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The Darss Sill, hydrographic threshold in the southwestern Baltic: Late Quaternary geology and recent sediment dynamics

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Abstract—About 73% of the water exchange between the Baltic and the North Seas is via the Darss Sill. Joint Danish and German marine geological investigations, including shallow seismic surveys and sediment sampling, have been carried out in the Darss Sill area between 1989 and 1991. Results from these studies and unpublished archive data from the Institute of Baltic Sea Research, Warnemünde, are presented. These show that the entire Quaternary sedimentary sequence in most of the area is at least 40 m thick. A zone of glacial till outcropping between Denmark and Germany belongs to the Late Weichselian ice marginal line G ("Velgaster Staffel"). The formation of this line caused the damming of a pre-existing (sub)glacial meltwater discharge system. At the beginning of the Baltic Ice Lake formation, a deep and presently buried channel incised in this ice marginal line was part of a (glacio)fluvial drainage system with discharge towards the northeast, i.e. into the Baltic Ice Lake. During the Baltic Ice Lake transgression damming of the Darss Sill occurred due to accumulation of sandy sediments within this channel. On the other hand, the recent Kadet Channel was only occasionally overflown during the Baltic Ice Lake highstand maximum, which was 18 m BSL (below present sea level) in the Darss Sill area. The main erosion and deepening of the Kadet Channel began during the Ancylus Lake highstand maximum.

At present, sediment transport on the Darss Sill is governed by northeasterly inflow of saline bottom waters in the entire area from the Kadet Channel to the German coast. Baltic outflow affects the seabed at shallower depth in the Danish sector. Large-scale current-induced bedforms in the area include, amongst others, sandwaves with a height of 5 m. Changes of the bedforms observed indicate a maximum bottom flow speed of 70–100 cm s^{-1}, both for inflow and for outflow.

INTRODUCTION

In the hydrographic terminology the Darss Sill is referred to as the relatively shallow (<20 m) area between the Danish Isle of Falster and the German peninsula of Darss (Fig. 1). The main morphological features are the Gedser Reef with a water depth of less than 10 m, and the Kadet Channel with a maximum water depth of 32 m (Fig. 2). The strait is the main gateway for Baltic water exchange. It separates two basins where fine-grained sediments accumulate, i.e. the Mecklenburg Bay to the southwest and the Arkona Basin to the northeast (WINN *et al.*, 1983; LANGE, 1984). Before the Littorina transgression,

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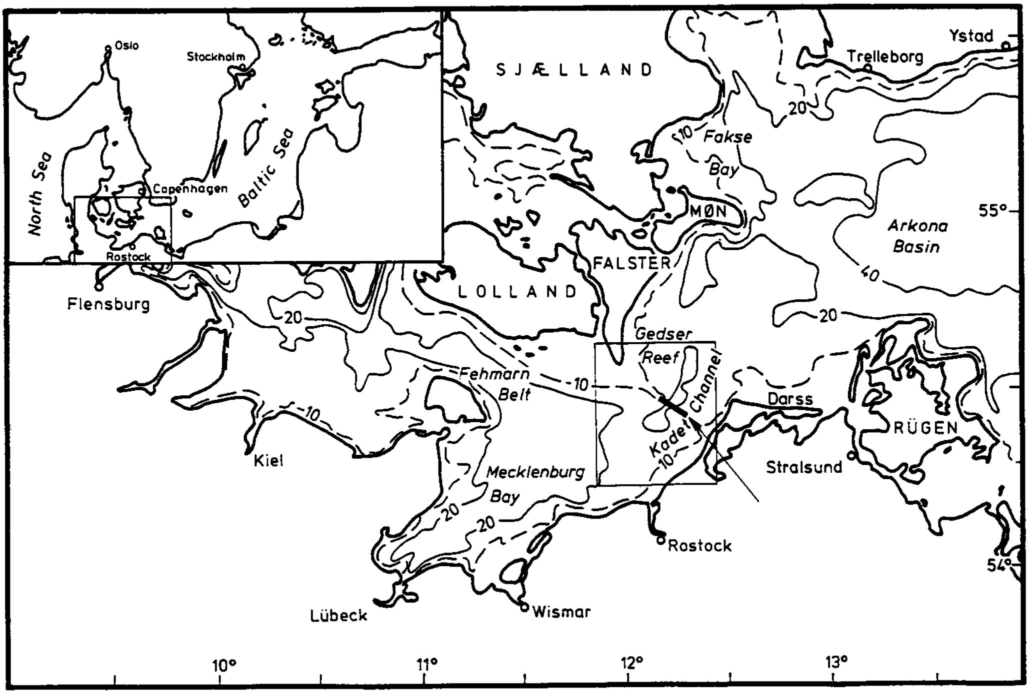

Fig. 1. Regional setting of the study area with main topographic features. Arrow indicates location of the cross section through the Kadet Channel with bathymetry (Fig. 2) and hydrography (Fig. 3).

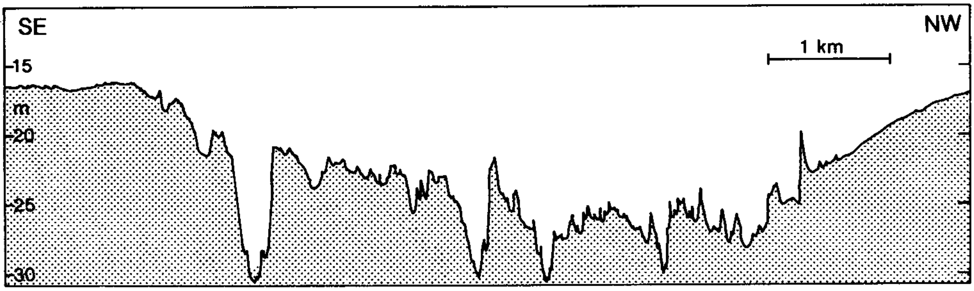

Fig. 2. Topographic cross section of the Kadet Channel between 54°26.39'N, 12°16.95'E and 54°28.98'N, 12°11.21'E.

damming by the Darss Sill played an important role in the environmental history of the entire Baltic Basin (e.g. Björck and Digerfeldt, 1991).

Numerous marine geological studies have been carried out in the western Baltic, particularly in Kiel Bay (e.g. Seibold *et al.*, 1971; Winn *et al.*, 1988) and in the Danish straits between Kattegat and Baltic Sea (Winn, 1974; Werner and Newton, 1975; Kuijpers, 1985). However, little has been known of the Late Quaternary sub-bottom structure of the Darss Sill area. The geological information available in this area was primarily based on the results from vibrocoring (KOLP, 1965), later combined with data from seismo-acoustical profiling. In the 1980s the Institute of Marine Research in Warnemünde introduced side-scan sonar for the study of surface sediments and sediment transport processes.

A marine geological mapping programme off Falster initiated by the Danish Ministry of the Environment and the changed political situation in the former GDR made conditions favourable for starting a joint Danish–German study of the area in 1989. The study area is shown in Fig. 1. The investigations included shallow seismic surveys and sediment sampling. Results from these studies together with unpublished German archive data are presented here.

The main purpose of this paper is to provide information on the Late Quaternary subbottom structure and development of the Darss Sill. Moreover, attention will be paid to recent sediment dynamics in this hydrographically crucial area.

HYDROGRAPHY AND GEOLOGICAL SETTING

The Baltic Sea is characterized by a positive balance of run-off water and precipitation vs evaporation (BROGMUS, 1952). This normally results in an outflow of Baltic water of low salinity (<15‰) through the Danish straits towards the Kattegat. In spring particularly, melt water discharge from the surrounding mainland raises the outflow rate through the Fehmarn Belt and the Sound. As it is known from various investigations made in the Fehmarn Belt and Darss Sill area (WEIDEMANN, 1948; WYRTKI, 1954; LANGE, 1975; MATTHÄUS *et al.*, 1982), outflow is mainly concentrated in the upper part of the water column and usually follows the coast of the Danish isles of Falster and Lolland. Inflow of more saline water from the Kattegat is concentrated in the southern part of the study area and in the deeper part of the Kadet Channel (Fig. 3). This generalized current pattern is subject, however, to considerable variation. This variation is not only due to local weather conditions, but can also be related to windshear and atmospheric pressure variations over the northeast Atlantic, North Sea and Baltic (DICKSON, 1973). According to MATTHÄUS *et al.* (1982), 73% of the Baltic Sea water exchange is through the Darss Sill area, the remaining part through the Sound between Zealand (Denmark) and Sweden. Tidal currents are negligible in the southwestern Baltic (KIELMANN *et al.*, 1973). Studies performed elsewhere in the Danish straits indicate that bottom currents sufficiently strong to induce significant sediment transport are intermittent and occur only relatively rarely on a monthly–yearly time-scale (KUIJPERS, 1985). Following KOLP (1965), in geological terminology the Darss Sill is restricted to a 10–12 km wide zone extending from the isle of Falster to Fischland-Darss, Germany. The zone is characterized by the presence of submarine till outcrops which were believed to belong to the Late Weichselian ice marginal zones G and H according to RICHTER (1937). The marginal zone G ("Velgaster Staffel") was formed between 14,000 and 13,000 yr BP as a product of the Late Weichselian deglaciation process (LIEDTKE, 1975; AURADA, 1988).

