DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2022/2**

Geological Screening of Kriegers Flak North and South

Geological seabed screening in relation to possible location of windfarm areas

Jørn Bo Jensen & Ole Bennike

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2022/2**

Geological Screening of Kriegers Flak North and South

Geological seabed screening in relation to possible location of windfarm areas

Client Danish Energy Agency

Jørn Bo Jensen & Ole Bennike

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

GEUS

Contents

Appendix N: Existing Kriegers Flak OWF Boreholes KF-BH002,004,011 and 015

1. Dansk Resumé

Energistyrelsen har bedt GEUS om at udføre en geologisk screening af de potentielle havvindmølle parker Kriegers Flak 2 Nord og Syd. Undersøgelsen har resulteret i en generel geologisk beskrivelse og en geologisk model for området. Studiet er baseret på eksisterende data og er tænkt som baggrund for en vurdering af områdernes geologiske egnethed som vindmølleparker, samt som baggrund for eventuelle fremtidige tolkninger af seismiske data, geotekniske undersøgelser og arkæologisk screening.

I studiet har vi benyttet en kombination af publicerede artikler og rapporter, samt GEUS-arkiv data, til at vurdere den generelle geologiske udvikling i de potentielle havvindmølle områder Kriegers Flak 2 Nord og Syd.

Som en del af studiet præsenterer vi data, som er relevant for en efterfølgende arkæologisk screening.

Kriegers Flak 2 Nord, har en relativ flad havbund med vanddybder på 20 – 35m. Havbunden består af Danien kalk dækket af få meter moræne med sten og et pletvis dække af få meter vekslende sand og dyndet sand. Generelt vurderes området til at være egnet til vindmølle fundering.

Krigers Flak 2 Syd har en hældende havbund med vanddybder fra 20m i nordvest til 45m i sydøst imod Arkona bassinet. Havbunden består af Kridttids kalk dækket af få meters moræne, som udgør fundamentet for et kileformet sandlegeme, der i vestlige del opnår tykkelser på op til 35m og aftager i tykkelse mod øst til at blive få meter tykt. Generelt vurderes området som egnet til vindmøllefundering. Den østlige tyndere del af kilelaget har stigende indehold af ler, og dynd, hvilket der bør være fokus på.

Den geologiske opbygning samt vanddybder over 20m, indikerer at der ikke er arkæologiske interesser i områderne.

2. Summary

The Danish Energy Agency has requested that GEUS undertakes a geological screening study of the Kriegers Flak North and South potential offshore wind farm (POWF) areas. The study has resulted in a general geological description and establishment of a conceptual geological model for the understanding of the area. The study is based on existing data and is to be used as a background for the evaluation of geological suitability of the areas as wind farm sites and a background for future interpretations of new seismic data, geotechnical investigations, and an archaeological screening.

In this study we have used a combination of published work, GEUS archive seismic data and sediment core data to assess the general geological development of the southwestern Baltic Sea area, including the Kriegers Flak North and South POWF.

Information on the existing Kriegers Flak OWF has been presented including the general geology, soil types and geotechnical characteristics.

As part of the geological desk study, we present a relative late glacial and Holocene sea-level curve for the area and describe the development that is relevant for an archaeological screening.

The general geological description includes the complete geological succession from the underlying pre-Quaternary geological framework, the pre-Quaternary surface, glacial deposits, the deglaciation and late glacial and Holocene deposits.

A surface sediment map has been compiled by a combination of Emodnet seabed substrate maps from the German and Swedish zones and the latest version (2020) of the Danish 1:100.000 seabed substrate map.

Details of the geology are presented from the Kriegers Flak North and South POWF areas and has been interpreted and described on the basis of existing knowledge, seismic profile sections modified from Baltic Pipe investigations and scientific seismic lines as well as vibrocores.

In the south-western part of the Baltic Sea, studies of late glacial and early Holocene shore level changes have formed the basis for evaluation of the potential for finding submerged settlements in the wind farm areas. We consider the early and mid-Mesolithic time to be the most likely for findings.

It is concluded that it will be possible to establish a windfarm at Kriegers Flak 2 North POWF, due to its flat seabed (20 – 35m below present sea-level (bsl.) and thin-skinned Holocene sediments on top of till and Danian limestone.

It is concluded that the Kriegers Flak 2 South POWF is probably geotechnically suited for Wind- turbine foundations with some focal points.

It is however also recommended to acquire an open grid of shallow seismic data and few vibrocores, combined with geotechnical investigation, as a low-cost pre-investigation, before next step of decisions and comprehensive studies.

The geological setting and water depths above 20m indicates no risk for archaeological interest in both areas.

3. Introduction

GEUS has been asked by the Danish Energy Agency to provide an assessment of the seabed in the Kriegers Flak 2 North and South potential offshore wind farm areas (POWF), located north and south of the exsiting Kriegers Flak Offshore Wind Farm (OWF). The assessment consists of the establishment of a conceptual geological model based on existing data as a background for evaluation of the suitability for windfarm establishment and a marine archaeological screening (Figure 3.1).

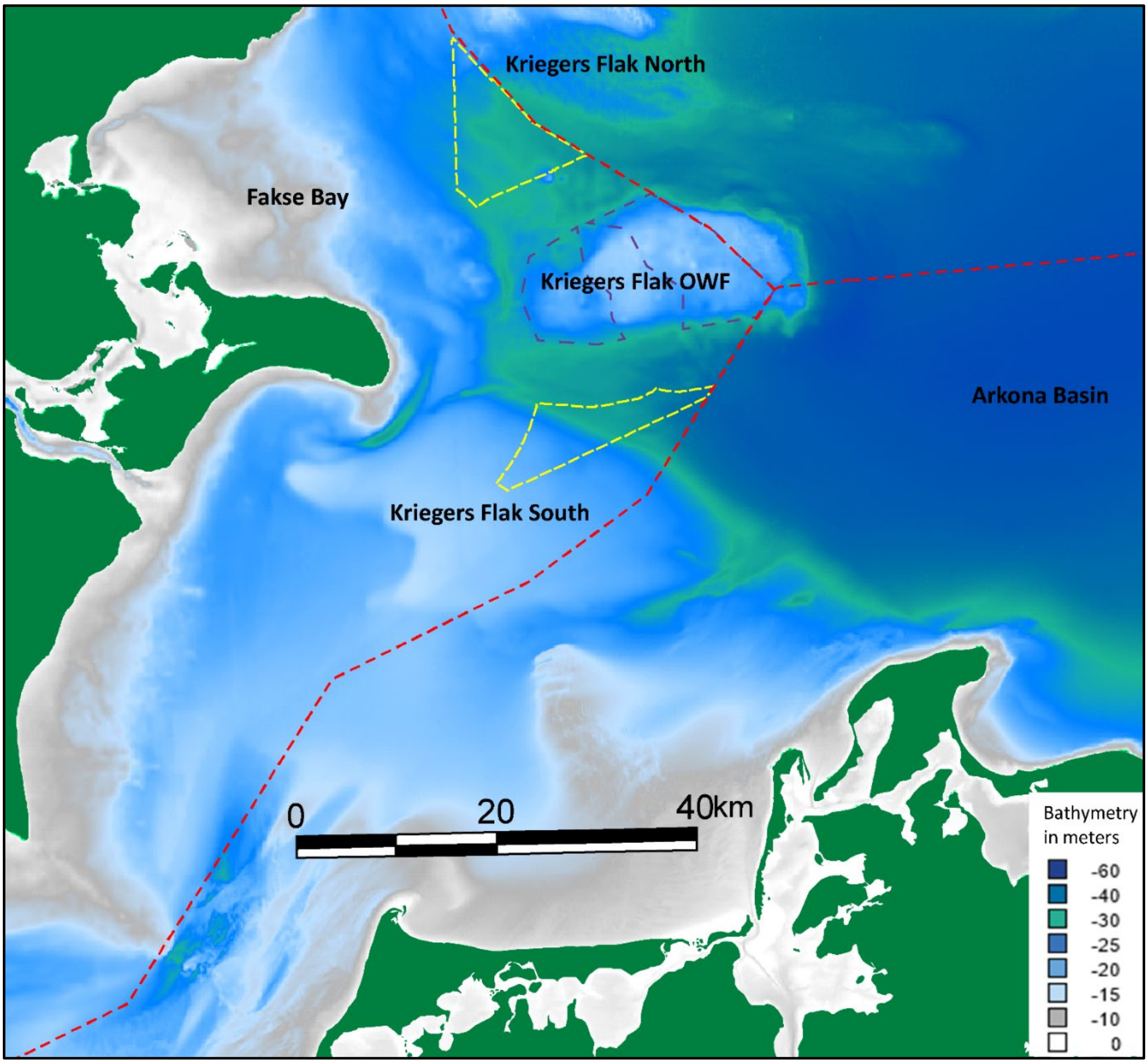


Figure 3.1 Overview map of the southwestern Baltic Sea with location of Kriegers Flak OWF (polygon with purple dashed lines), and the potential wind farm locations Kriegers Flak 2 North and Kriegers Flak 2 South (polygons with yellow dashed lines). The red dashed lines show the Exclusive Economic Zone (EEZ). The bathymetry is from Emodnet Bathymetry (https://www.emodnet-bathymetry.eu/).

4. Data background

As a basis for the desk study, existing background papers and reports have been used together with primary data from the GEUS Marta database (https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/marin-raastofdatabase-marta/), which is the national main archive of shallow seismic data and vibrocore data (Figure 4.1). In addition, data not included in the Marta database have been used. These data comprise boomer, pinger and vibrocore data from the Baltic Pipe project as well as boomer, airgun and vibrocore data from the Institute for Baltic Sea Research Warnemünde (IOW) and airgun and sediment echosounder data from Stockholm University.

4.1 Background reports and papers

Detailed information about The Baltic Pipe offshore pipeline transect is reported in Rambøll (2020). The Baltic Pipe transect crosses the Kriegers Flak 2 North POWF and the studies provide vital information from seismic transects and vibrocorings,.

In a geological desk study offshore Bornholm (GEUS 2021 a), the general geology of the region has been presented and existing seismic facies units have been described.

In the report Geological desk study Bornholm Windfarm cable transects (GEUS 2021 b), information about the Kriegers Flak North POWF location is reported.

Results from the existing Kriegers Flak OWF includes seismic- (Rambøll 2013) and geotechnical investigations (Geo 2013).

The Arkona Basin geology has been a subject for scientific investigations in Lemke (1998), with description of seismic facies and a combined distribution and thickness map of late glacial clay.

Additional scientific investigations of the southwestern Baltic Sea have in the past focused on the late- and postglacial development. A few papers describe the southern margin of the Arkona Basin including the Kriegers Flak 2 South POWF location (Jensen, 1993, Jensen et al. 1997, Jensen et al. 1999).

4.2 GEUS archive shallow seismic data and sediment cores

The Marta database includes available offshore shallow seismic data and core data in digital and analogue format (Figure 4.1). An increasing part of the seismic lines can be downloaded as SGY files from the web portal.

As seen on Figure 4.1, the Marta database contains a lot of archive data, but only sparse information is available from the Kriegers Flak 2 North and South POWF.

However, the existing seismic lines collected by the Baltic Pipe project (but not in Marta) provides information within, and close to, the potential wind farm areas. The acquired data include side scan, sediment echosounder and boomer data.

In our study we have further included archive data from Stockholm University (Tom Floden, airgun and sediment echosounder data) used for general mapping in the Arkona Basin by Lemke (1998) as well as scientific data from an IOW R/V Humboldt cruise from 1994 (boomer and airgun data).

The existing coring's are all vibrocorings with up to 6m penetration. Most of the vibrocores relate to the Baltic Pipe project and the Humboldt 1994 cruise. Core descriptions are in general available in the Marta database, while no samples have been preserved.

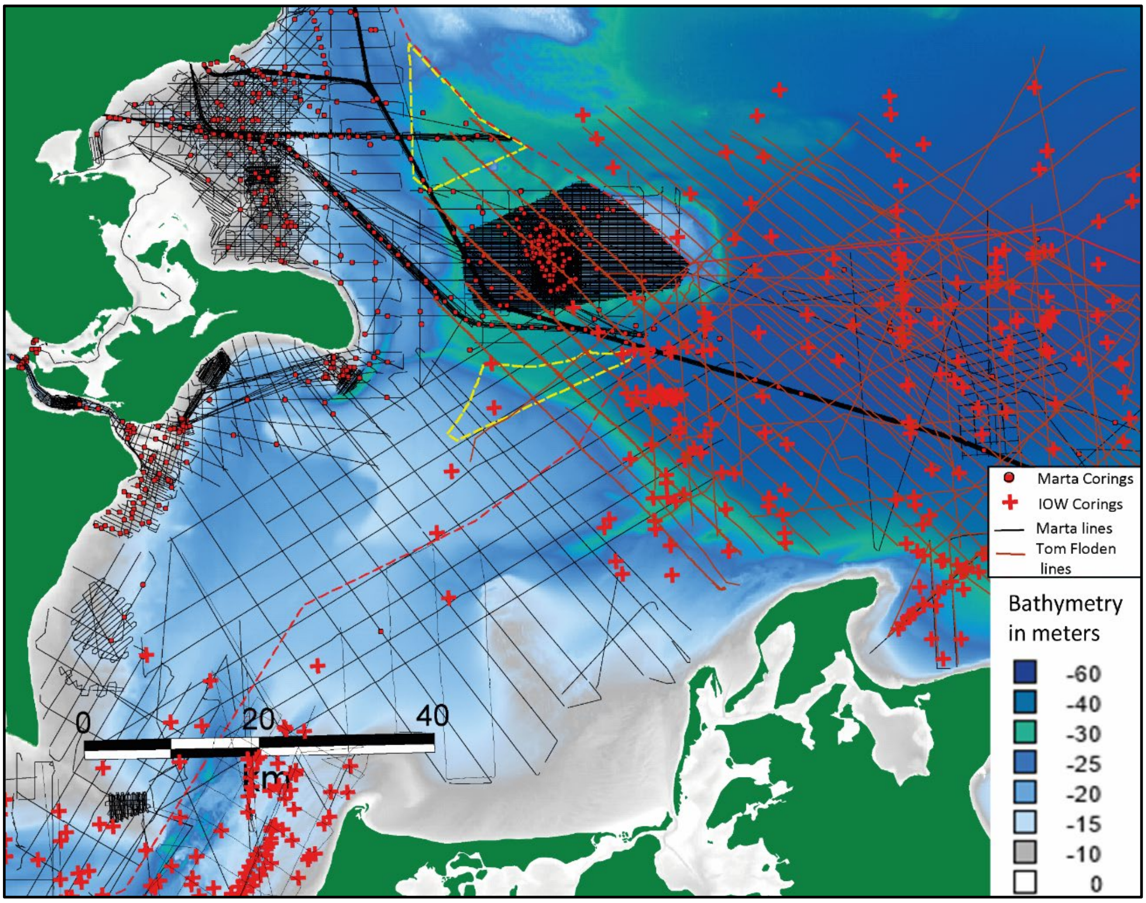


Figure 4.1 Distribution of Marta database seismic data and core data in the study area as well as IOW corings and Stockholm University (Tom Floden) airgun data used for general mapping in the Arkona Basin by Lemke (1998). The location of the proposed Wind farms Kriegers Flak 2 North and Kriegers Flak 2 South is indicated by polygons with yellow dashed lines. The red dashed lines show the EEZ. The bathymetry is from Emodnet Bathymetry (https://www.emodnet-bathymetry.eu/).

5. Pre-Quaternary geology of the south-western Baltic Sea

Detailed pre-Quaternary descriptions of the Bornholm and Arkona Basin region has been presented in geological desk studies offshore Bornholm GEUS (2021 a) and Arkona Basin cable transects GEUS (2021 b).

The southwestern Baltic Sea is crossed by the 30-50 km wide WNW-ESE-trending Sorgenfrei–Tornquist Zone that separates the Baltic Shield, the Skagerrak-Kattegat Platform and the East European Precambrian Platform in the northeast from the Danish Basin in the southwest (Figure 5.1). The Sorgenfrei–Tornquist Zone has been active during several phases after the Precambrian. The lineament is characterised by complex extensional and strike-slip faulting and structural inversion (Liboriussen et al. 1987; Mogensen & Korstgård 2003; Erlström & Sivhed 2001). The old crustal weakness zone was repeatedly reactivated during Triassic, Jurassic and Early Cretaceous times with dextral transtensional movements along the major boundary faults.

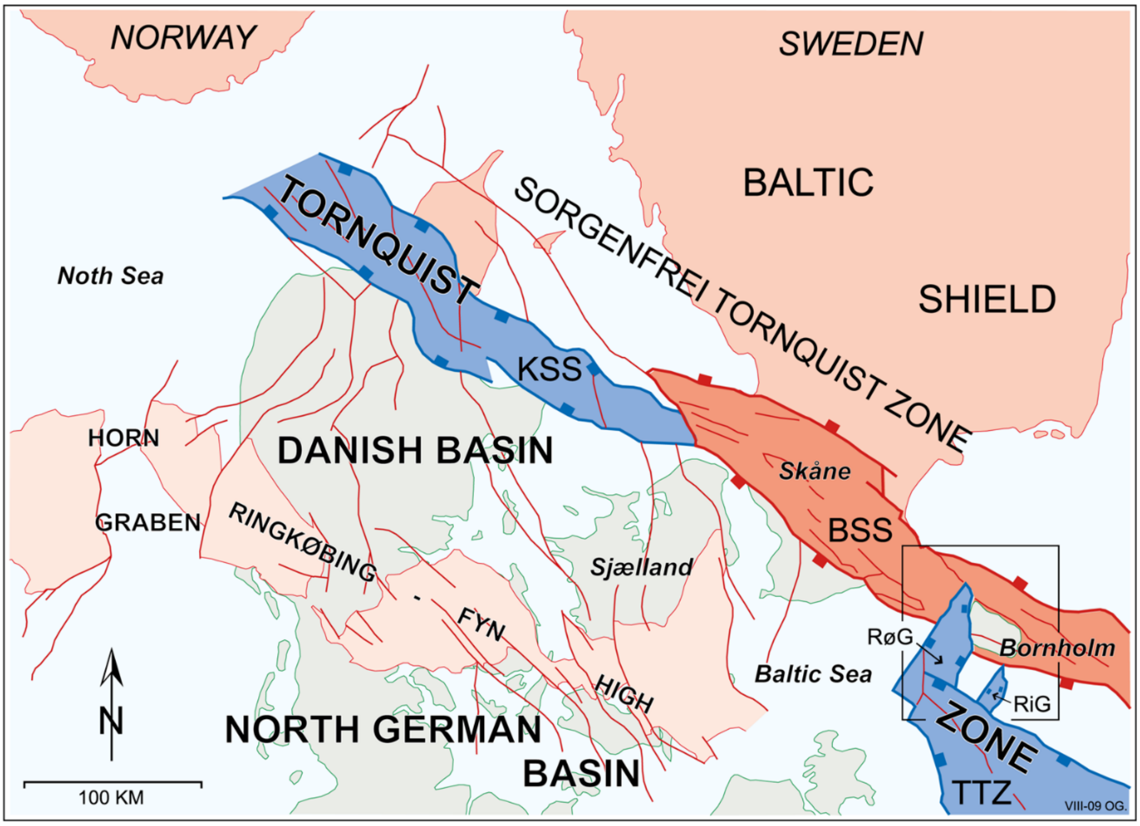


Figure 5.1 Position of the Bornholm area in the Tornquist Zone between the Baltic Shield/East European Platform and the Danish Basin/NW European craton (Graversen 2004, 2009).

The pre-Quaternary surface is presented in Figure 5.2 , where the Kriegers Flak region show Upper Cretaceous chalk and Danien limestone, bounded by faults related to the Ringkøbing Fyn High.

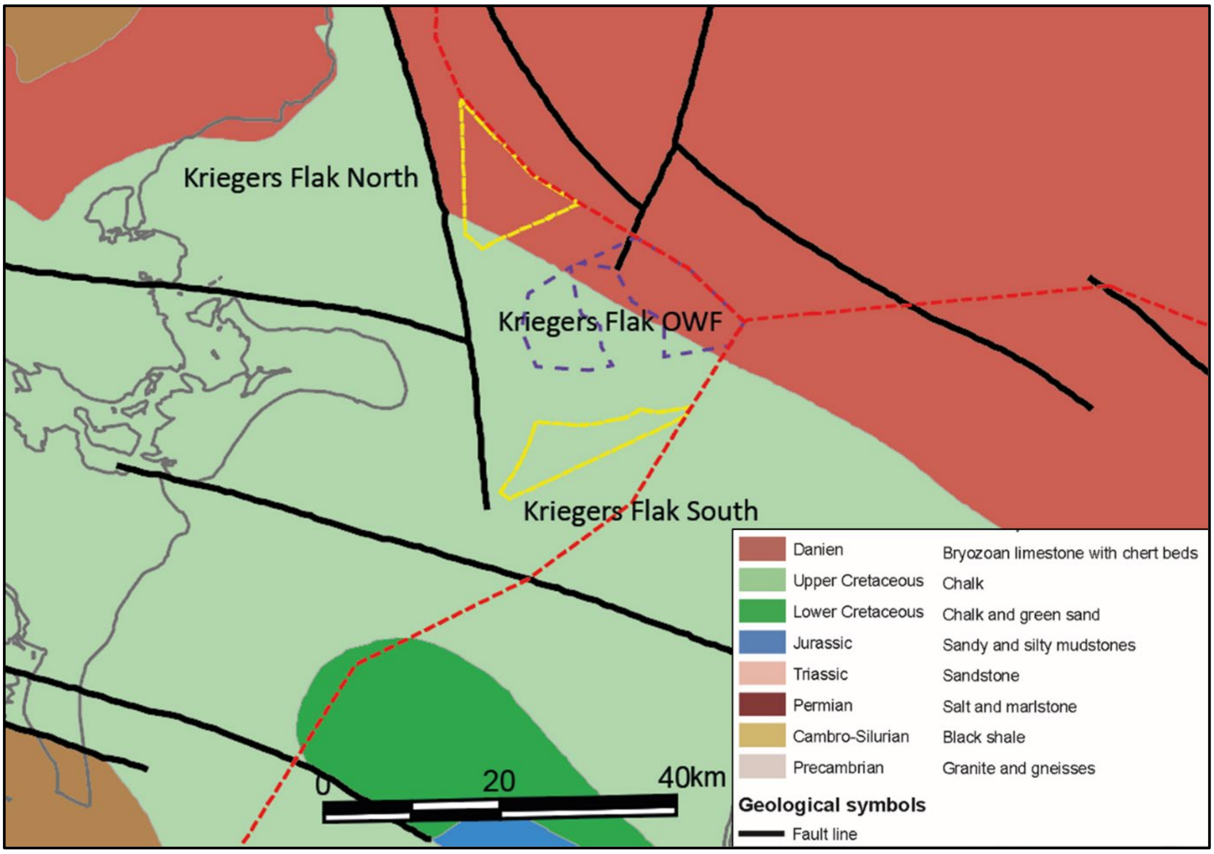


Figure 5.2 Bedrock geology in the Kriegers Flak area. From Varv (1992), with location of Kriegers Flak OWF (polygon with purple dashed lines), and the potential wind farm locations Kriegers Flak 2 North and Kriegers Flak South 2 (polygons with yellow dashed lines). The red dashed lines show the EEZ.

The general geological development of the study area has resulted in a characteristic pre-Quaternary surface topography (Binzer & Stockmarr 1994) (Figure 5.3).

The combined present bathymetry and pre-Quaternary surface topography shows that only a thin Quaternary top unit of a few metres to about 30m thickness can be expected in the mapped areas. Unfortunately, the Krieger Flak 2 South and North areas are not mapped in relation to pre-Quaternary surface topography. The expectation is however that the northern part of the Arkona Basin follows the same pattern, while increasing Quaternary sediment thickness is observed in the southern part of the Arkona Basin (Lemke 1998).

The seabed sediment map in Figure 7.1 shows large areas with exposed pre-Quaternary seabed sediments offshore Bornholm and in the near shore northern Fakse Bay area. Kriegers Flak 2 North POWF shows only a thin Quaternary top unit of a few metres above Danien limestone while Kriegers Flak 2 South POWF shows 10 – 30m Quaternary glacial (Till) and late glacial sand-clay above Upper Cretaceous chalk.

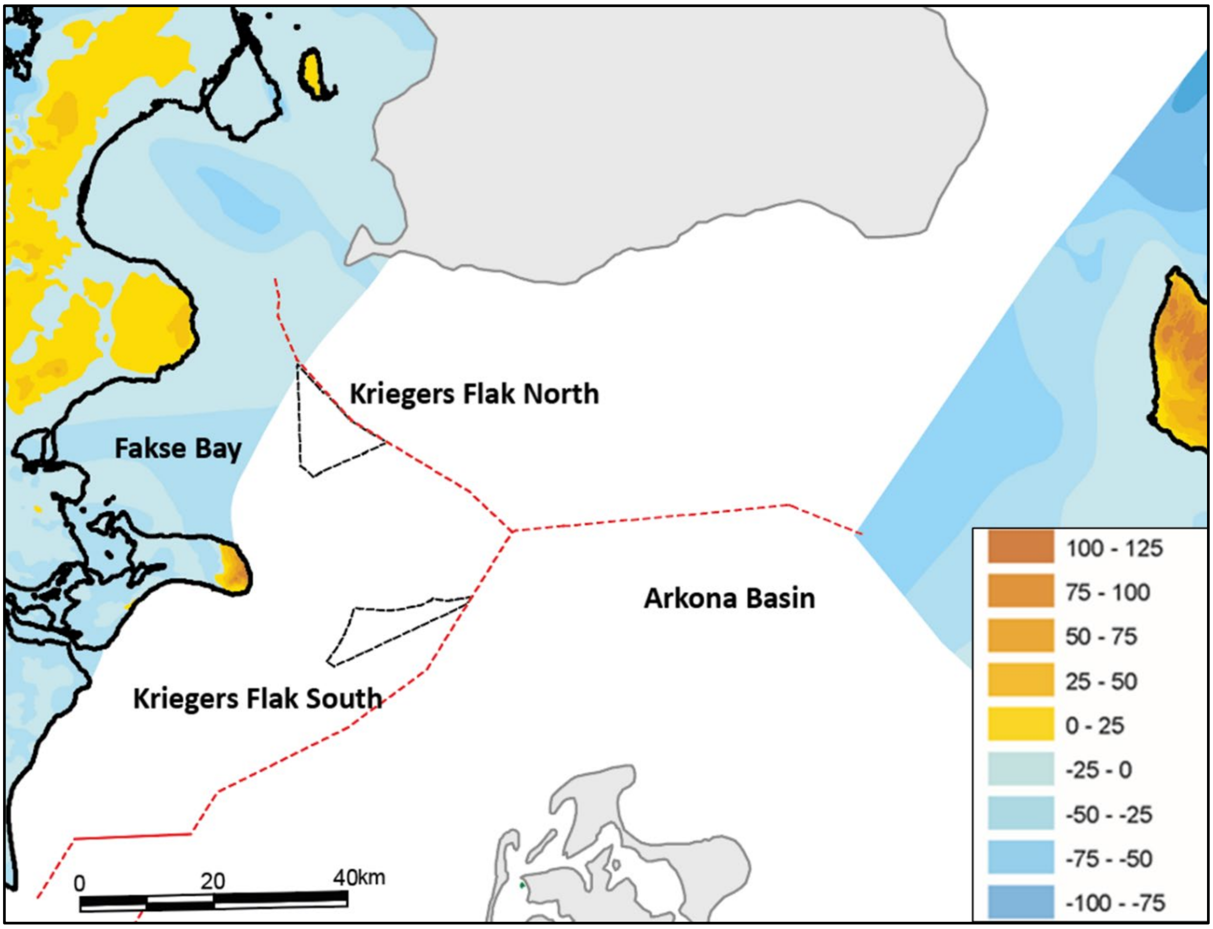


Figure 5.3 Pre-Quaternary surface topography in metre above sea level (Binzer & Stockmarr 1994). Location of Kriegers Flak 2 North and Kriegers Flak 2 South POWF is shown with black dashed lines. The red dashed lines show the EEZ.

6. Quaternary geology of the south-western Baltic Sea

Four Late Saalian to Late Weichselian glacial events, each separated by periods of interglacial or interstadial marine or glaciolacustrine conditions, have been identified in the south-western Baltic region. The thickness of Quaternary sediments in the region can exceed 100m in the basins (Jensen et al. 2017). The Scandinavian Ice Sheet reached its maximum extent in Denmark about 22000 years BP followed by stepwise retreat.

The Bornholm region was probably deglaciated shortly after 15000 years BP. Moraine ridges on Rønne Banke and Adler Grund trending parallel to the former ice margin resemble ridges reported southeast of Møn (Jensen 1993). They may mark short-lived re-advances during the winter, formed during the general retreat of the ice margin. An interpretation of the general deglaciation pattern is presented in Lange (1984).

Figure 6.1 Ice margin readvance stage model from Lange (1984).

After the deglaciation, a glaciolacustrine environment with icebergs, the Baltic Ice Lake, was established (Figure 6.2).

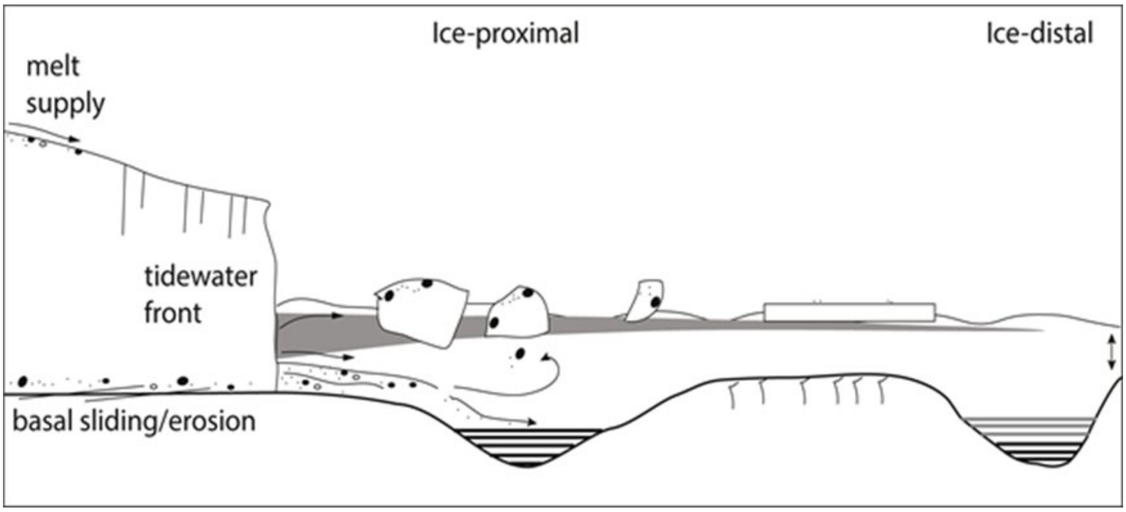


Figure 6.2 Illustration of a glaciolacustrine depositional environment.

Quaternary sedimentation in the Fakse Bay, Arkona- and Bornholm Basins, has been intensively studied in relation to the development of the late- and postglacial Baltic Sea phases (Jensen et al. 1997, 1999), because of the well-preserved Baltic Ice Lake clay and the Yoldia Sea and Ancylus Lake clay, as well as the brackish to marine Littorina Sea clay and mud deposits. The Holocene history was documented by Andrén et al. (2000).

6.1 Palaeogeography of the deglaciation of Denmark

The knowledge about the general deglaciation and postglacial history of the southwestern Kattegat and the western Baltic can be presented in a series of palaeogeographical maps (Figure 6.3 a and b):

- About 18000 years ago, the deglaciation from the largest glacier extension (Main Stationary Line) in Jutland had reached a stage where the ice margin roughly followed the Swedish west coast, the present Zealand northern coastline, extending southward along the western part of the Great Belt and with the distal margin found in the northernmost part of Germany. In this early phase, the deglaciated Kattegat region still was not isostatically adjusted and the relative sea-level was high with sea covering major parts of northern Jutland.

- At the next stage, about 16000 years ago, the ice margin had retreated to the Øresund region and the western part of Skåne leaving an ice lobe that covered the southern part of Zealand and followed the present southern coastline of the Baltic Sea. The ice margin was directly connected to the Kattegat marine basin by a broad meltwater channel, which at this stage was affected by an initial relative sea-level regression, while local lakes were under development along the ice margin in the south-westernmost Baltic Sea, e.g. in Køge Bugt.

- A controversial stage of the deglaciation was reached about 15000 years ago, as the ice margin retreat had reached central Skåne. For this stage, only limited information has so far been available about the present offshore area, but investigations in Polish waters combined with data from German and Danish waters show that the ice margin must have been situated west of Bornholm and a large lake started to be dammed in front of the ice sheet with connection through the Great Belt to the Kattegat, which at that time was increasingly affected by a regression. Apart from meltwater flow from the glacier area west of Bornholm, major meltwater contributions were provided by German and Polish rivers as proved by the existence of major late glacial delta and beach barrier deposits in Fakse Bay and South of the island of Møn (Kriegers Flak South POWF).

- The initial damming of The Baltic Ice Lake was followed by a regression, before a second damming occurred followed by a major discharge event (For relative sea-level changes see Figure 8.1 and Figure 8.2). The last and most extensive Baltic Ice Lake damming took its maximum about 12000 years ago, when minor channels drained the lake through the Great Belt and Øresund and only a small land bridge separated the Baltic Ice Lake from the sea in south-central Sweden. Under the second damming, reactivation and substantial beach barrier deposition continued in Fakse Bay and South of the island of Møn (Kriegers Flak South POWF). Further retreat resulted in a catastrophic discharge event in south-central Sweden with the water level in the lake dropping about 25m.

- About 11500 years ago, a strait was established through south-central Sweden, and the Baltic basin was transformed into a marine basin called the Yoldia Sea. This name comes from an arctic bivalve species called Portlandia (Yoldia) arctica, which is found in sediments deposited during this time. The postglacial eustatic sea-level rise surpassed the rate of glacio-isostatic rebound in the southern Kattegat and the lowest postglacial relative sea-level was reached about 35m below present sea-level. Curves of sea-level changes are shown in Figure 8.1 and Figure 8.2.

- Continuous glacio-isostatic uplift of south-central Sweden closed the connection to the ocean and the last lake phase of the postglacial Baltic, called the Ancylus Lake, was established, The stage is named after a fresh-water gastropod, Ancylus fluviatilis, which lives in rivers and in the coastal zone of large lakes. Due to damming, the lake reached a maximum water level about 10200 years ago with only a narrow drainage pathway through the Great Belt into the southern Kattegat. Here the initial transgression had resulted in the formation of a rather large lagoon/estuary basin, partly blocked by transgressive coastal barriers. Remains of this system are preserved on the sea floor as it is reported by Bennike et al. (2000) and Bendixen et al. (2017).

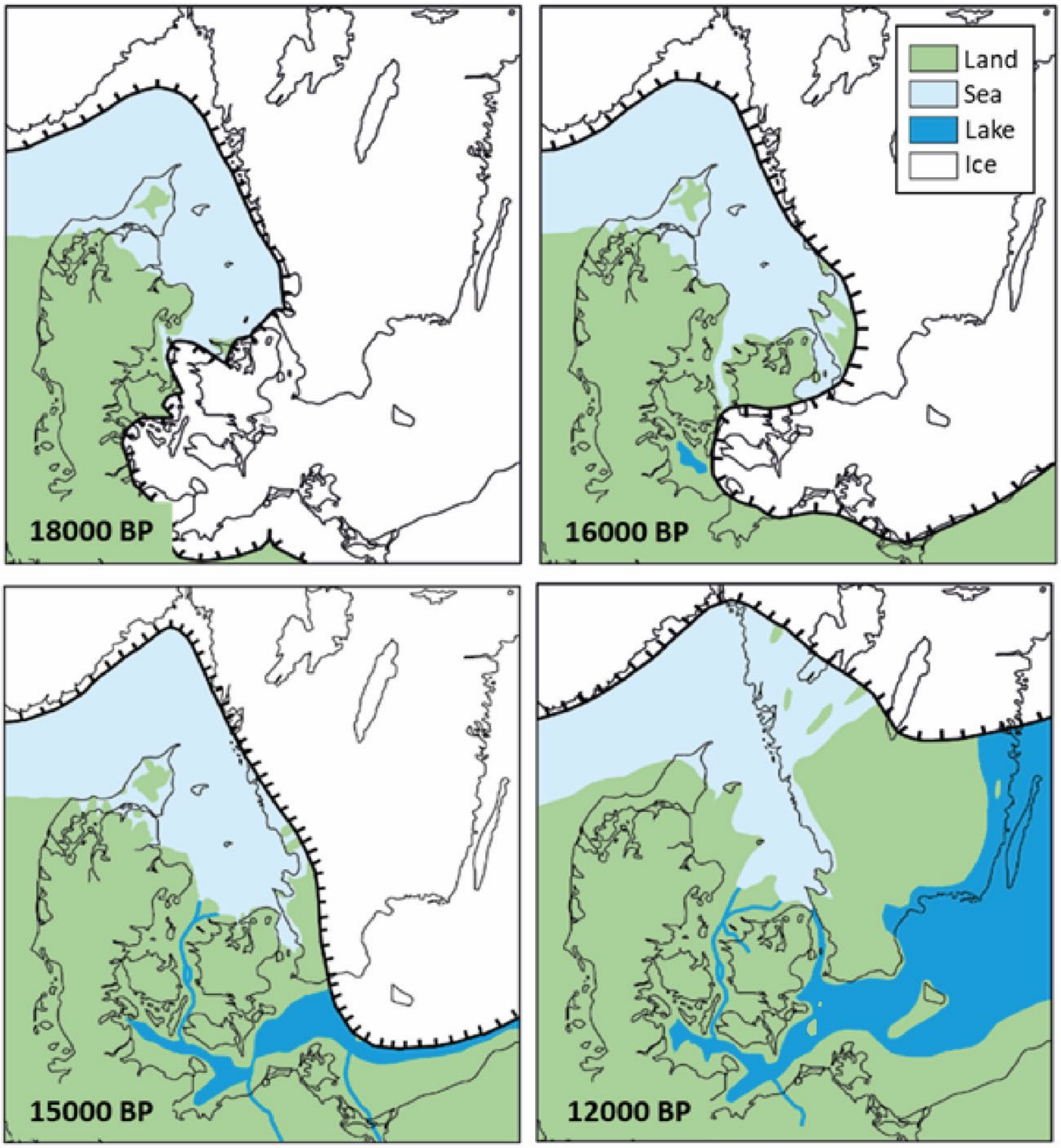
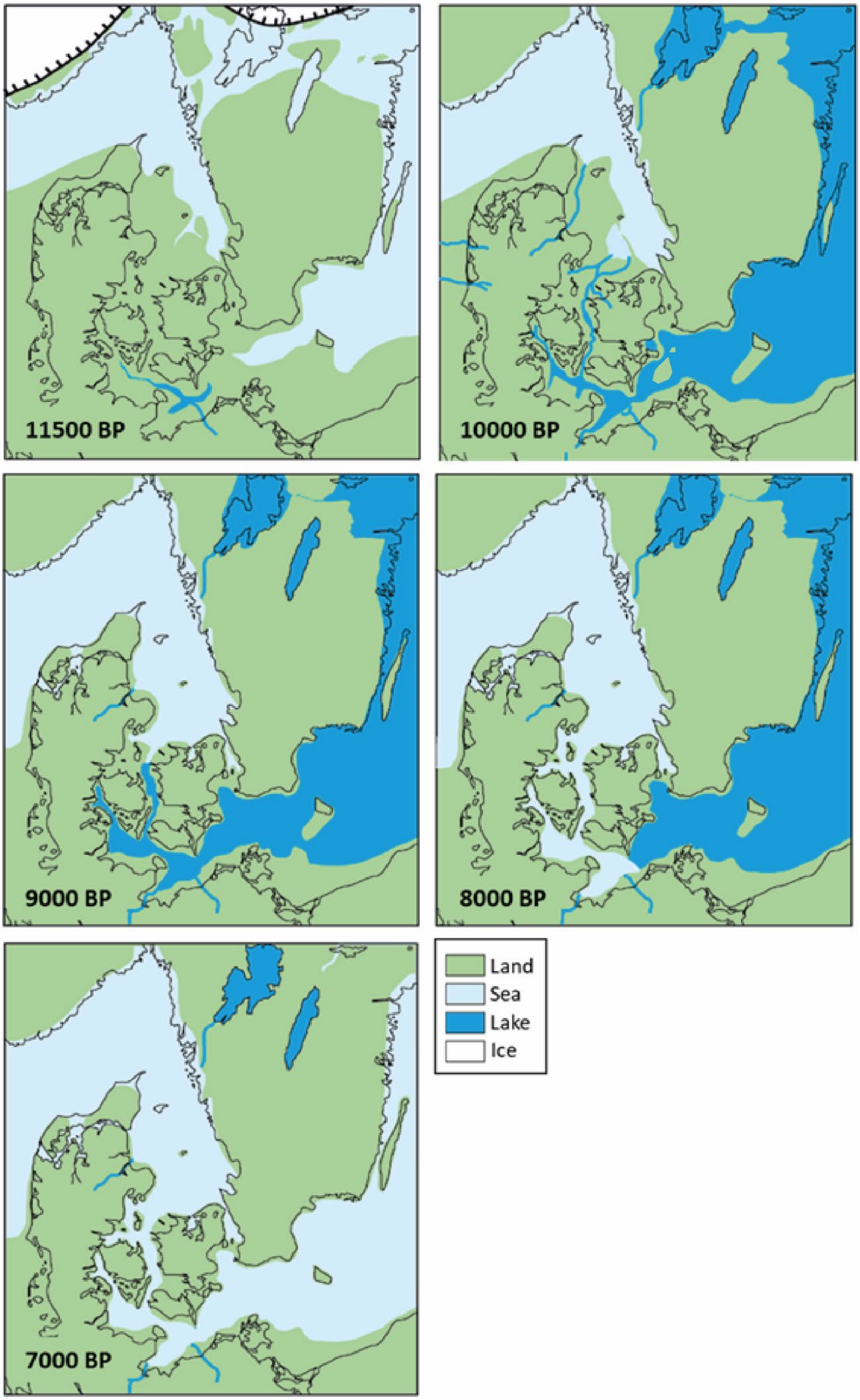


Figure 6.3 a and b. Palaeogeographical maps showing the development of the Danish area from c. 18000 to c. 7000 years BP. Modified from Jensen et al. (2003).


11500 BP
10000 BP
9000 BP
8000 BP
7000 BP
🟩 Land
Sea
🟦 Lake
☐ Ice

- About 10000 years ago, the Ancylus Lake water level dropped about 9m within a few hundred years. The traditional opinion was that the drainage was through the Great Belt. However, investigations in the southern Kattegat, the Great Belt as well as at the thresholds Gedser Reef – Darss Sill, south-east of Langeland and in the south-western Kattegat show that only a small lake level fall, in the order of a few metres, could be provided by this drainage route. Moreover, for the time of drainage, calm lake and estuarine sedimentation is recorded in the Great Belt and south-western Kattegat.
- The calm lake sedimentation was followed by a gradual transgression and change into brackish conditions about 9400 years ago, and a fully marine environment was reached in the Great Belt 9100 years ago, marking the beginning of the Littorina transgression.
- About 8000 years BP, the transgression had reached the Darss Sill – Gedser Reef area.
- And about 7000 years BP, also the western part of the Baltic Proper was marine.

6.2 The basic Quaternary conceptual geological model in the Southwestern Baltic, based on data from the Bornholm region

The Quaternary conceptual geological model for the region, builds on a network of seismic data from the Marta database as well as scientific data collected during the last few decades, mainly in connection with the EU BONUS project: Baltic Gas. A seismic stratigraphy was developed, and core positions were selected and followed by an Integrated Ocean Drilling Program (IODP 347).

During IODP Expedition 347 in October 2013, cores were recovered at Site M0065 (Figure 6.5, Figure 6.6 and Figure 6.7) in the Bornholm Basin, with an average site recovery of 99%. The water depth at the coring site was 84.3m, with a tidal range of <10 cm. A total depth of 73.9m below seabed was reached before bedrock was encountered. Piston coring was used to recover the clay lithologies before switching to a combination of open hole and hammer sampling to maximize recovery in the more sandy lithologies. No samples were recovered from the lower part and only the upper 49.2m could be described.

The obtained sediment sequence was divided into lithostratigraphical units by Andrén et al. (2015).

A conceptual geological model based on the combination of seismic data and core data was established by Jensen et al. (2017). Results from the rest of the southwestern Baltic Sea shows that the model is valid for the whole region and hence it forms the basis for the interpretations in this study.

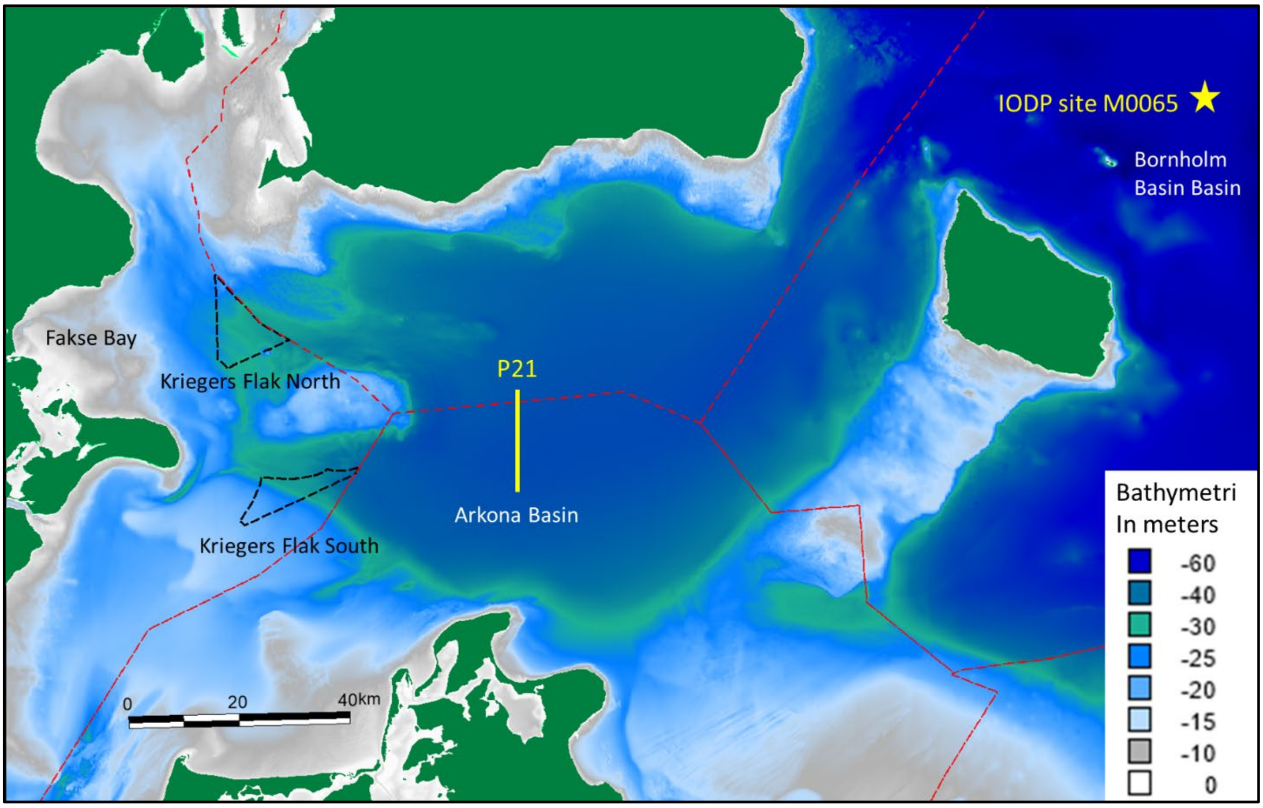


Figure 6.4 Map of the southwestern Baltic Sea with location of IODP site M0065 (yellow star) in relation to the Kriegers Flak 2 North and South POWF (polygons with black dashed lines). P21 is the location of seismic line from Mathys et al. (2005). The red dashed lines show the EEZ.

Five seismic units were described, all separated by unconformities (Figure 6.5).

The Crystalline basement and Sedimentary bedrock, Unit V, as well as the Glacial Unit IV, were mainly identified on deeper seismic airgun data, whereas details of the late- and post-glacial more soft deposits are best seen on the sediment echo-sounder profiles (Figure 6.6).

The bedrock distribution follows the deeper structures shown in Figure 5.1 and the glacial deposits follows the regional glaciations.

The late- and postglacial Units III–I were deposited in basins with a changing shore-level. The shore-level changes are well described in the southwestern Baltic Sea (Figure 6.5) (Andrén 2000 and Uscinowicz 2006), and a close match can be expected between shore-level lowstands and allostratigraphical unconformities.

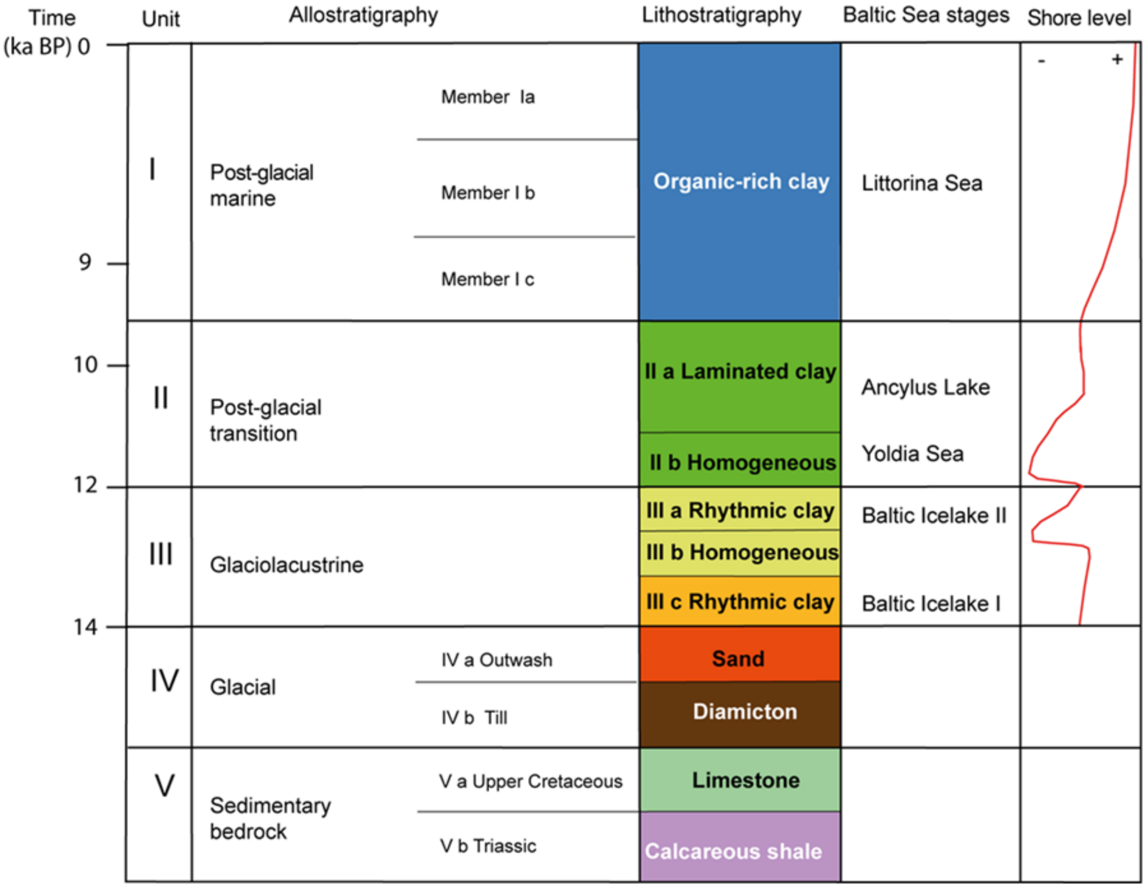


Figure 6.5 Stratigraphical subdivision of the Bornholm Basin (Jensen et al. 2017). The seismic Units I–V represent allostratigraphical formations, some of which are divided into members, all bounded by unconformities. Mappable lithostratigraphical formations (informal) are identified within the allostratigraphical framework and Baltic Sea stages as well as the general Baltic Sea shore-level changes are correlated with the established allostratigraphy.

6.2.1 Unit IV Glacial deposits

The glacial deposits drape the pre-Quaternary irregular surface. Unit IV is usually 10–20m thick, but in the Christiansø Ridge zone, crystalline basement rocks are sometimes found at the seabed, whereas the unit is more than 50m thick in the strike-slip fault basins. The upper reflector is an irregular unconformity, and the internal configuration is mostly chaotic except in some of the strike-slip fault basins, where internal unconformities exist. The glacial deposits consist of diamicton and glacial outwash sediments, as documented in the IODP 347 sites (Figure 6.6) and Andrén (2014).

The distribution of glacial sediment facies is in general chaotic with alternating sections of clast-rich muddy diamicton and parallel-bedded, medium grained sand with cm- to dm-scale laminated silt and clay interbeds as seen in IODP site 66. However, IODP site 65 is located in a strike-slip fault basin, where there is a clear subdivision into a lower diamicton member (IVb) and an upper outwash member (IIIa), separated by an unconformity.

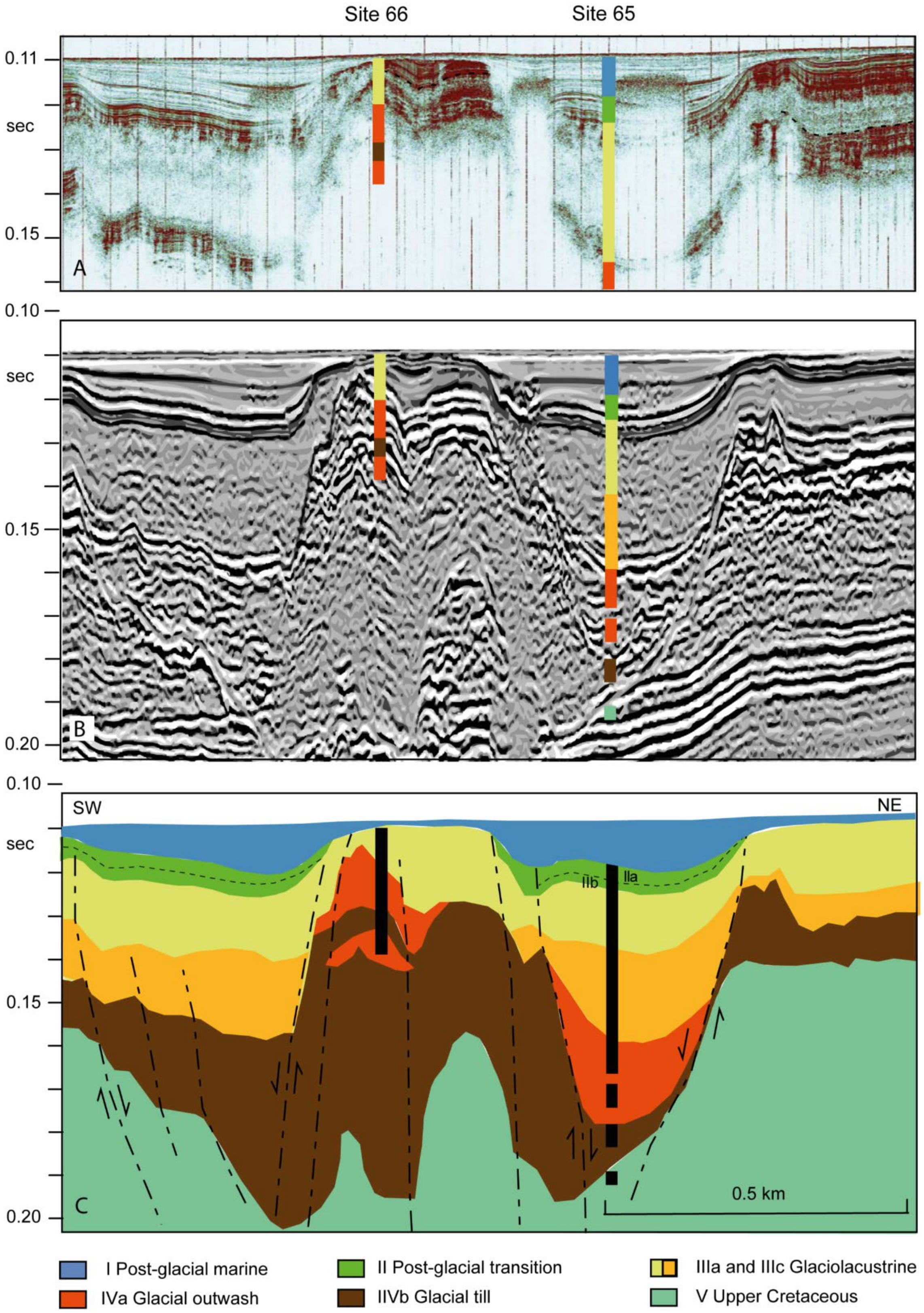


Figure 6.6 Seismic line across Site M0065 (Jensen et al. 2017). Original interpretation of the seismic transect: Airgun data (A) and Atlas parasound data (B) (Andrén 2014), as well as sediment documentation for sites 65 and 66. The interpretation (C) follows the classification in seismic units described in Figure 6.5. The location of the IODP sites are shown in Figure 6.4.

