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Sedimentation rates and surficial geology in the Canadian Forces Maritimes Experimental and Test Range exercise area Whiskey Golf, Strait of Georgia, British Columbia

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Abstract: Bathymetric and geological studies were undertaken in the Canadian Forces Maritimes Experimental and Test Range Whiskey Golf, Strait of Georgia, using multibeam echosounder, high-resolution seismic reflection, sidescan sonar, and sampling data. This work was completed in conjunction with the Department of National Defense and the Royal Military College (Kingston, Ontario). The objectives were to map seafloor features and determine the modern depositional regime in order to support environmental assessment of test-range activities. Detailed analysis of the data revealed a maximum thickness of late Holocene sediments of 21 m and the best estimate for the present-day sedimentation rate in the basin is 0.54 cm/a. The sedimentation rate has likely increased over the last 1500 years. The study demonstrates that previous interpretation of seismic data led to overestimates of sedimentation rate.

Résumé : En collaboration avec le ministère de la Défense nationale et le Collège militaire royal du Canada (Kingston, Ontario), nous avons entrepris des études bathymétriques et géologiques dans le Centre d'expérimentation et d'essais maritimes des Forces canadiennes – Whiskey Golf, dans le détroit de Georgia. Pour ce faire, nous avons utilisé des données de sondages acoustiques multifaisceaux, de sismique réflexion haute résolution, de sonar à balayage latéral et d'échantillonnage. Ces études avaient pour objectifs de cartographier les éléments du fond marin et de déterminer le régime sédimentaire actuel à l'appui d'une étude d'impact environnementale des activités du centre d'essais. L'analyse détaillée des données révèle que les sédiments de l'Holocène supérieur ont une épaisseur maximale de 21 m et que la meilleure valeur estimée du taux de sédimentation actuel dans le bassin est de 0,54 cm/a. Le taux de sédimentation a vraisemblablement augmenté au cours des 1500 dernières années. L'étude a montré que les interprétations antérieures de données sismiques ont donné lieu à une surestimation du taux de sédimentation.

INTRODUCTION

As part of an ongoing environmental assessment of the Canadian Forces Maritimes Experimental and Test Range (CFMETR), the Department of the National Defense is undertaking a detailed analysis of its exercise area Whiskey Golf (WG), located in Ballenas Basin of the Strait of Georgia, British Columbia (Fig. 1). The objectives of the present study are to characterize the seafloor and the underlying surficial sediments, and to determine sedimentation rates across the test area.

SETTING

The Strait of Georgia can be divided into three main regions: northern, central, and southern, of which the southern portion is largely influenced by the Fraser River's input (Clague, 1977; Thomson, 1981). The Ballenas Basin, located west of Vancouver in the central part of the Strait of Georgia, is the deepest part of the strait, with a maximum depth of 400 m. Ballenas Basin is the dominant geomorphologic feature of the seafloor in the area of the Whiskey Gulf test range. During a period of glacial advance in the early Wisconsinan, the southwesterly flowing valley glaciers carved the basin to great depths (Hamilton, 1991). The basin is now a major depositional site for Holocene sedimentation (Macdonald et al., 1991).

METHODS

The stratigraphy of the unconsolidated sediments of Ballenas Basin is interpreted from Huntec DTS© reflection records. A regional grid, consisting of seven seismic lines spaced 2 km apart, representing approximately 140 km of profiles, was obtained during a 2004 survey (Cruise PGC04004; Fig. 2). Sediment thickness was mapped from digital seismic data processed with SonarWeb's software (Chesapeake Technology, Inc.©). Navigation data were collected using differential GPS, and the layback of the instrument was taken into account when compiling the results. The fish was towed 60 m below the surface, and the GPS antenna was located 20 m ahead of the stern. Using simple trigonometry, a spatial precision ranging from -50 to -80 m is estimated. A sound velocity of 1500 m/s was used to calculate the thickness of stratigraphic units.

An isopach map displaying the thickness of the Holocene unit was created manually, since the data from the seismic survey were too sparse to perform statistical contouring.