Since the final deglaciation, the development of the entire Baltic basin has been closely related to the balance between eustatic sea level rise and isostatic uplift of Scandinavia (SAURAMO, 1958). With the retreat of the ice, meltwater lakes formed in the Baltic basin, creating the Baltic Ice Lake (around 11,500 yr BP). Its outlet was situated at the northern part of the Sound. Further melting of the ice in central Sweden and the following sea level rise caused the first postglacial marine transgression (Yoldia Sea; 10,000 yr BP) in the

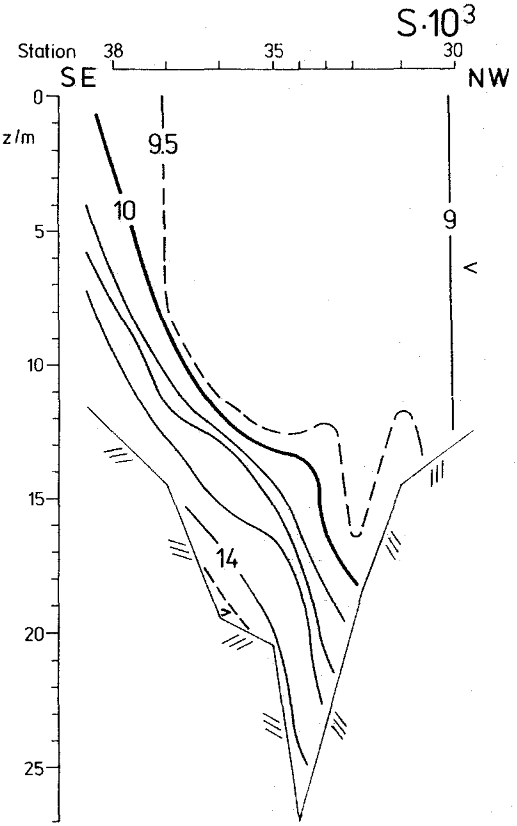

Fig. 3. Typical hydrographic conditions (salinity distribution) in a cross section of the Kadet Channel area (from Fennel and Sturm 1992).

Baltic area. The Yoldia Sea was connected to the open sea by a strait through central Sweden. Continuing uplift of Scandinavia, however, finally resulted in the closing of this marine inlet. Again, fresh water conditions were established in the Baltic basin and the Ancylus Lake was formed (9250 yr BP). In context with the final development of the Ancylus Lake, special attention was given to the Darss Sill by Sauramo (1958) and Kolp (1986). The latter author proposed a dramatic overflow of Ancylus Lake waters over the Darss Sill to have occurred in the upper Preboreal around 8800 yr BP. According to this author the incision of the Kadet Channel can be ascribed to this event. In addition, Björck and Digerfeldt (1991) suggest that erosion of the Darss Sill began at the culmination of the Ancylus transgression and continued during the following rapid regression. At the Boreal–Atlantic boundary, about 8000 yr BP, saline waters started to overflow the sills and thresholds of the Danish straits (Littorina Transgression), inducing the marine conditions in the southwestern Baltic that still prevail at present.

At the beginning of the Littorina Transgression a limnic–brackish environment was initially formed in the southwestern part of the Baltic. At least since 6500 yr BP the environmental regime of the Baltic has been directly related to the marine conditions prevailing in the Danish straits (Lange, 1984).

Table 1. *Development stages of the Baltic Sea* (*adapted from* Dietrich *and* Köster, 1974)

Stage	Years BP	Salinity	Index form
Coverage by inland ice	>14,000	—	—
Baltic Ice Lake	>10,000	fresh water	—
Yoldia Sea	10,000–9250	brackish–marine water	*Yoldia artica*
Ancylus Sea	9250–7100	fresh water	*Ancylus fluviatilis*
Littorina Sea	7100–4000	brackish–marine water	*Littorina littorea*
Limnea Sea	4000–1500	brackish water	*Limnea ovata*
Mya Sea	1500–present	brackish water	*Mya arenaria*

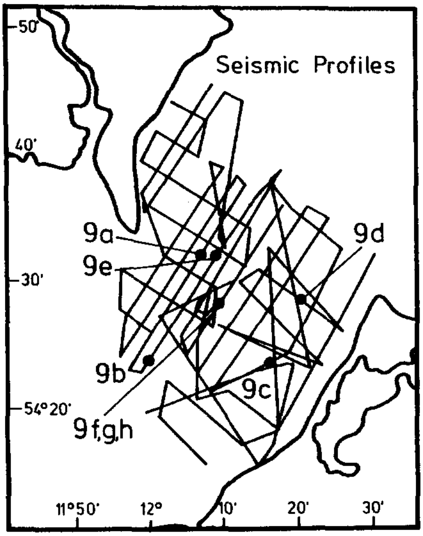

Fig. 4. Boomer tracks from the surveys run in 1989–1991, arrows indicate locations of seismic records shown in Fig. 9.

METHODS

The investigations were made with the research vessels *Alexander von Humboldt* and *Professor A. Penck* (Warnemünde); *Marie Miljφ* (Korsφr); and *Littorina* (Kiel).

Sediment sampling with a 6 m- and a 4 m-vibrocorer (Fig. 5), side-scan sonar (100 kHz) and acoustical profiling (15 and 210 kHz) surveys were carried out with the former two vessels. Furthermore, more than 1000 sites have been examined by scuba divers. These investigations included a general description and sampling of the seabed surface as well as the penetration of surface sediment layers using a 6 m flushing tube in order to determine sub-bottom depth of the glacial till.

Surface sediment sampling by grab, boxcorer or 1 m-gravity corer and shallow seismic surveys using a boomer (600–2500 Hz) (Fig. 4), side-scan sonar (100 and 500 kHz) and various sediment echosounders (3.5, 18 and 30 kHz) were performed with the latter two vessels. Positioning during these surveys was by the Syledis navigation system, providing an accuracy generally better than 10 m. This positioning system was also applied during

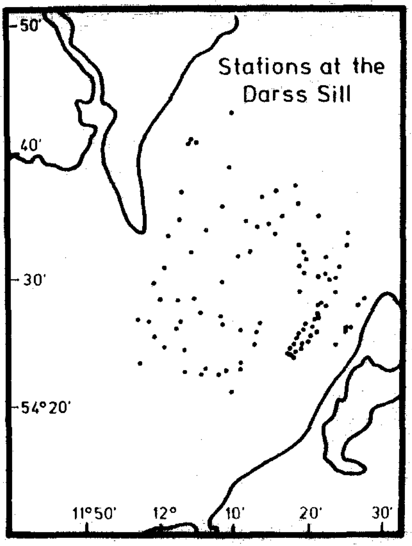

Fig. 5. Positions of the sediment sampling sites.

sediment sampling operations in the Danish sector. Other fieldwork was done with Decca navigation yielding a navigational accuracy not better than approximately 50 m, or more recently also with more accurate GPS.

Nine hundred and one sediment samples were analyzed for grain size distribution, either by sieving or by the pipette method (KÖHN, 1927). The analyses included also heavy mineral investigations on selected samples. ^{14}C age determinations have been done at the Physical Institute of the "Bergakademie Freiberg", Germany.

RESULTS AND DISCUSSION

Glacial deposits

Outcrops of glacial till are widespread east of Falster and in a zone extending in southeasterly direction from Falster to the German coast (Figs 6 and 7). Due to erosion by winnowing processes, large areas of the till outcrops are covered by a thin (<0.3 m) layer of coarse lag sediment.

Some of the boomer records from south of the Kadet Channel indicate the presence of a continuous strong reflector at sub-bottom depths of 40–80 m. This depth corresponds with the depth of the top of the Pre-Quaternary as given for this area by TER-BORCH (1987). The Pre-Quaternary surface consists here of Maastrichtian chalk (SORGENFREI, 1951; GELLERT, 1960).

