seen that the more classes the lower the score becomes. Figure 6.3 shows the score value for both pulse lengths. The number of iterations was set to 10, and the number of classes increased from four to eight. The lowest score value is in both cases found with eight classes, the largest number of classes checked. In this report we have selected the lowest number of classes best representing the data by visual inspection. If increasing the number of classes from N to N+1 and the classification result did not change essentially, we decided to use N classes further on. As the data processing went on, we found that four classes as used when grouping the bottom samples were one too few.

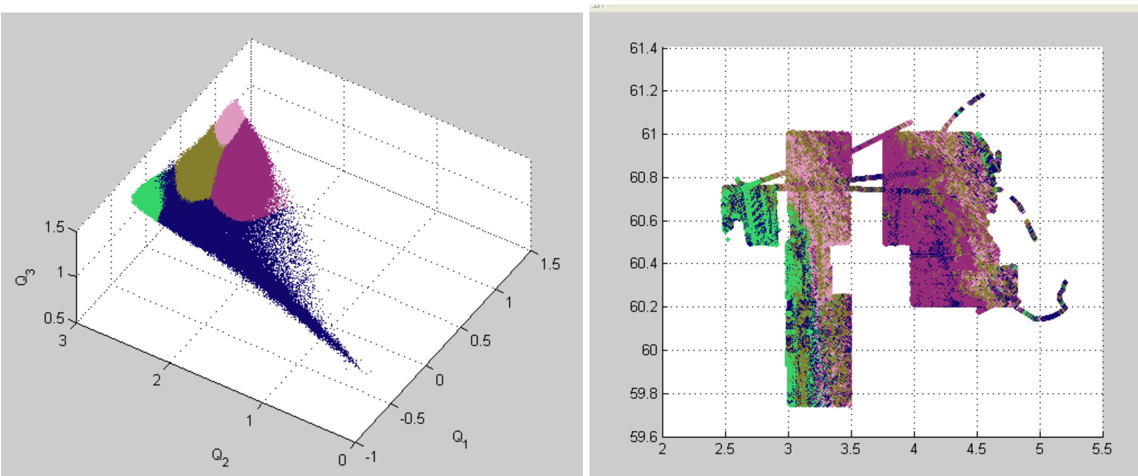

Figure 6.1 The Q-space with five classes. Pulse length 1.024 ms. The tracks classified using five classes are shown to right. The data are not interpolated. All the data are included in making the catalogue used for classification.

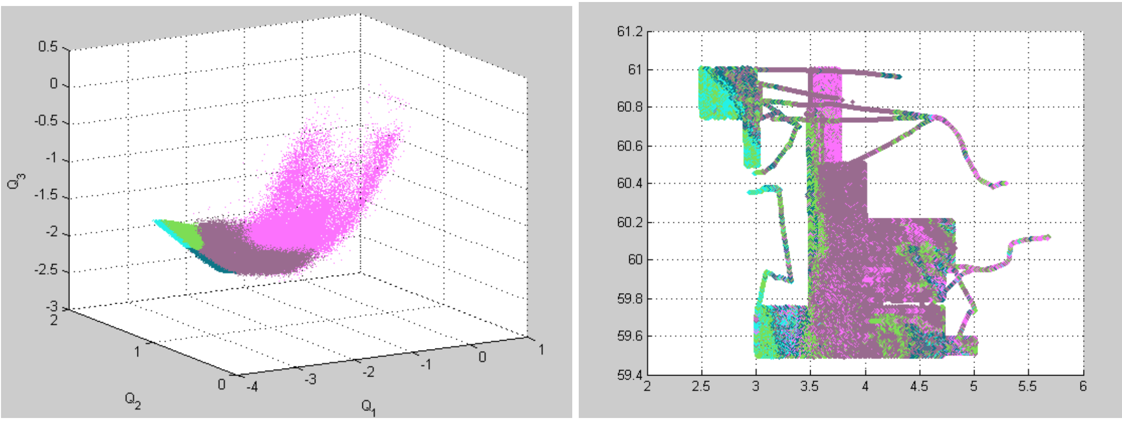

Figure 6.2 *The Q-space with five classes. Pulse length 0.512 ms. The tracks classified using five classes are shown to the right. The data are not interpolated. All the data are included in making the catalogue used for classification.*

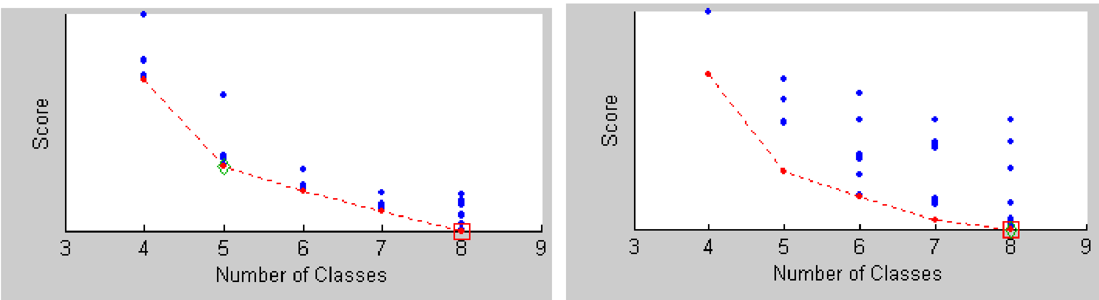

Figure 6.3 *The score value decreases as the number of classes increase. The highest number of classes selected for processing gives the lowest score for both pulse length 1.024 ms (left) and 0.512 ms (right). All the data are included in making the catalogues.*

