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Late Quaternary Evolution of Gravel Deposits in Tromper Wiek, South-western Baltic Sea

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ABSTRACT

The Late Quaternary history of the Baltic Sea is marked by a complex sequence of glacial, lacustrine and marine phases (late Pleistocene, Baltic Ice Lake, Yoldia Lake, Ancylus Lake, Littorina Sea). Boomer data, acquired in October 2004, permitted to improve the knowledge of the late Quaternary geological evolution of Tromper Wiek, a semi-enclosed bay, located in the north-eastern part of Rügen Island. The sedimentary deposits can be subdivided in 6 seismic units (U1 to U6). The upper part of the lowest unit (U1) corresponds to Pleistocene till. Channels incise the top of this till (surface S2), probably created during the first drainage of the Baltic Sea during the Late Glacial. Subsequent channel filling (U2) occurred in two phases beginning with chaotic deposits, probably fluviatile of origin, followed by graded deposits. This filling was stopped by an erosive period with the formation of surface S3, showing channels at the same location as S2. The facies of the channel filling (U3 and U4), during a second phase, is similar to the first one, but resembles a prograding sediment body, intercalated between the two units in the shallower part. U3 shows a bar-shaped deposit at its top. The facies of U4 is very similar to a barrier/back-barrier facies similar to the facies of unit U5, partly composed of gravel. The deposits of U6 correspond to the post-Littorina Sea deposits.
The presence of gravel is linked to coastal cliffs, in which chalk layers, pushed up by glaciers, alternate with sections of till and meltwater deposits and with submarine outcrops of till. Gravel deposits are present in unit U5. They are strongly linked to the presence of a barrier. Four of the six units show a barrier facies (U2, U3, U4 and U5); gravel deposits could be present inside all of these units and would represent a larger deposit than estimated previously.

ADDITIONAL INDEX WORDS: *Baltic Sea, coastal evolution, barrier development, marine resources.*

INTRODUCTION AND AIM OF THE STUDY

Gravel-dominated coastal deposits occur in several places where sediment supply and wave energy favour the accumulation of coarse debris in the littoral zone. The presence of rocky cliffs, submarine outcrops and tectonic setting (e.g. raised gravel beaches, associated with co-seismic uplift, such as in New Zealand (BERRYMAN *et al.*, 1992; WELLMAN, 1967), favour these deposits (DAVIES, 1972; ORFORD, FORBES, and JENNINGS, 2002). Moreover, there is a latitudinal control (>40° N and S) on the common occurrence of gravel deposits in continental shelves and shore zones (DAVIES, 1972; HAYES, 1967), which correspond to periglacial deposits (CHURCH and RYDER, 1972). On storm wave-dominated coasts gravel originates mainly from glacigenic deposits (CARTER *et al.*, 1987; FORBES and TAYLOR, 1987; FORBES and SYVITSKI, 1994).

The coastline of the Southwestern Baltic Sea (from Denmark via Germany to Poland) consists of an alternation of Pleistocene cliffs and lowlands, where the cliffs are composed mainly of till, partly of meltwater deposits or older material, pushed-up by advancing ice during the last glaciations. Most of these cliffs are under erosion with an average retreat of approximately 30 cm/year (SCHWARZER, 2003).

Exploration and exploitation of offshore mineral resources have been carried out in the former German Democratic Republic since the seventies (HARFF *et al.*, 2004; JÜRGENS, 1999; LEMKE *et al.*, 1998; LEMKE, SCHWARZER, and DIESING, 2002). Extraction has been carried out by means of anchor hopper dredging in depths of up to -9 m mean sea level (msl). As a result, the sea bottom is covered with furrows and pits with diameters between 20 to 50 m and depths of up to 6 m below the sea bed (DIESING, 2003; DIESING *et al.*, 2004; KLEIN, 2003; KUBICKI, MANSO, and DIESING, 2007; MANSO *et al*, this volume). Our study area is situated in the northwestern part of Tromper Wiek (Figure 1) where the seafloor is dominated by gravel. The aim of this paper is to improve the knowledge of the geological setting of the study area and especially to understand the geological development of gravel resources.

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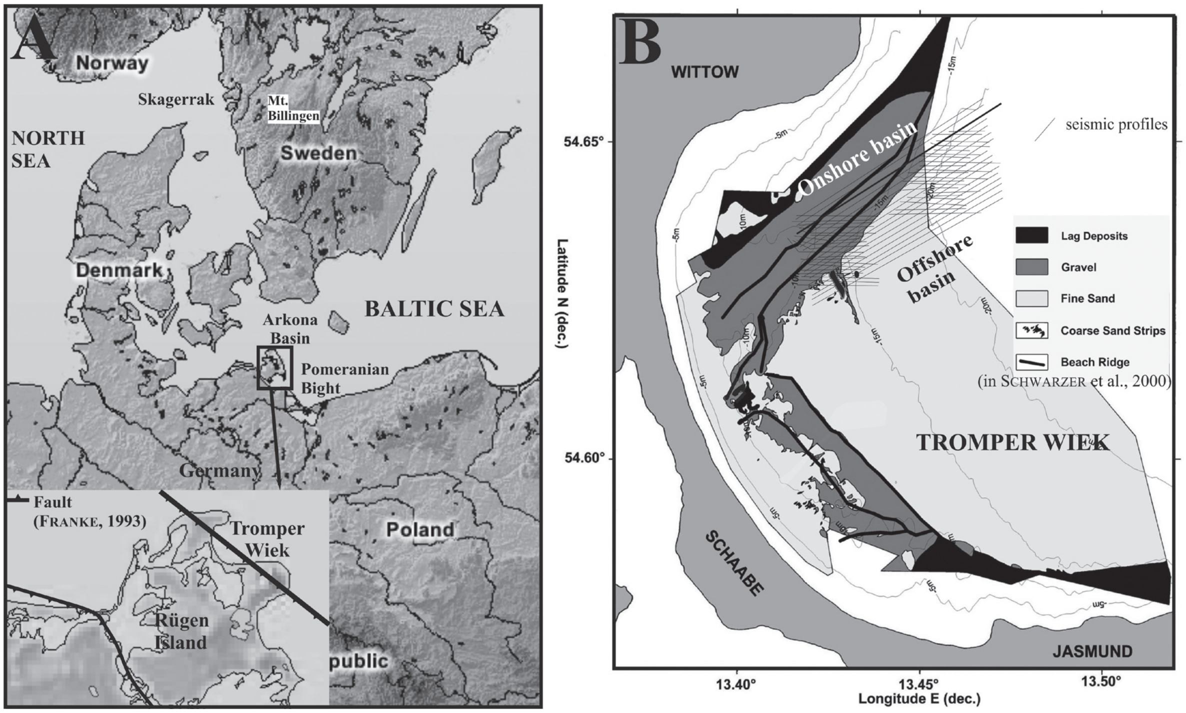


Figure 1. Localisation of Tromper Wiek. A- General map; B- Localisation of the seismic profiles and geological interpretation of the sea bottom (modified from Schwarzer et al., 2000).