Vibrocoring east of Falster revealed the presence of a chalk layer at only 5 m sub-bottom depth. This core was, however, obtained from an area near where the seabed morphology is formed by ice-pushed glacial diamict ridges. The shallow depth of the chalk layer in this case therefore most likely results from glacial thrusting processes.

The shallow seismic data further show that at least two moraines are present, of which the older one in large areas is characterized by displaying a sub-horizontal truncated surface.

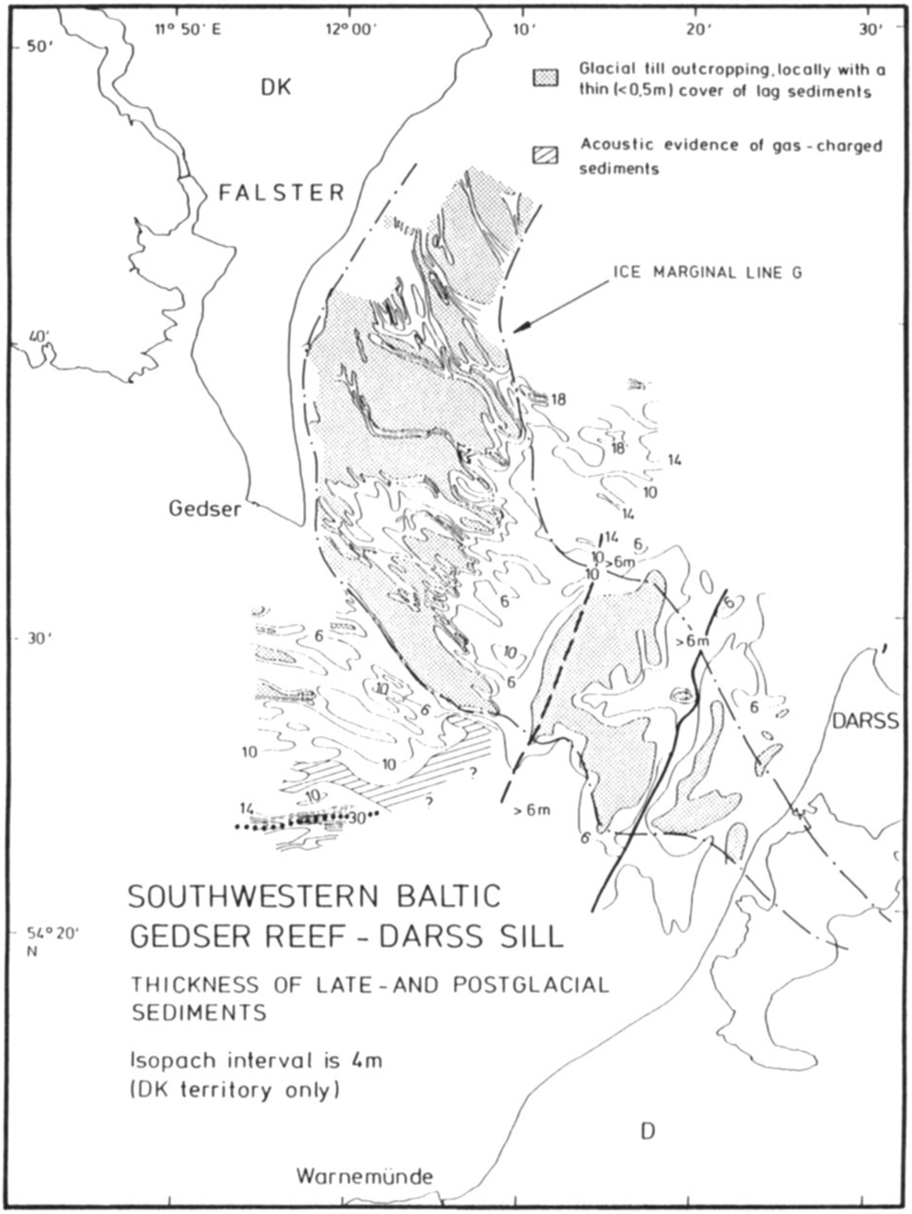

Fig. 6. Thickness of Late- and Postglacial sediments based on the results of seismoacoustical profiling (see Fig. 4). and 1778 diver observations. Location of the Kadet Channel is indicated by a dashed line, whereas the location of the deep buried channel is shown by a thick solid line. The dotted line indicates the position of the deep buried valley southwest of Gedser Reef. The outcropping till marks the course of the ice marginal line G (Velgaster Staffel).

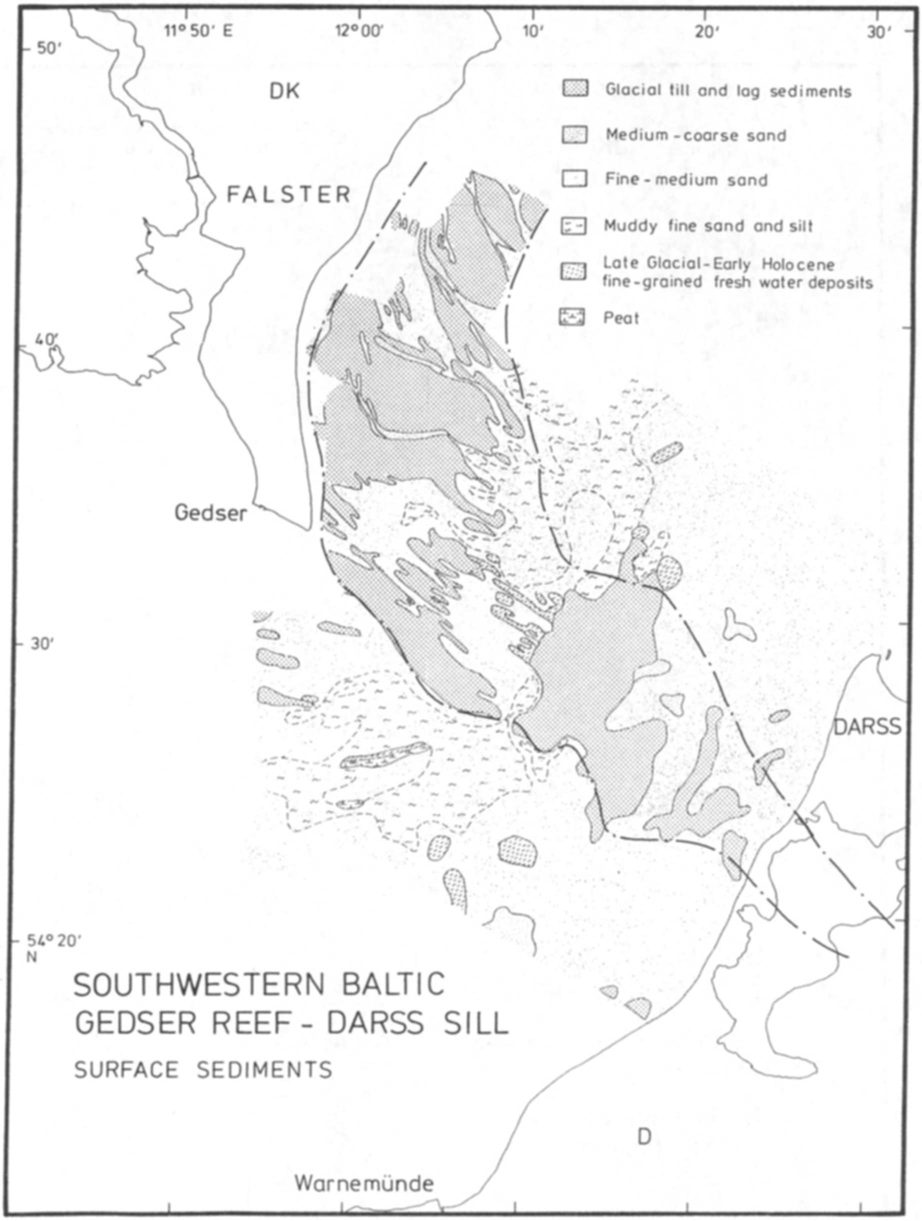

Fig. 7. Surface sediment distribution based on the results of 901 sieving analyses, 1778 diver observations and seismoacoustical profiles (see Fig. 4).

