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Submarine eskers preserved on Adler Grund, south-western Baltic Sea

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Abstract The position of offshore ice margins, especially in the Baltic Sea, is poorly known. Based on hydroacoustic surveys, we mapped a field of submarine eskers on the seafloor of the shoal Adler Grund, south-western Baltic Sea. The eskers comprise discontinuous, branching ridge structures with zigzag-shaped crests. These features are elevated up to 7 m above the surrounding seafloor with slope angles approaching 26°. The ridges are composed of gravel and boulders. Their interpretation as glacio-tectonic features is unlikely due to branching ridge crests and a continuous reflector at the base of several ridges. Based on their morphology and distribution, the ridges are interpreted as concertina eskers formed by meltwater outbursts close to an ice margin. Their good state of preservation indicates that the eskers were most likely formed during the last advance of the Weichselian glaciation across the study region.

Keywords *• Multibeam echo sounder • Submarine esker • Adler Grund • Baltic Sea*

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INTRODUCTION

The onshore ice margins of the Weichselian glaciation and the resulting morphology in Northern Europe are known in high detail (Böse *et al.* 2012). Offshore, information was compiled for the North Sea shelf (Sejrup *et al.* 2005) and for the central and northern part of the Baltic Sea (Noormets, Flodén 2008a, 2008b). Less information is available for the southern Baltic Sea, where ice margins and ice flow directions have been extrapolated from onshore data (Noormets, Flodén 2008b). Generally, the ice marginal lines of the late Weichselian are located within today's Baltic Sea basin (Böse *et al.* 2012). The main advance during the Last Glacial Maximum at 20 ka BP was NE-SW directed (Stephan 2001; Kjaer *et al.* 2003) (Fig. 1). Subsequently, the ENE-WSW directed Young Baltic Ice Streams (Kjaer *et al.* 2003) occurred between 17.0 and 15.0 ka BP, with ice margins of this age found south of the island of Rügen (Böse *et al.* 2012). While lobe-shaped ice margins further offshore between the islands of Rügen and Bornholm are shown in maps (Böse *et al.* 2012; Niedermeyer *et al.* 2011), little evidence of their existence has been published so far. This study presents bathymetric and seismic data of Adler Grund, situated in the SW Baltic Sea between the islands of Rügen and Bornholm (Fig. 1). Evidence of a preserved submarine field of concertina eskers (Knudsen 1995; Evans, Rea 1999) is shown, supporting the existence of a late-Weichselian ice margin close to the investigation area.

STUDY SITE

Adler Grund is a shoal in the south-western Baltic Sea, rising to water depths of less than 5 m. It is elevated up to 35 m relative to the Arkona Basin on its north-western side and the Bornholm Basin on its south-eastern side. South of Adler Grund, an elongated depression protruding from the Bornholm Basin towards west is observed (Fig. 1), incised approximately 10 m to a depth of 28 m. Adler Grund is separated from the north-west situated Rönne Bank by