6.2.2 Unit III Late glacial glaciolacustrine deposits

The glaciolacustrine sediments cover the irregular unconformity of the glacial deposits in the Bornholm Basin, except in the topographically high Christiansø Ridge area, where Unit IV is truncated or absent, indicating erosion. In the basin areas, a strong upper reflector marks the top of the glaciolacustrine deposits, which in general drape the underlying topography with a thickness of 10–20m. An increased thickness of more than 50m is found in the minor strike slip fault basins (Figure 6.6). The internal reflection configuration also varies through the basin.

Unit III is divided into three subunits:

- IIIc is the lowest unit characterized by greyish brown clay with weak lamination by colour and few silt laminae in mm scale, large intervals dominated by massive to contorted appearance; numerous interspersed, grey clay/silt intraclasts of mm to cm scale, very well sorted.
  Unit IIIc corresponds to Baltic Ice Lake sediments deposited in front of the retreating Weichselian glacier and represents an early stable phase of the glaciolacustrine environment. The parallel reflectors and rhythmically layered clay, seen all over the Bornholm Basin, are interpreted as varved glaciolacustrine clay. The upward decrease in grain size from silty clay to clay and the decreasing frequency of sand laminations indicate that the ice front became more and more distal to the Bornholm Basin.

- IIIb is the middle unit and consists of dark grey, homogenous clay. It is a basin-wide intermediate zone consisting of homogeneous clay that can be related to the first Baltic Ice Lake drainage that occurred during the late Allerød (Figure 6.7). This drainage led to a 10m drop in water level and to the formation of unconformities in the shallow parts of the southwestern Baltic Sea (Jensen et al. 1997; Bennike & Jensen 1998, 2013; Uscinowicz 2006). The relatively deep Bornholm Basin was covered by water even after this drainage event and the unconformity seen in shallow areas is replaced by a basin-correlative conformity. However, the water level drop in the Bornholm Basin is reflected in the changes in internal reflector configurations and the lithological shift to homogeneous clay.

- IIIa is the upper unit and consists of greyish brown, silty clay with parallel lamination, downwards coarsening to fine- to medium-grained sand with laminated silt; lowermost few metres massive, medium-grained sand with few dispersed pebbles and detrital carbonate in all grain sizes up to fine gravel. The indistinct lamination in formation IIIa, combined with homogeneous and contorted sedimentary structures, as well as clay intraclasts, may indicate slumping in an unstable sloping environment with high sedimentation rates. This could be due to piano key neotectonics (Eyles & McCabe 1989) that led to reactivation of minor, along-basin, strike-slip faults.

The sediments in unit III are barren of diatoms, foraminifers or ostracods and the depositional environment is interpreted as a glacio-lacustrine environment. The sandy sediments in the lowermost part of the retrieved succession represents a proximal glaciolacustrine environment.

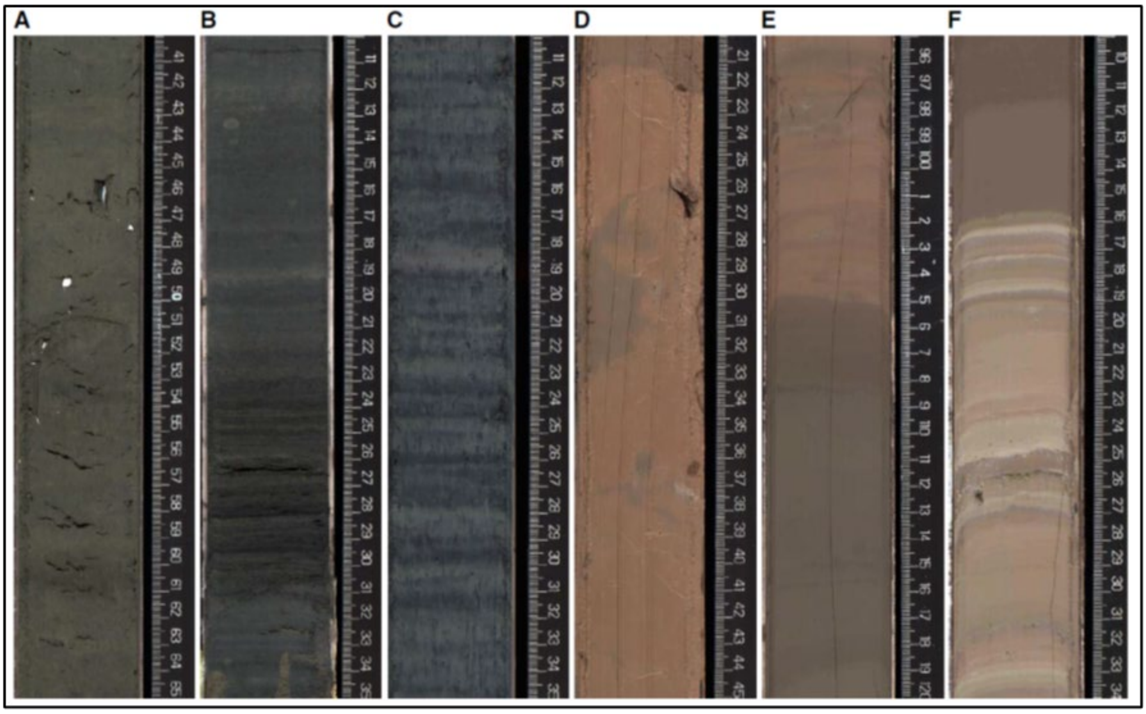


Figure 6.7 Examples of lithostratigraphic units, Hole M0065A. A. Unit I. B. Unit I. C. Unit II. D. Subunit IIIc. E. Subunit IIIb. F. Subunit IIIa.

6.2.3 Unit II Early postglacial transition clay

Unit II conformably drapes the glaciolacustrine sediments in the Bornholm Basin with a rather constant thickness of about 4m. The seismic characteristics of Unit II are closely spaced parallel reflectors with upward decreasing amplitude. A strong reflector is seen at the upper boundary. In the minor strike-slip fault basins, local thickening of the unit, on-lapping and erosional truncation is observed. This is probably due to synsedimentary down-faulting of the basins and relative uplift of the margin (Figure 6.6).

At IODP site 65, which is in one of the minor strike-slip fault basins, Unit II is 4m thick and consists of grey to dark grey clay. In the lowermost part (formation IIb) homogeneous brown clay is observed, gradually changing upwards to grey clay with intervals of black spots and specks. The uppermost part of the clay (formation IIa) is laminated by colour with very fine dark grey iron sulphide-rich, 2–3mm thick lamina. The density of laminae decreases downwards. The basin-wide clay drape indicates accumulation of Unit II in a deep-water basin with only weak bottom currents. Previous studies in the Bornholm Basin (Kögler & Larsen 1979; Andrén et al. 2000) documented the same lithological sequence. It has been interpreted to represent deposition in the Yoldia Sea (the lowermost homogeneous part) and Ancylus Lake clay (AY) deposition (the uppermost laminated part). Sulphide migration downwards from the upper organic-rich sediments is a likely explanation for the diagenetic iron sulphide enhanced laminations.

6.2.4 Unit I Mid- and late postglacial marine mud

In the central Bornholm Basin, northeast of the Christiansø Ridge, the basin infill of the youngest Unit I have an asymmetrical external wedge shape and the sediment echo-sounder data show complex internal reflection patterns (Figure 6.6). Frequent low amplitude, concave and internal on-lap parallel reflectors dominate the major synsedimentary down-faulting zone. In the minor strike-slip fault basins, we established three allostratigraphical members (Ic, Ib and Ia; Figure 6.5). These members show asymmetrical bundled on-lap infill of the basins and the bundles are bounded by reflectors representing internal unconformities and correlative conformities.

The complex reflection pattern indicates that late postglacial down-faulting resulted in episodic, synsedimentary deposition in the strike-slip basins and that sub-recent to recent sedimentation is still asymmetrical with sedimentation in the southern central basin and erosion at the north-eastern margin of the basin. Transport of sediments from the Arkona Basin west of Bornholm into the Bornholm Basin and along the southern basin margin is a likely process for the observed deposition of sediments as a wedge-shaped contourite.

At IODP site 65, Unit I is ~7m thick (Figure 6.6). The unit consists of well-sorted, dark greenish grey, organic-rich clay with indistinct colour lamination due to moderate bioturbation. The general stratification is overprinted by intervals of black layers with sharp bases. Scattered shell fragments are found down to the lowermost transition zone to Unit II, where about 10cm of non-bioturbated clay with prominent mm-thick laminae is found. Organic debris is common (possibly algal or plant debris) and large centric diatoms are found. Some silt and sand are also present. The boundary to Unit I is gradual. The organic-rich clay, with bioturbated indistinct lamination and intervals of black layers, indicates more oxic conditions during the mid- and late Holocene in the Bornholm Basin than in the central Gotland Basin. The lowermost laminated transition zone may represent an initial anoxic phase, similar to the anoxic phases reported in the Gotland Deep (e.g., Zillen et al. 2008).

6.3 The Arkona Basin geological background information

The Arkona Basin region is mainly situated in German and Swedish Exclusive Economic Zones (EEZ), and only very limited information is available from the GEUS archives.

From the Baltic Pipe project we use information about the Bornholm Wind Farm 1 and 2 (GEUS 2021 b) as well as longer stretches along the planned cable transects (GEUS 2021 a) including the Sweedish zone (transects B and C). The available information includes side scan, sediment echosounder and boomer data reported in Rambøll (2020).

In addition, we have included archive seismic data from Stockholms University (Tom Floden) used for general mapping in the Arkona Basin by Lemke (1998) and scientific papers (Moros et al. 2002, Mathys et al. 2005).

6.3.1 Arkona Basin stratigraphy

The Arkona Basin sediment stratigraphy is presented in Moros et al. (2002) and Mathys et al. (2005). Comparing Figure 6.8 and Figure 6.10 with the stratigraphical subdivision of the

Bornholm Basin (Jensen et al. 2017), the same units are observed representing the Baltic Ice Lake and younger sediments with similar characteristics.

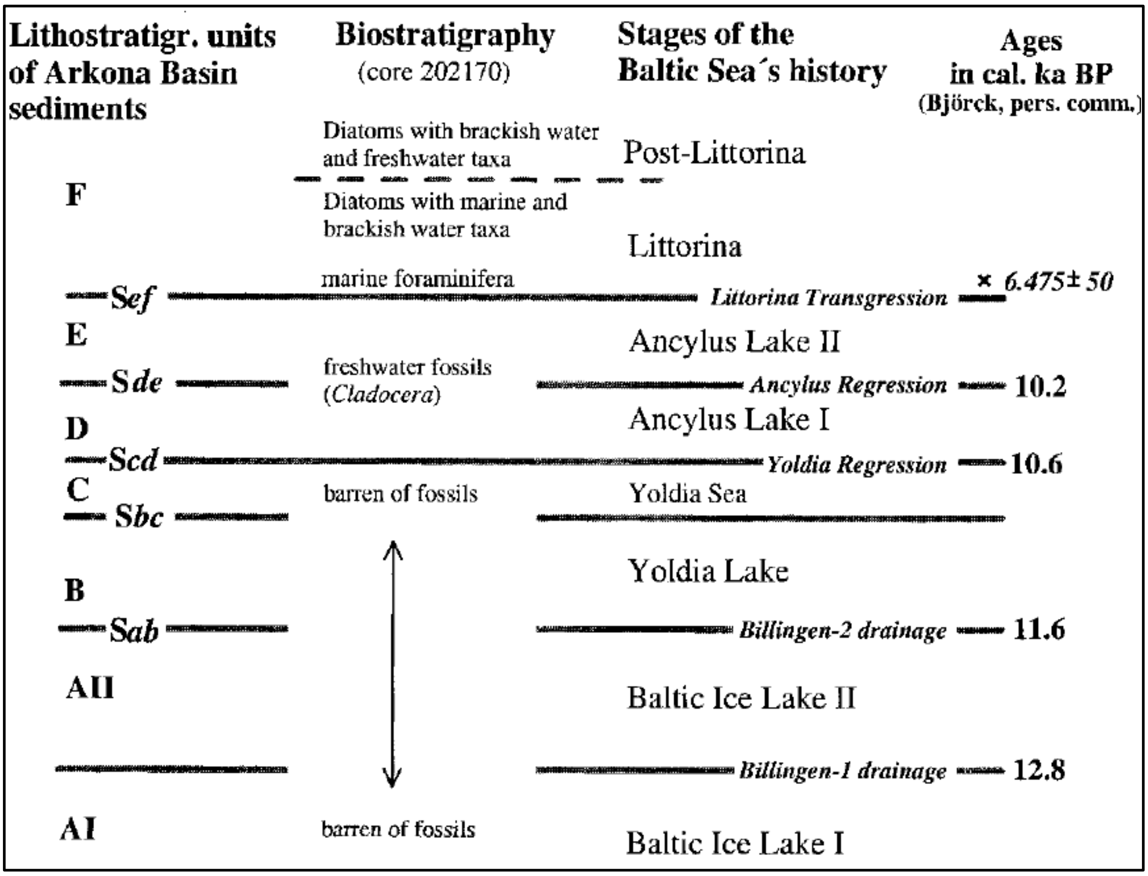


Figure 6.8 Link between the lithostratigraphic units, the sandy layers, biostratigraphic information observed in Arkona Basin sediments and the known stages of the Baltic Sea's history

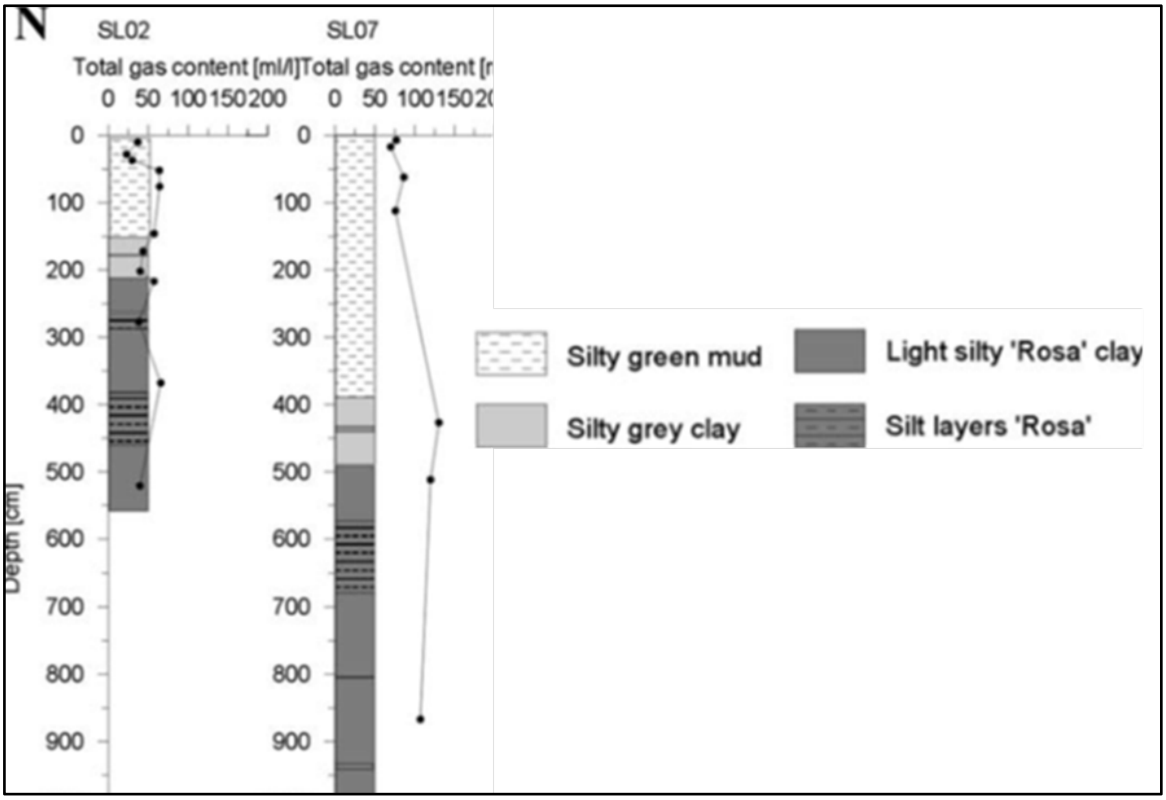


Figure 6.9 Lithological logs from profile P21 (Figure 6.10).

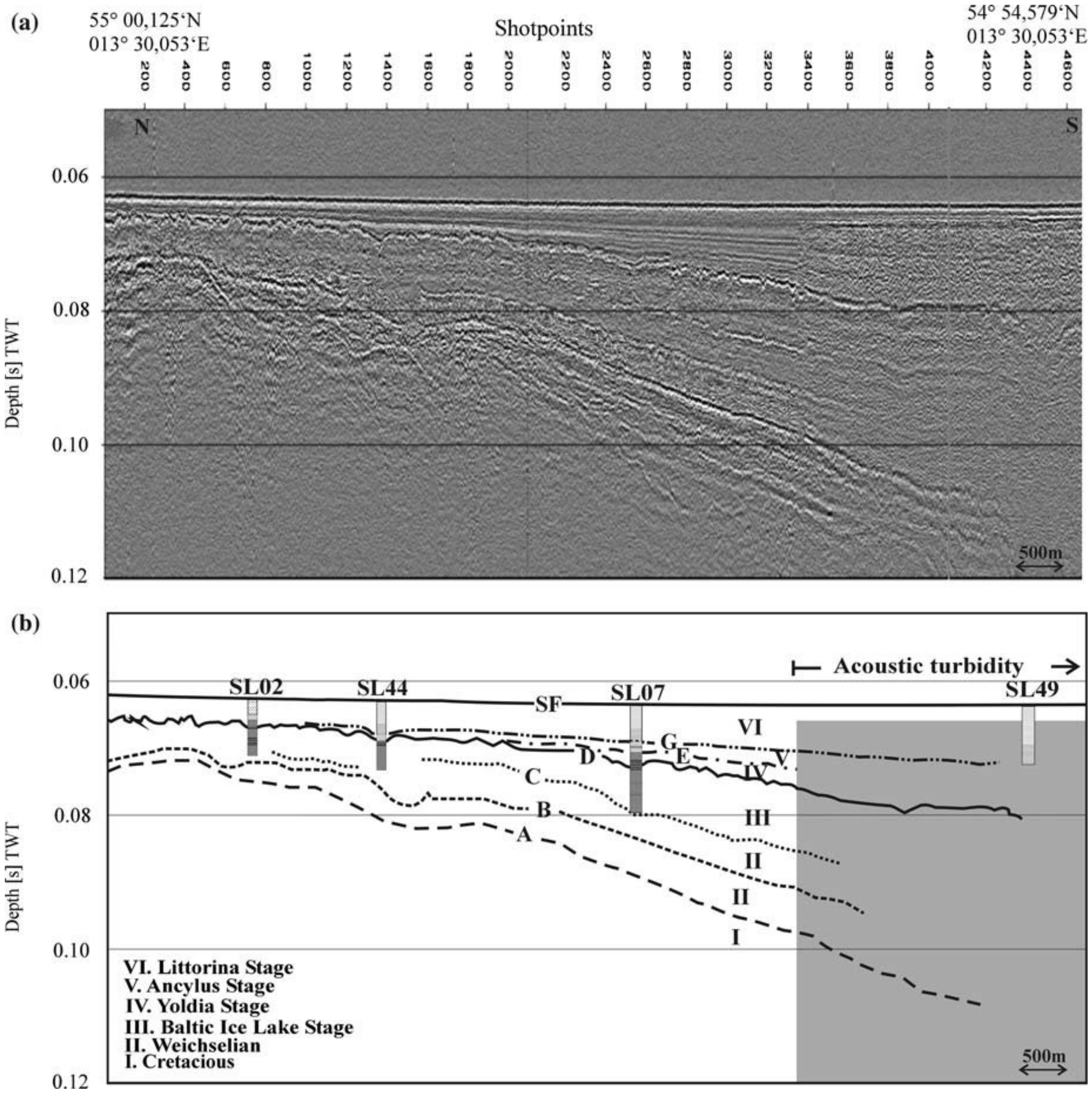


Figure 6.10 (a) Original seismic profile 21 with indication of an acoustic turbidity zone; (b) Seismostratigraphic interpretation of profile 21, SF = seafloor from Mathys et al. (2005). Location see Figure 6.4.

6.3.2 Arkona Basin sediments

The well-established stratigraphy for the Arkona Basin was used by Lemke (1998) in a substantial monograph about the late- and postglacial development of the western Baltic Sea region. The study is based on airgun data acquired by Tom Floden (University of Stockholm), supplemented by sediment echosounder data and 6m vibrocores.

The till surface of the basin is the oldest unit exposed at the seabed, with a patchy appearance in the marginal north-western part of the Basin (Figure 7.1). The till surface topography has a maximum depth of 75m below present sea-level (bsl.) in the central part of the basin, while the EEZ transect in the northern margin has a maximum depth to the till surface of 55m bsl., shallowing up to about 40m bsl. in the Kriegers Flak 2 South POWF area (Figure 6.11).

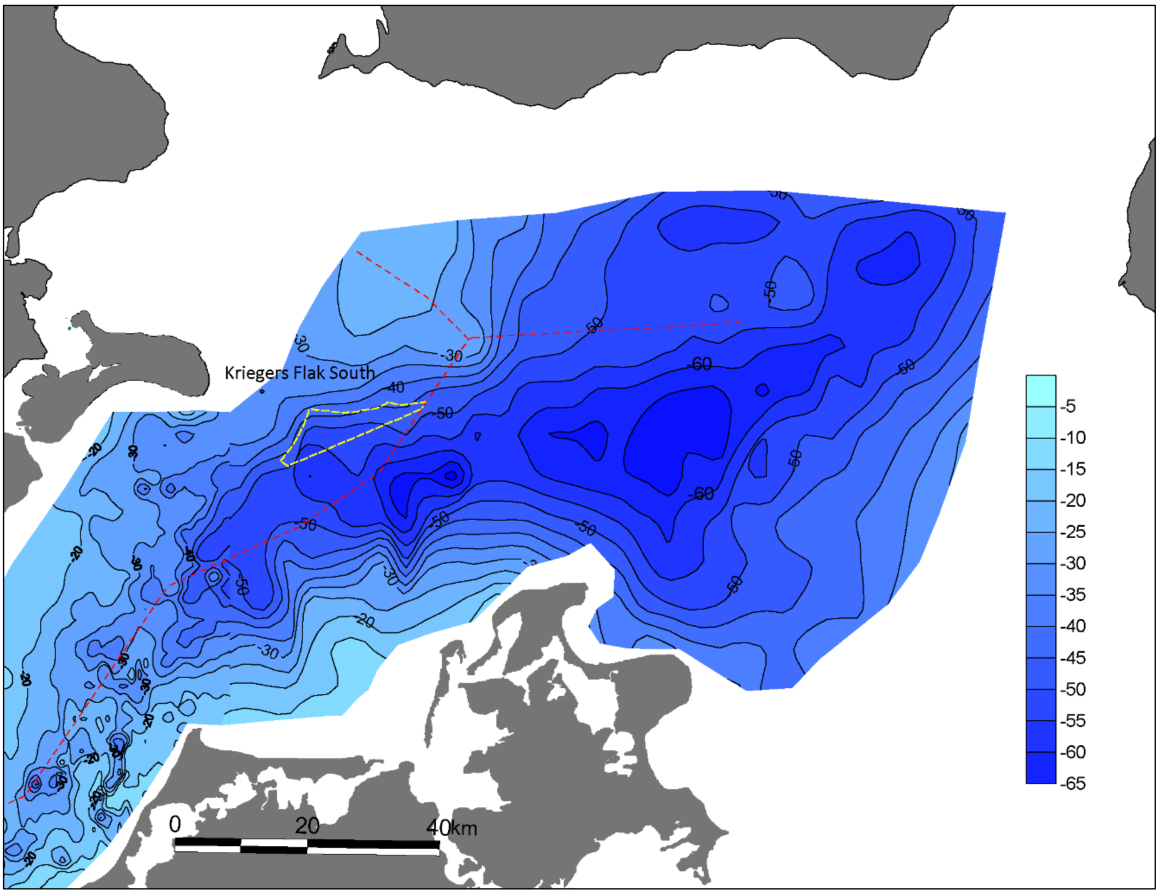


Figure 6.11 Till surface topography by Lemke (1998). Location of Kriegers Flak 2 South is shown with yellow dashed lines. The red dashed lines show the EEZ.

The till surface is covered by late glacial and Holocene clays and mud in the central parts of the Arkona Basin, changing to proximal sandy coastal deposits in the shallow western margin of the basin (Kriegers Flak 2 South POWF).

The combined mapped thickness of the late glacial clays (Figure 6.12) is up to 12m in the central and northernmost areas, while the thickness in the northern EEZ transition area is ranging from 10m in the east, to 0m in the west, with an average of about 4m.

Unfortunately, the thickness of proximal sandy coastal deposits in the shallow western margin of the Arkona Basin (Kriegers Flak 2 South POWF) has not been mapped in detail by Lemke (1998) (Figure 6.12), but a comparison of till surface topography (Figure 6.11) and late glacial surface topography (Figure 6.13) shows a thickness of up to 30m. Detailed information about Kriegers Flak 2 South POWF area follows in chapter 9.2.

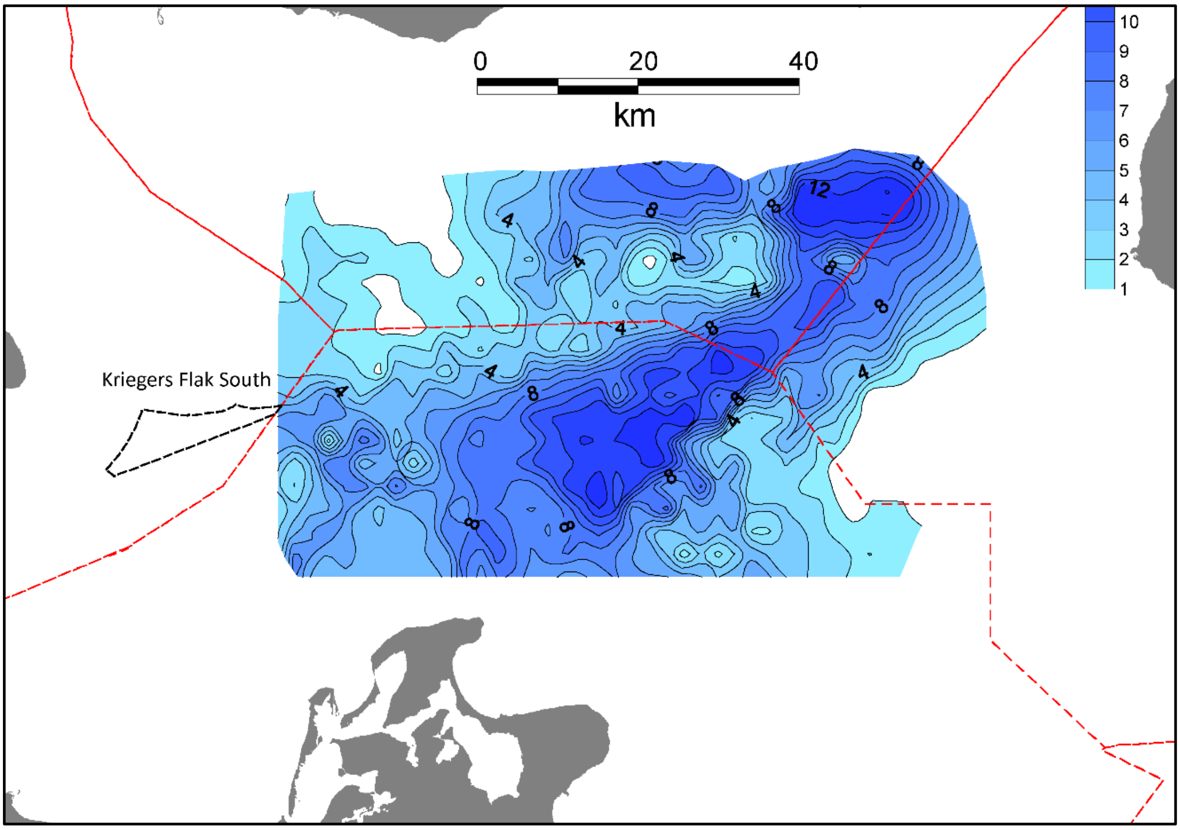


Figure 6.12 Thickness of late glacial clays by Lemke (1998). Location of Kriegers Flak 2 South POWF is shown with black dashed lines. The red dashed lines show the EEZ.

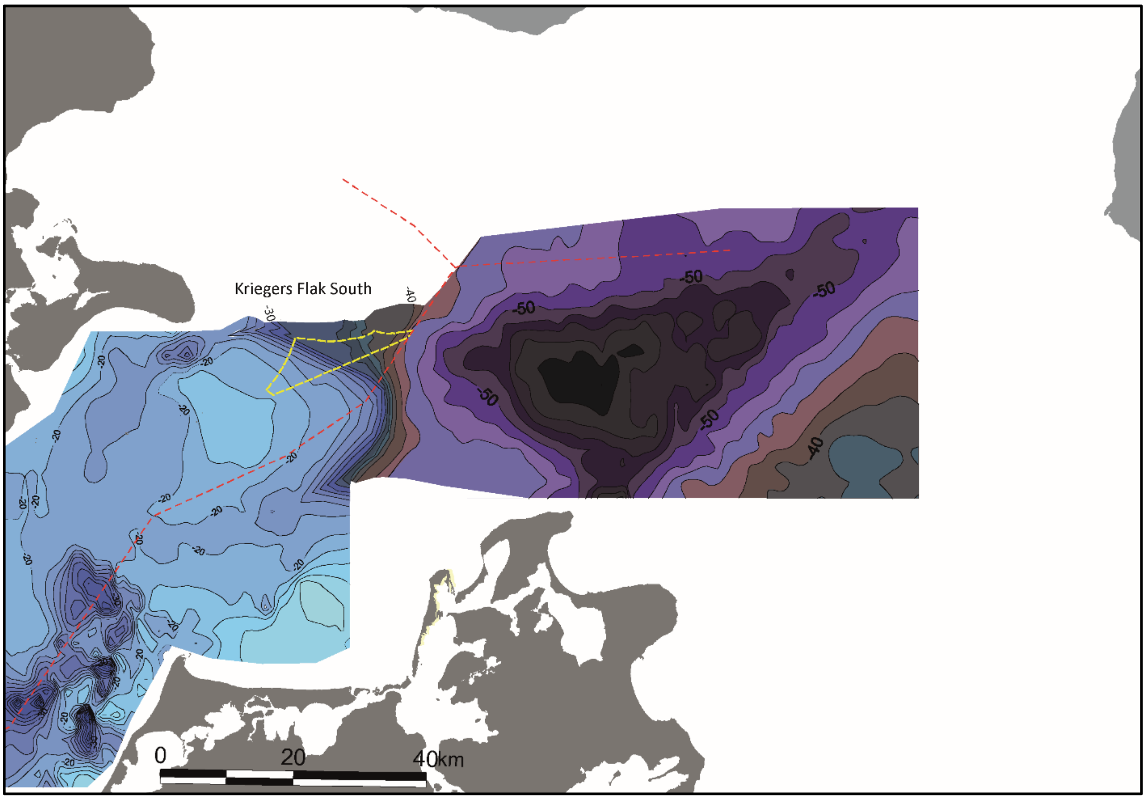


Figure 6.13 Late glacial surface topography by Lemke (1998). Location of Kriegers Flak 2 South POWF is shown with yellow dashed lines. The red dashed lines show the EEZ.

Mapping of the Holocene mud distribution (Figure 6.14) show that an up to 10m thick mud unit is deposited in the central part of the Arkona Basin. In the Kriegers Flak 2 South POWF area the thickness of Holocene mud is between 0 and 2m in the easternmost part, while a thin sandy layer is expected in the westernmost part.

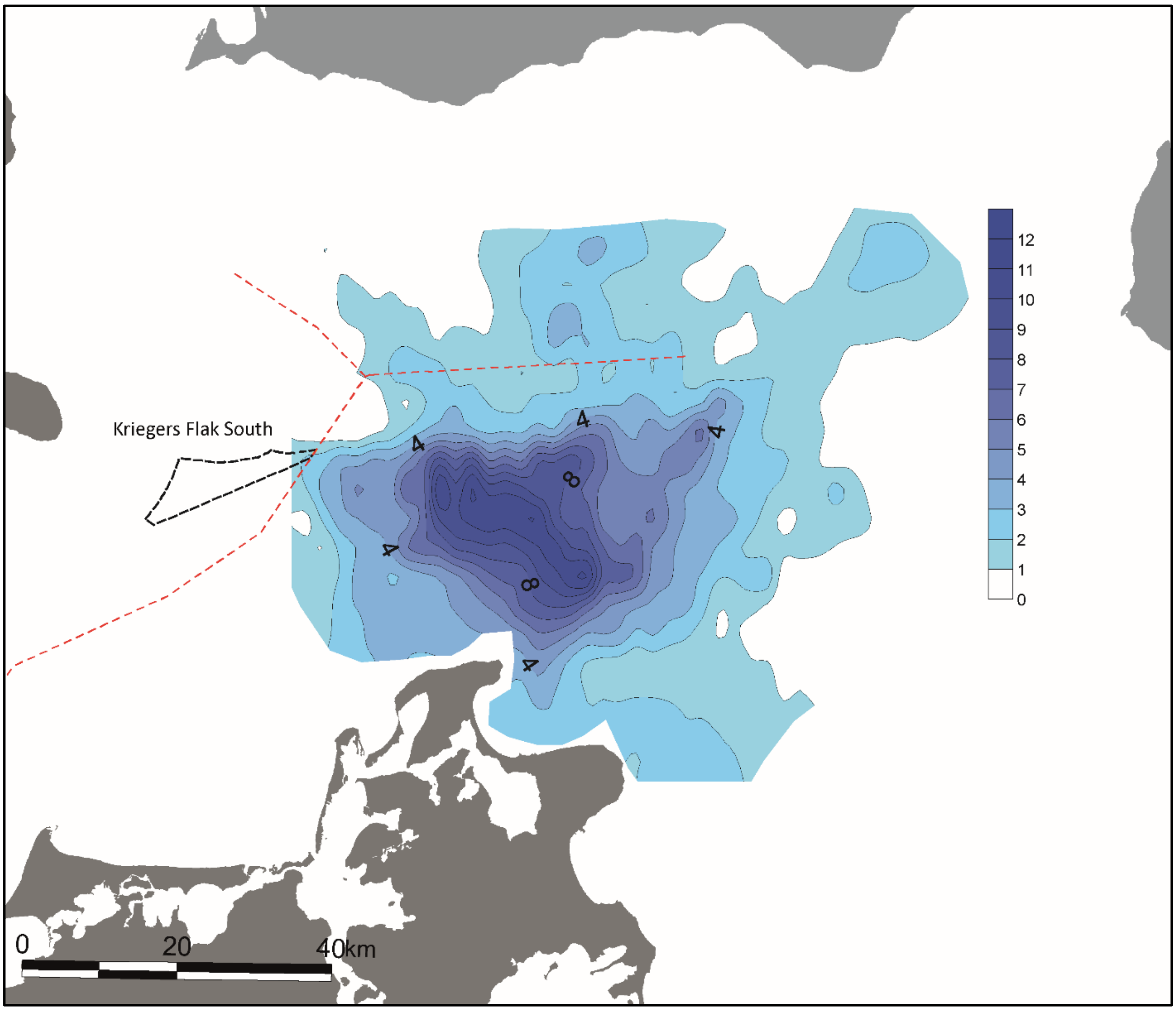


Figure 6.14 Thickness of Holocene mud by Lemke (1998). Location of Kriegers Flak 2 South POWF is shown with black dashed lines. The red dashed lines show the EEZ.

6.4 Fakse Bay geological background information

In the Fakse Bay the seabed shows evidence of both the rise of the Baltic Ice Lake and the transgression of the Littorina Sea. As the Baltic Ice Lake reached its highest water level at about 11500 years BP, the coastline of Fakse Bay was found at a level about 13 metre lower than today.

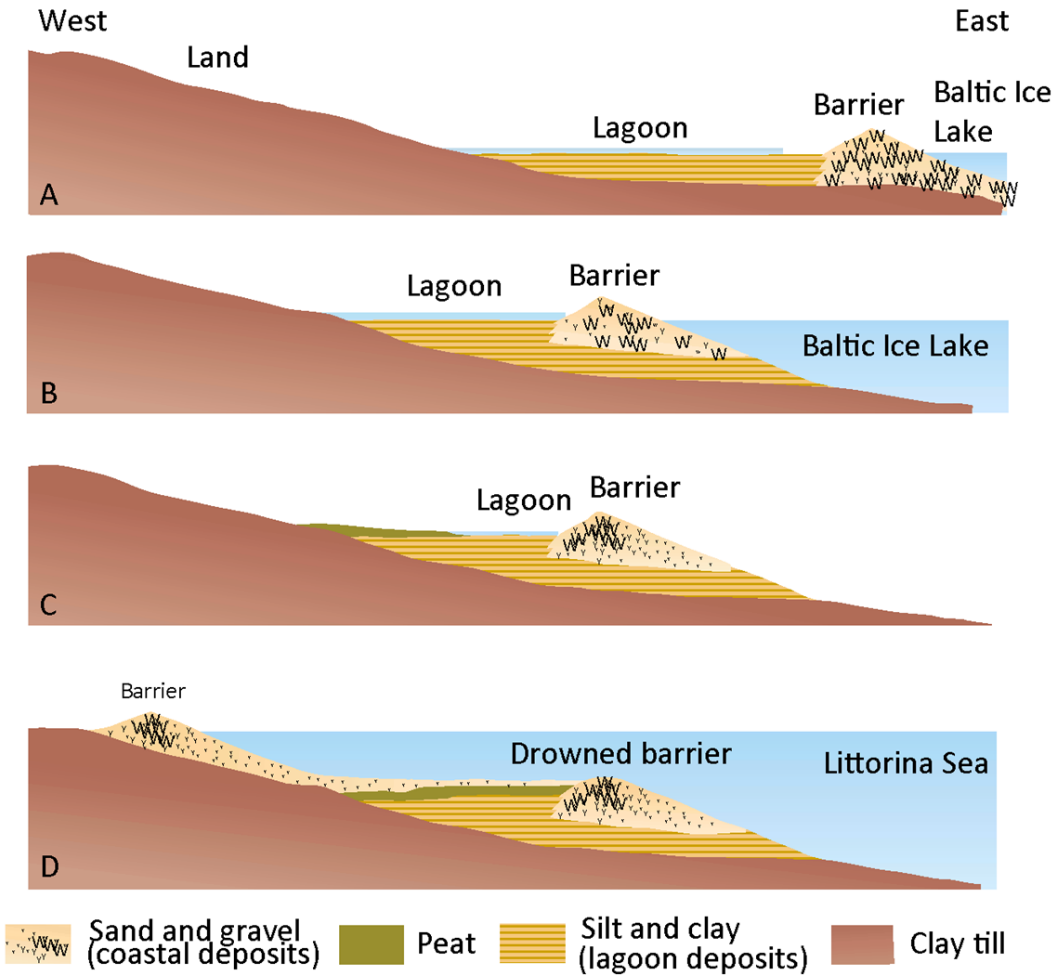


Figure 6.15 Presentation of the geological development of Fakse Bay from Jensen and Nielsen (1998). A: Barrier – lagoon system which was formed by the Baltic Ice Lake around 13000 years BP. B: The persisting rise of the lake level resulted in a westward migration of the barrier – lagoon system and reached its maximum about 11500 years BP at a level 13m below present sea level. C: With the drainage of the ice lake the Fakse Bay became dry land at about 11200 years BP. D: The transgression of the Littorina Sea caused a drowning of the former coast lines and a new spit system was formed about 6500 years BP

Later, a lake was again formed in the Baltic basin: the ‘Ancylus Lake’. The Ancylus lake lasted from 10600 to 8400 years BP, which coincides with the ‘Continental Period’, when sea level was still low. The following rise of the global sea level resulted in a renewed inflow of marine waters in the Baltic basin, this time through the Danish Belt Sea, and the ‘Littorina Sea’ was formed.

The moraine cliffs along the Baltic Ice Lake were exposed to erosion. Clay and silt were transported into deeper waters, whereas sand, fine gravel and coarse gravel primarily contributed to the formation of beach deposits. In the following time a coastal barrier system developed, which resulted in the damming of a local lake (Figure 6.15 and Figure 6.16 A). After lowering of the water level in course of the Yoldia Sea period (11200-10600 years BP), parts of the local sea became dry land. As the Littorina Sea (Stone Age Sea) had reached the older coastal formations from the Baltic Ice Lake period, the coastal processes were reactivated and continued to further develop the old barrier system. Later this system was inundated. Leeward of the elevated moraine cliffs, a system of spits developed, which likewise were gradually inundated (Figure 6.15 and Figure 6.16 B). Today this fascinating puzzle of drowned coastlines and lagoon sediments still exist on the seafloor.

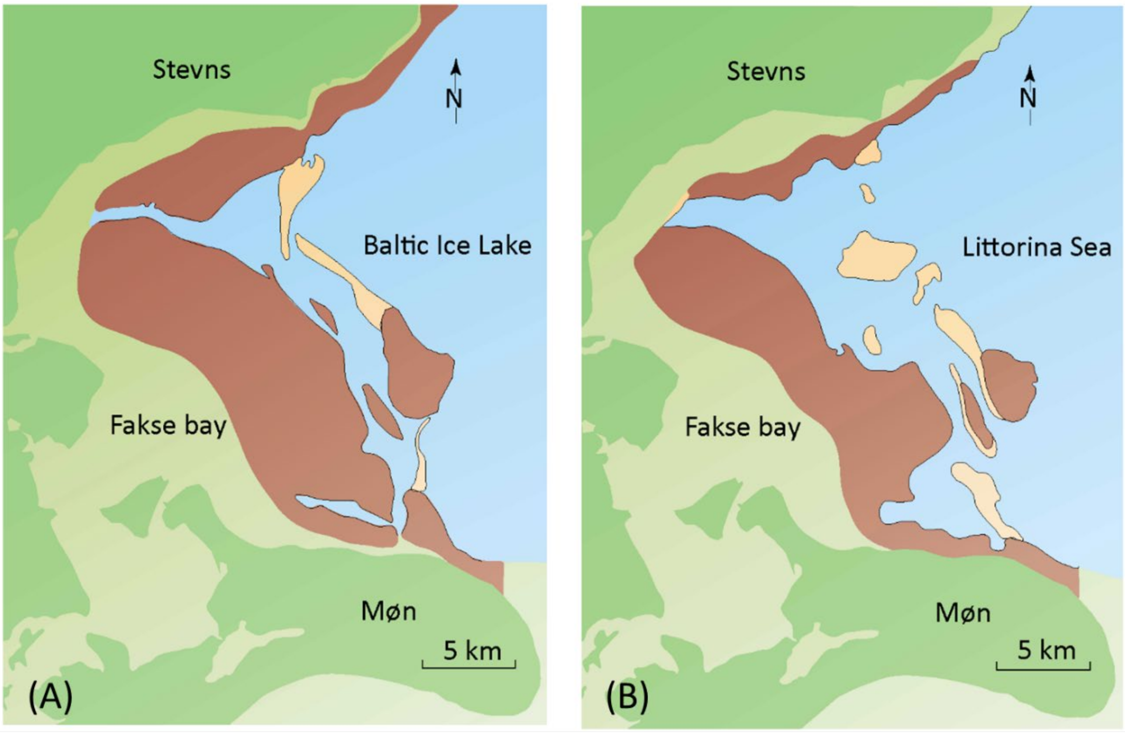


Figure 6.16 Palaeogeographic maps from Jensen and Nielsen (1998), which shows (A) the barrier island and lagoon system during the high stand of the Baltic Ice Lake and (B) The spit system formed when the sea level of the Littorina Sea was approximately 10m lower than present time.

The Fakse Bay fossil barrier lagoon system is preserved at the seabed (Figure 7.1) in the western and central part of the bay, while the Kriegers Flak 2 North POWF area is in an intermediate till zone, exposed to erosion or bypassing of clay and silt, that was transported into the deeper Arkona Basin and deposited as the Baltic Icelake Clay.

7. South - Western Baltic Sea surface sediments

A surface sediment map has been compiled by a combination of Emodnet seabed substrate 1:1M (https://www.emodnet-geology.eu/data-products/seabed-substrates) from the German and Swedish zones and the latest version (2020) of the Danish 1:100.000 seabed substrate map (Figure 7.1).

In the Arkona Basin, the upper seabed consists of a thin layer of Holocene mud and Baltic Ice Lake Clay, turning into patchy till and Baltic Ice Lake clay in the westernmost zone north of Kriegers Flak.

In the Danish outer Fakse Bay and in the Kriegers Flak 2 North POWF, Upper Cretaceous chalk or Danian limestone is covered by a few metres of till and thin patchy metre scale layers of postglacial freshwater- and marine clays, sand, and mud.

Southeast of Møn, Upper Cretaceous chalk is covered by a few metres of till with basin infill of late glacial sands, silt and clay, followed by patchy thin layers of Holocene metre scale layers of Postglacial freshwater- and marine clays, sand, and mud.

The Kriegers Flak 2 South POWF is dominated by late glacial sand with thin Holocene top layers.

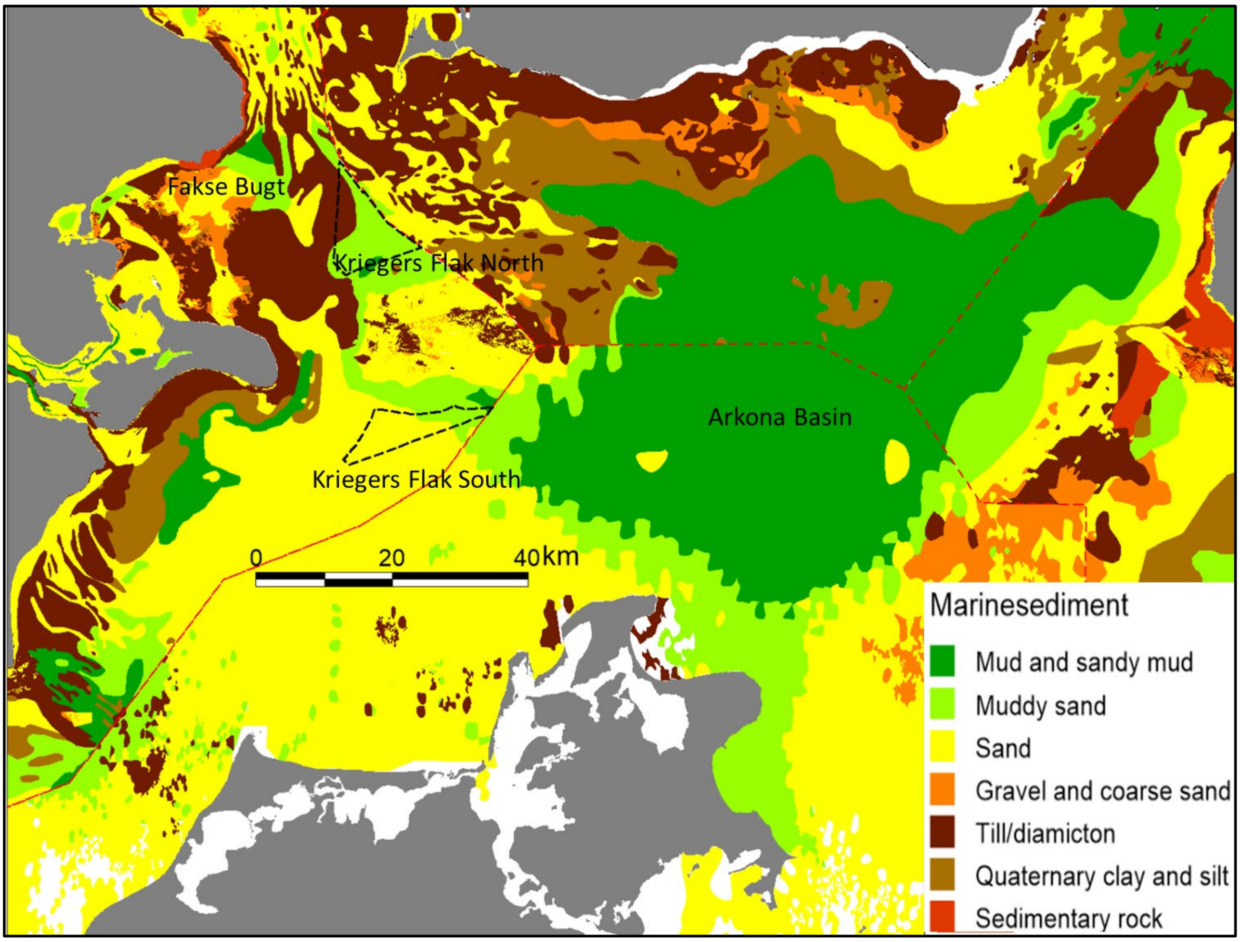


Figure 7.1 Seabed substrate map from Kriegers Flak North and South POWF areas base on a combination of Emodnet 1:1M and Danish 1:100.000 2020 version. POWF areas black- and EEZ red dashed lines.

8. Dynamic late glacial and Holocene shoreline history

After the last deglaciation, the south-western Baltic Sea region was characterised by highly fluctuating water levels (Figure 8.1). Transgressions were interrupted by two abrupt forced regressions, the first at c. 12800 years BP and the second at c. 11700 years BP. Prior to these regressions, the Baltic Ice Lake was dammed by glacier ice in south-central Sweden. In the Kriegers Flak South POWF and Rønne Banke region, the water level reached a maximum around 20m below present sea level during the Baltic Ice Lake stages (Figure 8.1). After the retreat of the Scandinavian Ice Sheet, the dam was broken twice, and the water level dropped by 20-25 metres over a few years. In Early Holocene, during the Yoldia Sea Stage, water level reached a minimum at around 40–45m below present sea level. During this period there was a land bridge from Bornholm to the continent, which allowed red deers, aurochs and hunters to invade Bornholm. A horn-core of an aurochs found on the sea floor south-west of Bornholm dates to this period. From around 10800 to 10200 years BP the water level increased rapidly, and pine forests in the region were submerged. The rapid increase was followed by a short period with relatively stable water level at around 9000 years BP. Soon, the Water level continued to rise, and at c. 7000 years BP marine waters inundated the region, which mark the beginning of the Littorina Sea Stage. During the past 6000 years, the water level has increased a few metres only. The global eustatic sea level rise has surpassed the glacio-isostatic uplift of the region, and fossil shorelines and landscapes are now submerged.

In the Fakse Bay and Køge Bugt region, the water level reached a maximum around 13m below present sea level during the Baltic Ice Lake stages (Figure 8.2). The difference between the Rønne Banke region (and Kriegers Flak South POWF) and the Køge Bugt region (and Fakse Bay), as can be seen from (Figure 8.1), is caused by higher glacio-isostatic uplift in the Køge Bugt region than in the Rønne Banke region. According to the presented curve, the water level reached a minimum between 35 and 40m below present sea level. During this period, all of Køge Bugt was dry land.

The Kriegers Flak 2 North POWF area is located between Køge Bugt and Kriegers Flak 2 South POWF with intermediate relative water level changes.

The deeper parts of the Arkona Basin have been continuously submerged after the last deglaciation, but the shallow water areas in the Kriegers Flak 2 South POWF developed coastal barrier deposits (Figure 6.3 a and b) with dry land for long periods after the last deglaciation of the region.

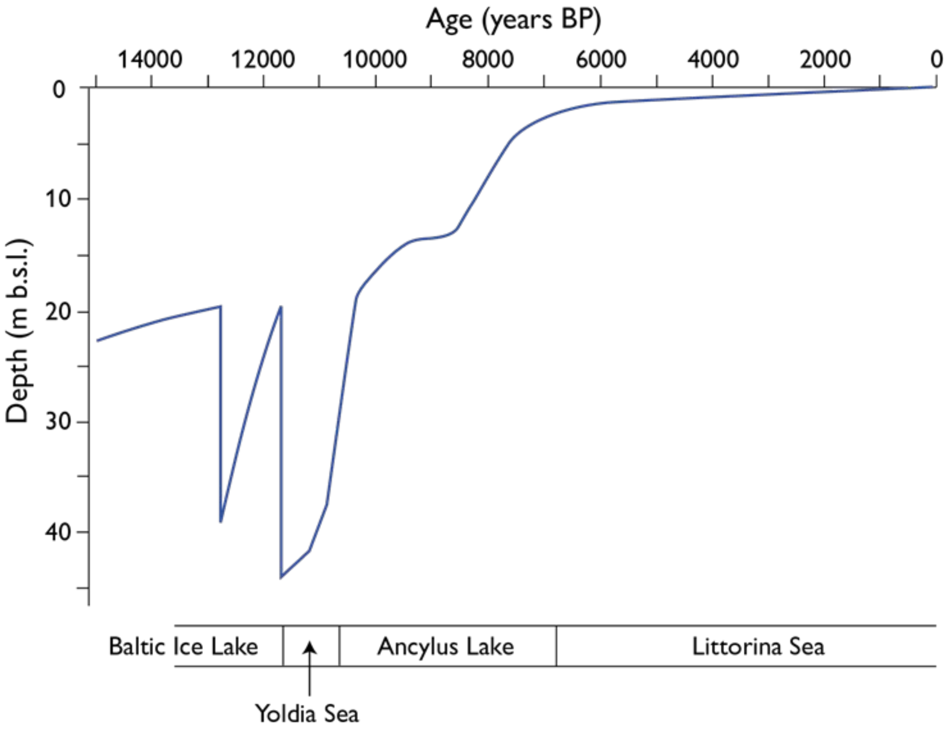


Figure 8.1 Shoreline displacement curve for the Rønne Banke region south-west of Bornholm. The curve is based on radiocarbon dating of samples collected from vibrocores (Table 1).

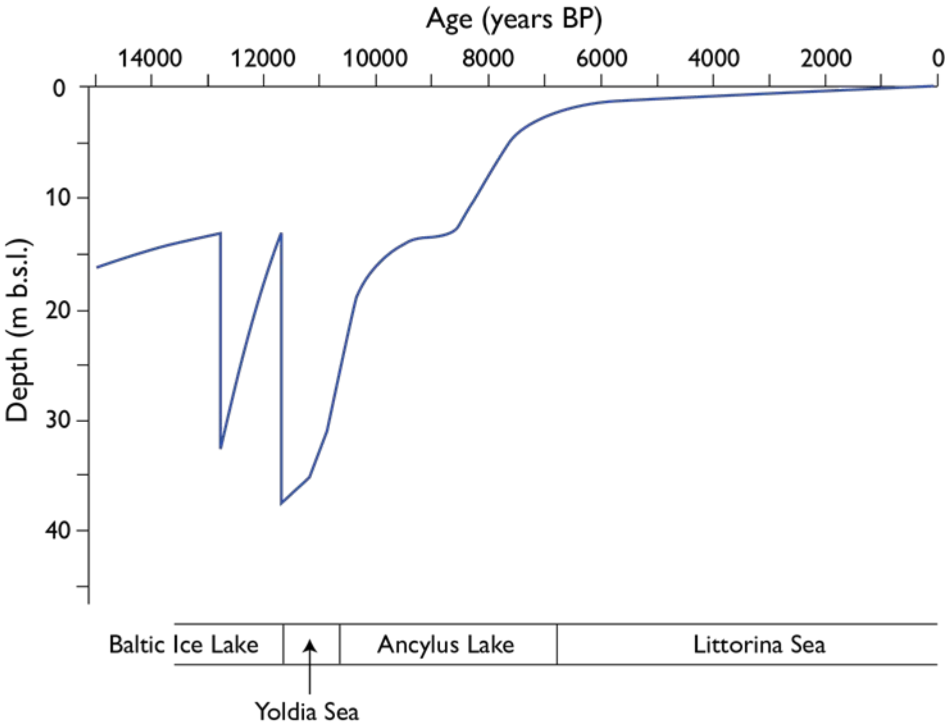


Figure 8.2 Shoreline displacement curve for the Køge Bugt region. The curve is based on radiocarbon dating of samples collected from vibrocores (Table 1).