After the classification in QTC Impact, the ASCII data files are median filtered in 200x200 m^2 blocks to reduce the amount of data and remove fine scale variations and plotted in Surfer. The median value within each block represents the block. Figure 6.4 shows the final classification result for the dataset with pulse length 1.024 ms. As seen, one class covers most of the trench. The slope on the western side is classified as two parallel classes following the topography. The part of the North Sea Plateau processed, becomes one class. Towards the east where there is heavy scouring from ice, the picture is more complex with a mixture of the same classes as observed in the west. In addition, close to the coast and in the fiords a fifth class is present.

The challenge with having two pulse lengths is the fitting of the classification results in adjacent areas. Figure 6.5 shows the classification result for the dataset with pulse length 0.512 ms. The colours are selected in accordance with Figure 6.4. The number of classes is set to five. All the data have been used to make the catalogue to do the classification. As for pulse length 1.024 ms the trench becomes one class. Towards east the moraines are one class with elements of other classes. Towards west the data are mainly divided into three classes.

Figure 6.6 shows the two datasets combined. Taking into account that the classification is performed on two different datasets, the correlation is amazing. The classification results for the transit lines fit across the two areas processed separately. The turquoise class in the trench fits very well across the borders. The red class covering the moraines in the east is also present in the west at shallower depths. Two of the fiords were surveyed using both pulse lengths. Hence the same colour is used here. As a consequence, the fiords, a small area north of the northern moraine and an area northeast become a common, purple class. Some mismatch is found along the western slope. Here, the orange class does not fit perfectly, neither in the south nor in the north of the western slope.

If using only data from the slope on the western side (survey 14/05 and 15/05) to make the catalogue for pulse length 0.512 ms, the fit is perhaps better in this area. This is shown in Figure 6.7. In this case six classes were necessary to use. The orange class extends further northwest around the North Sea Plateau. As a consequence of different classification, the yellow class at the bottom of the western slope is stretching further into the trench.

Figure 6.8 and Figure 6.9 show the classified areas in Figure 6.4 and Figure 6.5 on surface plots. The bathymetry data are decimated with a resolution of 200 m. It is interesting to notice the purple area north of the northern moraine, which does not point out as special in the surface plots.

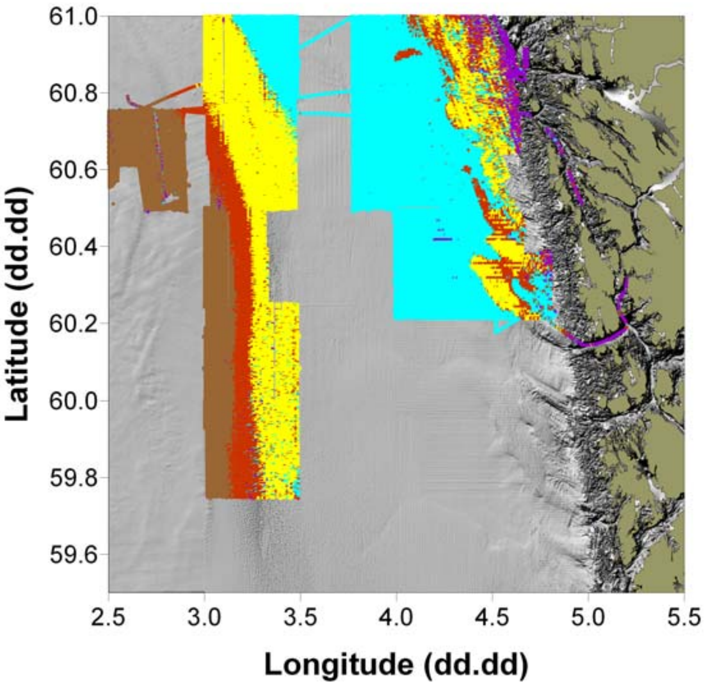

Figure 6.4 The classification result interpolated and interpreted. Pulse length 1.024 ms. All the data are used to make the catalogue for classification. Five classes are selected. Notice the classification results for the transit lines.

