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POSTGLACIAL TO HOLOCENE SEDIMENTATION HISTORY AND PALAEOGEOGRAPHICAL DEVELOPMENT OF A BARRIER SPIT (PUDAGLA LOWLAND, USEDOM ISLAND, SW BALTIC COAST)

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Abstract. Pudagla lowland is a Holocene barrier spit on the SW Baltic coast. Framed and underlain by Pleistocene deposits, the depression is filled up with up to 20 m of Late Glacial to Holocene sediments. 63 cores were collected using a vibrocore technique. Samples were analysed in terms of granulometry, species associations (molluscs, ostracods). Organic sediments (peat) were used for radiocarbon dating. In total 6 new ^{14}C-data are presented.

The sediment sequence starts with a Late Glacial till, overlain by glaciofluvial sand. A lake developed during the Late Preboreal/Early Boreal with a water level of –8 m mean sea level (m.s.l.) with sand the predominant sediment. Minor lakes existed during the Boreal. At around 6500 BP the Littorina transgression reached the study area. Mud and fine to medium sand were deposited forming a barrier spit. At around 1000 BP, the entire Pudagla lowland became terrestrial with peat as the most common surface sediment.

Palaeogeographical development is demonstrated by nine evolutionary stages. The assumption of Kliewe, Janke (1982) that the transgression onset varies regionally at the coast of the southern Baltic Sea can be proven by comparison with other areas which have been subject to prior investigations.

Key words: sea level, barrier spit, palaeogeography, Holocene, Usedom, Baltic coast.

INTRODUCTION

Quaternary research has a high significance for the area of the SW Baltic coast. Cliff-outcrops have been surveyed by geologists for more than hundred years (e.g. Preussner, 1862; Keilhack, 1899; Schulz, 1959; Ruchholz, 1979). Holocene barrier spits were early described as well, usually from a geomorphologic point of view (e.g. Keilhack, 1912; Wernicke, 1929, 1931; Haack, 1960; Kliewe, 1960). In most cases the geological structure of Holocene barrier spits has not yet been investigated, mostly because of insufficient access to drilling and sampling techniques until 1989.

The deeper-marine facies association as well as the sediments of earlier evolutionary stages of the Baltic Sea have been intensively analysed (e.g. Lemke, 1998; Kolp, 1983,1986).

Reconstruction of the palaeogeographical development of barrier spits in time and space allows the determination of the Holocene water-level development at the SW Baltic Sea. The sediments deposited here represent the shore-facies. Therefore regressions, transgressions as well as the maximum expansion of the waters can be determined. Coastal dynamics can be analysed and represented over a long space of time. Mass balances of sediments which have a high value for terms of coastal protection can be calculated.

The coastal areas of the SW Baltic Sea are predominantly made up of Quaternary sediments (Pleistocene and Holocene). Pleistocene deposits outcropping at the coastal cliffs are glaciogenic till (boulder clay) and glaciofluvial to glaciolacustrine deposited gravel, sand, silt and clay. Late Glacial to Early Holocene is characterised by terrestrial conditions. Lake marl deposits and peat, representing minor lakes, can be found sporadically at the cliff-sections.

Major environmental changes took place when the Baltic Sea, in addition to waters of the earlier evolutionary stages, reached the area of the present coast. Pleistocene sediments were eroded and re-deposited. Thus the present coastline came into being as an elongated coast with beach ridges and barrier spits covered by dunes cutting off lagoons from the Baltic Sea proper.