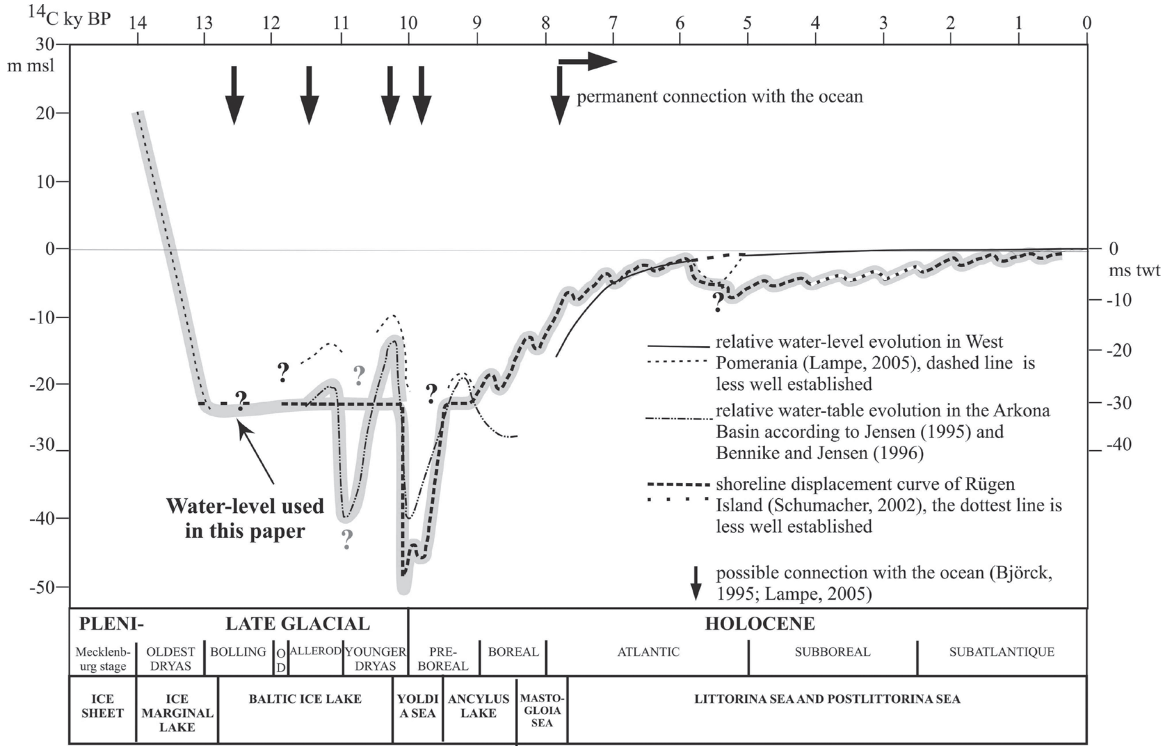


Figure 2. Water-level changes close to the study area (modified from Lampe, 2005). In grey: water-level, as used in this paper.

Table 1. *Baltic Sea stages (adapted from Lampe, 2005). The transgressive stages noted Rügen 1 to Rügen 7 are derived from Schumacher and Bayerl (1999). WL: water-level.*

Baltic Sea stages	**Date 14C (ky BP)**	**Possible evolution of the water-level**	**Events**
Post-Littorina	0		
	1.5	Rügen 7	
	3-2	Rügen 6	4-0 ky: only tectonic movements of minor importance (Uscinowicz, 2002)
		Rügen 5	
	5.8	Abrupt regression	6-5 ky: regression phase? Neotectonic movements?
	6	Much slower rise	
Littorina Sea		Rügen 3	7-6 ky: temporary increase of the uplift
	7.3-7.2	Rügen 4 then WL fall of ~1m	Depth: -2 m (Janke and Lampe, 2000)
		WL fall (from –6 to –7.5 m)	Flooding of the Danish Strait – Depth: -15 m
	7.8	Rapid rise (Lemke, 1998)	
Ancylus Lake	7.8		Connection with the ocean
	8-7.3	WL rise (Rügen 2)	8-7 ky: decrease of the rate of uplift
	9.2-8.8	Sudden WL fall after 8.8 ky	Regression (32 m below wl, Lemke et al., 1998)
	9.5	Rapid rise (Rügen 1)	
Yoldia Lake	9.5		
	9.9		Temporary link to the ocean
	10.3		
Baltic Ice Lake	10.3	WL drop of 25 m	Connection with open ocean-drainage. Start of the early Holocene incision phase on the mainland (Janke, 1978).
		WL rise	Late-glacial Lake transformed into a delta or river plain.
	11.5	WL drop of 5-10 m	Melt-water pulse (Fairbanks, 1989) - Subglacial drainage, channel incisions.
	12.5		14-11 ky: main uplift (Uscinowicz, 2002)
	13.5-13	WL rise	Connection with the ocean

GEOLOGICAL HISTORY OF THE BALTIC SEA AND STUDY AREA

The Baltic Sea is an almost non-tidal water body with only one narrow connection (Skagerrak) to the North Atlantic via the North Sea. Its history is controlled by isostacy, eustasy and resulting connections to the North Sea, for distinct periods during the Late Pleistocene and early Holocene (Björk, 1995). Therefore its evolution is marked by lacustrine and marine phases, resulting in four stages: Baltic Ice Lake, Yoldia Sea, Ancylus Lake and the Littorina Sea (Figure 2, Table 1) (Björck, 1995; Duphorn *et al.*, 1995; Lampe, 2005). Below, a description of the evolution of the Baltic Sea is given, with an indication of conventional radiocarbon years.

During the pleniglacial (Figure 2), the water-level was high in Pomerania, between 3 and 25 m above the mean sea level (Janke, 2002b). Here, the late Pleistocene history of the Baltic Sea started with the retreat of the active ice from Rügen Island and the Pomeranian Bight around 14 ky BP (Görsdorf and Kaiser, 2001; Kramarska, 1998; Lagerlund *et al.*, 1995; Uscinowicz, 1999). With the opening of several, probably subglacial drainage channels at Mt. Billingen app. 11.2 ky BP, the water-level dropped to at least –25 m msl and extensive river erosion occurred. During the Younger Dryas, the water level rose again from -40 to -20 m msl (Lampe, 2005) leading to the full development of the Baltic Ice Lake (Table 1). The reopening of a drainage pathway at Mt. Billingen, due to the retreat of the Scandinavian ice sheet around 10.3 ky BP, caused a drop of the water table to about -40 m (Björck, 1995). The early Holocene marine incision phase Yoldia Sea started (Janke, 1978), but due to rapid uplift of Scandinavia the closure of the connection to the open ocean followed 9.5 ky BP (Table 1). The Ancylus Lake period began with a water level rise reaching a maximum highstand of –18 m msl (Lampe, 2005; Lemke, 1998; Lemke *et al.*, 1999), similar to the level of the Baltic Ice Lake. This highstand was followed by a water level fall during the second half of the Ancylus Lake period. The first phase of the following Littorina Sea is marked by a rapid water level rise between 7.8-6 ky BP. Since then, the water level had fluctuated within a range of a few meters between –5 m msl and the present water level (Schumacher and Bayerl, 1999). After 5 ky BP, the water level almost reached its modern position (Figure 2). Water level lowstands occurred at the end of Dryas 1, at the Yoldia Sea stage and the regression of the Ancylus Lake (Table 1).

Rügen Island was reached by the Littorina transgression about 7.2 ky BP (Janke, 2002; Lampe *et al.*, 2002) and shows a strongly undulating shoreline displacement curve with up to 17 regression and transgression phases (Schumacher, 2002). This island, a former archipelago comprising more than a dozen larger and smaller Pleistocene islands, connected by barrier and spit development during the younger Holocene (Duphorn *et al.*, 1995, Janke, 2002), is an uplifted area with rates of 0.24 mm/yr for the north-eastern part (Schumacher, 2002). Kolp (1979) and Dietrich and Liebsch (2000) have shown the presence of a hinge line of zero isostatic uplift, which stretches from the southern Zingst peninsula to Usedom Island, separating an uplifted (Rügen Island) from a subsiding area (southwestern Baltic Sea, e.g. bays of Wismar, Lübeck and Kiel). The strong regression between 6-5 ky BP has been related to an uplift of 6 m between 7-5 ky BP (Schumacher and Bayerl, 1999; Schwarzer, Diesing, and Trieschmann, 2000) and as a land upheaval on Rügen Island of 8 m (Schumacher, 2002). The age of this uplift fits to the age of the uplift of the Pomeranian Bight shoreline around 5.8-5 ky BP (Janke and Lampe, 2000).