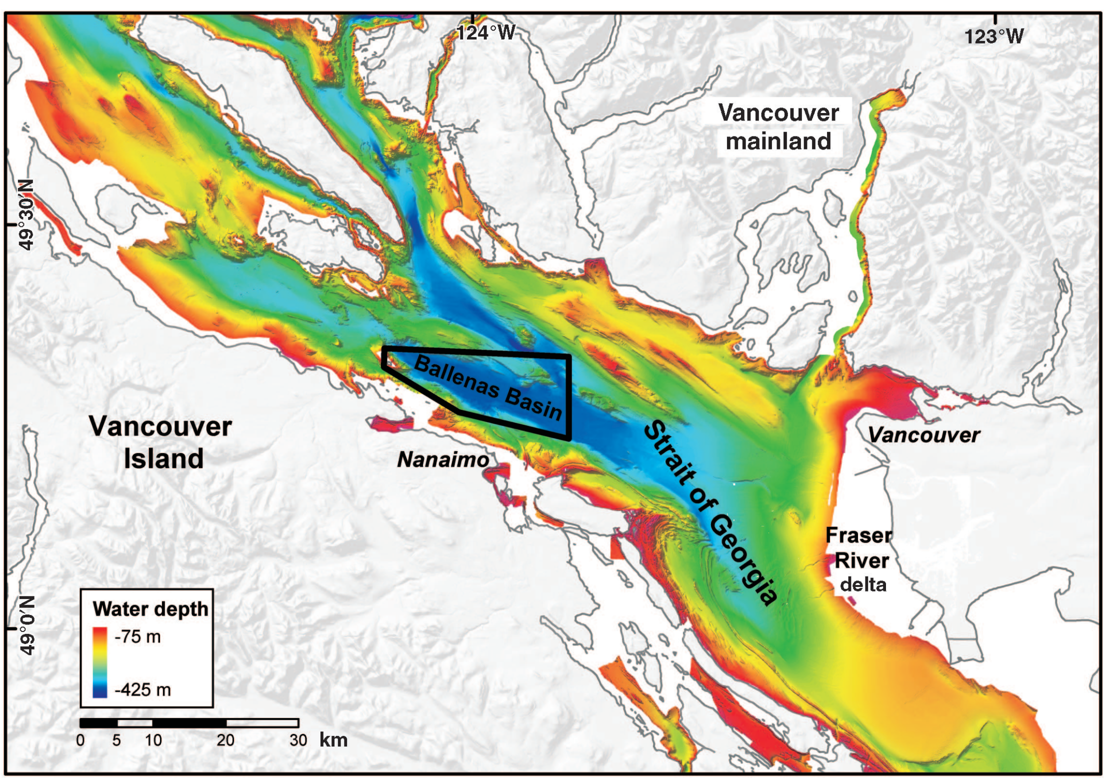

Figure 1. Location map of exercise area Whiskey Golf (WG, black polygon) in Georgia Strait and its main geomorphologic feature, Ballenas Basin.

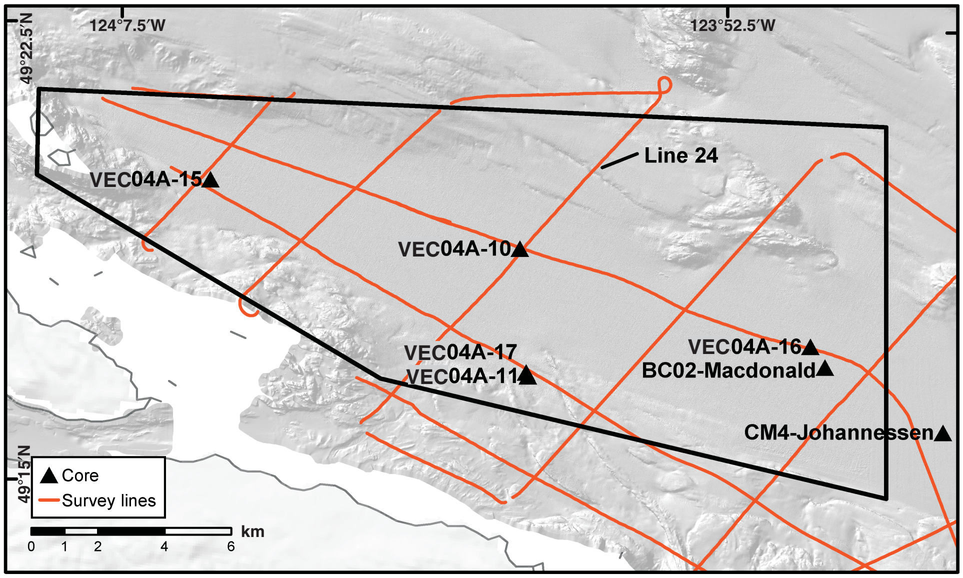

Figure 2. Location of the survey lines (PGC04004) and core stations. The Pederson cores VEC04A-10, VEC04A-11, VEC04A-15, and VEC04A-16 are located, as well as the piston core VEC04A-17. Labels BC-2 Macdonald (Macdonald et al., 1991) and CM-4 Johannessen (Johannessen et al., 2003) show the locations where two other sedimentation rates were calculated using Pb-210 method for previous studies. Survey line 24 shown on Figure 3 is also identified.