The Pudagla lowland is situated in the central part of Usedom Island (Fig. 1), representing the middle of three large Holocene lowlands on the island. The lowland covers an area

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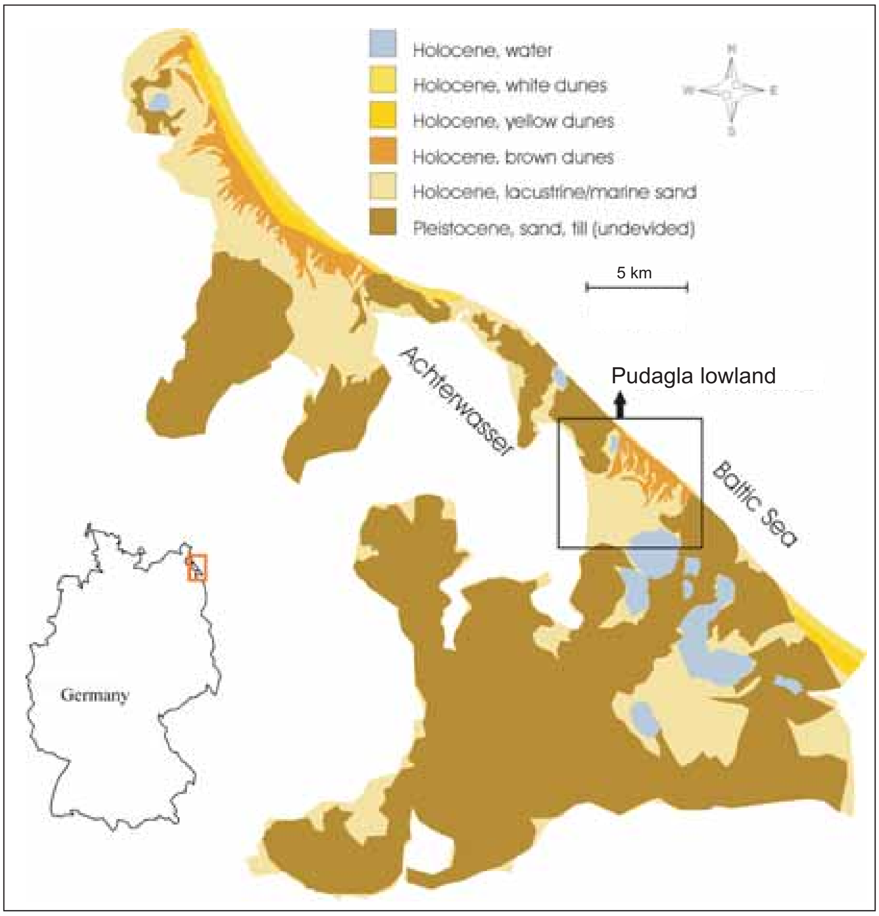

Fig. 1. Simplified geological map of Usedom Island; Pudagla lowland is situated in the central part of the island

of approximately 16 km^2 with altitudes around m.s.l. in most of the lowland. Dunes reach up to 3.0 m m.s.l. on the outer coast.

Framed by Pleistocene deposits to the North and South, the Baltic Sea to the East and a lagoon, the so called "Achterwasser" to the West, the Pudagla lowland is a depression filled by Late Pleistocene to Holocene deposits. Knowledge about the sedimentary filling has been published by Kliewe (1960) only. The analyses of 6 borings were used to reconstruct the evolution of the lowland. Wernicke (1929) and Haack (1960) give a geomorphologic overview of the geological evolution. Studies of the bordering Oder Lagoon have been published by Müller *et al*. (1996) and Müller (2001).

METHODS

To reconstruct the geological structure of the lowland 63 borings were made. A vibrocore technique was available which allows samples to be taken from depths of up to 25 m. Sampling-tubes of 36 to 80 mm in diameter were used depending on the penetration-resistance of the sediments. Sediment cores were taken in 2 m intervals. The deepest drilling reaches down –22 m m.s.l. All cores penetrated through the marine sequence. According to DIN 4022 lithological units were defined through changes in grain size, colour, fossil, calcium-carbonate and organic content. Stratified sampling was done using the lithological boundaries. Subsampling of the units was carried out to discriminate sub-facies types. Sand and gravel samples were analysed in terms of granulometry by sieving. Molluscs (bivalve, gastropods) were separated and species determined. Species-associations give hints to the ecological conditions of the associated habitat. Analysis of the ostracod-assemblages were carried out to demonstrate variations in salinity over time (Viehberg, Hoffmann, 2003). Organic sediments, peat as a rule, were used for radiocarbon dating. All radiocarbon ages given here are uncalibrated ^{14}C a BP. The palaeogeographical reconstruction was done by modelling surfaces of lithological units using ordinary kriging as interpolation-method.