Tromper Wiek is a semi-enclosed bay located in the north-eastern part of Rügen Island between the cliffs of Wittow and

Jasmund (Figure 1). The cliffs are connected by a 12 km long Holocene barrier named Schaabe, which developed after the Littorina Transgression (Duphorn *et al.*, 1995; Schumacher and Bayerl, 1999). The cliffs, with a maximum height of 118 m at Jasmund, are characterized by a complicated pattern of glacio-tectonically uplifted Late Cretaceous chalk and Pleistocene deposits subdividing the chalk units (Herrig and Schnick, 1994). The chalk is soft and weakly cemented, inheriting black flint concretions (Janke, 2002; Schnick, 2002). The waters off Jasmund and Wittow are characterized by a steep bathymetric gradient which continues in the north-western part of Tromper Wiek where the water depth increases rapidly from -12 to -18 m msl (Stephan *et al.*, 1989).

The latest result of sediment distribution patterns in this bay (Figure 1B) can be found in Schwarzer, Diesing, and Trieschmann (2000). Lag deposits occur in front of Wittow and Jasmund cliffs. They situate the gravel deposit, which is located in front of Wittow cliff and Schaabe barrier between –8 and –14 m msl. This deposit shows prominent morphological ridges composed of well-rounded pebbles and cobbles up to 25 cm in diameter. Shallower than -10 m some till crops out. Fine sand is located in front of Schaabe spit between –10 and –14 m msl. Muddy fine sand and sandy mud occurs in deeper parts of Tromper Wiek.

Jensen (1992); Jensen *et al.* (1997); Lemke *et al.* (1998); Lemke, Schwarzer, and Diesing (2002) have identified five seismostratigraphic units (E1 to E5) in the western Baltic Sea and the area around Rügen. An uppermost till (E1) was incised by late glacial channels, probably filled with glacio-lacustrine sediments (E2) of the early Baltic Ice Lake stage. A thick sedimentary complex (E3) covered these deposits during the final phase of the Baltic Ice Lake. The boundary separating E2 and E3 corresponds to a major discontinuity. At least in Tromper Wiek E3 is subdivided into E3a and E3b. E3a corresponds to an associated beach ridge - lagoon system and E3b is interpreted to be either of fluvial or coastal origin, deposited during the lowstand of the Yoldia Sea. E4 was deposited in the deeper central part of the bay during the final phase of the Yoldia stage and in the beginning phase of the Ancylus Lake. The maximum highstand of the Ancylus Lake was around -18 m msl. It was followed by a regression to about 30 m msl. Unit E5 is a brackish marine mud, which reflects recent sedimentation.

In the shallower part of Tromper Wiek, an inner basin is characterised by lagoonal deposits of E3a which are covered by gravelly beach ridges. Further offshore, towards the central part of Tromper Wiek, the till surface dips steeply, reaching a level of more than –40 m msl and delimiting an outer basin created by former ice (Lemke, Schwarzer, and Diesing, 2002).

METHODS

The Uniboom is an electro-acoustic sound converter producing a broad frequency band of acoustic pulses (0.5 to 15 kHz) emitted vertically into the water column (Atzler, 1995). The boomer acoustic source is mounted on a catamaran and towed behind the ship. The sound signal is reflected from boundaries between different layers/structures within the sedimentary sequence, consisting of different impedances. Reflected signals are received by a streamer, additionally towed behind the ship, close beneath the sea surface. This signal is tuned in a receiver and transferred to analogue and digital acquisition units. Processing of the digital data consists of bandpass filtering, stacking and the adjustment of a time varied gain (TVG). Very-high resolution seismic profiles are interpreted according to seismo-stratigraphy principles (Posamentier *et al.*, 1992; Posamentier, Jervey, and Vail, 1988; Vail *et al.*, 1977; Van Wagoner *et al.*, 1988). Originally developed for low resolution seismics, it can also be applied for high to very-high resolution seismic (e. g. Browne, 1994; Chiocci, Orlando, and Tortora, 1991; Cirac *et al.*, 1997; Lericolais, Berné, and Fenies, 2001).

Limitations in the quality of the seismic profiles, due to bad weather conditions during the surveys, complicate partly the interpretation of the data into different seismostratigraphic units.

RESULTS

Several seismic units (U1 to U6) are present on the seismic profiles (Figures 3 to 7). They are bounded by high amplitude and often strongly erosive surfaces S2-S6. These units essentially correspond to the filling of two basins. The first one, in the shallower part of the bay, would correspond to a lagoonal facies (Lemke, Schwarzer, and Diesing, 2002) and is located between –13 to –20 ms twt (app. –10 to –15 m msl) behind the gravel barrier (Schwarzer, Diesing, and Trieschmann, 2000) on our seismic profiles. Its maximum depth is about 20 ms (app. -15 m) twt (two-way travel time) in our study area. The second basin is situated offshore deeper than –24 ms twt (app. -18 m msl) (Figure 3) and is marked by a steeply dipping surface. The thickness of the sediment fill is more or less 25 ms twt (app. 20 m). Correlation between the two basins was achieved by comparing the seismic facies and the number of the seismic units above unit U1, occurring in the whole study area without interruption. The unit U1 dips steeply offshore where it delimits the offshore basin. The base of U1 is not accessible. Its upper part constitutes of indented reflections which form channels.

The base of the onshore (lagoonal) basin corresponds to an uneven high amplitude and to low to good continuity surface S2 which can be followed throughout the whole study area (Figures 3, 4 and 5). S2 shows channels right to the offshore boundary of the inner basin where it almost reaches the sea bottom. In this area, three channels show a general NW-SE strike and incise the substratum down to 36 ms twt (app. -27 m) (Figure 5). They are separated by interfluves shallower than 28 ms twt (app. 21-22 m h). The channels, which almost disappear at the boundary between the two basins, are filled by two different facies: the first one (U2a) is chaotic and evolves upwards into a second facies (U2b), which shows wavy parallel reflections (Figure 4). There is no clear reflection horizon visible between these two seismic facies.

Surface S3 shows similar characteristics as S2. It is an uneven high amplitude and good continuity surface showing channels. Nevertheless, the channels are generally smaller than the previous ones. The first deposits filling the channels (U3a) are composed of a chaotic facies with few parallel reflections on the interfluves. Another type of deposits (U3b) is only located in the westernmost area. Its base is quite tabular. The seismic facies corresponds to prograding reflections. U3b rapidly pinches out offshore. U3 shows a bar-shaped body in this upper part (Figure 6).