Selected radiocarbon ages from the cable route region

Core/ site	N. lat. °	E. long. °	Laboratory number	Material	Deprh (m)	Age (^{14}C years BP)[1]	Cal. age (years BP)[2]
Marine							
7250/26	54.821	12.523	AAR-2647	Mytilus edulis	26.3	7090±90	7530
282080	54.845	13.925	KIA-26266	Mytilus edulis	46.5	6675±35	7141
Lake deposits							
548021-1	55.64	12.292	Ua-57758	Salix polaris	15.81	12863±47	15373
200540	54.725	12.766	AAR-2637	B. nana, S. herbacea	27.7	12700±110	15132
520002	55.145	12.398	AAR-1313	Salix polaris	18.7	12440±150	14605
212860	54.248	14.74	AAR-4058	Salix sp.	21.0	12400±90	14530
258000	54.750	13.765	KIA-21680	Cladium	45.2	10980±55	12896
Køge Havn			Beta-488168	Terr plant	9.04	10480±40	12536
257910	54.786	14.59	AAR-8837	Phragmites	29.9	10120±90	11695
222810	54.457	15.156	KIA-9342	Scirpus, Pinus	35.9	9930±45	11337
222820	54.483	15.172	KIA-9343	Pinus, Betula Albae	36.1	9740±55	11177
526015-1	54.949	15.362	Ua-57754	Betula Albae	44.6	9581±59	10934
526030-4	55.135	14.641	Ua-57755	Lycopus, Ranunculus	35.3	9593±51	10938
222810	54.457	15.156	KIA-9341	Menyanthes, Phragmites	34.5	9365±50	10583
548021-1	55.64	12.292	AAR-29111	Cladium mariscus	12.92	9361±35	10577
5775/01	54.913	13.05	AAR-1923	Cladium	44.3	9360±90	10574
BP09 ext 11	54.946	14.744	Beta-560826	Populus	23.0	9240±30	10407
526189	54.806	14.5	Ua-4863	P. sylvestris, Betula	24.4	9230±85	10404
Køge Sønakke			K-5099	Homo sapiens	8.0	8250±85	9227
Køge Nordhavn	55.469	12.228	K-4779	Wood peat	7.5	8090±90	9007
RAM-05-09	54.942	14.754	Beta-560827	Cladium, Scirpus	19.6	8070±30	9002
258010	54.920	13.151	KIA-21682	Phragmites	46.3	7880±50	8522
Køge Havn			AAR-24741	Corylus, fish weir	8.7	7450±32	8267

[1] Radiocarbon ages are reported in conventional radiocarbon years BP (before present = 1950; Stuiver & Polach (1977)).

[2] Calibration to calendar years BP (median probability) is according to the INTCAL20 and MARINE20 data (Reimer *et al.* 2020).

Table 1 Selected radiocarbon ages from the cable route region.

9. Details from Kriegers Flak North and South POWF

In the following sections, detailed data will be presented from Kriegers Flak 2 North and South POWF, described on the basis of existing knowledge and profile sections modified from Baltic Pipe investigations (Rambøll 2020) and scientific surveys (Lemke 1998). The interpretations are based on boomer and sediment echosounder data as well as vibrocores.

The Kriegers Flak 2 POWF's are located north and south of the existing Kriegers Flak OWF. Kriegers Flak 2 North has a rather flat seabed with a gentle southward dip, ranging from 20 to 35m bsl. (Figure 9.1).

Kriegers Flak 2 South shows a shallow western seabed platform 15 - 20m bsl. interrupted by a central rather steep eastward sloop down to about 30m bsl., followed by a gentle eastward dipping seabed from 30 to about 45m bsl., in the easternmost part (Figure 9.1).

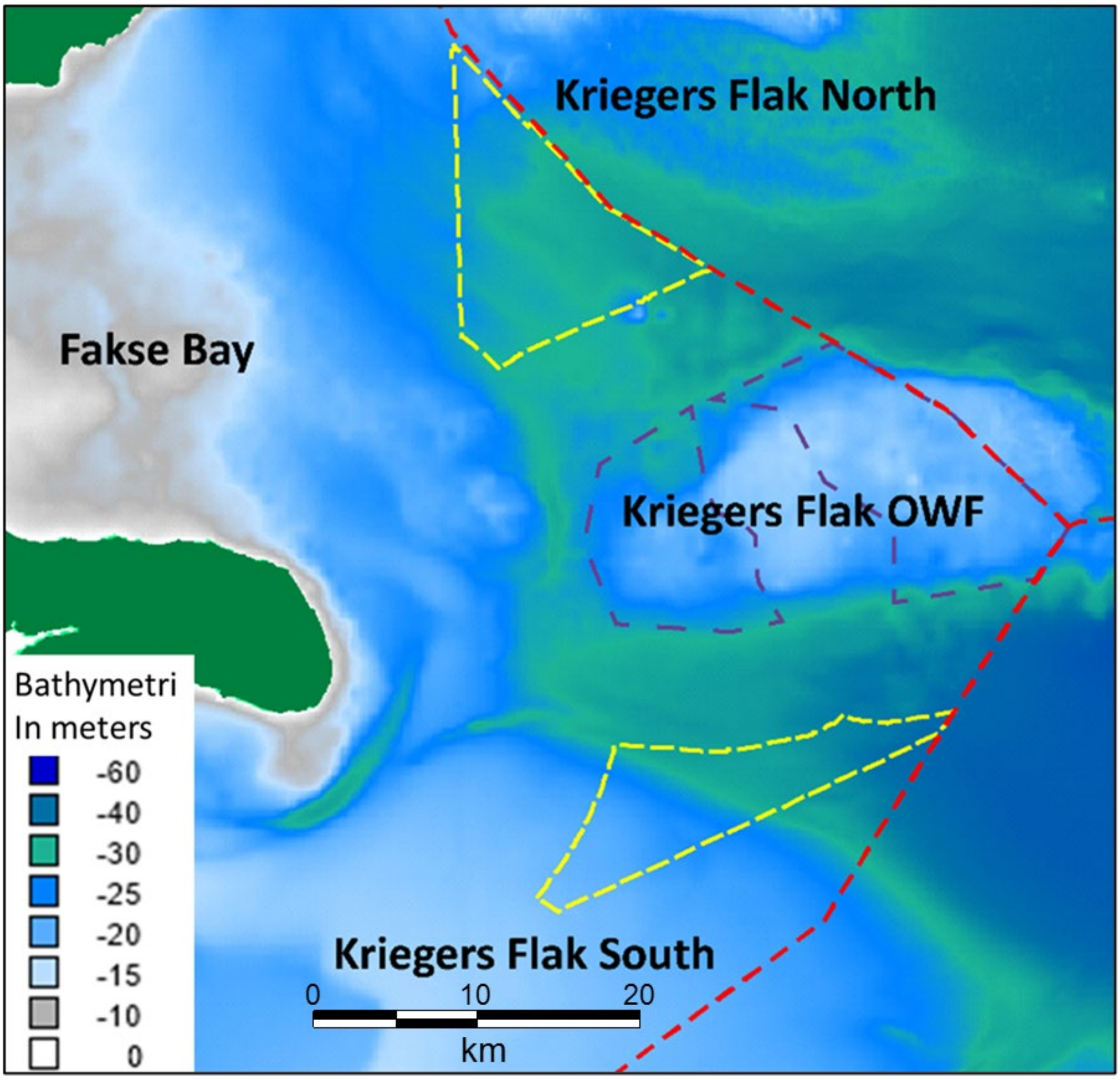


Figure 9.1 Bathymetric map of the Kriegers Flak 2 North and South POWF areas (yellow dashed lines). Kriegers Flak *OWF* (Purple dashed lines) *as well as EEZ* (*red dashed lines*) are indicated.

The surface sediment map (Figure 9.2) shows a north-western area dominated by till in the shallower part of the Kriegers Flak 2 North POWF, followed by muddy sand in the deeper south-eastern part of the POWF area.

In Kriegers Flak 2 South POWF the shallow western platform and the central eastward slope is represented by medium-fine sand at the seabed, gradually changing into muddy sand and sandy mud in the easternmost part of the POWF area.

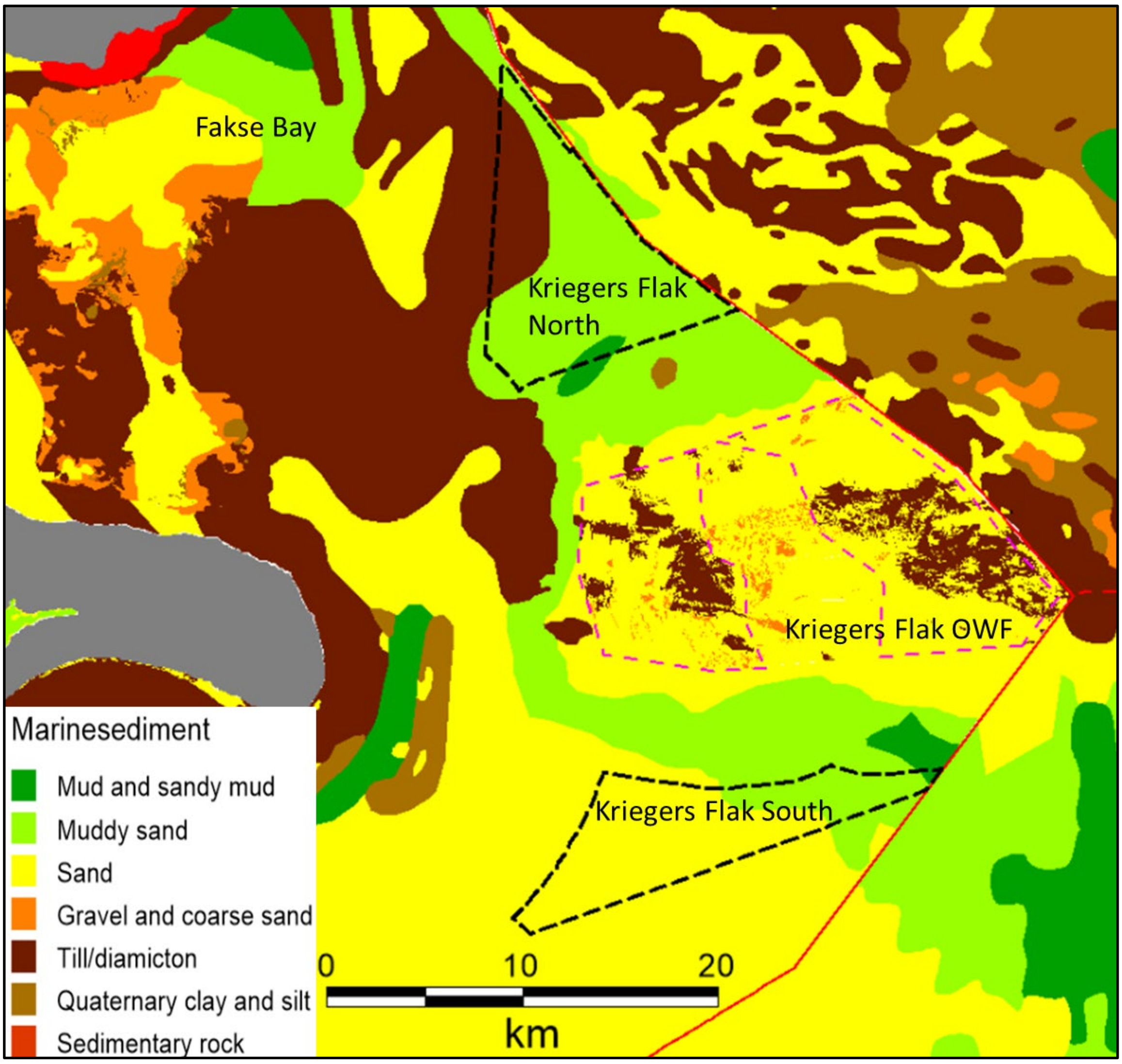


Figure 9.2 Seabed sediment map from the Kriegers Flak 2 North and South POWF areas (black dashed lines) based on a combination of Emodnet 1:1M and Danish 1:100.000 2020 version. Kriegers Flak OWF (purple dashed lines) as well as EEZ (red dashed lines) are indicated. For details, see Appendix B.

9.1 Kriegers Flak 2 North geology

A combination of the sediment distribution map (Figure 9.2) together with 3 profiles from the Baltic Pipe studies, profiles E – F, G – H and N – M (Figure 9.4, Figure 9.5 and Figure 9.6) and a few vibrocore logs (Figure 9.6) gives a general indication of the expected seabed geology in the Kriegers Flak 2 North POWF area.

9.1.1 Baltic Pipe profile E – F

The profile has a west-northwest – east-southeast orientation crossing the southernmost part of Kriegers Flak 2 North (Figure 9.3). The Profile shows that the deepest easternmost part from 35m bsl. to the westernmost part about 25m bsl., has up to 10m till covered by about 5m Baltic Ice Lake clay (highest level of Baltic Ice Lake clay about 30m bsl.) and a top unit of 2 – 4m Holocene muddy sand.

The till unit thins to the west to be a few metres thick on top of Danien limestone. Till with boulders is observed around 25m bsl., with a patchy coverage of a few metres of Holocene sands and muddy sands.

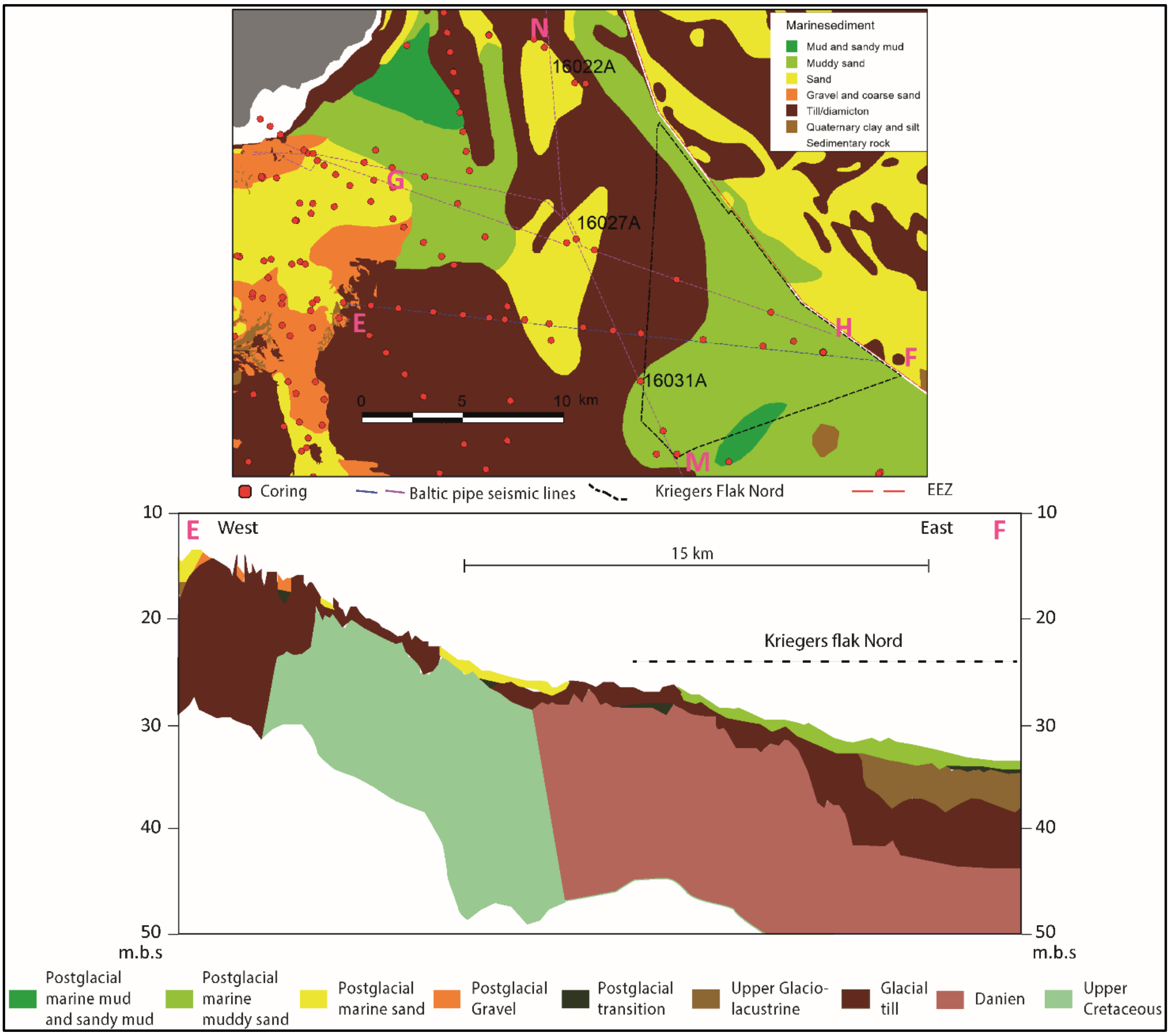


Figure 9.3 Upper figure: Surface sediments in the outer Fakse Bay region. Location of Baltic Pipe profile section E - F is indicated. Lower figure: Interpretation of Baltic Pipe seismic profile E - F with indication of Kriegers Flak 2 North crossing. For details, see Appendix C.

9.1.2 Baltic Pipe profile G – H

The orientation is northwest – southeast, and the profile is crossing the central part of Kriegers Flak 2 North (Figure 9.4). It confirms the general picture from the description of profile E – F (Figure 9.3) and documents that in general the seabed consist of a few metres of Holocene sand and muddy sand on top of a few metres of late glacial clay and till overlying sedimentary bedrock consisting of Danien limestone.

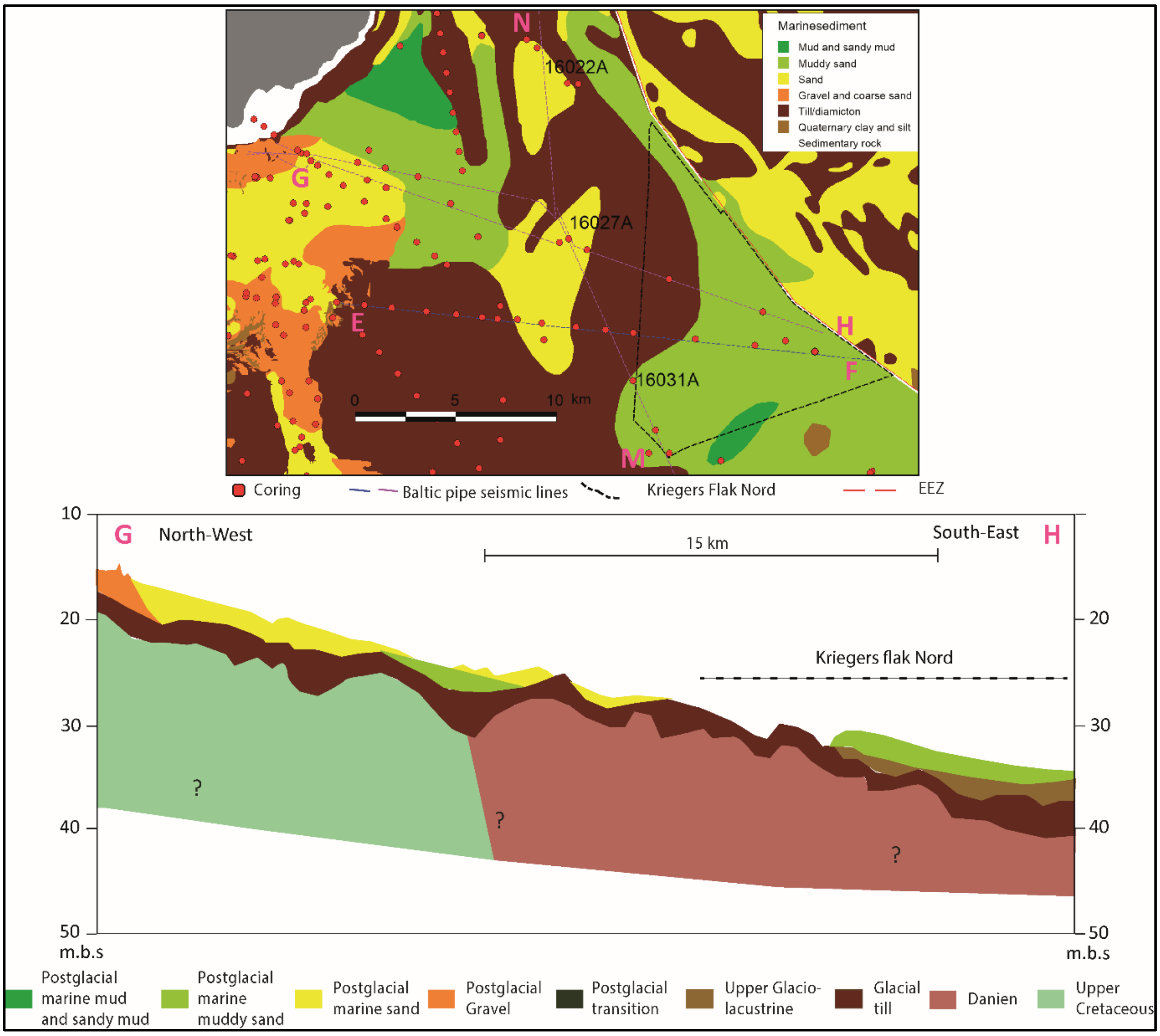


Figure 9.4 Upper figure: Surface sediments in the outer Fakse Bay region. Location of Baltic Pipe profile section G – H is indicated. Lower figure: Interpretation of Baltic Pipe seismic profile G – H with indication of Kriegers Flak 2 North crossing. For details, see Appendix D.

9.1.3 Baltic Pipe profile N – M

The profile has a north – south orientation, just west of Kriegers Flak 2 North (Figure 9.5). The Bedrock is very close to the seabed, with only a few metres of variations of till, late glacial clay, Holocene freshwater sediments, sandy mud and muddy sand on top of it.

Consultation with the bedrock map in Figure 5.2 shows that the bedrock below the thin-skinned quaternary sediments along profile N - M consists of Upper Cretaceous chalk.

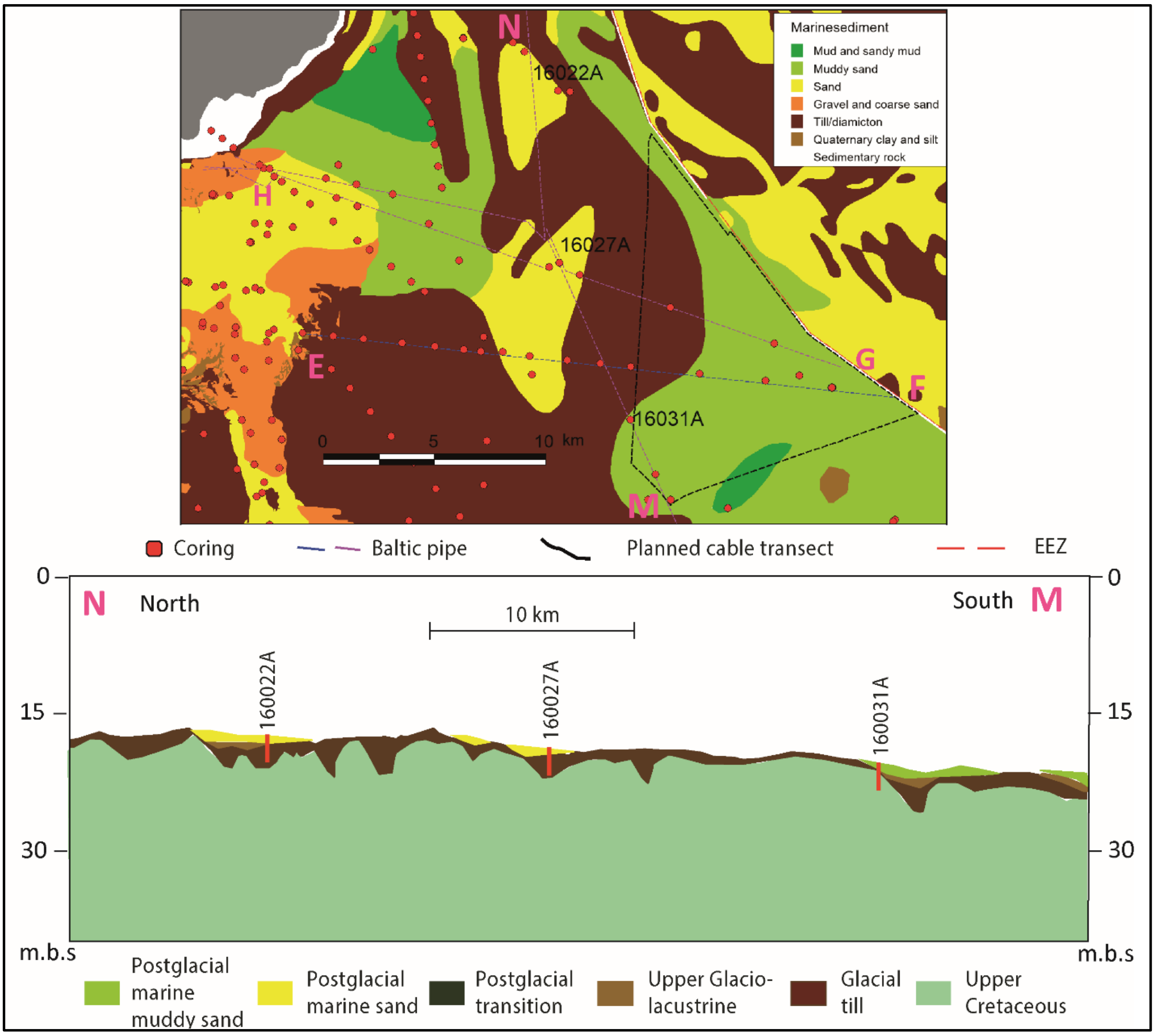


Figure 9.5 Upper figure: Surface sediments in the outer Fakse Bay region. Location of Baltic Pipe profile section N - M is indicated. Lower figure: Interpretation of Baltic Pipe seismic profile N - M with indication of Kriegers Flak 2 North crossing. For details, see Appendix E.

9.1.4 Vibrocore logs from Krieger Flak 2 North POWF

The profiles presented above (E - F, G - H and N – M), are Baltic Pipe boomer survey lines and the seismic interpretations shown in Figure 9.3, Figure 9.4 and Figure 9.5 has been documented by vibrocores located along the lines, with lithological descriptions similar to Figure 9.6 representing profile N – M.

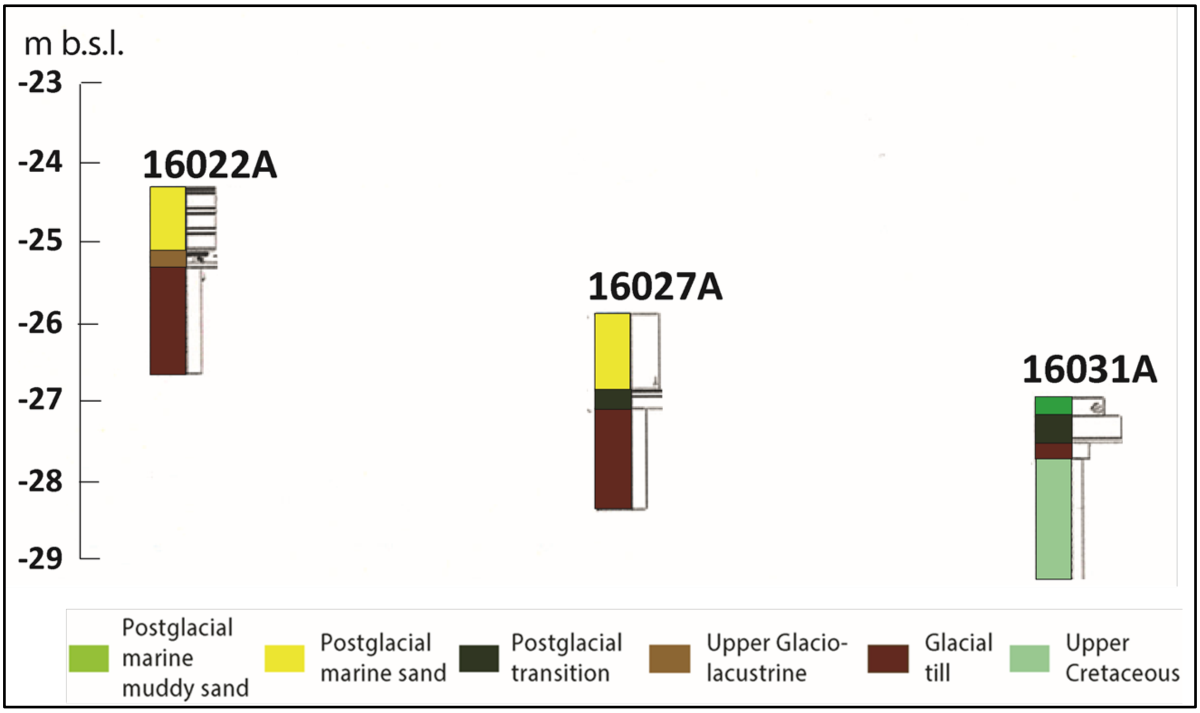


Figure 9.6 Vibrocore logs along profile N – M crossing Kriegers Flak 2 North POWF.

9.2 Existing Kriegers Flak Windfarm

As background for establishment of the existing Kriegers Flak OWF a detailed seismic grid was acquired (Rambøll 2013) followed by 17 geotechnical boreholes including CPT's (GEO 2013). The boreholes were drilled to the target depth between 70 m 50 m below seabed.

The OWF pre-investigation area encompasses the Danish part of the Kriegers Flak bank. Water depths across the Kriegers Flak pre-investigation area vary approximately between 15 m to 30 m (Figure 9.7).

The Kriegers Flak OWF is composed of a rather complex sequence of glacial deposits, as well as Lateglacial and Postglacial deposits, all overlying the Cretaceous Limestone.

The Postglacial and Lateglacial deposits consist of sand and clay and are in general less than 4 metres thick. The deposits are generally loose/soft and have locally organic content (gyttja).

The glacial deposits mainly consist of stiff to very stiff clay till or dense to very dense sand till and vary in thickness approximately between 20 m to 40 m. The till is generally intersected by meltwater layers/lenses of clay and sand.

The Cretaceous Limestone is found in all boreholes except borehole KF-BH006 (glacial deposits not penetrated). The Prequaternary bedrock is made of Maastrictian Limestone deposited during the Late Cretaceous period. This deposit occurs very widespread in NW-Europe, in the Kriegers Flak area mainly as a muddy, white limestone with many nodules and thin layers of dark grey/black flint. The upper part of the limestone is locally showing evidence of glacial deformation.

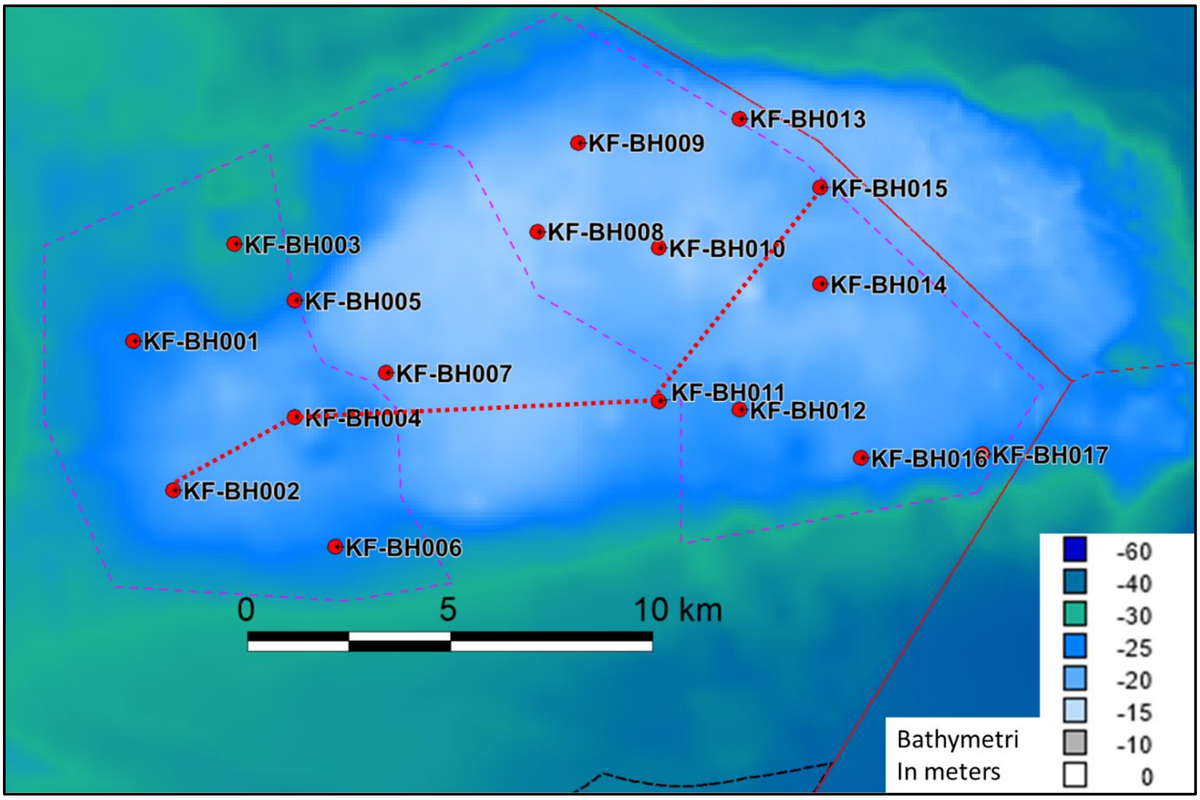


Figure 9.7 Bathymetry and borehole locations Kriegers Flak OWF. Red stippled line combines boreholes KF–BH002, KF-BH004, KF-BH011 and KF-BH015 and shows location of geological profile in Figure 9.9. For regional bathymetry see Figure 3.1

9.2.1 Details on soil types

Detailed sidescan and shallow seismic studies of the Kriegers Flak Bank (Rambøll 2013) combined with surface samples and borings (GEO 2013) show that the seabed surface sediments, with only few minor exceptions, consist of postglacial sand and gravel, as well as glacial clay with stones exposed at the seabed (Figure 9.8).

On top of a rather uniform Upper Cretaceous limestone, the glacial deposits form the core of Kriegers Flak Bank while late- and postglacial clays and sands onlaps the flanks and a central depression. The general geology, soil types and geotechnical characteristics is presented in a west-east profile (Figure 9.9) combined with selected boreholes (KF-BH002, KF-BH004, KF-BH011 and KF-BH015) (Appendix N) and a table with geotechnical results (Tabel 2).

9.2.1.1 Postglacial marine sand

The top unit of marine sand and gravel has been deposited during the Postglacial transgression.

The top unit mainly consists of non-graded sand deposited during the Postglacial. In large parts of the central part, it occurs in thicknesses less than 1 m, while in the outermost boreholes and in a central bank the thickness is 1.3 - 4.5 m (KF-BH002 Appendix N).

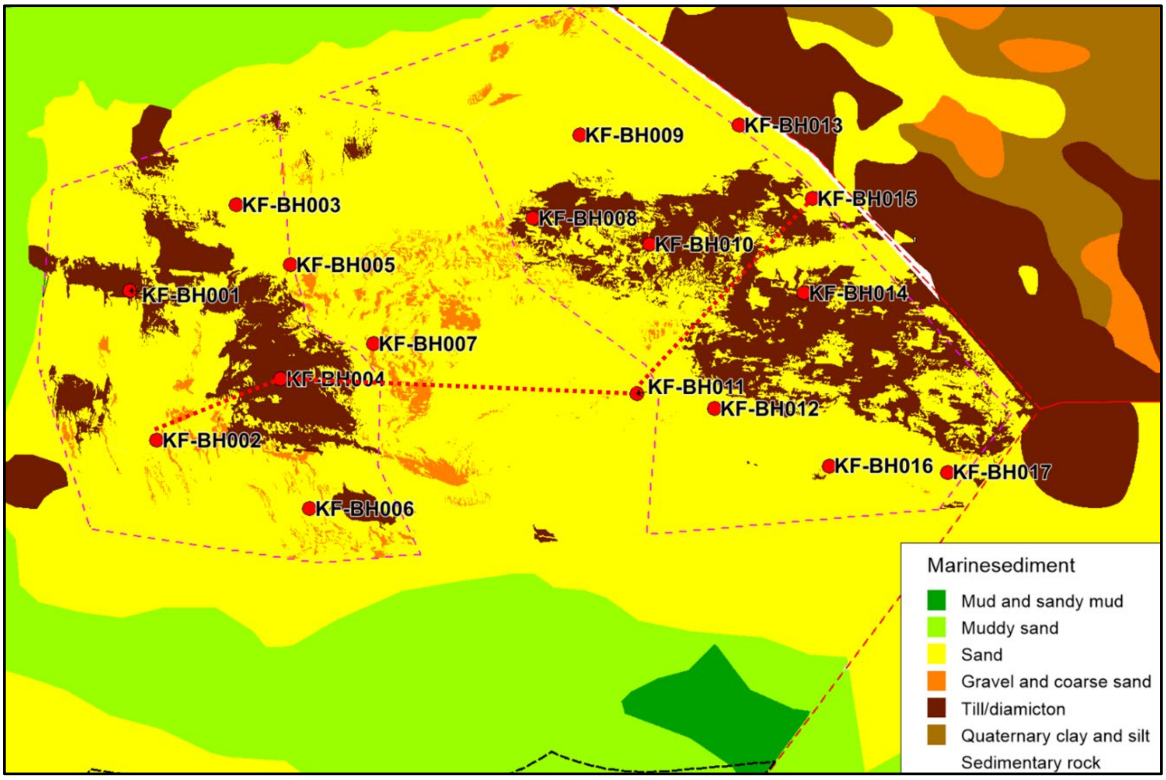


Figure 9.8 Surface sediment and borehole locations Kriegers Flak OWF. Red stippled line combines boreholes KF–BH002, KF-BH004, KF-BH011 and KF-BH015 and shows location of geological profile in Figure 9.9. For regional seabed sediment map see Figure 7.1

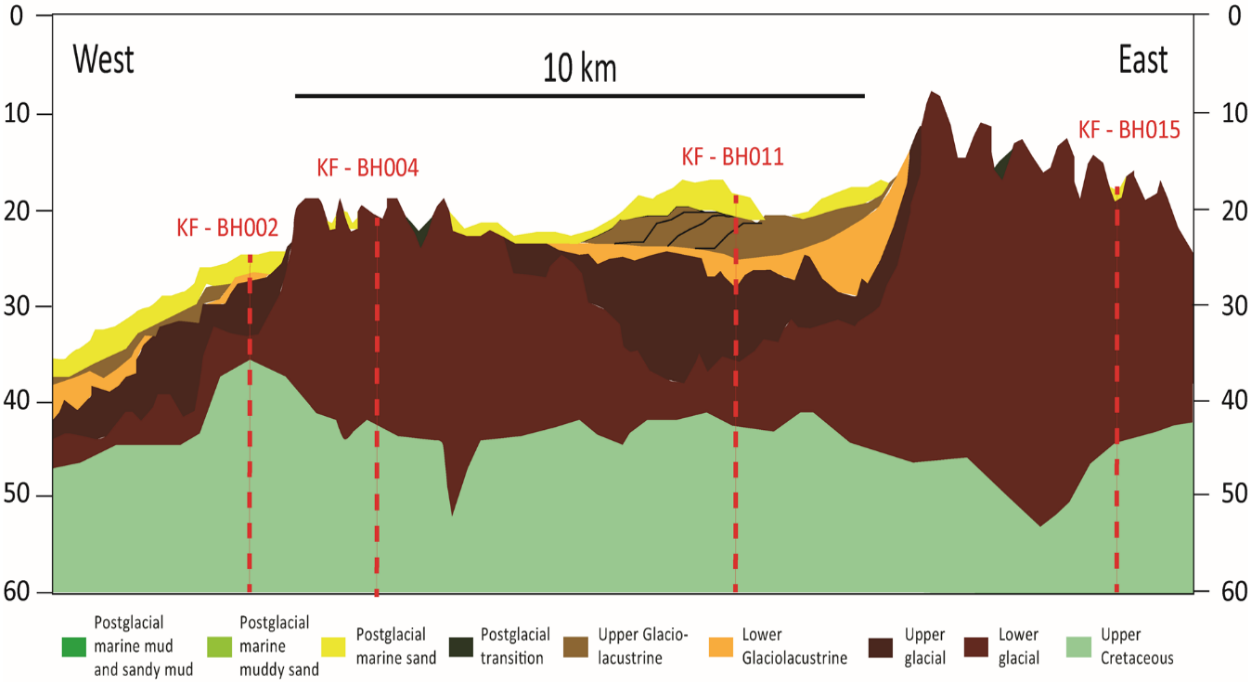


Figure 9.9 Geological west – east profile with location of boreholes KF–BH002, KF-BH004, KF-BH011 and KF-BH015. Location of profile see Figure 9.7 and Figure 9.8

9.2.1.2 Glaciolacustrine freshwater deposits

In Lateglacial time thinly laminated freshwater clay was deposited in the Baltic Ice Lake basin and sand in the coastal zone.

In borehole KF-BH011 (Appendix N) there have been observed medium sand on top of glaciolacustrine clays (Tabel 2) which are rich in silt and fine sand laminae or streaks. These laminated clays have been deposited on top of siltier Lateglacial meltwater deposits and clay tills and are interpreted as varve deposits in the Baltic Ice Lake.

9.2.1.3 Meltwater clay, silt and sand

These units have been deposited in ice-free environments during the melting of the glacier responsible for Prior tills.

The Upper and Lower till units both includes meters of medium plasticity meltwater clay, and sand probably deposited during the melting of an earlier glacial advance. The Lower Till is covered by varying thicknesses of medium to high plasticity clay or poorly graded sand. The clay often contains varve-like, thin silt and sand laminae, pointing to a meltwater or glaciolacustrine origin (Appendix N).

9.2.1.4 Upper Glacial unit (mostly Till)

The Upper Till has been deposited during an Upper Weichselian glacial advance.

The Upper Till is very similar to the Lower Till. The boundary between the upper and Lower Till has introductory been assessed based on water contents and/or strengths measured by the pocket penetrometer; see borehole KF-BH004, KF-BH011, KF-BH015. The water contents of the Upper Till are in most of the mentioned boreholes higher than the water contents of the Lower Till. An inverse pattern has been registered in the strengths measured by the pocket penetrometer, indicating lowest strengths in the Upper Till (Tabel 2). A rough indication of the boundary between the Upper Till and Lower Till has been made in Figure 9.9. In most of the area this unit has been intersected by several meltwater layers or lenses with thicknesses between 0.1 m and 15.1 m.

9.2.1.5 Lower Glacial unit (mostlyTill)

The Lower Till unit has probably been deposited during a Middle Weichselian glacial advance. The top of this unit appears to be quite planar, occurring at levels around -35 m to -45 m over most of the area.

All boreholes in the area have penetrated this often silty or medium plastic clay till that locally shows inclined limestone layers and smears. In most of the boreholes the pocket penetrometer indicates high or maximum values of undrained shear strengths (Tabel 2). In all boreholes the Lower till is resting directly on top of the limestone.

9.2.1.6 Limestone

Prequaternary rock composed of muddy, white limestone with many dark grey/black flint nodules and thin layers. Locally the upper part shows evidence of glacial deformation.

In the entire area the Prequaternary rock is made of Maastrictian Limestone deposited during the Late Cretaceous period. This deposit occurs very widespread in NW-Europe, in the Kriegers Flak area it appears mainly as a muddy, white limestone with many dark grey/black flint nodules and thin layers. The upper part of the limestone is locally showing evidence of glacial deformation. This unit has been found in the bottom of all boreholes.

9.2.1.7 geotechnical characteristics

Laboratory classification tests and advanced tests have been listed and related to the corresponding geological soil unit to present the geotechnical parameter variation (Tabel 2). Based on this typical values, ranges of the geotechnical parameters have been identified and tabulated.

The values presented cover all encountered soil units including post- and late Glacial units as well as Glacial and Cretaceous units.

Parameter	Unit	Marine and Glacio-lacustrine sand	Glacio- lacustrine freshwater clay and silt	Upper till	Melt-water clay	Lower till	Limestone
Water content (w)	%	10-81	22-82	7-26	18-57	7-32	19-37
Bulk density (γ_m)	Mg/m^3	1.7-2.1	NA	2.1-2.7	1.7-2.0	2.1-2.6	1.6-2.1
Medium grain size (d_{50})	mm	0.178-0.6	0.002	0.002-0.364	0.002	0.007-0.128	NA
Uniformity coef. (U)	-	1.6-3.9	NA	2.2-64.4	NA	NA	NA
Dry density (Max/Min)	Mg/m^3	1.45/2.0	NA	NA	NA	NA	NA
Clay fraction (<0.002 mm)	%	NA	49-63	6-38	46	12-36	NA
Plasticity index (Ip)	%	NA	22-37	6-25	12-36	6-21	NA
Carbonate cont. (Ca)	%	0.8-8	7-23	1-22	13	2-26	NA
Undrained Shear Strength (c_u)	kPa	15	NA	47-620	19-56	137-1235	50-2046
Friction Angle (φ')	Degree	37	NA	NA	NA	NA	NA
Unconfined Compression Strength (σ_c)	kPa	NA	NA	NA	NA	NA	99-4091

Tabel 2 Geotechnical results

It shall be noted that the boundary between the upper and Lower Till is not clearly defined in all boreholes. The boundary in each borehole has been established based on geological description, index tests and CPT results. Due to the above uncertainty in the boundary the geotechnical classification of these two “formations” are therefore subject to uncertainties.

The form of presentation is not a statistical work up of all data for the individual parameters leading to determination of characteristic design values for each soil type. The presentation of data is prepared as guide to get a quick overview of the geotechnical parameter variation for each geological soil type to be used only for initial engineering purposes.

9.3 Kriegers Flak 2 South POWF geology

The previous sections describing the general geology of the southwestern Baltic Sea and the Arkona Basin have revealed, that the Kriegers Flak 2 South POWF is located at the margin of the Arkona Basin (Lemke 1998). The bedrock geology is represented by Upper Cretaceous chalk and the glacial till deposits are dominated by ice margin readvance marginal ridges following the general deglaciation pattern.

The till surface topography has a maximum depth of 75m below present sea-level (bsl.) in the central part of the Arkona Basin, shallowing up to about 40m bsl. in the Kriegers Flak 2 South POWF area (Figure 6.11).

The till surface is covered by late glacial and Holocene clays and mud in the central parts of the Arkona Basin, changing to proximal sandy coastal deposits (Jensen et al. 1997) in the shallow western margin of the Arkona Basin, i.e. in the Kriegers Flak 2 South POWF area.

Unfortunately, the thickness of proximal sandy coastal deposits in the Kriegers Flak 2 South POWF area has not been mapped in detail by Lemke (1998) (Figure 6.12), but a comparison of till surface topography (Figure 6.11) and late glacial surface topography (Figure 6.13) shows a thickness of up to 30m. Detailed information about the Kriegers Flak 2 South POWF area, is provided in the following and illustrated by a set of seismic profiles and vibrocore data (see Figure 9.10 for locations).

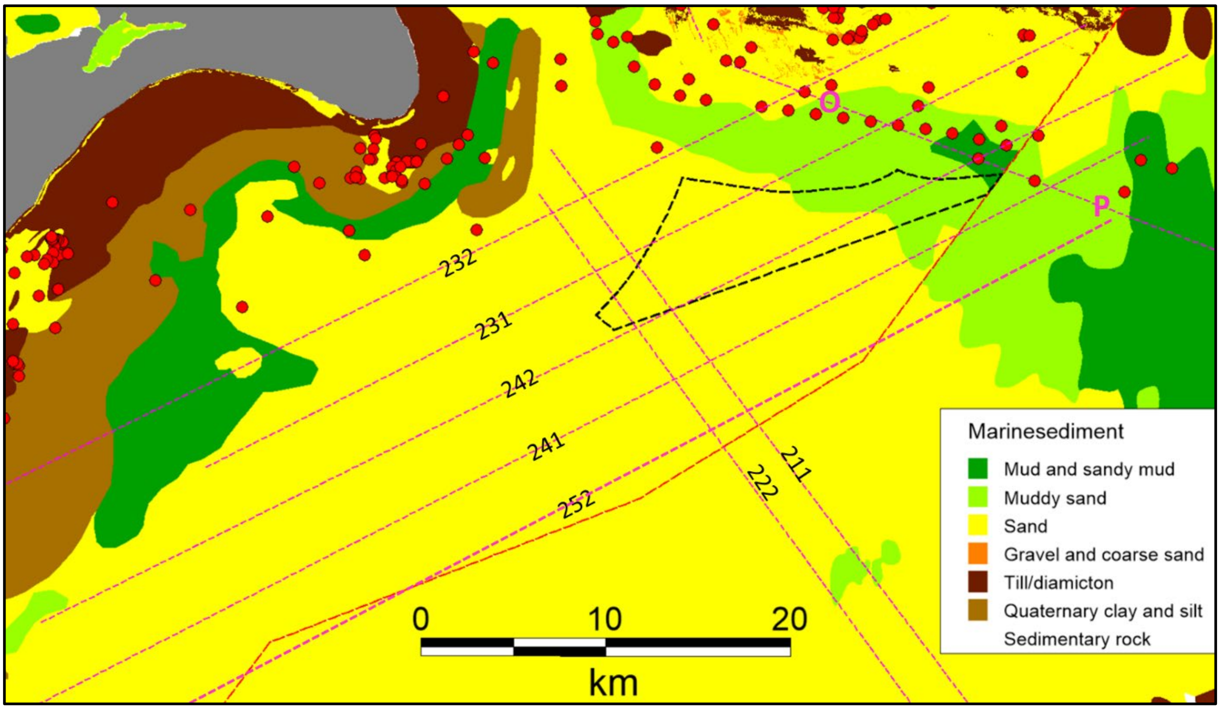


Figure 9.10 Kriegers Flak 2 South POWF (dashed black lines) surface sediment map with location of seismic profiles (pink dashed lines) and vibrocores (red dots). The red dashed lines show the EEZ.

9.3.1 Baltic Pipe profile O – P

Baltic Pipe sparker profile O – P (Figure 9.10) is located just east of Kriegers Flak 2 South POWF, in the marginal area of the Arkona Basin. The seismic profile in Figure 9.12, combined with a few vibrocores (Figure 9.11) document that the bedrock consists of Upper Cretaceous chalk found at a level of 50 – 65m bsl. A thin till unit covers the bedrock with a thickness between 0 and 5m and is followed by Baltic Ice Lake clay in a lower and an upper unit, with a combined thickness of between 5 and 10m. Then follows an early Holocene, freshwater transition, organic clay – silt, 0 – 2m thick covered by an uppermost unit of marine Holocene sandy mud to muddy sand, 3 – 4m thick.

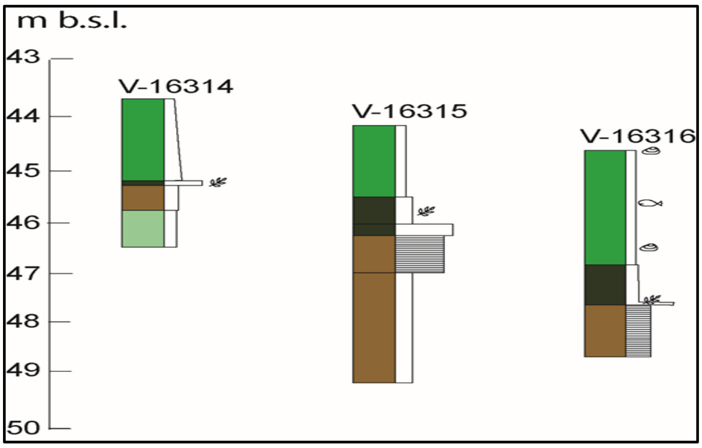


Figure 9.11 Vibrocore logs along Baltic Pipe profile O – P. See Figure 9.9 for legend.

The geological succession along the Baltic Pipe profile O – P probably represents what can also be expected in the easternmost part of Kriegers Flak 2 South POWF.

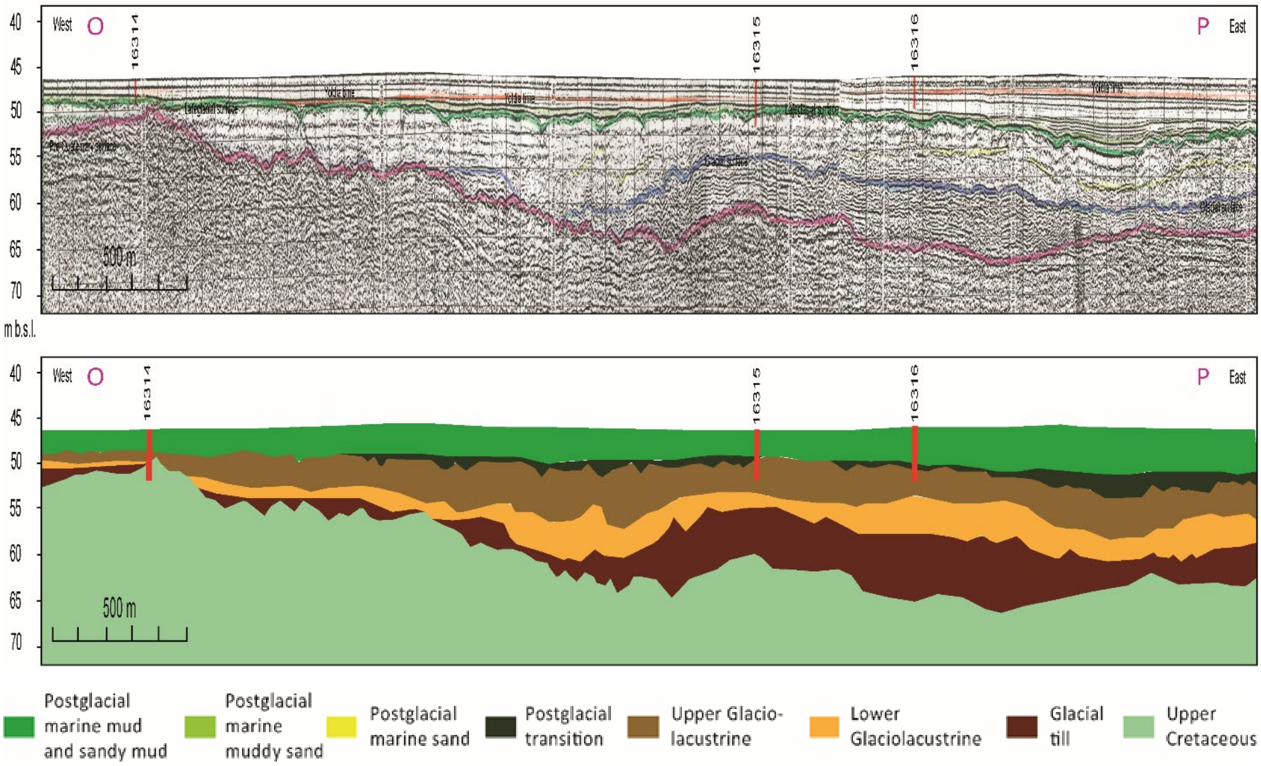


Figure 9.12 Baltic Pipe sparker profile O – P (upper figure) and geological interpretation (lower figure). Vibrocore positions are marked with red lines. For location, see Figure 9.10. *For details, see Appendix F.*

9.3.2 Seismic lines crossing Kriegers Flak 2 South POWF

A series of archive boomer and airgun seismic lines crosses the Krigers Flak 2 South POWF area. These data have been collected for scientific purposes and has been reported in Jensen et al. (1997) and Lemke (1998). The main conclusion is that the till surface was covered by an up to 35m thick wedge of late glacial proximal sandy coastal beach barrier deposits, that developed between Møn and Rügen in connection with two late glacial Baltic Ice Lake high stand periods, interrupted by two abrupt forced regressions; The first at c. 12800 years BP and the second at c. 11700 years BP (Figure 8.1 and Figure 8.2). The high stands reached a level of about 20m bsl. with progradation from west into the Arkona Basin on top of clay sediments in the basin. The prograding units represent the present eastward dipping seabed slope into Arkona Basin.