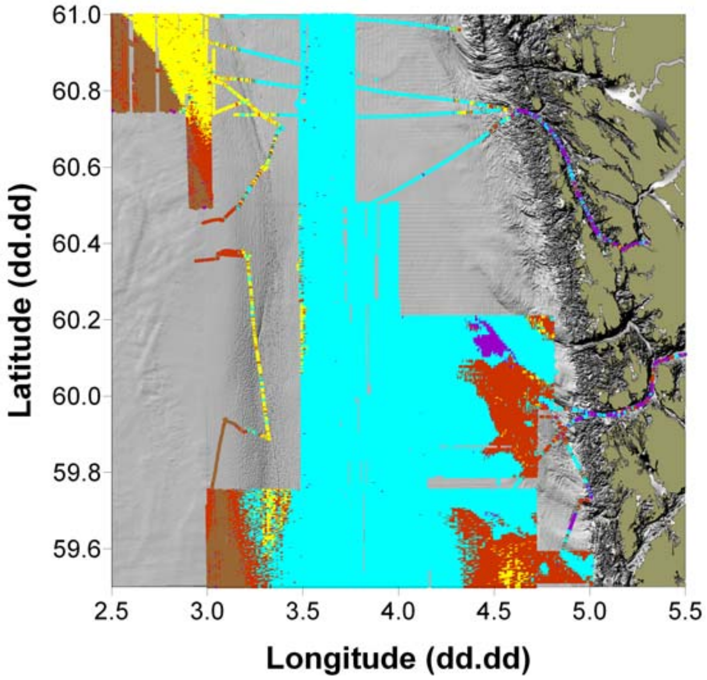

Figure 6.5 The classification result interpolated and interpreted. Pulse length 0.512 ms. All the data are used to make the catalogue for classification. Five classes are selected. Notice the classification results for the transit lines.

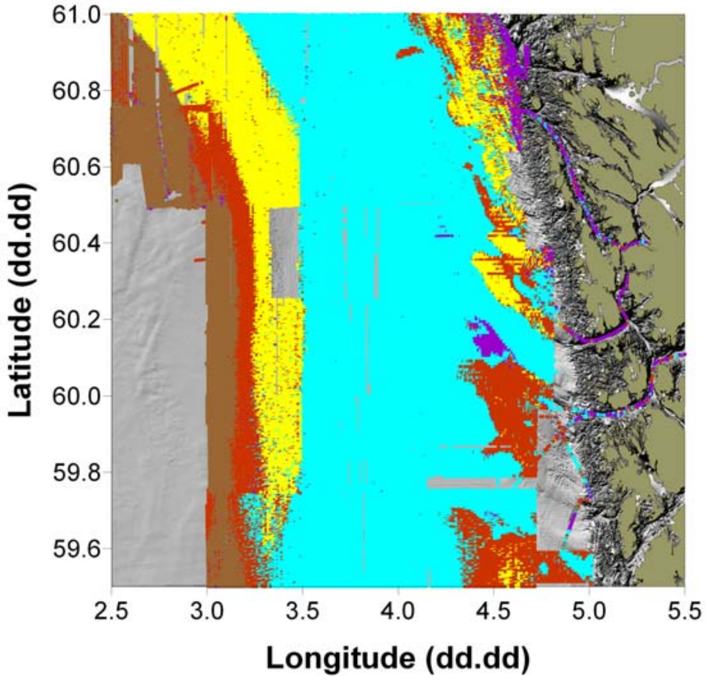

Figure 6.6 The classification result for the entire area. Two datasets are combined. All the data are used to make the catalogue for classification. Five classes in both datasets.

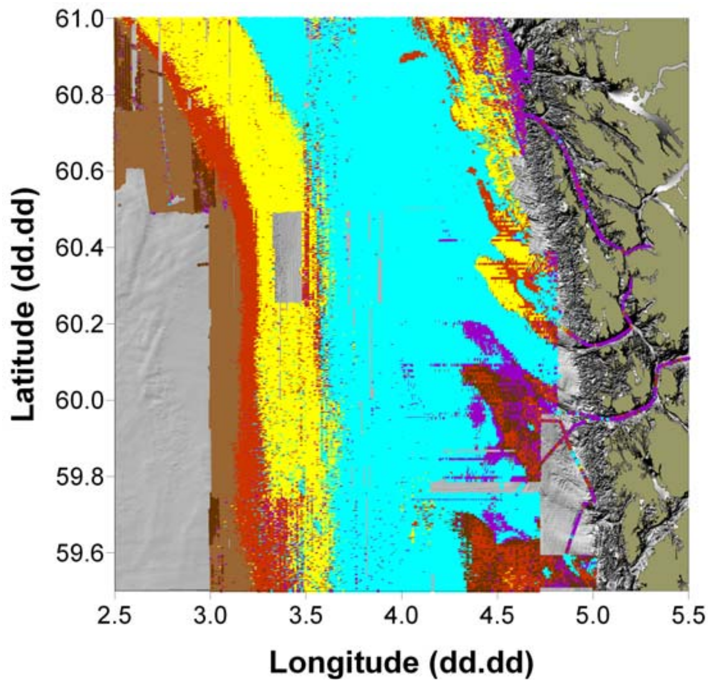

Figure 6.7 The classification results for the entire area. Two datasets are combined. All the data available are used to make the catalogue for pulse length 1.024 ms (five classes). Only data from the western slope (14/05 and 15/05) are used to make the catalogue for pulse length 0.512 ms (six classes).