RESULTS

SEDIMENT SEQUENCE

The base of the Quaternary sediments described here is made up of grey, calcareous boulder clay (Fig. 2). Usually it is a clay-rich till with localised zones of increased sand content. Stratigraphy is not known for sure. It is assumed to be either the W2- or the W3-till (after Müller *et al.*, 1995) of the Late Pleistocene Weichselian ice advance.

Calcareous, silty, fine to medium sand follows in the columnar section (Fig. 2). Thickness reaches up to several metres, possibly more than 10 m. Often the unit could not be penetrated. It is not known for sure whether this is only one or even more lithological units with different genesis. There are similarities to the Pleistocene glaciofluvial deposits which can be observed at the cliffs on the outer coast of Usedom Island (see Schumacher, 1995; Malmberg-Persson, 1999). A peat-layer was observed within this unit. Radiocarbon dating gave an age of 11,500±65 yr. BP.

In the upper parts some molluscs (*Stagniola* sp., *Sphaerium* sp., *Pisidium* sp.) can be found, suggesting a fluvial-lacustrine depositional environment. Plant remains are dispersed in the sand. The sediment-colour is grey predominantly, to the top changing to greenish-grey, and being decalcified.

Minor depressions or channels on the surface are equalised by the following unit made up of ostracod-rich lake marl deposits (Fig. 3A, C). Analysis of the ostracod-assemblage (Viehberg, Hoffmann, 2003) revealed lacustrine to oligohaline environmental conditions in small lakes or ponds which existed only in some parts of the area. The ponds were isolated and shallow. Index species are *Candona candida* and *Limnocythere inopinata*. *Cyprideis torosa* is missing, thus an isolation of the sea is assumed.

Peat or organic mud could be found in almost all sampling-sites in the central part of the lowland (Fig. 3A–D). Facies shifting in time and space is common for these deposits due to changing water levels. Taking the mollusc-assemblage into account, lacustrine environmental conditions can be assumed for the deeper parts of this unit. Where the lower limit is above –10 m m.s.l. marine conditions are recognised, however, at some sites this can be at –13 m m.s.l. Thickness of this unit is not more than 50 cm. Radiocarbon dating gave an Early Atlantic age. The age of a peat-layer, sandwiched in between lacustrine deposits, towards the edge of the lowland, has been determined to be 7430 ±65 yr. BP.

An almost identical age (7440 ±65 yr. BP) was given by a peat overlain by marine deposits in a nearby sampling site. A hiatus of several hundred years is most likely here because in deeper parts of the depression peat of lacustrine environment gave an age of 7180 ±65 yr. BP. A peat-layer bound to a beach ridge in a depth of –6.80–6.85 m m.s.l. was analysed. Radiocarbon-dating gave 6360 ±90 yr. BP. Overlying the peat in the columnar section (Fig. 2) is a light-brown organic mud of a lacustrine environment. The environmental conditions are shown by the presence of mollusc-species *Bithynia* sp., *Valvata* sp., *Acroluxus* sp., *Anisus* sp., *Radix* sp. and *Stagnicola* sp. which are very common within this unit. Occurrence of the brackish ostracod *Cyprideis torosa* indicates that this water was influenced temporarily by brackish sea water.

There is no change within the sedimentation conditions coming to the next unit which is also an organic mud. However, a change of environmental conditions can be observed. Dominating molluscs are species of *Cerastoderma* sp., *Hydrobia* sp., *Mytilus* sp., *Theodoxus* sp. and *Scrobicularia* sp., indicating a marine to marine-brackish environment. Ostracod analysis hints at a salinity of approximately 5‰. This unit is widely spread in depths of –10 to –6 m m.s.l. (Fig. 3A–D). The content of fine sand increases upwards; in most cases there is an indistinct boundary to the overlying sandy-marine unit.