In addition, a channel system incised in the underlying older moraine could be detected in the immediate vicinity of Gedser Reef [Fig. 9(a)]. The channel floor of this system is found at about 30 m subbottom depth. This depth is slightly smaller than the subbottom depth of the floor of a large buried glacial valley present southwest of Gedser Reef [Fig. 9(b)]. The location of this large buried valley is shown in Fig. 6 (see dotted line). The

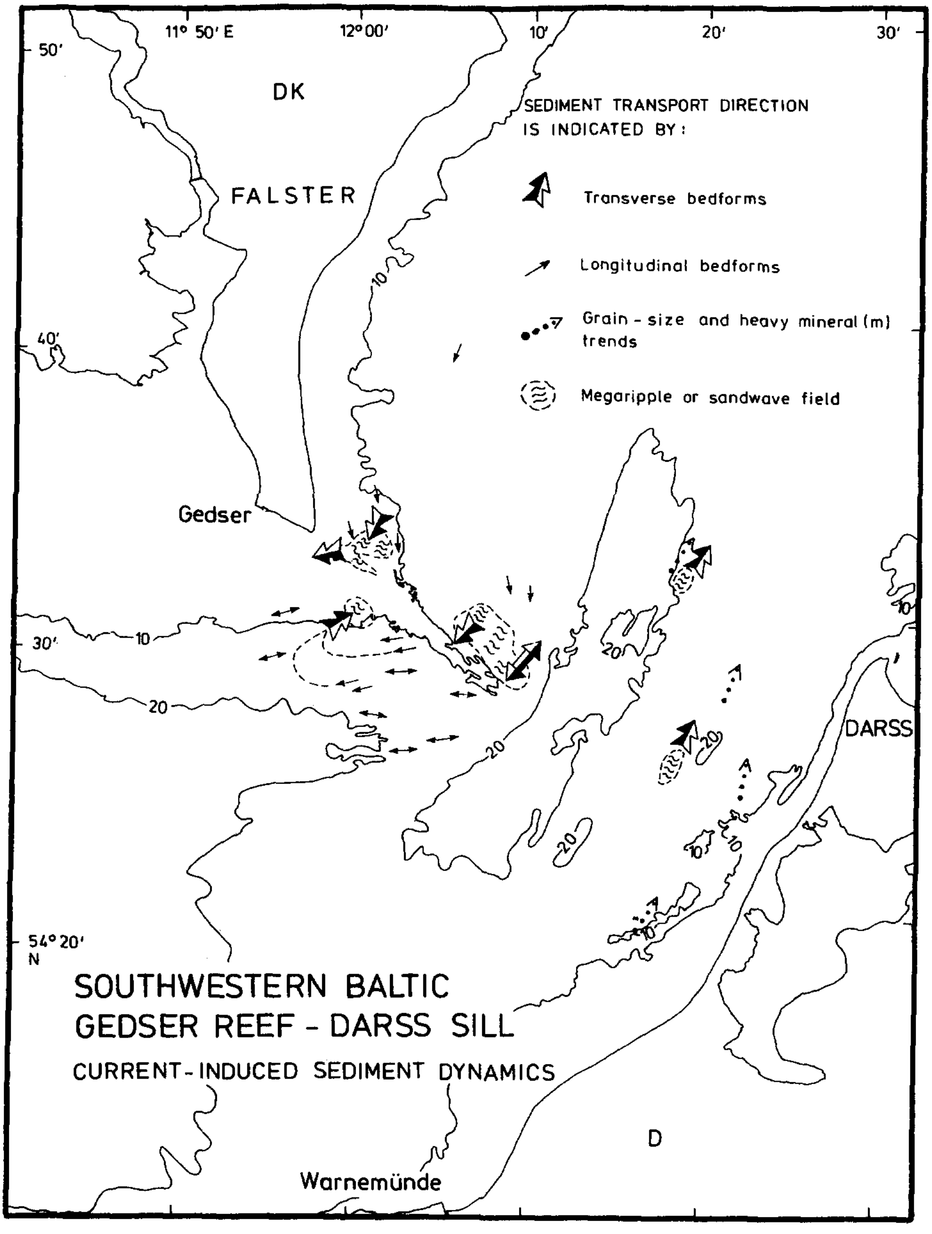

Fig. 8. Distribution of current-induced bedforms, grain-size and heavy mineral trends.

acoustic characteristics of the valley infill indicate the presence of a layered, predominantly fine-grained, sediment sequence in the central part of this valley. It is proposed that prior to the formation of ice marginal line G a (sub)glacial channel system existed, which was dammed when the line G was formed. Accumulation of mainly fine-grained lake sediments must have started in the valley southwest of Gedser Reef after the damming.

A second buried channel incised in the glacial deposits has been detected south of the recent Kadet Channel [Fig. 9(c) and (d)]. This buried channel runs southwest–northeast perpendicular across the ice marginal line G. Sub-bottom depth of the channel floor likewise is at around 30 m, which implies a recent depth of about 50 m (BSL). This is 20 m deeper than the maximum depth of the Kadet Channel valley (32 m BSL, Fig. 2).

The available shallow seismic information shows that this buried channel and the channel system in the surroundings of Gedser Reef were not connected.

We suggest that the buried channel south of the Kadet Channel was the main water discharge system in the period immediately after the formation of ice marginal line G.

Development after the final deglaciation

The Baltic Ice Lake stage. When dealing with the situation immediately after the final deglaciation (*ca* 12,000 yr BP), it should be noted that, corrected for isostatic subsidence, the original topographic level of all features was about 10 m above the present level (KÖSTER, 1961; KOLP, 1981). On the other hand, the central Baltic basin floor to the northeast was deeper than its present level.

Throughout most of the investigation area, grey and brown-reddish varved clays occur locally in small basins. Northeast of Gedser Reef these sediments and associated organic-poor silts and sands are more wisespread. We interpret this type of sediment to have been deposited in glacial meltwater lakes immediately after retreat of the ice. WINN *et al.* (1983) report that prior to the younger Dryas similar conditions, with small glacially formed lakes, existed in the adjacent Mecklenburg Bay.

More widespread glaciolacustrine sediments northeast of Gedser Reef were probably deposited in a large preglacial lake. This lake extended from the area south of Møn (FREDNINGSSTYRELSEN, 1974) to the east, and was part of the Baltic Ice Lake (JENSEN, in press). Assuming a transgressive evolution of the initial Baltic Ice Lake the latter author demonstrates that the sedimentary sequence representative of the initial Baltic Ice Lake (*ca* 11,500 yr BP) in the area east of Møn is confined to depths in excess of 20 m BSL. KOLP (1979, 1986) reports from the deeper Arkona Basin east of the present study area that varved glaciolacustrine deposits occur at depths below 45 m BSL. We may therefore conclude that the buried channel south of Kadet Channel with its valley floor at about 50 m BSL was part of the drainage system at the beginning of the Baltic Ice Lake transgression.

The main question is how long this system was active, and whether the system could have been an outlet of the Baltic Ice Lake.

Unlike the fine acoustic stratification of the glacial valley infill found southwest of Gedser Reef, acoustic characteristics of the channel infill south of Kadet Channel suggest the dominance of coarser, presumably sandy sediments. Vibrocoring in this area showed the occurrence of thick grey or grey-brownish sand, partly of fluviatile origin. A shallow seismic line run in an ENE direction at low angle to the channel axis reveals an acoustically transparent bottom part of the infill [Fig. 9(c)]. Weakly westward dipping reflectors are present in the upper part below 2 m sub-bottom depth (16–17 m BSL) in the east and below 6 m sub-bottom depth in the west. Seismic crossings of the channel revealed a steep sharp-cut erosional wall at its south side [Fig. 9(d)], whereas such a feature is lacking at the north side.