The combination of Boomer and airgun seismic lines gives good general information of the deeper till and bedrock units (airgun lines 231 (Figure 9.14), 241 (Figure 9.17) and 211 (Figure 9.19)) as well as more detailed information of the late glacial and Holocene deposits (Boomer lines 232 (Figure 9.13), 242 (Figure 9.15), 252 (Figure 9.18) and 222 (Figure 9.20)).

The surface of the Upper Cretaceous chalk is dipping to the south and east from about 20m bsl. north and west of Kriegers Flak 2 South POWF to between 30 and 55m bsl. in the POWF area. The bedrock is covered by till ranging in thickness from a few metres to more than 15m, due to the development of ice marginal ridges (airgun lines 231 (Figure 9.14), 241 (Figure 9.17) and 211 (Figure 9.19)).

The late glacial Baltic Ice Lake deposits follows the general pattern in the southwestern part of the Baltic Sea, as described in section 6.1 and 6.2, but the lower and upper glaciolacustrine deposits changes facies from clay deposits in the Arkona basin (Figure 9.11 and Figure 9.16) to fine to medium sand coastal sediments, deposited in a wedge structure, on the margin of the Arkona Basin (Boomer line 252, Figure 9.18).

Only a very few vibrocores have been taken and they consist of fine to medium late glacial sand on the wedge and glaciolacustrine clay at the foot of the wedge, but they only penetrate maximum 6m into the uppermost part of the late glacial deposits. The seismic lines indicate that the late glacial wedge deposits reaches a maximum thickness of up to 35m (Seismic line 252, Figure 9.18) south of Kriegers Flak 2 South POWF, with an internal reflection pattern indicating prograding sandy costal deposits (about 25m thick) above basin clay (about 10m thick).

In the Kriegers Flak 2 South POWF area (seismic profiles 231 (Figure 9.14), 242 (Figure 9.15), 211 (Figure 9.19) and 222 (Figure 9.20)), the late glacial deposits mainly include the upper prograding sandy costal deposits (about 25m thick) on top of Till as seen from the internal reflection pattern.

Early Holocene, freshwater, fine-grained, organic rich sediments (0 – 3m thickness) are located in the Arkona basin (Profile O – P, Figure 9.9) and inside the POWF at the foot of the prograding unit (seismic profiles 231 (Figure 9.14) and 242 (Figure 9.15)) as well as in depressions west of the POWF (seismic profiles 232 (Figure 9.10), 252 (Figure 9.18)).

The final Holocene transgression of the region resulted in erosion of the older sediments and redeposition of sand and muddy sand on top of the palaeo late glacial coastal deposits.

In the Kriegers Flak 2 South POWF area only about 1m of Holocene sand is located on top of late glacial sand, while depressions west of the POWF may hold up to 5m of Holocene sand.

Muddy sand and sandy mud represent subrecent to recent sedimentation in the Arkona Basin and the shallow waters close to Møn, with a typical thickness of 1 – 3m (seismic profiles 231 (Figure 9.15), 242 (Figure 9.15) and 252 (Figure 9.18)).

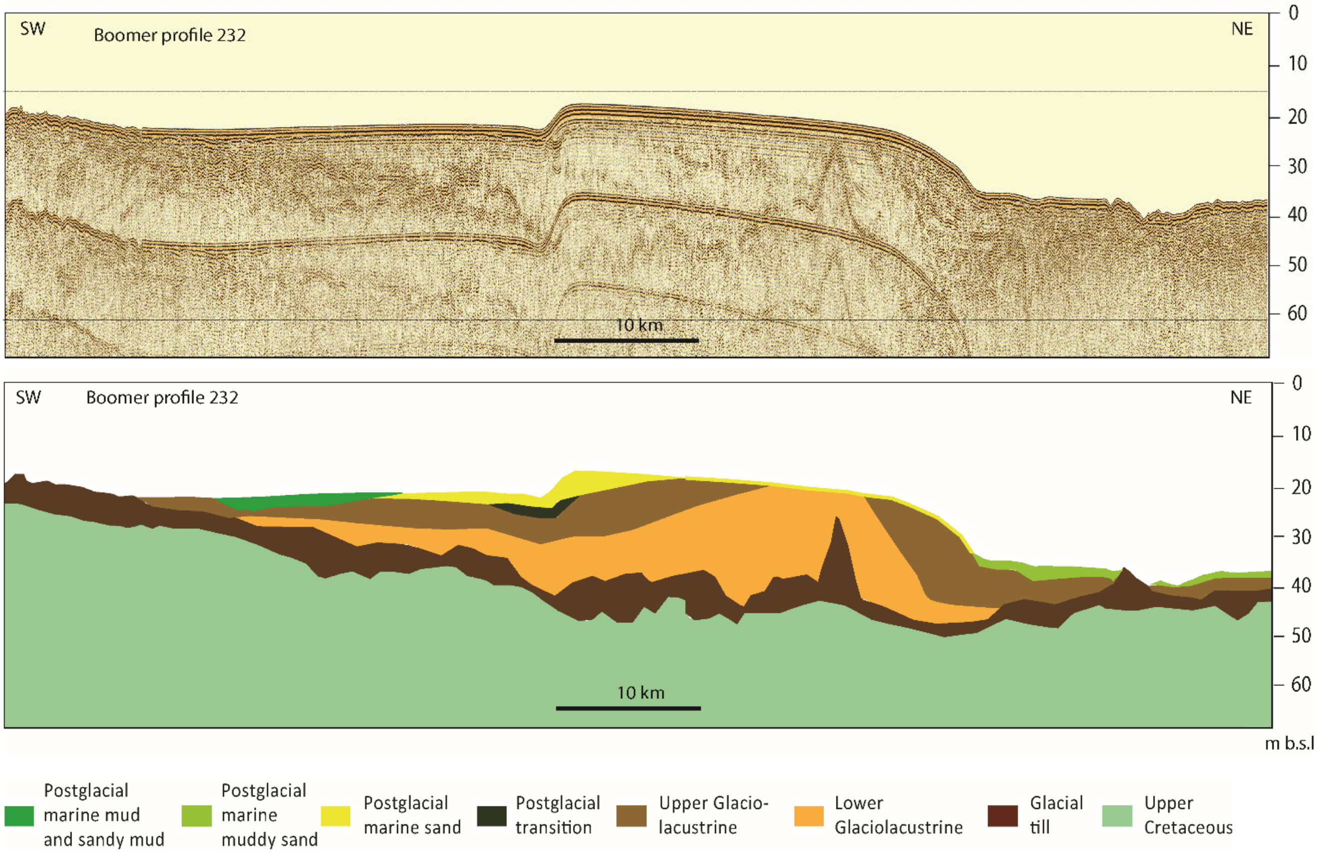


Figure 9.13 Boomer profile 232 and geological interpretation. For location, see Figure 9.10. For details, see Appendix G.

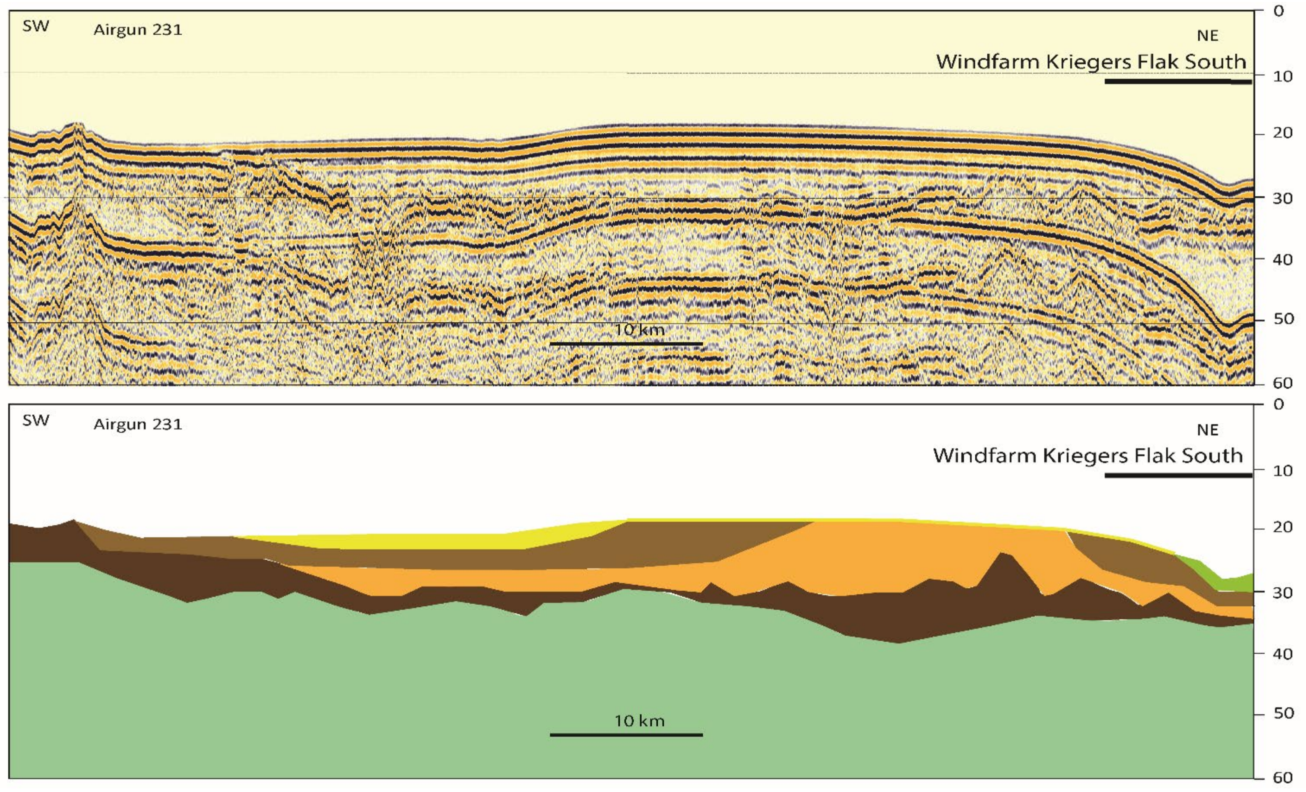


Figure 9.14 Airgun profile 231 and geological interpretation. For location, see Figure 9.10. For details, see Appendix H.

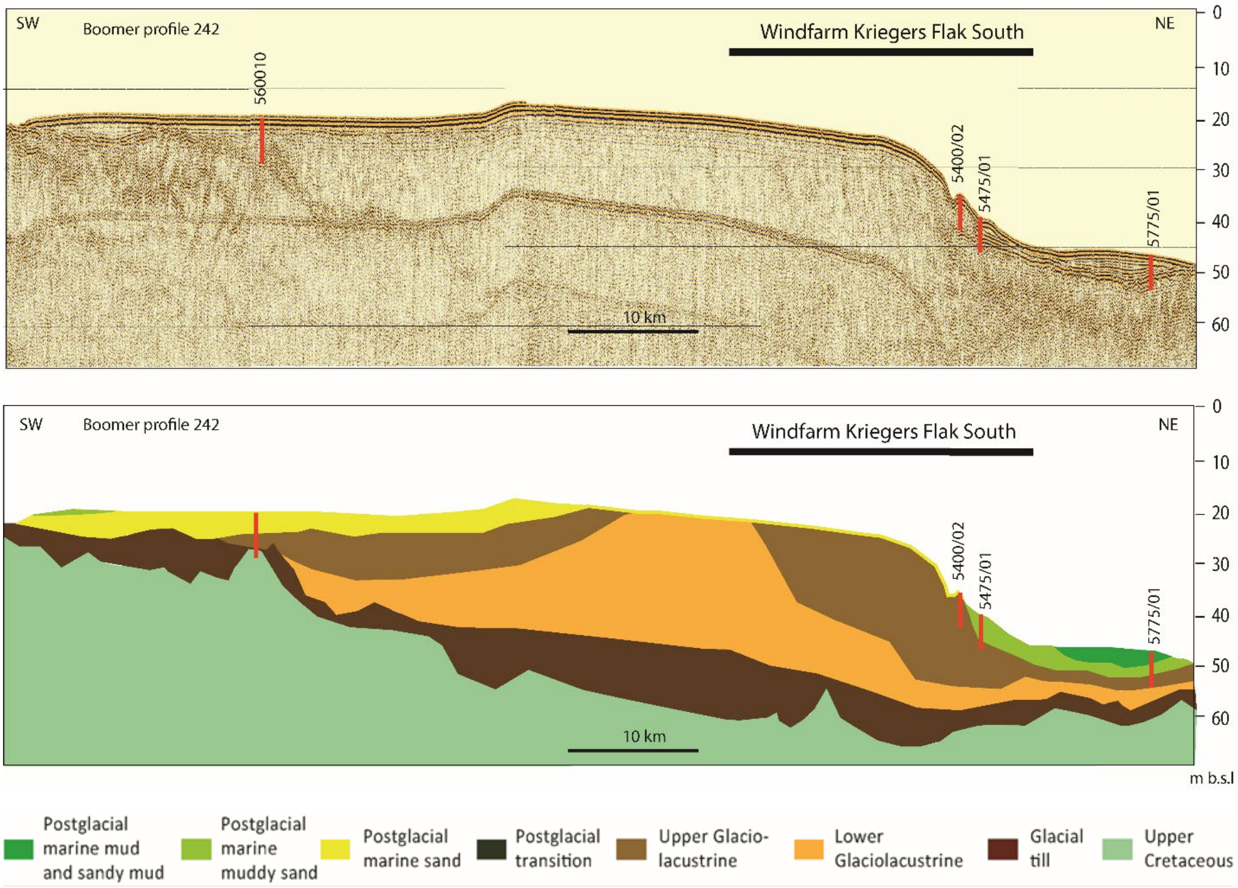


Figure 9.15 Boomer profile 242 and geological interpretation. For location, see Figure 9.10. For details, see Appendix I.

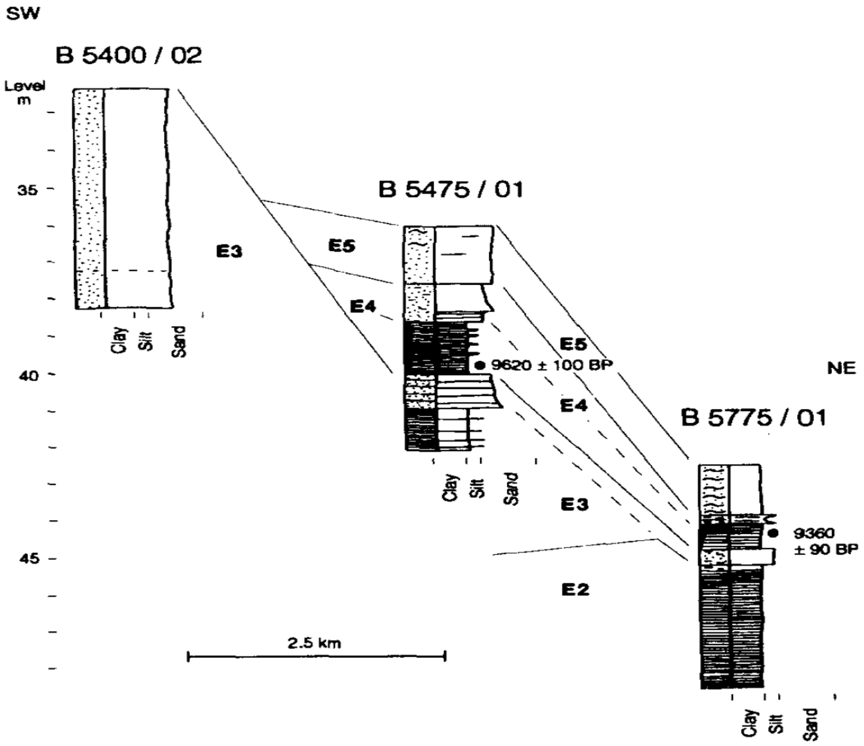


Figure 9.16 Vibrocore logs along Boomer profile 242, from Jensen et al. (1997).

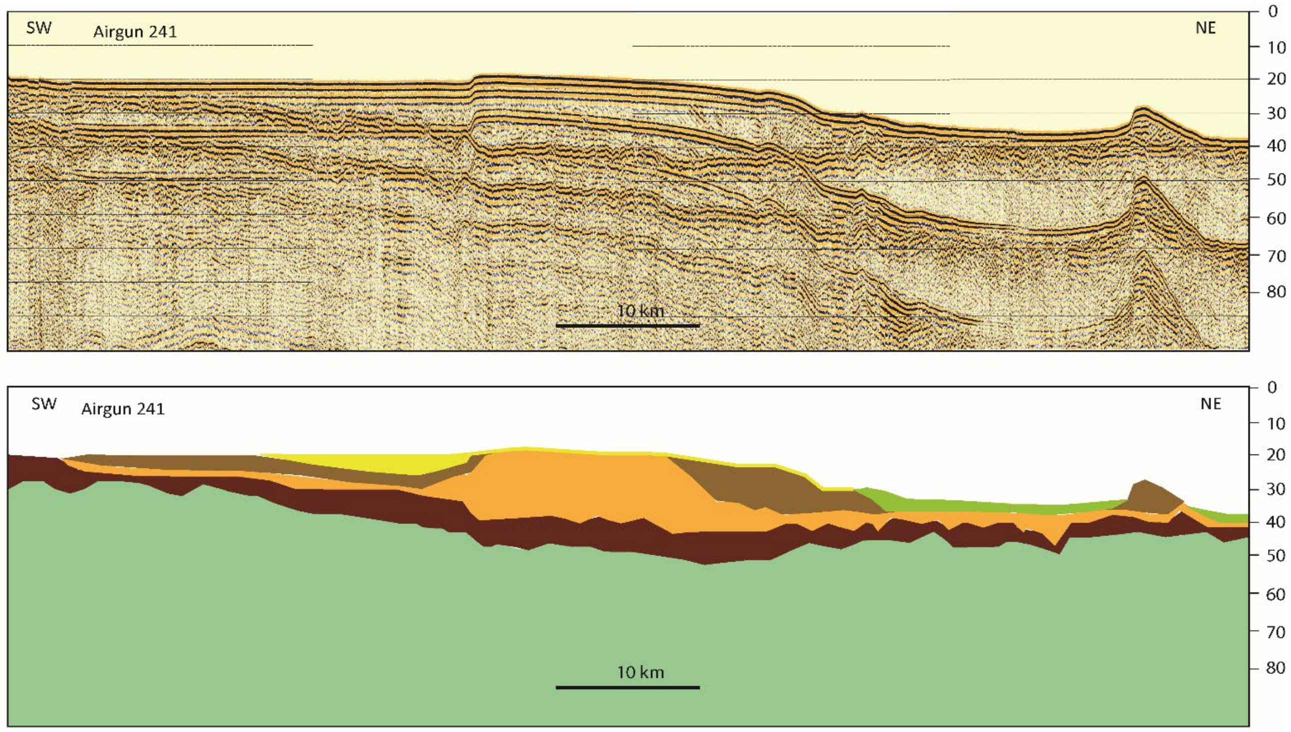


Figure 9.17 Airgun profile 241 and geological interpretation. For location, see Figure 9.10. For details, see Appendix J.

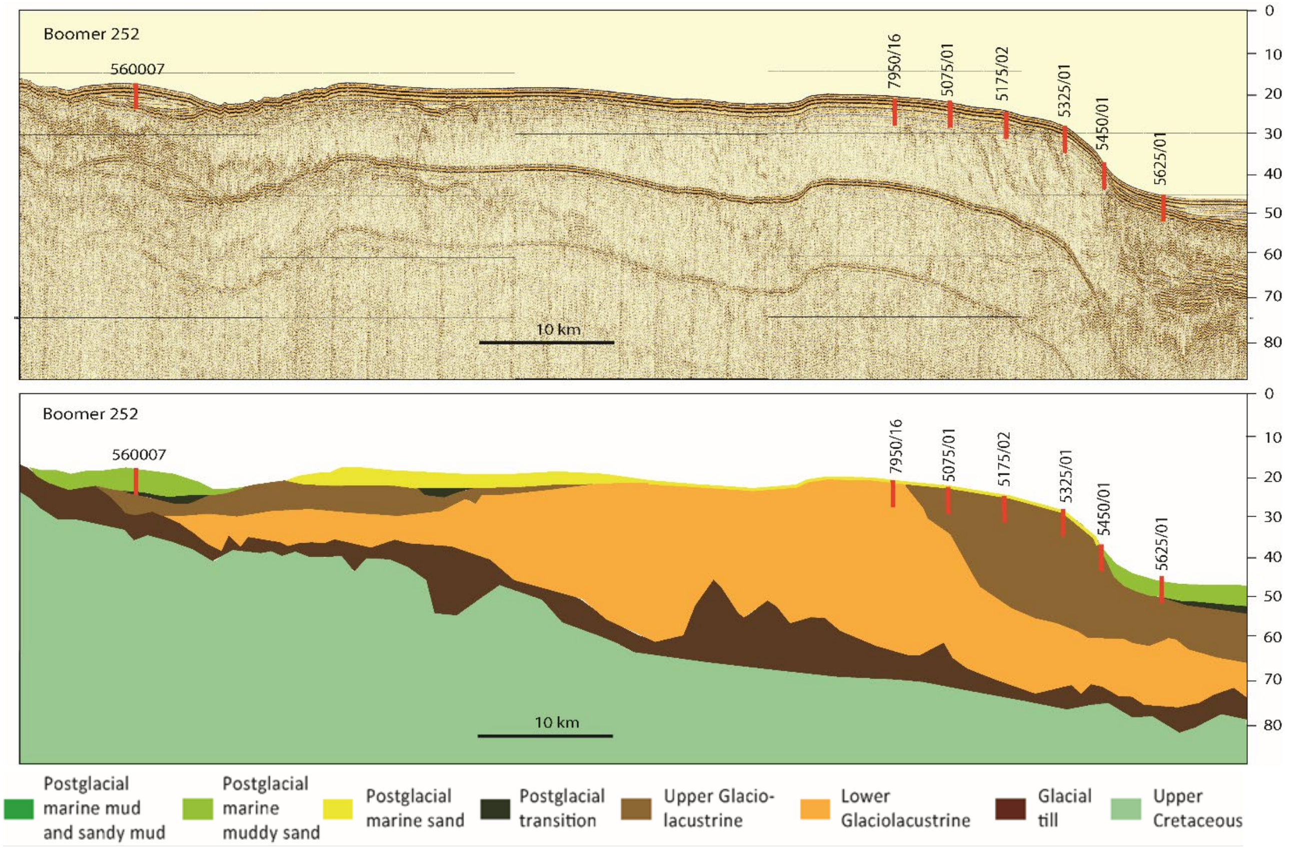


Figure 9.18 Boomer profile 252 and geological interpretation. For location, see Figure 9.10. For details, see Appendix K.

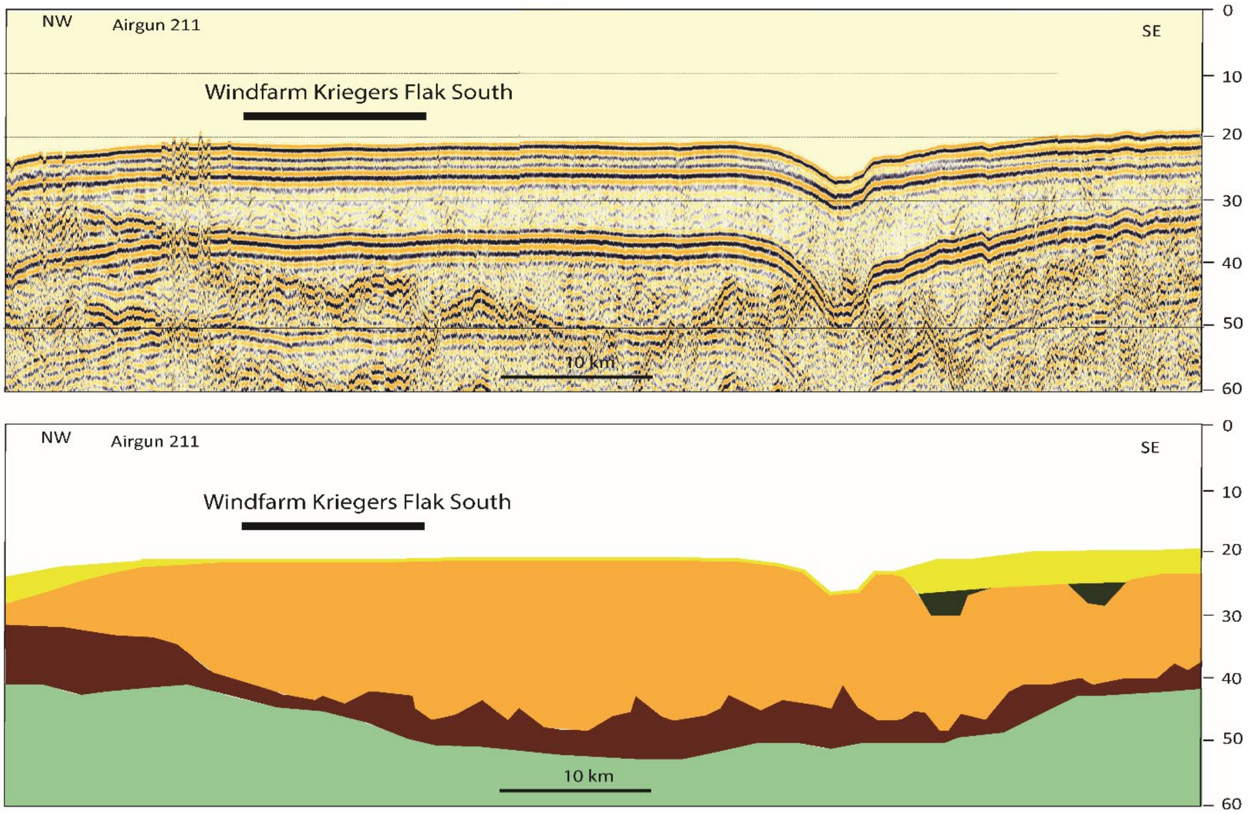


Figure 9.19 Airgun profile 211 and geological interpretation. For location, see Figure 9.10. For details, see Appendix L.

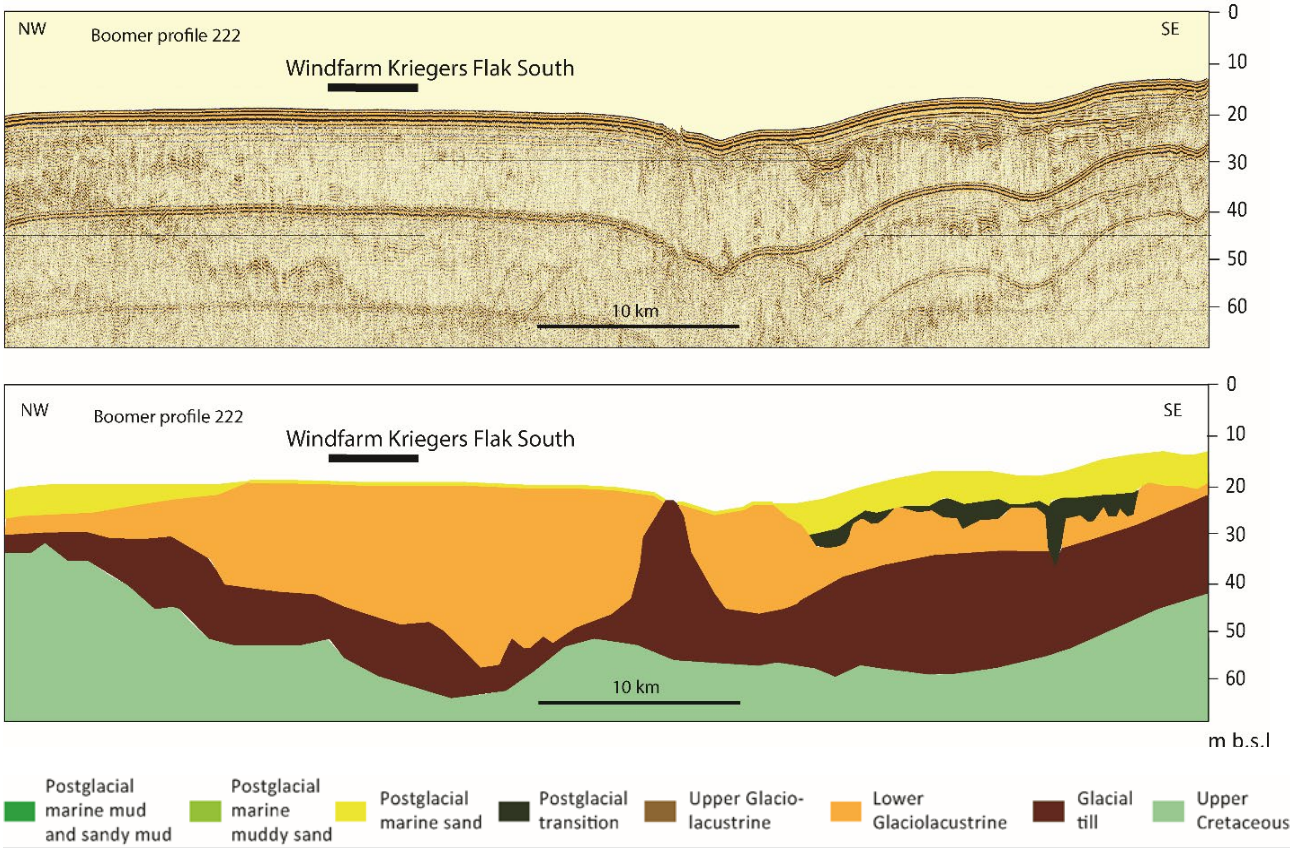


Figure 9.20 Boomer profile 222 and geological interpretation. For location, see Figure 9.10. For details, see Appendix M.

10. Key geological conditions

The screening has revealed geological conditions and sediment characteristics that may have implications for the assessment of wind farm foundation conditions. The following key geological characteristics are shortly discussed here:

- Chalk bedrock
- High-lying over-consolidated glacial sediments
- Meltwater clay
- Marine dynamic sand deposits
- Soft silty marine clays and gyttja
- Peat layers
-

With reference to Velenturf et al. (2021), some of the possible implications of these geological conditions are described below:

Soft sediments can imply a risk for low geotechnical strength and be a challenge for the foundation design. At the seabed, soft sediments can potentially be unable to bear large loads from e.g. a jack-up rig during construction.

Marine dynamic sand deposits may imply migrating erosional and depositional bedforms that can change the seabed topography over the operational lifetime of an OWF site in terms of scouring or burial of e.g. piles or cables.

Clay deposited in lakes in front of the retreating glacier has not been over consolidated and may be very soft, with similar challenges as younger soft sediments.

The old glacial deposits may represent over-consolidated and strong sediments, which generally can provide a difficulty during construction e.g. for driving piles. They may also comprise more specific hard, potentially heterogeneous, coarse lag deposits (gravel to boulders) that can be difficult to penetrate and may lead to refusal of foundation infrastructure or damage of equipment. Near the seabed, a hard, heterogeneous surface can make it more difficult predict scour behavior.

The chalk bedrock is characterised by varying degrees of weathering, leading to significant variation in properties ranging from those typical for stiff soil to soft rock.

In Table 10-1 an overview of sediment types met in the screening area and potential critical geotechnical conditions and general foundation suitability is given.

Table 10 -1

Sediment type	**Critical geotechnical conditions/challenges**	**Foundation suitability**
Marine sand	n.a.	Well suited
Marine clay/soft mud	Low geotechnical strength	Not well suited if thick
Peat	High compressibility, low geotechnical strength	Not well suited
Meltwater clay	Low geotechnical strength if not overconsolidated	Not well suited if thick
Moraine clay/till	Overconsolidated and potentially heterogeneous. Can contain coarse lag deposits, boulder stones and dislocated slabs of older sediments	Potentially problematic
Chalk bedrock	Provides a hard substrate for emplacement of seabed infrastructure (e.g., drilled piles). However, may be weathered with lower strengths at the interface with Quaternary sediments	Potentially problematic

Kriegers Flak 2 North POWF is a rather flat area, located in the outer Fakse Bay at water depths of 20 – 35m. The area is dominated by Danian limestone covered by a few metres of till, with boulders and patchy coverage of a few meters of Holocene sands and muddy sands. The sediment distribution indicates that the Quaternary sediment succession will be well suited for foundation, while the Danian limestone, if weathered, may be potentially problematic.

Kriegers Flak 2 South POWF has a seabed slope, from 45 to 20m bsl. and the Cretaceous limestone and till is covered by an up to 35m thick wedge of late glacial proximal coastal sands prograding south-eastward into the Arkona Basin over the basin clay.
The seabed slope must be considered, while the wedge sand in general is considered well suited for foundation. The easternmost slope foot however consists of more than 10m of soft late glacial clay and Holocene muddy sand to sandy mud, not well suited for foundation. Below the sand wedge complex few meters of till is followed by Cretaceous chalk. The till is well suited for foundation while the Cretaceous chalk, if weathered, may be problematic.

11. Archaeological interests

In addition to geotechnical interests in a conceptual geological model and detailed understanding of the geology of the Kriegers Flak 2 North and South POWF areas, it is also important for an archaeological screening to understand the development and distribution of land and lake/sea after the last deglaciation.

The initial period after the deglaciation was characterised by highstand water-level in the south-western Baltic Sea. The region was deglaciated around 16000 to 15000 years ago and major parts of the Kriegers Flak 2 North and South POWF were covered by the glaciolacustrine Baltic Ice Lake. This corresponds to the archaeological Hamburg culture or Hamburgian (15500–13100 years BP) – a Late Upper Palaeolithic culture of reindeer hunters.

The highstand period was followed by an abrupt regression and development of an erosional unconformity at around 12800 years BP. During this lowstand period the water level was about 40m below present sea level and reed plants were growing in parts of the Arkona Basin. Major parts of the Kriegers Flak region would have been dry land during this lowstand. However, the low-stand period was short-lived and followed by a rapid transgression. A new low-stand period is dated to c. 11700 years BP, and this time the water level was c. 40–45m below present sea level and Bornholm was a peninsula connected to mainland Europe (Figure 10.1). Again the POWF would have been exposed, but this second low-stand period was also short-lived and soon followed a new fairly rapid transgression. The second low-stand period corresponds to the early part of the Maglemose Culture.

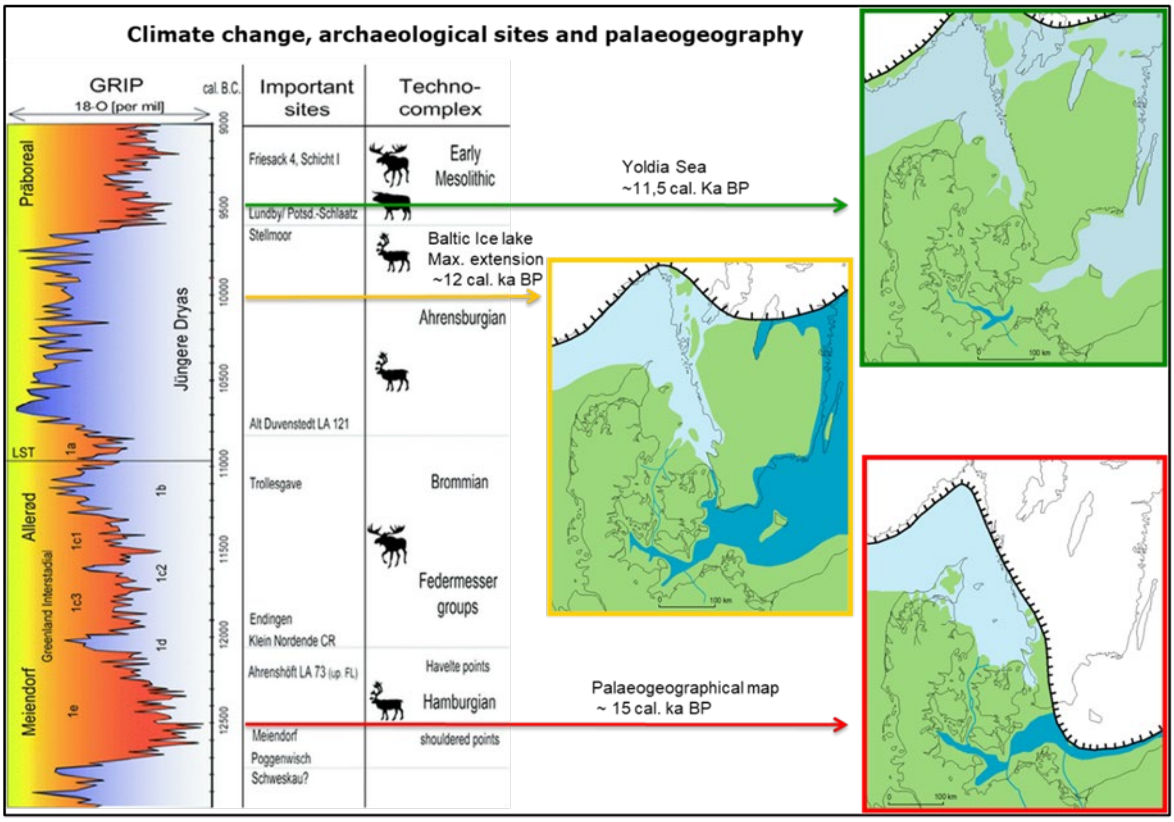


Figure 10.1 Late glacial and Holocene general palaeogeography in the Danish area and related archaeological cultures. The maps are from Jensen et al. (2003).

The shallow-water parts of the Kriegers Flak 2 North and South POWF have been dry land for long periods during the late glacial and Early Holocene. Submerged archaeological sites from the Maglemose, Kongemose and Ertebølle Cultures are for example known from Mecklenburg Bay off northern Germany (Schmölcke et al. 2006; Hartz et al. 2011; Lübke et al. 2011), from Køge Bugt and near Amager. Submerged fishing constructions made of hazel rods and dated to 9000-8400 years BP have been reported from Hanö Bugt off Skåne (Hansson et al. 2018). Due to the fluctuating and dynamic shoreline history in the southern Baltic Basin, it is possible to find submerged landscapes and archaeological sites from throughout the Holocene, but we consider the early and mid-Mesolithic time to be the most likely for findings. The chances to find submerged archaeological sites are probably small in areas with a long fetch and high energy environment. The chances are higher along the east coast of Møn and Zealand, which is protected from the dominating westerly winds.

12. Conclusions

In this study we have used a combination of published work, archive seismic and sediment core data, to assess the general geological development of the south-western Baltic Sea region, including the Kriegers Flak 2 North and South POWF. Detailed information has been acquired from the GEUS Martha database, supplemented by a few lines from The Baltic Pipe offshore pipeline transect, which are passing through and close by the Kriegers Flak 2 North and South POWF as well as from scientific studies (Jensen et al. 1997). The seismic transects and vibrocorings from various sources has all been vital for the understanding of the area.

A geological description of the areas has been provided and a conceptual geological model for the development of the south-western Baltic Sea area has been presented.

A surface sediment map has been compiled by a combination of Emodnet seabed substrate map for the German and Swedish zones and the latest version (2020) of the Danish 1:100.000 seabed substrate map.

Information on the existing Kriegers Flak OWF has been presented including a geological model based on detailed seismic studies (Rambøll 2013) and boreholes (GEO 2013) The Kriegers Flak OWF is composed of a rather complex sequence of glacial deposits, as well as Lateglacial and Postglacial deposits, all overlying the Cretaceous Limestone.

The general geology, soil types and geotechnical characteristics is presented in a west-east profile (Figure 9.9) combined with selected boreholes (Appendix N) and a table with geotechnical results (Tabel 2).

The planned Kriegers Flak 2 North and south POWF will include Upper Cretaceous chalk and Danien limestone bedrock, followed by glacial and late glacial clays and sands. The western margin of the Arkona Basin is dominated by late glacial basin clays and proximal shallow costal platform sands, as well as Holocene sand and sandy mud, while outer Fakse Bay has a base of glacial till, with a thin patchy coverage of late glacial and Holocene sand and muddy sands.

As a result of the geological desk study, it has been possible to present a relative late glacial and Holocene sea-level curve for the area and to describe the development relevant for an archaeological screening.

Data are presented from the Kriegers Flak 2 North and South POWF areas, and the interpretations are described on the basis of existing knowledge and profile sections (Figure 9.3 to Figure 9.6) modified from the Baltic Pipe project investigations (Rambøll 2020) and scientific airgun and boomer seismic lines as well as vibrocores (Figure 9.10 to Figure 9.17).

Several focal points and recommendations are relevant for the future geotechnical and archaeological evaluation of the areas:

12.1 Focal Points and recommendations Kriegers Flak 2 North POWF

- Kriegers Flak 2 North POWF is a rather flat area, located in the outer Fakse Bay at water depths of 20 – 35m. The area is dominated by Danian limestone covered by a few metres of till, with boulders and patchy coverage of a few metres of Holocene sands and muddy sands.

- Despite few datapoints and no geotechnical evidence. It is concluded that the Kriegers Flak 2 North POWF flat seabed (20 – 35m bsl.), with thin skinned Holocene sediments on top of till and Danian limestone, will be an area where it is possible to establish a wind farm.

- The geological setting and water depths above 20m indicates no risk for archaeological interest.

- Only few seismic lines cross the area and few nearby vibrocores. We have no geotechnical data form the area. However, the succession of geological units indicates that the area is rather uniform in its geological setting.

- It is recommended do acquire an open grid of shallow seismic data and few vibrocores, combined with geotechnical investigation, as a low-cost pre-investigation, before next step of decisions and comprehensive studies.

12.2 Focal Points and recommendations Kriegers Flak 2 South POWF

- South of Møn, in the north-western margin of the Arkona Basin, the seabed slope shallows up westwards, from 45 to 20m bsl. and the Cretaceous limestone and till is covered by an up to 35m thick wedge of late glacial proximal coastal sands prograding south-eastwards into the basin over the basin clay.

- In the Kriegers Flak 2 South POWF area the late glacial deposits mainly include the upper wedge, indicating prograding sandy costal deposits (about 25m thick) on top of Till.

- Detailed studies of the existing Krigers Flak OWF show a similar seabed geology as Kriegers Flak 2 South POWF and offers boreholes as well as geotechnical properties of the individual geological units, that can be transferred to similar units in the Kriegers Flak 2 South POWF

- It is concluded that the Kriegers Flak 2 South POWF is probably geotechnical suited for wind turbine foundation.

    1. It should however be considered that the POWF includes a seabed slope in the eastern part of the area from 20m- to 45m bsl.
    2. A late glacial fine to medium grained sand wedge, with a thickness of up to 35m, covers till and Cretaceous chalk in the westernmost part of the area
    3. At the easternmost slope foot, more than 10m of late glacial clay and Holocene muddy sand to sandy mud, covers till and Cretaceous chalk.

- The chances to find submerged archaeological sites in the Kriegers Flak 2 South POWF is small due to water depths above 15 – 20m and lack of postglacial deposits.

- Only few seismic lines cross the area and few vibrocores with no geotechnical information.

- It is recommended do acquire an open grid of shallow seismic data and few vibrocores, combined with geotechnical investigation, as a low-cost pre-investigation, before next step of decisions and comprehensive studies.

13. References

13.1 Background reports

GEO 2013: Kriegers Flak Offshore Wind Farm Geo Investigations 2013 Factual Report – Seabed CPTs and Geotechnical Boreholes

GEUS 2021: (a) Geology desk study off-shore Bornholm, Baltic Sea Windfarm investigations. GEUS Rapport 2021/18

GEUS 2021 (b) Geological desk study Bornholm Windfarm, cable transects Geological seabed screening in relation to possible location of cable transects GEUS Rapport 2021/63.

Jensen, J.B. and Nielsen, P.E. 1998: Treasures hiding in the Sea Marine raw material and Nature Interests. An evaluation by GEUS & TheNational Forest and Nature Agency. Geologi Nyt fra GEUS No. 4 December 1998.

Lemke, W. 1998: Sedimentation und paläogeographische Entwicklung im westlichen Ostseeraum (Mecklenburger Bucht bis Arkonabecken) vom Ende der Weichselvereisung bis zur Litorinatransgression. Meereswissenschaftliche Berichte, Warnemünde, 31.

Ranbøll 2013: KRIEGERS FLAK OWF INTERPRETIVE SURVEY REPORT. KRIEGERS FLAK & HORNS REV 3 – GEO INVESTIGATIONS 2012.

Rambøll 2020: BALTIC PIPE OFFSHORE PIPELINE – PERMITTING AND DESIGN Interpretive geophysical survey report -Danish territorial and EEZ waters.

13.2 Supplementary papers

Andrén, T. & Expedition 347 participants 2014: Integrated Ocean Drilling Program Expedition 347 Preliminary Report. Baltic Sea Basin Paleoenvironment. Paleoenvironmental evolution of the Baltic Sea Basin through the last glacial cycle. Published by Integrated Ocean Drilling Program. http://publications.iodp.org/preliminary_report/347/347PR.PDF.

Andrén, T, Jørgensen, B. B., Cotterill, C., Green, S. & Expedition 347 Scientists 2015: Baltic Sea palaeoenvironment. Proceedings of the IODP, Integrated Ocean Drilling Program 347. Integrated Ocean Drilling Program. Available at: http://publications.iodp.org/proceedings/347/347title.htm

Andrén, E., Andrén, T. & Sohlenius, G. 2000: The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. Boreas 29, 233–250.

Bendixen. C., Boldrell, L.O, Jensen. J.B., Bennike, O., Clausen, O.R., Hübscher, C. 2017: Early Hol-ocene estuary development of the Hesselø Bay area, southern Kattegat, Denmark and its impli-cation for Ancylus Lake drainage. Geo-Mar Lett. 37, 579-591 June 2017

Bennike, O. & Jensen, J. B. 1998: Late- and Postglacial shore level changes in the southwestern Baltic Sea. Bulletin of the Geological Society of Denmark 45, 27–38.

Bennike, O., Jensen, J. B., Konradi, P. B., Lemke, W. & Heinemeier, J. 2000: Early Holocene drowned lagoonal deposits from the Kattegat, southern Scandinavia. Boreas 29, 272–286.

Bennike, O. & Jensen, J.B. 2013: A Baltic Ice Lake lowstand of latest Allerød age in the Arkona Basin, southern Baltic Sea. Geological Survey of Denmark and Greenland Bulletin 28, 17–20.

Binzer, K. & Stockmarr, J. 1994: Pre-Quaternary surface topography of Denmark. Geological Survey of Denmark, Map Series No. 44.

Brüsch, W. 1984: Bavnodde Grønsandets palæomiljø og -geografi. M. Se. Thesis, Københavns Universitet, 181 pp.

Erlström, M., Thomas, S. A. A., Deeks, N. & Sivhed, U. 1997: Structure and tectonic evolution of the Tornquist Zone and adjacent sedimentary basins in Scania and the Southern Baltic Sea area.Tectonophysics 271, 191–215.

Eyles, N. & McCabe, A. M. 1989: The Late Devensian (<22,000 BP) Irish Sea Basin: the sedimentary record of a collapsed ice sheet margin. Quaternary Science Reviews 8, 307–351.

Hansson, A., Nilsson, B., Sjöström, A., Björck, S., Holmgren, S., Linderson, H., Magnell, O., Rundgren, M. & Hammarlund, D. 2018: A submerged Mesolithic lagoonal landscape in the Baltic Sea, southeastern Sweden - Early Holocene environmental reconstruction and shore-level displacement based on a multiproxy approach. Quaternary International 463, 110-123.

Hansson, A., Björck, S., Heger, K., Holmgren, S., Linderson, H., Magnell, O., Nilsson, B., Rundgren, M., Sjöström, A. & Hammarlund, D. 2018: Shoreline displacement and human resource utilization in the southern Baltic Basin coastal zone during the early Holocene: New insights from a submerged Mesolithic landscape in south-eastern Sweden. The Holocene 28, 721–737.

Hartz, S., Jöns, H., Lübke, H., Schmölcke, U., von Carnap-Bornheim, C., Heinrich, D., Klooß, S., Lüth, F. & Wolters, S. 2011: Prehistoric settlements in the south-western Baltic Sea area and development of the regional Stone Age economy. In: Harff, J. & Lüth, F. (eds): SINCOS II – Sinking Coasts: Geosphere, Eosphere and Anthroposphere of the Holocene southern Baltic Sea. Bericht der Römisch-Germanischen Kommission 92, 77–210. Frankfurt A.M.: Verlag Philip von Zabern.

Jensen, J.B. 1993: Late Weichselian deglaciation pattern in the southwestern Baltic: Evidence from glacial deposits off the island of Møn. Denmark. Bulletin of the Geological Society of Denmark 40, 314-331.

Jensen, J. B., Bennike, O., Witkowski, A., Lemke, W. & Kuijpers, A. 1997: The Baltic Ice Lake in the southwestern Baltic: sequence-, chrono- and biostratigraphy. Boreas 26, 217–236.

Jensen, J. B., Bennike, O., Witkows,ki, A., Lemke, W. & Kuijpers, A. 1999: Early Holocene history of the southwestern Baltic Sea: the Ancylus Late stage. Boreas 28, 437–453.

Jensen, J.B. Kuijpers, A, Bennike, O. and Lemke, W. 2003: Thematic volume "BALKAT" – The Baltic Sea without frontiers. Geologi, Nyt fra GEUS 2003, 19 pp.

Jensen, J.B., Moros, M., Endler, R. & IODP Expedition 347 Members. 2017: The Bornholm Basin, southern Scandinavia: a complex history from Late Cretaceous structural developments to recent sedimentation. Boreas 46, 3–17.

Jensen, J.B. and Nielsen, P.E. 1998: Treasures hiding in the Sea Marine raw material and Nature Interests An evaluation by GEUS & The National Forest and Nature Agency. GEOLOGI, Nyt fra GEUS. Nr. 4 . 1998.

LANGE, D., 1984: Geologische Untersuchungen an spätglazialen und holozänen Sedimenten der Lübecker und Mecklenburger Bucht. Unveröffentlichte Dissertation (B), Institut für Meereskunde Warnemünde, 166 S.

Lemke, W. 1998: Sedimentation und paläogeographische Entwicklung im westlichen Ostseeraum (Mecklenburger Bucht bis Arkonabecken) vom Ende der Weichselvereisung bis zur Litorinatransgression. Meereswissenschaftliche Berichte, Warnemünde, 31.

Liboriussen, J., Ashton, P. & Tygesen, T. 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. Tectonophysics 137, 21–29.

Lübke, H., Schmölcke, U. & Tauber, F. 2011: Mesolithic hunter-fishers in a changing world: a case study of submerged sites on the Jäckelberg, Wismar Bay, northeastern Germany. In: Benjamin, J., Bonsall, C., Pickard, C. & Fisher, A. (eds): Submerged Prehistory, 21-37. Oxford Books.

Mathys , M., Thießen, O., Theilen, F and Schmidt, M. 2005: Seismic characterisation of gas-rich near surface sediments in the Arkona Basin, Baltic Sea. Marine Geophysical Research 26:207–224

Mogensen, T.E., and Korstgård, J.A. 2003: Triassic and Jurassic transtension along part of the Sorgenfrei–Tornquist Zone in the Danish Kattegat. Geological Survey of Denmark and Greenland Bulletin 1, 439–458.

Moros, M., Lemke, W., Kuijpers, A., Endler, R., Jensen, J.B., Bennike, O. & Gingele, F. 2002: Regression and transgressions of the Baltic basin reflected by a new high-resolution deglacial and Postglacial lithostratigraphy for Arkona Basin sediments (western Baltic Sea). Boreas 31, 151–162.

Reimer, P. et al. 2020: The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0-55 cal kB). Radiocarbon 62, 725–757.

Schmölcke, U., Endtmann, E., Klooss, S., Meyer, M., Michaelis, D., Rickert, B.-H. & Rößler, D. 2006: Changes of sea level, landscape and culture: A review of the south-western Baltic area between 8800 and 4000 BC. Palaeogeography, Palaeoclimatology, Palaeoecology 240, 423–438.

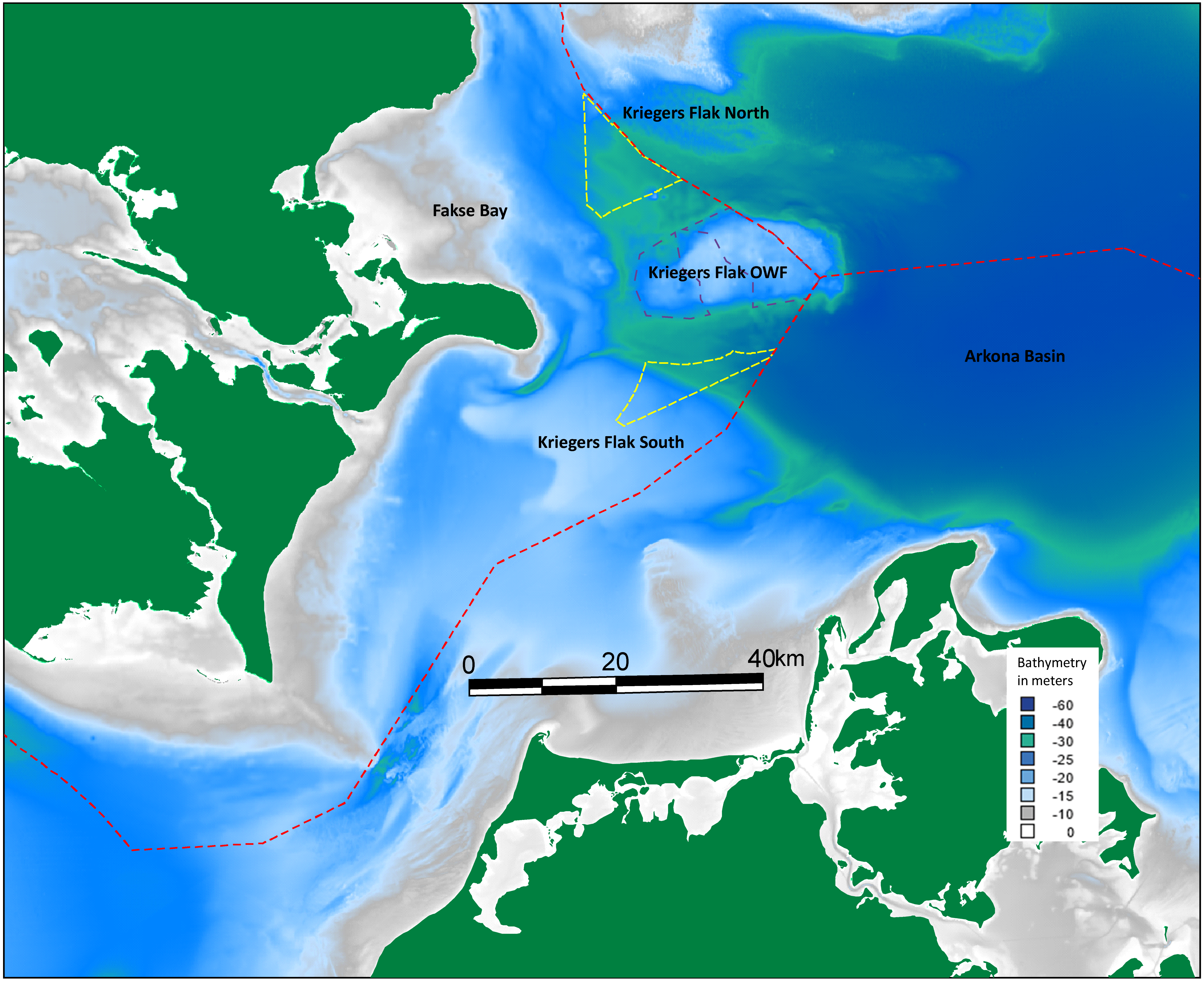
Stuiver, M. & Polach, H.A. 1977: Discussion of reporting 14C data. Radiocarbon 19, 355–363.