Silty fine sand is the most common grain size within the sandy-marine unit. Again, molluscs permit the definite determination of marine-brackish conditions. This unit is defined by a facies association of different depositional environments. They are distinguishable by the grain size composition, making of the main difference between beach-ridge-facies (medium to coarse sand, gravel), channel-facies (fine to medium sand) and slack-water-facies (silty fine sand). Huge amounts of the sandy-marine unit were deposited on wind-generated flats (flat-facies)

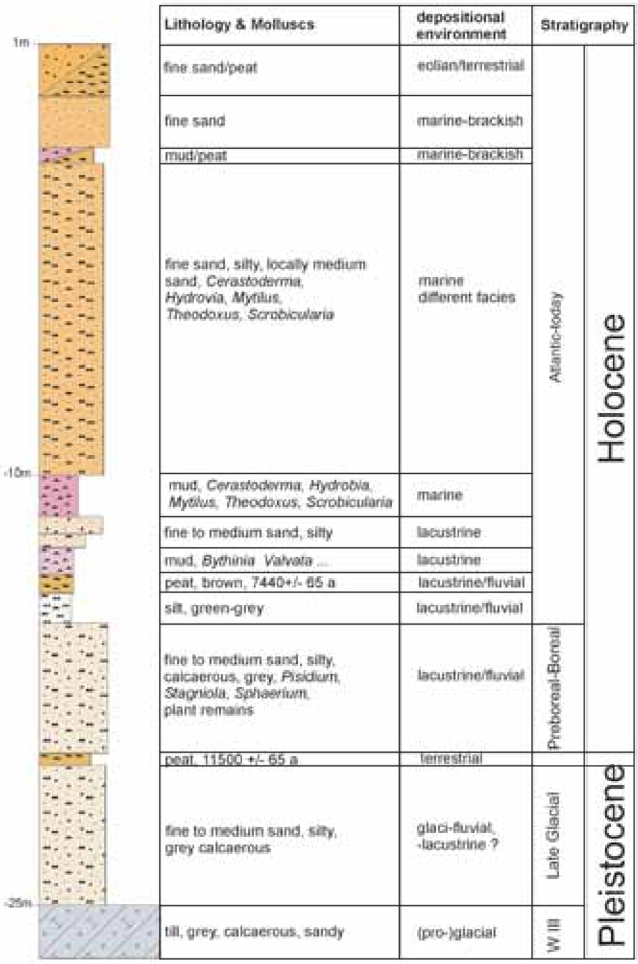

Fig. 2. Columnar section of the Pudagla lowland; lithological units are shown here in their stratigraphical position