While points in close proximity to one another were easily correlated, the geomorphology was also used to interpolate the relationship between more widely separated data points.

Surficial sediment type and seafloor morphology were interpreted using Simrad© sidescan sonograms, as well as multibeam backscatter and bathymetric data provided by the Canadian Hydrographic Service. Pederson cores, piston cores, grab samples, and video images from ROPOS (an unmanned submersible) collected during two cruises in 2004 (PGC04004 and PGC04012) provided ground-truth information and chronostratigraphy.

The sedimentation rates were estimated using three methods: Pb-210 profiles, piston core stratigraphy, and seismic records. The Pederson cores (VEC04A-10, VEC04A-11, VEC04A-15, and VEC04A-16) were analyzed to determine a depth profile of the activity of Pb-210 and Ra-226 in the uppermost 50 cm of the sediment column. Sedimentation rates were calculated using models based on the Lavalle and Massoth (1992) method (*see* Johannessen et al. (2003) for complete method). The piston core VEC04A-17 was split, photographed, and visually logged before subsampling for bulk-density analysis (measurements at 20 cm interval) and radiocarbon dating. Seismic profiles were used to measure the thickness of the Holocene unit, from which the apparent sedimentation rate was derived.

RESULTS

Stratigraphy

Unit 1

The oldest observed unit (Fig. 3) is the acoustic basement, identified as bedrock (Mosher and Hamilton, 1998). This unit is most obvious in Whiskey Golf, where it outcrops along the edges of the basin, though it can also be traced below thick layers of Quaternary sediments in Ballenas Basin.

Unit 2

Four acoustic subunits consisting of stratified, transparent, and chaotic seismic facies characterize unit 2. The lowermost subunit is approximately 10 m thick and consists of a well stratified seismic facies that onlaps the underlying bedrock surface at the margins of the basin. Overlying the basal stratified subunit is a 10–15 m thick subunit of incoherent to amorphous internal reflections with a rough hummocky surface characterized by hyperbolic reflectors. This subunit is present in all the seismic records, but best observed on the margins of Ballenas Basin where it thins to zero in an onlapping contact with the bedrock. This subunit is in turn overlain by a 20–30 m thick transparent layer that also

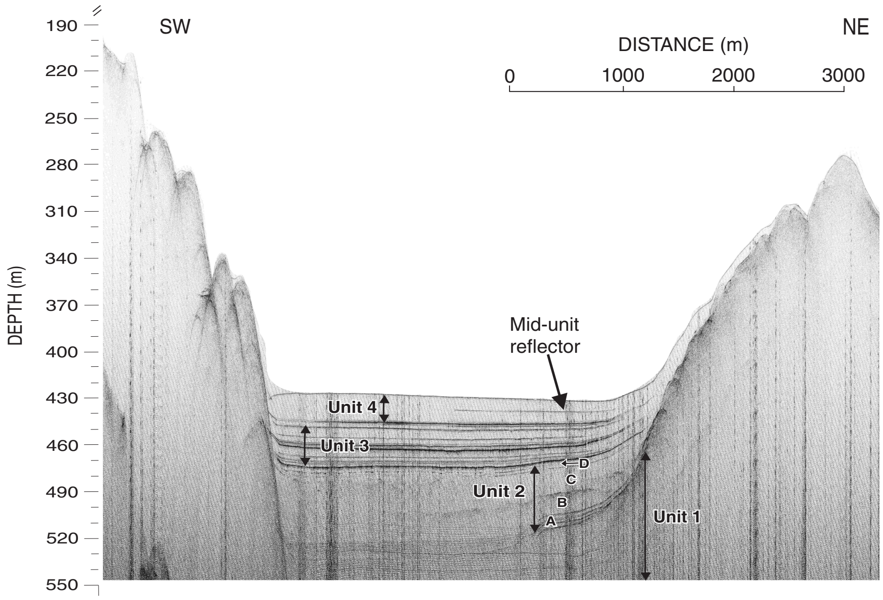

Figure 3. Huntec DTS subbottom profile (PGC04004) from exercise area Whiskey Golf (WG, Fig. 1). Major seismic units are identified by numbers 1 through 4 and described in the text. Seismic facies of unit 2 are identified by letter: A:= well stratified, onlapping facies; B = incoherent to amorphous facies; C = transparent facies; D = upper stratified facies. Note also that unit 4 is delimited by a very strong basal reflector and the presence of an event reflector midway through unit 4.

wedges out at the basin margin. The uppermost subunit is similar to the basal subunit, consisting of less than 10 m of a stratified facies.

