NGU Report 2008.059

Volume of disposed sediments in the deep water confined disposal facility at Malmøykalven, inner Oslofjord

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REPORT

Report no.: 2008.059	ISSN 0800-3416	Grading: Open

Title:
Volume of disposed sediments in the deep water confined disposal facility at Malmøykalven, inner Oslofjord

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County: Norway	Commune: Oslo, Nesodden
Map-sheet name (M=1:250.000)	Map-sheet no. and -name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 33 Price (NOK): 225,- Map enclosures: 10

Fieldwork carried out: June 2004, April 2008	Date of report: 26.06.2008	Project no.: 301804	Person responsible: Øystein Nordgulen

Summary:

Acoustic methods including GeoSwath 250 kHz interferometric sonar and TOPAS parametric sub-bottom profiler have been used to determine the volume of dredged sediments disposed in the natural submarine depression at Malmøykalven in the inner Oslofjord since the beginning of the Oslo harbor remediation project in 2006. This natural depression that has a threshold at 66 m towards the north-east, and which had a maximum water depth of 72 m before the start of the remediation project, is used as a deep water confined disposal facility (CDF). Calculation of the volume of disposed sediments in the CDF is based on elevation change, derived from two high-resolution bathymetric datasets obtained in 2004, i.e. before the onset of the remediation project, and on April 1-7, 2008. Seismic profiles through the CDF have been used to estimate the settling of the original seabed, caused by loading-induced dewatering and compaction of the seabed sediments below the disposed masses.

Detailed bathymetry and backscatter data demonstrate the lateral spread of disposed sediments within a well-confined area covering ca. 195 000 m^2. The sea bottom within this area is distinctly softer than the surrounding seabed as shown by very low acoustic backscatter amplitude, signifying a very loose character of disposed sediments. The thickness of disposed sediments reaches 6 m in the deepest part of the original depression. The volume calculation of disposed sediments in the CDF, based solely on bathymetric data, gives a value of ca. 310 000 - 320 000 m^3. Settling of the original seabed as a result of loading has been estimated to be 30 cm at 5 m of disposed sediments. Under the condition that the settling rate is linearly correlated with the thickness of disposed sediments, the settling-corrected volume of disposed sediments is ca. 330 000 - 340 000 m^3.

The results presented in this report show high accuracy and good reproducibility of acoustic seafloor data, and indicate a great potential of such methods as monitoring tools in environmental projects that involve dredging and subaqueous disposal.

Keywords: Marine geology	Seabed sediments	Dredged material
Bathymetry	GeoSwath	Seismic profiling
Topas	Sediment sampling	Deep water confined disposal facility (CDF)

CONTENTS

FIGURES

Figure 11. Backscatter amplitude of the seafloor allows outlining of the area covered with disposed sediments. The disposed sediments have typically low backscatter amplitude due to their very soft nature.

Figure 12. Change in seafloor elevation from 2004 to 2008 in the area covered with disposed sediments. The data are not corrected for the offset between datasets. Shaded-relief image of the 2008 dataset is given at the background. The shaded-relief image clearly shows seafloor topography and irregularities. Note that old slide deposits related to a slide scar at the northern margin of the disposal area are partly covered by disposed sediments. Also note numerous ship wrecks and the irregular seafloor due to earlier dumping activities northeast of the disposal area.

Figure 13. Histograms of seabed elevation differences between the 2004 and 2008 datasets in three reference areas of 22871 m^2 each (Fig. 9).

Figure 14. TOPAS seismic reflection profile (NGU0803148) across the CDF. Lower panel includes seafloor elevation lines from the 2004 and 2008 sonar datasets. Location of the profile is given on Fig. 6..

Figure 15. TOPAS seismic reflection profile (NGU0803163) across the CDF. Lower panel includes seafloor elevation lines from the 2004 and 2008 sonar datasets. Location of the profile is given on Fig. 6.

Figure 16. Thickness of disposed sediments in cores, superimposed on the isopach (thickness) map derived from acoustic data. Shaded-relief image of the 2008 dataset is given at the background. Thickness data from the Niemistö cores at the margins of the CDF show a reasonable correspondence with acoustic data. Thickness of disposed sediments in gravity cores is, however, considerably smaller than calculated from the acoustic data. Many Niemistö cores and two gravity cores did not penetrate down to the base of the disposed sediments. The thickness of recovered disposed sediments is shown for these stations, and the symbol ">" denotes that the actual thickness is greater.

Figure 17. Contact between disposed sediments and natural sediments (at 63 cm) in gravity core 0803028. Gray to black disposed sediments (right hand part of the core), mainly mud, are commonly banded/laminated and contain sandy and gravelly interlayers. Natural olive gray mud (left hand part of core) is typically homogeneous, bioturbated, and has ca. 5 cm black, organic-rich layer at the top (57-63 cm).

Figure 18. Gravelly interlayer (at 80 cm) within finely banded/laminated, disposed sediments in core 0803030.

Figure 19. Thickness of disposed sediments in the CDF. Calculated thicknesses include corrections for settling of the original seabed and the offset (5 cm) between the 2004 and 2008 bathymetric datasets. Shaded-relief image of the 2008 dataset is given at the background.

TABLES

Table 1. Calculated volume changes at the seabed in three reference areas (Fig. 9). The elevation difference between the 2004 and 2008 datasets was corrected for a systematic error, considered to be 5 cm (see Fig. 13). Assuming that the real volume changes in the reference areas have been insignificant, the calculated volume changes give a measure of analytical uncertainties in volume estimates. The calculated volume changes in the reference areas were up-scaled to the area covered with disposed sediments (194 693 m^2) to assess the effect of analytical uncertainties in volume estimation of disposed sediments. Note that the apparent volume change in the CDF is primarily influenced by the offset value, and the apparent volume change is negligible when the offset is correct.

Table 2. Physical properties of natural seabed sediments (green shading) and disposed sediments in four gravity cores (0803029-0803030, 0803033) and five Niemistö cores (0803034-0803038). For core localities see Fig. 8.

Table 3. Calculated volume changes in the area of the CDF with disposed sediments (194 693 m^2) using different offset values between the 2004 and 2008 bathymetric datasets and applying correction for settling. An offset value within the range -5 to -10 cm is considered most reliable.

1 INTRODUCTION

The Oslo harbor remediation project aims at dredging significant amounts (originally planned 700 000 m^3) of contaminated sediments from the shallow areas of the harbor. These dredged sediments are disposed in the deep water confined disposal facility (CDF) at Malmøykalven in the Bekkelag Basin (Figs. 1,2). Seabed elevation/bathymetry changes caused by dredging and aquatic disposal of sediments can be documented at high-resolution using acoustic techniques such as multibeam echosounder and interferometric sonar (cf. Gostnell, 2005).

However, the relevance of these techniques in monitoring elevation changes and related volumes of disposed sediments in the CDF at Malmøykalven has been a matter of debate. Using the available sonar and multi-beam echosounder data, it was calculated that the CDF contained 158 000 m^3 of disposed sediments on July 9, 2007, which was considerably less than the reported volume of dredged and disposed sediments (209 000 m^3 on July 12, 2007) (note to Norwegian Pollution Control Authority from Innbyggerinitiativet på Nesodden). Based on this discrepancy it was argued that significant quantities of contaminated sediments were discharged into the fjord either during dredging and transport to the CDF, or were remobilized from the CDF by currents. This environmentally worrisome supposition of spreading of significant amounts of contaminated sediments was, however, in disagreement with the results obtained in the CDF's monitoring programs run by the Norwegian Geotechnical Institute (NGI) and the Norwegian Institute for Water Research (NIVA) that have indicated very limited spreading of disposed sediments.

To provide insights into the discussion on applicability of acoustic methods as a tool for assessing the volume and lateral extent of disposed sediments in the area of the CDF at Malmøykalven, the Geological Survey of Norway (NGU) decided to perform an independent research project to map the CDF and calculate the volume of disposed sediments. This initiative found support with the Norwegian Pollution Control Authority (SFT), who decided to co-fund the CDF mapping project.

New acoustic data acquired in the period April 1-7, 2008 are complementary to the large dataset that was obtained in 2004 and 2005, when NGU undertook high-resolution seabed mapping of the entire inner Oslofjord (Fig. 1). The basin at Malmøykalven was mapped in June 2004 as part of this major effort, and the dataset obtained then provides a record of the seabed within the CDF before the onset of the Oslo harbor remediation project in February 2006. Volume assessment of disposed sediments in the CDF presented in this report is based on comparison of two high-resolution bathymetric datasets (2004 and 2008) obtained by GeoSwath interferometric sonar. Seismic data acquired with TOPAS parametric sub-bottom profiler are used for correcting the volume for settling. Seabed backscatter intensity in combination with the elevation change data allows evaluation of the lateral spread of disposed sediments.

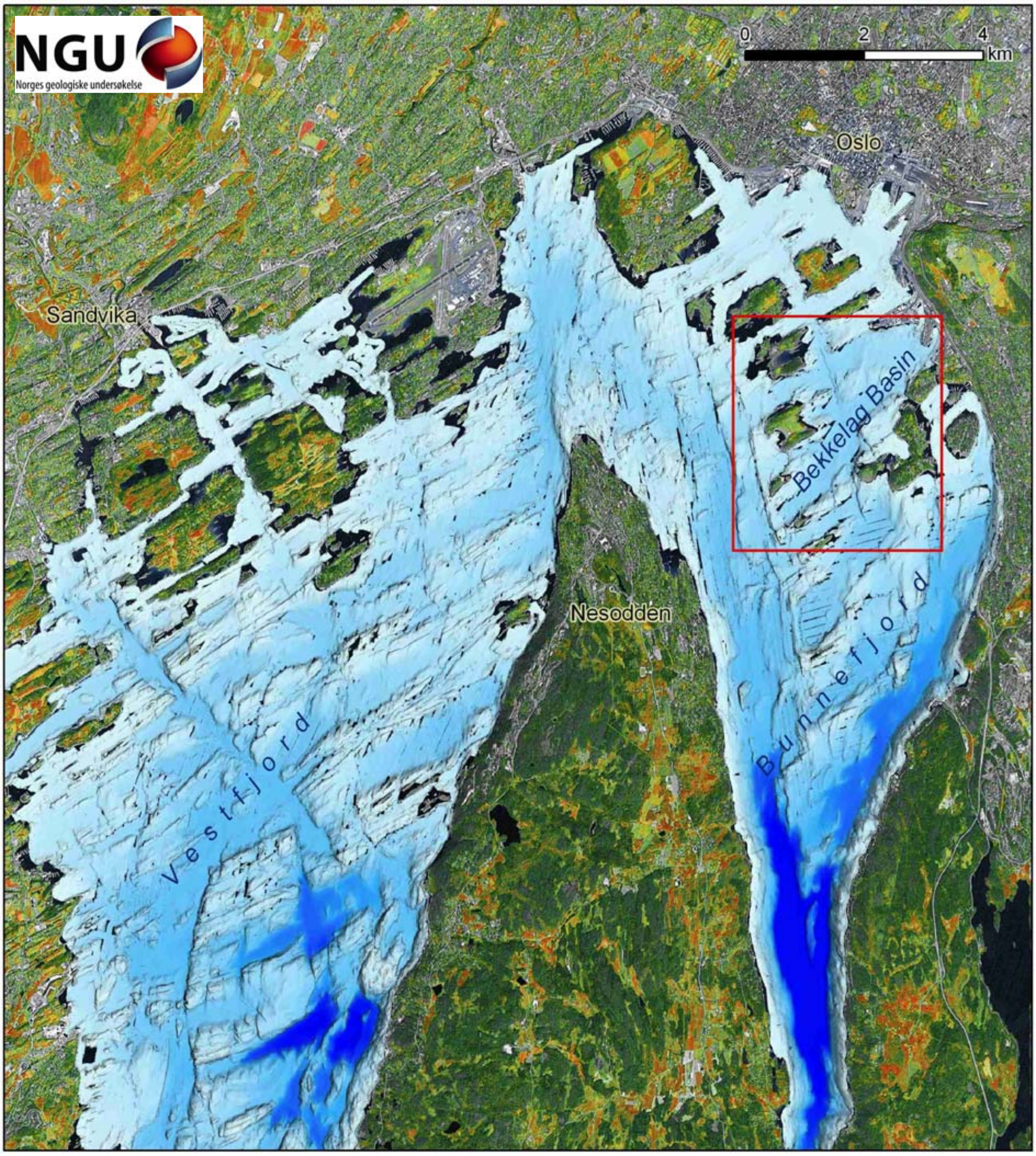

Figure 1. Depth-colored shaded-relief image of the northern part of the inner Oslofjord. Data are derived from the high-resolution bathymetric datasets collected by the Geological Survey of Norway (water depth 0-80 m) and the Norwegian Defense Research Establishment (water depth > 80 m). The red box gives the position of the Bekkelag Basin shown on Fig. 2 that is the study area treated in this report.