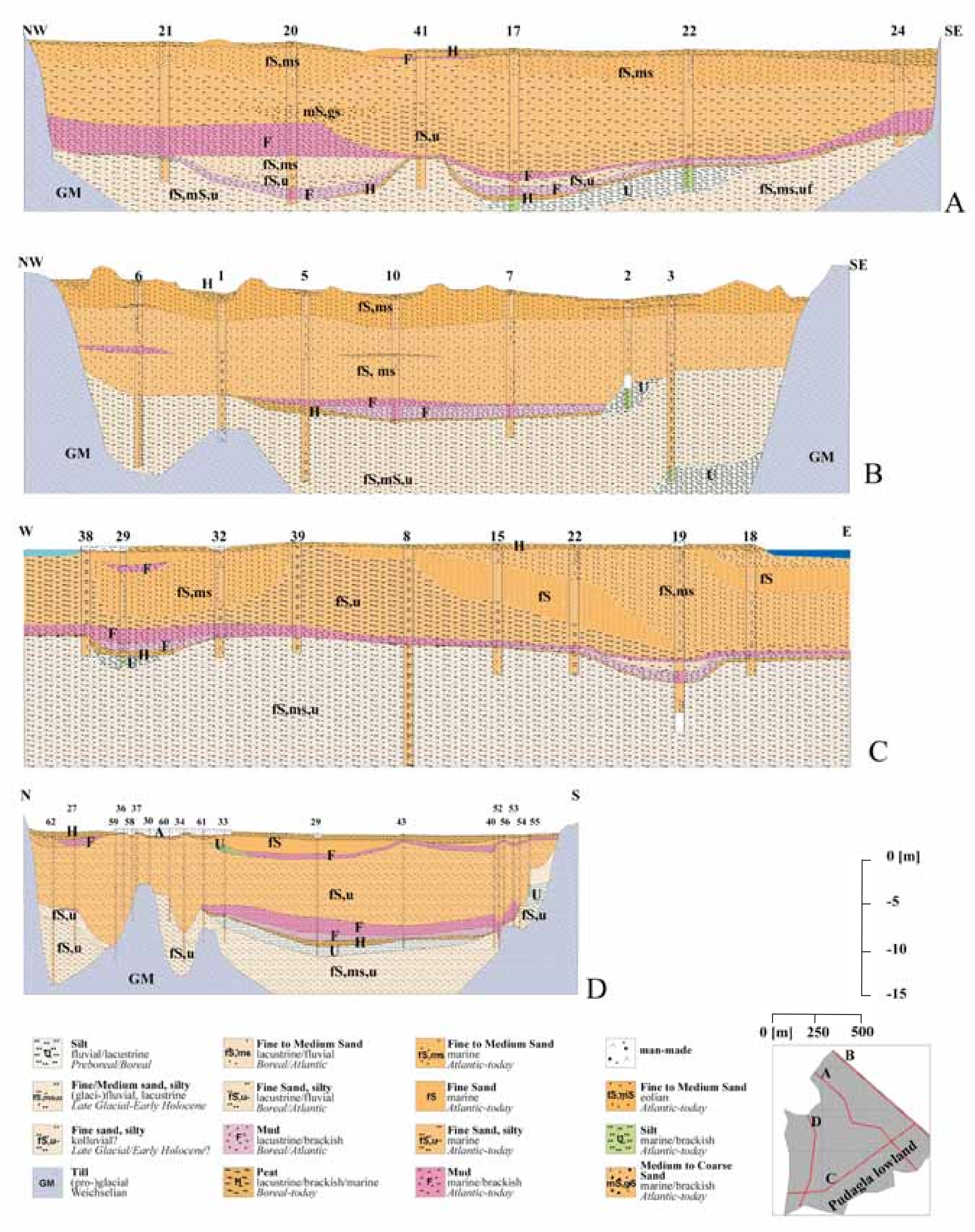

Fig. 3. Geological cross sections in the study area, based on the indicated borings (numbers above)

represented by fine sand. Peat is the most common sediment at the surface of the lowland. In the west of the study area sand layers occur within the peat. They are interpreted as evidence of storm surges. Exact determination of historically mentioned storm events is not yet possible, nevertheless the occurrence of the bivalve *Dreissena polymorpha* prove a comparatively young age. Radiocarbon dating of a peat underlying such a storm-layer gave an age of 975 ±50 yr. BP. To the east, fine to medium sand (dunes) make up the uppermost parts of the columnar section.

PALAEOGEOGRAPHICAL DEVELOPMENT

At around 14,000 BP the ice retreated from the area (Kaiser, 2001). The till-surface of the W3(?)-advance can be reconstructed for the margins of the lowland and in some sampling sites at elevations of around –6 m m.s.l. (Fig. 4A). In the central part it is situated below –20 m. The deposition of the till already determined the configuration of the present coast. Afterwards, sandy (glacio-)fluvial, -lacustrine sediments were deposited until the Alleröd, as shown by a radiocarbon-dated peat-layer (Fig. 4B). A water level of at least –8 m m.s.l. is assumed for the Late Preboreal/Early Boreal (Fig. 4C). Mainly terrestrial conditions prevail for the time interval of Boreal to Early Atlantic (Fig. 4D). Calcareous mud was deposited in isolated, oligohaline lakes or ponds. Thus, the former Preboreal/Boreal lake must have run off, lowering the erosion-level. At the end of Early Atlantic, the (ground-)water level rose again, with lakes growing and communicating.