Unit 2 is tentatively interpreted to represent ice-contact and ice-proximal glaciomarine deposits. The interfingered association between well stratified sediments and chaotic sediments is consistent with deposition in distal and proximal glaciomarine environments, respectively (Syvitski and Praeg, 1989; Mosher and Hamilton, 1998).

Unit 3

Flat-lying, subparallel, semicoherent, and high-amplitude reflections characterize unit 3. The unit infills the basin with over 25 m of sediment. The top of the layer is marked by a regionally extensive, high-amplitude, low-frequency reflection horizon.

This unit is interpreted to represent deposition related to the retreat of glaciers at the end of the Fraser Glaciation (Mosher and Hamilton, 1998). The spatial relationship of unit 3 with unit 2 indicates that these sediments are most likely to be ice-distal glaciomarine and possibly postglacial sediments; however, due to the limited data, no attempt is made here to distinguish between ice-distal deposits and stratified postglacial sediments.

Unit 4

Unit 4, the uppermost unit, is characterized by its transparent character. The base of the unit is the top of the third unit and the seafloor delineates the top of the unit. In some areas, gas brightening (enhancement of the impedance contrast at a boundary) is present. In most of the basin there is a reflector midway through the unit that disappears toward the edge of the basin.

Unit 4 is interpreted to represent late postglacial hemipelagic sedimentation. It includes the most recent deposits, largely derived from the Fraser River. The mid-unit reflector represents an exceptional depositional event that caused a disruption to the regular hemipelagic sedimentation, sometime during the Holocene. Conway et al. (2001) identified a clay layer in cores collected north of Ballenas Basin and in Saanich Inlet that they interpreted as evidence of an outburst flood event that happened during the early Holocene (between 9100 BP and 9800 BP (radiocarbon years)). It is unlikely that the distinctive mid-unit reflector found in our seismic record is related to the same flood event. Extrapolating the radiocarbon age of 1570 ± 125 BP, in core VEC04A-17, to the reflector would give an approximate age for this event between 2000 BP and 3000 BP. Furthermore, the reflector is only present in the south part of the basin and does not appear to be regional in extent.

Thickness of late Holocene sediments

The reflector delineating the top of unit 3, records a significant change in the oceanography and sedimentation in the Strait of Georgia during postglacial time. The reflector was assigned an approximate age of 5000 years by Clague (1977) and Clague et al. (1983) and is interpreted to represent the time when the Fraser River delta had almost reached its present position and regular hemipelagic sedimentation started in the central region of the strait.

The thickness of late Holocene sediments (unit 4) between the seabed and the top of unit 3 is shown as isopachs on Figure 4. The maximum thickness of 21 m is located in the northeast corner of the basin. Areas where late Holocene sediments are absent are located mostly along the edge of the basin, the seabed in these region being characterized by outcropping bedrock or glaciomarine sediments (Fig. 5, 6).

Core data

Figure 7 shows the Pb-210 profiles from which the sedimentation rates for the four sites were determined. Figure 8 shows details of piston core VEC04A-17, which consists of 842 cm of mostly homogenous mud with a 10 cm layer of sand at 300 cm, as well as some bedding and laminations at 700 cm. Some organic debris and shells are found scattered throughout the core. Paired bivalve shells (*Cardiomya planetica*) at 502 cm depth yielded a radiocarbon age of 2340 ± 60 BP (TO-12064) (Fig. 8). After applying corrections for natural and sputtering isotope fractionation, the measured $^{13}C/^{12}C$ ratio, and the marine reservoir (720 ± 90 years; Hutchinson et al. (2004)), the resulting age of the sample is 1570 ± 125 BP. The bulk-density measurements derived from the piston core revealed minimal compaction in the first 8 m of sediments (Fig. 8). This analysis suggests that the sedimentation rates calculated from Pb-210 and the radiocarbon dating methods can be compared. This comparison is further discussed in the next section.

Sedimentation rates

Sedimentation rates calculated by the three methods described above and/or published in previous studies are compiled in Table 1. The calculated apparent sedimentation rates from seismic records range from 0.34 cm/a (VEC04A-10) to 0.43 cm/a (VEC04A-15), using 5000 years as the age for the mapped reflector described earlier (Clague et al., 1983). The radiocarbon age of the shell found in the