In addition, airgun data from the area between the Kadet Channel and the isle of Rügen (FLODÉN, University of Stockholm, unpublished data) indicate the presence of sandy distal delta deposits within a 30–40 m thick glaciolacustrine sequence (JENSEN, in press). When

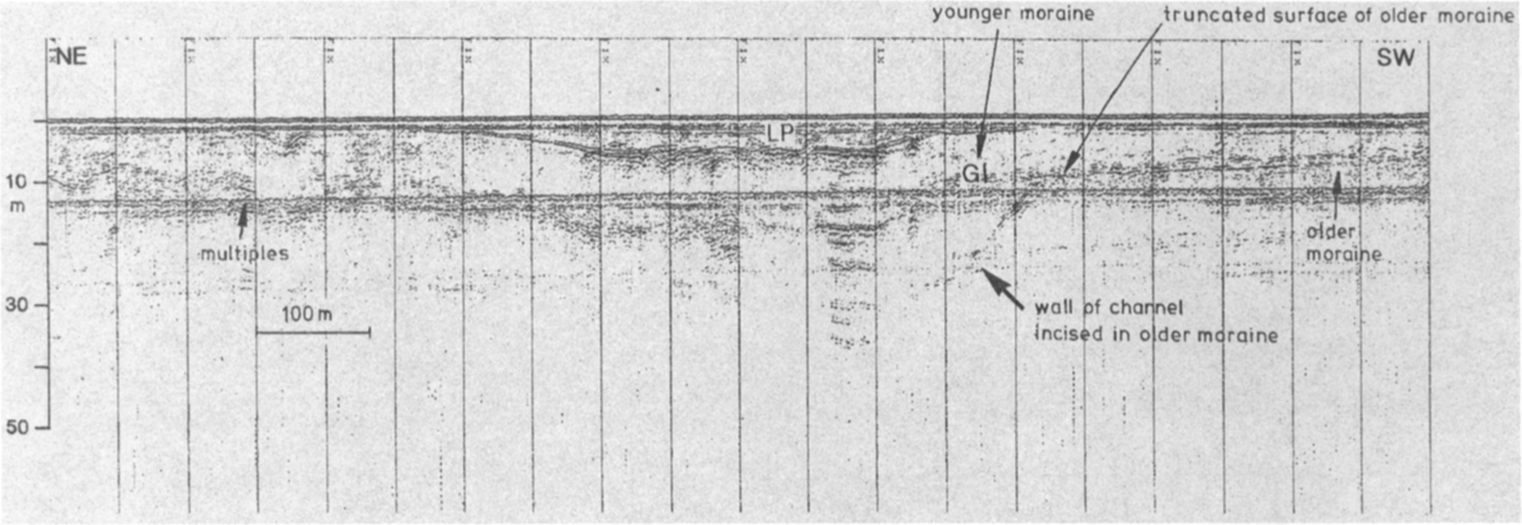

Fig. 9. Various examples of boomer, pinger (3.5 kHz) and side-scan sonar records. Location of the records is indicated on Fig. 4. (a) channel system incised in older moraine underneath the Gedser Reef moraine (Boomer section; LP = Late and postglacial deposits; Gl = glacial till).

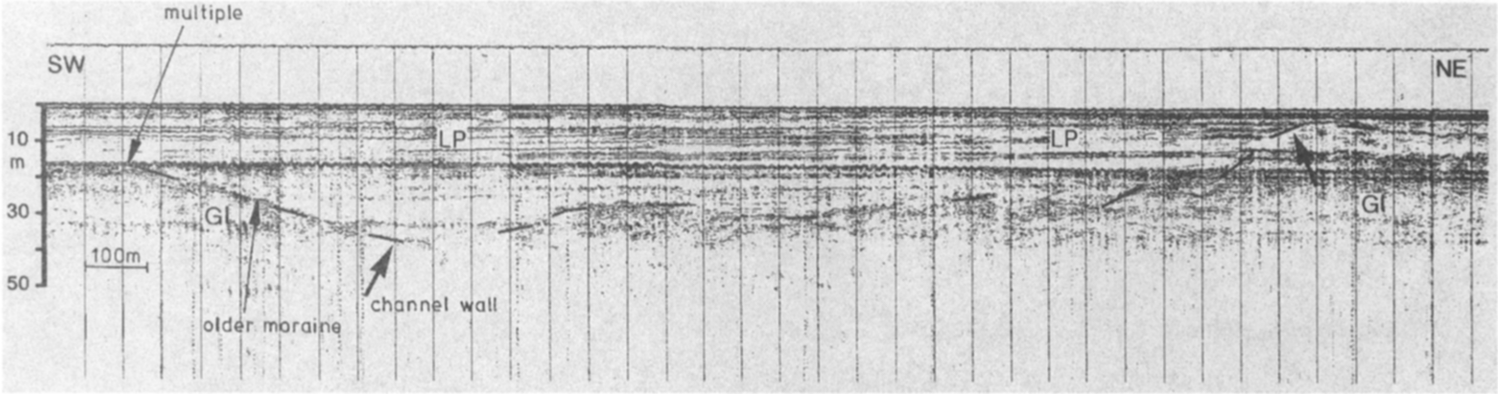

Fig. 9(b). Buried glacial valley southwest of Gedser Reef (Boomer section; LP = Late and postglacial deposits; Gl = glacial till).

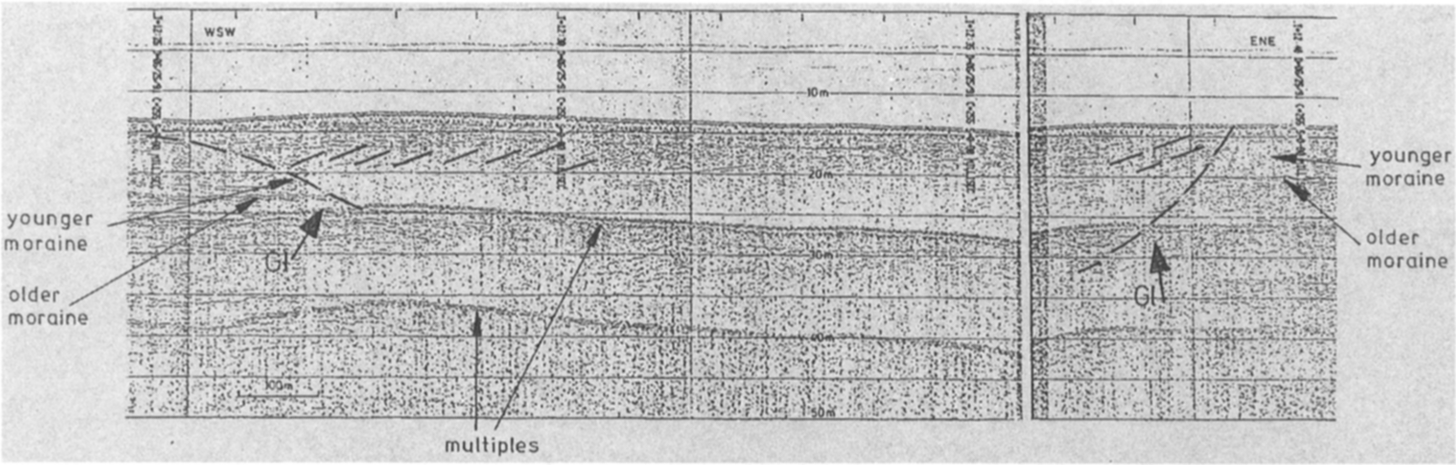

Fig. 9(c). Boomer section run at low angle to the axis of the deep buried channel south of Kadet Channel. Note weakly westward dipping reflectors in upper part of the infill (Gl = glacial till).