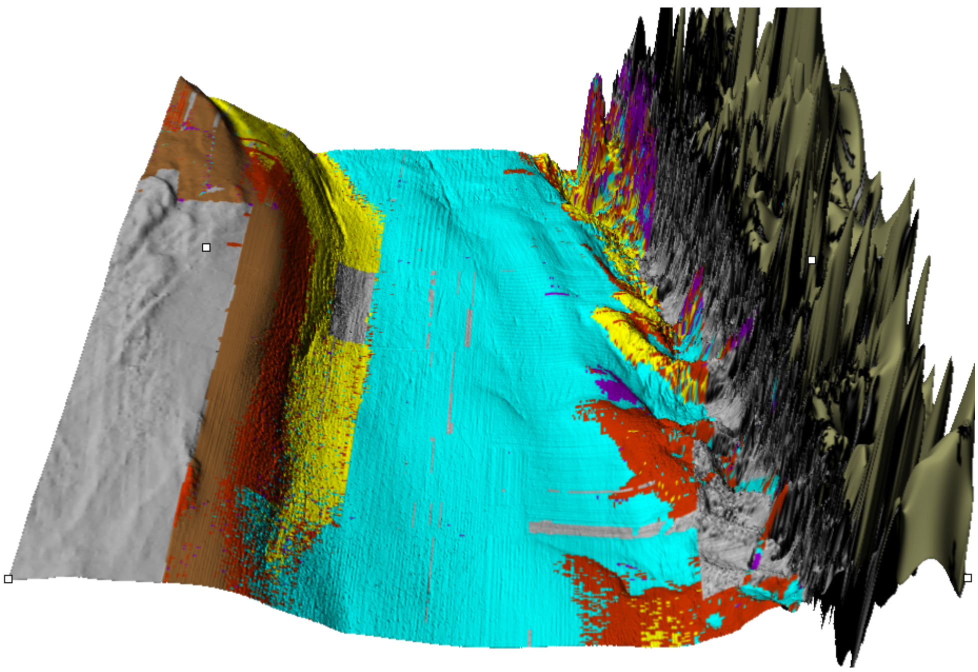

Figure 6.8 The classification results plotted on a surface map, seen from the south. All the data FFI has acquired up to April 2008 have been used to make the two catalogues for the seabed classification.

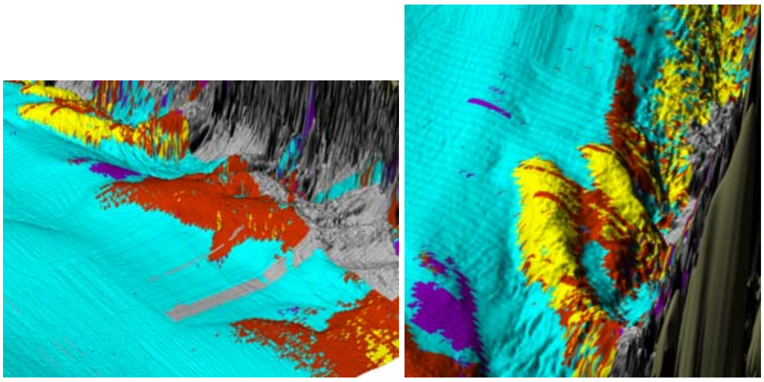

Figure 6.9 Selected areas from the above figure.

Figure 6.10 shows bottom sediment samples compared with the classification results. Only the samples where the grain size distribution is known are used since these are analyzed quantitatively. The turquoise area covers mainly bottom samples with mud (M) and silt (Z). Two samples in the area are classified as sandy mud (sM) and sandy silt (sZ). The yellow area in the west has bottom samples classified as sandy mud (sM) and sandy silt (sZ), and is stretching out into the Norwegian Channel.

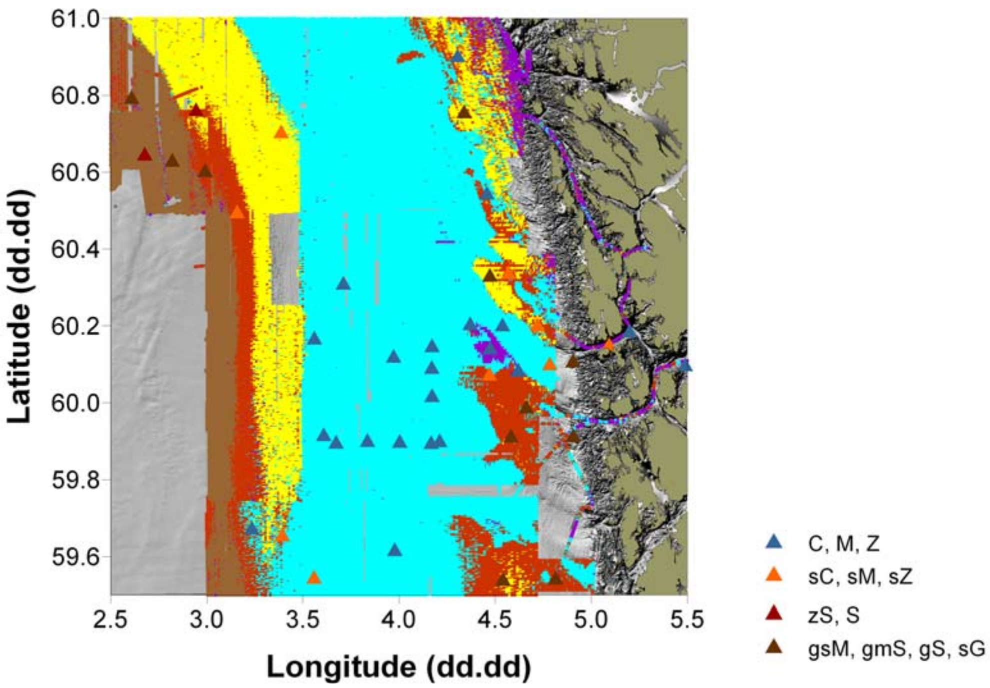

Figure 6.10 The classification results compared with the bottom samples obtained from the area.