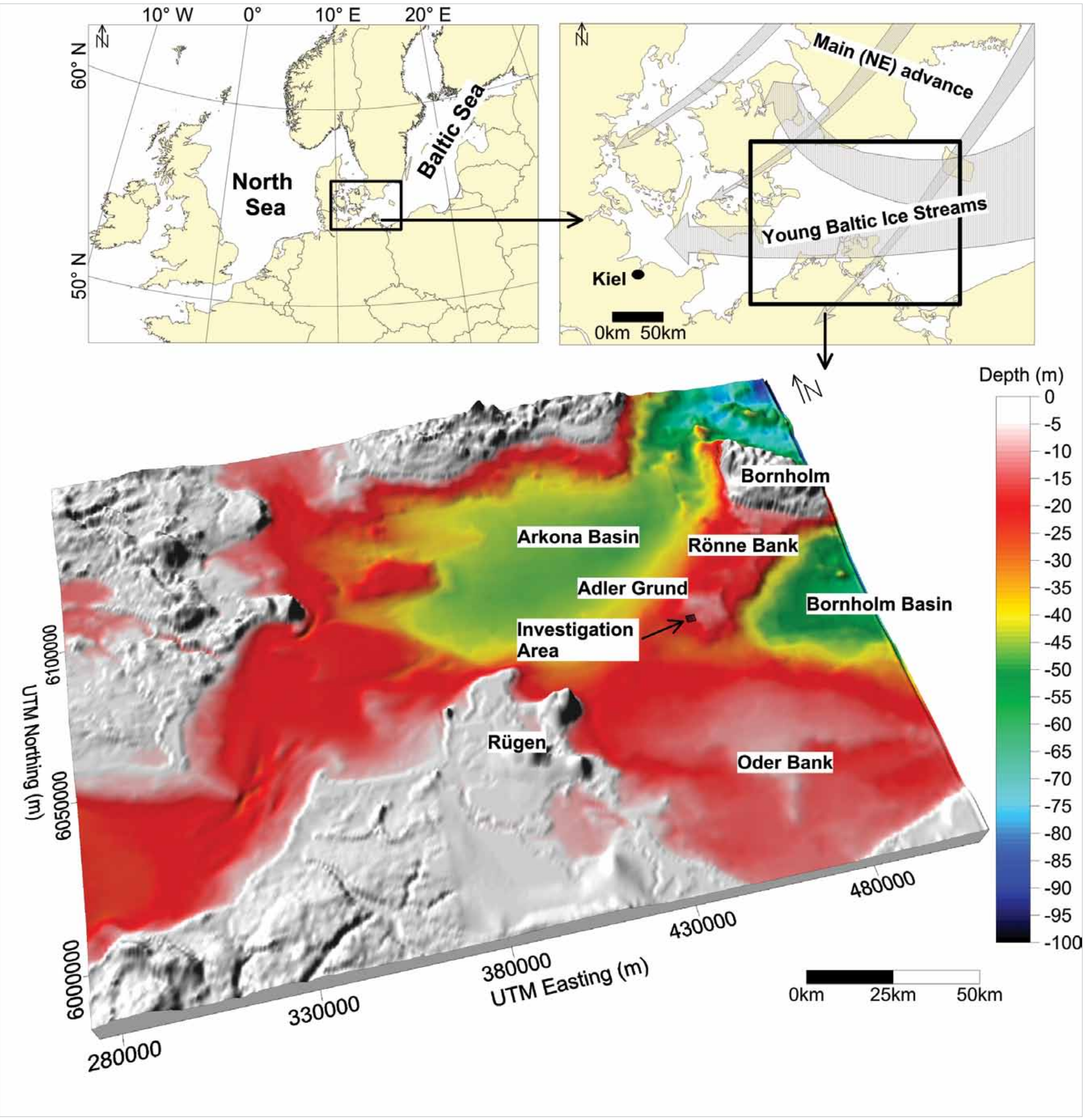

Fig. 1 Location of the study site. Bathymetric data based on Seifert *et al.* (2001). The directions of the Main Weichselian ice advance and the Young Baltic Ice Streams are indicated (based on Kjaer *et al.* 2003). Compiled by P. Feldens, 2013.

several SE-NW aligned depressions, partly more than 10 m in depth. Its central area is widely covered with coarse-grained lag deposits (Emelyanov *et al.* 1994; Nielsen *et al.* 2004).

Asymmetric ridges on the central Adler Grund were previously interpreted as glacio-tectonically deformed lodgement till resulting from the last glaciation (Gromoll, Störr 1989; Nielsen *et al.* 2004). At the slopes of Adler Grund towards the Bornholm and Arkona Basins sand accumulations prevail, mainly deposited or reworked during the time of the Ancylus Lake and the Littorina Transgression (Nielsen *et al.* 2004).

Tectonically, Adler Grund is part of the Arnager Block, connected to the Bornholm Block at approximately 55°N. Directly to the west of the Arnager Block two segments of the NW-SE directed Tornquist Zone (Graversen 2010) are connected by the Rönne Graben (Krzywiec *et al.* 2003; Obst *et al.* 2004). Relative movements of the Bornholm and Aranger Block and the graben structures in the vicinity are assumed to have occured in three phases, namely in the Triassic, the Early Jurassic to Early Cretaceous and the Late Cretaceous (Graversen 2004).

METHODS

Bathymetric data were collected using a multibeam echo sounder (SeaBeam 1185, L3 Communication/ELAC Nautik, 180 kHz) onboard FK *Littorina* in 2006.