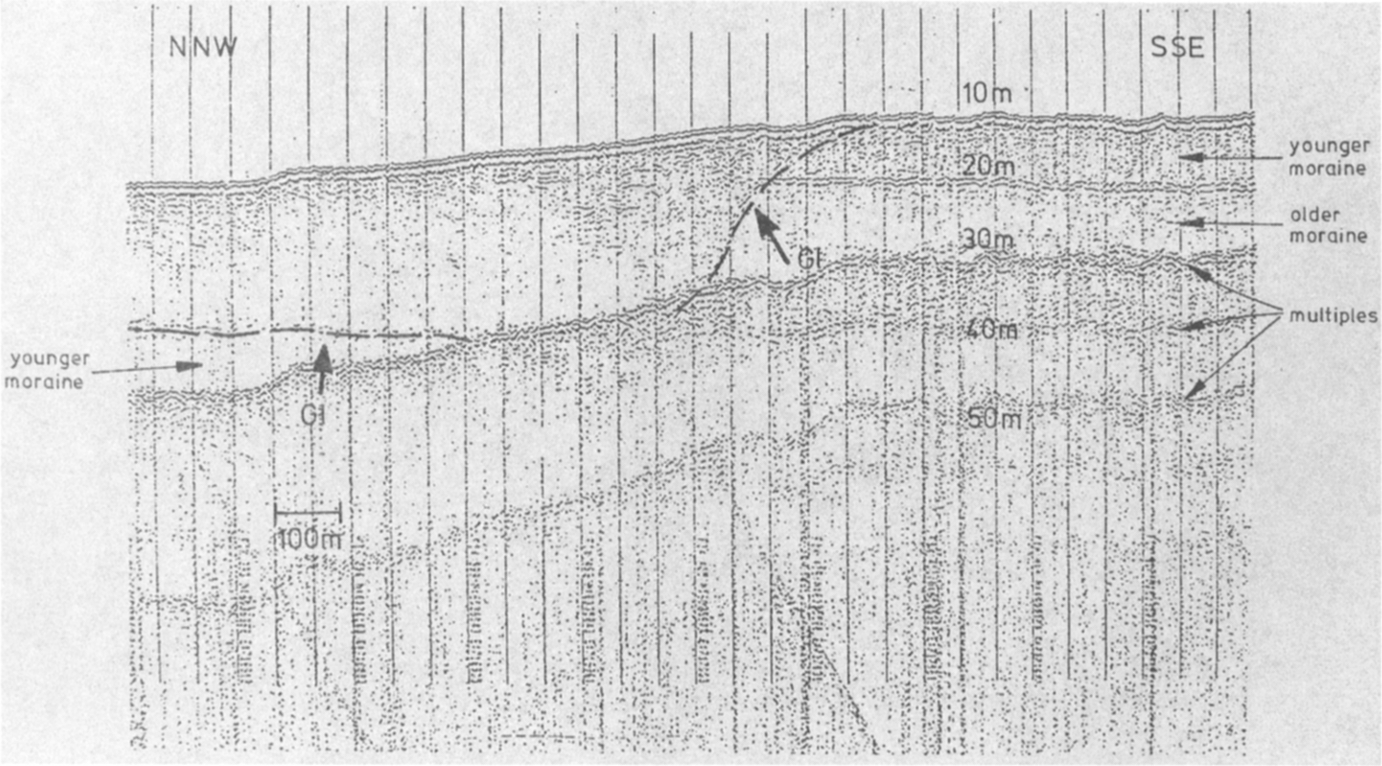

Fig. 9(d). Cross section (boomer) of the buried channel south of Kadet Channel (Gl = glacial till).

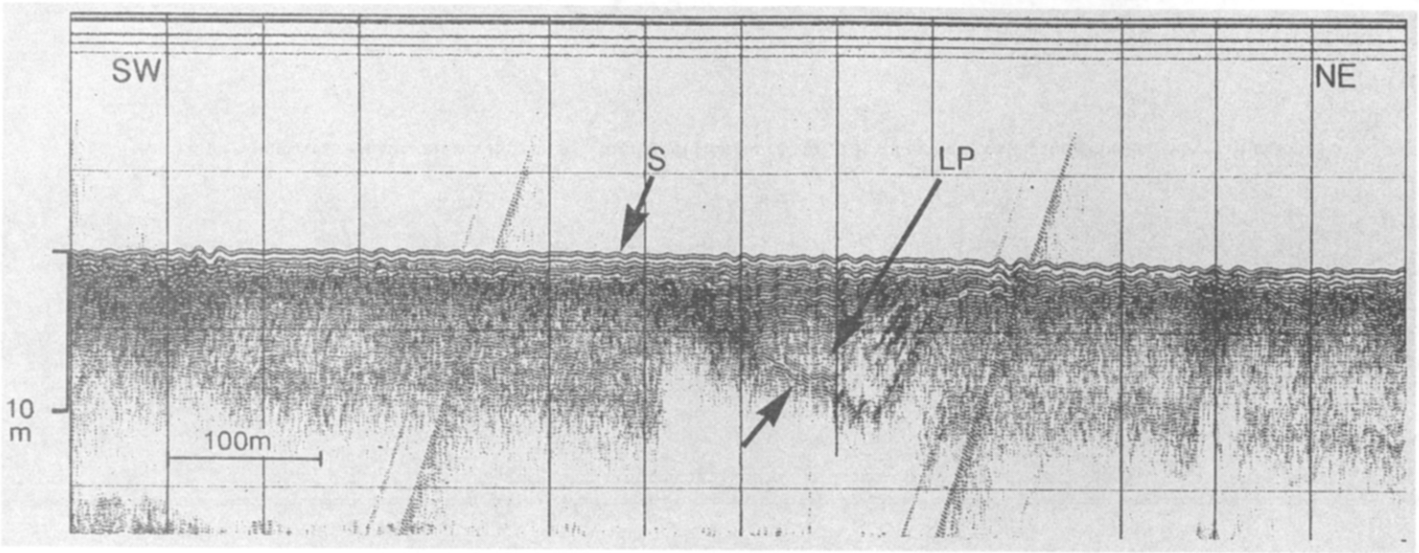

Fig. 9(e). Pinger section of small buried valley east of Falster (LP = Late and postglacial deposits; S = marine sand).

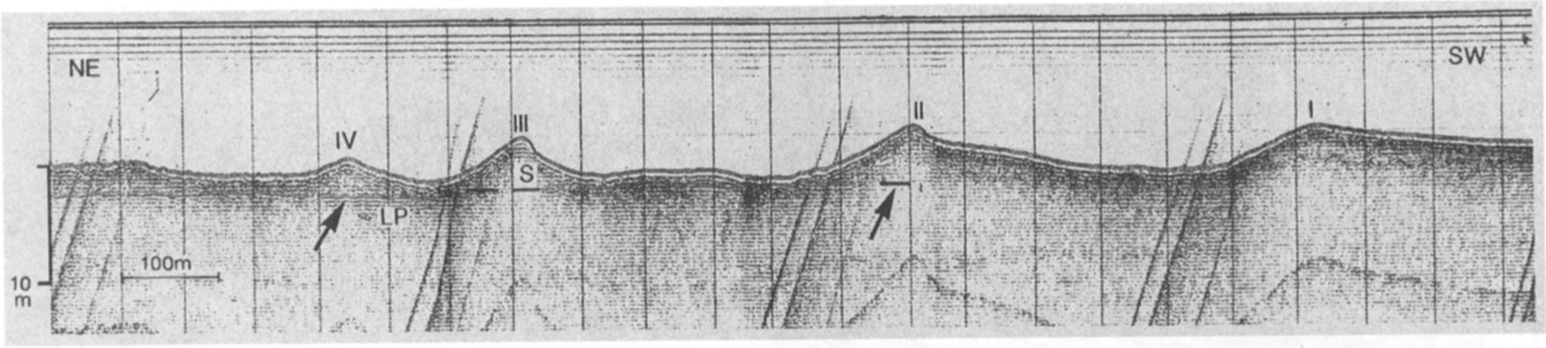

Fig. 9(f). Large sandwaves immediately northeast of Gedser Reef (Pinger record; LP = late and postglacial deposits; S = marine sand).

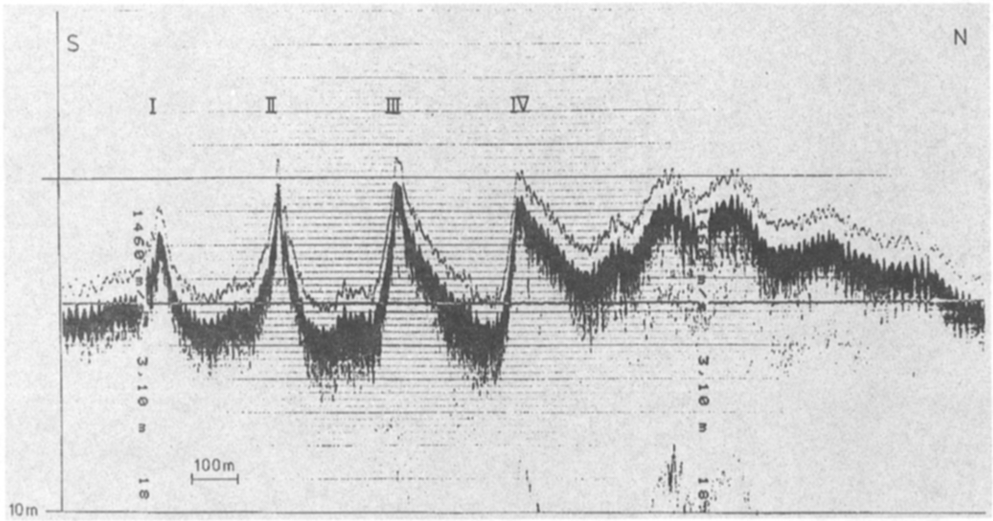

Fig. 9(g). Echosounder (210 kHz) profile of sandwaves shown in Fig. 9(f) from April 1991 indicating the disappearance of superimposed asymmetric bedform profiles with southwest leeside slopes in the top region of sandwaves No. II and III. Note different scales.