The amplitude of the surface S4 is variable, but its continuity is good (Figure 4). It erodes the top of unit U3. Unit U4 corresponds to the last filling of the channels formed by S2 and

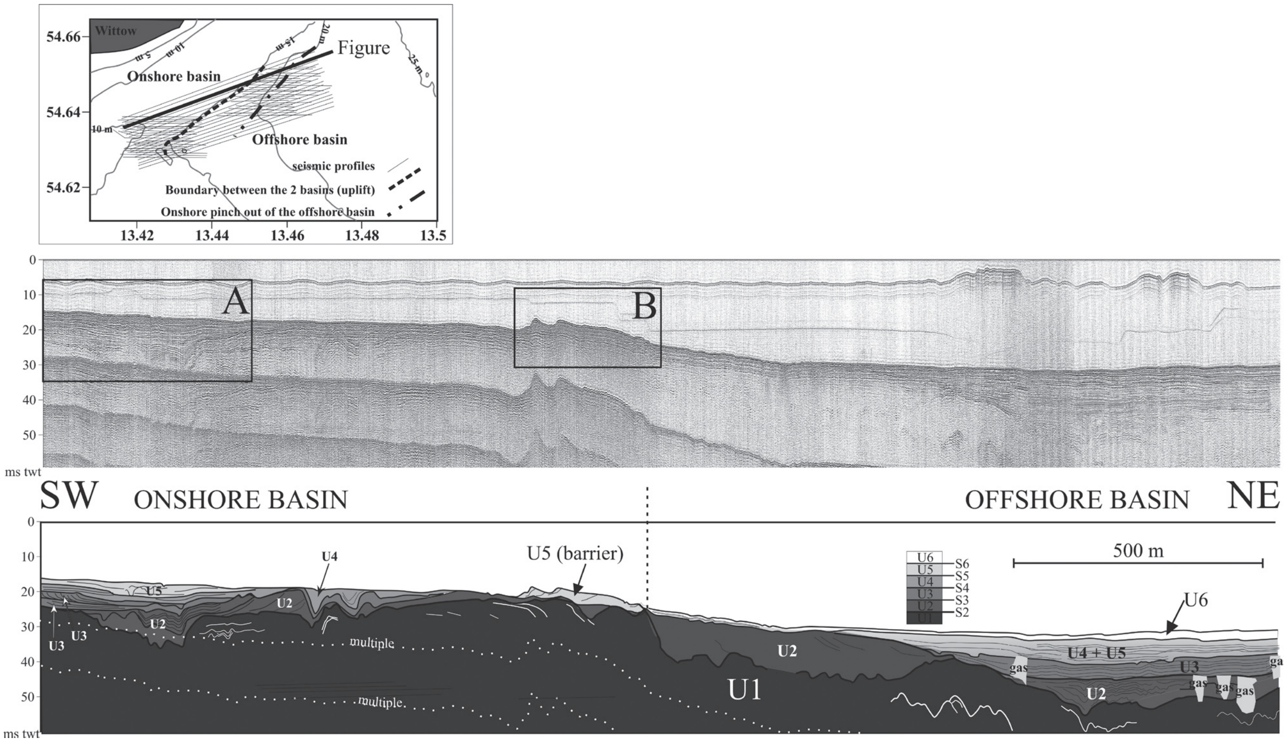


Figure 3. Boomer profile showing the different seismic units. See details A and B on Figure 4.

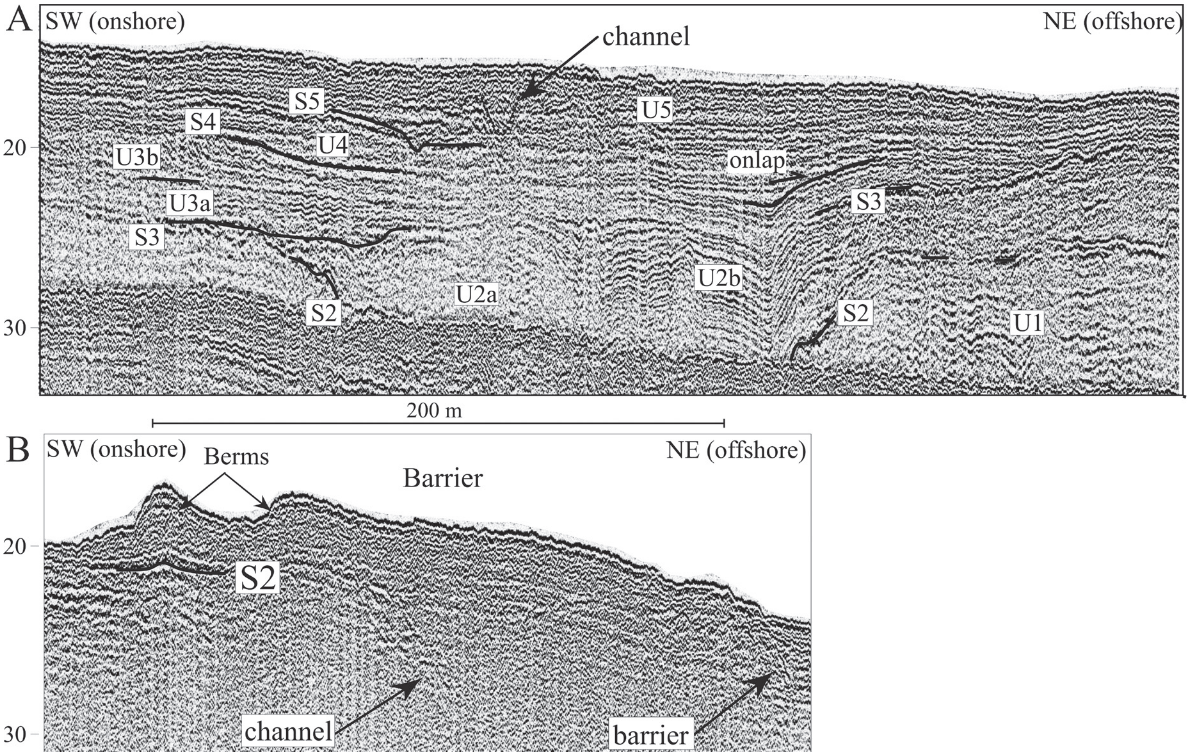


Figure 4. Details of the seismic profile displayed in Figure 3.

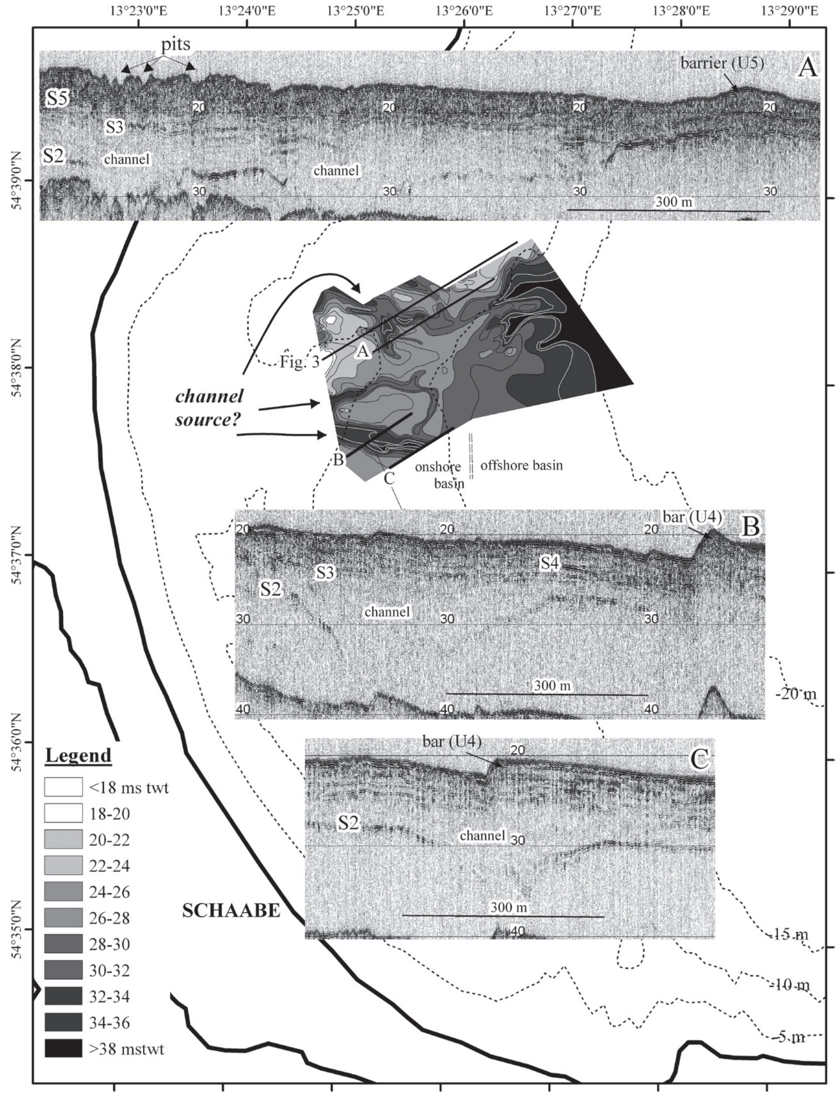


Figure 5. Isochrons of surface S2 and details of the seismic profiles.

onlaps on S4. Further south this unit shows a complex pattern of retrograding, prograding reflections and small channels with only a few milliseconds (twt) deep. An offshore bar-shaped body is present between the two basins, at the same place than the U3 bar-shaped body. Its facies is chaotic (Figure 6).