Processing included roll calibration, corrections for local sound velocity variability with depth and manual removal of outliers. Due to stormy weather conditions, wave artefacts are partly present in the data due to insufficient heave compensation. Backscatter data were previously acquired using a Klein 595 side scan sonar (Diesing, Schwarzer 2006). A standard processing scheme was used for side scan sonar data (Blondel 2009). Ground truthing of hydroacoustic data was achieved with underwater video footage. Reflection seismic data were acquired onboard FS Poseidon in 2009 using a boomer source and a single channel hydrophone-streamer with eight elements. Processing included a trapezoidal bandpass filter opening from 55 Hz to 100 Hz and closing from 1000 Hz to 1800 Hz and trace normalisation as well as constant gain.

RESULTS

Seafloor surface

A generally NE-SW striking ridge system extends over the central Adler Grund (Fig. 2A). Ridge crests are zigzag-shaped, with individual ridge segments reaching 0.1 to 1.5 km in length and striking E-W to N-S. Branching is observed in several places. The base of the ridges is situated between 15 m and 22 m below sea level (b.s.l.), with a 7 m maximum relative elevation of the crests above the seafloor. Regardless of the ridge base depth, the crests typically rise to 13.5–16 m b.s.l. The distance between the crests varies between a few tens of metres to a few hundred metres. The ridges are asymmetric, with higher slope angles of up to 26° and adjacent local depressions on their southern flanks (Fig. 2B and C). The northern slopes frequently show a marked change in slope angle, reaching 10° at maximum. The change correlates with a decrease in side scan sonar backscatter intensity. The ridges are mainly composed of boulders and gravel that are observed both in side scan sonar data (Fig. 2C) and in the underwater video footage (Fig. 2D). Distinct boundaries exist between the ridges and surrounding seafloor, which is composed of rippled sand (Fig. 2D).

Subsurface

Two boomer profiles recorded in the central area of Adler Grund (Figs 3, 4 and 5) allow differentiating the relationship between the ridges and the subsurface.