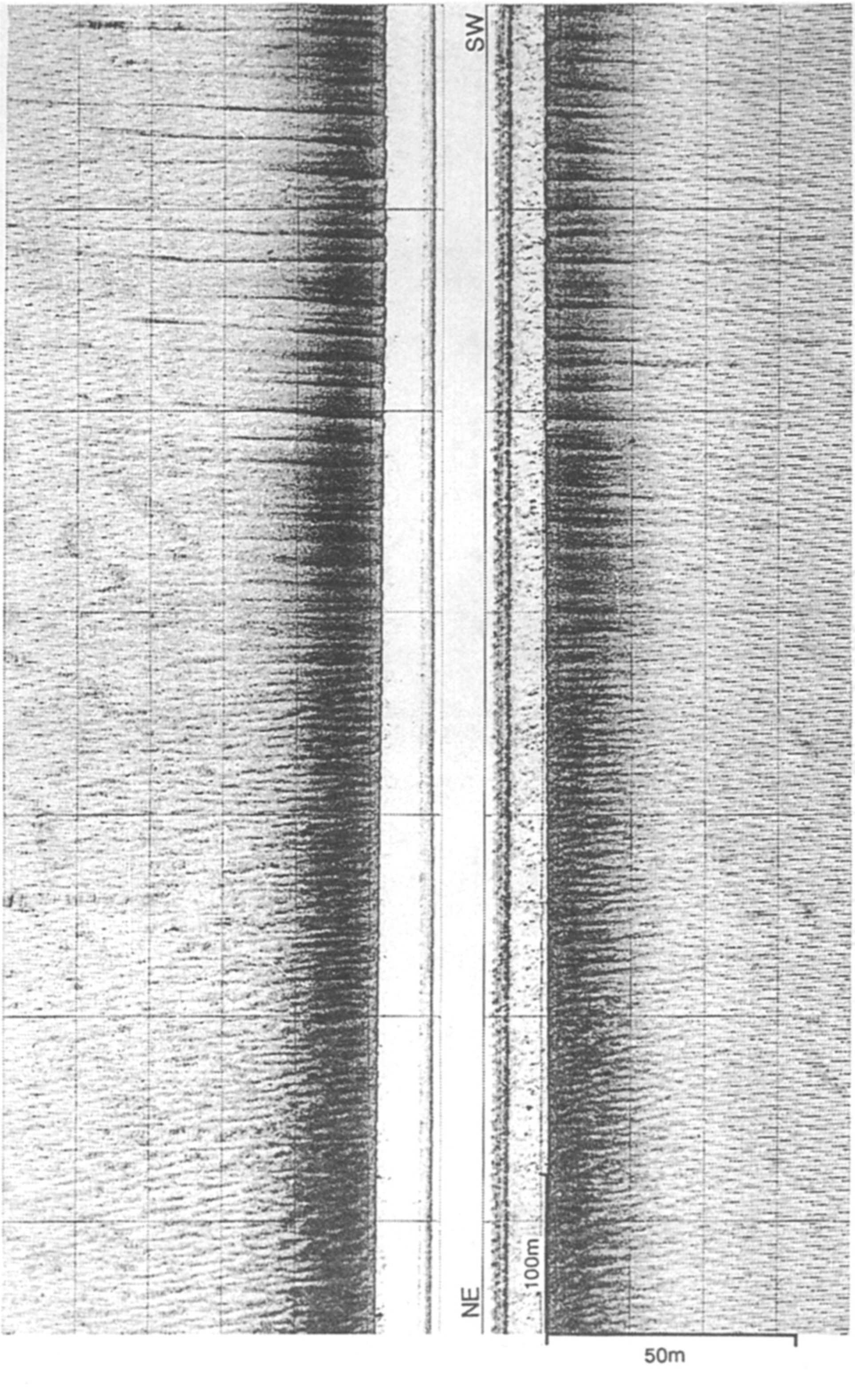

Fig. 9(h). Megaripples from the same area as 9f detected in the 1989 survey (Side Scan Sonar image; 100 kHz), a generally flat seafloor was found during the survey in April 1991.

attributing asymmetric channel erosion to the Coriolis effect, we thus may conclude that the channel was part of a (glacio)fluviatile system discharging towards the northeast. Consequently it did not function as an outlet of the initial Baltic Ice Lake. Within this context we should bear in mind that at that time, because of the different position relative to the zero-line of isostatic movement, a more pronounced regional topographic gradient towards the central Baltic must have existed. According to BERGSTEN and NORDBERG (1992) the initial Baltic Ice Lake was drained by a passage in the Öresund Strait between 12,700 yr BP until 10,300 yr BP.

JENSEN and STECHER (1992) demonstrated that the Baltic Ice Lake transgression was continuous until it reached a level of 13–14 m BSL in the Fakse Bay in the period between 10,500 and 10,000 yr BP. The latter site located north of the isle of Møn is close to the zero-line of isostatic subsidence.

With the rise of the Baltic Ice Lake, the sedimentary regime in the channel at the Darss Sill must have changed, finally resulting in a situation in which accumulation of presumably sandy sediments from an apparent easterly source became prevalent. As referred to above, proof for such a sediment influx is given by the direction of dipping reflectors in the seismic section shown in Fig. 9(c).

Seismic data yield no evidence for reactivation or erosion of the buried channel south of the Kadet Channel at any later time. This suggests that the channel infill blocked the channel at about the time of the Baltic Ice Lake highstand maximum.

The upper boundary of the dipping reflectors near the east end of the buried channel [see Fig. 9(c)] suggest a Baltic Ice Lake highstand maximum not in excess of 16–17 m BSL in the Darss Sill area. This level is concluded to represent extreme highstand conditions.

The Ancylus Lake stage. The following Ancylus Lake transgressive phase reached its highstand maximum at 9200–9300 yr BP (SVENSSON, 1989; ERONEN *et al.*, 1990). At that time the lake level was lower than during the highstand maximum of the Baltic Ice Lake (JENSEN and STECHER, 1992). The latter study suggests, however, that the difference was probably not much more than several meters. BJÖRCK and DIGERFELDT (1991) concluded that the Kadet Channel could not have been eroded at the final drainage of the Baltic Ice Lake, but during the culmination of the Ancylus transgression and the following rapid regression.

If this is the case, the rate of isostatic subsidence of the Darss Sill area must have outmatched the water level difference between the Baltic Ice Lake and Ancylus Lake highstand maximum. KOLP (1965) reports a highstand maximum of the Ancylus Lake not shallower than 20 m BSL in the Darss Sill area. This is supported by our data, since otherwise the infill of the buried channel south of Kadet Channel with a similar maximum water depth would have been eroded. Further evidence may be provided by *in situ* remains of trees found at 18 m water depth on the Darss Sill, immediately southeast of Kadet Channel.

^{14}C age determination of these trees and the associated sediments in which they were found, yielded an age of near 9000 years BP. Erosion of Kadet Channel is proposed by BJÖRCK and DIGERFELDT (1991) to have started when the Ancylus transgression reached its maximum.

Since the buried channel was not reactivated or eroded during the Ancylus transgression maximum, we have to conclude, however, that the Kadet Channel at the beginning of this highstand must have had a greater (>16–17 m BSL) depth than the buried channel. According to the above, it thus must have been at least 20 m BSL. Consequently, during the previous Baltic Ice Lake highstand maximum (17 m BSL) damming of the Kadet Channel can not have been complete, and occasional overflow and a beginning of erosion must be assumed. A basic difference between the sedimentary conditions of the two channel systems was obviously the availability of sand. Whilst the buried channel functioned as a trap for sandy material from the pre-existing (glacio)fluvial delta system, the possibility of sediment supply to the more distant Kadet Channel must have been less.

We agree, however, with BJÖRCK and DIGERFELDT (1991) in attributing the main erosion of the Kadet Channel to the Ancylus overflow event rather than ascribing it to the Littorina transgression. If the depth difference between the Kadet Channel and the buried channel would still have been small during the Littorina transgression, the buried channel rather than the Kadet Channel would have been eroded. This can be concluded from the fact that easily erodible unconsolidated sediments form the infill of the buried channel, whereas the Kadet Channel has been formed in glacial till. Moreover, as illustrated in Fig. 8, the recent bottom flow pattern indicates that inflow is particularly concentrated in the southern part of the study area where the buried channel is found. It is also evident that during a situation in which the Kadet Channel apparently was the only outlet of the Ancylus Lake, erosion must have been very strong here. Thus, it must be concluded that during the Ancylus period most of the deepening of the Kadet Channel from initially at least 20 m to present 32 m BSL occurred.

East of Falster a number of small buried valleys and depressions have been found at water depths of less than about 15 m [Fig. 9(e)]. These valleys running in a northwest–southeast direction doubtless represent the drainage system from the period before the area was flooded by the Littorina transgression. A similar drainage system was found in the western Mecklenburg Bay at water depths of less than 20 m (WINN *et al.*, 1983). This depth difference may for most part be attributed to greater subsidence in the latter area. On the other hand, the valleys east of Falster may have originated in the period of the Baltic Ice Lake highstand, when damming by the Darss Sill would have caused a shallowing of the erosional base east of the sill. Thickness of the sediment infill of these small valleys in both areas normally is less than 4–5 m. Maximum thickness found in the present study area is 9 m. The valley infills contain a wide variety of sediments ranging from clay to sand, gravel and coarser material.