2 STUDY AREA

Seabed topography in the study area is strongly influenced by the Early Paleozoic stratified metasedimentary rocks that form the bedrock in a large part of the northern Oslofjord. NE-SW-striking Early Paleozoic limestones, sandstones and shales have variable competence and resistance to alteration. Selective erosion of less resistant strata has formed a pattern of NE-

SW trending depressions and ridges at the seabed (Fig. 1). Numerous faults, fractures and mafic dykes cut the Early Paleozoic metasediments nearly perpendicular to the strike, and create a set of NW-SE extending depressions and ridges (Fig. 1).

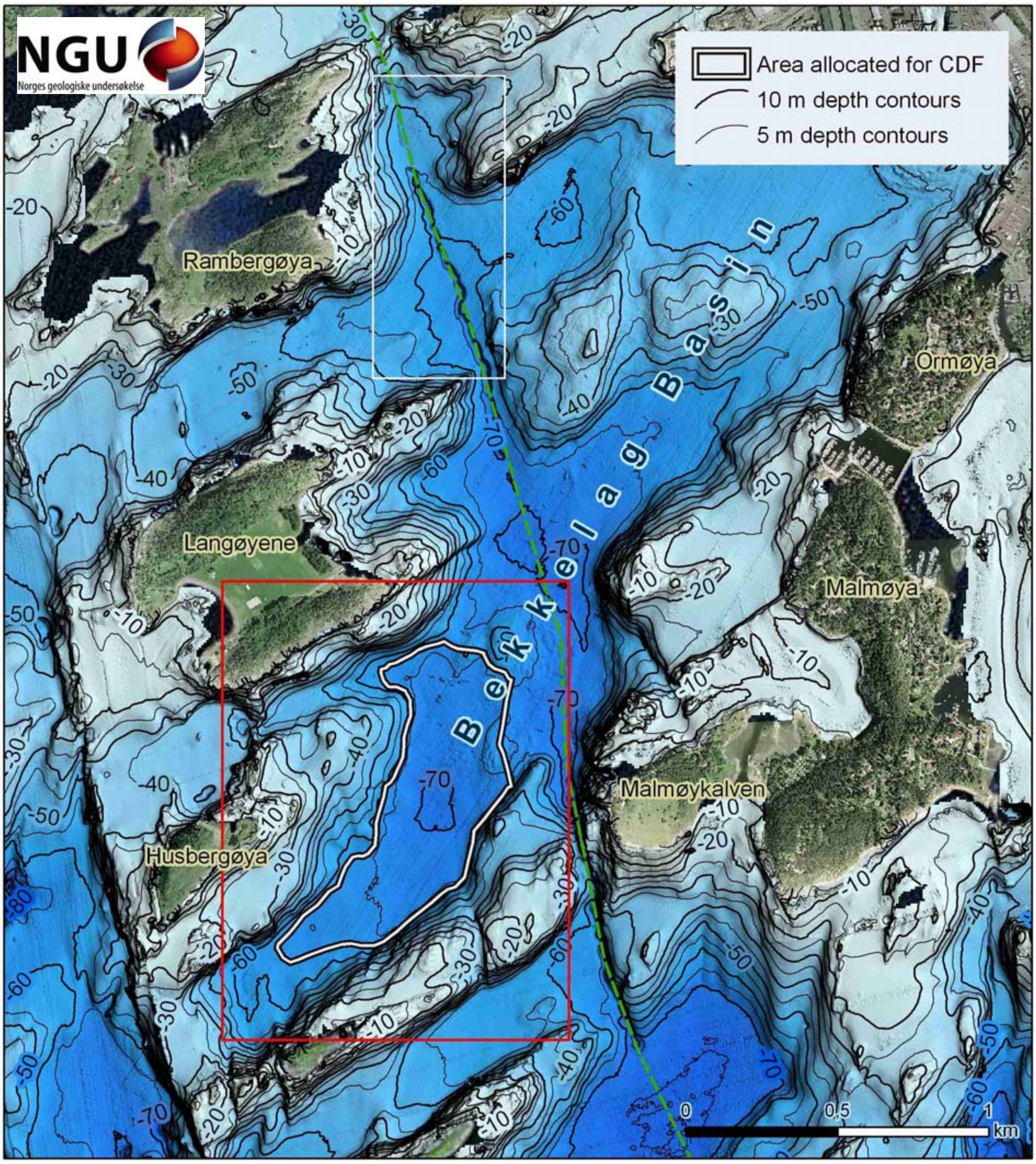

Figure 2. Depth-colored shaded-relief image with depth contours of the Bekkelag Basin in 2004. The red rectangle gives the position of the CDF area shown in Fig. 3. Green dashed line shows the location of a major fault/permeable fracture that cuts across the Bekkelag Basin. Pockmarks, illustrated by the 3D model from the area of the white rectangle (Fig. 4), are common along this fault.

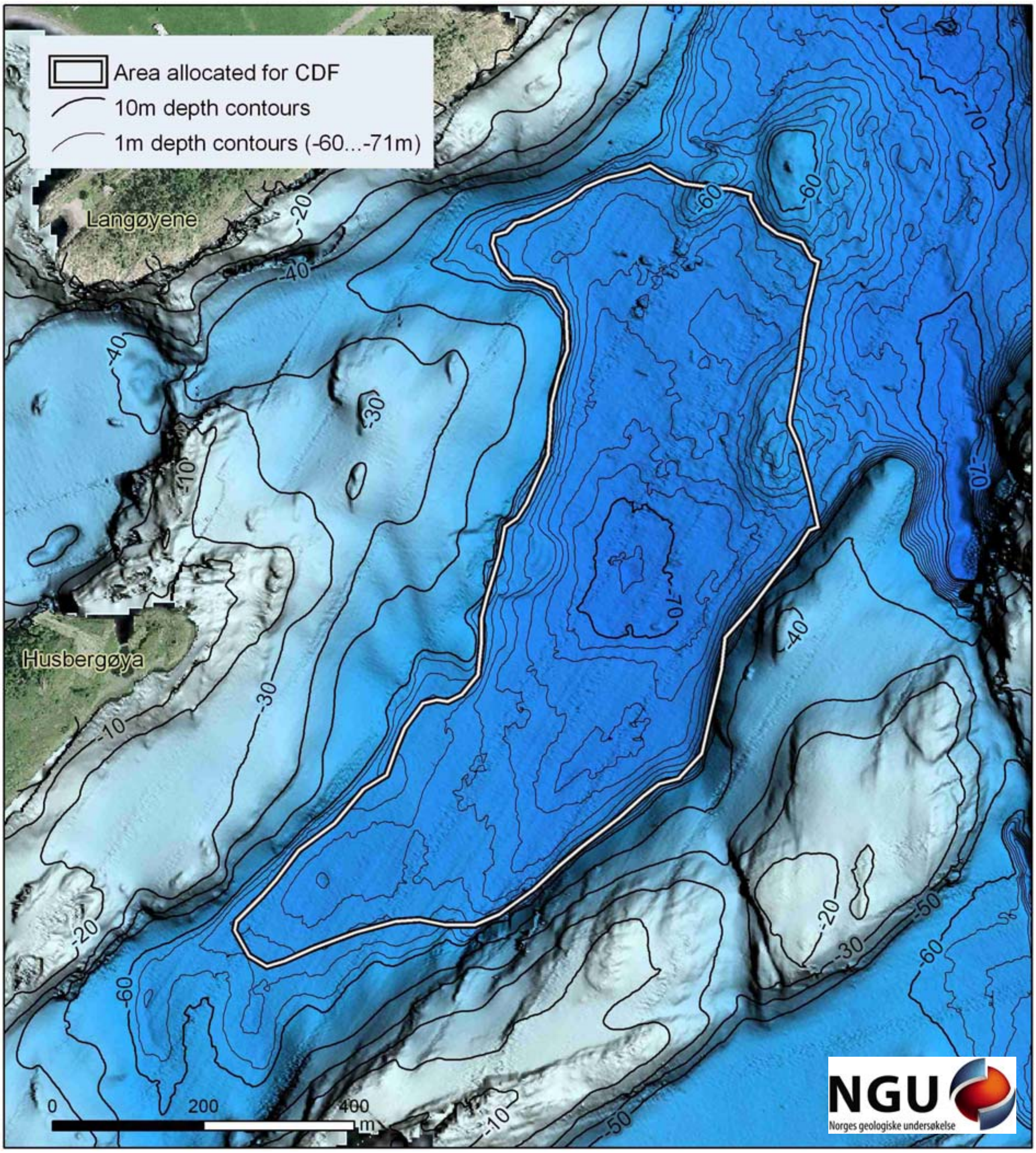

Figure 3. Depth-colored shaded-relief image with depth contours of the CDF area in 2004.

The SW-NE trending depression in the southwestern part of the Bekkelag Basin that is being utilized as a CDF, is bordered by ridges of Paleozoic metasedimentary rocks in the north and the south, and by a N-S trending mafic dyke in the west (Fig. 2). This depression has a threshold at 66 m depth towards the main body of the Bekkelag Basin in the northeast, and had a maximum water depth of 72 m before the remediation project started (Figs. 2, 3). The threshold area was used as a dumping site for dredged sediments and shipwrecks in the middle of the last century. This dumping has elevated the seabed in the area and artificially created a threshold. The result is an irregular, bumpy and wavy seabed with numerous shipwrecks that stick out (Fig. 3). The northern slope of the CDF basin has experienced submarine sliding with a prominent slide scar at 48 m depth, and a slide lobe with typical wavy morphology extending down to 69 m depth in the basin (Fig. 3). The slide lobe is largely buried beneath the sediments currently being disposed (Fig. 3).

A major, NW-SE trending fault/permeable fracture cuts through the metasedimentary rocks of the Bekkelag Basin ca. 300 m east of the CDF. Pockmarks, i.e. 5-8 m deep crater-like depressions with ca. 60 m diameter that form in connection with fluid escape from underlying sediments and bedrock, are common along this fault. Tens of closely spaced individual pockmarks are merged and arranged in chains to form elongated, up to 1500 m long composite pockmarks (Fig. 4). The sediment stratigraphy indicates that these pockmarks are currently active. The latest fluid escape has formed a coarse-grained, sand- and gravel-dominated lag deposit in the pockmark, whereas muddy, fine-grained components that were remobilized and thrown out from the pockmark accumulated on the adjacent seabed. Five centimeters of black mud has accumulated in the pockmark and on the adjacent seabed since the last outburst. Sedimentation rate estimates using data from three nearby cores dated by the ^{210}Pb-method suggest that the last outburst in the large composite pockmark in the Bekkelag Basin occurred ca. 15-20 years ago. No pockmarks have been found at the seabed allocated for the CDF.