Uścinowicz, S. 2006: A relative sea-level curve for the Polish Southern Baltic Sea. Quaternary International 145–146, 86–105.

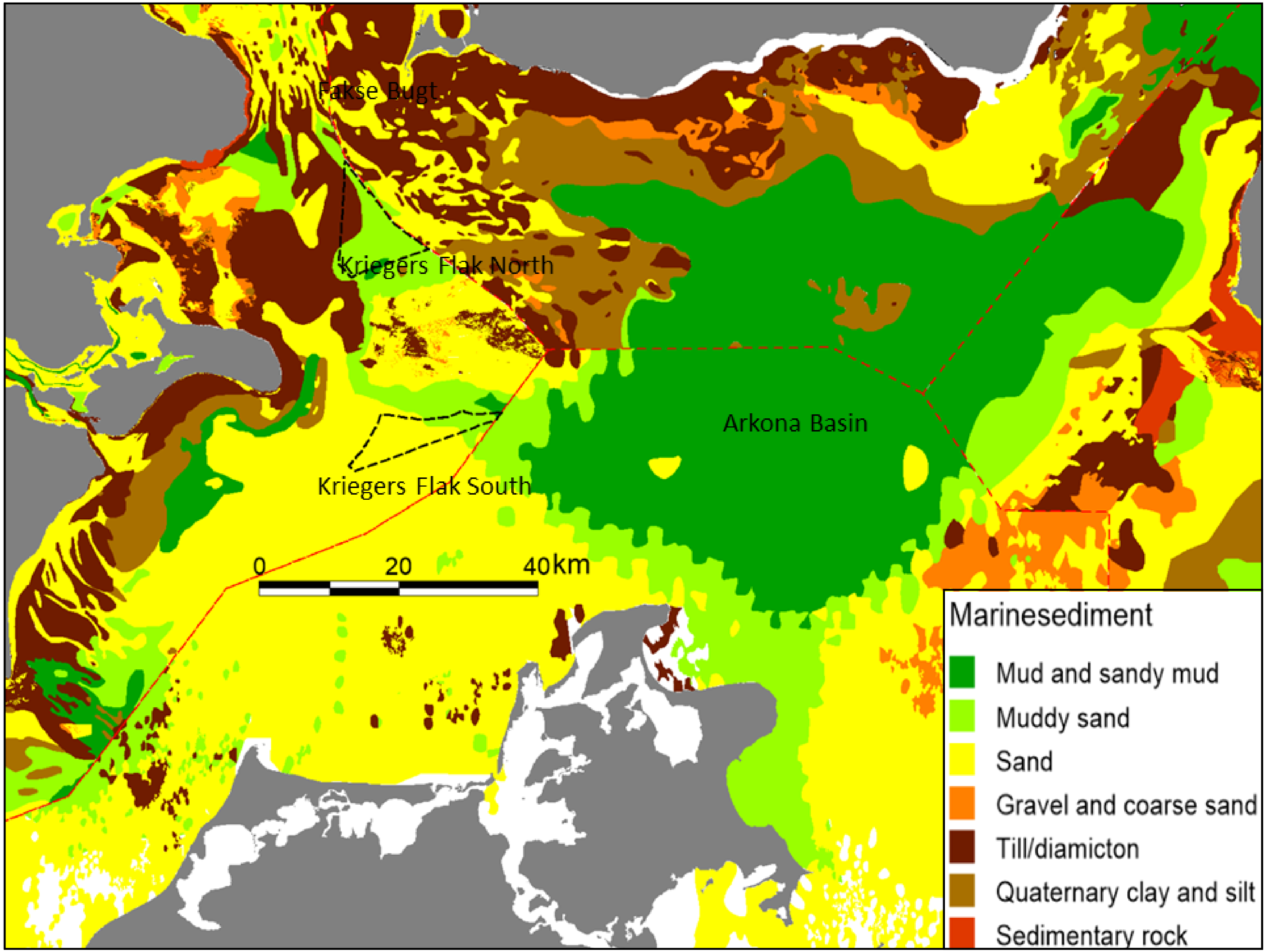
Velenturf, A.P.M., Emery, A.R., Hodgson, D.M., Barlow, N.L.M., Mohtaj Khorasani, A.M., Van Alstine, J., Peterson, E.L., Piazolo, S. & Thorp, M. 2021. Geoscience Solutions for Sustainable Offshore Wind Development. Earth Science, Systems and Society. The Geological Society of London. 2 November 2021. Volume 1. Article 10042.

Zilléen, L., Conley, D. J., Andrén, E., Andrén, T. & Björck, S. 2008: Past occurrences of hypoxia in the Baltic Sea and the role of climate variability, environmental change, and human impact. Earth- Science Reviews 91, 77–92.

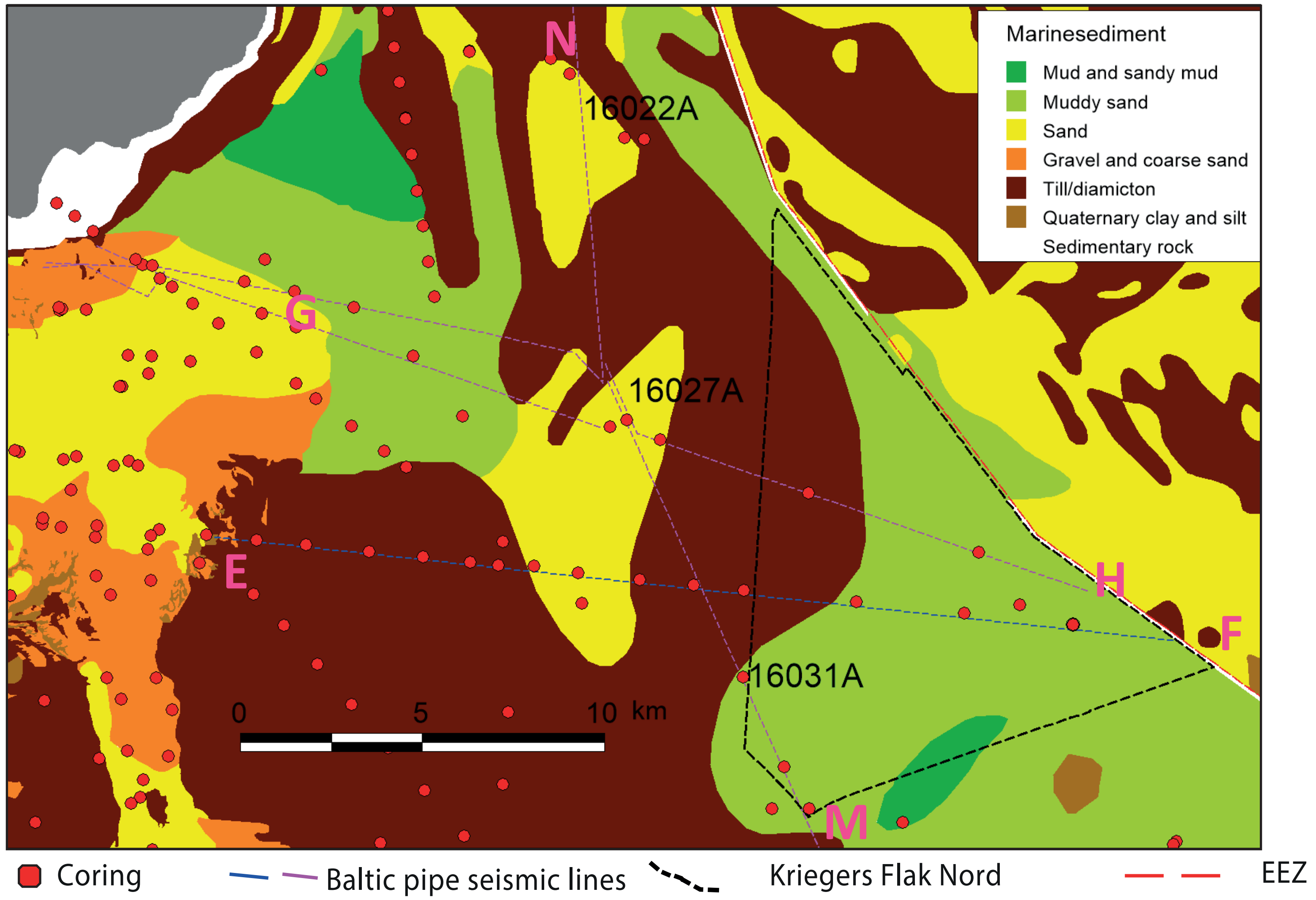
Appendix A: Bathymetry and location of Kriegers Flak 2 North and South POWF

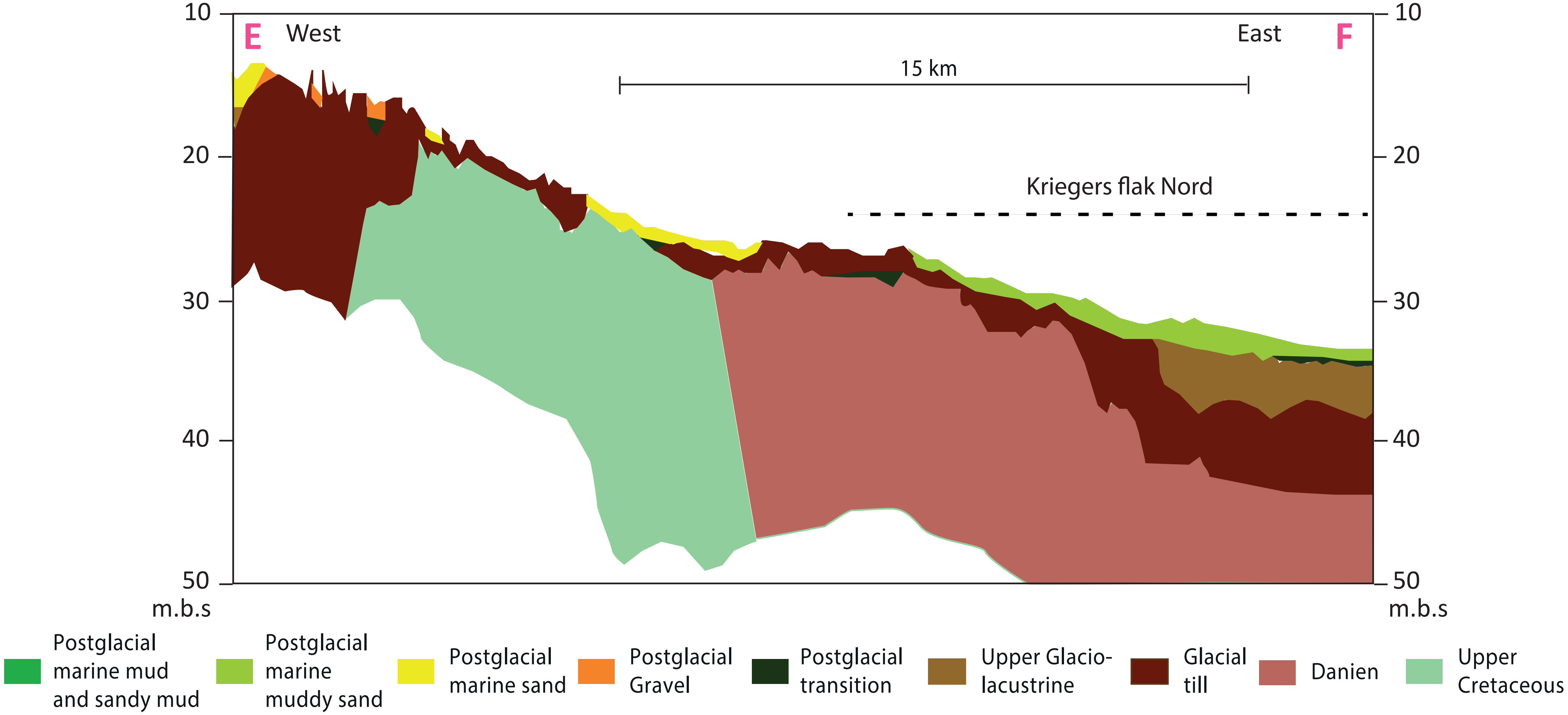


Appendix B: Seabed sediments and location of Kriegers Flak 2 North and South POWF

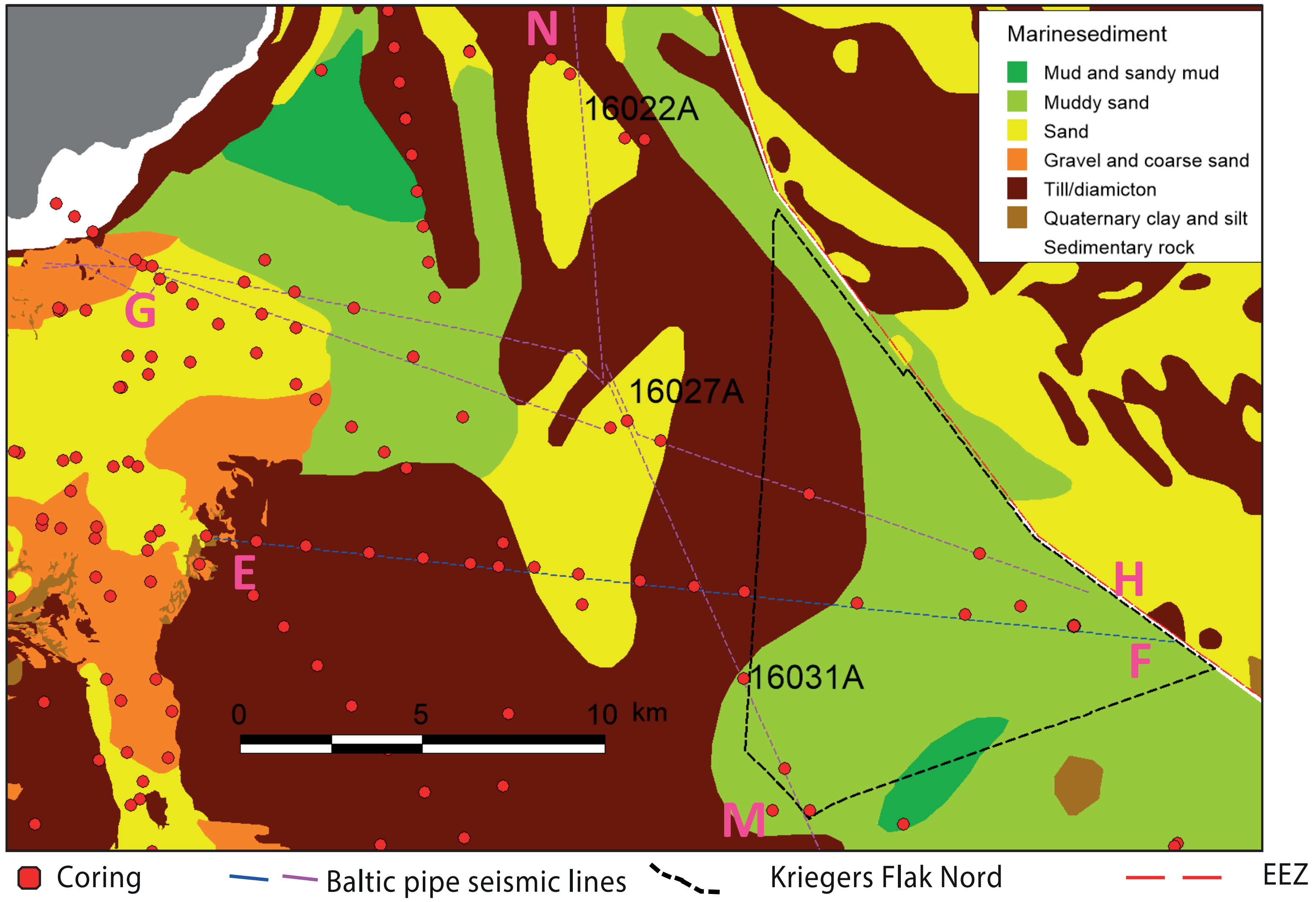


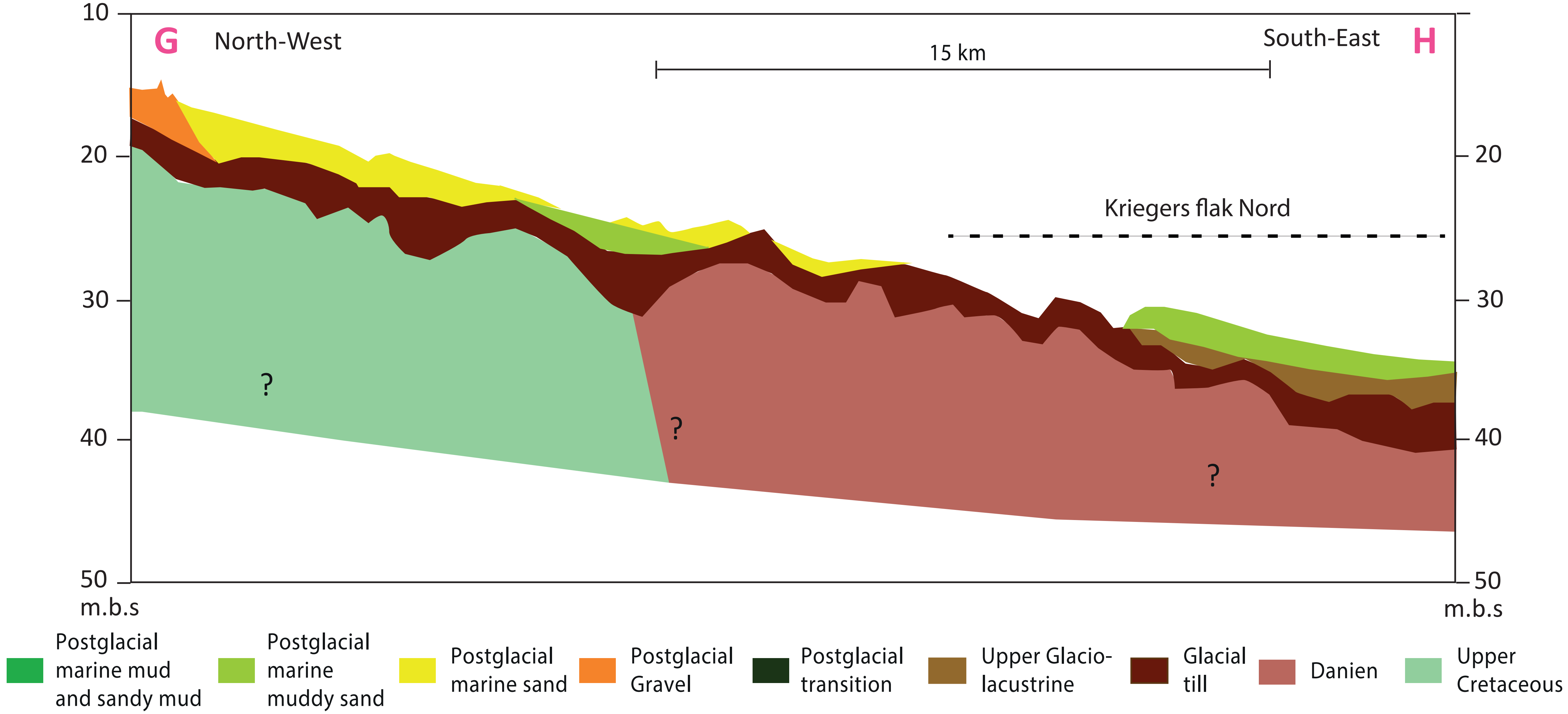
Appendix C: Profile E - F



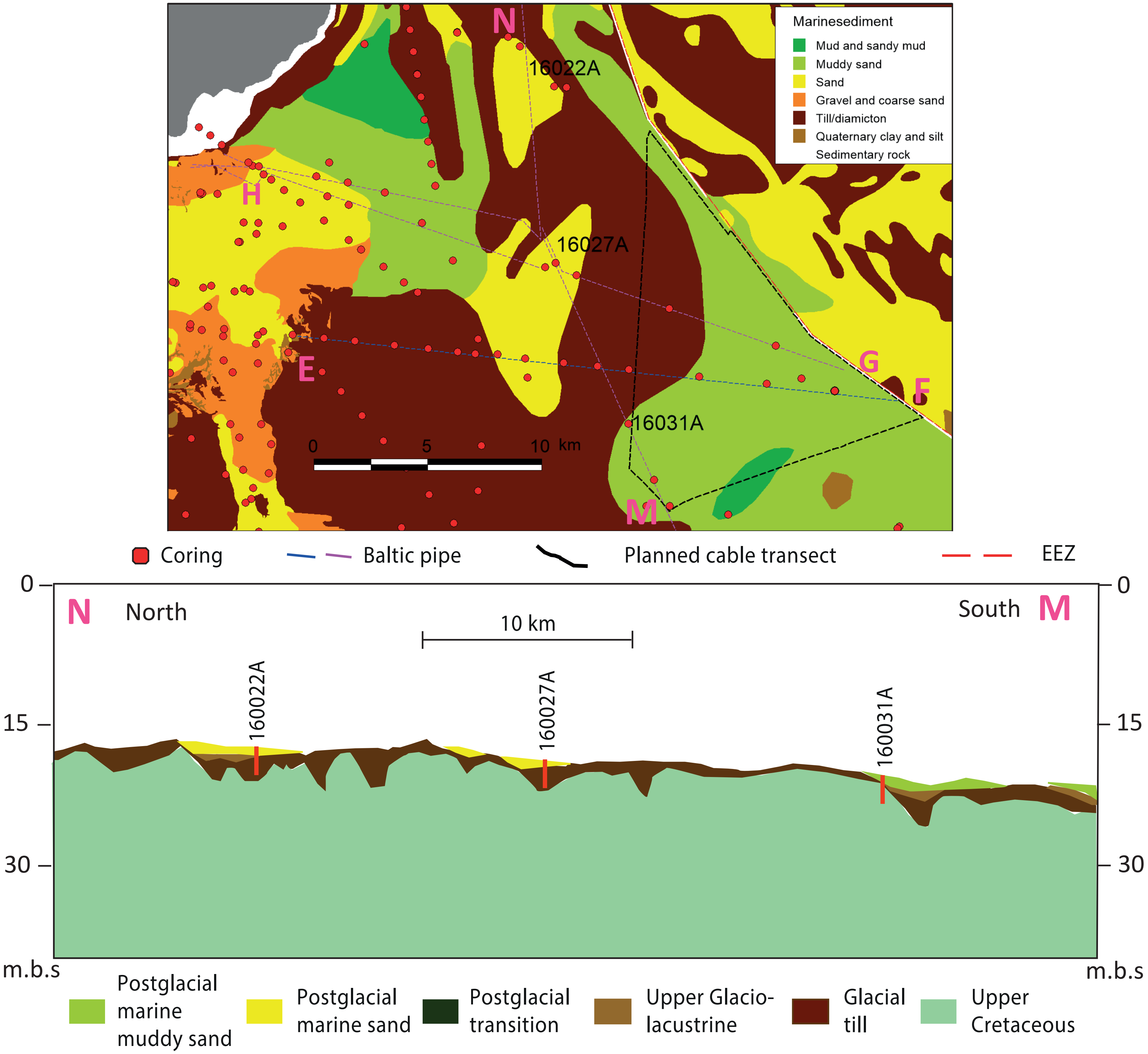


Appendix D: Profile G . H

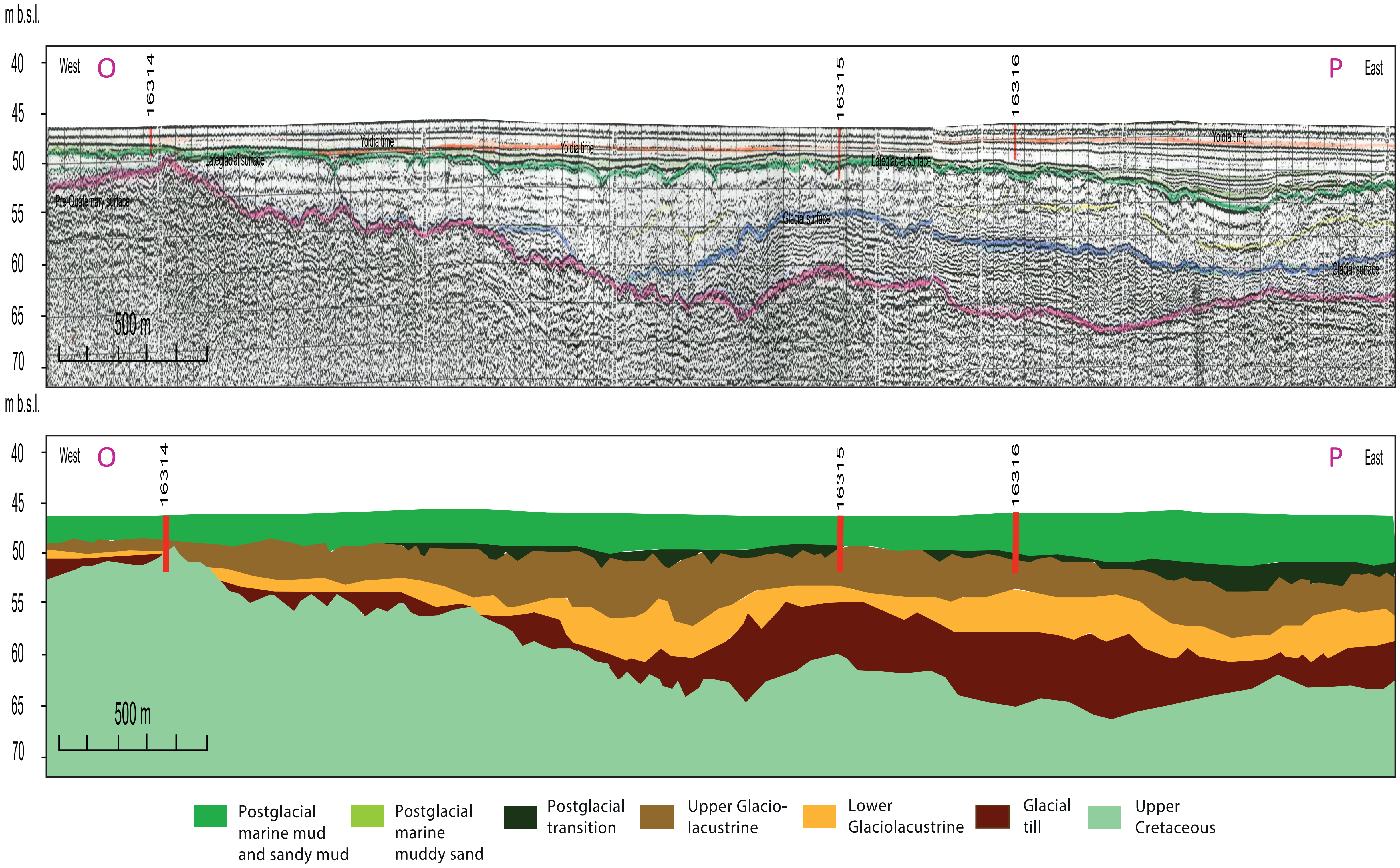




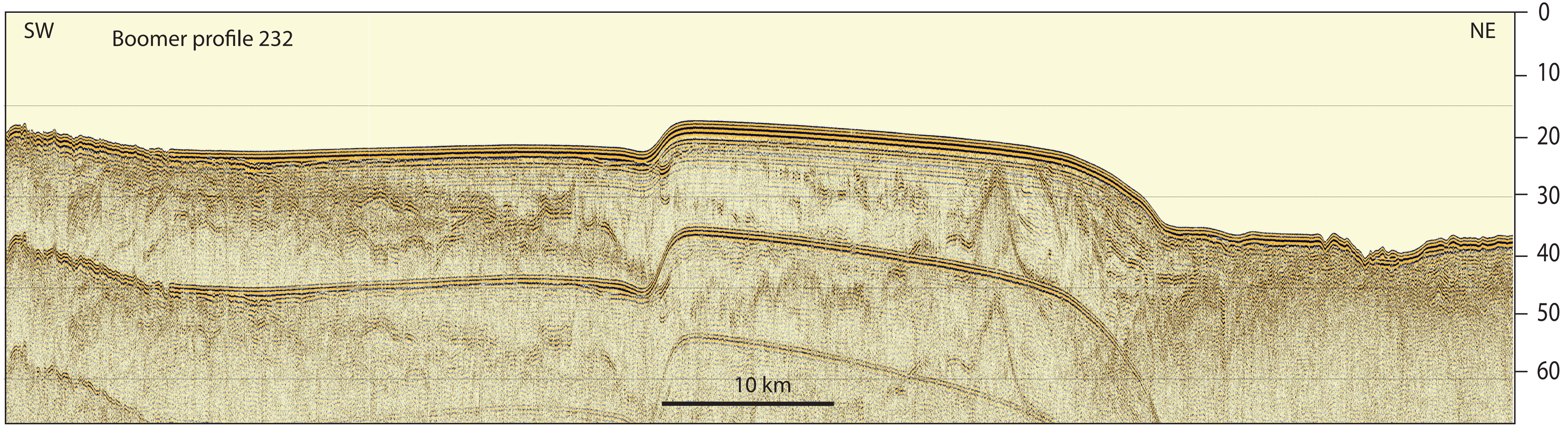
Appendix E: Profile N - M

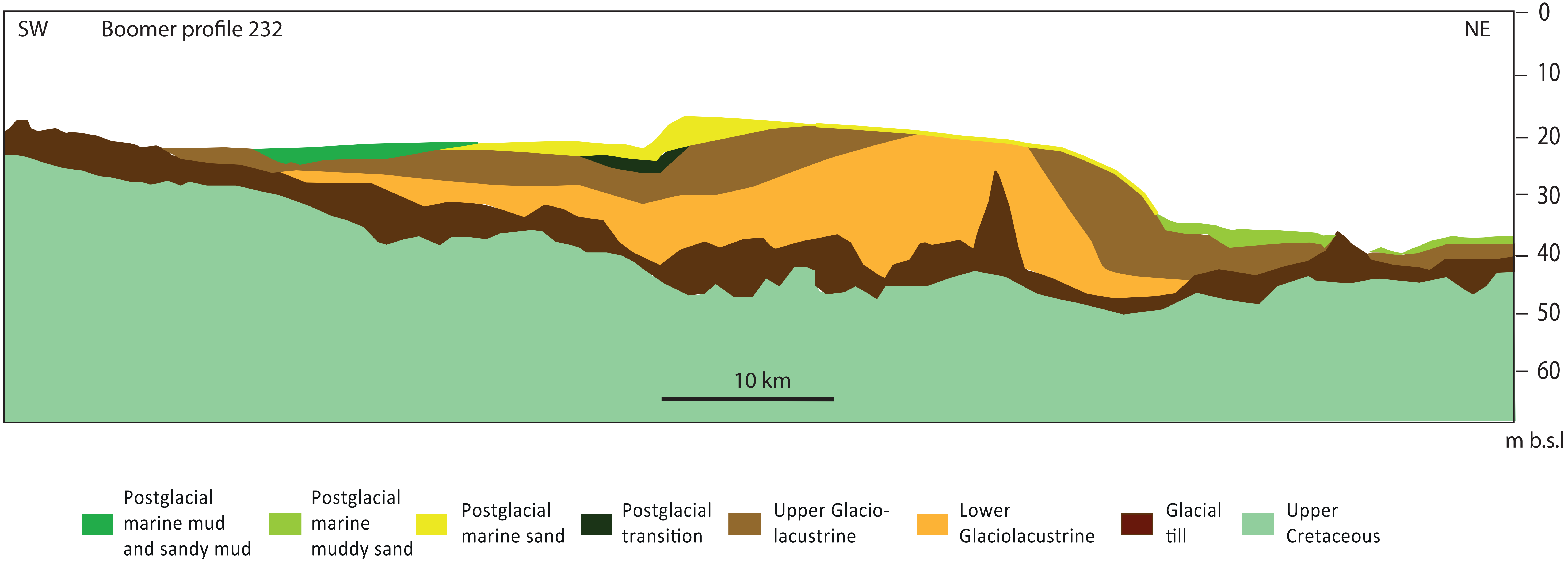


Appendix F: Kriegers Flak 2 South Profile O - P

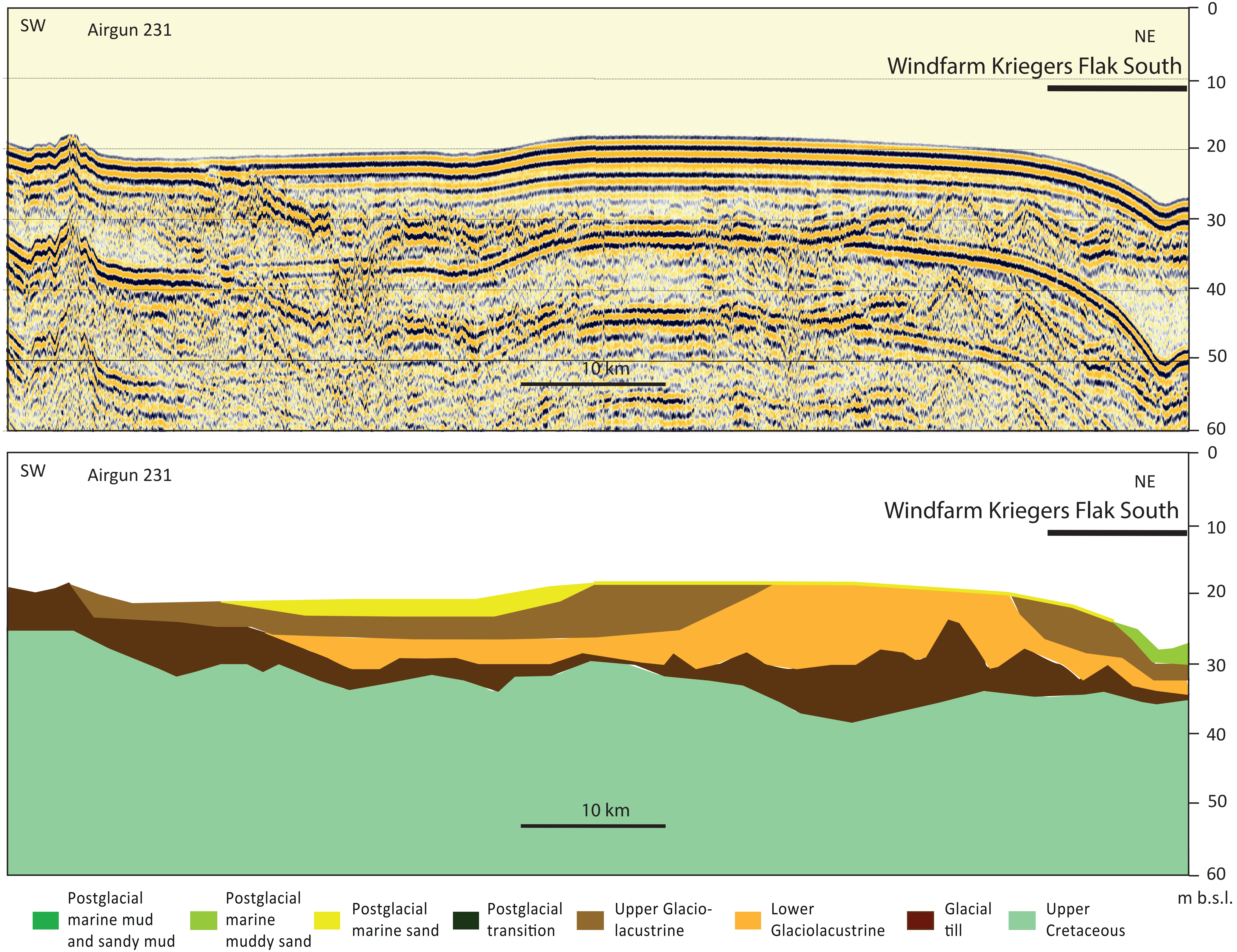


Appendix G: Kriegers Flak 2 South Profile 232

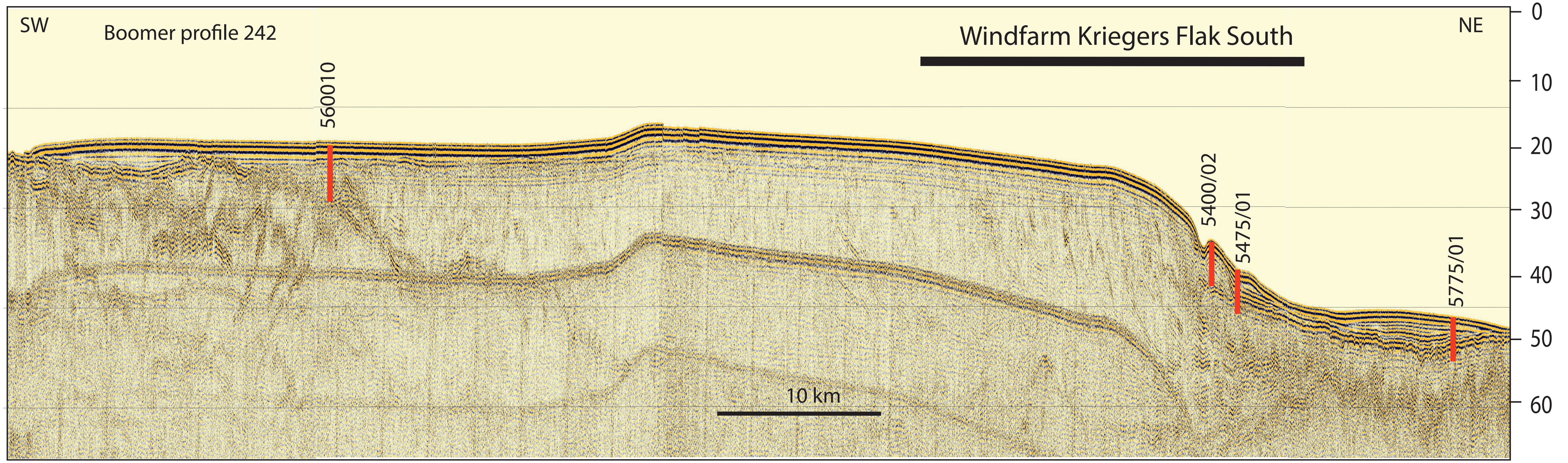


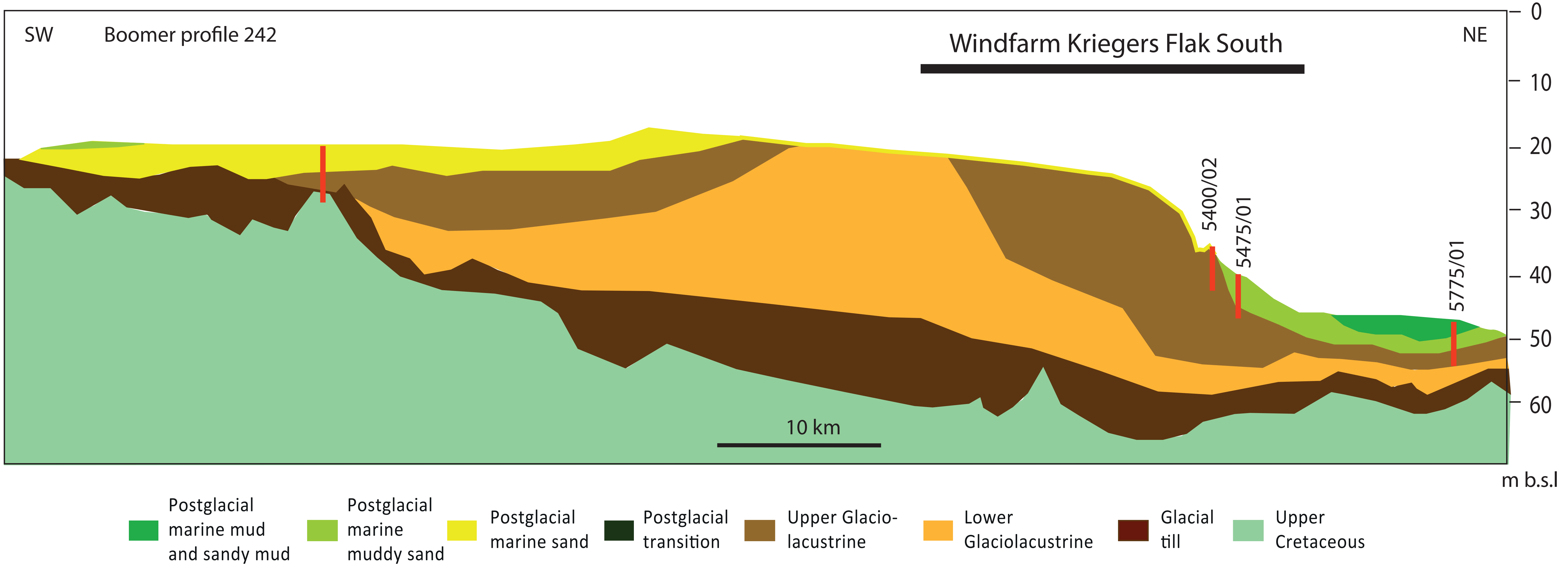


Appendix H: Kriegers Flak 2 South Profile 231

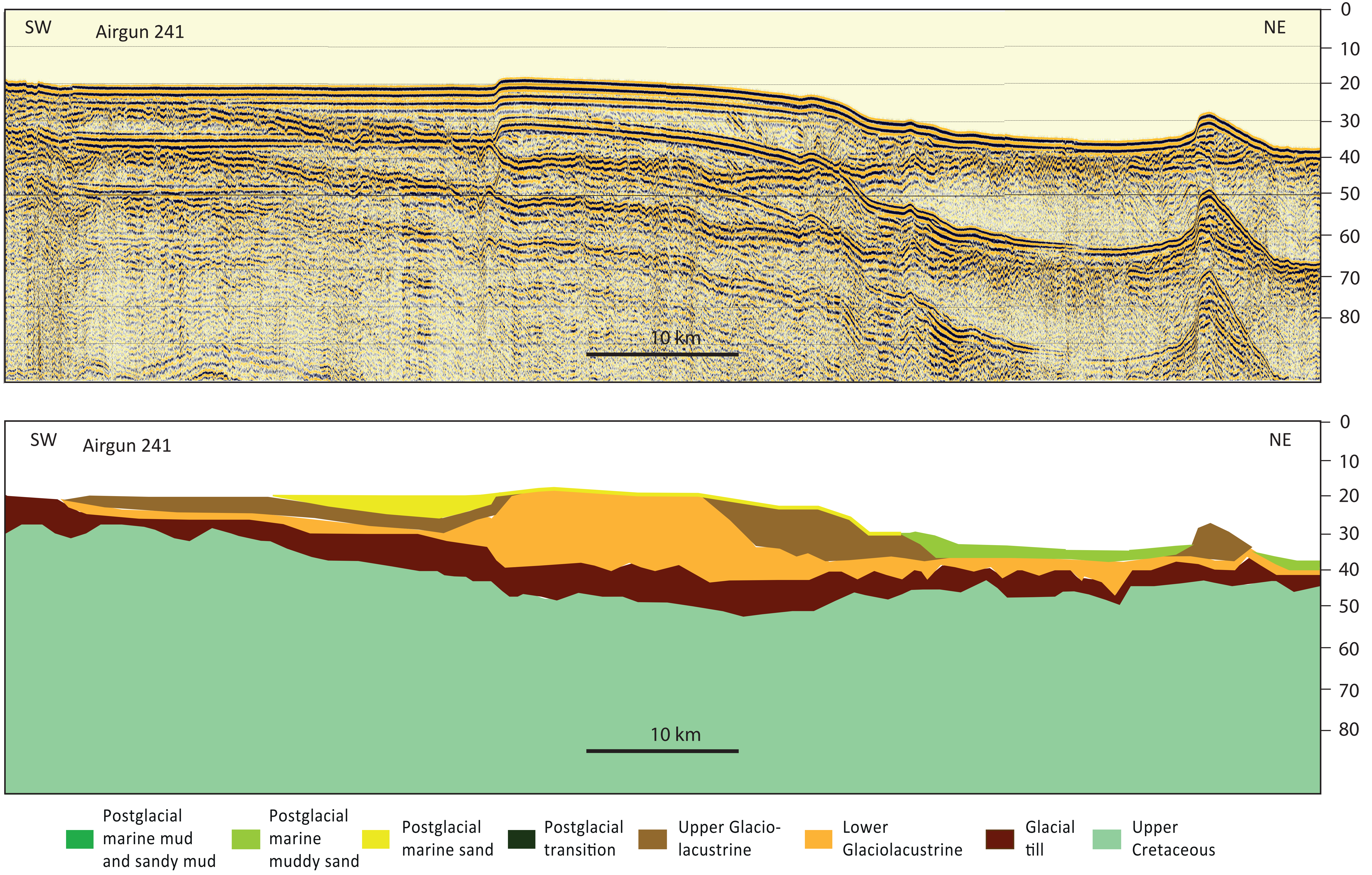


Appendix I: Kriegers Flak 2 South Profile 242

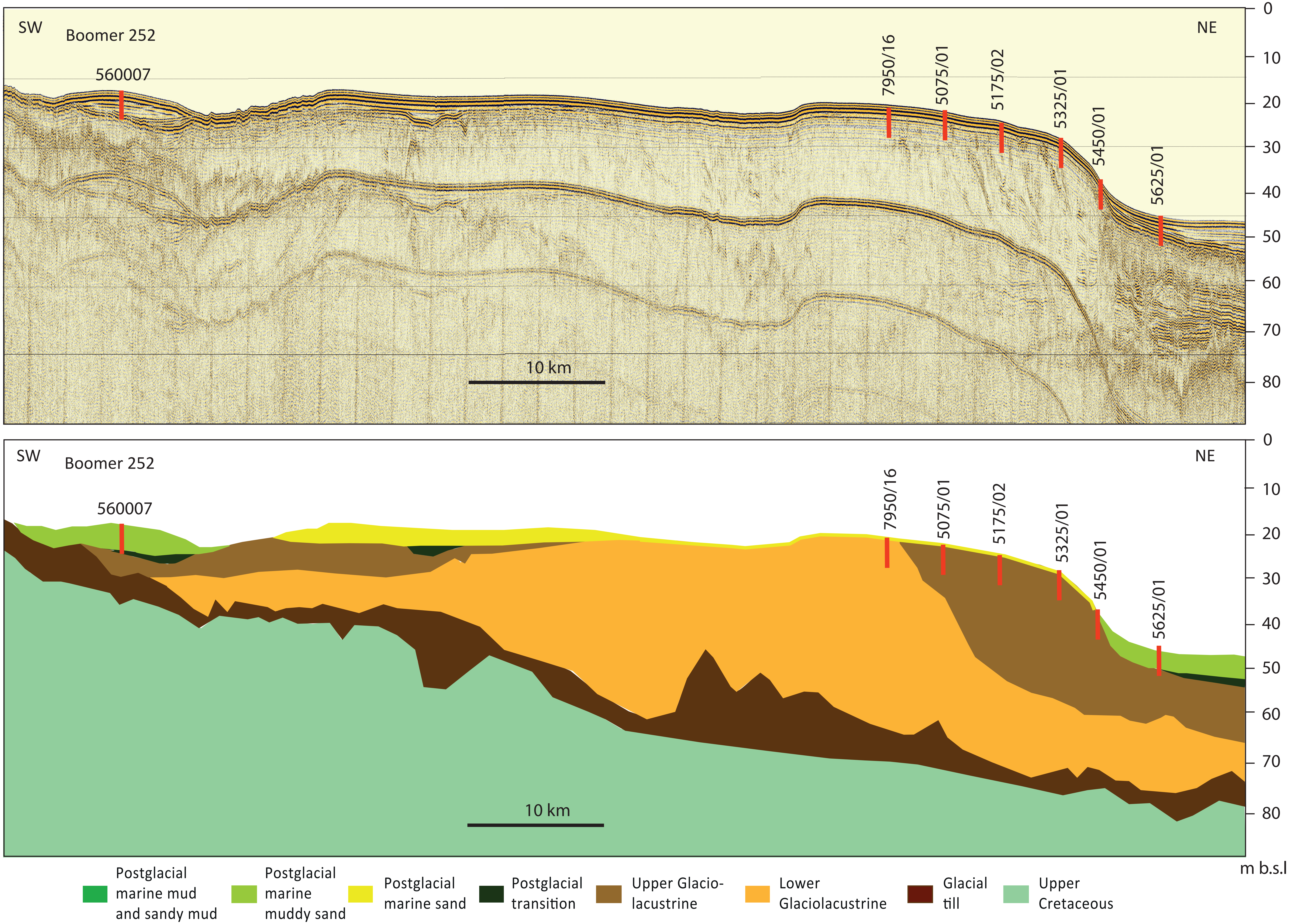




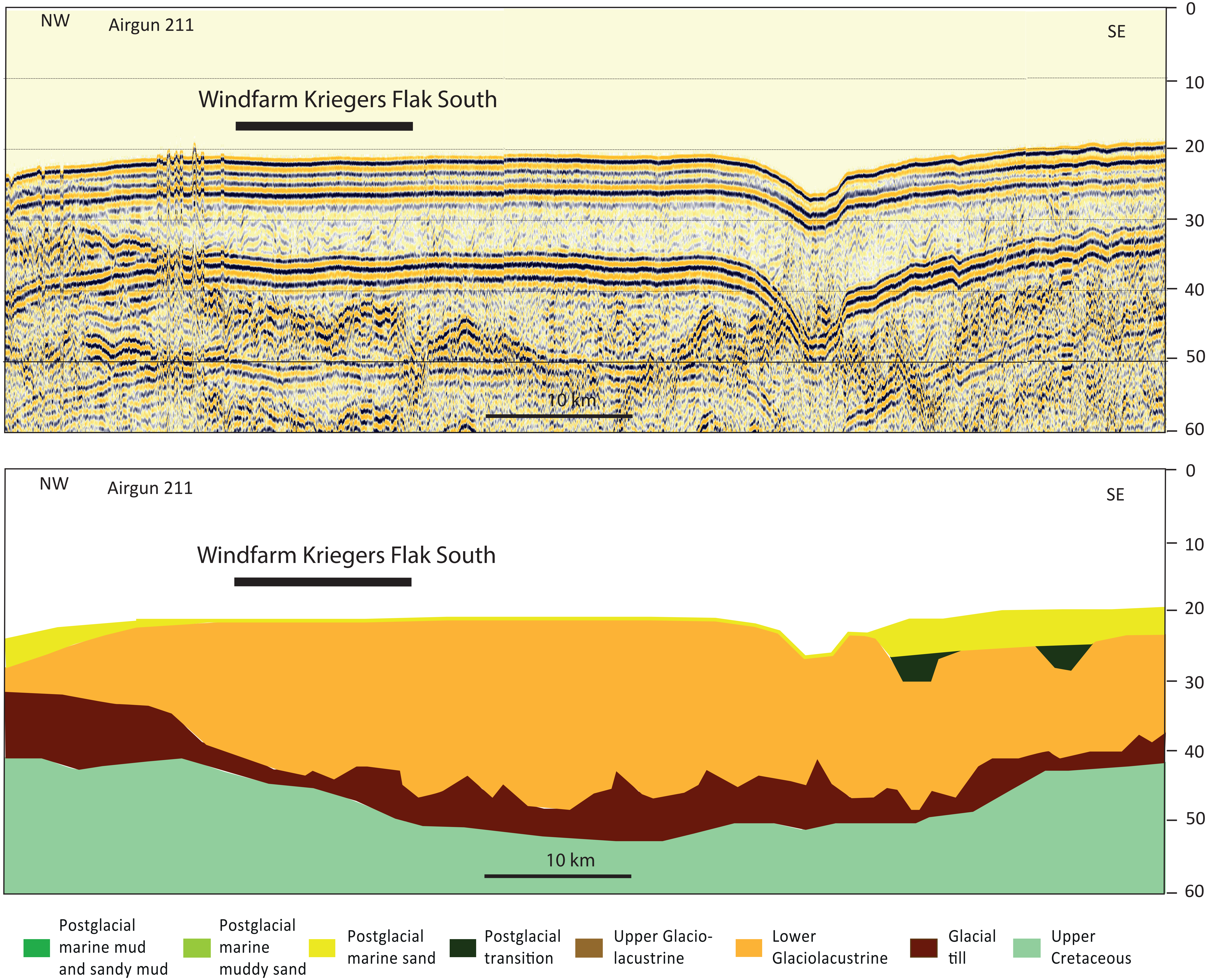
Appendix J: Kriegers Flak 2 South Profile 241



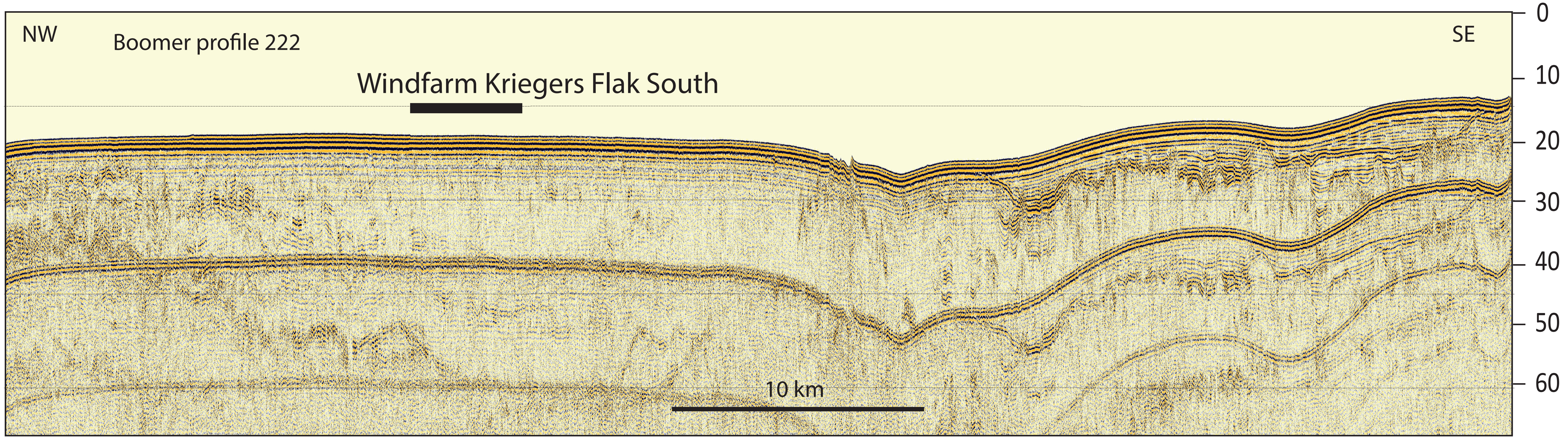
Appendix K: Kriegers Flak 2 South Profile 252

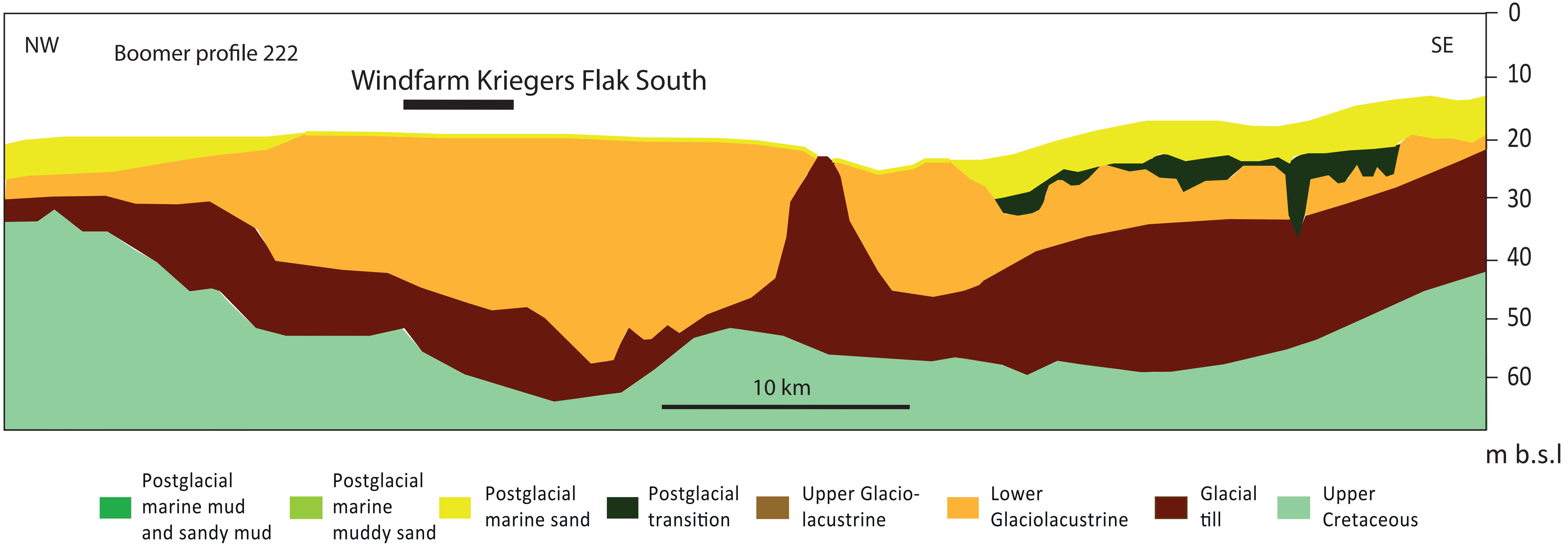


Appendix L: Kriegers Flak 2 South Profile 211



Appendix M: Kriegers Flak 2 South Profile 222





Appendix N: Existing Kriegers Flak Boreholes KF-B002, KF-BH004, KF-BH011 and KF-BH015.