The upper surface S5 exhibits high amplitude and good continuity and can be followed almost throughout the inner basin (Figures 3, 4 and 7). It shows NW-SE oriented isochrons between 16 and 24 ms twt (app. -12 and -18 m) and a small E-W oriented channel of only a few milliseconds deep. It is covered by the high amplitude facies U5 which is composed of two units: a basin filling showing chaotic facies (U5a), prograding and retrograding reflections as well as channels of 3-4 ms twt which are very similar to the facies of U4, and a barrier-shaped body (U5b) which ends up the facies offshore. The steep slope of the ridges on the barrier (Figure 4) is directed towards the coast and the gentle slope towards the sea. This barrier facies is located exclusively in the shallow part of the bay where it shows a thickness of up to 6 ms twt (app. 4,5 m). The thicker parts are located on the barrier and in the shallowest area. The unit U6 is a thin layer (less than 1 m) of deposits, which is difficult to follow because it is mixed with the seafloor signal.

The seismic units U2, U3 and U4 reach the position of the outer ridges and U3 and U4 pinch out at the end of the ridge deposit. The thickness of each unit does not exceed 8 ms twt (app. 6 m), with a mean around 3-4_ms twt (app. 2-3 m).

Between the two basins, the till deposit U1 is bounded by the surface S2, covered by U2 in the northwest (Figures 3, 4 and 6). The facies of this unit shows channel filling in the north (U2a, Figure 4). Towards the southeast, prograding and retrograding reflections form a dome-shaped deposit (U2c) on S2 and sometimes cover the channels formed by this surface. Small channels are also present in the dome-shaped deposit. U2c was gently eroded by the formation of S3, except on its top

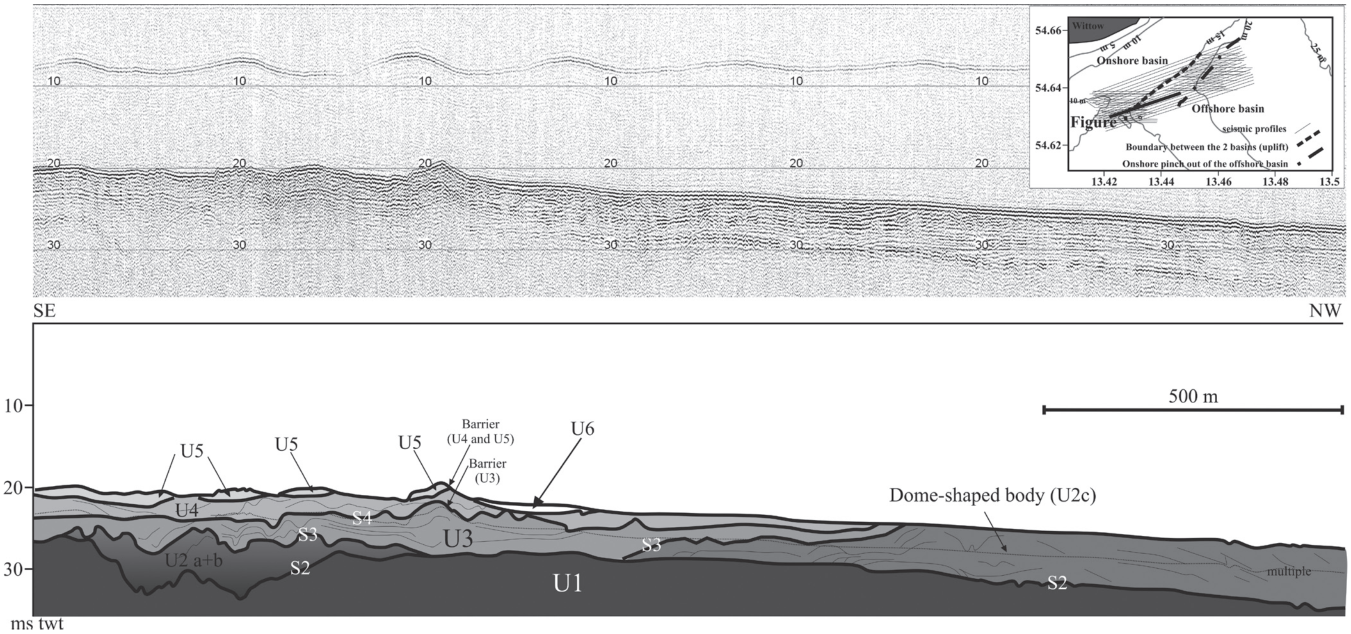


Figure 6. Boomer profile showing the interfluve between the two basins.

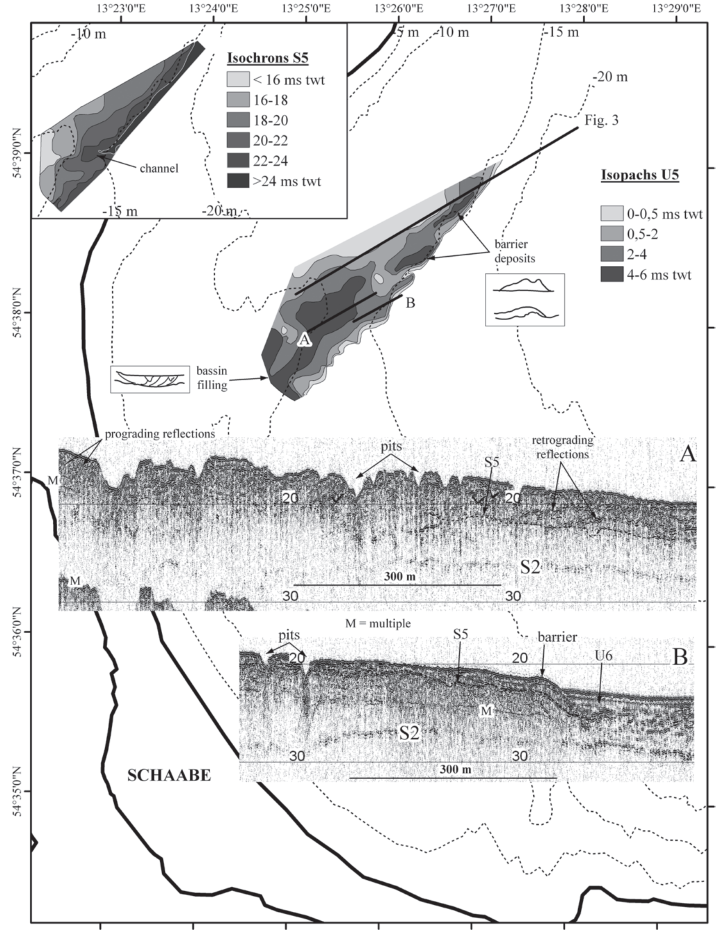


Figure 7. Isochrons and isopachs of S5 and U5 and seismic profiles details.

where the erosion was stronger and probably younger than the formation of S3, as U3 deposits are only present on each side of the dome-shaped deposit (Figure 6). U2 and U3 are covered by a thin layer composed of the younger unit U6, which thickens just at the foot of the barrier (app. 2-3 m thick), showing parallel reflections at this location.