The Littorina-sea reached the study area at around 6500 BP (Fig. 4E). Saltwater-tolerating species can be observed within the sediments of the ponds. The sea level rose fast, reaching –7 m at around 6300 BP. Organic mud with a high content of mollusc-species (most common: *Cerastoderma* sp. and *Mytilus* sp.) is deposited in the deeper parts. Till-elevations in the northern part of the study area form an island-archipelago as the sea level rose. The basin was filled up with the sandy--marine unit until 1000 BP (Fig. 4G). The connection to the open sea was narrowed by constant growing of beach ridges and dunes. Coastal-lakes were disconnected from the sea (e.g. Lake Wockninsee) and almost the entire area developed as a wind-generated flat, as defined by Lehfeldt, Barthel (1998). Shifting flood channels and beach ridges existed on top of the flat. Lake Schmollensee and the lagoon Achterwasser were at least temporarily connected with the open sea. The barrier spit closed between 1000 BP and 800 BP. Freshwater conditions established in Lake Schmollensee and Lake Wockninsee with sedimentation of calcareous organic mud (Fig. 4H). Salinity dropped to 2–4‰ in the Achterwasser-lagoon. A permanent dune-belt developed on the outer coast and peat started to grow within the entire Pudagla lowland.

CONCLUSIONS

After the ice sheet retreated, the area of the islands on the Oder river mouth had a high relief (Kliewe, 1960). There were only minor periglacial transformations of the landscape. Kliewe recognised a sandy Boreal freshwater unit, reaching up to –8 m m.s.l., underlying the marine deposits, and concluded that these sediments represent the Ancylus-Lake as an earlier stage of the Baltic Sea evolution. The results presented here confirm the existence of this lithological unit. Kliewe's definition of deposition within the Ancylus-Lake is doubted. Recent researches in the Baltic Sea basin revealed a maximum water level of –18 m m.s.l. (Jensen *et al*., 1999; Lemke *et al*., 1999).

As far as known, this lithological unit can be found in the northern part of Usedom Island as well (Hoffmann, Lampe, 2002; Hoffmann *et al*., 2002). Recent surveys on Rügen-Island also revealed the existence of this unit (Lampe *et al*., 2002). A Boreal fresh-water lake in the vicinity of the Oder river mouth must be required and is the subject for further investigations.

The peat on top of the Boreal fresh-water unit is described as a regression-deposit by Kliewe (1960). Peat-accumulation is believed to continue until the transgression of the Littorina Sea. As demonstrated here, minor lakes existed after the Boreal regression, partly overlying the peat. Due to the facies shifting in time and space, it is hard to determine whether the peat is of regression- or transgression-type. It has to be assumed that both types are represented, partly the regression-type passing into the transgression-type.

Marine conditions were most probably established in the Pudagla lowland slightly before 6360 ±90 yr. BP. For the Oder Lagoon adjacent to the south Müller (2001) determined the start of the transgression at 5500 yr. BP. For the Greifswalder Bodden to the north the transgression is dated to 6500 yr. BP. (Müller, 1999). The depth of the transgression-contact varies. But taking into account the rapid sea level rise during the first main stage of the Littorina transgression (Kliewe, 1995; Janke, Lampe, 2000), the depth could be neglected. Thus, there seems to be a NW–SE dipping gradient in the onset of the transgression.

Kliewe and Janke (1982) already pointed out that the transgression onset varies regionally at the coast of the southern Baltic Sea. Further investigations will have to prove it.