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

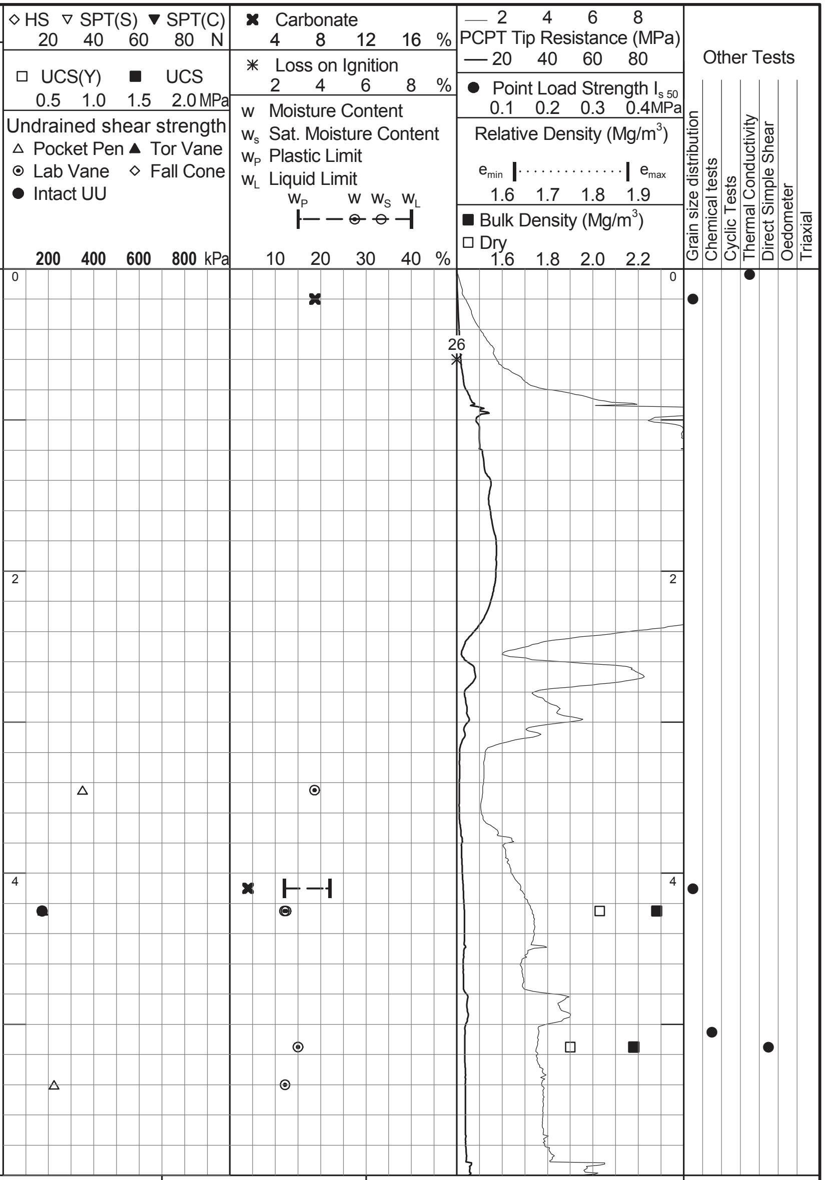
Seabed Level (m): -21.8

Notes:

Drill tool: Dry rotary drilling

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
1-LB 2-B	2.1D	0.00-1.50
	1.1D	0.20
	1.2D	
	1.3D	
	1.4D	
	1.5D	0.60
	1.6D	
3-LB 4-B		
	4.1D	2.50
5-TW		
	5.2D	3.10
	5.3D	3.20-3.35
	5.4D	
	5.5D	
	5.1U	
6-TW		
	6.1D	4.10
	6.2D	4.25-4.50
	6.3D	
	6.4D	
	6.5U	
7-TW		
	7.1D	5.05
	7.2U	5.15-5.40

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age
1.5	-23.3	*SAND, medium, non graded, gravelly, w. shell fragments, light yellowish brown* 0.15 becoming grey, w. plant remains 0.20 angularity: subrounded 0.60 w. 50 mm black peat layer	Ma	Pg
2.3	-24.1	*SAND, medium - coarse, non graded, gravelly, sl. calcareous, w. plant remains, grey*	Ma	Pg
2.6	-24.4	*CLAY, very silty, sl. gravelly, calcareous, grey*	Mw	Lg
3.0	-24.8	*SAND, fine - medium, graded, sl. gravelly, calcareous, w. clay lumps, grey*	Mw	Lg
3.6	-25.4	*CLAY, very silty, sl. sandy, calcareous, grey*	Mw	Lg
3.8	-25.6	*SAND, fine - medium, poorly graded, sl. gravelly, calcareous, w. few clay lumps, brownish grey*	Mw	Lg
		CLAY TILL, sandy, gravelly, sl. calcareous, brownish grey 3.75 - 3.95 silty 3.95 - 5.40 w. limestone grains 4.85 - 4.95 w. silty parts	Gl	Gc



Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	1 / 12

W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:17

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

G e o l o g y

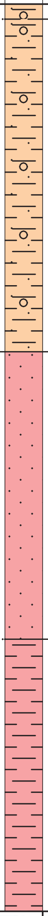
Drill tool: Dry rotary drilling (continued); Geobor-S

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
8-TW	8.1D	6.10
	8.2U	6.25-6.55
9-TW		
10-TW	10.1D	7.70
11-B		
12-LB	11.1D	8.50
	12.1D	8.90
	12.2D	
	12.3D	
	12.4D	9.20
	12.5D	
	12.6D	9.40
	12.7D	
13-B		
14-C		
15-TW	15.1D	11.75
	15.2D	

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age
6.1	-27.9	*CLAY TILL, silty, sandy, gravelly, calcareous, brownish grey* 6.10 w. 35x60 mm granite gravel	Gl	Gc
8.3	-30.1	*SAND, medium, non graded, sl. gravelly, calcareous, grey*	Mw	Gc
10.2	-32.0	*CLAY, silty, sl. sandy, sl. calcareous, dark grey* 11.75 - 12.00 w. iron sulphides	Mw	Gc
12.0	-33.8			

Core Runs and Core Quality: TCR (%) 67; 60 — SCR (%) — RQD (%)

Fissures 1 ----- 5 — Induration 1 ----- 5

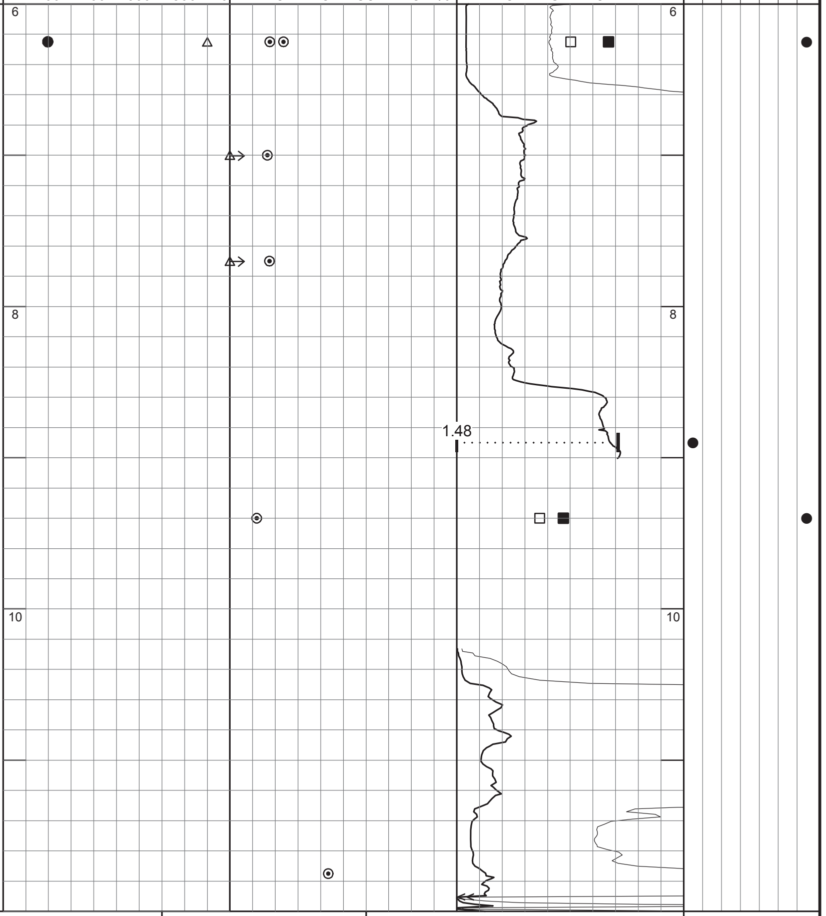


◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N
☐ UCS(Y) 0.5 1.0 1.5 2.0 MPa ■ UCS
Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %
✳ Loss on Ignition 2 4 6 8 %
w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
10 20 30 40 %

— 2 4 6 8 PCPT Tip Resistance (MPa)
— 20 40 60 80
● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4 MPa
Relative Density (Mg/m³) e_{min} e_{max} 1.6 1.7 1.8 1.9
■ Bulk Density (Mg/m³)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:17

GEO WWW.GEO.DK

Borehole Log: KF-BH002

Project: 36642 Kriegers Flak

Remarks:

Drilled:	TBH/KHH	Date:	2013-06-01	Report No.:	1
Prepared:	LTR/LFJ	Date:	2013-06-03	Encl No.:	
Checked:	JSP	Date:	2013-06-03	Rev :	
Approved:	LAR	Date:	2013-08-08	Page:	2 / 12

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

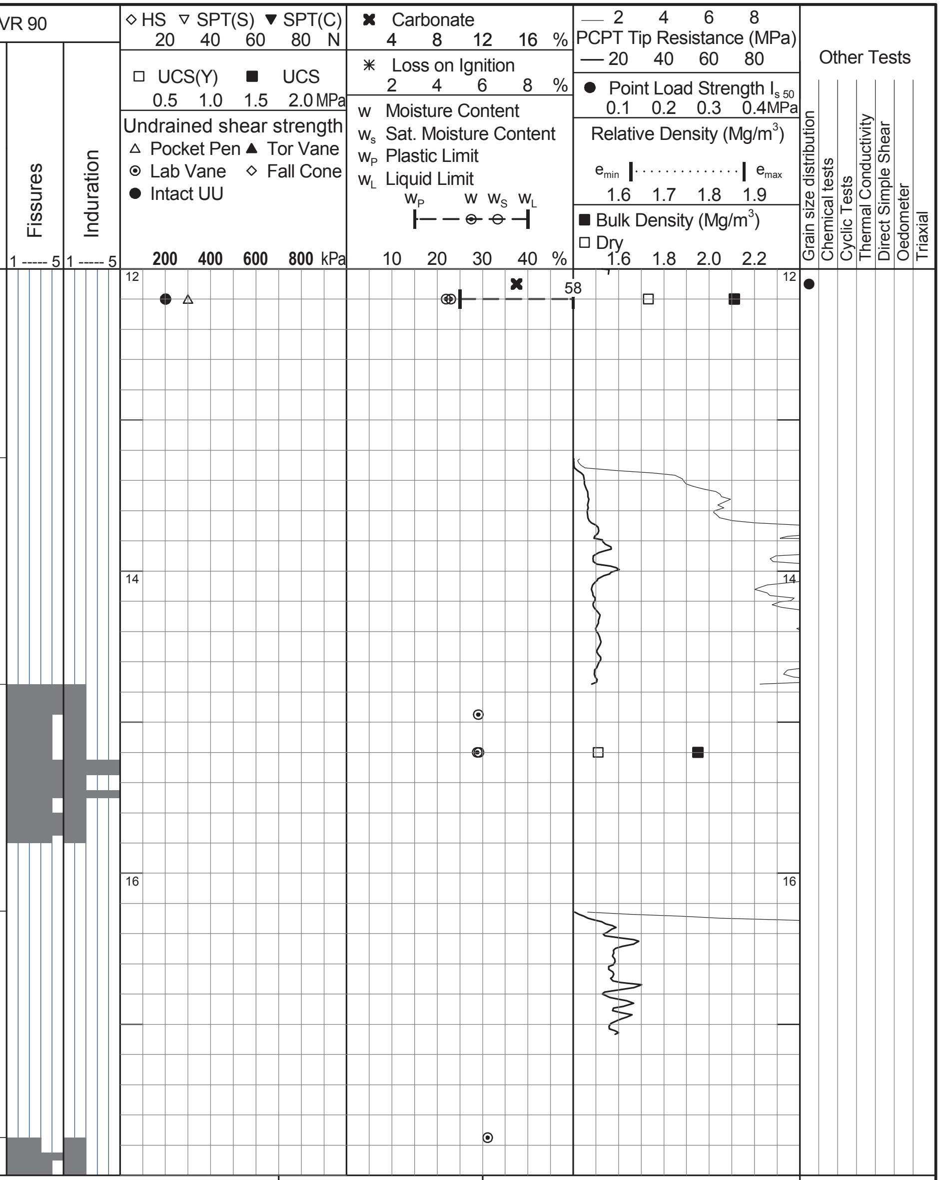
Notes:

Drill tool: Geobor-S (continued)

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
16-C	15.3D 15.4D 15.5D 15.6D 15.7U 16.1D	12.10 12.20-12.40 12.60
17-C		
18-TW 19-C	19.1D	15.20
20-C		
21-C		

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age
		11.90 - 12.00 w. many sand streaks	Mw	Gc
13.3	-35.1	*CLAY, high plasticity, silty, sl. calcareous, w. silt and fine sand laminae, w. few gravels, dark olive brown* 12.35 - 12.50 w. many 10 mm sand layers 12.65 w. diagonal fracture 12.70 w. 40 mm sand layer 12.90 w. diagonal fracture 12.95 w. diagonal fracture 13.00 becoming very silty 13.05 w. 20 mm silt laminae		
14.0	-35.8	*CLAY TILL, sandy, gravelly, calcareous, olive brown*	Gl	Gc
		LIMESTONE, muddy, white	Ma	Ct

Core Runs and Core Quality TCR (%)	SCR (%)	RQD (%)
50		
70		0
83		
83		10



Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 3 / 12

GEO
W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:17

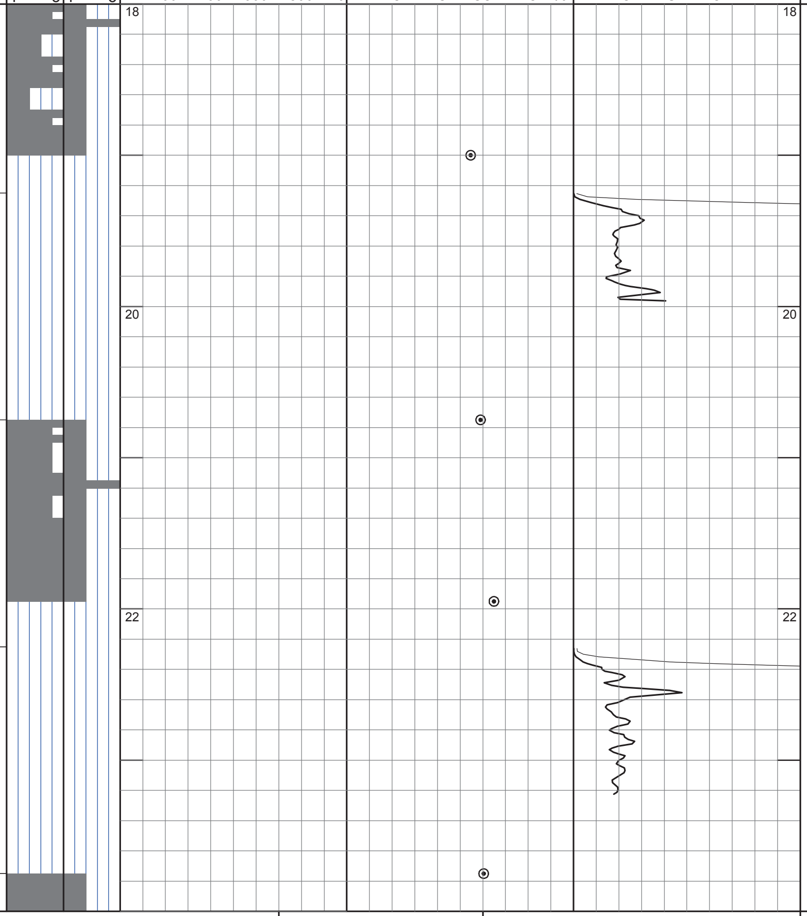
Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		18					*LIMESTONE, muddy, white (continued)* 18.20 - 18.30 w. many light grey burrows	Ma	Ct			
			21.1D	18.65								
	22-C	19								87		
		20										
	23-C									80		0
		21	23.1D	21.00								
	24-C	22								50		
		23										
	25-TW 26-C									70		20



Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

Core Runs and Core Quality

G e o l o g y

W W W . G E O . D K

Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 4 / 12

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:17

Borehole: KF-BH002

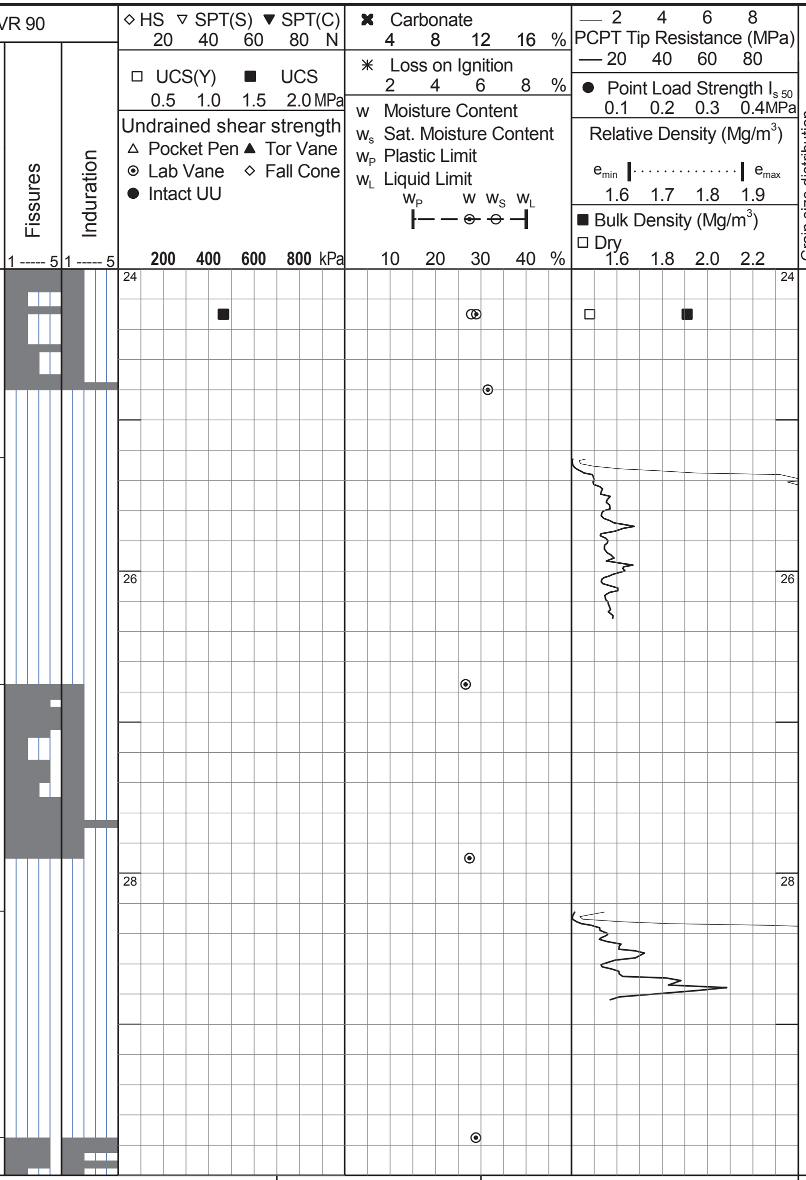
Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

G e o l o g y

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		24					*LIMESTONE, muddy, white (continued)*	Ma	Ct			
			26.1U	24.30-24.45								
							24.55 - 24.65 w. diagonal fracture					
		25										
	27-C									93		
		26										
	28-C									77		10
		27	28.1D	27.10								
		28										
	29-C									20		
		29										
	30-C		30.1D	29.90						47		7



Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

W W W . G E O . D K

Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 5 / 12

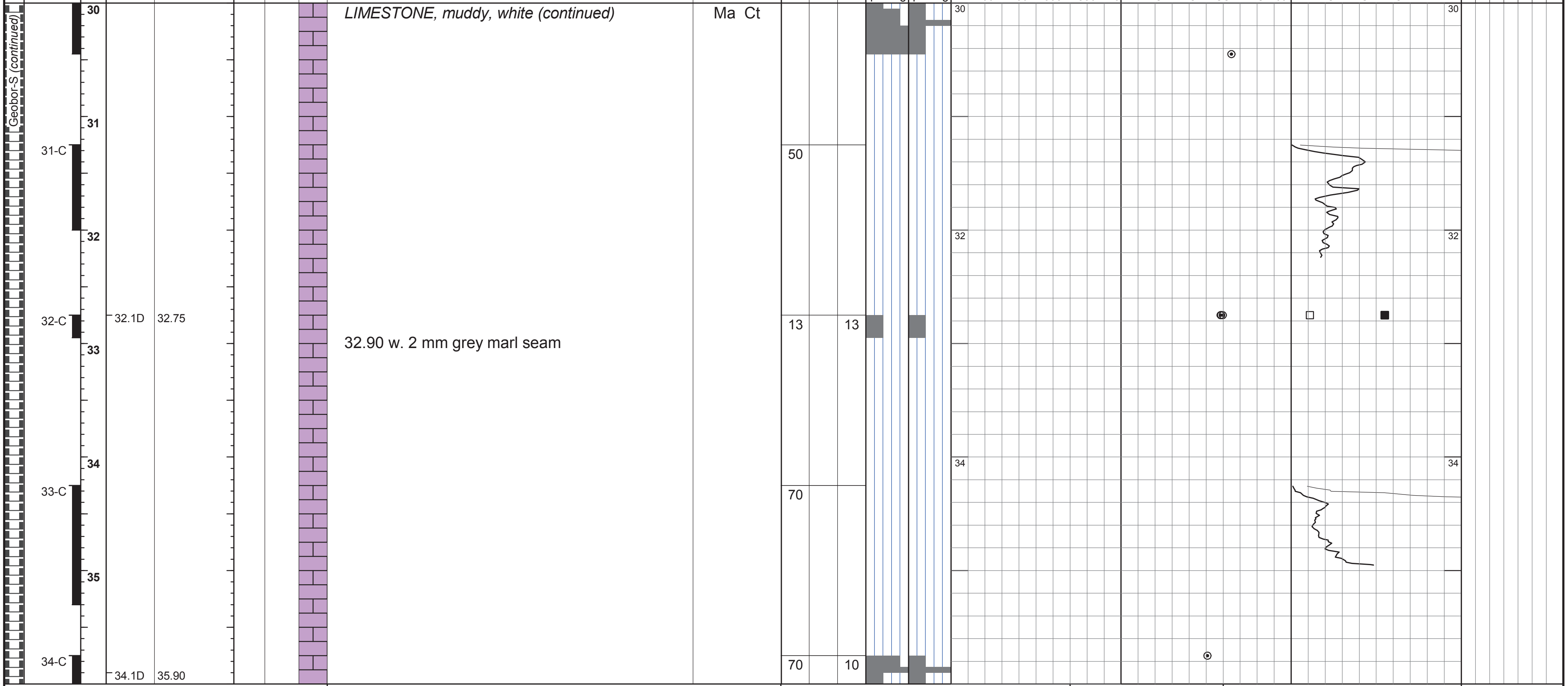
Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Graphic Log	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S (continued)		30						*LIMESTONE, muddy, white (continued)*	Ma	Ct			
		31											
	31-C										50		
		32											
	32-C		32.1D	32.75							13		13
		33						32.90 w. 2 mm grey marl seam					
		34											
	33-C										70		
		35											
	34-C		34.1D	35.90							70		10



Borehole Log: KF-BH002	Drilled:	TBH/KHH	Date:	2013-06-01	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-06-03	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-06-03	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 6 / 12

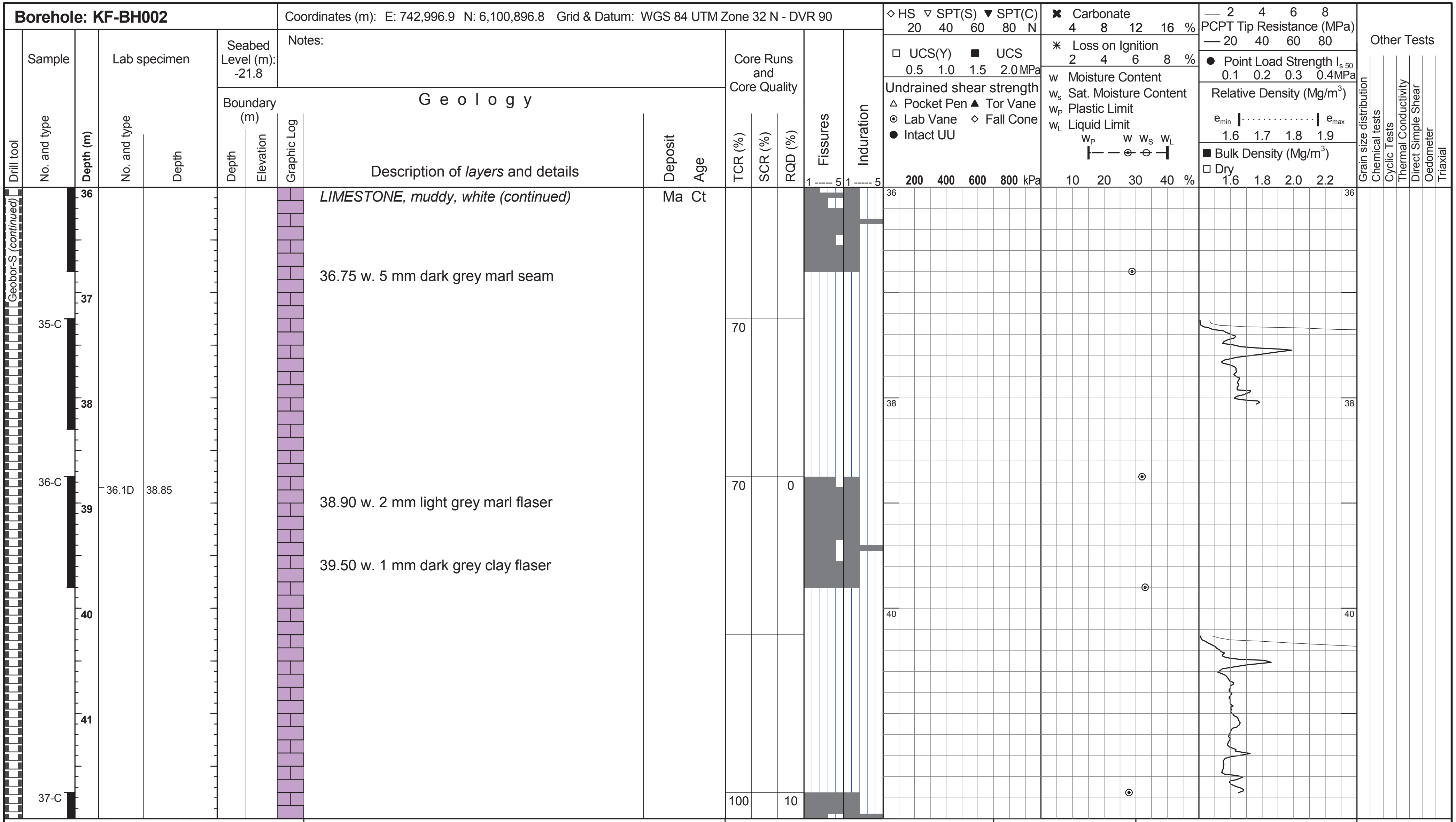
W W W . G E O . D K

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:



LIMESTONE, muddy, white (continued) — Ma Ct

36.75 w. 5 mm dark grey marl seam

38.90 w. 2 mm light grey marl flaser

39.50 w. 1 mm dark grey clay flaser

GEO
W W W . G E O . D K

Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	7 / 12

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:17

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

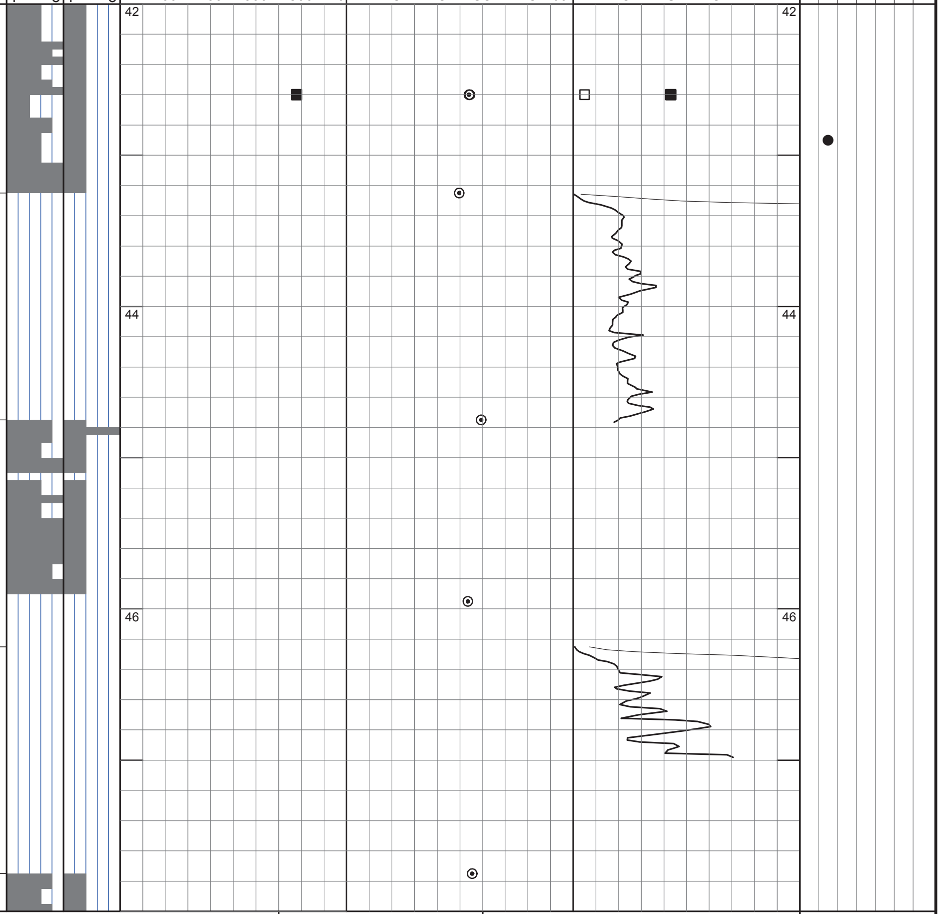
◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N
☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa
Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %
✳ Loss on Ignition 2 4 6 8 %
w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
10 20 30 40 %

PCPT Tip Resistance (MPa) 2 4 6 8 / 20 40 60 80
● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4 MPa
Relative Density (Mg/m³) e_{min} … e_{max} 1.6 1.7 1.8 1.9
■ Bulk Density (Mg/m³)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		42					*LIMESTONE, muddy, white (continued)* 42.15 w. 50x50 mm echinoderm	Ma	Ct			
			37.1U	42.60-42.75								
			37.2D	42.90			42.80 - 42.95 w. many 1-2 mm grey marl flasers					
		43										
	38-C									50		
		44										
	39-C									80		7
			39.1D	44.90								
		45					45.10 w. 1 mm grey marl flaser 45.30 - 45.40 w. vertical fracture					
		46										
	40-C									77		
		47										
	41-C		41.1D	47.85						70		0



Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	8 / 12

W W W . G E O . D K

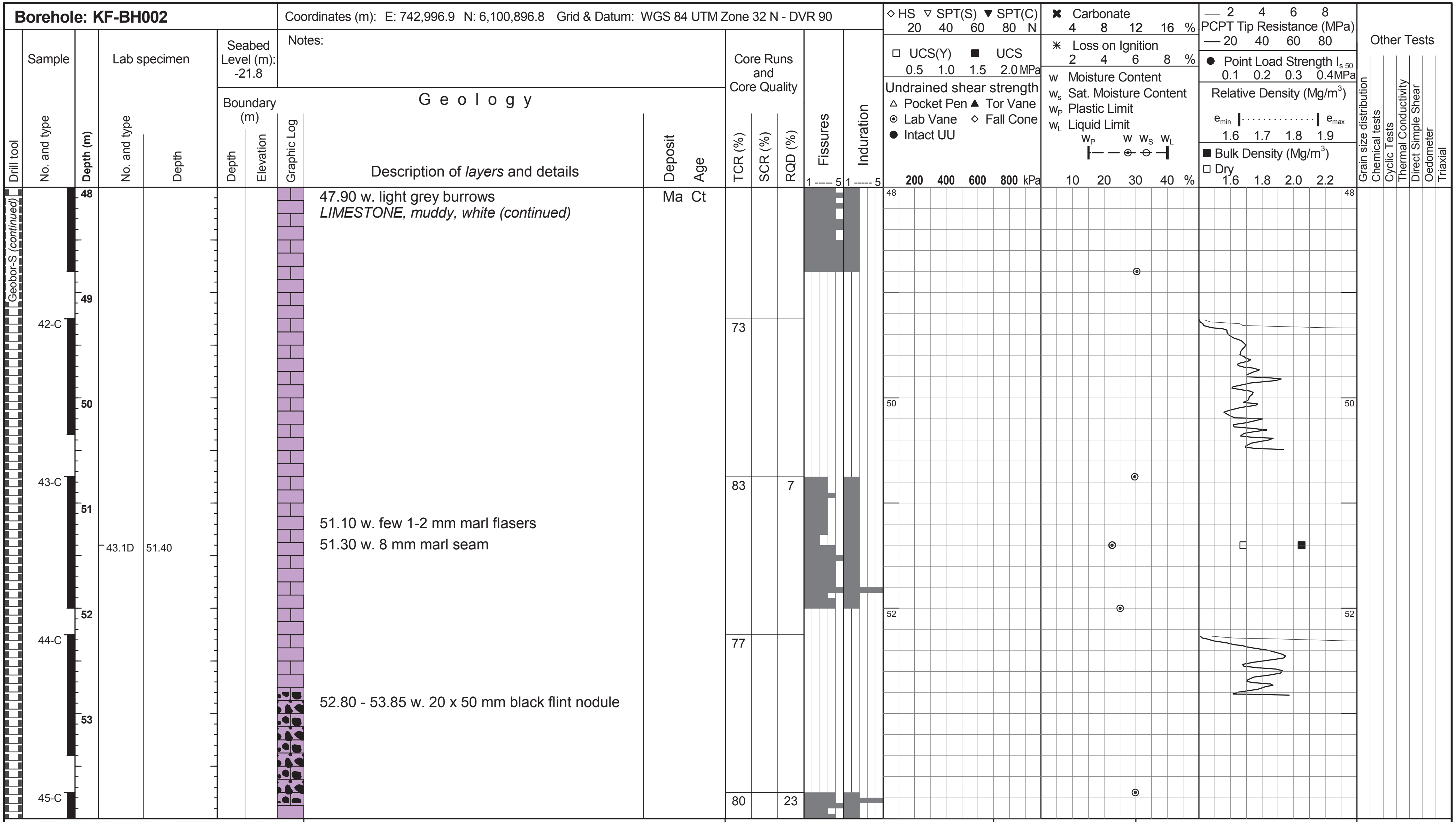
MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:17

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:



47.90 w. light grey burrows
LIMESTONE, muddy, white (continued) — Ma Ct

51.10 w. few 1-2 mm marl flasers

51.30 w. 8 mm marl seam

52.80 - 53.85 w. 20 x 50 mm black flint nodule

GEO
W W W . G E O . D K

Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	9 / 12

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

Drill tool | Sample: No. and type | Depth (m) | Lab specimen: No. and type, Depth | Boundary (m): Depth, Elevation

G e o l o g y: Graphic Log | Description of *layers* and details | Deposit | Age

Core Runs and Core Quality: TCR (%) | SCR (%) | RQD (%)

Fissures 1 ----- 5 | Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

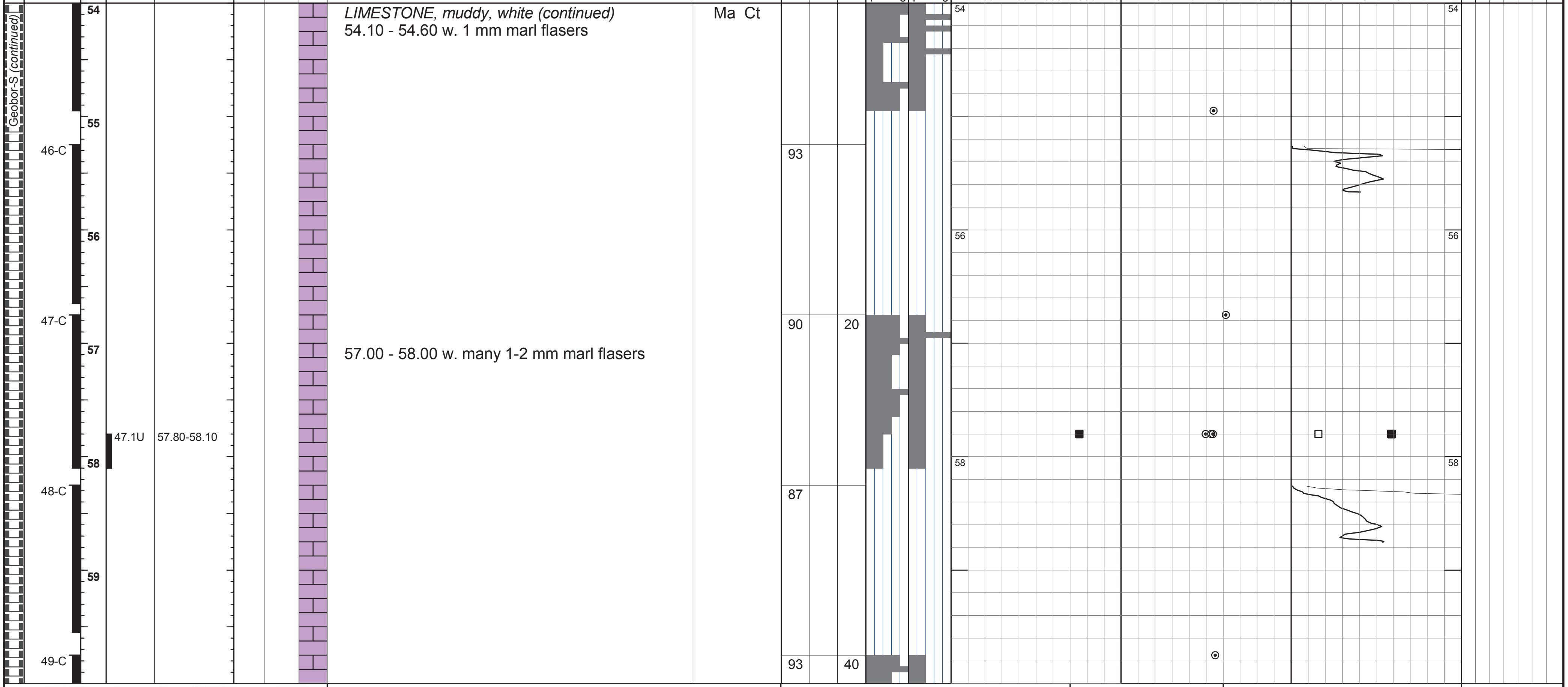
— 2 4 6 8
PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa

Relative Density (Mg/m^3)
e_{min} e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution | Chemical tests | Cyclic Tests | Thermal Conductivity | Direct Simple Shear | Oedometer | Triaxial



LIMESTONE, muddy, white (continued) Ma Ct
54.10 - 54.60 w. 1 mm marl flasers

57.00 - 58.00 w. many 1-2 mm marl flasers

Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :	
	Approved: LAR	Date: 2013-08-08	Page: 10 / 12	

W W W . G E O . D K

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
10 20 30 40 %

PCPT Tip Resistance (MPa) —— 2 4 6 8 / —— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4 MPa

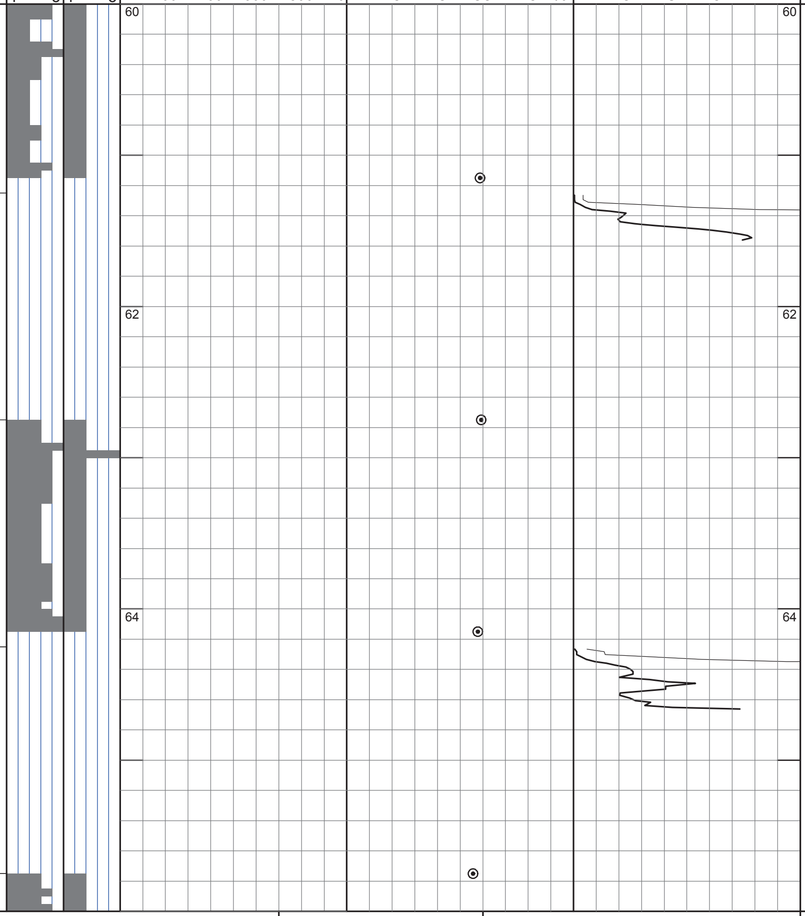
Relative Density (Mg/m^3) e_{min} … e_{max} 1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3) ☐ Dry 1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

Drill tool: Geobor-S (continued)

Depth (m)	Sample No. and type	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
60						*LIMESTONE, muddy, white (continued)*	Ma	Ct			
61		49.1D	61.00								
	50-C								90		
62											
	51-C								93		0
63						63.55 - 63.90 w. few 1 mm marl flasers					
64											
	52-C								80		
65											
	53-C								93		0



Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:
Remarks:	Checked: JSP	Date: 2013-06-03	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 11 / 12

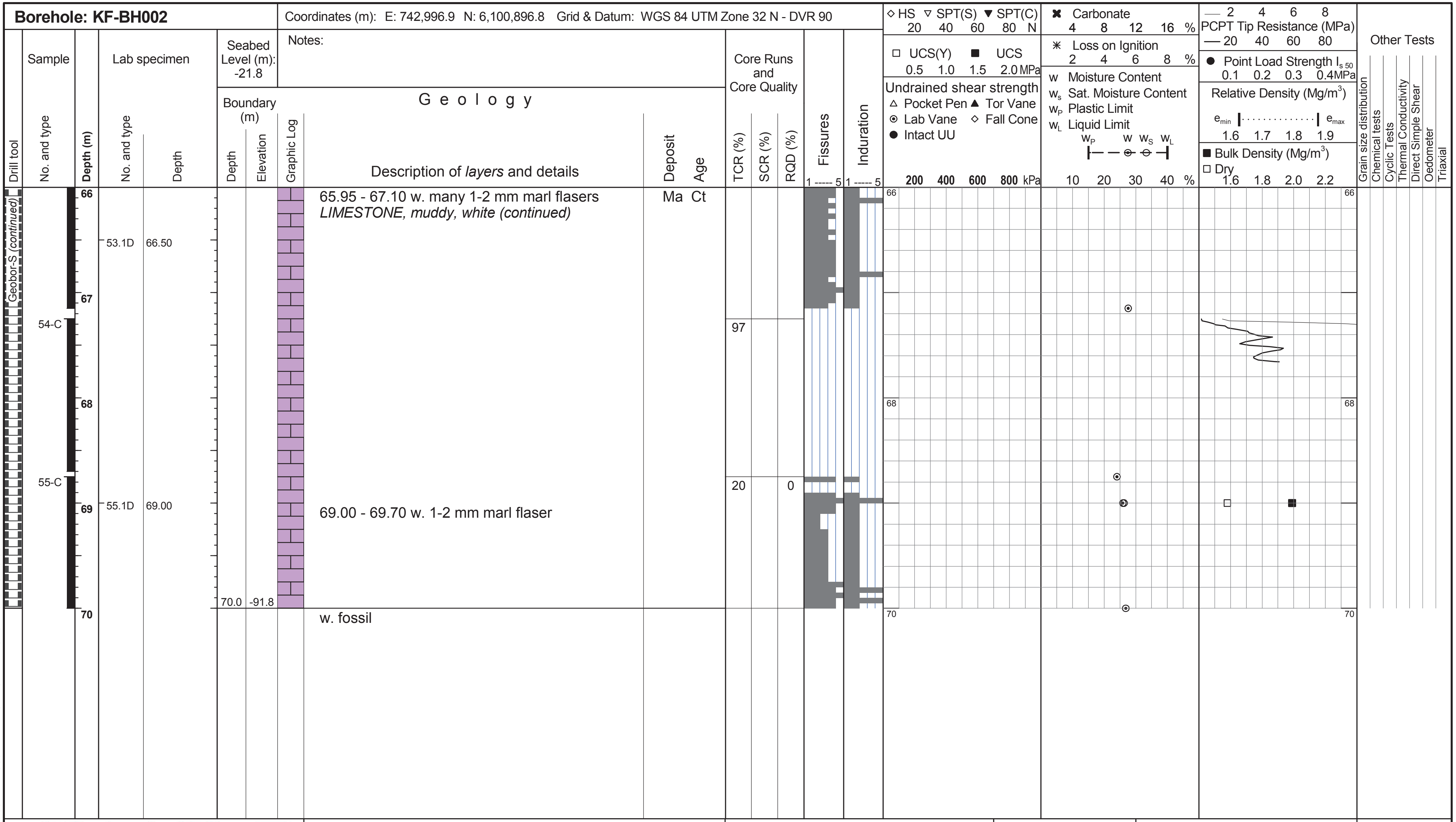
W W W . G E O . D K

Borehole: KF-BH002

Coordinates (m): E: 742,996.9 N: 6,100,896.8 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.8

Notes:



Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
	66					65.95 - 67.10 w. many 1-2 mm marl flasers *LIMESTONE, muddy, white (continued)*	Ma	Ct			
		53.1D	66.50								
	67										
54-C									97		
	68										
55-C									20		0
	69	55.1D	69.00			69.00 - 69.70 w. 1-2 mm marl flaser					
				70.0	-91.8						
	70					w. fossil					

GEO W W W . G E O . D K	Borehole Log: KF-BH002	Drilled: TBH/KHH	Date: 2013-06-01	Report No.: 1	
	Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-06-03	Encl No.:	
	Remarks:	Checked: JSP	Date: 2013-06-03	Rev :	
		Approved: LAR	Date: 2013-08-08	Page: 12 / 12	

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.0

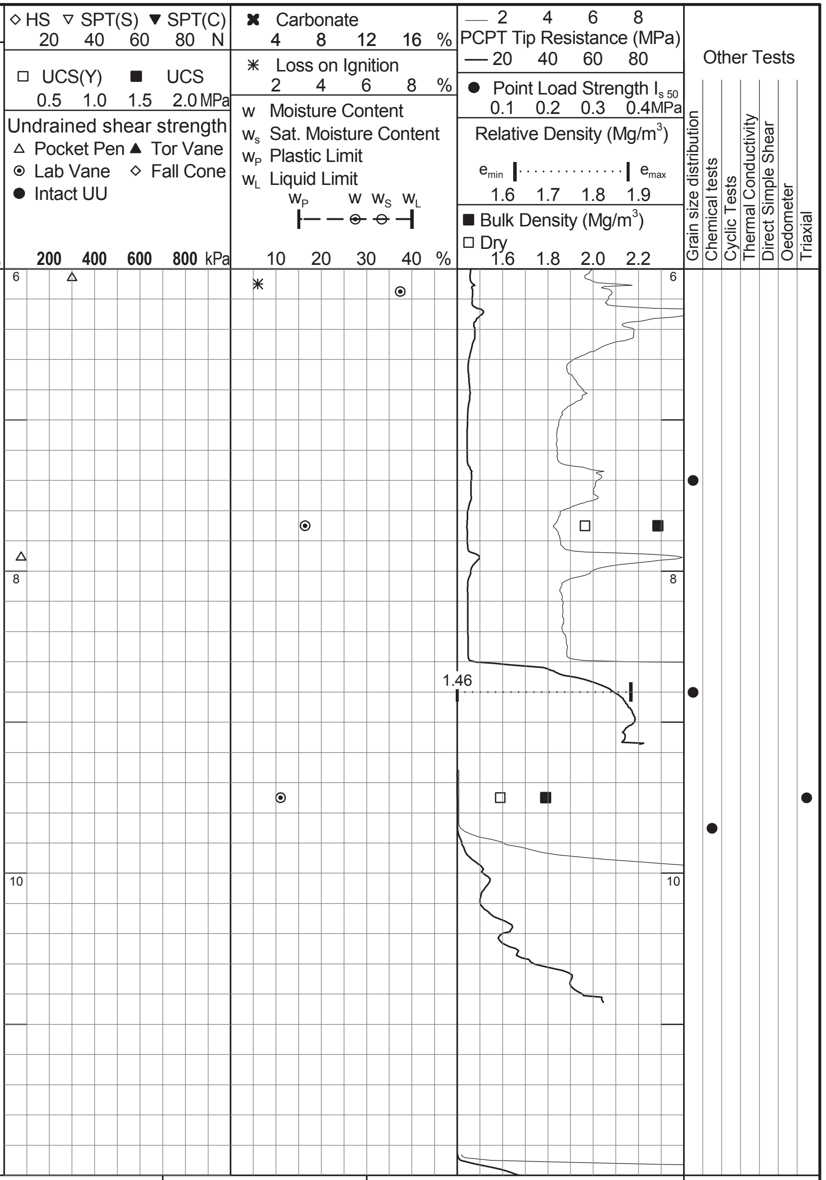
Notes:

Geology

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth
Dry rotary drilling *(continued)*	10-B	6	9.2D	6.10
		7		
	11-TW 12-B		11.1D 11.2D 11.3D 11.4D 11.5U 11.6U	7.40 7.50-7.70 7.70-7.90
		8		
			12.1D 12.2D 12.3D 12.4D 12.5D	8.80
		9		
	13-LB 14-B		13.1D 13.2D	9.50 9.70
		10		
		11		
Geobor-S	15-TW		15.1D 15.2D 15.3D	11.40

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age
6.1	-27.1	brown *CLAY TILL, medium plasticity, silty, sl. sandy, gravelly, calcareous, brown (continued)*	Mw	Gc
		CLAY, medium plasticity, silty, calcareous, laminated, w. iron sulphides, grey 6.05 - 6.10 w. many 1-5 mm fine sand laminae, w. black specks, w. odour		
7.3	-28.3	*CLAY TILL, medium plasticity, sandy, gravelly, calcareous, w. limestone grains, brownish grey*	Gl	Gc
8.6	-29.6	*SAND, medium, non graded, sl. gravelly, non calcareous, grey* 8.80 angularity: subangular-subrounded 9.30 becoming fine, well graded, silty, gravelly	Mw	Gc

Core Runs and Core Quality TCR (%)	SCR (%)	RQD (%)	Fissures 1 ----- 5	Induration 1 ----- 5
13				



Borehole Log: KF-BH004	Drilled:	TBH/KHH	Date:	2013-05-28	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-30	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-29	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 2 / 9

WWW.GEO.DK

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:18

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.0

Notes:

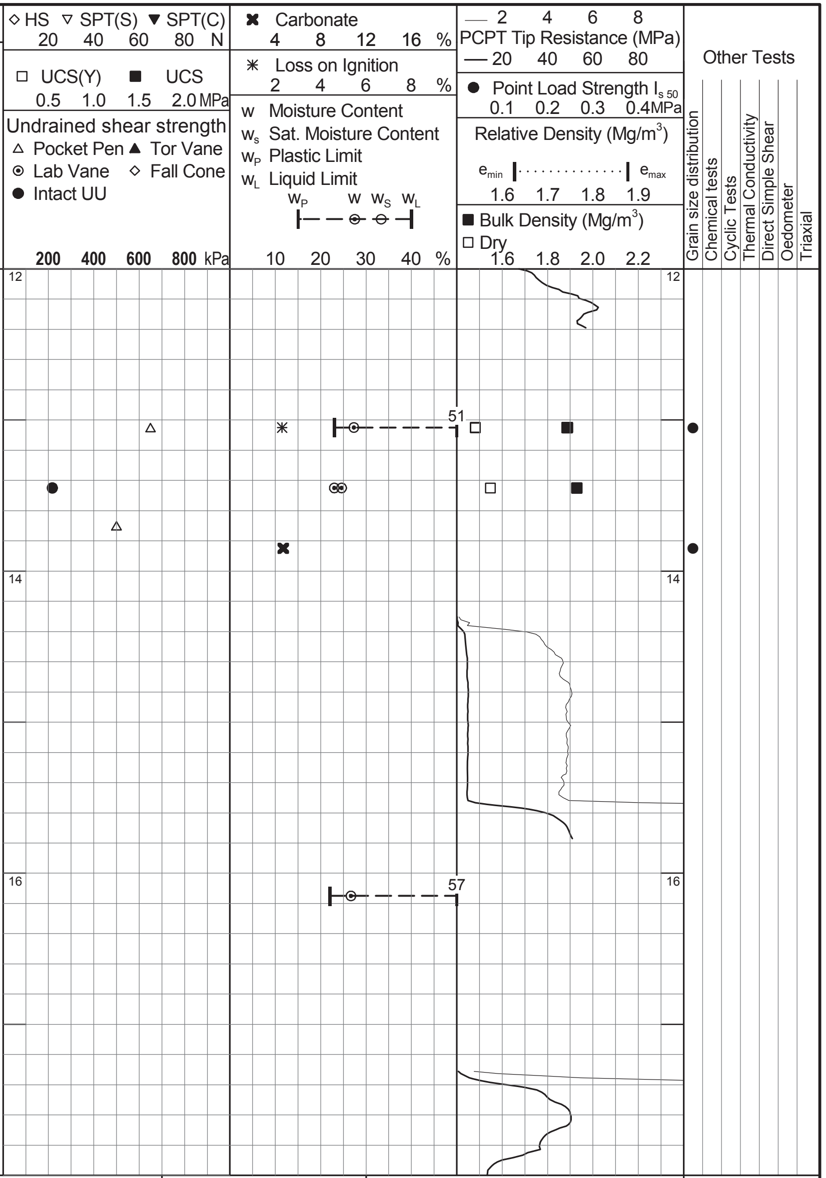
Drill tool: Geobor-S *(continued)*

Geology

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age	TCR (%)
		SAND, medium, non graded, sl. gravelly, non calcareous, grey (continued)	Mw	Gc	
12.4	-33.4	*CLAY TILL, sandy, gravelly, calcareous, dark grey*	Gl	Gc	
12.8	-33.8	*CLAY, high plasticity, silty, calcareous, organic, w. few shell fragments, w. iron sulphides, dark grey*	Fw	Is	80
13.3	-34.3	*CLAY, high plasticity, calcareous, w. many silt and fine sand laminae, brown* 14.30 - 15.80 w. many fine to coarse, non graded, grey sand layers	Mw	Gc	47
17.3	-38.3	*CLAY TILL, sandy, gravelly, calcareous, grey*	Gl	Gc	67