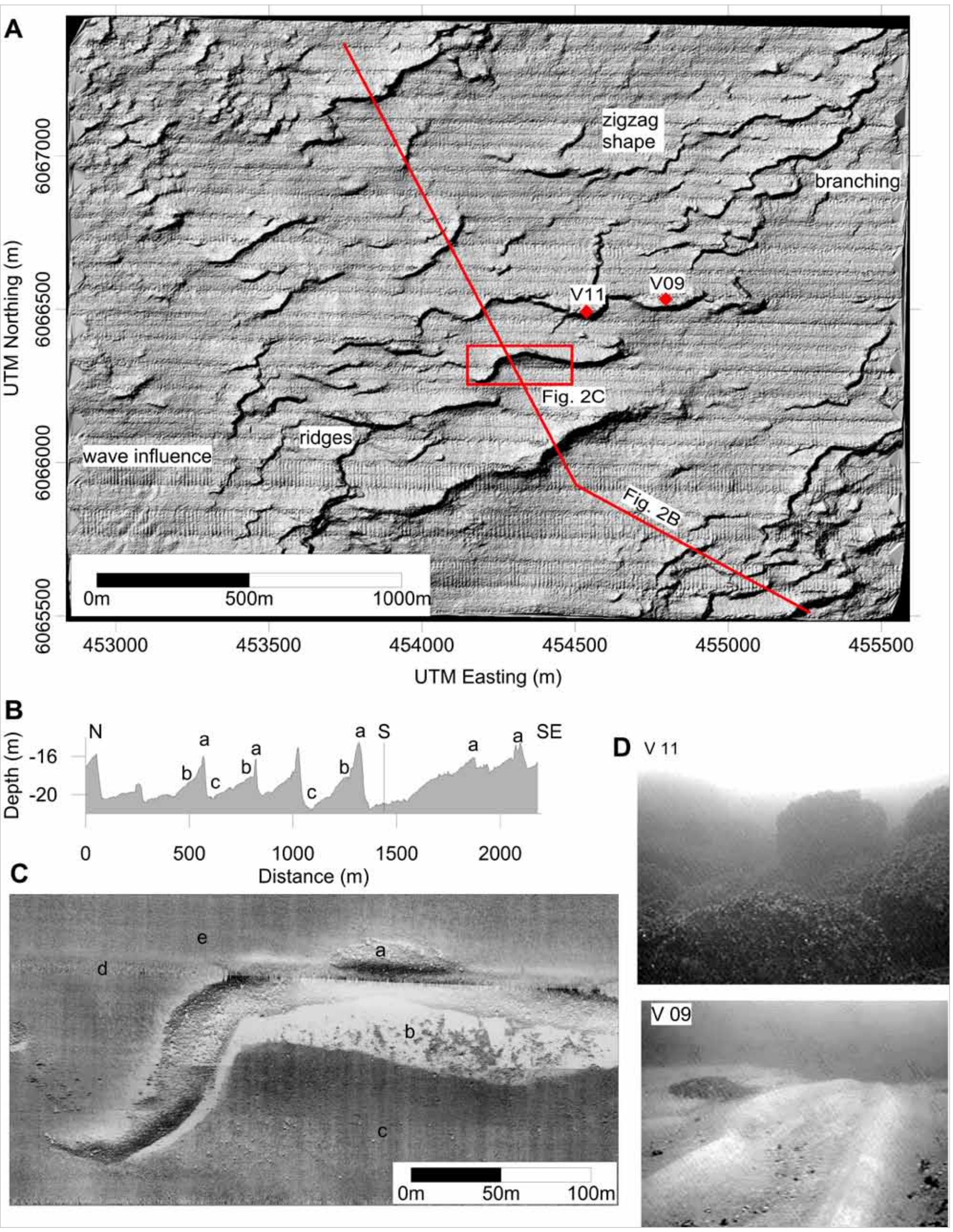

Fig. 2 **A.** Shaded relief image (multibeam echo sounder data) of the central Adler Grund (refer to Fig. 1 for location). The northwest-southeast striking ridge system is visible. **B.** Bathymetric profile. The ridges (a) are asymmetric, with a bend in slope angle (b). On their southern flank, small depressions are observed (c). **C.** Detailed side scan sonar image of a ridge (Diesing, Schwarzer 2006) (a) Sediment with low backscatter intensity is observed south of the ridge (b). Numerous boulders reveal themselves by their acoustic shadows (a, c) The nadir artefact (d) crosses the ridge. **D.** Underwater video images, image width approx. 1 m. Large boulders (V11) and a sharp contact between the ridges and the surrounding sediment (V09) are visible. Compiled by P. Feldens, 2013.

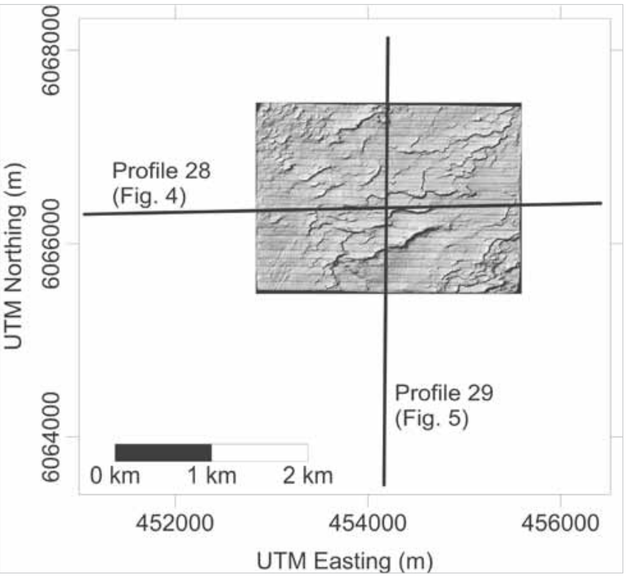

Fig. 3 Position of the seismic profiles shown in Figs 4 and 5. Compiled by P. Feldens, 2013.

These profiles are orientated North-South and East-West, both crossing the identified ridge system. In the area of the central Adler Grund and especially beneath the ridges, boomer penetration depths are severely limited due to the lag deposit and boulders at the seafloor. A succession of several seismic units is recognised in boomer data, forming unit 1, 2 and 3. The thickness of these units generally increases towards south. In E-W direction, unit 2, showing a synclinal shape, fades out both towards east and west. Despite the absence of core data for ground-truthing purposes, the units can be interpreted as a succession of glacial deposits. This is due to the chaotic internal structure and the presence of diffraction hyperbolae, indicating boulders. Close to the seafloor, the ridge structures are recognised on top of unit 1 and 2. The internal structure of the ridges is not resolved. In several places a continuous reflector is observed at their base.