Into the offshore basin (Figure 3), the uneven surface S2 also corresponds to the base of the basin, which dips offshore around 30 ms twt (app. 22 m). S2 shows channels of less than 5 ms twt (app. 3,5 m). S2 is covered by U2, which present similar seismic facies than in the onshore basin: the bottom deposit is chaotic and evolves upwards from wavy to more or less parallel reflections. S3 does not correspond to an uneven surface in the offshore basin. It corresponds to a planar surface with a medium amplitude and continuity, locally disturbed by gas presence. U3 presents high frequency parallel reflections. The upper surface S4 is quite horizontal with a high amplitude and continuity. It shows small channels of 2-3 ms twt deep (app. 1.5-2 m). The seismic facies of unit U4 also corresponds to high frequency parallel reflections. It is partly difficult to differentiate U5 from U4 in the offshore basin, as U5 could correspond to a part of facies U4. U6 is composed of parallel reflections and becomes thicker offshore, increasingly.

The thickness of the units is regular and corresponds to 8 ms twt (app. 6,5 m) for U2, about 5-7 ms twt (app. 4-5,5 m) for U3, 6-8 ms twt (app. 5-6,5 m) for U4 (plus U5?) and 1 to 3 ms twt (app. 1-2,5 m) for U6.

DISCUSSION AND INTERPRETATION

History of the Western Part of Tromper Wiek

Comparing the results with previous investigations on land, (Hoffmann, Lampe, and Barnasch, 2005; Schumacher and Bayerl, 1999) and inside Tromper Wiek (Lemke *et al.,* 1998; Lemke, Schwarzer, and Diesing, 2002; Schwarzer, Diesing, and Trieschmann, 2000), the upper part of the unit U1 corresponds to Pleistocene till (unit E1 in Lemke *et al.*, 1998; Lemke, Schwarzer, and Diesing, 2002; Table 2). In fact, these authors indicate that the surface of the uppermost till is characterised by a high relief and channel-like depressions with the surface dipping steeply towards the central part of Tromper Wiek, as is the case for surface S2.

After the last glacial maximum about 18.5 ky BP (Lambeck *et al.,* 2000), during the Ice Sheet and the Ice Marginal Lake periods, the melting of the ice led to an opening of the Baltic Sea towards the North Sea (Lampe, 2005). The water-level dropped more than 40 m, which probably initiated the formation of the channels bounded by S2 (Figures 8A and 8B). Channels generally form during water-level fall, but can also be formed due to melt-water pulses or subglacial draining. There were two important water-level falls due to the drainage of the Baltic Ice Lake. The first one (drainage at 13 ky BP, Figure 2) occurring in the Baltic Sea was combined with a melt-water pulse, as the ice retreat on Rügen Island is situated about 14 ky BP (Görsdorf and Kaiser, 2001; Kramarska, 1998; Lagerlund *et al.*, 1995; Uscinowicz, 1999), and so could lead to the formation of the more important channels, bounded by surface S2. Between about 13 and 10 ky BP, the water-level had been more or less stable, around -20 to -25 m msl (Schumacher, 2002) or rose up to a few meters on Rügen Island considering the water-level evolution in the Arkona basin or in west Pomerania (Bennike and Jensen, 1996; Jensen, 1995; Lampe, 2005). The three channels, present in Figure 4, incise from 26-28 ms twt (19-21 m msl) down to more than 36 ms twt (27 m msl). Therefore a water-level around 20-25 m msl probably allowed the filling of the channels (U2, Figure 8C). Unit U2 was deposited in two steps during the water-

Table 2. *Comparison between the seismic units of* Lemke *et al. (1998) and those in this paper.*

Lemke *et al.*, 1998			This paper	
Seismic units	**Sediment type**	**Age**	**Seismic units**	**Supposed Age**
E1: Till	hyp: grey, partly clayey, chalk fragments	Pleistocene	U1	Pleistocene
Channel surface		Late glacial	S2 (channel)	~13 ky (drainage)
E2: channel filling, glacio-lacustrine sequence	hyp : Silty to sandy material	Early Baltic Ice Lake stage	U2	Baltic Ice Lake
Major unconformity			S3 (channel)	~11.5 ky (drainage)
E3 : E3a: ………………. E3b (below 35 m depth): fluvial or coastal	Thick silt then olive grey, fine laminated silt ………….. Silty fine sand	Baltic Ice Lake Upper part: ~10.1-10.5 ky ………… From ~10.3 ky	U3? U4? U5? U5?	Baltic Ice Lake to Yoldia Sea
E4: fresh water lake deposit	Below -34 m: grey silts	Base: ~9.6 ky Ancylus Lake	U5 ? U6?	Ancylus Lake
E5	Olive grey sandy mud	Post-Littorina	U6	Post-Littorina Sea