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
16-C		
17-C	17.10D	13.05
	17.1D	
	17.2D	13.30
	17.3D	
	17.4D	13.45-13.70
	17.5D	
	17.6U	
	17.7D	13.85
	17.8D	
	17.9D	
18-B		
19-C	19.1D	16.15
20-C		

Depth (m): 12, 13, 14, 15, 16, 17



Borehole Log: KF-BH004	Drilled: TBH/KHH	Date: 2013-05-28	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-30	Encl No.:
Remarks:	Checked: JSP	Date: 2013-05-29	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 3 / 9

WWW.GEO.DK

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:18

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

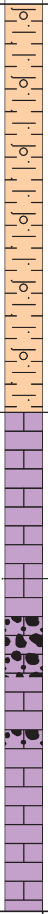
Seabed Level (m): -21.0

Notes:

Drill tool: Geobor-S (continued)

Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
	18					*CLAY TILL, sandy, gravelly, calcareous, grey (continued)*	Gl	Gc			
21-C		21.1U	18.85-19.10						93		
	19	21.2D	19.15								
		21.3U	19.20-19.45								
		21.4D 21.5D 21.6D	19.60								
						19.85 w. 30x60 mm granite gravel					
	20					20.10 w. 100x140 mm granite stone					
				20.7	-41.7						
22-C						*LIMESTONE, muddy, white (glacial disturbed)* 20.70 - 21.25 w. clay till parts, many gravels (granite and flint)	Ma	Ct	50		
	21										
				21.8	-42.8						
23-C						*LIMESTONE, muddy, white*	Ma	Ct	80		0
	22					22.05 - 22.45 w. 10x10 mm black flint nodules					
						22.80 - 22.90 w. 80x100 mm dark grey to black flint nodule					
	23	23.1D	23.00								
24-C									60		

Graphic Log



Core Runs and Core Quality

Fissures 1 ----- 5

Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C)
20 40 60 80 N

☐ UCS(Y) ■ UCS
0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate
4 8 12 16 %

✳ Loss on Ignition
2 4 6 8 %

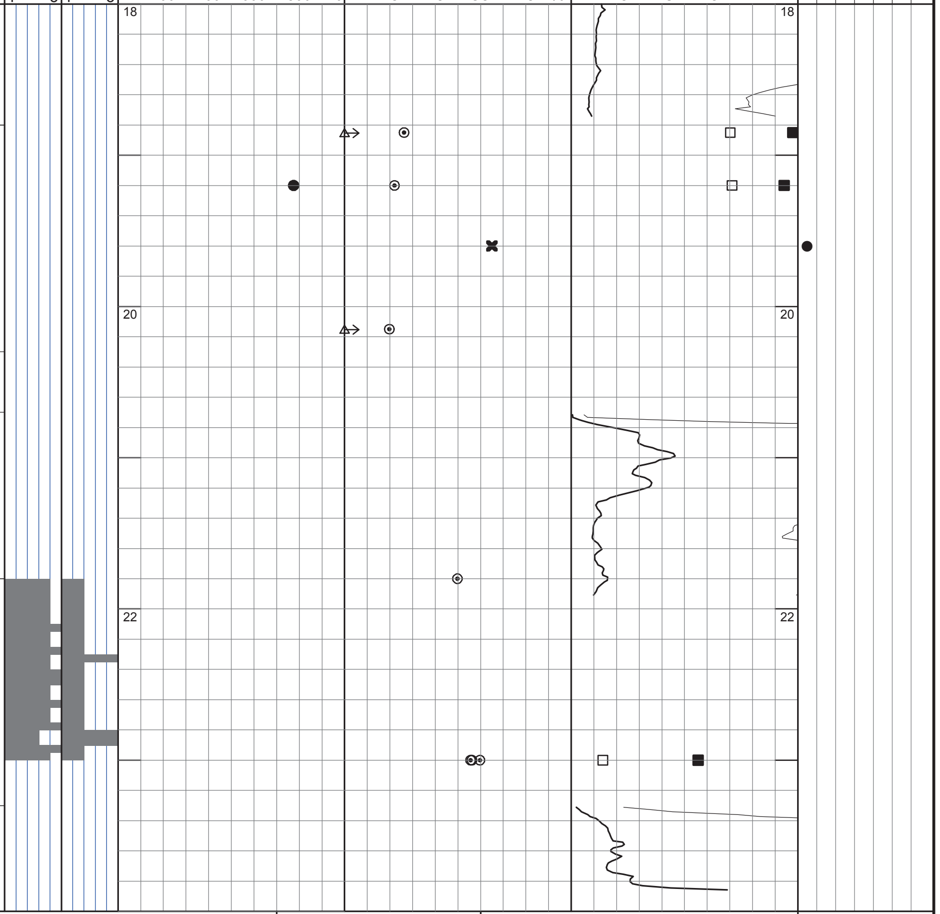
w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
10 20 30 40 %

— 2 4 6 8
PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$
0.1 0.2 0.3 0.4 MPa

Relative Density (Mg/m^3)
e_{min} e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2



Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

GEO WWW.GEO.DK

Borehole Log: KF-BH004	Drilled: TBH/KHH	Date: 2013-05-28	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-30	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-29	Rev :	
	Approved: LAR	Date: 2013-08-08	Page: 4 / 9	

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:18

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Notes:

Seabed Level (m): -21.0

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Graphic Log	Geology: Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S (continued)		24						*LIMESTONE, muddy, white (continued)*	Ma	Ct			
	25-C							24.80 - 24.95 w. dark grey to black fractured flint			77		0
	26-C		26.1D	28.30							67		30

Fissures 1 ----- 5 | Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

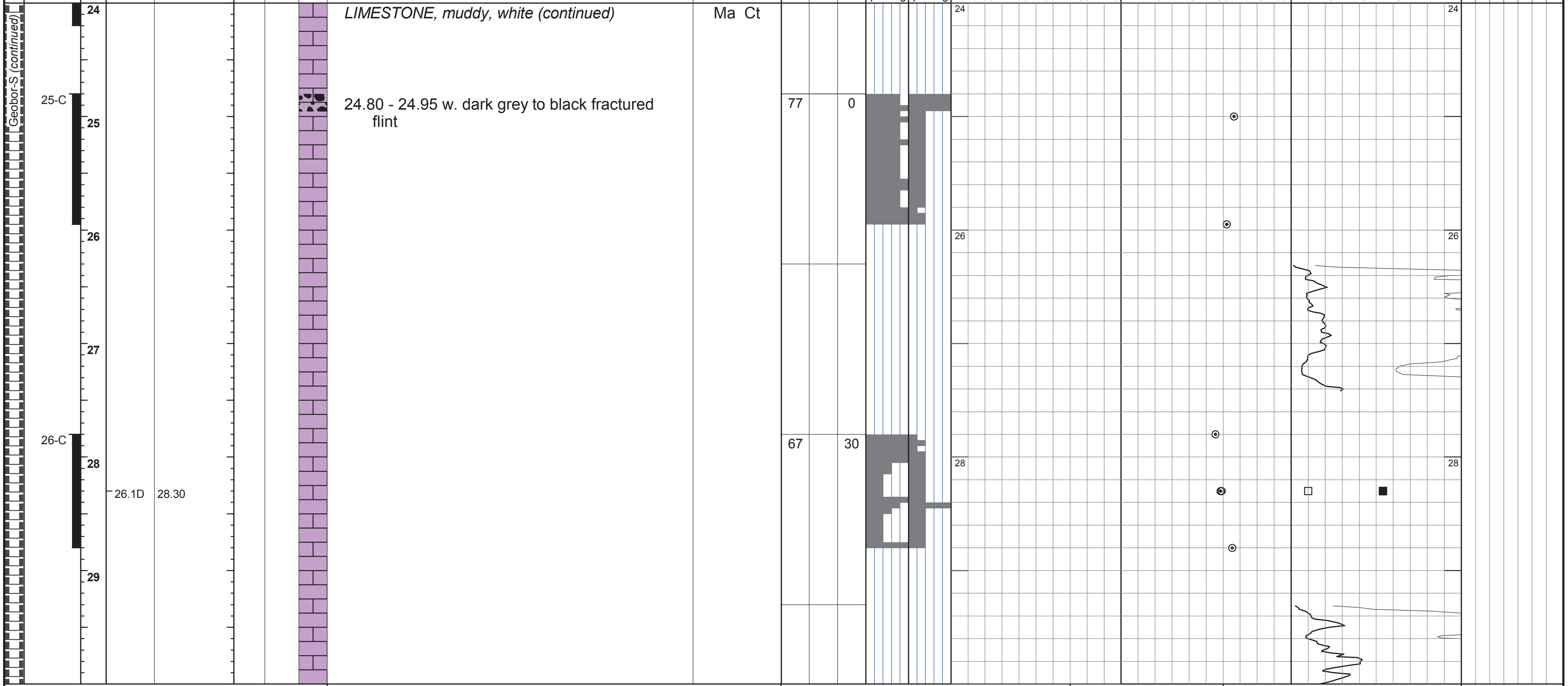
— 2 4 6 8
PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa

Relative Density (Mg/m^3)
e_{min} e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



Borehole Log: KF-BH004	Drilled:	TBH/KHH	Date:	2013-05-28	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-30	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-29	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 5 / 9

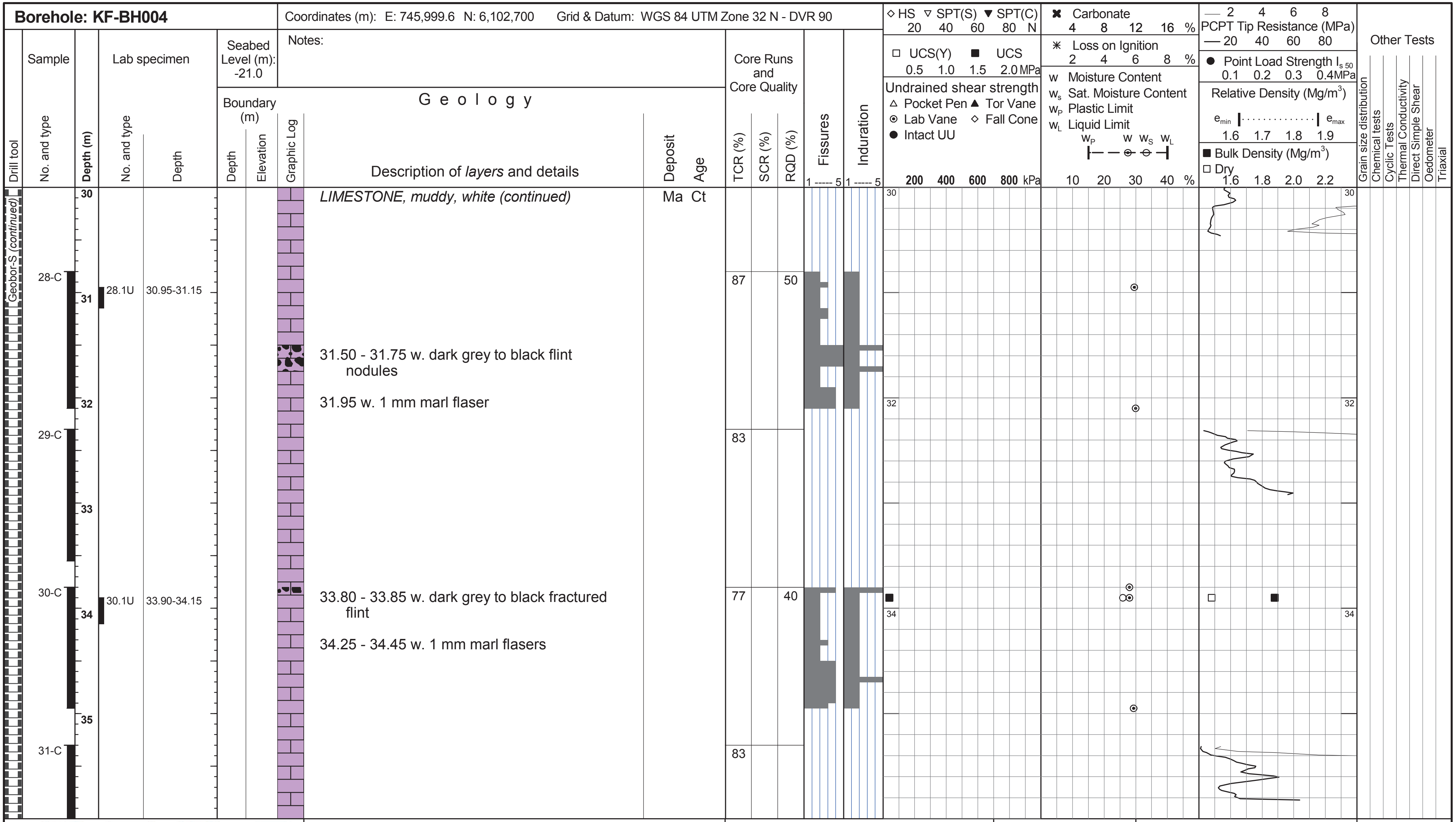
WWW.GEO.DK

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.0

Notes:



Sample No. and type	Lab specimen No. and type	Lab specimen Depth	Description of layers and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
			LIMESTONE, muddy, white (continued)	Ma	Ct			
28-C	28.1U	30.95-31.15				87		50
			31.50 - 31.75 w. dark grey to black flint nodules					
			31.95 w. 1 mm marl flaser					
29-C						83		
30-C	30.1U	33.90-34.15	33.80 - 33.85 w. dark grey to black fractured flint			77		40
			34.25 - 34.45 w. 1 mm marl flasers					
31-C						83		

GEO
WWW.GEO.DK

Borehole Log: KF-BH004	Drilled: TBH/KHH	Date: 2013-05-28	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-30	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-29	Rev :	
	Approved: LAR	Date: 2013-08-08	Page: 6 / 9	

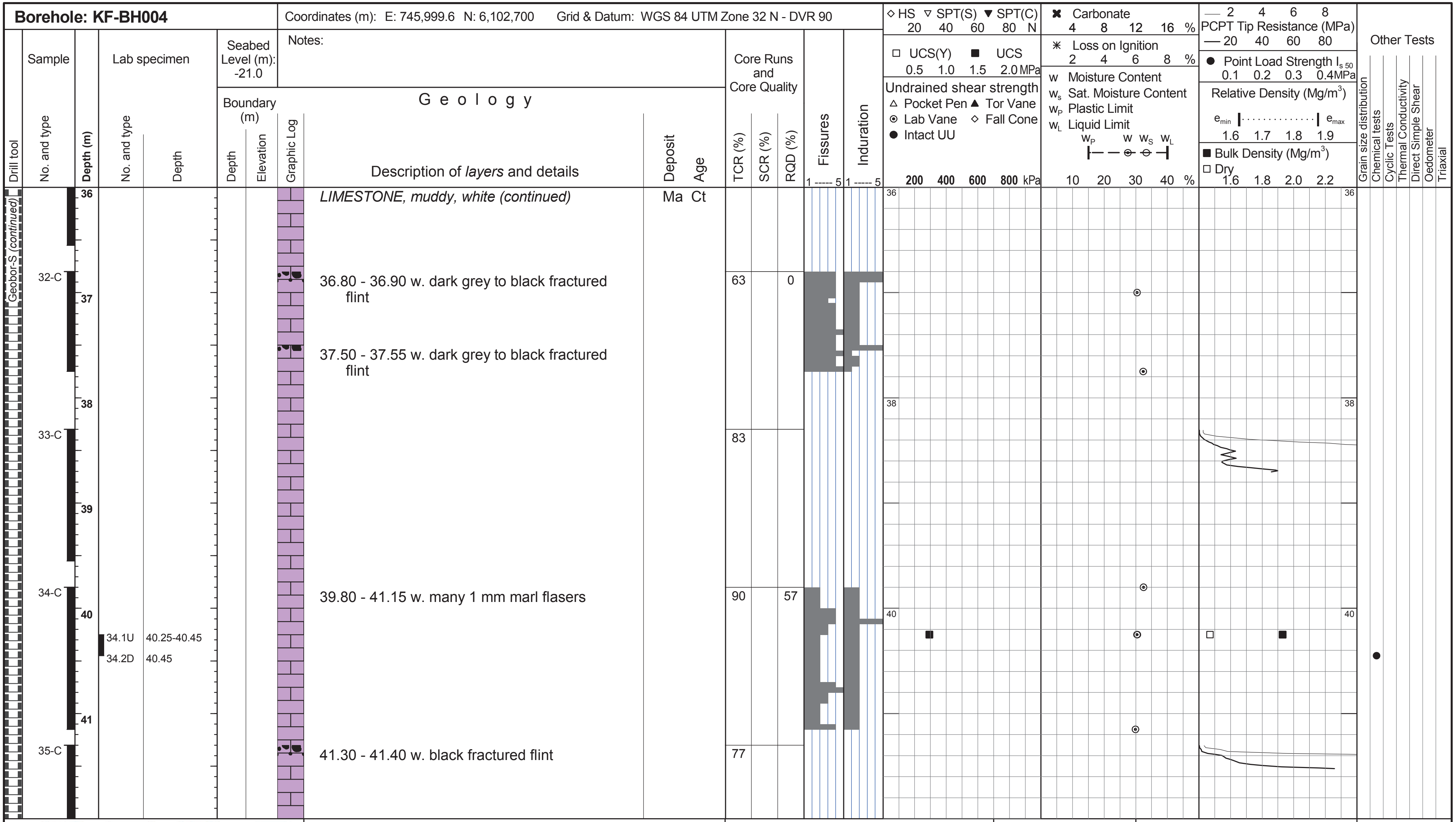
MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:18

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.0

Notes:



Description of *layers* and details	Deposit	Age
LIMESTONE, muddy, white (continued)	Ma	Ct
36.80 - 36.90 w. dark grey to black fractured flint		
37.50 - 37.55 w. dark grey to black fractured flint		
39.80 - 41.15 w. many 1 mm marl flasers		
41.30 - 41.40 w. black fractured flint		

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
32-C		
33-C		
34-C	34.1U	40.25-40.45
	34.2D	40.45
35-C		

TCR (%)	SCR (%)	RQD (%)
63		0
83		
90		57
77		

Borehole Log: KF-BH004	Drilled: TBH/KHH	Date: 2013-05-28	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-30	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-29	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	7 / 9

W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:18

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.0

Notes:

Drill tool | Sample: No. and type | Depth (m) | Lab specimen: No. and type | Depth | Boundary (m): Depth | Elevation | Graphic Log | Geology: Description of *layers* and details | Deposit | Age | Core Runs and Core Quality: TCR (%) | SCR (%) | RQD (%) | Fissures 1 ----- 5 | Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N
☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa
Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

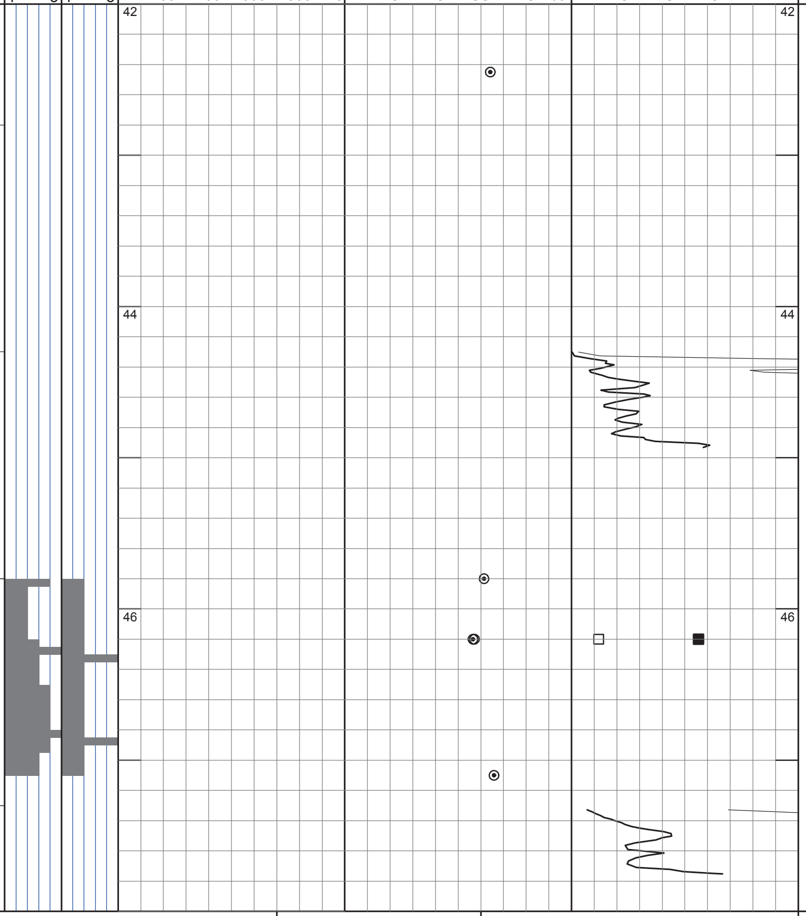
✖ Carbonate 4 8 12 16 %
✳ Loss on Ignition 2 4 6 8 %
w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

PCPT Tip Resistance (MPa) 2 4 6 8 / 20 40 60 80
● Point Load Strength $I_{s\ 50}$ 0.1 0.2 0.3 0.4 MPa
Relative Density (Mg/m^3)
e_{min} ········ e_{max}
1.6 1.7 1.8 1.9
■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution | Chemical tests | Cyclic Tests | Thermal Conductivity | Direct Simple Shear | Oedometer | Triaxial

Geobor-S (continued)

Depth (m)	Sample	Lab specimen	Specimen depth	Description	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
42				41.90 - 42.10 w. many 1-2 mm marl flasers *LIMESTONE, muddy, white (continued)*	Ma	Ct			
44	36-C						40		
45	37-C						87		23
46		37.1D	46.20						
				46.60 - 46.70 w. few 20-30 mm dark grey to black flint nodules					
47				47.00 w. vertical fracture					
	38-C						90		



GEO
WWW.GEO.DK

Borehole Log: KF-BH004	Drilled: TBH/KHH	Date: 2013-05-28	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-30	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-29	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	8 / 9

Borehole: KF-BH004

Coordinates (m): E: 745,999.6 N: 6,102,700 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -21.0

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Graphic Log	Geology Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S (continued)		48						*LIMESTONE, muddy, white (continued)*	Ma	Ct			
	39-C										100		54
		49						49.00 - 50.10 w. few 1 mm marl flasers					
		50			50.0	-71.0							

Core Runs and Core Quality

Fissures 1 ----- 5

Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

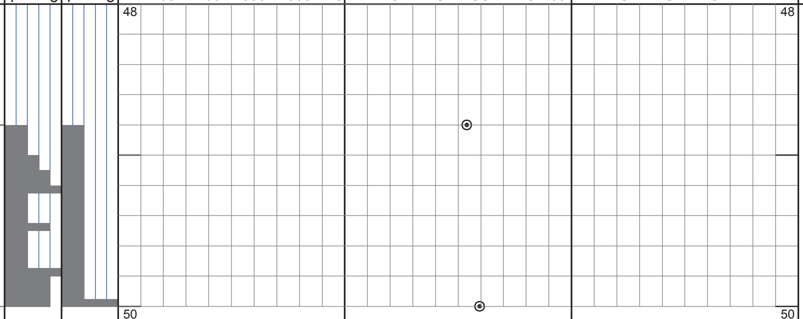
— 2 4 6 8
PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa

Relative Density (Mg/m^3)
e_{min} ┃·············┃ e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



Borehole Log: KF-BH004	Drilled: TBH/KHH	Date: 2013-05-28	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-30	Encl No.:
Remarks:	Checked: JSP	Date: 2013-05-29	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 9 / 9

W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:18

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

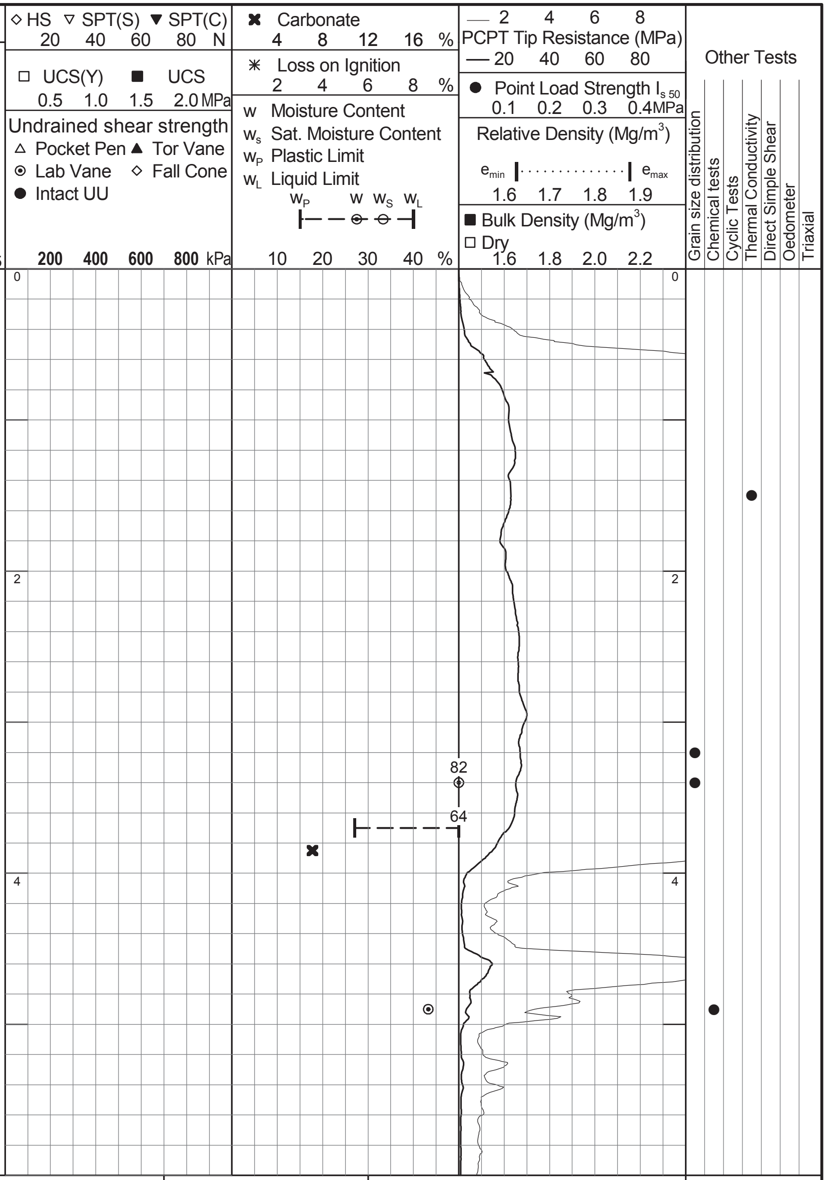
Drill tool: Dry rotary drilling

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
1-LB	1.1D	0.10
	1.2D	0.30
	1.3D	0.40
2-LB	2.1D	1.50-2.00
	2.2D	2.25
3-LB	3.1D	3.20
	3.2D	3.40
	3.3D	3.70
	3.4D	3.85
4-LB	4.1D	4.90
	4.2D	5.10

G e o l o g y

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age
0.2	-20.6	*SAND, medium, non graded, yellowish brown*	Ma	Pg
0.4	-20.8	*SAND, medium - coarse, non graded, gravelly, grey*	Ma	Pg
		SAND, fine - medium, non graded, grey	Ma	Pg
3.3	-23.7	*CLAY, medium plasticity, silty, w. many 1-2 mm fine sand laminae, grey*	Fw	Lg
		5.00 - 6.15 becoming brown		

Core Runs and Core Quality: TCR (%) SCR (%) RQD (%) Fissures 1 ----- 5 Induration 1 ----- 5



Borehole Log: KF-BH011	Drilled: JWJ/ELF	Date: 2013-05-20	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-22	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-22	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	1 / 12

GEO W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool: Dry rotary drilling (*continued*); Geobor-S

Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth
5-LB	6	5.1D	6.30
		5.2D	6.60
		5.3D	6.85
	7		
6-TW		6.1D	7.60
		6.2D	7.80
		6.3U	7.85-8.05
	8		
7-C			
	9		
8-C			
	10		
9-C		9.1D 9.2D 9.3D 9.4D	10.50
10-C	11		

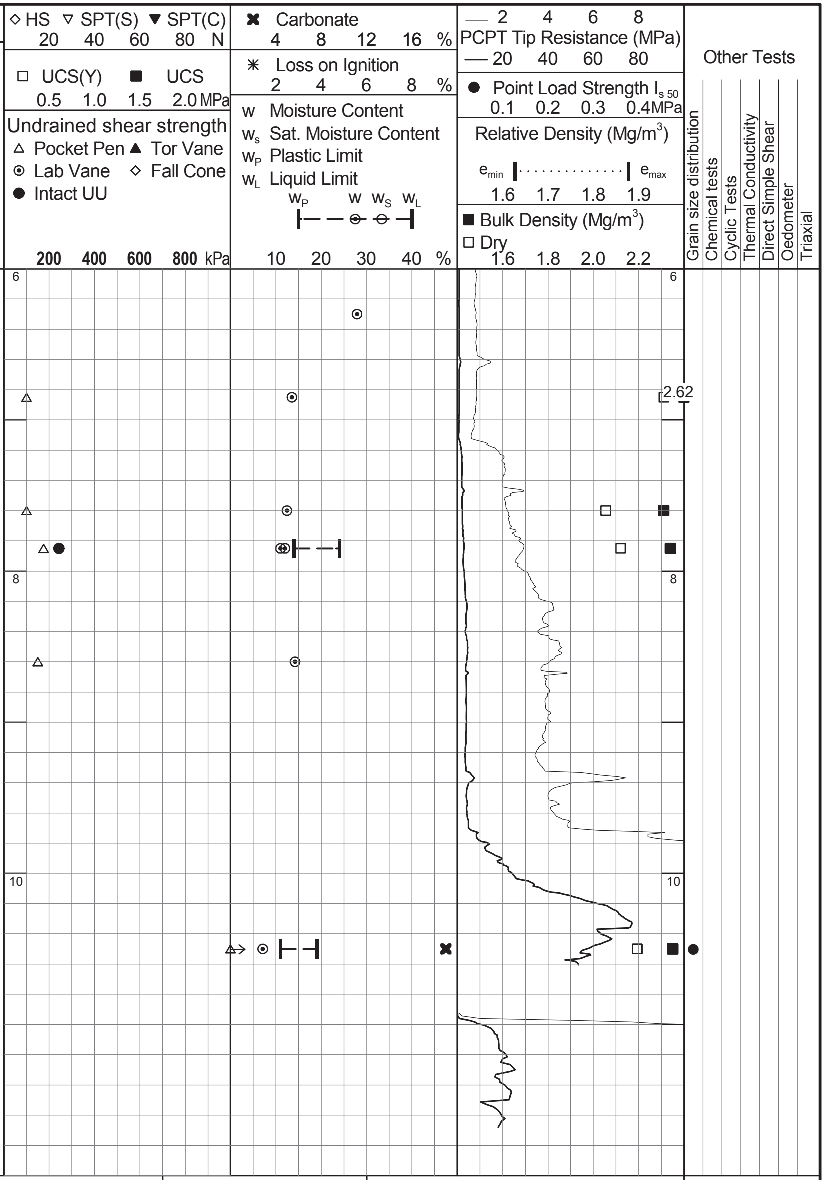
G e o l o g y

Boundary (m) Depth	Elevation	Description of *layers* and details	Deposit	Age
6.2	-26.6			
6.5	-26.9	*CLAY, medium plasticity, silty, calcareous, grey*	Mw	Lg
6.7	-27.1	*CLAY TILL, silty, sl. sandy, calcareous, grey*	Gl	Gc
6.8	-27.2	*SAND, fine, poorly graded, clayey, silty, calcareous, grey*	Mw	Gc
		CLAY TILL, sandy, sl. gravelly, calcareous, grey	Gl	Gc
7.8	-28.2	*SAND, medium - coarse, non graded, grey*	Mw	Gc
7.8	-28.2	*CLAY TILL, sandy, gravelly, calcareous, grey*	Gl	Gc

Core Runs and Core Quality

TCR (%)	SCR (%)	RQD (%)
41		
56		
100		
87		

Fissures 1 ----- 5 | Induration 1 ----- 5



Borehole Log: KF-BH011	Drilled: JWJ/ELF	Date: 2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-22	Encl No.:
Remarks:	Checked: JSP	Date: 2013-05-22	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 2 / 12

W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool: Geobor-S (continued)

Sample No. and type	Lab specimen No. and type	Lab specimen Depth
11-C		
C		
12-TW	12.1D	15.50
13-C		
14-C	14.1D 14.2D 14.3D 14.4D	16.70
15-C		

G e o l o g y

Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age	TCR (%)
		CLAY TILL, sandy, gravelly, calcareous, grey (continued)	Gl	Gc	30
13.1	-33.5	*SAND, fine - medium, non graded, calcareous, brown*	Mw	Gc	0
15.7	-36.1	*CLAY TILL, silty, sandy, gravelly, calcareous, grey*	Gl	Gc	56
		16.50 - 16.90 sl. sandy, w. few gravels			100
					33

Core Runs and Core Quality: TCR (%) SCR (%) RQD (%)

Fissures 1 ----- 5

Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
10 20 30 40 %

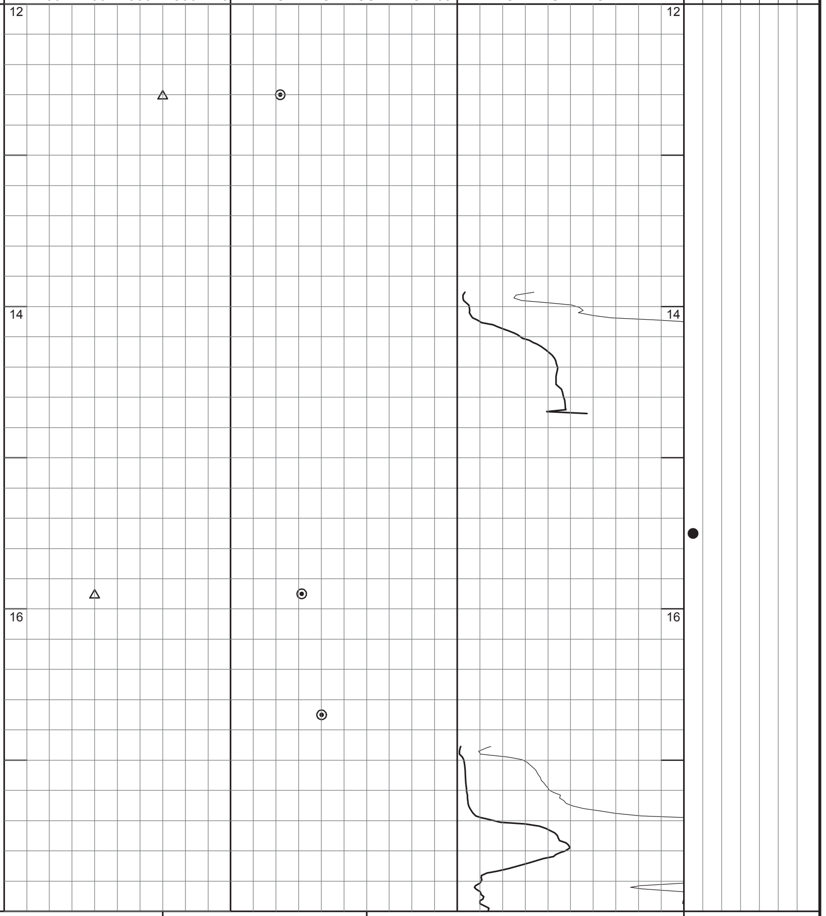
— 2 4 6 8 PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa

Relative Density (Mg/m^3)
e_{min} e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



Borehole Log: KF-BH011	Drilled:	JWJ/ELF	Date:	2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-22	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-22	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 3 / 12

W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool: Geobor-S (continued)

Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth
	18		
16-C			
17-C	19	17.1D 17.2D 17.3D 17.4D 17.5U	19.20 19.50-19.75
18-C	20		
	21		
19-C		19.1D 19.2D 19.3D 19.4D 19.5U 19.6U	21.60 21.85-22.10 22.10-22.35
	22		
20-C	23		

G e o l o g y

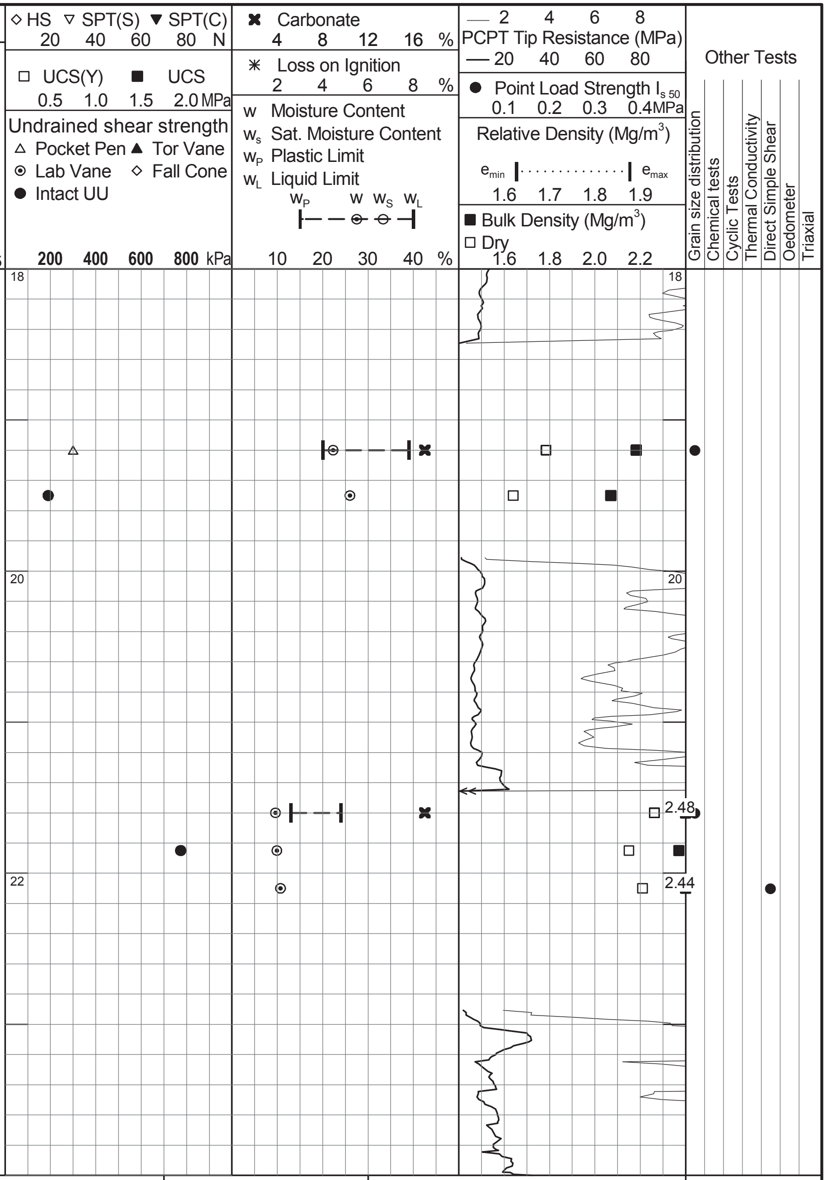
Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age
		CLAY TILL, silty, sandy, gravelly, calcareous, grey (continued) 18.40 - 18.45 w. limestone parts 18.40 - 18.70 sl. gravelly	Gl	Gc
19.1	-39.5	*CLAY, medium plasticity, very silty, calcareous, brown* 19.10 - 19.70 w. sand streaks 19.70 - 19.90 w. iron sulphide stains	Mw	Gc
20.5	-40.9	*CLAY TILL, silty, sandy, gravelly, calcareous, grey*	Gl	Gc

Core Runs and Core Quality

TCR (%)	SCR (%)	RQD (%)
67		
100		
30		
100		
87		

Fissures 1 ----- 5

Induration 1 ----- 5



Borehole Log: KF-BH011	Drilled:	JWJ/ELF	Date:	2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-22	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-22	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 4 / 12

GEO
WWW.GEO.DK

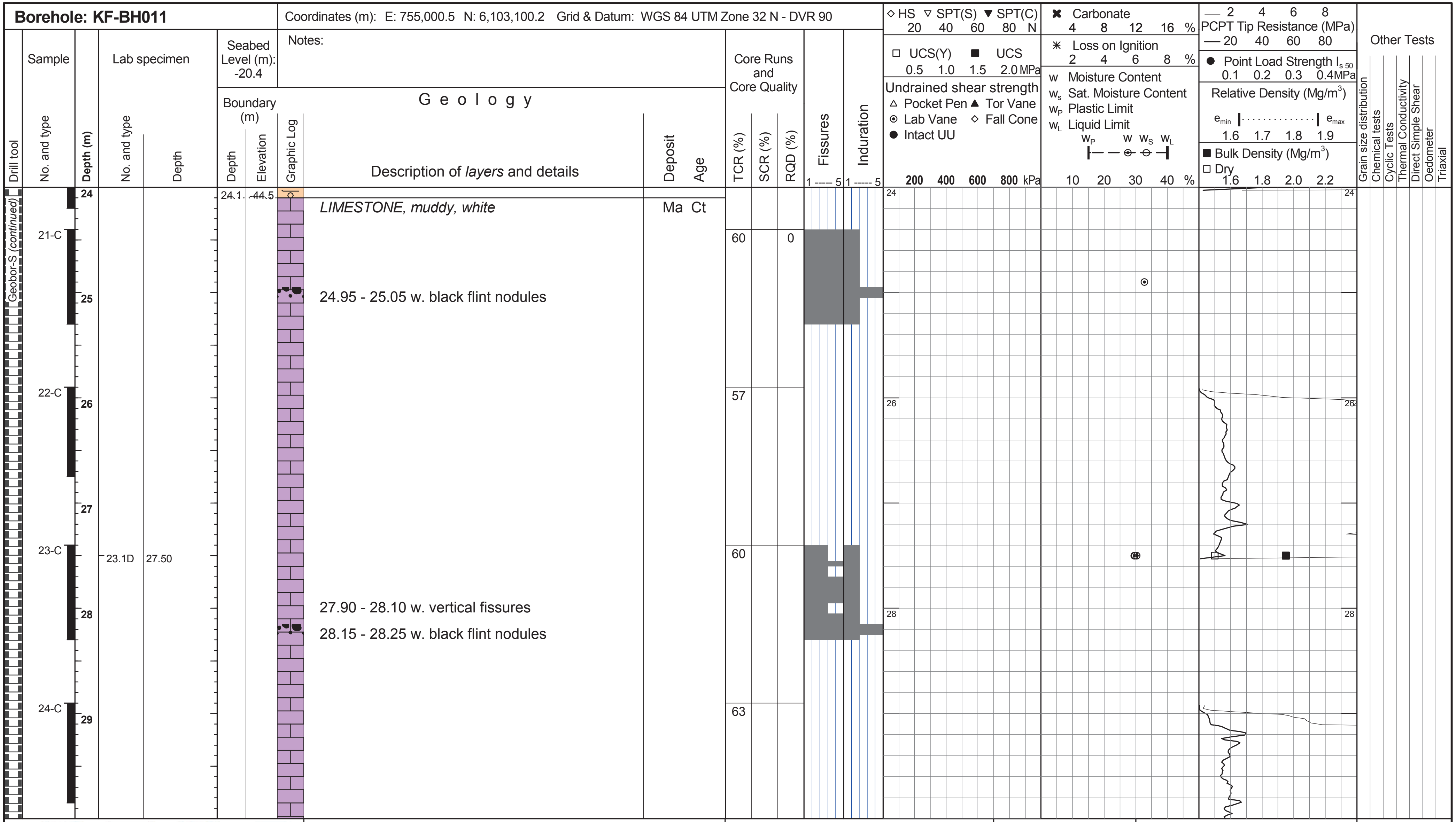
Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Graphic Log	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)	Fissures 1 ----- 5	Induration 1 ----- 5
Geobor-S *(continued)*		24			24.1	-44.5		*LIMESTONE, muddy, white*	Ma	Ct					
	21-C										60		0		
		25						24.95 - 25.05 w. black flint nodules							
	22-C	26									57				
		27													
	23-C		23.1D	27.50							60				
		28						27.90 - 28.10 w. vertical fissures							
								28.15 - 28.25 w. black flint nodules							
	24-C	29									63				



GEO
W W W . G E O . D K

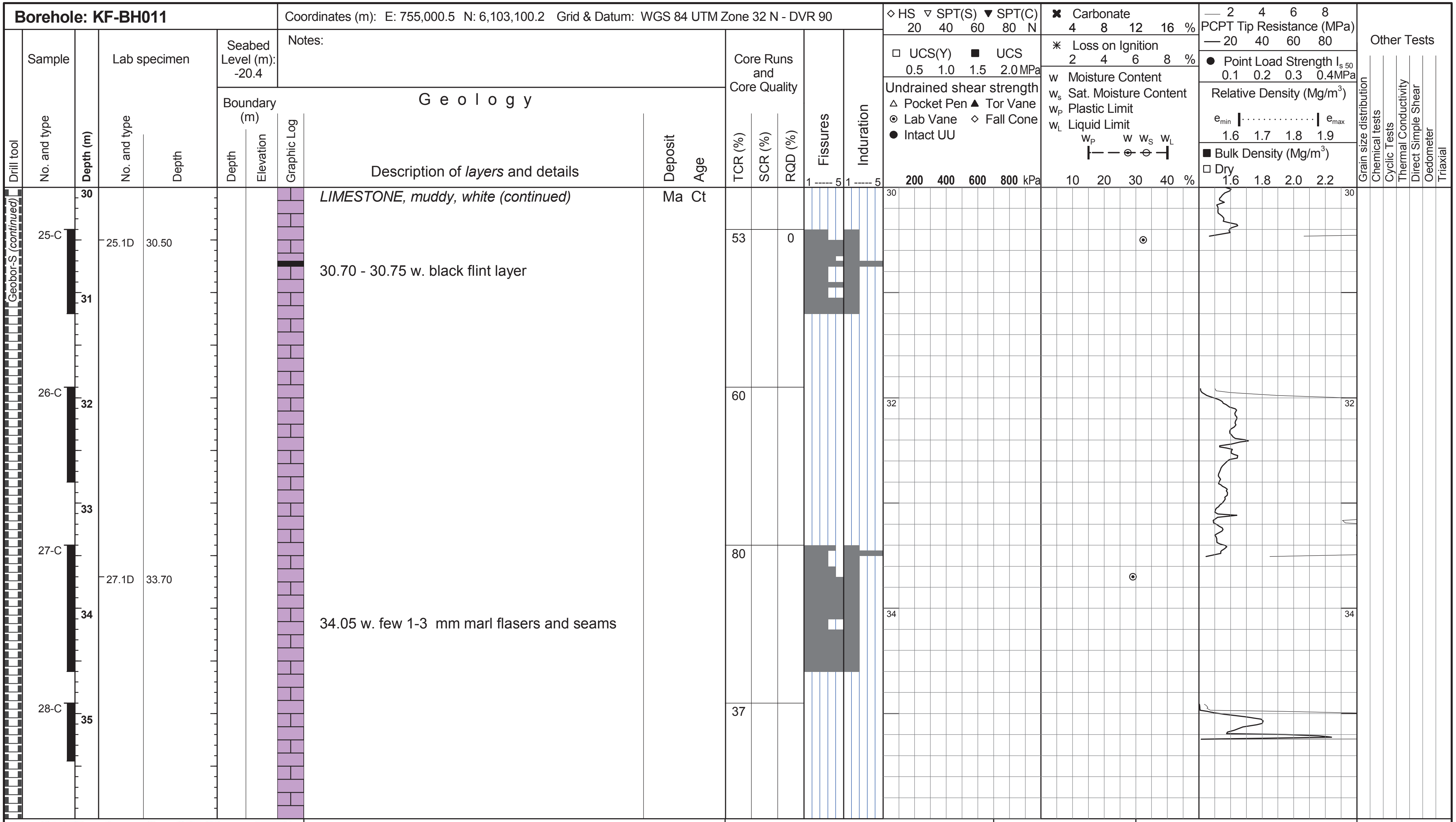
Borehole Log: KF-BH011	Drilled: JWJ/ELF	Date: 2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-22	Encl No.:
Remarks:	Checked: JSP	Date: 2013-05-22	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 5 / 12

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:



LIMESTONE, muddy, white (continued)

30.70 - 30.75 w. black flint layer

34.05 w. few 1-3 mm marl flasers and seams

Borehole Log: KF-BH011	Drilled:	JWJ/ELF	Date:	2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-22	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-22	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 6 / 12

W W W . G E O . D K

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool | Sample: No. and type | Depth (m) | Lab specimen: No. and type, Depth | Boundary (m): Depth, Elevation | Graphic Log | Geology: Description of *layers* and details | Deposit | Age | Core Runs and Core Quality: TCR (%), SCR (%), RQD (%) | Fissures 1 ----- 5 | Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

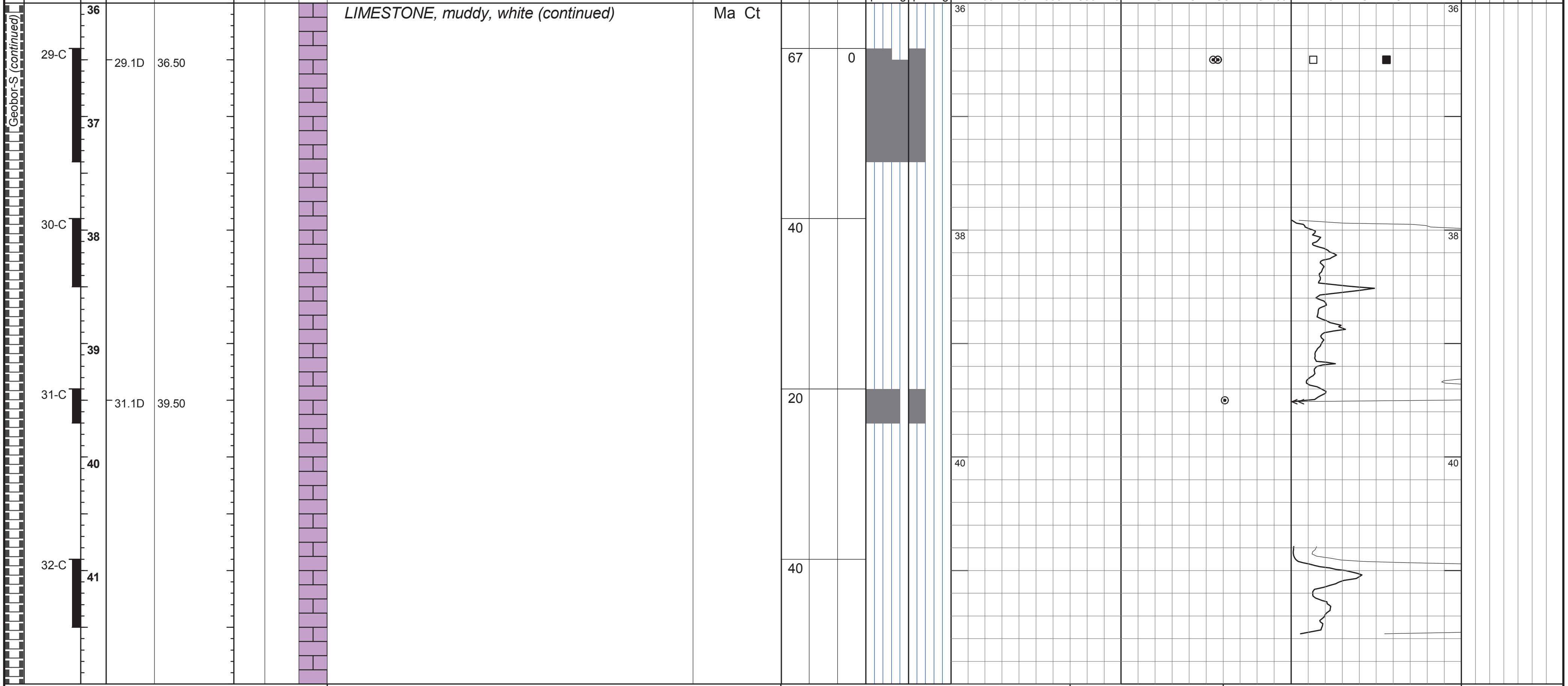
— 2 4 6 8
PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa

Relative Density (Mg/m^3)
e_{min} e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



Sample	Lab specimen	Depth
29-C	29.1D	36.50
30-C		
31-C	31.1D	39.50
32-C		

LIMESTONE, muddy, white (continued) — Ma Ct

TCR (%)	SCR (%)	RQD (%)
67		0
40		
20		
40		

Borehole Log: KF-BH011

Project: 36642 Kriegers Flak

Remarks:

Drilled:	JWJ/ELF	Date:	2013-05-20	Report No.:	1
Prepared:	LTR/LFJ	Date:	2013-05-22	Encl No.:	
Checked:	JSP	Date:	2013-05-22	Rev :	
Approved:	LAR	Date:	2013-08-08	Page:	7 / 12

GEO WWW.GEO.DK

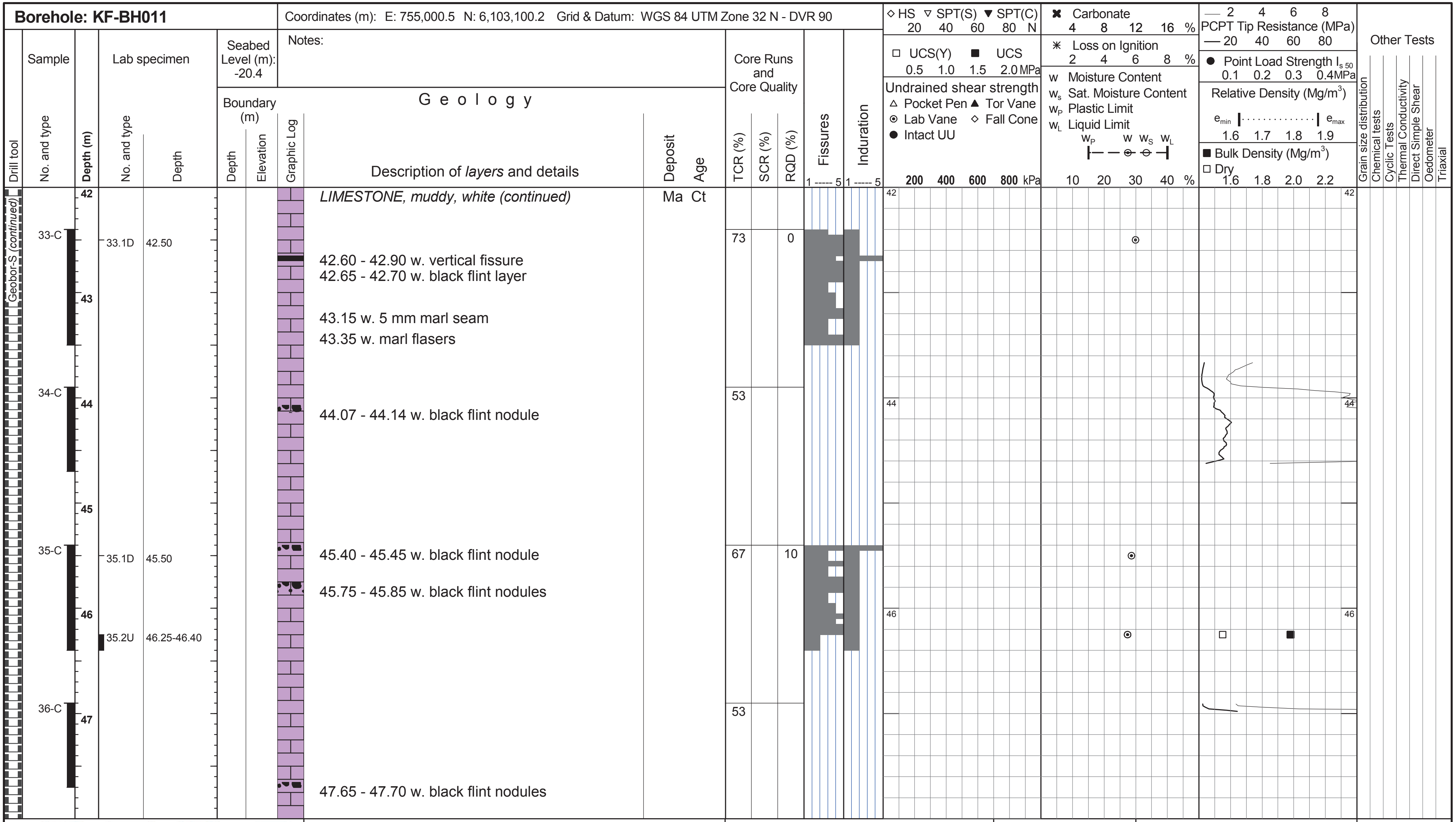
MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:



LIMESTONE, muddy, white (continued) — Ma Ct

42.60 - 42.90 w. vertical fissure
42.65 - 42.70 w. black flint layer

43.15 w. 5 mm marl seam
43.35 w. marl flasers

44.07 - 44.14 w. black flint nodule

45.40 - 45.45 w. black flint nodule

45.75 - 45.85 w. black flint nodules

47.65 - 47.70 w. black flint nodules

Sample No. and type	Lab specimen No. and type	Depth
33-C	33.1D	42.50
34-C		
35-C	35.1D	45.50
	35.2U	46.25-46.40
36-C		

TCR (%)	SCR (%)	RQD (%)
73		0
53		
67		10
53		

Borehole Log: KF-BH011	Drilled: JWJ/ELF	Date: 2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-22	Encl No.:
Remarks:	Checked: JSP	Date: 2013-05-22	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 8 / 12

W W W . G E O . D K

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

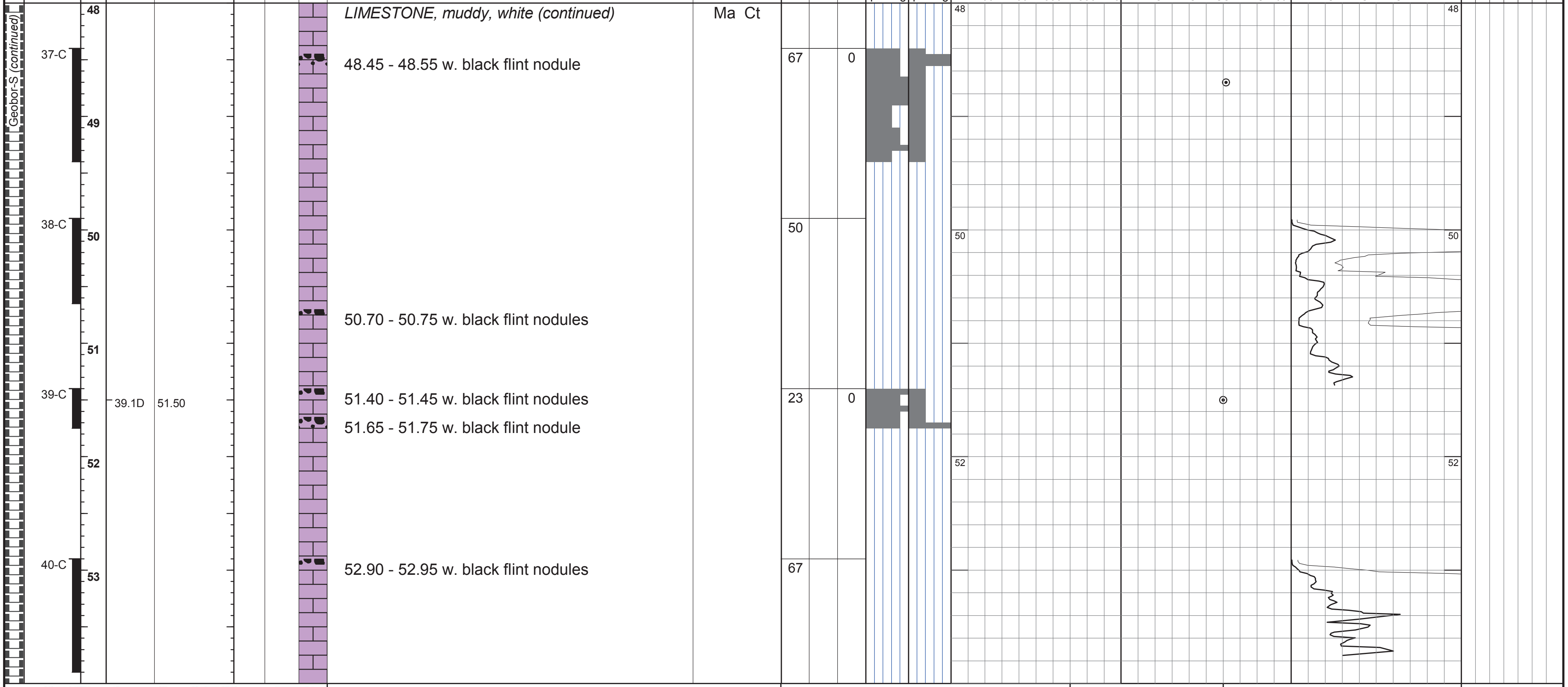
Notes:

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N
☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa
Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %
✳ Loss on Ignition 2 4 6 8 %
w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
10 20 30 40 %

— 2 4 6 8 PCPT Tip Resistance (MPa)
— 20 40 60 80
● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa
Relative Density (Mg/m^3) e_{min} … e_{max} 1.6 1.7 1.8 1.9
■ Bulk Density (Mg/m^3)
☐ Dry 1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S (continued)		48			*LIMESTONE, muddy, white (continued)*	Ma	Ct			
	37-C				48.45 - 48.55 w. black flint nodule			67		0
		49								
	38-C	50						50		
					50.70 - 50.75 w. black flint nodules					
		51								
	39-C		39.1D	51.50	51.40 - 51.45 w. black flint nodules			23		0
					51.65 - 51.75 w. black flint nodule					
		52								
	40-C	53			52.90 - 52.95 w. black flint nodules			67		

WWW.GEO.DK

Borehole Log: KF-BH011	Drilled: JWJ/ELF	Date: 2013-05-20	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-22	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-22	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	9 / 12

Borehole: KF-BH011

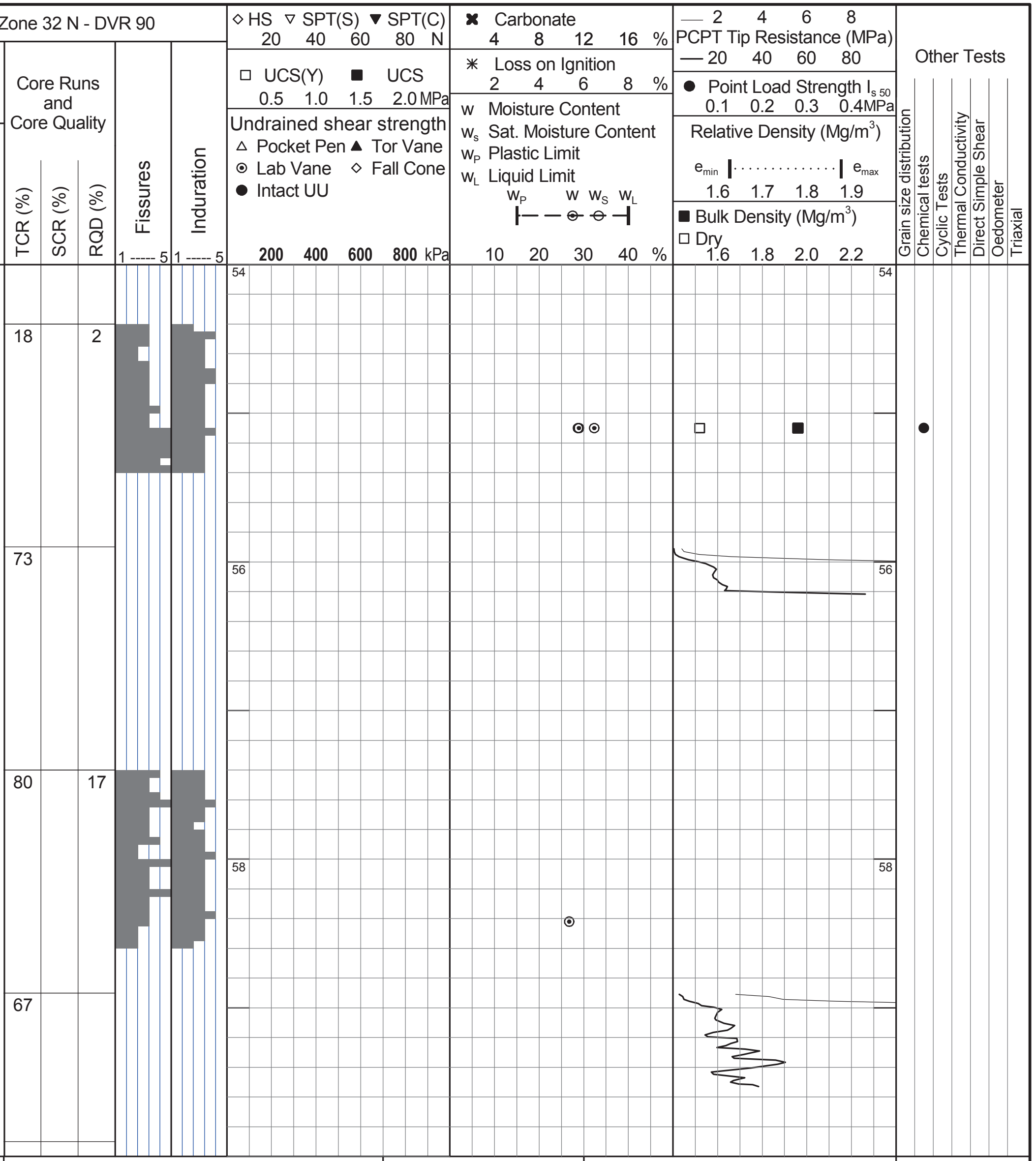
Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool: Geobor-S (continued)

Depth (m)	Sample No. and type	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age
54						*LIMESTONE, muddy, white (continued)*	Ma	Ct
	41-C							
						54.50 - 54.60 w. 1-2 mm marl flasers 54.55 w. few silicified parts 54.70 - 55.00 w. 1-2 mm marl flasers 54.80 w. 8 mm marl seam 54.95 w. slickenside		
55		41.1D 41.2D	55.10					
	42-C					55.90 - 56.00 w. 90 mm black flint nodule		
56								
57								
	43-C							
						57.75 - 58.10 w. 1-2 mm marl flasers		
58								
		43.1U	58.42-58.60			58.30 - 58.55 w. many 1-2 mm marl flasers 58.50 w. few 3-5 mm marl seams		
	44-C					58.90 - 58.95 w. black flint nodules		
59								



WWW.GEO.DK

Borehole Log: KF-BH011	Drilled:	JWJ/ELF	Date:	2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-22	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-22	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 10 / 12

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

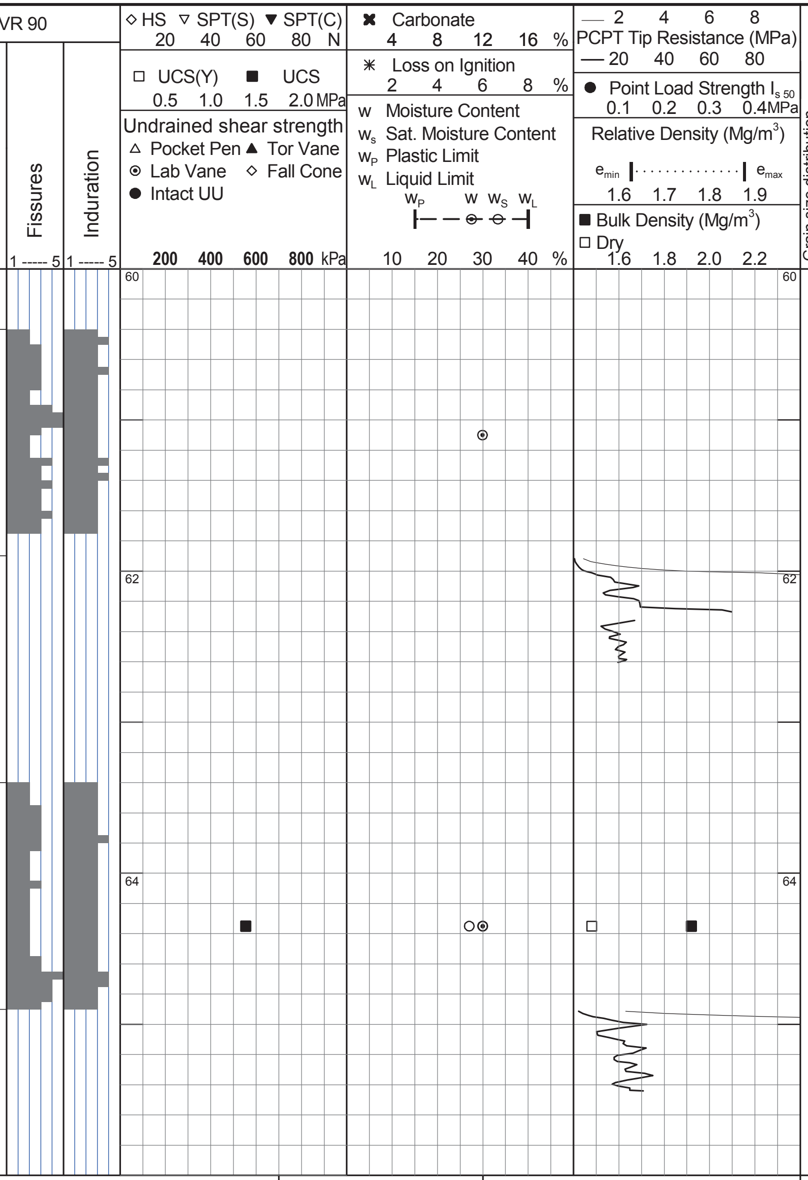
Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -20.4

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Description of *layers* and details	Deposit	Age	Core Runs and Core Quality TCR (%)	SCR (%)	RQD (%)
Geobor-S (continued)		60					*LIMESTONE, muddy, white (continued)*	Ma	Ct			
	45-C						60.45 - 60.90 w. 1-2 mm marl flasers			90		23
							60.80 - 60.85 w. many 3-5 mm mark seams					
		61	45.1U	61.10-61.25			61.25 - 61.65 w. silicified parts					
	46-C	62								63		
		63										
	47-C						63.55 w. 5 mm marl seam 63.65 - 63.85 w. grey flint nodules, w. silicified parts			100		53
		64	47.1U	64.35-64.55			64.15 w. 5 mm marl seam 64.20 - 64.65 w. 3-6 mm marl seams 64.50 - 64.60 w. few silicified parts 64.65 - 64.80 w. few light grey flint nodules, w. very silicified parts					
	48-C	65								60		



Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

WWW.GEO.DK

Borehole Log: KF-BH011	Drilled:	JWJ/ELF	Date:	2013-05-20	Report No.: 1
Project: 36642 Kriegers Flak	Prepared:	LTR/LFJ	Date:	2013-05-22	Encl No.:
Remarks:	Checked:	JSP	Date:	2013-05-22	Rev :
	Approved:	LAR	Date:	2013-08-08	Page: 11 / 12

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

Borehole: KF-BH011

Coordinates (m): E: 755,000.5 N: 6,103,100.2 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Notes:

Seabed Level (m): -20.4

G e o l o g y

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		66					*LIMESTONE, muddy, white (continued)*	Ma	Ct			
	49-C		49.1D	66.60			66.55 w. 2x40 mm light grey marl seam			30		0
		67										
	50-C	68								87		27
		69	50.1U	69.00-69.20								
		70			70.0	-90.4						

Core Runs and Core Quality

Fissures 1 ----- 5

Induration 1 ----- 5

◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

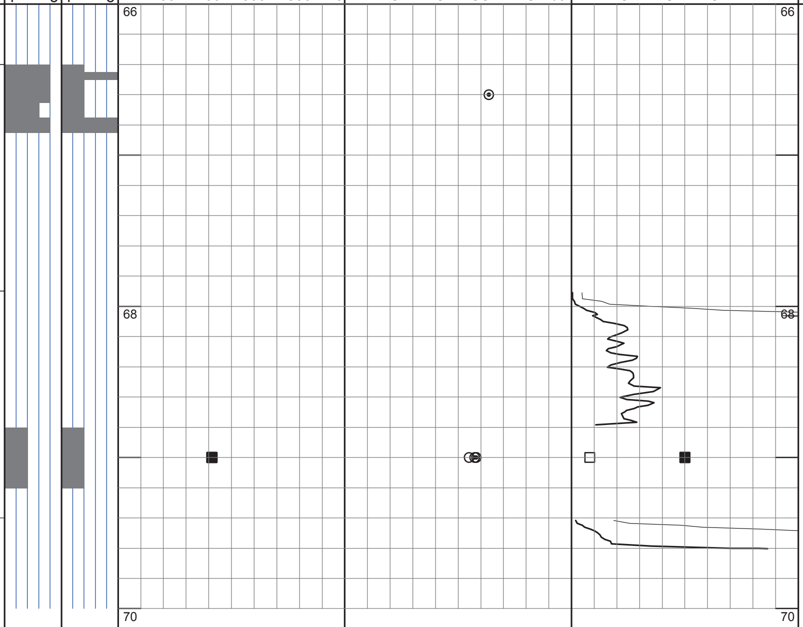
— 2 4 6 8
PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4MPa

Relative Density (Mg/m^3)
e_{min} ·············· e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2

Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial



MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:22

GEO
W W W . G E O . D K

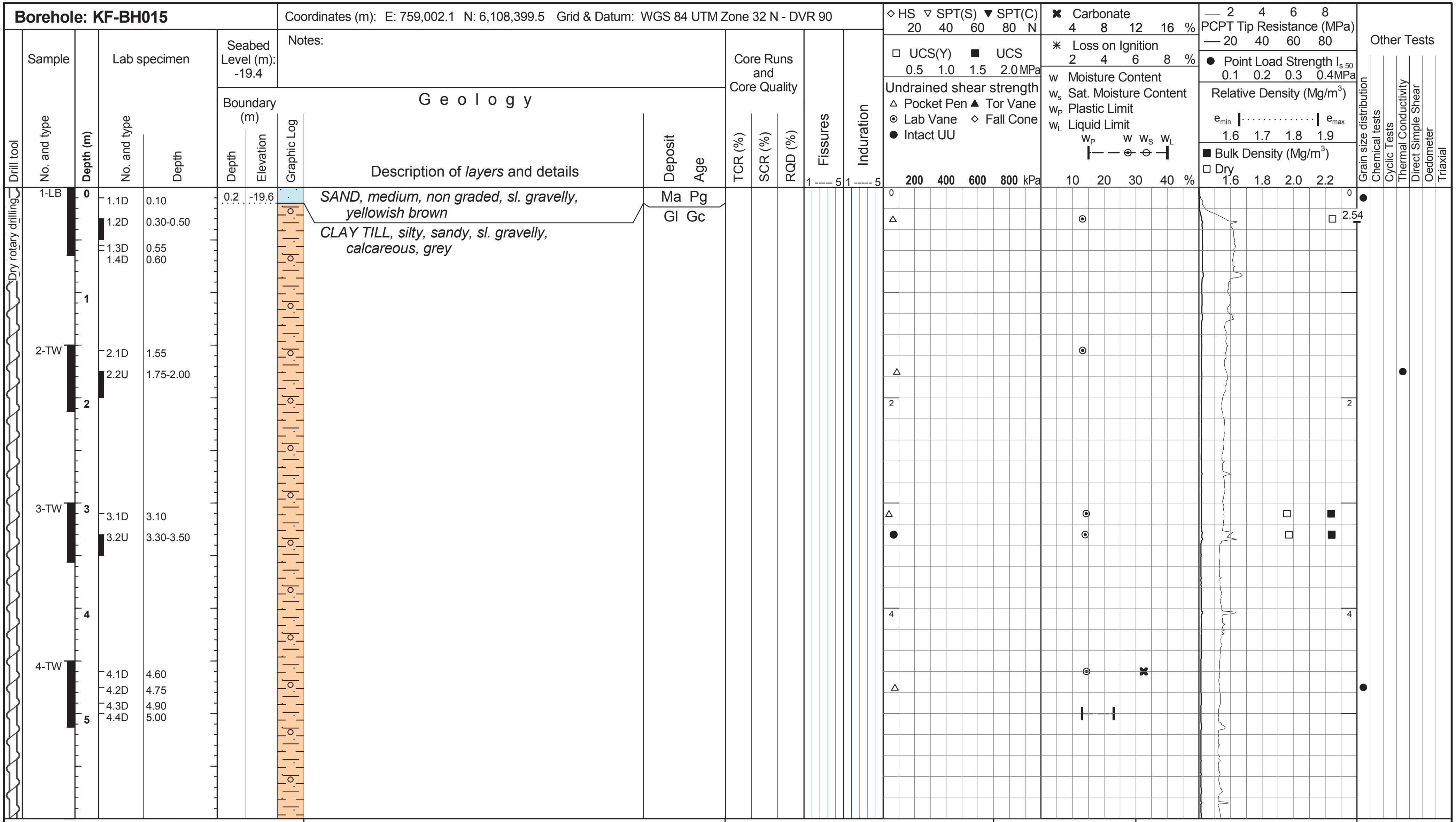
Borehole Log: KF-BH011	Drilled: JWJ/ELF	Date: 2013-05-20	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: LTR/LFJ	Date: 2013-05-22	Encl No.:	
Remarks:	Checked: JSP	Date: 2013-05-22	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	12 / 12

Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:



Sample No. and type	Lab specimen No. and type	Lab specimen Depth
1-LB	1.1D	0.10
	1.2D	0.30-0.50
	1.3D	0.55
	1.4D	0.60
2-TW	2.1D	1.55
	2.2U	1.75-2.00
3-TW	3.1D	3.10
	3.2U	3.30-3.50
4-TW	4.1D	4.60
	4.2D	4.75
	4.3D	4.90
	4.4D	5.00

Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age
0.2	-19.6	*SAND, medium, non graded, sl. gravelly, yellowish brown*	Ma	Pg
		CLAY TILL, silty, sandy, sl. gravelly, calcareous, grey	Gl	Gc

GEO

WWW.GEO.DK

Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1	
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:	
Remarks:	Checked:	Date:	Rev :	
	Approved: LAR	Date: 2013-08-08	Page:	1 / 9

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:24

Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

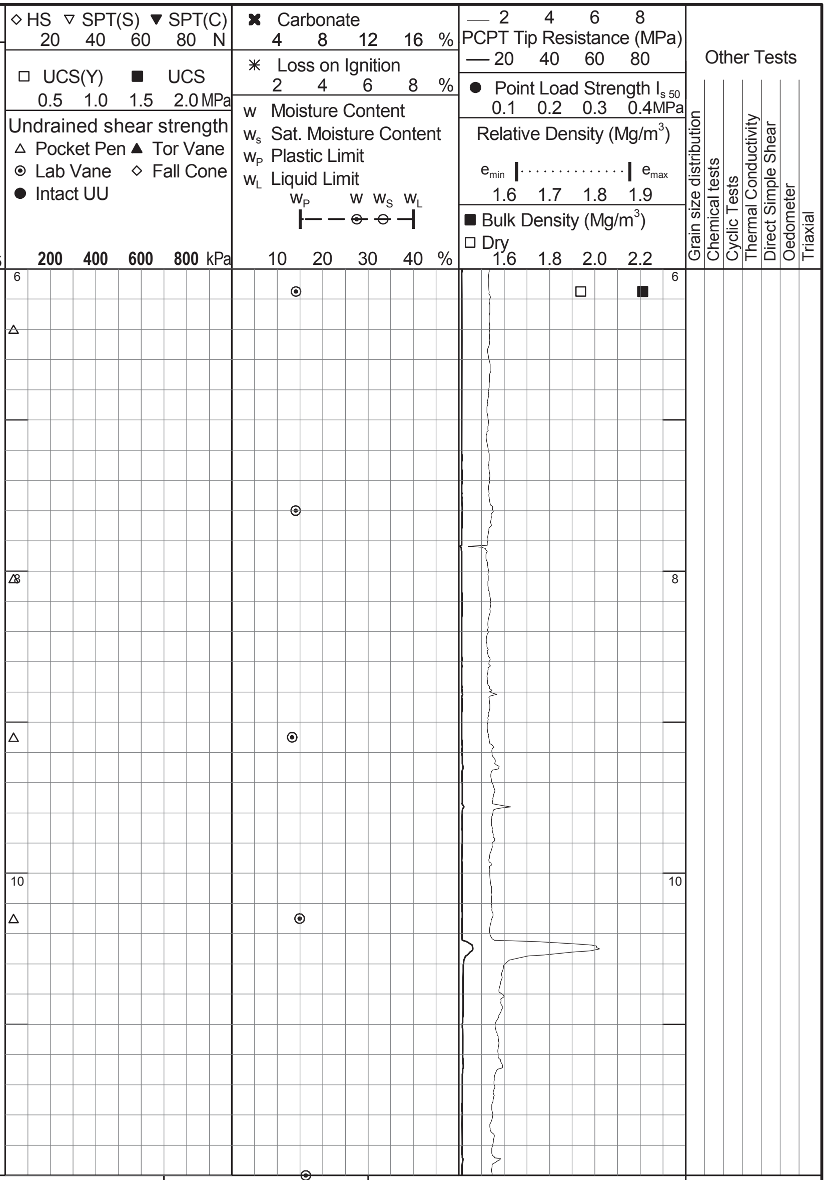
Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Description of *layers* and details	Deposit	Age
Dry rotary drilling (*continued*)	5-TW	6	5.1U	6.15-6.40			*CLAY TILL, silty, sandy, sl. gravelly, calcareous, grey (continued)*	Gl	Gc
			5.2U	6.40-6.57					
		7							
	6-TW		6.1U	7.60-7.90					
			6.2U	7.90-8.03					
Geobor-S	7-C	8	6.3D	8.05					
	8-C	9	8.1D 8.2D 8.3D	9.10					
		10							
	9-C								
		11							
	10-C								

Core Runs and Core Quality

TCR (%)	SCR (%)	RQD (%)
10		
42		
27		
33		

Fissures 1 ----- 5 | Induration 1 ----- 5



Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 2 / 9

W W W . G E O . D K

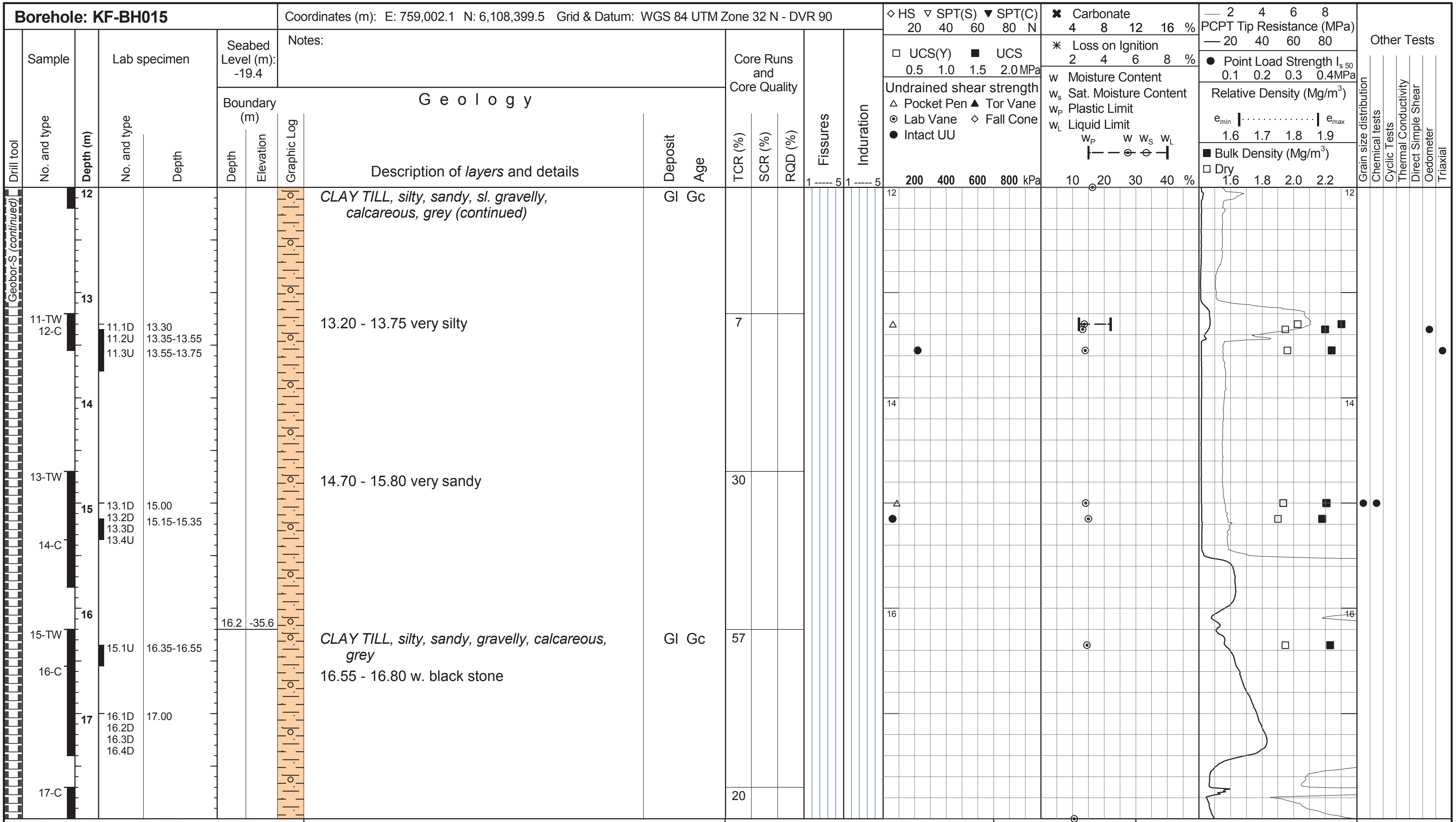
MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:24

Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:



Sample No. and type	Lab specimen No. and type	Depth
11-TW		
12-C	11.1D	13.30
	11.2U	13.35-13.55
	11.3U	13.55-13.75
13-TW		
	13.1D	15.00
	13.2D	15.15-15.35
	13.3D	
	13.4U	
14-C		
15-TW		
	15.1U	16.35-16.55
16-C		
	16.1D	17.00
	16.2D	
	16.3D	
	16.4D	
17-C		

Boundary Depth	Elevation	Description of layers and details	Deposit	Age
		CLAY TILL, silty, sandy, sl. gravelly, calcareous, grey (continued)	Gl	Gc
		13.20 - 13.75 very silty		
		14.70 - 15.80 very sandy		
16.2	-35.6	*CLAY TILL, silty, sandy, gravelly, calcareous, grey*	Gl	Gc
		16.55 - 16.80 w. black stone		

TCR (%)
7
30
57
20

Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 3 / 9

W W W . G E O . D K

Borehole: KF-BH015

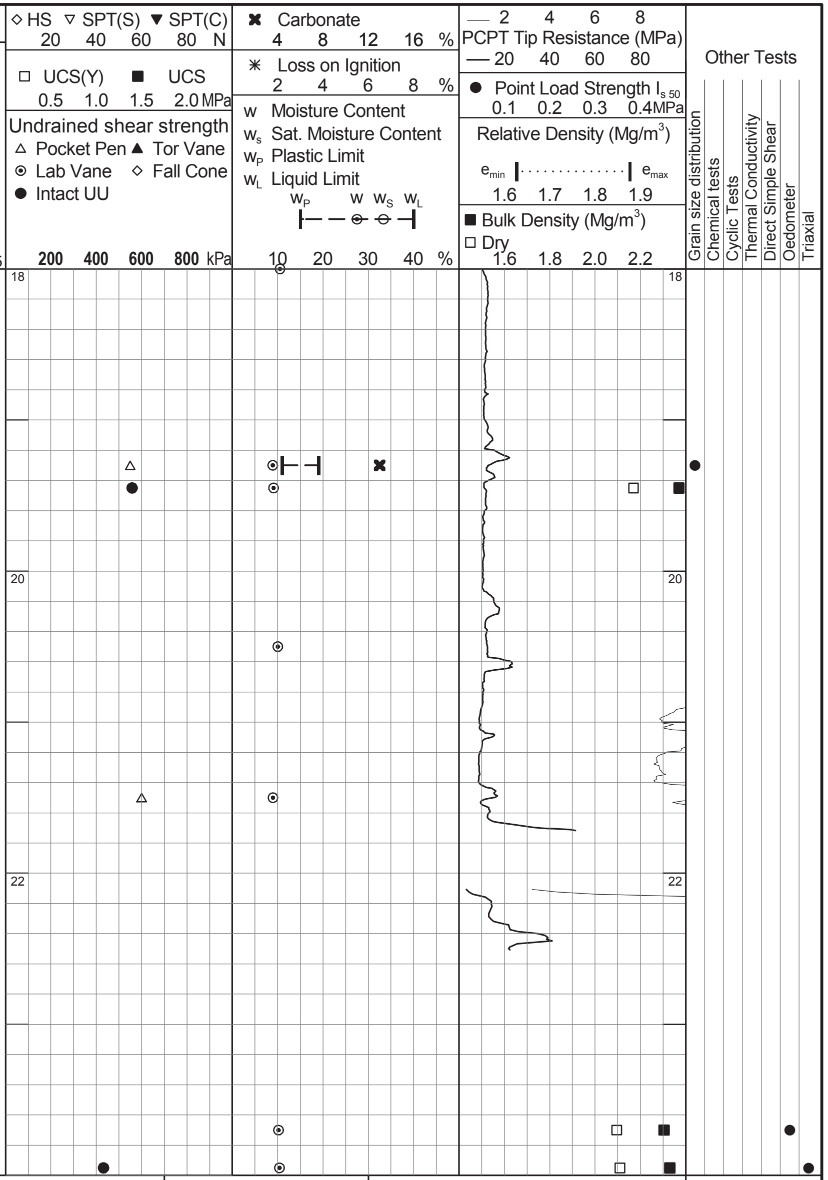
Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Description of *layers* and details	Deposit	Age	TCR (%)
Geobor-S *(continued)*		18					*CLAY TILL, silty, sandy, gravelly, calcareous, grey (continued)*	Gl	Gc	
		19								
	18-C		18.1D 18.2D 18.3D 18.4D 18.5U	19.30 19.45-19.70						50
		20			20.2	-39.6				
	19-C						*CLAY TILL, silty, very sandy, gravelly, calcareous, grey* 20.20 - 28.20 very sandy	Gl	Gc	70
		21								
	20-C		20.1D 20.2D 20.3D 20.4D	21.50			21.50 - 21.70 w. black stone			55
		22								
	21-C									90
		23								
	22-C		22.1U	23.70-23.95						87

Core Runs and Core Quality: TCR (%), SCR (%), RQD (%); Fissures 1 ----- 5; Induration 1 ----- 5



Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 4 / 9

W W W . G E O . D K

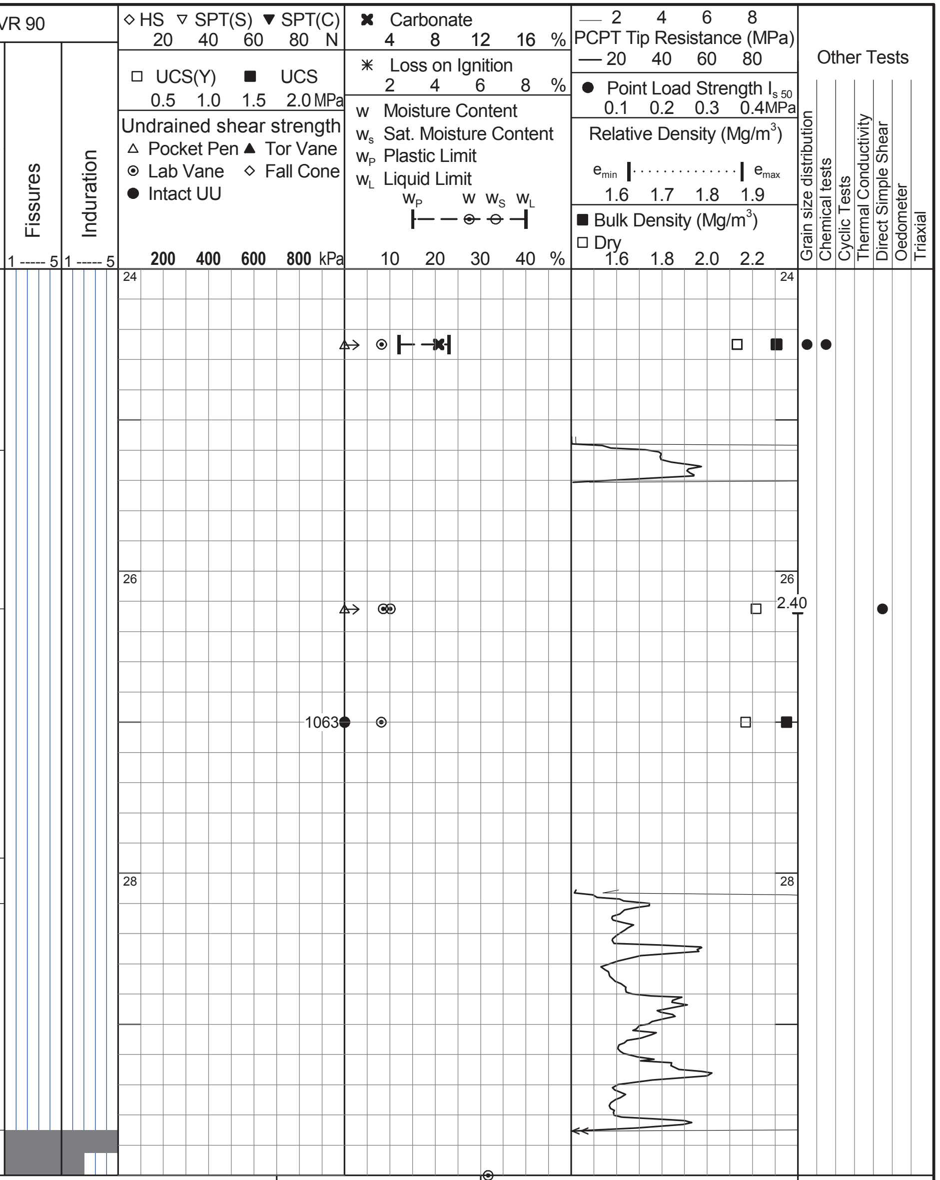
Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth (m)	Boundary Elevation (m)	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		24	22.2U	23.95-24.20			*CLAY TILL, silty, very sandy, gravelly, calcareous, grey (continued)*	Gl	Gc			
			22.3D 22.4D 22.5D 22.6D 22.7D	24.50			24.20 - 24.35 w. black stone					
	23-C	25								62		
	24-C	26	24.1U	26.25-26.50						100		
			24.2U	26.50-26.75								
			24.3U	26.75-27.00								
		27	24.4U	27.00-27.30								
	25-C	28								100		
	26-C				28.2	-47.6	*LIMESTONE, muddy, white*	Ma	Ct	17		
		29										
	27-C						29.70 - 29.85 w. many black flint nodules			33		0



Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 5 / 9

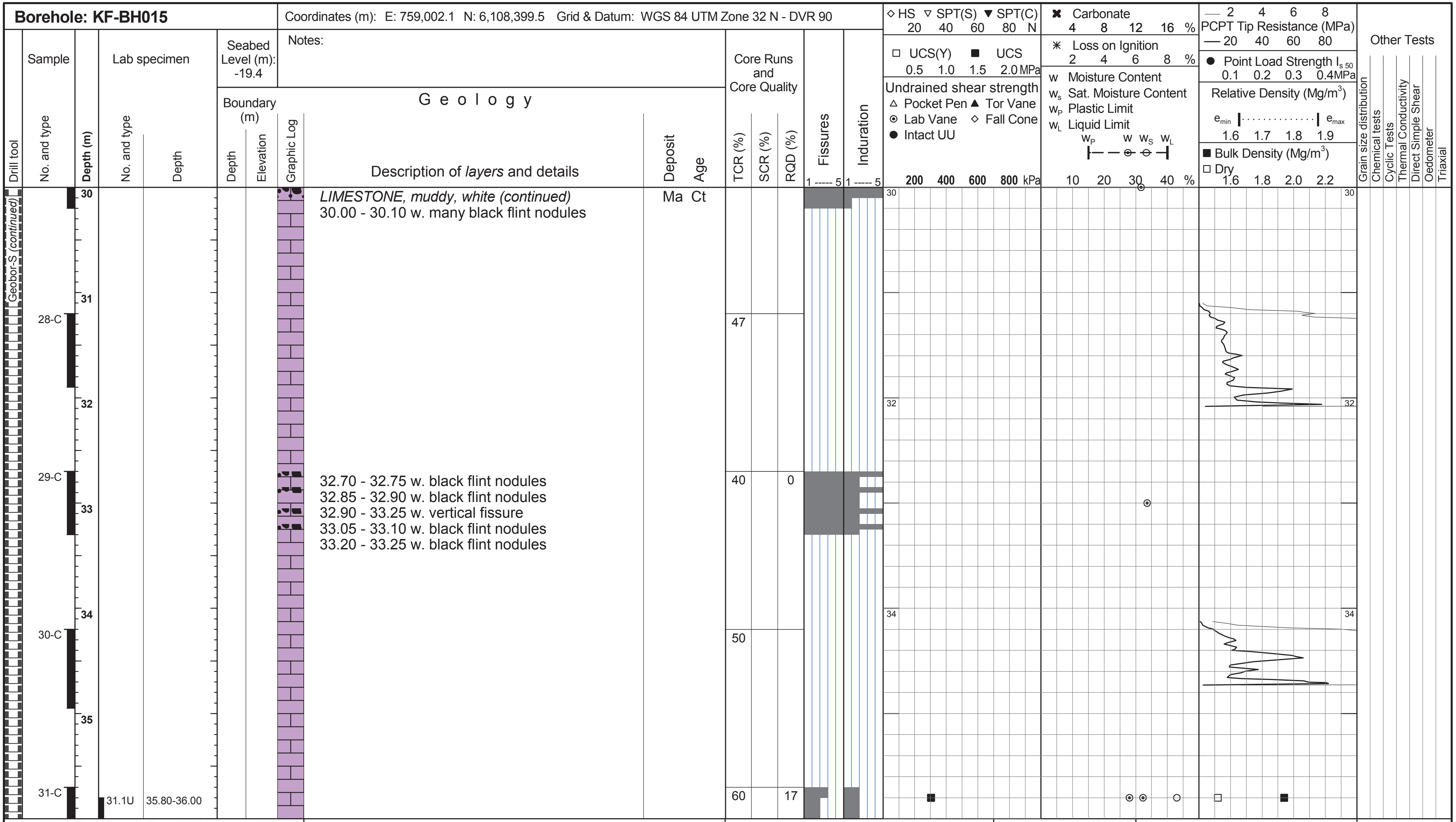
W W W . G E O . D K

Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:



LIMESTONE, muddy, white (continued) Ma Ct

30.00 - 30.10 w. many black flint nodules

32.70 - 32.75 w. black flint nodules
32.85 - 32.90 w. black flint nodules
32.90 - 33.25 w. vertical fissure
33.05 - 33.10 w. black flint nodules
33.20 - 33.25 w. black flint nodules

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:24

WWW.GEO.DK

Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 6 / 9

Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:

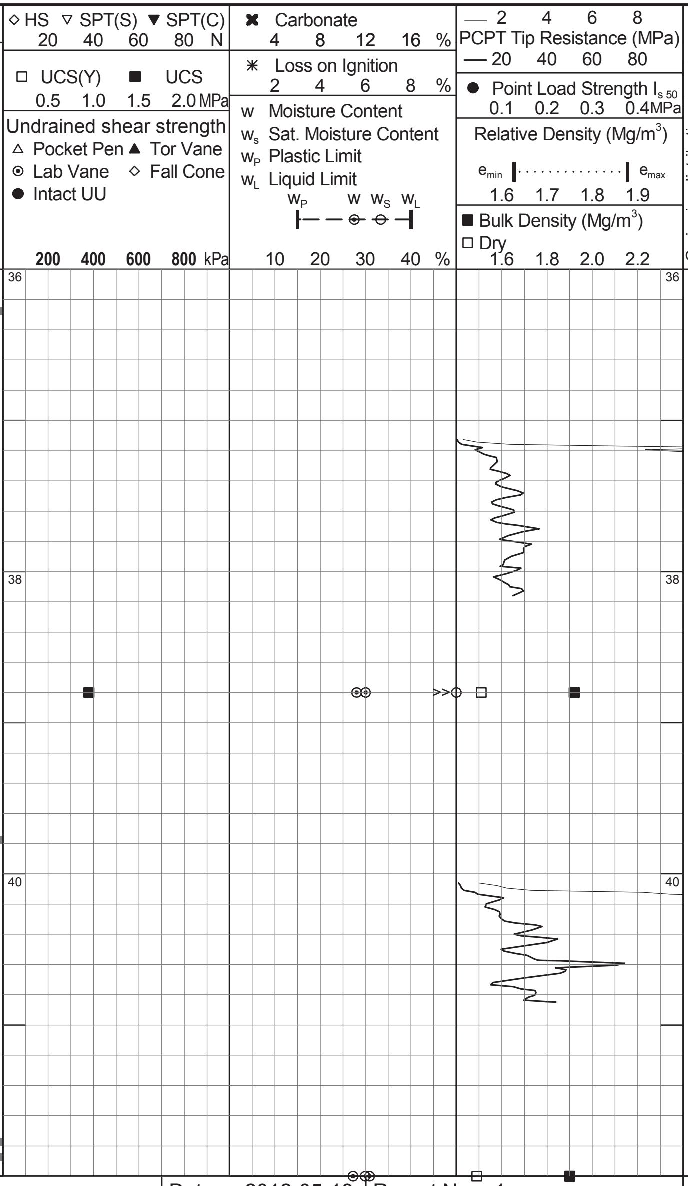
G e o l o g y

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary Depth	Boundary Elevation	Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		36					*LIMESTONE, muddy, white (continued)*	Ma	Ct			
							36.20 - 36.30 w. many black flint nodules					
	32-C	37					37.20 - 37.30 w. many black flint nodules			51		
		38					37.90 - 37.97 w. many black flint nodules					
	33-C		33.1U	38.80-39.10						73		20
		39	33.2D	39.15			38.90 w. 20 mm marl seam 39.00 w. 15 mm marl seam 39.15 - 39.30 w. many marl flasers 39.30 - 39.75 w. vertical fracture 39.50 - 39.75 w. fossilized sea urchin spines 39.75 - 39.80 w. black flint nodule					
	34-C	40					40.20 - 40.25 w. black flint nodule			77		
		41										
	35-C						41.75 - 41.80 w. black flint nodule			37		0

Core Runs and Core Quality

Fissures 1 ----- 5

Induration 1 ----- 5



Other Tests

- Grain size distribution
- Chemical tests
- Cyclic Tests
- Thermal Conductivity
- Direct Simple Shear
- Oedometer
- Triaxial

WWW.GEO.DK

Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 7 / 9

MUL-LOG&B1UK-B1&03-FIH / 36642 KRIEGERS FLAK.GPJ / 2013-10-16 08:24

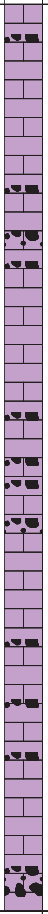
Borehole: KF-BH015

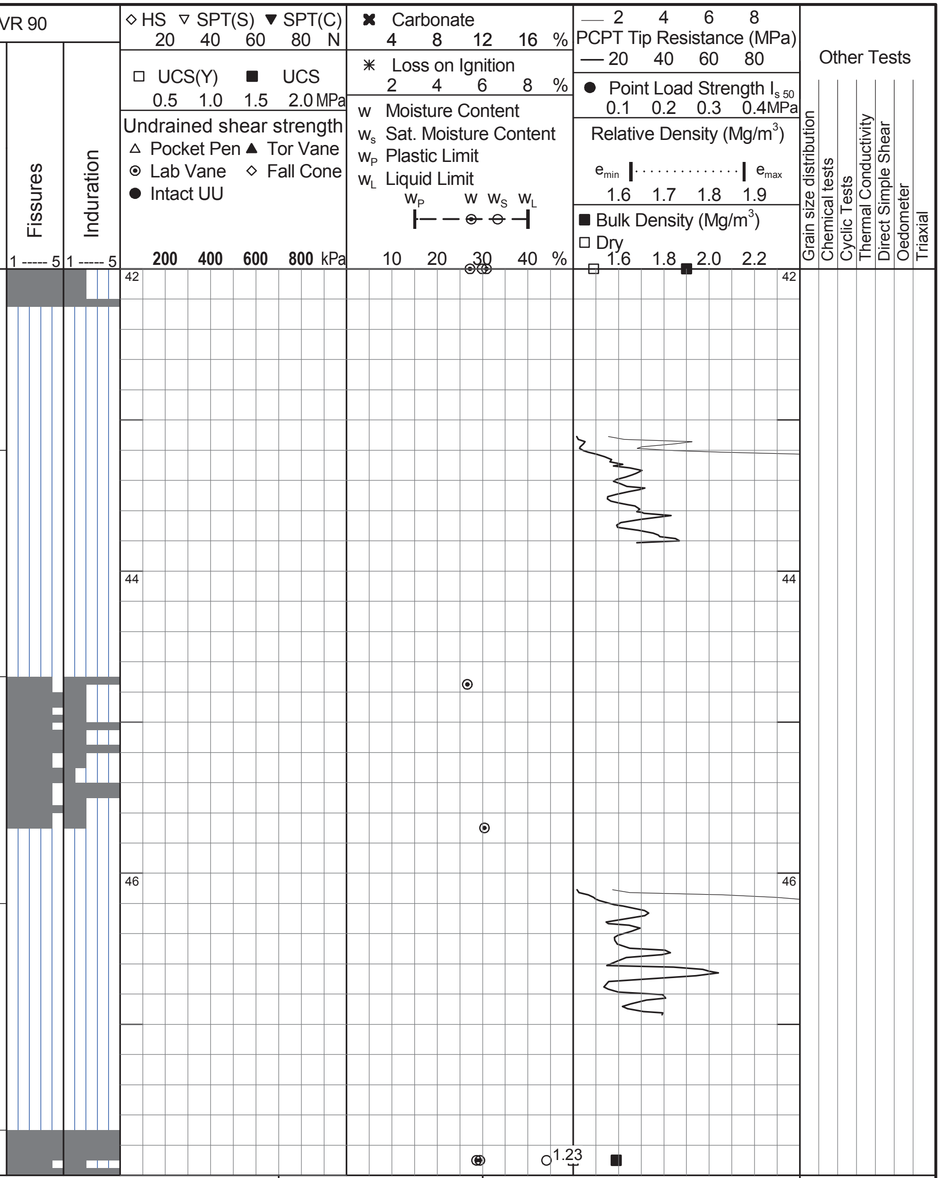
Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:

Drill tool	Sample No. and type	Depth (m)	Lab specimen No. and type	Lab specimen Depth	Boundary (m) Depth	Boundary (m) Elevation	Geology: Description of *layers* and details	Deposit	Age	TCR (%)	SCR (%)	RQD (%)
Geobor-S *(continued)*		42	35.1D	42.00			41.85 - 41.90 w. black flint nodule	Ma	Ct			
							LIMESTONE, muddy, white (continued)					
							42.20 - 42.25 w. black flint nodule					
		43										
	36-C						43.20 - 43.25 w. black flint nodules			57		
							43.50 - 43.60 w. black flint nodule					
							43.70 - 43.75 w. black flint nodule					
		44										
	37-C						44.70 - 44.75 w. black flint nodule			67		0
		45					45.00 - 45.05 w. black flint nodule					
							45.15 - 45.20 w. black flint nodule					
							45.40 - 45.50 w. many black flint nodules					
		46										
	38-C						46.20 - 46.25 w. black flint nodule			57		
							46.60 - 46.65 w. black flint nodule					
		47					46.95 - 47.00 w. black flint nodule					
	39-C		39.1D	47.90			47.70 - 47.90 w. black flint nodules			30		0





W W W . G E O . D K

Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 8 / 9

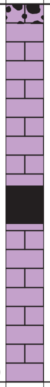
Borehole: KF-BH015

Coordinates (m): E: 759,002.1 N: 6,108,399.5 Grid & Datum: WGS 84 UTM Zone 32 N - DVR 90

Seabed Level (m): -19.4

Notes:

Drill tool	Sample: No. and type	Depth (m)	Lab specimen: No. and type	Lab specimen: Depth	Boundary (m): Depth	Boundary (m): Elevation	Graphic Log	Geology: Description of *layers* and details	Deposit	Age	Core Runs and Core Quality: TCR (%)	SCR (%)	RQD (%)	Fissures 1 ----- 5	Induration 1 ----- 5
Geobor-S *(continued)*		48						*LIMESTONE, muddy, white (continued)* 48.00 - 48.13 w. black flint nodules	Ma	Ct					
		49													
	40-C							49.20 - 49.45 w. black flint layer			60				
		50													
					50.5	-69.9									



◇ HS ▽ SPT(S) ▼ SPT(C) 20 40 60 80 N

☐ UCS(Y) ■ UCS 0.5 1.0 1.5 2.0 MPa

Undrained shear strength
△ Pocket Pen ▲ Tor Vane
⊙ Lab Vane ◇ Fall Cone
● Intact UU
200 400 600 800 kPa

✖ Carbonate 4 8 12 16 %

✳ Loss on Ignition 2 4 6 8 %

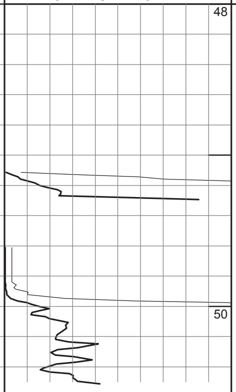
w Moisture Content
w_s Sat. Moisture Content
w_P Plastic Limit
w_L Liquid Limit
w_P w w_S w_L
10 20 30 40 %

— 2 4 6 8 PCPT Tip Resistance (MPa)
— 20 40 60 80

● Point Load Strength $I_{s\,50}$ 0.1 0.2 0.3 0.4 MPa

Relative Density (Mg/m^3)
e_{min} ⊢·········⊣ e_{max}
1.6 1.7 1.8 1.9

■ Bulk Density (Mg/m^3)
☐ Dry
1.6 1.8 2.0 2.2



Other Tests: Grain size distribution, Chemical tests, Cyclic Tests, Thermal Conductivity, Direct Simple Shear, Oedometer, Triaxial

Borehole Log: KF-BH015	Drilled: SKA/ELF	Date: 2012-05-13	Report No.: 1
Project: 36642 Kriegers Flak	Prepared: KRA/RSC	Date: 2013-05-12	Encl No.:
Remarks:	Checked:	Date:	Rev :
	Approved: LAR	Date: 2013-08-08	Page: 9 / 9

GEO
W W W . G E O . D K

Danish Ministry of Climate,
Energy and Utilities

Geological survey of
Denmark and Greenland (GEUS)

Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

GEUS is a research and advisory
institution in the Danish Ministry
of Climate, Energy and Utilities