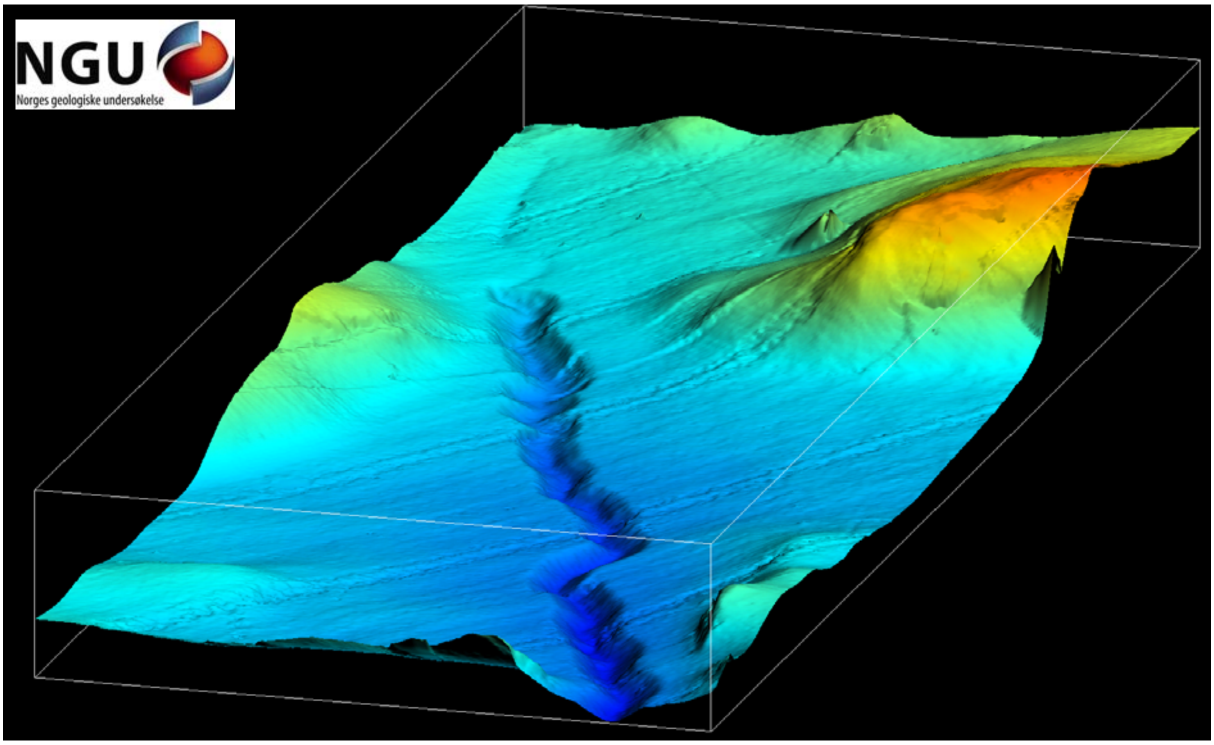

Figure 4. Depth-colored shaded-relief 3D model of a composite pockmark above the fault/permeable fracture cutting the bedrock of the Bekkelag Basin. The diameter of individual pockmarks within the composite pockmark is ca. 60 m, and the depth is ca. 6m. See Fig. 2 for location.

3 METHODS AND MATERIALS

3.1 Interferometric sonar

The seabed in the Bekkelag Basin was mapped during two cruises in June 2004 and April 2008 with NGU's research vessel "FF Seisma" using the GeoAcoustics 250 kHz GeoSwath interferometric sonar. This sonar produces high-resolution bathymetric and backscatter data from the water depth range 0-80 m. The sonar has two transducers mounted on a V-plate at 30 degrees to vertical that alternately collect the signal. A sound velocity probe, a single beam echosounder, and a motion reference unit (MRU) for measuring heave, pitch and roll are also fitted to the V-plate (Fig. 5). Each transducer is equipped with one transmitter stave and four phase differencing interferometric and sidescan receiving staves. All four receiving staves record time series of the returning echo from the ensonified area. The relative phase and phase delay between the four staves is used for determining the angle of returning echo, which combined with the elapsed time, permits calculation of the distance to the scattering location at the seabed. The amplitude of the signal provides backscatter information, which is a measure of the relative hardness of the seabed. The across track sampling density of the GeoSwath system is 1.5 cm, and vertical resolution is estimated to be ± <2 cm (GeoAcoustics 2004). Vessel speed during the profiling was 4 knots, which with a ping rate of ca. 6 pings sec^{-1} gives along-track resolution of ca. 65 cm. Line spacing during the 2004 and 2008 sonar surveys were 140 m and 60 m, respectively. This implies that recordings from adjacent survey lines have limited overlap in the 2004 dataset whereas a full overlap (double coverage) was obtained in the 2008 survey. Consequently the 2008 dataset is of higher quality.

In order to correct for sound velocity variations and refractive effects in the water column due to temperature and salinity differences, two types of sound velocity measurements were undertaken. Valeport Mini SVS sound velocity probe, mounted on the sonar head, provided a continuous, real-time sound velocity record during acquisition. Sound velocity profiles with 25 cm vertical resolution from the surface down to the seafloor were obtained several times every day at different parts of the survey area using a Valeport 650 SVP (Sound Velocity Profiler). Sub-metre accuracy for horizontal positioning was accomplished by a Trimble differential GPS system. A gyrocompass, connected to the DGPS was used to obtain heading data. For calibration of the sonar for roll, latency, pitch and yaw, four calibration lines were run in the area of gently sloping seabed in water depth range 30-50 m. The calibration parameters were found using GeoSwath calibration software.

The sonar data were filtered for water column noise below the transducer during acquisition. All data processing operations including (i) filtering for outliers, (ii) calibration for sonar parameters, (iii) sound velocity corrections, (iv) tidal corrections, (v) navigation check, and (vi) gridding with 1 m cell size were done with GeoSwath software. The sea level time series from Oslo harbour, measured by the Norwegian Mapping Authority, were used for the tidal corrections.

Figure 5. Sonar head with dual transducers mounted at 30 degrees to the vertical. The red device at the top of the photo is a single beam echosounder whereas the device at the side of it is a sound velocity probe.

Volume calculations of disposed sediments in the CDF are based on seafloor elevation differences between 2004 and 2008. Bathymetric datasets (1 m grids) were subtracted from each other using the Formula Editor tool in ER Mapper. The resulting 1 m grid of elevation change was imported into ArcGIS in which volume calculations and offset corrections were made using Spatial Analyst's Surface and Math tools.

3.2 Parametric sub-bottom profiler

High-frequency shallow seismic data were acquired using parametric sub-bottom profiler (Topas PS 40 from Kongsberg) simultaneously with the acquisition of sonar data. Positions of seismic lines that run through the area with disposed sediments are shown on Fig. 6. Topas uses a parametric acoustic source that forms a 5 degrees wide beam. The profiler was operated in the chirp mode with primary frequency of 38 kHz. The returning signal was sampled within the frequency range of 2-8 kHz with the median frequency of 5 kHz. Such secondary frequency provides a vertical resolution of ca. 0.2 milliseconds (ca. 15 cm). An acoustic velocity of 1520 m/s that has been measured in soft surface sediments of shelf seas (Hamilton 1979, Orsi & Dunn 1991, Kim et al. 2001) was used for assessing thicknesses of disposed sediments.

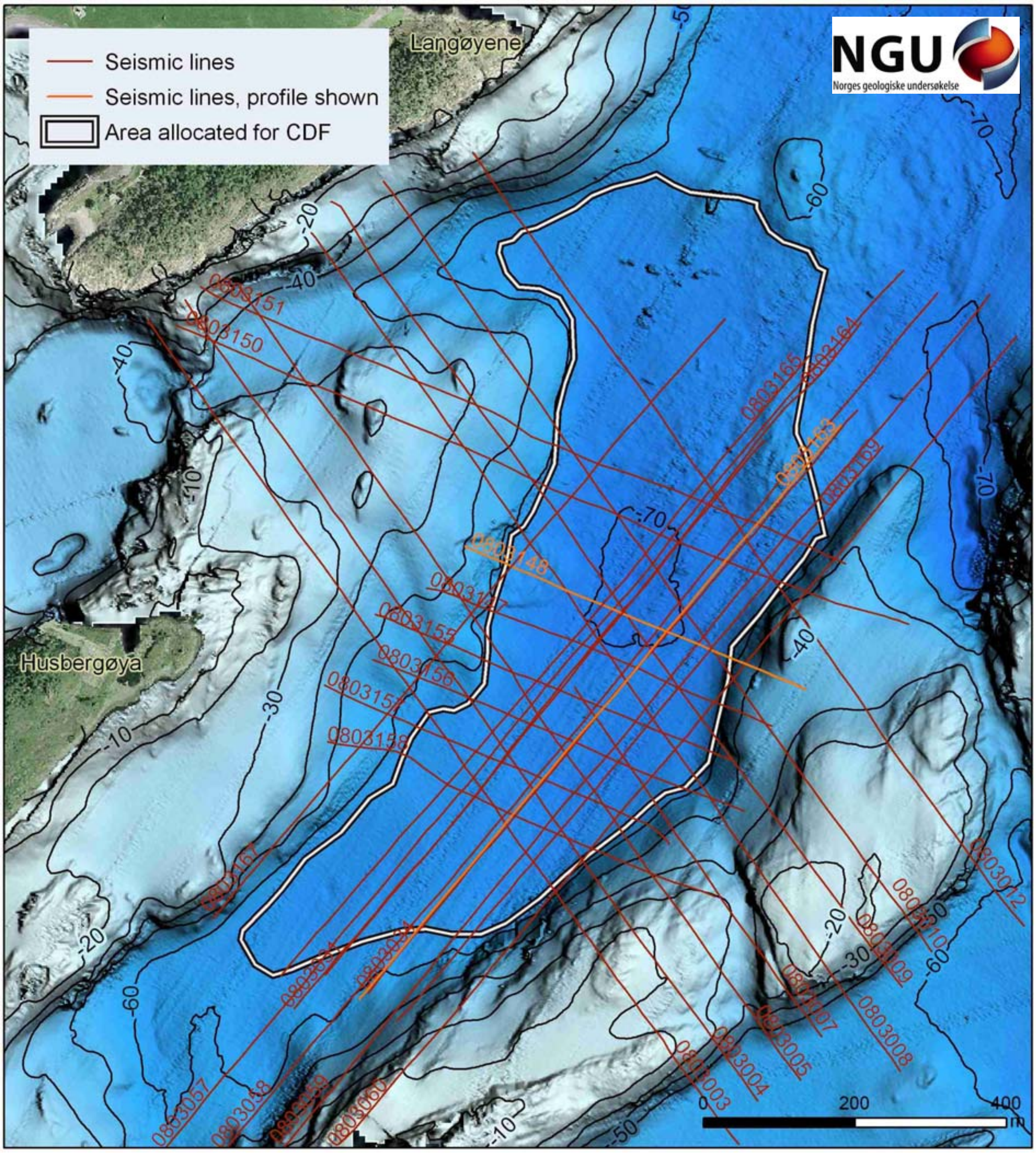

Figure 6. Locations of TOPAS shallow seismic profiles in the area of the CDF.

3.3 Sediment cores and determination of physical properties of sediments

The thickness, stratigraphy and physical properties of disposed sediments were investigated with the help of sediment cores that were obtained using gravity corer and Niemistö sampling device (Niemistö 1974). Transparent PVC liner was used in both sampling devices. This enabled quick examination, through the core liner, of disposed sediments and the contact to the underlying natural sediments (Fig. 7). Six gravity cores with diameter of 98 mm and lengths from 1.40 to 2.55 m were obtained (Fig. 8). Four gravity cores were capped and saved for density and water content determinations in the laboratory, whereas two gravity cores were opened and sedimentologically described onboard. Niemistö sampling was attempted at 32 localities (Fig. 8), but failed at two localities (0803012 and 0804027). This device uses 63 mm liner, and enables to collect up to 1.2 m long cores with relatively undisturbed sediment-water interface. Twenty six Niemistö cores were described onboard, and five were saved for laboratory examination.