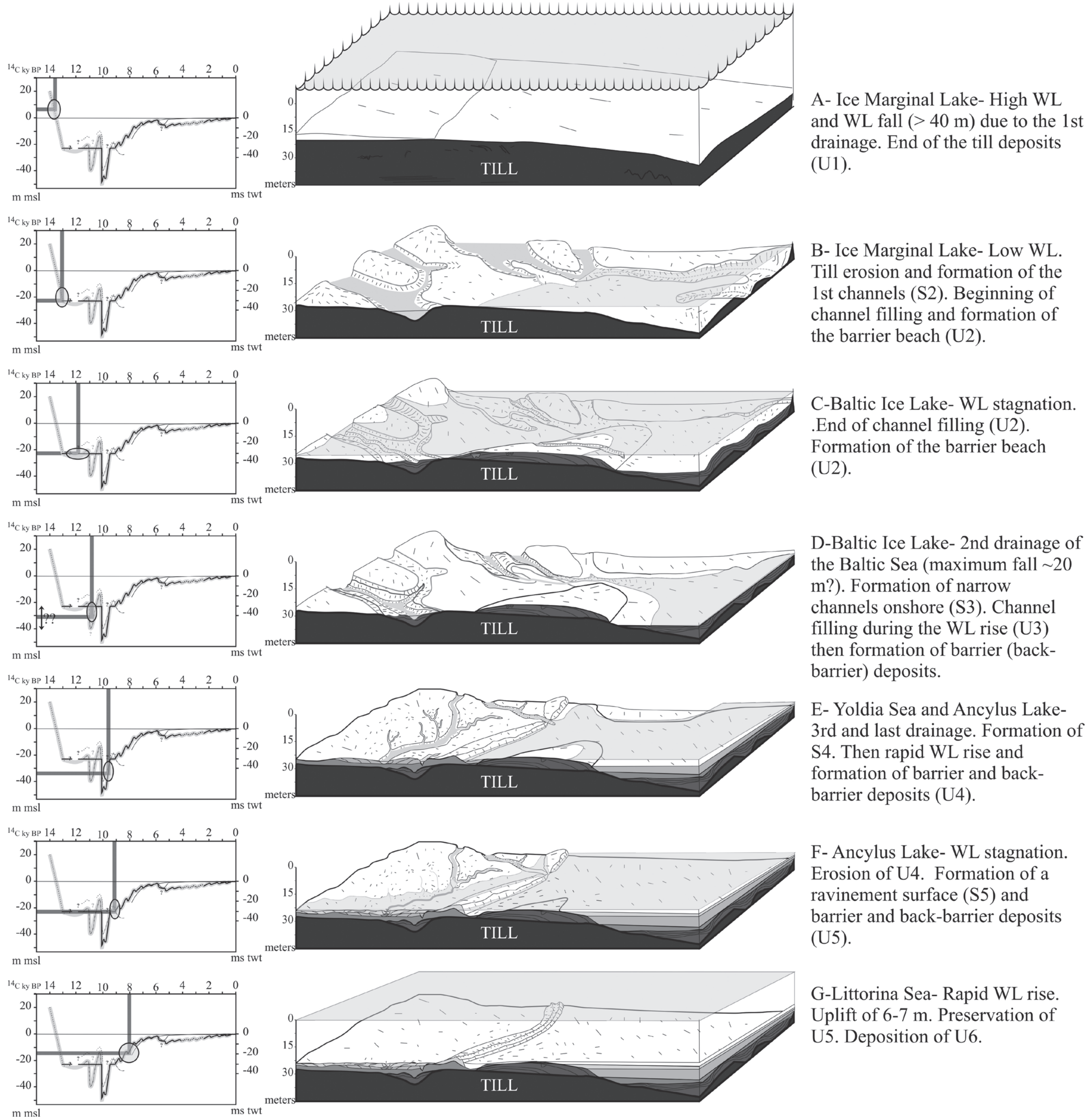
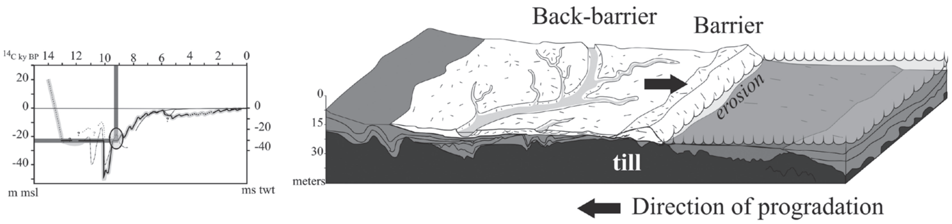
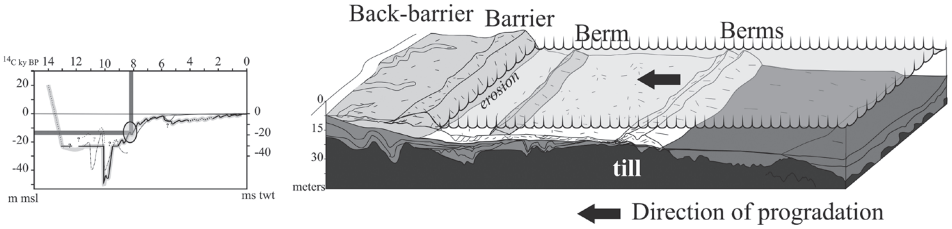


Figure 8. Deposition model of the 6 seismic units, interpreted from the boomer profiles. WL: water-level.

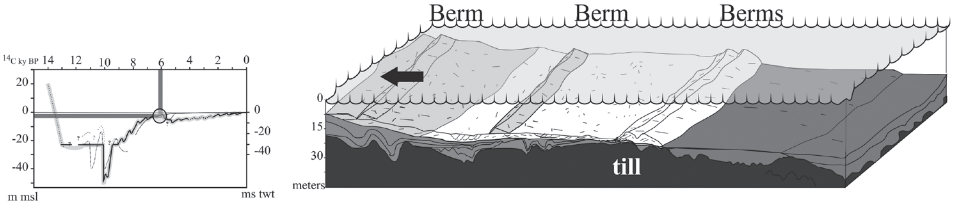
level stagnation after 13 ky BP (Figure 8C). The lowest unit (U2a) shows a chaotic facies, which might represent the final melt water deposits, composed of heterogeneous and/or coarse material. The unit above (U2b) shows alternating wavy bedded reflections, following the underlying relief. This generally gives evidence of more homogeneous and/or finer deposits. This wavy facies is very similar to the E2 facies mentioned in LEMKE, SCHWARZER, and DIESING (2002) where the authors also indicate that the seismic facies represents silty to sandy material. They interpret E2 as a glacio-lacustrine sequence formed immediately after the final deglaciation of the area. In front of the offshore basin, a dome-shaped body (U2c, Figure 6) seems to correspond to a barrier beach, formed during or after the filling of the channels since their deposition. It should indicate a stabilisation of the water-level around 20-25 m msl for a duration which is sufficient to create these deposits. This



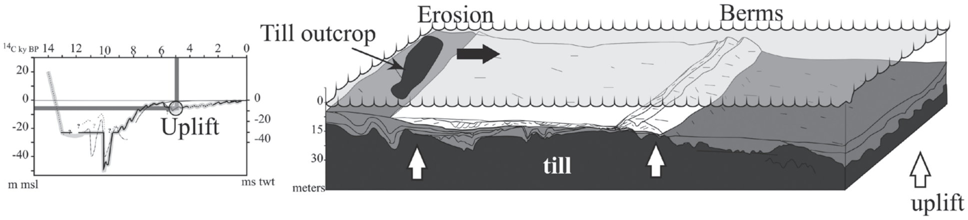
A-WL stagnation ~20-25 m depth. Formation of the ravinement surface S5 then deposition of the gravel marsh and the barrier (U5).



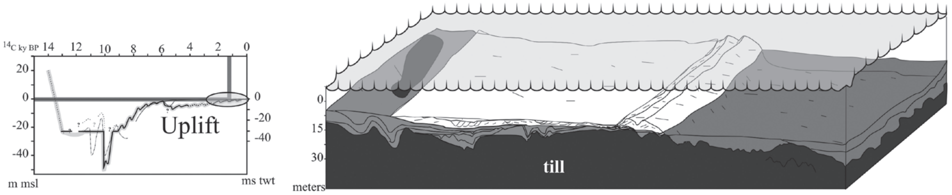
B- Rapid WL rise. Preservation of a part of the old barrier which shows berms (landwards steep slope). Onshore formation of a new barrier and back-barrier system.



C- WL rise before uplift (about 6000 years BP). WL ~2 m. Deposit of gravels and formation of barriers goes on. Gravels located between ~14 m and ~22 m depth.



D- Uplift of 6 m after 6000 years BP. Regression. Erosion of the sediment, till outcrops. Onshore gravel boundary: 8 m depth, offshore gravel boundary: 16 m depth.



E- Actual. Preservation of the gravel deposits.

▨ Post-gravel deposits
☐ Gravels
▨ Post-till deposits
■ Till

Figure 9. Model of gravel barrier deposits in Tromper Wiek. WL: water-level.

meets the water level curves for Rügen Island, presented by Schumacher (2002) and the position around 20-25 m depth of the channels (S2). In the offshore basin, the initial filling of the channels consists of similar facies.

The formation of the second set of channels, located in the onshore basin (surface S3, Figure 8D), should be due to the second important drainage of the Baltic Ice Lake around 11 ky BP present on the water-level curves of the Arkona basin or the west Pomerania (Bennike and Jensen, 1996; Jensen, 1995; Lampe, 2005) (Figure 2). When forming this surface S3, a part of the beach barrier, located offshore, was eroded. S3 seems to correspond to the boundary between the units E2 and E3 which is mentioned in Lemke, Schwarzer, and Diesing (2002); Schwarzer, Diesing, and Trieschmann (2000). Moreover, these authors indicate that E3, corresponding to the seismic unit of U3, was deposited prior to 10.3 ky BP.