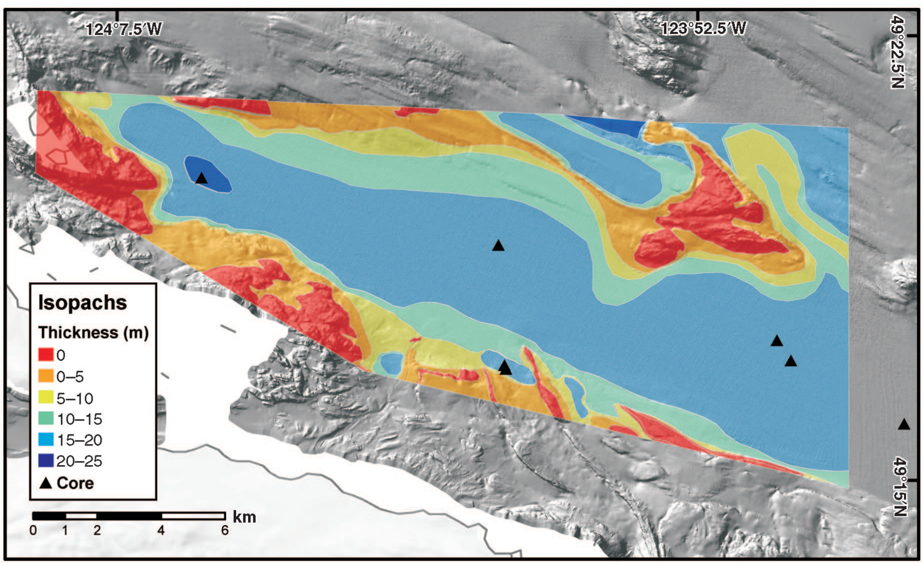

Figure 4. Isopach map of the late Holocene sediment unit for exercise area Whiskey Golf. The hypsometric colouring represents 5 m intervals. Note that the thickness of the sediments, where VEC04A-11 and VEC04A-17 (*see* Fig. 2) are found, is higher than average

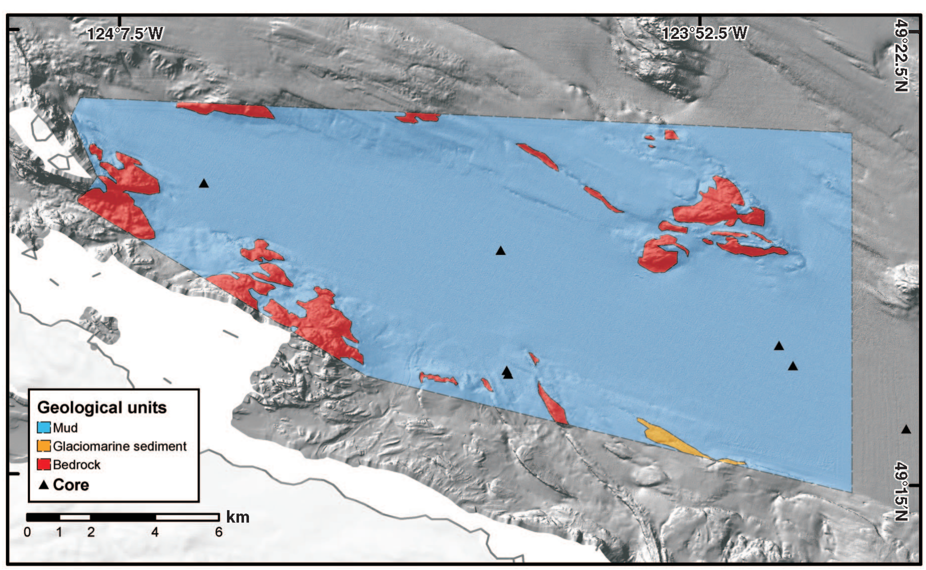

Figure 5. Distribution of surficial sediments in exercise area Whiskey Golf.

piston core supports the assumed age of 5000 years for base of unit 4, from which apparent sedimentation rates were calculated. Factors such as compaction, consolidation, and erosion are not taken into consideration in these values. In addition the thickness values calculated depend on the sound velocity used. Sound velocity varies with sediment type from 1500 m/s to 1650 m/s and increases with depth (Hamilton, 1991). Using this range of sound velocity gives an uncertainty of ±2 m. The measurement uncertainty in data manipulation is estimated to be ±1 m, bringing the total estimated vertical error to ±3 m or 0.06 cm/a.