DISCUSSION

A tectonic origin of the NW-SE directed ridge system unrelated to glacier influence is unlikely. Little tectonic deformation is indicated for Upper Cretaceous and younger sediments in the Adler Grund and Rönne Bank area (Graversen 2004, 2010) with shallow seismic profiles on the Rönne Bank showing no displacement of Quaternary sediments (Krzywiec *et al.* 2003).

The ridges on the central Adler Grund have been previously interpreted as deformed lodgement till (Gromoll, Störr 1989; Nielsen *et al.* 2004). The newly gathered data suggest a different interpretation of the ridges and their formation: The observed branching of the ridge crests is an unlikely result of glaciotectonic deformation. Seismic data show that the ridges are not connected to a decollement surface, and appear on top of different seismic units. Further, a high-amplitude reflector can be observed beneath several ridges (Figs. 4 and 5). While this reflector is not always visible, we assume that it is present beneath most of the ridges, as they have a very similar appearance in bathymetric and side scan sonar data and are likely of identical origin. Thus, seismic data supports the interpretation of the ridges as individual sediment bodies.

The ridge composition, mainly of gravel and boulders, is uncommon for various moraine types that are typically poorly sorted comprising a wide range of grain sizes (Evans *et al.* 2006). Changing water levels during the Baltic Sea evolution (Björck 1995) could be responsible for reworking of the original material, with isostatic movements being minor in the Adler Grund area (Lampe *et al.* 2010). Water levels between

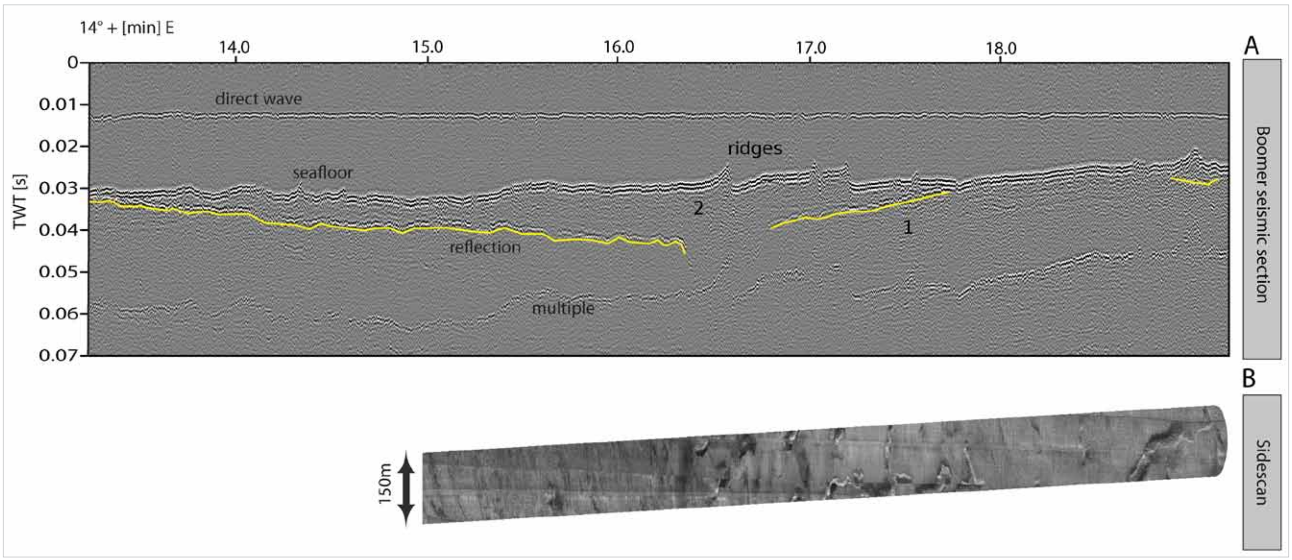

Fig. 4 Profile 28, crossing the observed ridge system in East-West direction. Boomer data (A) and corresponding side scan sonar data (B) are displayed. Refer to Fig. 3 for position. Seismic units are indicated by numbers 1 to 3. Compiled by D. Wilken, 2013.