More in detail, the lowermost deposits of U3 in the channels look similar to the facies of U2, i.e. heterogeneous and/or coarse deposits (U3a). The facies above is different and corresponds to a small prograding deposit (U3b). Normally, this indicates sediment input during a constant water-level. As it is only located in the west part of the profile (Figures 3 and 4), it could be formed due to local conditions, e.g. progradation of the channel wall. U3 deposits do not show a large beach barrier facies as U2c. Nevertheless, a deposit similar to a barrier is present downstream of U2c (Figure 6). Lemke, Schwarzer, and Diesing (2002); Schwarzer, Diesing, and Trieschmann (2000) also indicate that this unit is correlated with a barrier-lagoon system in the central part of Tromper Wiek, where the barriers are composed of gravel. A barrier is also present in our study area. So the barrier-lagoon system probably extended towards the north. Nevertheless, in our study area the gravel deposits do not correspond to U3, but to the younger unit (U5). Therefore there should have been several periods of gravel deposition with a shift of the centre of deposition towards the north.

A third erosive surface is indicated by S4. This surface could have been formed during the last drainage after 10.3 ky BP. Onlaps, which are characteristic for a transgressive facies, are present on S4 (Figures 4 and 8E). As such, U4 is a transgressive facies which should have been formed during the first part of the water-level rise about 10-9.5 ky BP. The channel-filling continued as well, as also the construction of the barrier which is already present in U3. A back-barrier/lagoon facies is present also (Figure 6).

About 9.5 ky BP, the speed of the water-level rise slowed down and remained stable at a level of 23-25 m msl, which is about 10 m below the back-barrier system. Nevertheless, if we consider an uplift of 6 m after 7 ky BP, then the gravel deposits would have been located around 16-20 m msl, which was the depth of the shoreface 9.5 ky BP ago (Figure 9A). The shape of the gravel confirms this fact, as observations by scuba divers revealed that these ridges are composed of well-rounded pebbles and cobbles of up to 25 cm in diameter (Schwarzer, Diesing, and Trieschmann, 2000).

The water-level stagnation may have favoured the formation of a wave erosion surface (S5) at the top of U4 (Figures 8F and 9A). Due to stable water-level conditions during several centuries, a barrier, larger than the former ones, had been developed. Behind this barrier, a facies similar to the U4 facies has been deposited. The U5 deposit is oriented parallel to the barrier (Figure 7). U5 would correspond to a barrier and a back-barrier facies with channels alternating interfluves showed by retrograding or prograding reflections.

The next water-level rise, after 9 ky BP, was likely relatively fast. Due to the very coarse material, the gravel deposits were preserved partly. Nevertheless, the barrier was probably in part eroded due to its shallow water location, and its morphology evolved in a berm system (steep slope shifted landwards; Figure 9B). The deposition of gravel probably decreased quickly with increasing water depth. No gravel is present on the actual coast, below -15 m msl. New systems of barriers and berms might have formed on the gravel deposits (Figure 9C). Prior to the uplift approximately 5-7 ky BP, the gravel deposits were probably located in 22 m water-depth. The onshore boundary is more difficult to establish, but, by comparison with the actual depth, it was likely in approximately 15 m water-depth. Uplift raised Rügen Island with about 6 m (Schumacher and Bayerl, 1999; Schwarzer, Diesing, and Trieschmann, 2000). Then the gravel deposits were located between 8 and 16 m msl, which is the actual depth (Figure 9D and E). Due to the very coarse granulometry of the barrier sediments, it was mostly preserved.

The last unit, U6, is a thin cover of fine sand, which represents the actual sedimentation onshore. Offshore, it can be subdivided in several sub-units, which have probably recorded the oscillations of the water-level since 9000 years BP (Figure 8G). This unit probably corresponds to the unit E5 of Schwarzer, Diesing, and Trieschmann (2000), which shows typical deposits of the post-Littorina brackish marine Baltic Sea.

Gravel deposits: Barrier and back-barrier facies

We found a barrier facies in four of the six units (U2, U3, U4 and U5), generally in their upper part/top. In our study area, a back-barrier/lagoon facies is present in two units (U4 and U5) and other investigations (Lemke, Schwarzer, and Diesing, 2002; Schwarzer, Diesing, and Trieschmann, 2000) showed the presence of a lagoon in E3/U3 in the central part of Tromper Wiek. Two of these units crop out on the sea floor (U3 in the central part of Tromper Wiek and U5 in our study area) showing barriers composed of gravely sediments with a northwest-southeast orientation for U3 and a northeast-southwest orientation for U5.

The with gravel built-up unit U5 is intensively dredged, showing pits of up to a few m deep (Diesing, 2003) (Figure 7). The thickness of the gravel unit (U5) reaches 6 ms twt on our seismic profiles (about 5 m thick) (Figure 7). U5 spreads over more than 3500 m in a NE-SW direction and from about 300 m (in the north) to more than 1000 m (in the south) in a NW-SE direction.

It is possible that each of these units (U2, U3, U4 and U5) shows gravel deposits on their upper part, especially in the barrier facies. That means that the total gravel deposit is probably much more spread than the gravel deposits on the sea bottom shows.

Generally, there are two sources of gravel: the seafloor itself and the erosion of the cliffs (Anthony, 2002; Caviola, 1997; Johnson, 1919; Orford, Forbes, and Jennings, 2002; Regnauld, Mauz, and Morzadec-Kerfourn, 2003; Schrottke, 2001). The gravel deposits formed when the water-level was about 15-20 m msl, considering the uplift of about 15-10 m modern msl. Moreover, the barrier deposit built during quite high and stable water-levels. If the seafloor was the only source of the gravel, we should find gravel deposits in the outer basin; this is not the case. So, the most probable source of the gravel deposits is the erosion of Wittow cliff, composed of chalk, meltwater sediments, boulder and clay, present close to our study area. This erosion is only possible when the water-level was about 15-20 m msl. Following, the cliff was eroded by wave and current action and supplied the gravel needed for the formation of the gravel deposits.

CONCLUSIONS

Six units (U1 to U6) have been identified in the western part of Tromper Wiek and are bounded by 5 surfaces (S2 to S6). U1 is attributed to the presence of Pleistocene till; its upper part was eroded by the formation of channels (S2), probably related to the water-level drop during the Late Glacial. The filling of these channels (U2) began by fluviatile sediments, which were later replaced with finer and homogeneous sediments. U2 shows a beach barrier facies deposited during or after the filling of the channel. The location of this barrier is slightly offshore of the modern barrier. The first reactivation of the channels (S3) occurred probably during the Baltic Ice Lake about 11 ky BP. Their filling (U3) is very similar to U2. At the top of U3, a barrier is found at more or less the same position as the actual barrier. Outside of the study area, investigations have shown that U3 is partly composed of gravel barriers. S4 corresponds to the last reactivation of the channels formed by S2 and could have been formed about 10 ky BP. The filling of the channels (U4) occurred during the Yoldia Sea and the Ancylus Lake. It is slightly different as it shows transgressive deposits and a barrier and back-barrier facies. S5 would be an erosional surface caused by waves as the water-level rise speed decreased. U5 also shows a barrier and a back-barrier facies similar to the U4 facies. This unit is nowadays dredged intensively, because of its high gravel content. Due to the uplift of 6 m about 5-7 ky BP, the gravel deposited originally around 15-20 m msl depth, which are the mean depth of the high water-level between 9 and 13 ky BP, are now at about 10-15 m msl. U6 would correspond to the last Littorina deposits.

Four of the six units (U2, U3, U4 and U5) show barrier deposits. The two units (U3 and U5), outcropping on the sea bottom, and showing a barrier, are composed of gravelly sediments. It is possible that the two others units (U2 and U4), showing a barrier, are also composed, at least partly of gravel. The gravel came from the erosion of the Wittow cliff during periods of high water-level. The volume of gravel resources can be more important than estimated before.

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