Figure 7. Contact between dark gray disposed sediments and underlying olive gray original seabed sediments seen through the plastic liner in gravity (left) and Niemistö (right) cores.

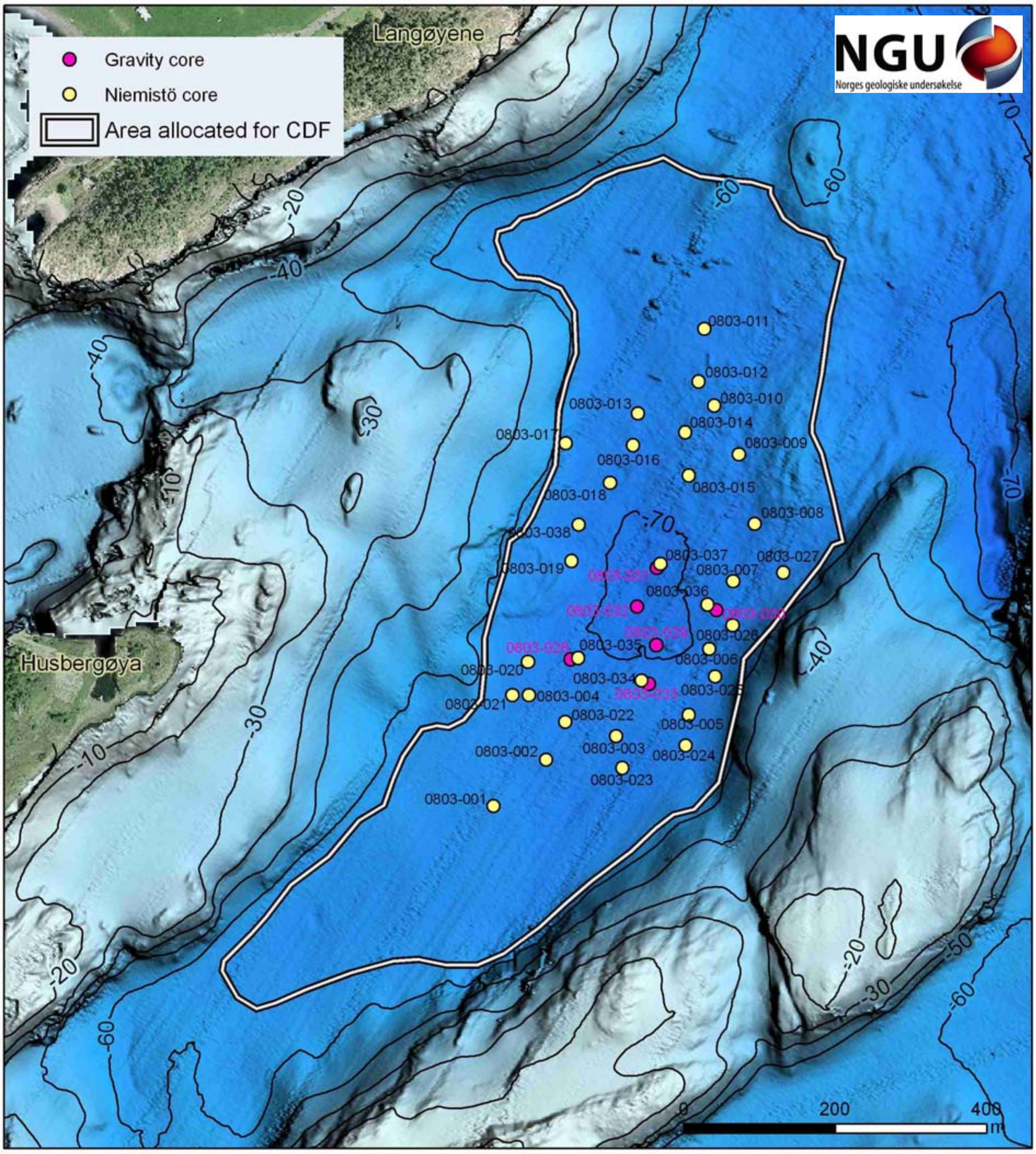

Figure 8. Locations of sampling stations in the CDF.

In the laboratory, cores were fixed vertically, and a piston was used to push the sediment out of the core liner (up to 20 cm long sections). Individual sections were placed on the laboratory bench, lithologically logged and subsampled. Sediment water content, wet density and dry density were determined with the aid of a thin-walled steel cylinder with known volume (7.12 cm^3). This cylinder was inserted into the sediment and known volumes of wet, undisturbed sediments were subsampled. Weights of wet and dry (drying at 70 ºC for 24 hours) subsamples, combined with the known volume, allowed calculating water content, wet density and dry density according to the following formulas:

Water content = Weight of pore water / Weight of dry sediment

Wet density = Weight of wet sample / Volume of wet sample

Dry density = Weight of dry sample / Volume of wet sample

4 RESULTS

4.1 Elevation changes and seafloor backscatter

The sonar data collected during the cruise in April 2008 (Figs. 9, 10) demonstrate that the seafloor in the deepest part of the basin used as a CDF has been elevated up to 6 m during the course of the Oslo harbor remediation project. Disposed sediments are considerably softer than the natural sediments in the area, resulting in distinctly lower backscatter response (Fig. 11). Both the elevation change and backscatter characteristics of the seafloor allow assessment of the lateral extent of disposed sediments in the CDF, which are estimated to cover an area of ca. 195 000 m^2 (Figs. 10, 11, 12).

The accuracy of the bathymetric data is assessed with depth deviation histograms (Fig. 13) from three reference areas (Fig. 9) of relatively flat seabed (water depth 60-70 m) outside the CDF. The histograms were made using bathymetry from the 2004 and 2008 datasets. Neglecting the natural sedimentation after 2004 (a few millimeters per year), and considering that these areas have not been affected by disposed sediments as indicated by the backscatter data (Fig. 11), the histograms should peak at or near 0 m deviation. The obtained histograms show a slight deviation of the mean towards positive values (0.04, 0.05 and 0.09 m), and demonstrate a nearly symmetrical distribution with standard deviation < 0.2 (Fig. 13). Such cm-scale variations between the 2004 and 2008 datasets indicate a good match.

Numerous factors, including spatial and temporal variations in sound velocity profiles, imperfect calibration and vessel's loading may contribute to small discrepancies between datasets. The fact that all three reference areas show a consistent positive mean deviation value suggests a systematic 4-9 cm error between datasets. The 2008 elevation model is 4-9 cm higher than the 2004 model, but it remains to be assessed which of these models is more accurate. However, the symmetry of the distribution about the peak (Fig. 13) indicates that slightly inaccurate measurements at both sides of the mean compensate each other, and should not cause a significant error in volume calculations using these bathymetry datasets.

In order to assess the error margin in volume calculations due to such inaccuracies in the bathymetric datasets, volume calculations where undertaken in all three reference areas. Ideally these calculations should show limited if any volume change. The elevation changes, corrected for a chosen 5 cm systematic offset between datasets, yield a small calculated volume loss in area A, and volume gain in areas B and C (Table 1). The calculated volume changes in the reference areas are primarily dependent upon the offset between datasets, and calculations give negligible volume changes when applied offset correction is correct (Area B, Table 1).

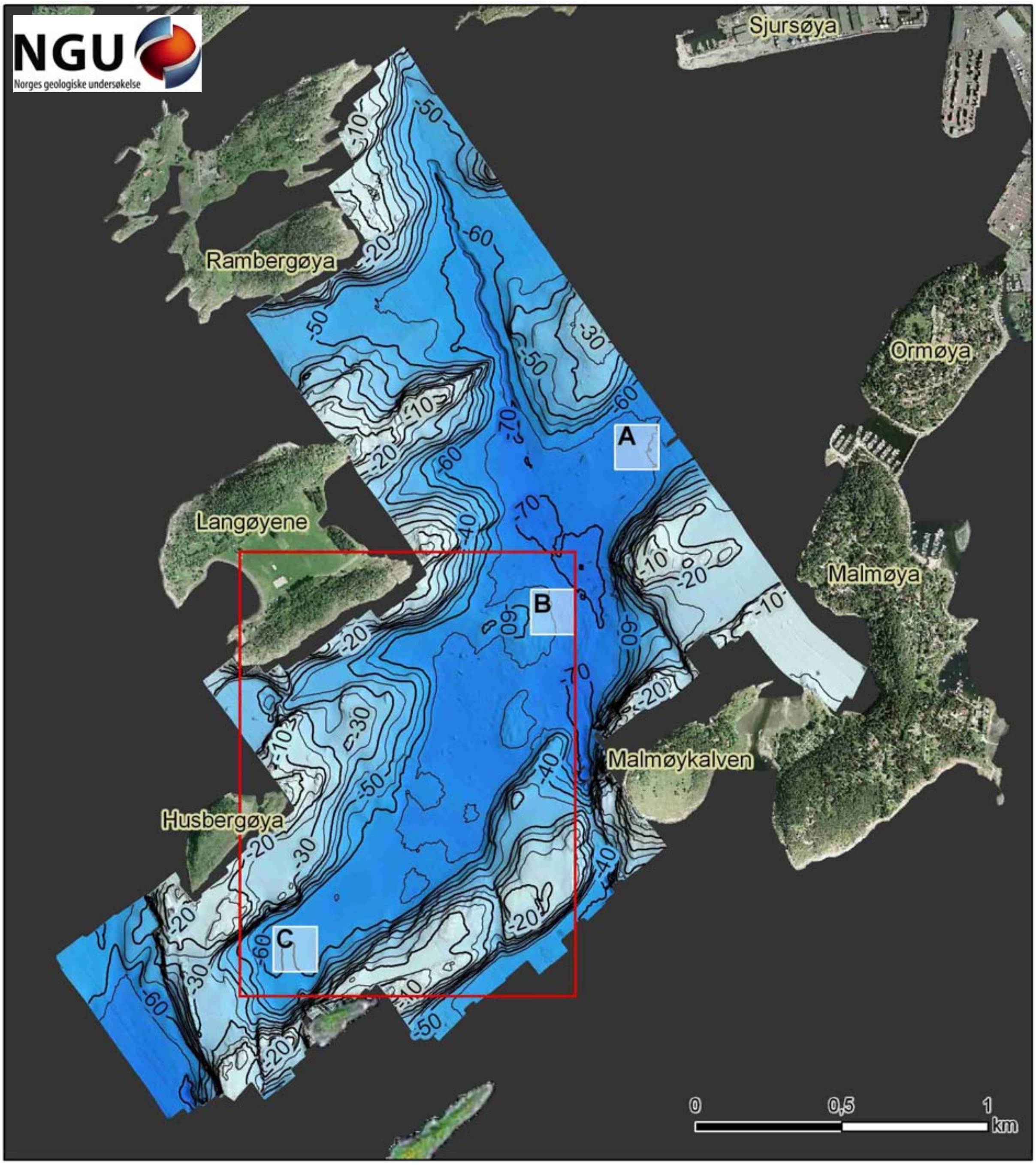

Figure 9. Depth-colored shaded-relief image with depth contours of the area of the Bekkelag Basin mapped in 2008. The red rectangle shows the position of the CDF area shown in Fig. 10. White rectangles outline reference areas A, B and C that were used for assessing the match between the 2004 and 2008 datasets (Fig. 13).