The Pb-210 results range from 0.43 cm/a to 0.74 cm/a, where the minimum and maximum were found for cores VEC04A-10 and VEC04A-11 respectively. Using the average of 0.54 cm/a, the authors can estimate that a Pederson

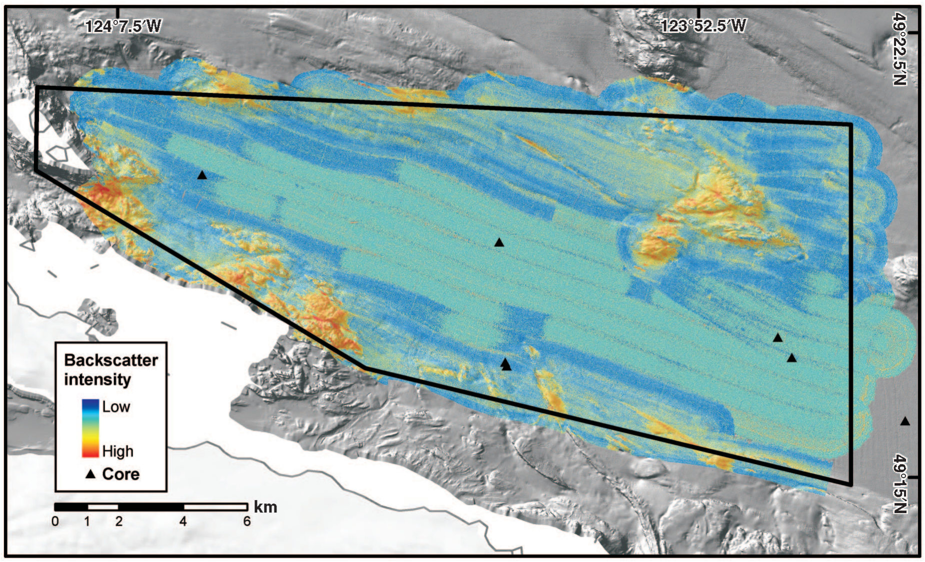

Figure 6. Seafloor morphology draped with the multibeam backscatter intensity used to map the surficial geology presented in Figure 6.

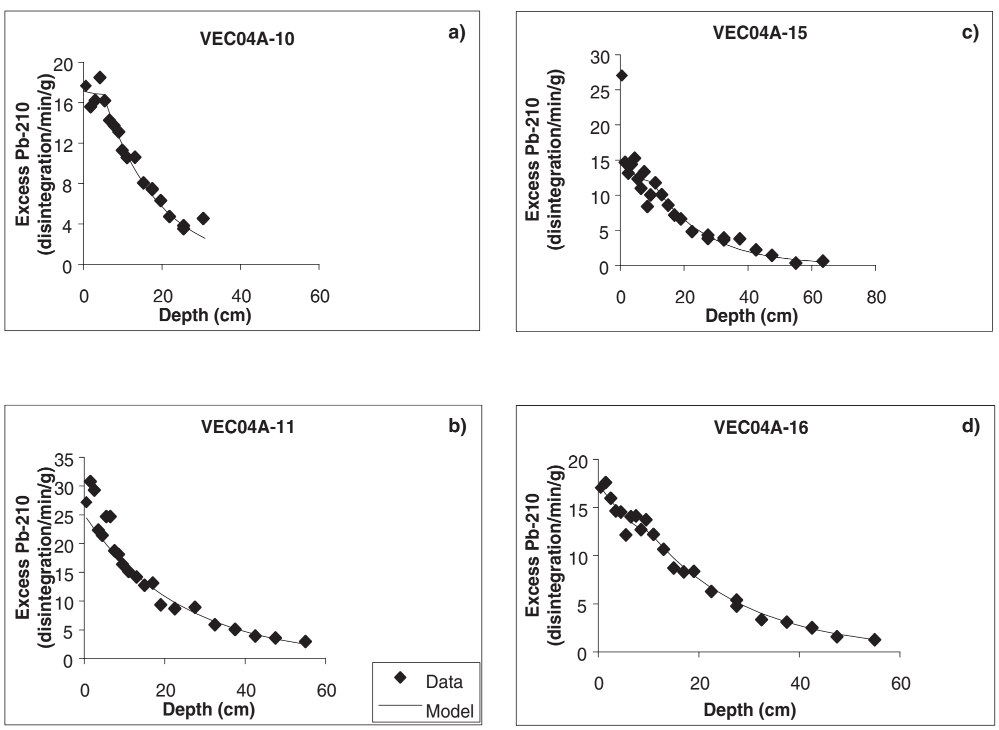

Figure 7. Measured and modelled excess Pb-210 profiles used to calculate the sedimentation rates for the Pederson cores: **a)** VEC04A-10, **b)** VEC04A-11, **c)** VEC04A-15, and **d)** VEC04A-16). The points represent the data and the line represents the model. Note the horizontal scale differs between the four graphs.