According to the bottom samples the brown area consists mainly of silty sand (zS), sand (S) and coarser sediments. The red areas in both the east (covering the moraines) and the west (along the slope) have a mixture of samples classified as sandy mud (sM), sand (S) and gravelly muddy sand (gmS). The yellow areas to the east have bottom samples of all kinds. This area has been influenced by heavy ice scouring and sediments are heterogeneous and rapidly varying according to analyses of seismic data, parametric sonar data and multibeam bathymetry data acquired by FFI, see Chapter 2. It is interesting to observe that the muddy core southwest at about 59.7° N, 3.3° E fits with the turquoise class. The purple class in the fiords and north of the northern moraine contains cores classified as clay (C), the finest sediment considered in this report, and sandy clay (sC).

Figure 6.11 shows the percentage of gravel, sand, silt&clay and clay only, compared with the seabed classification results. The brown class is mainly sandy with varying amounts of gravel, and no silt or clay. The red class is mainly sandy, and partly gravelly, silty and clayey. The yellow class is mixture of sand, silt and clay. The turquoise class is mainly silt with some clay, but no sand or gravel. The purple class is mainly clay with some silt. Sand is present to different degrees.

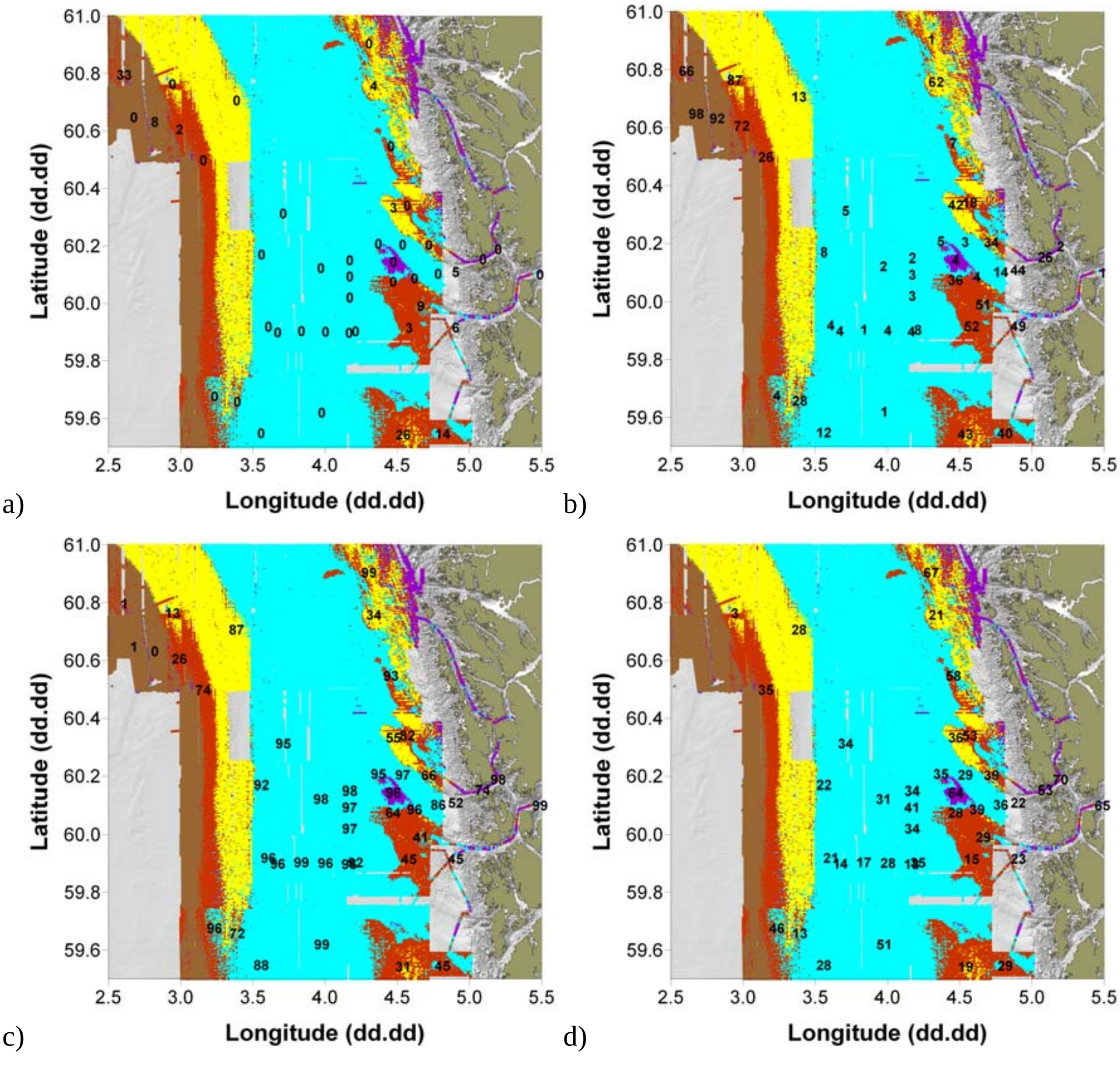

Figure 6.11 The amount of a) gravel, b) sand, c) silt&clay and d) clay only in the bottom samples obtained in the area of interest, compared with the seabed classification results.