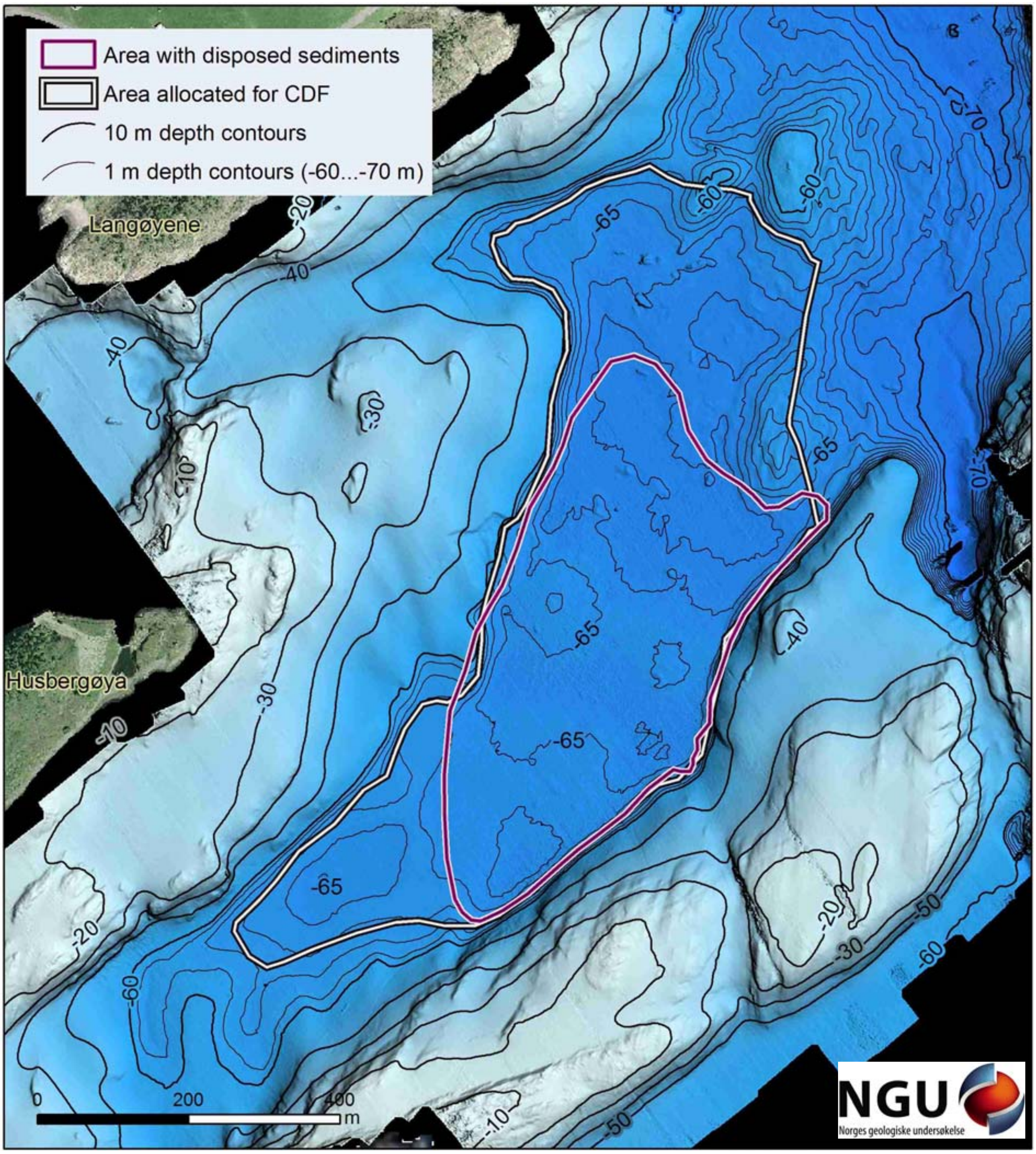

Figure 10. Depth-colored shaded-relief image with depth contours of the CDF area in April 2008.

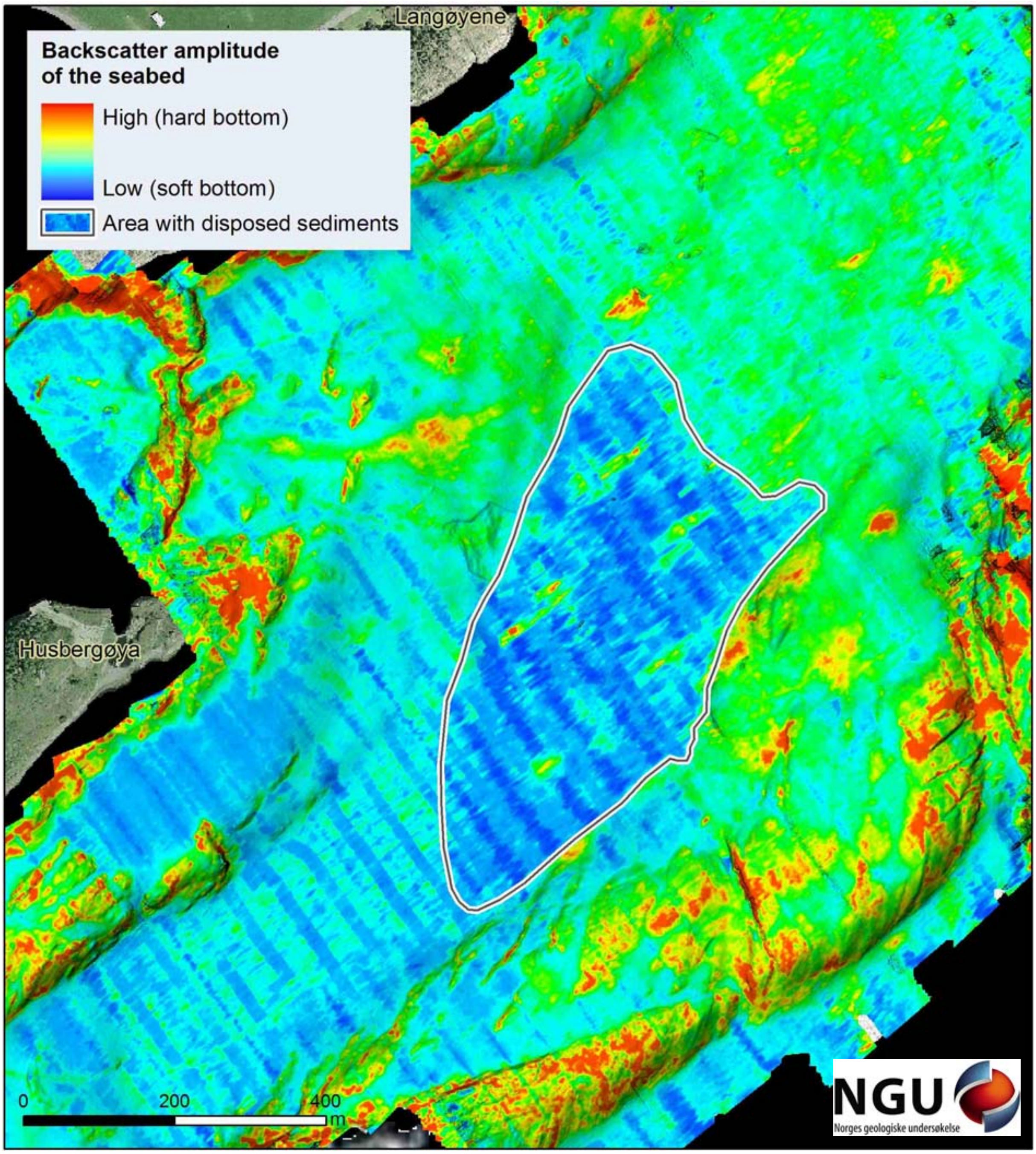

Figure 11. Backscatter amplitude of the seafloor allows outlining of the area covered with disposed sediments. The disposed sediments have typically low backscatter amplitude due to their very soft nature.

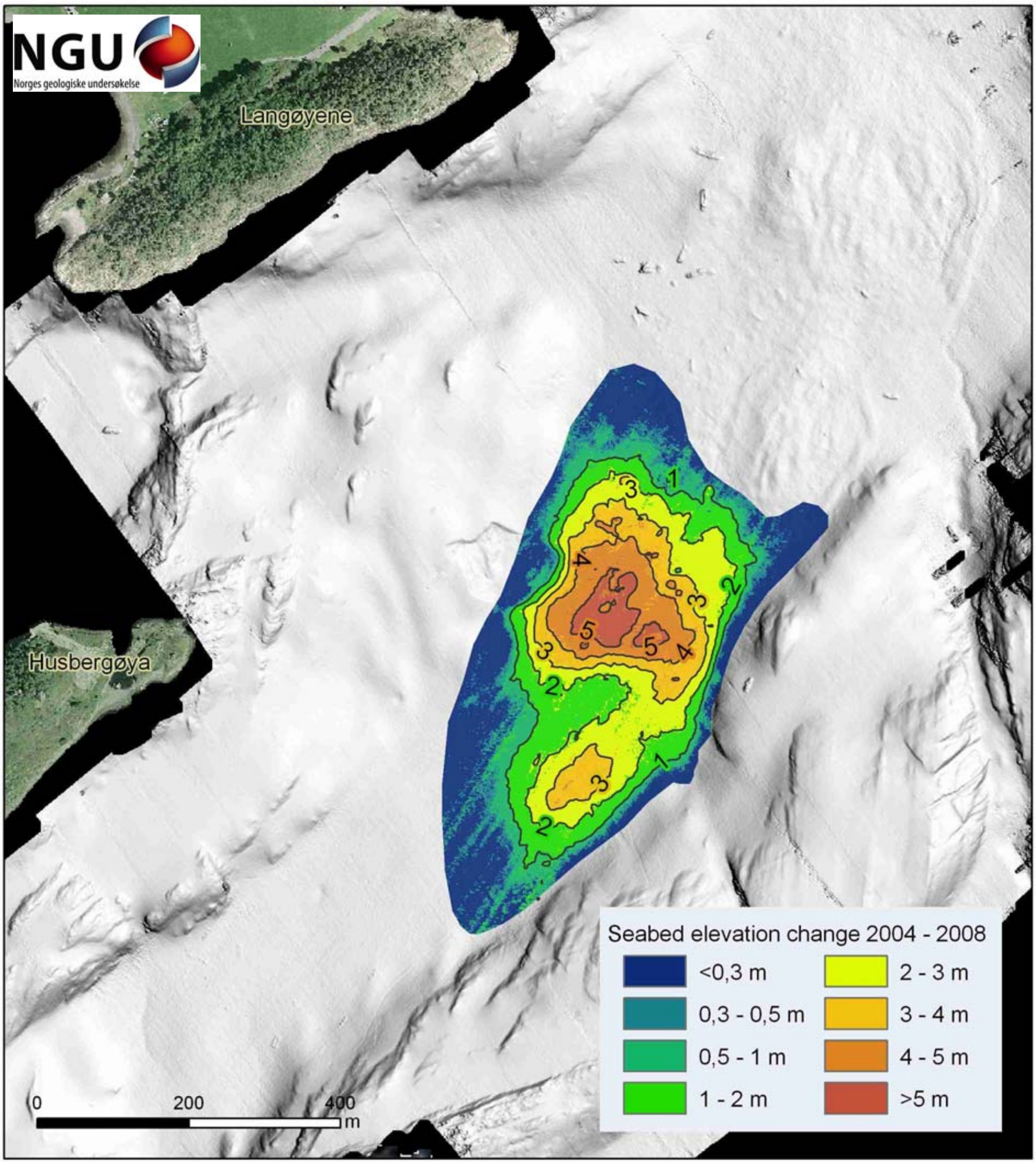

Figure 12. Change in seafloor elevation from 2004 to 2008 in the area covered with disposed sediments. The data are not corrected for the offset between datasets. Shaded-relief image of the 2008 dataset is given at the background. The shaded-relief image clearly shows seafloor topography and irregularities. Note that old slide deposits related to a slide scar at the northern margin of the disposal area are partly covered by disposed sediments. Also note numerous ship wrecks and the irregular seafloor due to earlier dumping activities northeast of the disposal area.