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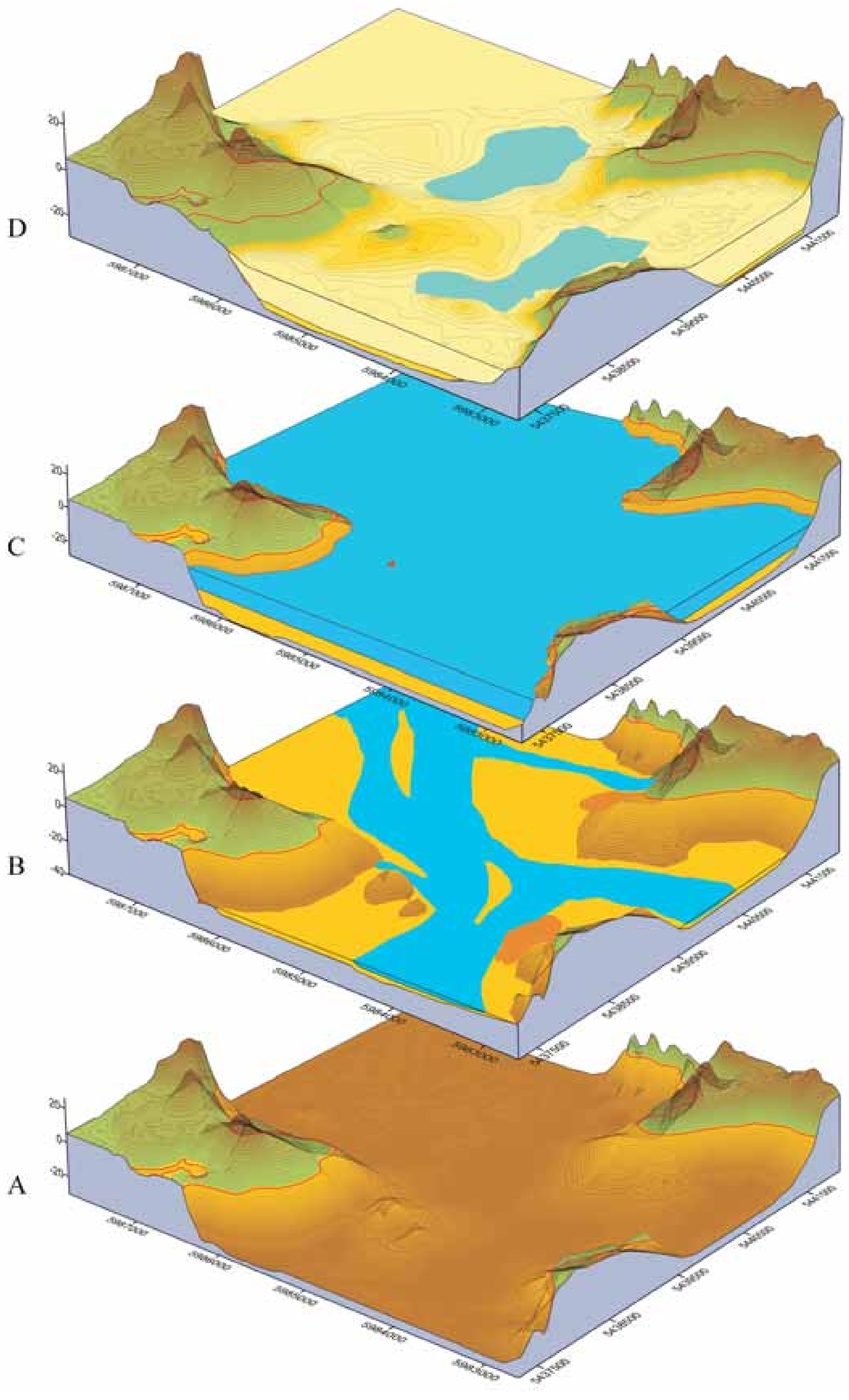
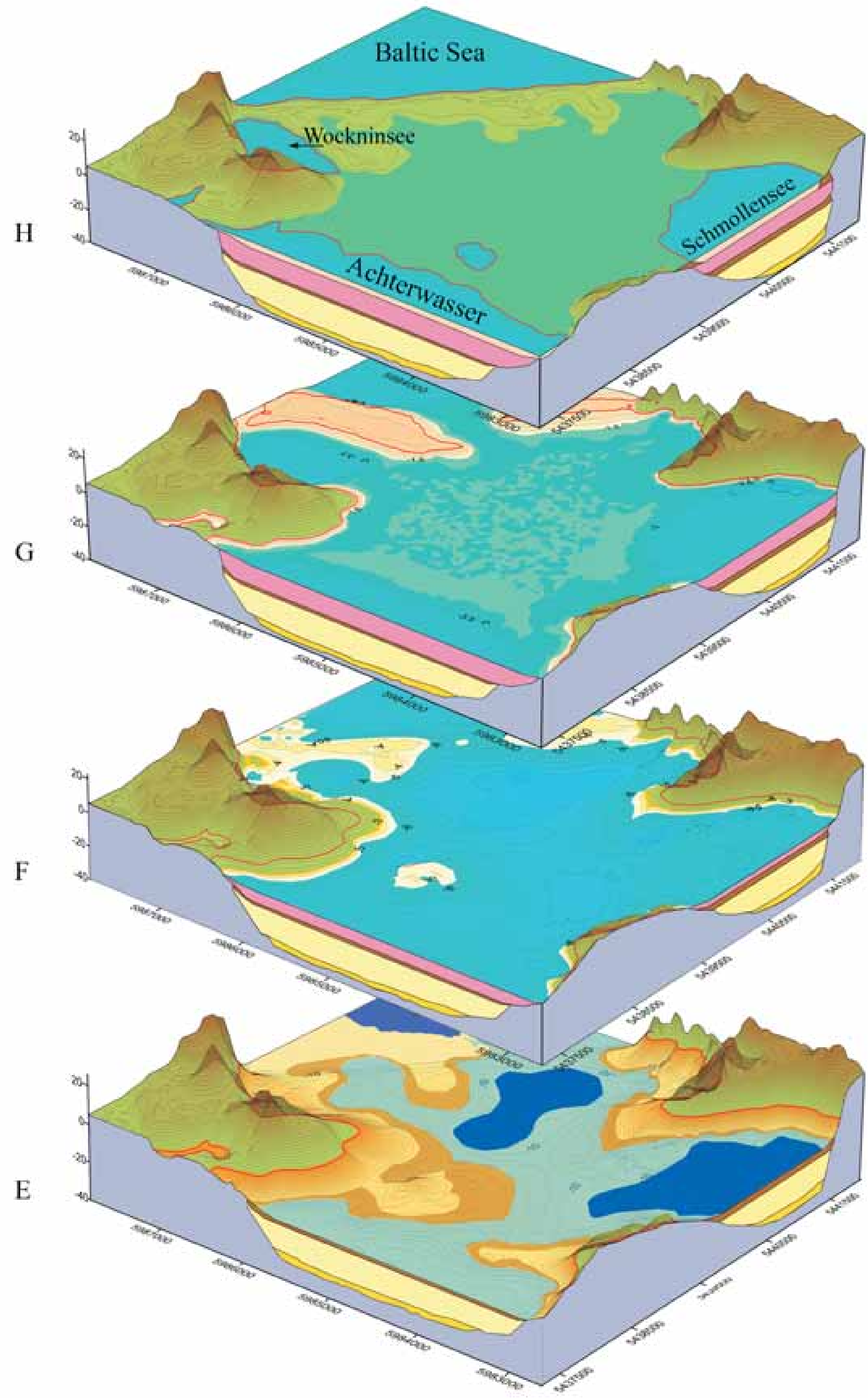


Fig. 4. Palaeogeographical reconstruction

A. ~14,000 BP, deposition of glacial sediments, **B**. Alleröd, fluvial sands and peat-accumulation, **C**. Preboreal/Boreal, fresh-water lake, deposition of fine sand, **D**. Boreal/Early Atlantic, terrestrial conditions, locally isolated ponds with mud-sedimentation



of the Pudagla lowland

E. Atlantic, ~6500 BP, Littorina-transgression reaches the area, peat-accumulation in the vicinity of the lakes, **F**. Atlantic, ~6300 BP, fast rising water level, mud sedimentation, **G**. Subatlantic, ~1000 BP, beach ridges, sand-sedimentation, **H**. Today, the barrier spit is closed, a dune-belt developed on the outer coast

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