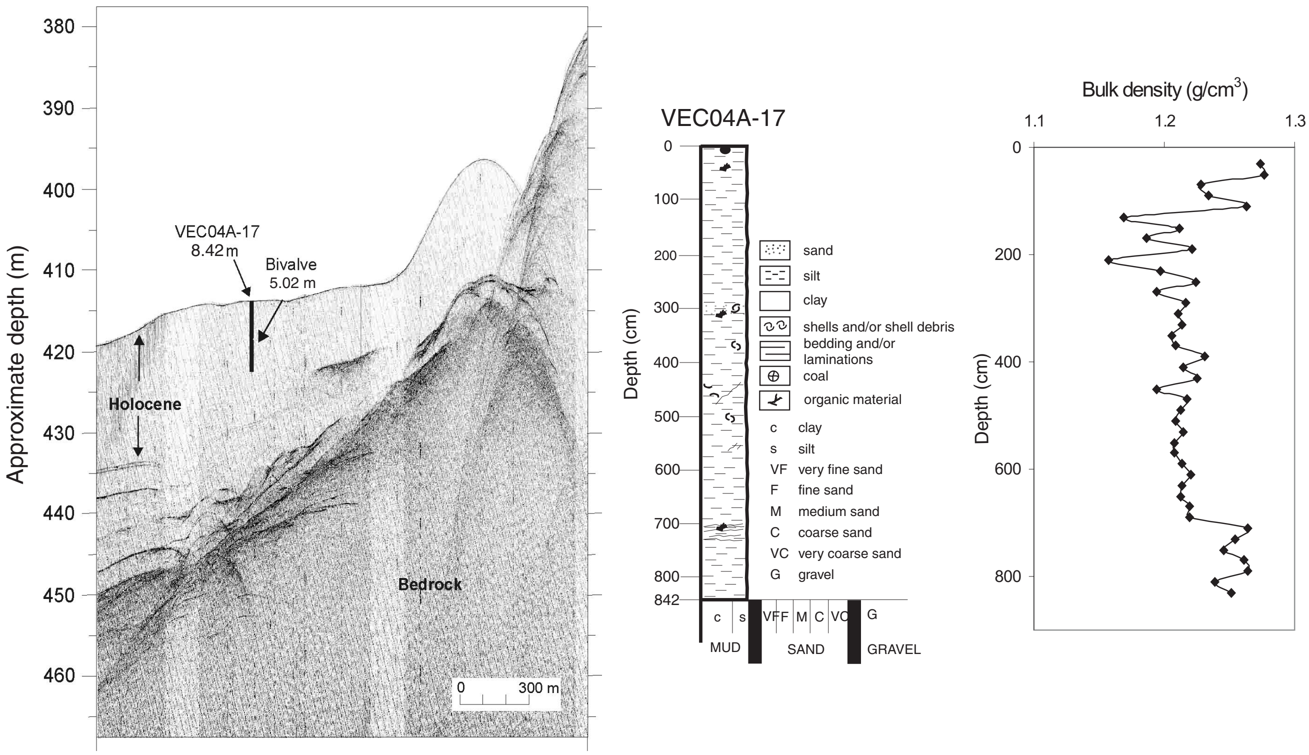

Figure 8. Huntec DTS subbottom profile and sediment core (VEC04A-17) from exercise area Whiskey Golf. This figure shows the location in the core where the bivalve shell was found (502 cm) and the bulk-density profile. The seismic profile illustrates the Holocene sediment stratigraphy and the bedrock basement. Deeper units of glacial stratigraphy beneath the Holocene mud are hard to identify on this part of the profile.

Table 1. A comparison of published sedimentation rates with those calculated for the study area. The station numbers of this study also include the location descriptions and original authors of those used in previous studies. The rates compiled from previous studies were calculated using seismic profiles (assuming sedimentation started 10 000 years ago) and Pb-210 profiles. In this study, the sedimentation rates were calculated using Pb-210 profiles, ^{14}C radiocarbon dating, and seismic records (assuming the age of the basal reflector of unit 4 to be 5000 BP).

Station numbers	Sedimentation rates (cm/a)	Analysis method	Authors
Previous studies			
Central strait basins	0.6	Seismic profile (10 000 a)	Mathews and Murray, 1966
Central strait	0.55	Seismic profile (10 000 a)	Mathews and Murray, 1966
Ballenas Basin	2	Seismic profile (10 000 a) - average thickness	Tiffin, 1969
Ballenas Basin	2.6	Seismic profile (10 000 a) - maximum thickness	Tiffin, 1969
BC-2	0.8	Pb-210	Macdonald et al., 1991
CM-4	0.6	Pb-210	Johannessen et al. 2003
Present study			
VEC04A-11	0.74 ± 0.01	Pb-210	
VEC04A-16	0.38	Seismic profile (5000 a)	
	0.61 ± 0.01	Pb-210	
VEC04A-10	0.34	Seismic profile (5000 a)	
	0.43 ± 0.01	Pb-210	
VEC04A-15	0.43	Seismic profile (5000 a)	
	0.51 ± 0.004	Pb-210	
VEC04A-17	0.32	Carbon dating (apparent rate)	
	0.38	Seismic profile (5000 a)	

core represents about 100 years of sedimentation. Figure 9 shows there is little relation between the sedimentation rates calculated from Pb-210 and the thickness of late Holocene sediments determined from the seismic profiles.