Assuming that the systematic offset between the bathymetric datasets in the CDF area is comparable to the reference areas, up-scaling of apparent volume changes in the reference areas (22871 m^2) to the area covered with disposed sediments (194 693 m^2) allows to assess the measurement related error in volume calculations using sonar data. The calculations indicate that if the sonar data in the area of disposed sediments had the same offset between datasets (5 cm) and deviation from the mean as in reference area A, then this would result in erroneous underestimation of disposed sediments by 1592 m^3. The analogy with reference area C would on the other hand, give erroneous overestimation of disposed sediments by 7346 m^3 (Table 1).

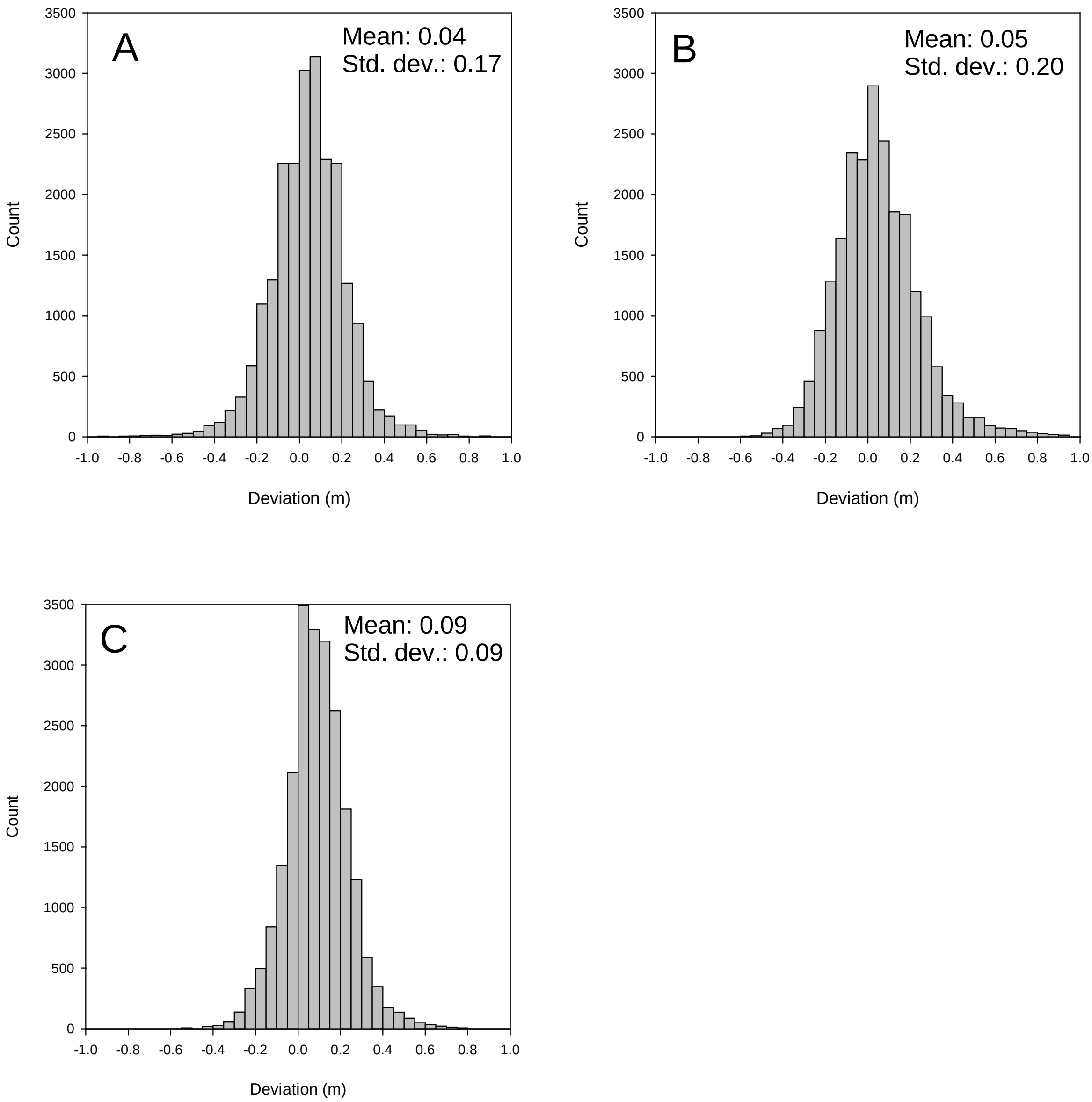

Figure 13. Histograms of seabed elevation differences between the 2004 and 2008 datasets in three reference areas of 22871 m^2 each (Fig. 9).

Table 1. Calculated volume changes at the seabed in three reference areas (Fig. 9). The elevation difference between the 2004 and 2008 datasets was corrected for a systematic error, considered to be 5 cm (see Fig. 13). Assuming that the real volume changes in the reference areas have been insignificant, the calculated volume changes give a measure of analytical uncertainties in volume estimates. The calculated volume changes in the reference areas were up-scaled to the area covered with disposed sediments (194 693 m^2) to assess the effect of analytical uncertainties in volume estimation of disposed sediments. Note that the apparent volume change in the CDF is primarily influenced by the offset value, and the apparent volume change is negligible when the offset is correct.

Ref. area	Deviation of mean between datasets, corrected for 5 cm offset (cm)	Calculated volume change (m^3)	Size of ref. area (m^2)	Lateral extent of disposed sediments in CDF (m^2)	Apparent volume change in CDF area due to analytical inaccuracies (m^3)
Ref. area A	-1	-187	22871	194693	-1592
Ref. area B	0	6	22871	194693	51
Ref. area C	4	863	22871	194693	7346

4.2 Disposed sediments on seismic profiles

Seafloor elevation profiles along seismic lines, extracted from the 2004 and 2008 bathymetric datasets, were superimposed on the seismic profiles (Figs. 14, 15). Sonar data were scaled to obtain a match between the 2008 elevation profile and the seafloor reflection reordered on the seismic profiles. The match between the two complementary seabed data was found to be reasonably good within the area of the CDF. The slight discrepancies between the two datasets can be explained by (i) sound velocity variations in the water column that have not been corrected for in the seismic data, (ii) minor stretching and squeezing of seismic profiles due to deviations from constant vessel speed during data acquisition, and (iii) slightly different seabed detection (vertical variation) of the fluffy, transitional sediment-water interface between Topas and sonar.

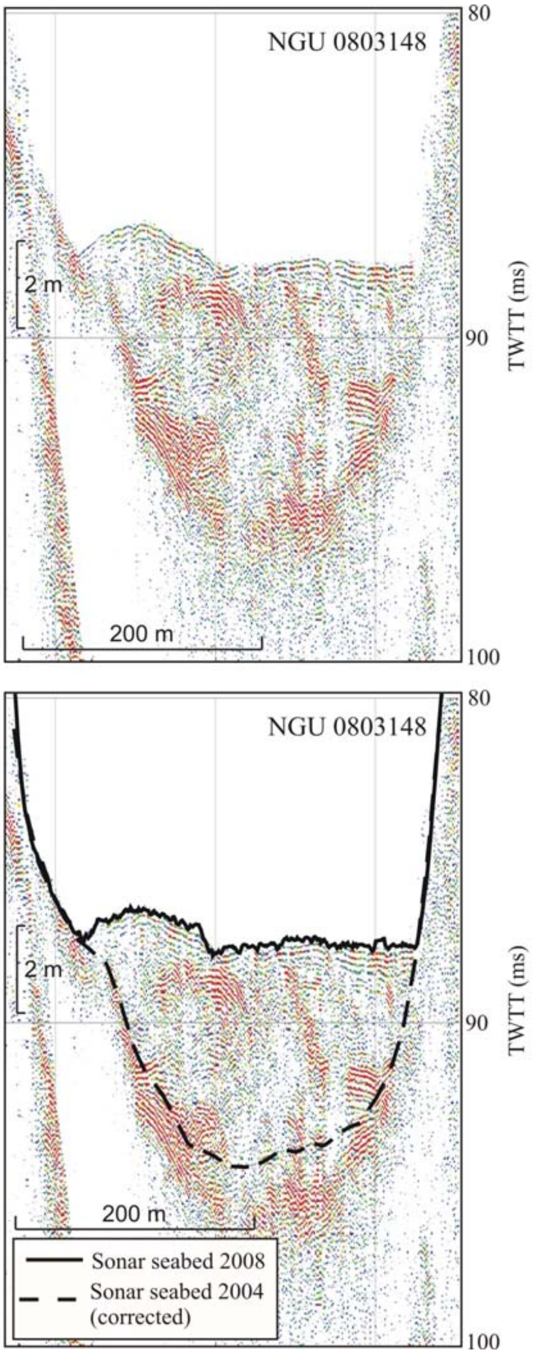

Figure 14. TOPAS seismic reflection profile (NGU0803148) across the CDF. Lower panel includes seafloor elevation lines from the 2004 and 2008 sonar datasets. Location of the profile is given on Fig. 6.

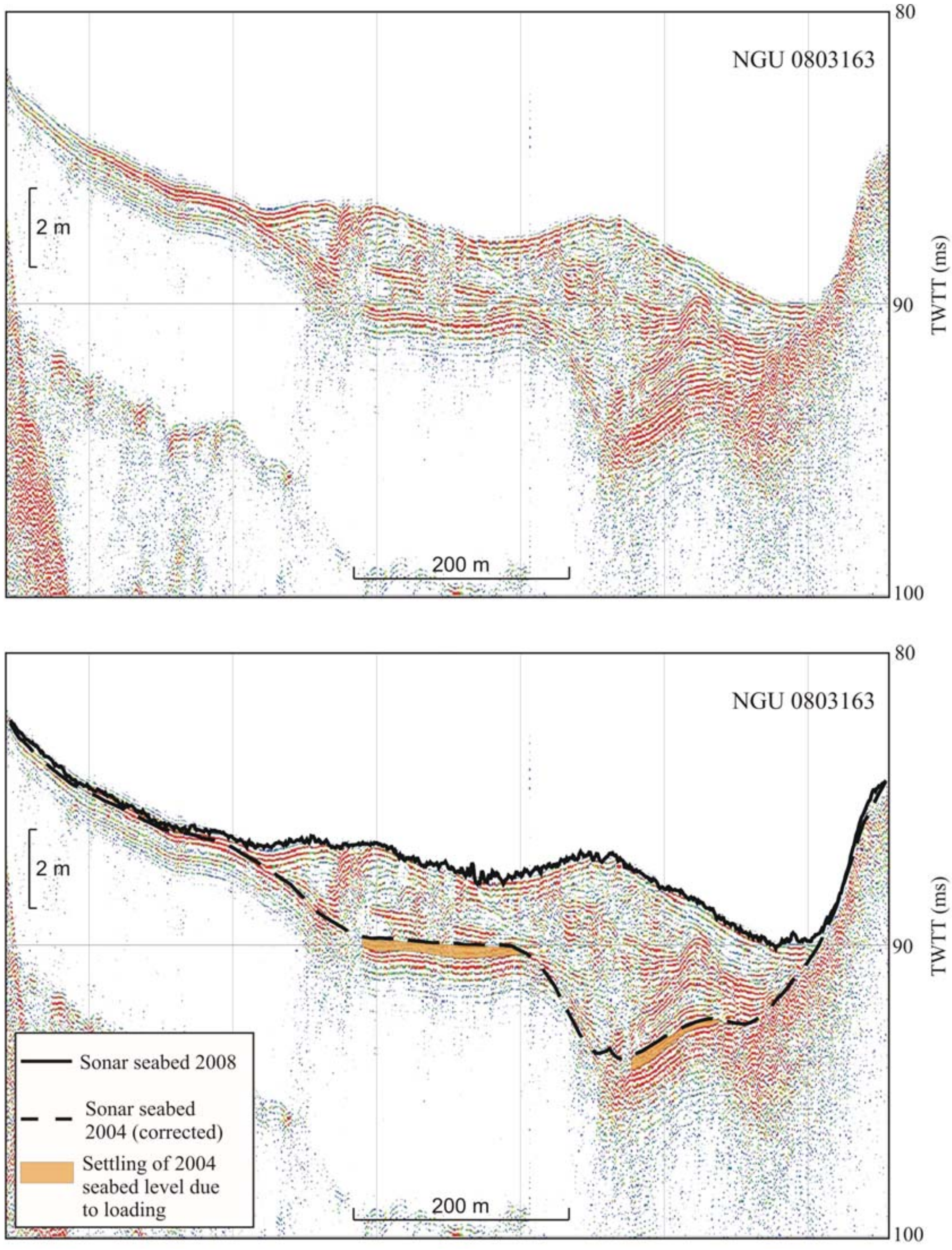

Figure 15. TOPAS seismic reflection profile (NGU0803163) across the CDF. Lower panel includes seafloor elevation lines from the 2004 and 2008 sonar datasets. Location of the profile is given on Fig. 6.