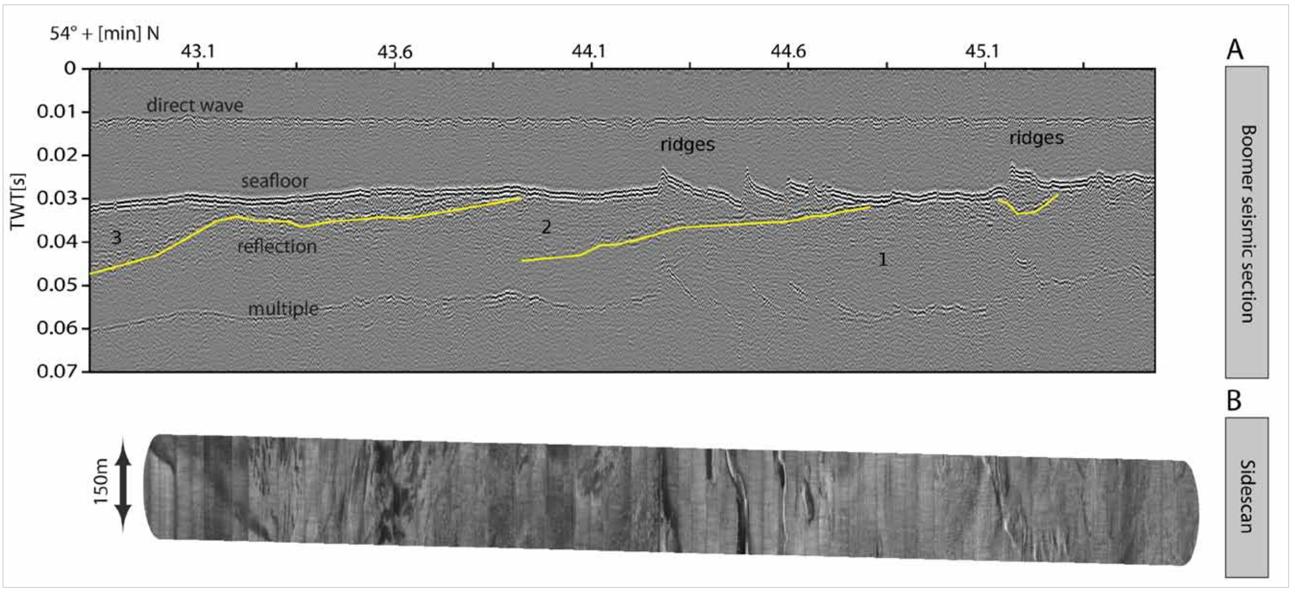

Fig. 5 Profile 29, crossing the observed ridge system in North-South direction. Boomer data (A) and corresponding side scan sonar data (B) are displayed. Refer to Fig. 3 for position. Seismic units are indicated by numbers 1 to 3. Compiled by D. Wilken, 2013.

15 and 24 m b.s.l. were met during a) the Baltic Ice Lake during the Allerød and Younger Dryas, b) the Ancylus Lake during the Pre-Boreal and Boreal and c) the water level rise of the Littorina Sea in the Atlantic (Lampe 2005). However, the morphology of the ridges is very distinct, with sharp crests preserved (Fig. 2). This leaves a significant reworking of till deposits or the formation of crevasse-squeeze ridges unlikely, as a diffuse morphology would be expected due to erosion of their fine gravel and finer sediment fractions in the near shore environment.