The single radiocarbon age determination from piston core VEC04A-17 gives a sedimentation rate of 0.32 ± 0.02 cm/a. Based on the bulk-density measurements, consolidation of the sediments in the uppermost 8 m of the sediment column is negligible (Fig. 8). Comparing the sedimentation rates of 0.74 cm/a from the Pb-210 analysis and 0.32 cm/a from the radiocarbon analysis (from cores collected very close together) it can be inferred that sedimentation rates may have increased over the last 1500 years.

A best estimate of the present sedimentation rate in Ballenas Basin of 0.54 cm/a was determined from the average of the sedimentation rates calculated at the four basin sites using the Pb-210 method (Table 1). Using this average value minimizes the error due to local spatial differential sedimentation. One reason for the spatial variation in sedimentation rates can be seen at the site VEC04A-11, which reports the highest sedimentation rate. Looking at the general seafloor morphology and the seismic profile of the area, it can be seen that the site is located close to an island where the complexity of the seafloor is high (Fig. 2). The site is located on a bedrock ridge on which swell and moat features are present (Fig. 8). Core site VEC04A-11, therefore is the least representative site for determining the sedimentation rate for Ballenas Basin.

Sedimentation rates reported from previous studies range between 0.55 and 2.60 cm/a (Johannessen et al. (2003); Macdonald et al. (1991); Luternauer et al. (1983); Pharo and Barnes (1976); Tiffin (1969); Mathews and Murray (1966); Table 1). The present study shows a maximum sedimentation rate of 0.74 cm/a, obtained from the Pb-210 method. Higher sedimentation rates reported in the literature may be incorrect and are most certainly not representative for the region. It is essential when comparing with previous studies that the location and method of calculation of sedimentation rate is determined. The use of Holocene sediment thickness from seismic profiles does not appear to be a robust method. For example, Tiffin (1969) determined sedimentation rates up to 2.60 cm/a from seismic profiles, based on an assumed basal age of 10 000 years for the entire package of glacial and postglacial sediments overlying acoustic basement (Fig. 3). Even if a more accurate age of 11 300 years were assumed for the glacial-postglacial boundary, Tiffin's (1969) rates would be higher than those determined in the present study, because they would include sediments deposited in ice-marginal conditions, not just present-day conditions. Furthermore, Figure 9 shows that, at least in the study area, estimates from Holocene sediment thickness tend to average out the local variations in short-term sedimentation rates.

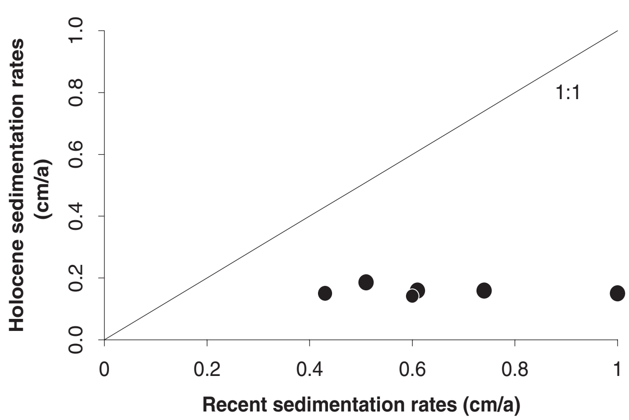

Figure 9. Relation between the recent rate of sedimentation calculated using Pb-210 and Holocene sedimentation rate calculated from the thickness of the sediment unit on the Huntec DTS subbottom profile records.

CONCLUSIONS

The thickness of the late Holocene sediments in the Whiskey Golf exercise area reaches a maximum of 21 m on the western side of the basin. Bedrock outcrops and mud are the main units composing the seafloor surface in the area. A best estimate for present-day sedimentation rate in the basin is 0.54 cm/a. Comparing this rate with that obtained from a single radiocarbon date suggests that sedimentation rates have probably increased over the last 1500 years. The study also demonstrates that when determining a sedimentation rate for an area of active Holocene deposition, factors such as location in the basin and the calculation method need to be taken into account. Previous higher estimates of sedimentation rates, based on erroneous seismic interpretation, should be discounted.

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