Most seismic profiles through the CDF show a layered structure of the disposed sediments with hummocks at former positions of the disposal pipeline opening. A prominent reflection at the base of the layered unit is interpreted to mark the surface of the original seabed before the onset of the Oslo harbor remediation project. This reflection can be traced on most profiles crossing the CDF area. The position of the 2004 seabed elevation line, displayed on the seismic profile has been corrected for the higher sound velocity in sediments (assumed

1520 m/s) compared to the seawater (1480 m/s). This difference results in slightly deeper position of the elevation line on the seismic profile prior to correction (ca. 0.2 ms at 5 m of disposed sediments). Thicknesses of disposed sediments, obtained using the difference between the two seabed elevation models, were used to calculate this correction. The corrected 2004 elevation line typically overlaps or is in places slightly above the reflector that is interpreted to mark the base of the CDF (Figs. 14, 15). The gap between the reflector and the 2004 elevation line is attributed to settling due to compaction and dewatering of the original seabed as a result of loading, generated by the weight of disposed sediments. The settling in the deepest part of the CDF, where the thickness of disposed sediment is ca. 5 m, is estimated to be ca. 30 cm. The settling decreases with thinning of disposed sediments upslope (Fig. 15). However, the data also indicate ca. 30 cm settling in the area of 2 m of disposed sediments (Fig. 15). In some areas with a thick cover of disposed sediments, the seismic character of the contact is too diffuse for settling quantification (Fig. 14).

Differences in apparent settling rates are possibly related to textural variations of the sediments at the original seabed. The NE-part of the CDF, where disposed sediments are placed on top of old dumping masses (Fig. 12), should be considered less susceptible to settling compared to the SW-part of the CDF that is on softer, natural seabed (Fig. 11). Accounting for such differences, it is difficult to establish a function that accurately characterizes the settling in the CDF. The settling correction that is made in the volume calculation uses 30 cm settling at 5 m elevation change in sonar data, and assumes a linear relationship between settling rate and thickness of disposed sediments (cf. Janbu 1970). In other words, an elevation change of 5 m in sonar data corresponds to a thickness of 5.3 m of disposed sediments after settling correction.

4.3 Thickness of disposed sediments in cores and comparison with acoustic data

Seven Niemistö cores uncovered the contact between disposed sediments and underlying natural sediments, at 0.17 m to 1 m depth at the margins of the CDF (Fig. 16). The contact is typically distinct, showing a change from gray and black, layered and color-banded disposed mud with sandy and gravelly interlayers, to olive gray, homogeneous, bioturbated natural mud (Fig. 17). The upper part (ca. 5 cm) of the natural seabed sediments is dark colored due to elevated content of organic matter, and may in places be confused with disposed sediments.

The sediments disposed during the Oslo harbor remediation project overly the old dumping area in the NE-part of the CDF. The lower contact of recently disposed sediments in Niemistö cores, is not always obvious in this part of the CDF because disposed sediments and old dumping masses may be lithologically similar. However, recently disposed sediments are typically more fine-grained and well dispersed than old dumping masses, hence the distinction appears possible. The thicknesses of disposed sediments recorded in four Niemistö cores that uncovered the lower contact at the margins of the CDF generally agree with the acoustic data, whereas in three cores the thickness is smaller than indicated by the acoustic data (Fig. 11).

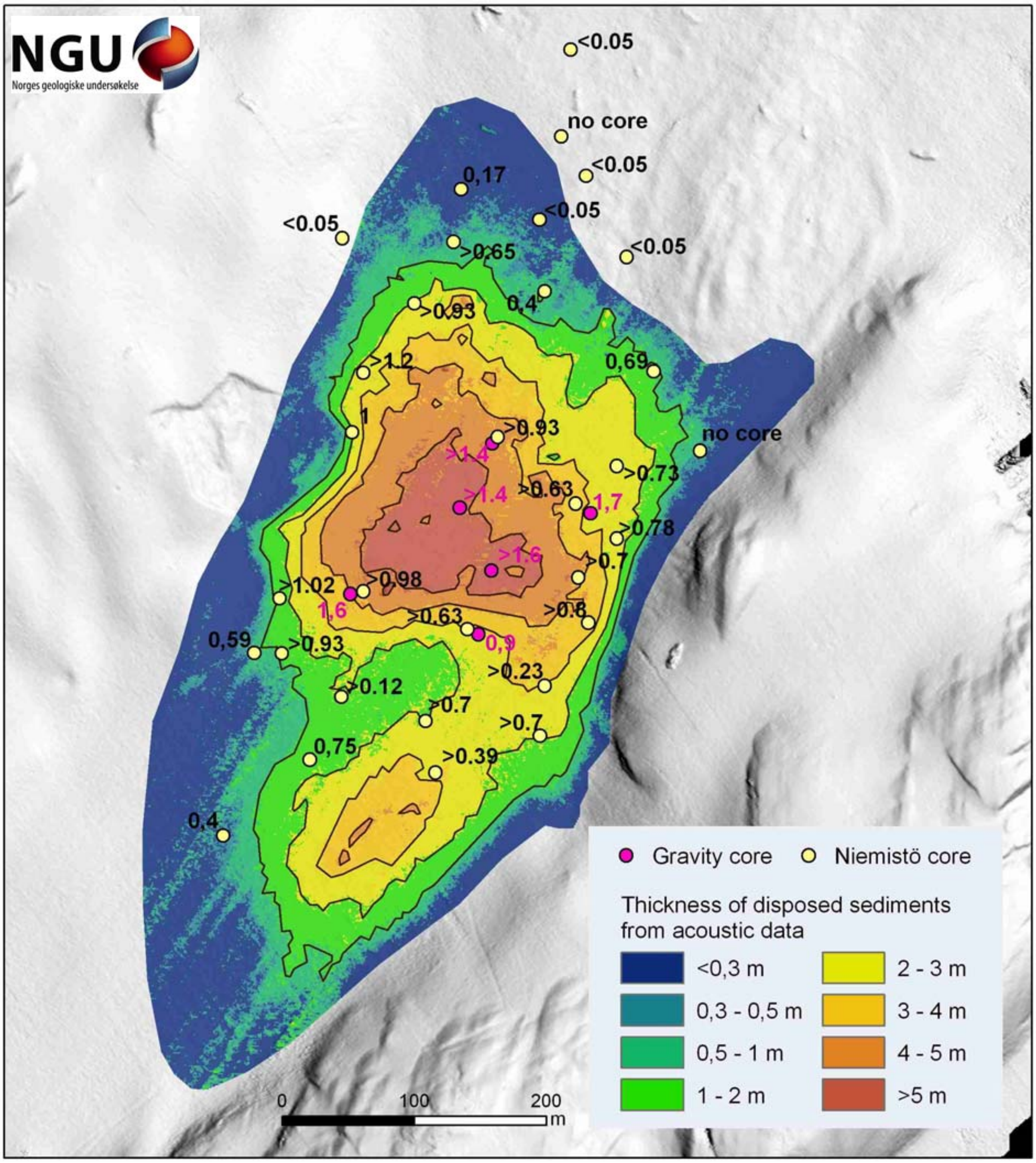

Figure 16. Thickness of disposed sediments in cores, superimposed on the isopach (thickness) map derived from acoustic data. Shaded-relief image of the 2008 dataset is given at the background. Thickness data from the Niemistö cores at the margins of the CDF show a reasonable correspondence with acoustic data. The thickness of disposed sediments in gravity cores is, however, considerably smaller than calculated from the acoustic data. Many Niemistö cores and two gravity cores did not penetrate down to the base of the disposed sediments. The thickness of recovered disposed sediments is shown for these stations, and the symbol ">" denotes that the actual thickness is greater.

Attempts to verify the thickness of disposed sediments with the aid of gravity coring failed. Three gravity cores achieved a penetration through disposed sediments into underlying natural seabed sediments (Fig. 17). However, the thickness of disposed sediments recovered in gravity cores (0.9-1.7 m) was considerably smaller than calculated from acoustic information (2.45-4.1 m) at the coring sites. This large discrepancy is caused by apparent limitations of gravity coring in stratified, very soft sediments. Due to the loose character of the disposed sediments, the passage of disposed material into the plastic liner of the gravity corer, having a cutting head with flexible fingers (core catcher) at the end, is hindered. Very loose disposed sediments, particularly in the upper part of the CDF, are apparently pushed aside without entering the sampling liner. Weakly consolidated materials that are able to open the core catcher, enter the sampling liner with smaller diameter than the aperture, presumably due to the resistance from the core catcher. In such cases, the weakly consolidated sediments are prone to collapse and fill the space in the liner, which results in shortening of sediments in the core liner. Interlayers of firmer sandy and gravelly sediments (Fig. 18, Table 2) that have relatively high liner wall friction compared to muddy disposed sediments, cause the corer to act partly as a plough. This leads to lateral extrusion and shortening of soft, muddy sediments that are below coarse-grained interlayers (Blomqvist, 1985). Compaction of sediments in the process of sampling may also cause sediment shortening in the core (Axelsson and Håkanson 1978).

Figure 17. Contact between disposed sediments and natural sediments (at 63 cm) in gravity core 0803028. Gray to black disposed sediments (right hand part of the core), mainly mud, are commonly banded/laminated and contain sandy and gravelly interlayers. Natural olive gray mud (left hand part of core) is typically homogeneous, bioturbated, and has ca. 5 cm black, organic-rich layer at the top (57-63 cm).

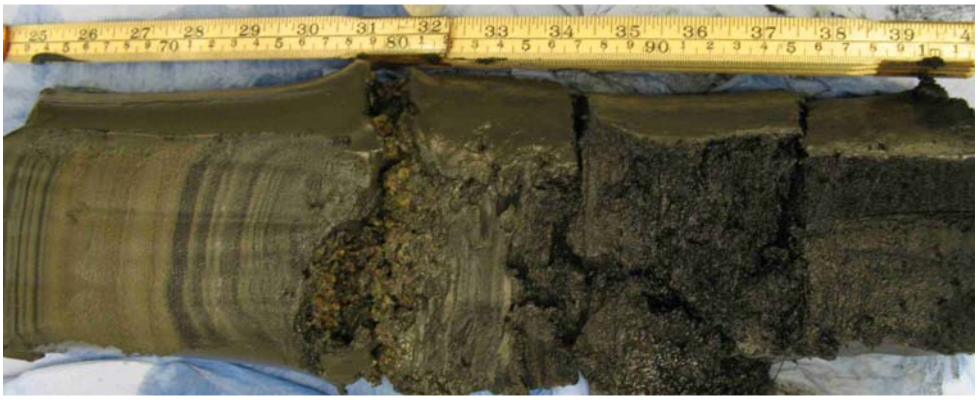

Figure 18. Gravelly interlayer (at 80 cm) within finely banded/laminated, disposed sediments in core 0803030.