Significant accumulation (>3 m) of marine sediments deposited after the Littorina transgression is only found in the immediate vicinity of Gedser Reef and in the deeper northeastern part of the area north of the Kadet Channel. Sediment in the latter area consists of silty and muddy fine sand, whereas the typical sediment near Gedser Reef is fine sand.

Thus, when dealing with the sedimentary sequence covering the glacial till (Fig. 6), it should be noted that Holocene marine sediments form only a minor part of the entire sequence.

The area southwest of Gedser Reef is characterized by the presence of gas-charged sediments. Normally, in the Baltic Sea shallow gas is formed in thick fine-grained marine sediments. In our case, however, the gas most likely originates from buried peat or other non-marine organic-rich layers.

Occurrence of such layers that were formed between Allerød and Atlantic time has been described by KOLP (1965).

Surface sediments and sediment dynamics

As outlined before, the oldest sediment exposed on the seafloor is glacial till, which is found over large areas east of Falster and in a zone extending from Falster to the German coast (Fig. 7). Most of the till is covered by a thin (<0.3 m) layer of coarse lag sediment.

Late Glacial and Early Holocene clays, silt and sand as well as peat outcrops also occur. At the German side only locally small outcrops of peat have been found, whereas in the Danish sector southwest of Gedser Reef (see Fig. 7) a larger area with peat exposed on the seafloor has been detected. Most of the latter outcrops are covered by a thin (<0.3 m) layer of fine sand. The peat outcrops commonly form the substrate for *Mytilus edulis* colonies, as was revealed by side-scan sonar and diving observations.

As referred to before, major accumulation of marine sediment is restricted to only a small part of the study area. This implies that most of the area typically has a sediment transport or erosion regime.

The Kadet Channel, with its irregular topography (Fig. 2), has a specific sedimentary regime characterized by abrupt changes from depositional to erosional conditions. A typical sediment found here is dark grey to black fine sandy mud in which pebbles also occur.

The sand found in large parts of the Danish sector of the study area is generally finer and has a larger silt and mud content than the sand from the German sector, where coarse sand also occurs locally. Well-sorted fine sand in the Danish sector is for most part confined to the immediate surroundings of Gedser Reef.

The areal distribution of well-sorted sand may well reflect the bottom current regime as illustrated in Fig. 8. Direction of sediment transport has been inferred from large-scale current-induced bedforms and from grain-size and heavy mineral studies. Thus, it can be shown that inflow of saline bottom water most strongly affects the seabed of the Kadet Channel and the entire area south of it, whereas outflow affects the seafloor in the Danish sector at depths of generally less than 15 m. This pattern corresponds with the general current pattern with Baltic outflow most concentrated along the coast of Falster (e.g. MATTHÄUS *et al.*, 1982).

Evidence has been found that under conditions of strong outflow a bottom flow gyre may be formed at the leeside of Gedser Reef (Fig. 8). Such a feature has previously been observed elsewhere in the Danish straits, i.e. at the northern entrance of the Sound, where gyre formation may be related to strong inflow (KUIJPERS, 1985).

Large-scale current-induced bedforms observed include transverse bedforms ranging from large sandwaves to small megaripples and various longitudinal bedforms. The maximum sandwave height is about 5 m, with associated wavelength up to 400 m [Fig. 9(f)]. Large sandwaves of this size are uncommon in the non-tidal shallow Danish waters between Skagerrak and Baltic Sea. Sandwaves of comparable size have been observed in the southwestern Skagerrak (KUIJPERS *et al.*, in press).

Longitudinal bedforms observed are small comet marks (<20 m), ill-defined narrow sand ribbons and, more generally, current lineations. Well-defined sand ribbons and large comet marks which occur locally elsewhere in the Danish straits (WERNER and NEWTON, 1975; KUIJPERS, 1985) have not been detected. The latter types of bedforms can be assumed to reflect higher energy flow than the forms we found in the Darss Sill area.

From the latter studies it also appears that bedform formation in the Danish straits only seldom occurs (time-scale: months–years). Furthermore, conditions for bedform formation are more favourable in the winter period, when thermohaline layering is negligible.

In this study we may report on bedform formation having occurred in the period August 1989–June 1991. The observations were made in the sandwave field just north of where Gedser Reef ends [see Figs 8 and 9(f)]. This area is located in the transitional zone between inflow and outflow action (Fig. 8). The first survey was made a few days after an exceptional weather situation, when northeasterly gale-force winds of 25 m s^{-1} had raised sea level in Kiel Bay by more than 1.5 m (31 August 1989). Such a situation may occur in winter time, but is extremely rare during summer (METEOROLOGISCHER DIENST DER DDR, 1989). As is evident from the exceptional sea level rise in Kiel Bay, east–west water mass transport must have been large, and associated westerly currents can be assumed to have been very strong. At the same time it can be assumed that owing to a large fetch wave-action may temporarily have destroyed thermohaline layering in our study area.

Records from the first survey show two of the four large sandwaves [No. II and III, Fig. 9(f)] having an asymmetric top induced by outflow action. The basic form of all four sandwaves is stressed, however, to have resulted from northeasterly inflow. A later survey made in June 1991 revealed a change of the top region of Sandwaves No. II and III, with the outflow-induced forms being no longer visible [Fig. 9(g)]. Moreover, it was also found that a large megaripple field immediately northeast of the large sandwaves meanwhile had disappeared. The megaripples observed here during the first survey [Fig. 9(h)] had a wavelength of up to 18 m, and had been formed by outflow.

The bedform changes reported clearly indicate that in the specific area dealt with both inflow and outflow can induce sediment transport. Associated bottom current speed during these events have been demonstrated to be in the order of 70–100 cm s^{-1} (e.g. DALRYMPLE *et al.*, 1978, KUIJPERS, 1985). Lack of well-defined sand ribbons and large comet marks suggests that this is probably the maximum bottom current speed that can occur in the area.

Within this context it should be noted that wave-action can also affect the seafloor down to considerable depth. East of Falster this depth is at least 17 m. This is indicated by virtue of X-radiographs from boxcore samples clearly revealing superimposed generations of oscillation ripples. Furthermore, some cores taken from this area where muddy and silty fine sand occurs occasionally display thin layers of significantly coarser material of medium to coarse sand and shells. The occurrence of these layers can most likely be ascribed to storm events.

CONCLUSIONS

The main conclusions from the data set discussed above are:

—In a large part of the area the typical thickness of the entire Quaternary sedimentary sequence is between 40 and 80 m. At least two different moraines were deposited during the Late Quaternary.

—The zone of glacial till extending from Falster to the German coast represents only one ice marginal line, i.e. line G ("Velgaster Staffel"). Formation of this ice marginal line caused the damming of a 30 m deep (sub)glacial meltwater discharge system having previously existed in the surroundings of Gedser Reef.

—Immediately after retreat of the ice at the beginning of the Baltic Ice Lake formation (glacio)fluvial discharge occurred through a deep channel cutting the ice marginal line G south of Kadet Channel. Discharge was towards the northeast, into the Baltic Ice Lake.

—The Darss Sill must have had a damming function during most of the Baltic Ice Lake highstand maximum, which was 17 m BSL in this area. This was due to sand accumulation in the deep channel referred to above during the Baltic Ice Lake transgression. Occasionally, however, overflow through the Kadet Channel must have occurred. The main erosion and deepening of the Kadet Channel can be ascribed to Ancylus Lake overflow.

—Major accumulation (3–7 m) of marine sediment deposited after the Littorina transgression has occurred only in the vicinity of Gedser Reef and at greater (>15 m) water depth east of Falster.

—Recent sediment transport in the Kadet Channel and in the entire area south of it is mainly governed by inflow. The seabed in the shallower area north of the Kadet Channel is more affected by outflow. This pattern is reflected by the grain-size distribution of sandy sediments in the deeper parts of the study area, showing generally coarser grain sizes and a better sorting in the area south of the Kadet Channel.

—Large-scale current-induced beforms include large sandwaves with a maximum height of about 5 m, megaripples, small (<20 m) comet marks, ill-defined sand ribbons and, more generally, current lineations.

Changes of the bedform configuration observed between August 1989 and June 1991 indicate a maximum bottom flow speed in the order of 70–100 cm s^{-1}, both for inflow and for outflow. These current events can be assumed to be seldom (time-scale: months–years).

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