Still, ridges on Słupsk Bank with a morphology similar to those described in this study have been interpreted as de Geer moraines (Uścinowicz 2010), which form near ice margins during subaqueous deglaciation. There is no consensus on the formation of de Geer moraines, which might form in basal crevasses or as annual recessional moraines (Sollid 1989; Larsen *et al.* 1991; Blake 2000; Lindén, Möller 2005; Golledge, Phillips 2008). While the composition and morphologies of de Geer moraines varies widely, none are reported to dominantly consist of gravel and boulder (Golledge, Phillips 2008; Winkelmann *et al.* 2010). Further, the undulating and branching configuration of the ridges observed on the central Adler Grund points to the impact of glaciofluvial processes involved in the deposition of the ridges, resulting e.g. in the formation of eskers. Subglacial conduits may extend for large distances in warm-based ice, and thus many eskers are traceable for several hundred kilometres (Brennand 1994). In contrast, *"concertina eskers"* are constricted to the ice margin (Evans, Rea 2005; Hansen 2003; Knudsen 1995). Concertina eskers were originally attributed to the deformation of previously existing eskers deformed by surging ice (Knudsen 1995). However, Evans and Rea (1999, 2005) have recently argued that concertina eskers form during the termination of ice surges, and their zig-zag shape is determined by crevasse networks. Thus, the formation of concertina eskers has been ascribed to short-lived high-discharge events (Evans, Rea 1999). For eskers that formed after meltwater outbursts, a composition of gravel and boulders has been described (Burke *et al.* 2008, 2009). Further, branching is observed within such esker systems due to switching water pathways (Boulton *et al.* 2007; Ottesen *et al.* 2008). Due to the discontinuous ridge morphology, the gravel and boulder composition, the zigzag crest shape as well as the missing continuation of the ridges in side scan sonar mosaics of the surrounding Adler Grund area over distances larger than a few kilometres (Diesing, Schwarzer 2006), we interpret the ridges as concertina eskers. The untypical asymmetric appearance of the supposed eskers, different to previously observed submarine eskers (Ottesen *et al.* 2008), is attributed to asymmetric sediment deposition. It may be assumed that the ridges form obstacles to sediment transport, with sediment deposition preferably taking place at the ridge's northern slopes. This interpretation is consistent with the observed lower backscatter intensity on the lower flanks of the ridges, which indicates the deposition of sand that was also observed in video footage in such a case (see Fig. 2D). Additionally, the occurrence of local depressions towards the south of the ridges might indicate a sediment deficit due to sediment accumulation on the northern flanks.

Typically, the orientation of esker systems is parallel to the ice flow direction (Boulton *et al.* 2007; Burke *et al.* 2008). However, it may be difficult to determine the ice flow direction based on the strike direction of concertina eskers. This is due to the formation of concertina eskers within the pre-existing crevasse network (Evans, Rea 2005), which may form at an oblique angle to the ice flow (Rea, Evans 2011). However, the good preservation of the observed ridge sections indicates that they were deposited during the last ice advance that reached the study site as the ENE-WSW directed Young Baltic Ice stream. Especially in the late Weichselian, warm based and surge type glaciers were abundant (Boulton *et al.* 2009), increasing the likelihood of concertina esker formation due to the increasing formation of crevasses (Evans, Rea 1999; Rea, Evans 2011). The exact position of the ice margin and the ice flow direction during the time of the concertina esker formation cannot be determined. However, concertina eskers are located in the proximal part of the glacial landsystem of surging glaciers (Evans, Rea 2005). Therefore, it may be possible to extrapolate the stratigraphic position of the observed ridges. Ice margins dated to 15–16 ka BP have been identified at the island of Rügen (Böse *et al.* 2012). Given the general trend of preserved ice margins becoming progressively younger towards the north in the southern Baltic (Böse *et al.* 2012), the ice margin close to the identified esker system is less than 15–16 ka BP old. It may correspond to the local Bornholm ice advance at approx. 14.8 ka BP (Niedermeyer *et al.* 2011), or to the Słupsk bank phase at 13.5 – 13.2 ka BP (Uścinowicz 1999). Eventually, further geomorphological signatures of this system, for example remnants of thrust and push moraines in its distal part, could be identified to reconstruct the ice margin in more detail. An extensive amount of hydroacoustic data may be available for this task, due to the recent rise of offshore windparks as well as extensive acoustic habitat mapping for marine spatial planning and conservation.

CONCLUSION

A system of discontinuous, distinct ridges exists on Adler Grund, SW Baltic Sea, elevated up to seven metres above the seafloor and several hundred metres in length. Based on bathymetric, side scan sonar and seismic data, the ridges are interpreted as a field of concertina eskers. These concertina eskers indicate an ice margin in close vicinity, and likely formed at the end of the Weichselian glaciation during the Bornholm ice advance at 14.8 ka BP or the Słupsk bank phase at 13.5 – 13.2 ka BP.

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