6.2 Comparison with parametric sonar data

After classification of single beam echosounder data had been completed in QTC, the results were compared with parametric sonar data along selected transects shown in Figure 6.12**.** Parametric sonar data was acquired with a Topas PS18 from Kongsberg Maritime, using a 20 ms 2 – 4 kHz chirp pulse. Figure 6.13 – Figure 6.16 show deconvolved data with instantaneous amplitude, oriented west to east or south to north, and with two-way travel time (s) on the vertical axis. The seabed classes according to results of the previous section are shown in colour bars above each profile. Clear changes in acoustic signature can be seen as the terrain shifts from horizontally layered marine sediments to terminal moraines. To the far right on Figure 6.15, the outcrop of crystalline rocks is also just visible.

On each profile, the strongly reflecting and irregular boundary corresponding to the top of the Weichselian till/moraine is indicated in green. The terminal moraines to the east, as seen on profile G (Figure 6.13) and H (Figure 6.14), connect naturally with this till formation which is found across the Norwegian Channel but exposed at the seafloor only on the eastern side of the study area.

Figure 6.15 and Figure 6.16 clearly show the laminated marine/glaciomarine sediments covering this boundary. This formation too is well developed across the channel, but pinches out to the east (Figure 6.13 and Figure 6.14). The topmost layer of this formation is acoustically transparent and homogeneous and is interpreted as a soft, muddy, marine deposition of the postglacial Holocene period (roughly the last 10.000 years).

Considering Figure 6.13, which shows a north-south profile intersecting four classes, it seems that the turquoise class corresponds well with the Holocene unit (silty-clayey). The red class and the yellow class both correspond with the top of the Weichselian till/moraine. It is difficult to distinguish between the red and the yellow class based on parametric sonar data alone. It is expected that both classes represent compact, muddy sand with presence of pebbles and boulders (see Chapter 2). This is in agreement with results of Chapter 3 and Section 6.1.

The bottom samples obtained from the purple core areas indicates that this class consists of clay. The parametric sonar profiles Figure 6.13 and Figure 6.15 show that this class corresponds to a thin surface layer covering the top of the Weichselian moraines. It is interesting that QTC discriminates between the purple and turquoise classes, although it is not clear why the thin surface layer on the moraines should be more fine-grained than the turquoise class sediments.

A remaining point of uncertainty concerns the transition from muddy plain to sandy slope on the western side of the area. Looking at the parametric sonar profile in Figure 6.16 it would seem that the marine sediments terminate further to the west than the turquoise-yellow boundary found from QTC. The gravity core obtained nearby classified as sandy silt however confirms that there is sand far into the flat area. It is possible that sandy sediment from the North Sea slope may accumulate on the seafloor well into the western part of the trench. The QTC classification may therefore be correct even though this transition is not evident from seismo-acoustic data.

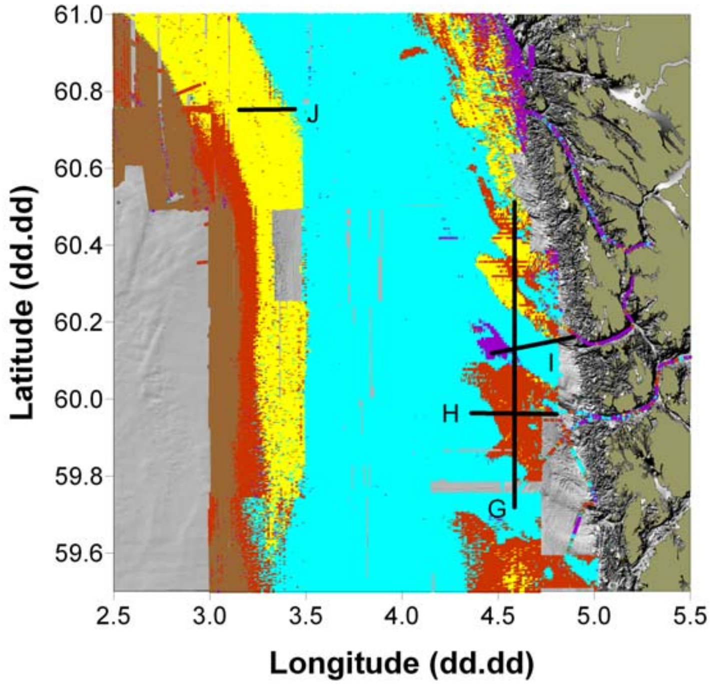

Figure 6.12 The classification results compared with parametric sonar data. The four selected transects G, H, I, and J are studied closer in the report.

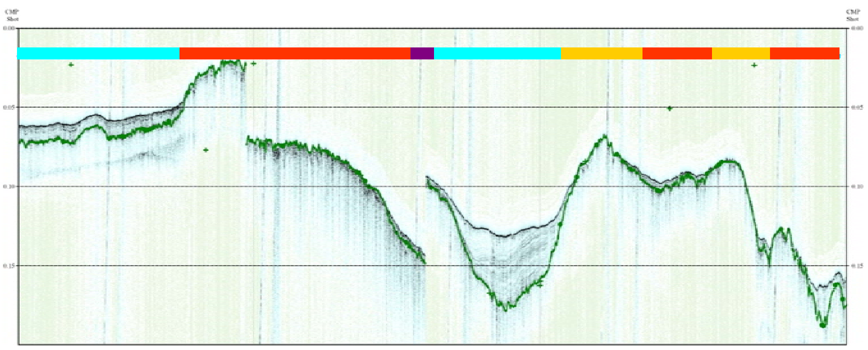

Figure 6.13 Parametric sonar profile (N-S) with QTC classes indicated with colour bars. Top moraine is shown in green. Line 59.72° N 4.59° E - 60.50° N 4.59° E. Apparent discontinuity is due to a shift in recording delay. Line labeled G in Figure 2.1. The strongly reflecting and irregular boundary corresponding to the top of the Weichselian till/moraine is indicated in green.