4.4 Physical properties of sediments

Results on physical properties (Table 2) demonstrate considerable startigraphic scatter within disposed sediments. Water content and density values of disposed sediments in the CDF are both higher and lower than these values of underlying natural seabed sediments.

While these values clearly show that the disposed sediments are compositionally heterogeneous, the accuracy of given water content and density values (Table 2) can be questioned. Coring problems, including shortening due to lateral extrusion of soft sediments and compaction, have resulted in incomplete recovery of penetrated sediments and modification of physical properties during coring. The obtained sediment cores and derived water content and density values are thus not fully representative for the disposed sediments. This has to be kept in mind while assessing the weight of disposed sediment and doing the mass balance between dredged and disposed sediments. Accounting for the heterogeneous nature of the disposed sediments and the above highlighted uncertainties in the physical properties dataset, there is not enough information to calculate a reliable average density of disposed sediments.

Table 2. Physical properties of natural seabed sediments (green shading) and disposed sediments in four gravity cores (0803029-0803030, 0803033) and five Niemistö cores (0803034-0803038). For core localities see Fig. 8.

Gravity core	Depth (cm)	Water content (%)	Wet density (g/cm^3)	Dry density (g/cm^3)
0803028	20	127.3	1.44	0.63
0803028	45	121.2	1.38	0.62
0803028	70	101.6	1.44	0.71
0803028	95	87.3	1.49	0.80
0803028	125	62.0	1.72	1.06
0803028	155	121.2	1.38	0.62
0803028	175	106.2	1.44	0.70
0803028	210	93.7	1.52	0.78
0803029	40	109.8	1.41	0.67
0803029	60	115.5	1.38	0.64
0803029	80	108.6	1.42	0.68
0803029	102	248.2	1.21	0.35
0803029	120	103.1	1.46	0.72
0803029	130	91.9	1.50	0.78
0803030	20	154.1	1.35	0.53
0803030	40	128.4	1.42	0.62
0803030	70	100.7	1.52	0.76
0803030	95	131.5	1.38	0.60
0803030	120	66.5	1.61	0.97
0803030	140	74.6	1.58	0.91
0803030	150	101.6	1.45	0.72
0803030	160	42.2	1.88	1.32
0803030	168	233.0	1.25	0.38
0803030	180	106.0	1.53	0.74
0803030	195	101.8	1.58	0.78
0803033	10	139.9	1.41	0.59
0803033	15	44.7	1.85	1.28
0803033	40	86.3	1.54	0.83
0803033	60	126.9	1.48	0.65
0803033	70	81.5	1.55	0.85
0803033	88	124.7	1.41	0.63
0803033	95	111.5	1.45	0.69
0803033	110	108.0	1.49	0.72

Niemistö core	Depth (cm)	Water content (%)	Wet density (g/cm^3)	Dry density (g/cm^3)
0803034	5	171.7	1.35	0.50
0803034	15	101.3	1.53	0.76
0803034	25	106.5	1.53	0.74
0803034	50	94.6	1.51	0.77
0803035	5	170.6	1.39	0.52
0803035	15	119.6	1.43	0.65
0803035	25	128.5	1.42	0.62
0803035	50	94.6	1.51	0.77
0803035	75	116.7	1.44	0.67
0803036	5	89.3	1.62	0.86
0803036	15	150.4	1.40	0.56
0803036	25	134.1	1.37	0.59
0803036	50	100.6	1.50	0.75
0803037	5	142.3	1.35	0.56
0803037	15	122.5	1.40	0.63
0803037	25	121.1	1.41	0.64
0803037	50	136.1	1.36	0.58
0803037	75	113.3	1.53	0.72
0803038	5	175.2	1.20	0.44
0803038	15	133.5	1.43	0.61
0803038	25	124.8	1.39	0.62
0803038	50	176.1	1.33	0.48
0803038	75	104.5	1.46	0.71
0803038	100	89.0	1.49	0.79

4.5 Volume of disposed sediments in the CDF

The results of the volume calculation in the area of the CDF that is occupied by disposed sediments (194 693 m^2, Fig. 19), are given in Table 3. Calculations show that the deviation from the correct offset value between the 2004 and 2008 elevation datasets causes an error in volume calculation of ca. 10 000 m^3 per 5 cm vertical offset (Table 3). Based on the offset data obtained from reference areas B (5 cm offset) and C (9 cm offset, Fig. 13), in the immediate vicinity of the CDF, an offset correction value within the range -5 to -10 cm is considered to be most reliable for the CDF area. Such offset corrections, but without correcting for settling, yield a volume of disposed sediments of 310 000-320 000 m^3 (Table 3).

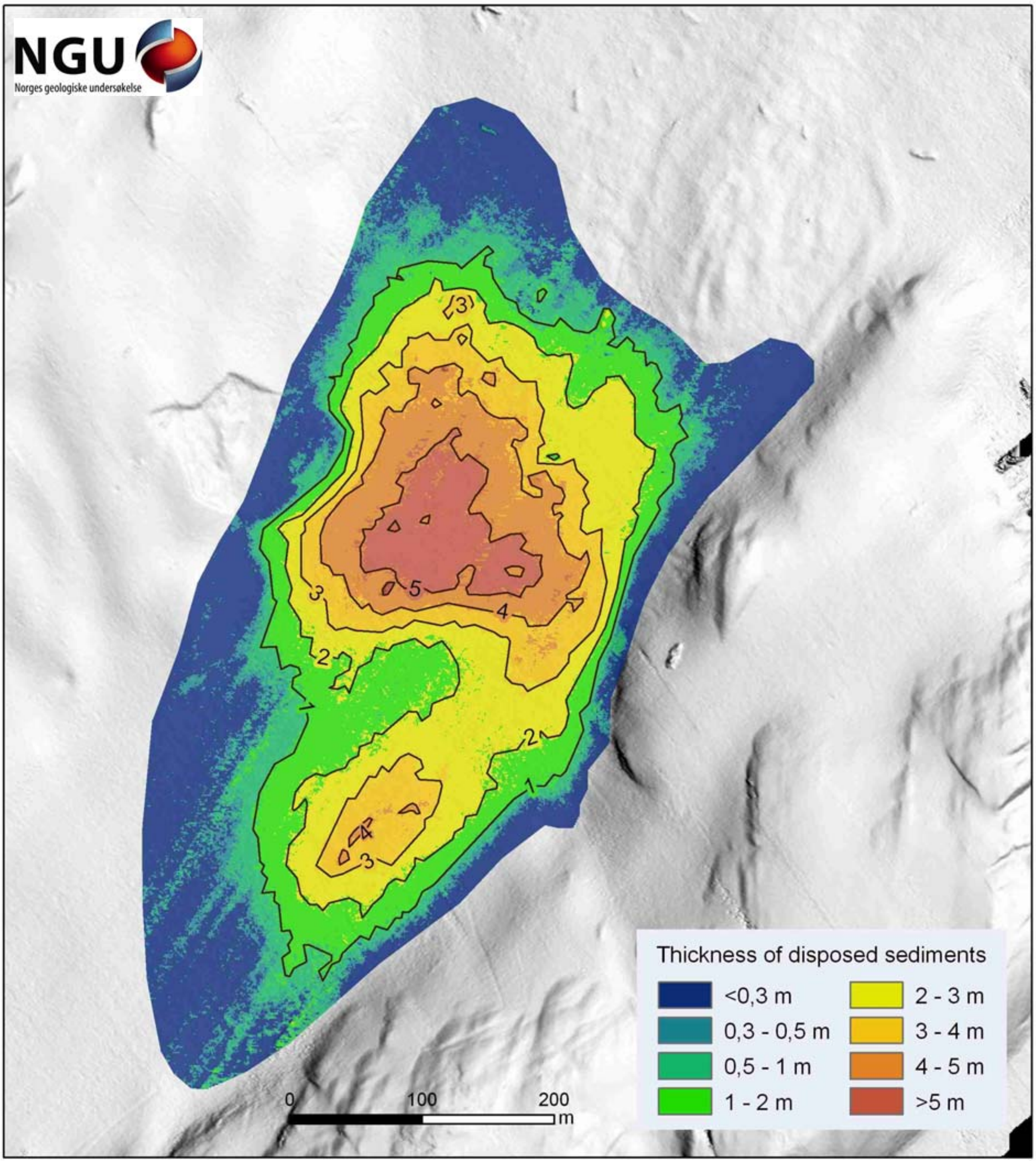

Figure 19. Thickness of disposed sediments in the CDF. Calculated thicknesses include corrections for settling of the original seabed and the offset (5 cm) between the 2004 and 2008 bathymetric datasets. Shaded-relief image of the 2008 dataset is given at the background.

Settling of the original seabed, which is estimated to be 30 cm at ca. 5 m of disposed sediments and linearly correlated with the thickness of disposed sediments, also affects the volume. Applying the settling correction (factor 1.06) to the volumes obtained from the elevation data results in a volume of 330 000 - 340 000 m^3 of disposed sediments at offset corrections of -5 and -10 cm (Table 3).

Accounting for the very fluffy nature of the surface of the disposed sediments, the acoustic reflection at the sediment-water interface in the 2008 dataset might be a few centimeters deeper compared to the 2004 dataset. If this is true, the calculated volume of disposed sediments (i.e. 330 000 - 340 000 m^3) is slightly smaller (estimated to be up to 10 000 m^3) than the actual volume. Under the condition that the used offset correction (within the range from -5 to -10 cm) is correct, there is no major analytical inaccuracy in sonar measurements that may cause significant errors in the volume calculations (Fig. 13, Table1).

Table 3. Calculated volume changes in the area of the CDF with disposed sediments (194 693 m^2) using different offset values between the 2004 and 2008 bathymetric datasets and applying correction for settling. An offset value within the range -5 to -10 cm is considered most reliable.

Offset correction between 2004 and 2008 datasets (cm)	Volume of disposed sediments from seabed elevation change (m^3)	Settling corrected (factor 1.06) volume of disposed sediments (m^3)
-15	300506	318536
-10	310117	328724
- 5	319726	338909
0	329339	349099
+5	338950	359287

There is uncertainty involved in the settling correction. However, based on seismic data integrated with elevation profiles, it appears unlikely that the applied settling correction has resulted in under- or overestimation of the volume by more than 10 000 m^3. The data and interpretations presented in this report thus indicate that the volume of disposed sediments in the CDF in the beginning of April 2008 was 330 000 - 340 000 m^3 with estimated error margins between -10 000 m^3 and +20 000 m^3.

5 CONCLUSION

High-resolution acoustic data acquired with GeoSwath 250 kHz interferometric sonar and TOPAS parametric sub-bottom profiler allow the assessment of the lateral extent and volume of sediments disposed in the CDF at Malmøykalvem in the frame of Oslo harbor remediation project. Bathymetric and backscatter data acquired in April 2008 demonstrate the lateral spread of disposed sediments within a well-confined area covering ca. 195 000 m^2. Very low backscatter amplitude within this area, distinctly different from the surrounding natural seabed, indicates a very loose character of disposed sediments. The change in seafloor elevation using bathymetric datasets from 2004 and 2008, integrated with the seismic information, shows that the thickness of disposed sediments reaches 6 m in the central part of the CDF. The volume calculation of disposed sediments in the CDF, based solely on bathymetric data, gives a value of ca. 310 000 - 320 000 m^3. Correction for the settling of the original seabed as a result of loading yields a volume of ca. 330 000 - 340 000 m^3 of disposed sediments in the CDF. The results presented in this report show high accuracy and good reproducibility of acoustic seafloor data, and indicate a potential of such methods as monitoring tools in environmental projects that involve dredging and subaqueous disposal.

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