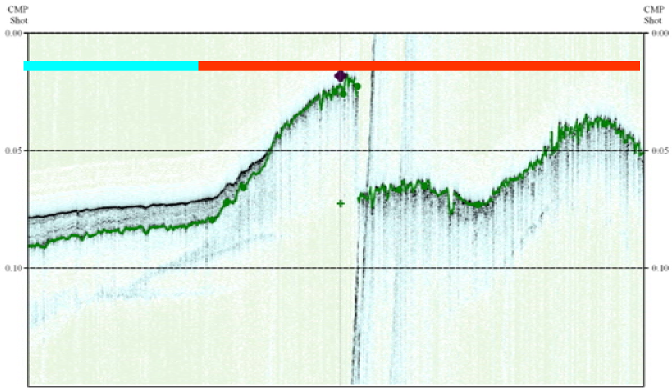

Figure 6.14 Parametric sonar profile with QTC classes indicated with color bars. Top of moraine is shown in green. Apparent discontinuity is due to a shift in recording delay. Line labeled H in Figure 2.1.

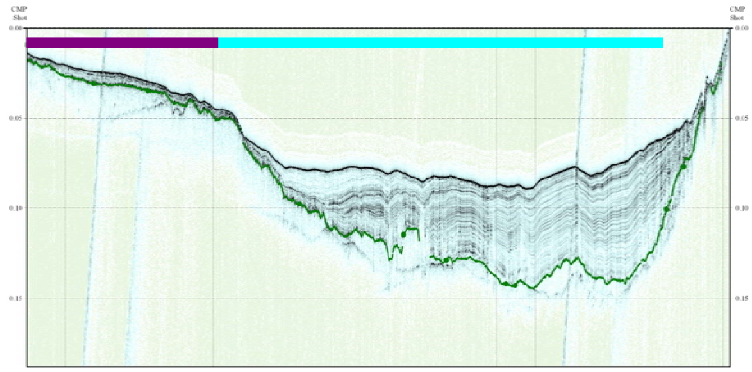

Figure 6.15 Parametric sonar profile with QTC classes indicated with color bars. Top of moraine is shown in green. Line 60.07° N 4.48° E - 60.11° N 4.89° E. Line labeled I in Figure 2.1.

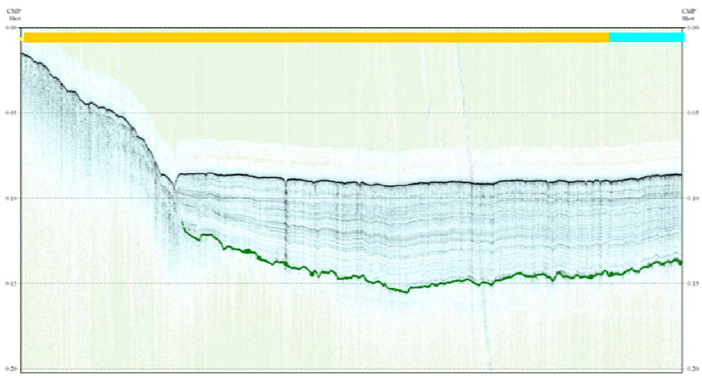

Figure 6.16 Parametric sonar profile from the NW side of the study area, with QTC classes indicated with colour bars. Line 60.75° N 3.16° E - 60.75° N 3.43° E. Line labeled J in Figure 2.1. A gravity core nearby at 60.71° N 3.39° E confirms that there is sand far into the flat area.

7 Production of AML

One of the main purposes with this study has been to produce an electronic map according to the NATO standard Additional Military Layers (AML), which may assist the Navy in sonar predictions. A preliminary map was produced based on some of the single beam backscatter data in November 2007. The process was as follows. After the classification had been carried out, the data points were median filtered in 50x50 m^2 blocks to reduce the amount of data and remove fine scale variations, and then plotted with colour codes on a relief map of the bathymetry. The data were then hand contoured to produce a vector map of polygons representing zones of roughly homogeneous bottom type. Some boundaries to the east where single beam echo sounder data was not available were drawn with the help of seismic, parametric sonar and bathymetric data (in particular crystalline rock outcrop). On the North Sea Plateau on the northwestern side, interpretation was aided by an existing Quaternary geology map [8]. The vector map was then prepared in electronic form according to the NATO standard [19;20]. The dKart Editor chart production software from Hydroservice was used for this purpose. Map objects and attributes were chosen from the Environmental, Seabed and Beach product specification [21]. Bottom zones were designated as Geological Layer. Attributes include Nature of geological layer (e.g. silt and clay) and MGS type. A suggested bottom type for the acoustic model LYBIN was also indicated [22]. The AML map was stored in S-57 format, which is the standard format for electronic navigation charts. The map was also converted so that it can be displayed and queried in the GIS program MARIA.

The AML map is not presented in this report. Since November 2007 additional areas have been surveyed and data from 2005 have been fixed to include navigation. The preliminary AML map therefore needs to be updated. Due to the termination of the FFI project Poseidon, time did not allow for this work to be done.

8 Conclusions and further work

The seabed of the Navy's exercise area in northern North Sea has been classified using the commercial software QTC Impact on single beam echosounder data. The classification results have been compared with sediment samples from the bottom and parametric sonar data. To conclude, the seabed classification results are supported by the ground truths and seismic profiles of the upper layer of the seabed.

Five sediment classes seem to be enough to represent the seabed in the area. The five classes found are (sediment classes according to Folk/NGU – dominant sediment types)

1) mud (M) and silt (Z) – mainly silt with some clay
2) sandy mud (sM) and sandy silt (sZ) – a mixture of clay, silt and sand
3) gravelly muddy sand (gmS) and gravelly sandy mud (gsM) – mainly sand, with a mixture of clay, silt and gravel
4) sand (S), silty sand (zS), sandy gravel (sG), gravelly sand (gS), gravelly, muddy sand (gmS) – sand with varying amounts of gravel
5) clay (C) and sandy clay (sC) – mainly clay, with some silt and varying amounts of sand

We find however QTC Impact to be time-consuming on the large data amounts we have processed. It is a drawback with QTC Impact that each day of data acquisition has to be processed separately. The latest version of EchoView used is fortunately reducing this problem, since larger files (and fewer files) can be imported into QTC Impact. The latest version of QTC Impact purchased by FFI has the option to import raw data directly from the echosounder, making the data processing easier. If using this version however, the feature vectors are not compatible with the feature vectors already computed from data imported through EchoView. This version is therefore recommended to use in other areas. Another drawback with QTC Impact is that the data from the Navy's exercise area have been acquired using two pulse lengths, and that the two datasets need to be processed separately in QTC Impact.

8.1 Suggestions for further work

Based on the experiences of the present work reported herein, we suggest taking more sediment samples in the western part of the Norwegian trench to investigate the transition from the turquoise class to the yellow class. This is due to difficulties with combining echosounder data with different pulse lengths, and also the fact that a transition is not evident in seismo-acoustic data, although we believe the transition is real.

In addition, we recommend taking more samples from the North Sea Plateau when surveying the remaining area to confirm that seabed sediments consist of mainly sand or if the southern part of the area contain more gravel than the far north-western corner.

It is also interesting to obtain more samples of the purple class to confirm the relatively dominance of clay and that we can distinguish between this class and the turquoise class. The red and yellow classes are also expected to be related, and more samples with grain size analysis would help in distinguishing these two classes.

With HUGIN or other autonomous unmanned vehicles video observations of the seabed is possible to achieve, which will be helpful in the seabed classification. We recommend this strongly.

Further, we suggest using other classification software on the exercise area to support and complement our work. The commercial software SeaBec from Kongsberg Maritime have been tested with promising results on a small area northwest [23]. However, SeaBec requires both 38 kHz and 200 kHz single beam data, and the better part of the exercise area is not surveyed using the 200 kHz echosounder. Hence, SeaBec can only be used processing single beam data from the western part of the exercise area. Further, we recommend processing the multibeam backscatter data from the area, either using commercial available software or studying the raw data.

When the remaining area is surveyed, we recommend finishing the seabed classification using QTC Impact.

Time did not allow for updating the electronic sediment map (AML), which thus exists only in a preliminary form. This map needs to be improved with the latest results reported herein.

Another remaining issue is how the sediment classes obtained in the present work should be represented in the LYBIN raytracing program [22] or other acoustic models. The optimal solution seems to be a map of sound velocity, density and bottom type.

Appendix A Sediment classes

The sediment classes and abbreviations of these are given in the below table. The classes are based on modified versions of Folk classification systems.

Sediment class	Definition		Abbreviation
Gravel	>80 % gravel		G
Sandy gravel	30 – 80 % gravel	Mud:sand < 1:9	sG
Muddy sandy gravel	“	Mud:sand < 1:1	msG
Muddy gravel	“	Mud:sand > 1:1	mG
Gravelly sand	2 – 30 % gravel	Mud:sand < 1:9	gS
Gravelly muddy sand	“	Mud:sand < 1:1	gmS
Gravelly sandy mud	“	Mud:sand > 1:1	gsM
Gravelly mud	“	Mud:sand > 9:1	gM
Clay	Sand < 10 %, gravel < 2 %	Clay:silt > 2:1	C
Mud	“	Clay:silt from 1:2 to 2:1	M
Silt	“	Clay:silt < 1:2	Z
Sandy clay	Sand < 50 %, gravel < 2 %	Clay:silt > 2:1	sC
Sandy mud	“	Clay:silt from 1:2 to 2:1	sM
Sandy silt	“	Clay:silt < 1:2	sZ
Clayey sand	Sand > 50 %, gravel < 2 %	Clay:silt > 2:1	cS
Muddy sand	“	Clay:silt from 1:2 to 2:1	mS
Silty sand	“	Clay:silt < 1:2	zS
Sand	Sand > 90 %, gravel < 2 %		S

Table A.1 The modified Folk classification systems used in the report. The grain size definitions of gravel, sand, silt and clay are found in Table 3.1.

References

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