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Winsløw, Line Bayer; Schack Pedersen, Stig A. ; Boldreel, Lars Ole; Nørmark, Egon

Published in:
Bulletin of the Geological Society of Denmark

DOI:
[10.37570/bgsd-2020-68-08s1](https://doi.org/10.37570/bgsd-2020-68-08s1)

Publication date:
2020

Document version
Publisher's PDF, also known as Version of record

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Citation for published version (APA):
Winsløw, L. B., Schack Pedersen, S. A., Boldreel, L. O., & Nørmark, E. (2020). Wrench-fault structures superimposed by glaciotectonic complexes, interpreted from high-resolution reflectionseismic sections and boreholes along the western bank of Esrum Sø, north-east Sjælland, Denmark. *Bulletin of the Geological Society of Denmark*, 68, 171-193. <https://doi.org/10.37570/bgsd-2020-68-08s1>

Wrench-fault structures superimposed by glaciotectonic complexes, interpreted from high-resolution reflection-seismic sections and boreholes along the western bank of Esrum Sø, north-east Sjælland, Denmark

LINE BAYER WINSLØW, STIG A. SCHACK PEDERSEN, LARS OLE BOLDREEL & EGON NØRMARK



Geological Society of Denmark
<https://2dgf.dk>

Received 7 February 2019
 Accepted in revised form
 12 May 2020
 Published online
 7 August 2020

Supplementary file: Uninterpreted main seismic profile.
<https://doi.org/10.37570/bgsd-2020-68-08s1>

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Winsløw, L.B., Pedersen, S.A.S., Boldreel, L.O. & Nørmark, E. 2020. Wrench-fault structures superimposed by glaciotectonic complexes, interpreted from high-resolution reflection-seismic sections and boreholes along the western bank of Esrum Sø, north-east Sjælland, Denmark. *Bulletin of the Geological Society of Denmark*, vol. 68, pp. 171–193. ISSN 2245-7070.
<https://doi.org/10.37570/bgsd-2020-68-08>

Wrench-fault structures below Danian limestone and Palaeogene marl, and an overlying structural framework of Quaternary glacial deposits in north-east Sjælland, Denmark, are interpreted from two vibro-seismic sections recorded to 600 msec TWT depth. The main seismic section is 6.3 km long, N–S oriented, and intersected by a 0.7 km long, E–W oriented satellite seismic section. In addition, boreholes in the vicinity of the seismic profile are used for the interpretation. The sections were acquired in 2014 along the western shoreline of the lake Esrum Sø in the Gribskov area. In the lower part of the seismic section (the interval 100–300 msec TWT), parallel-bedded geological layers occur along most of the profile apart from six locations, where six wrench-fault structures displace the upper part of the Chalk Group and lower Palaeogene marl. The northernmost of the six wrench-fault locations correlates to the eastern slope of the buried Esrum–Alnarp valley, which suggests that the valley is an inherited tectonic feature. The location of the wrench-fault structures supports the outline of faults related to the Sorgenfrei-Tornquist Zone on previous geological maps, which had almost no seismic data from the area.

Above the stratigraphic level presented by the Danian limestone and lower Palaeogene marl, a composite glaciotectonic complex comprising two glaciodynamic sequences is recognized by e.g. thrust-fault structures and the lithostratigraphy of glacial successions recorded in the wells. In parts of the seismic sections, the lowermost level of the glaciotectonic complex inherited the wrench-tectonic fault structures, most significantly seen in the northern segment. The advance of the Scandinavian ice sheet caused the glaciotectonic structures displayed in the seismic section. The two sequences represent events related to the Norwegian and the Swedish glacial advances. From the interpretation of the seismic section it is found that the glaciotectonic complex conceals the wrench-tectonic flower structures.

Keywords: Seismic architecture, glaciotectonics, glaciodynamics, Esrum–Alnarp valley, wrench-fault tectonics, flower structures.

Line Bayer Winsløw [line.winslow@gmail.com], *Stig A. Schack Pedersen* [sasp@geus.dk], *Geological Survey of Denmark and Greenland (GEUS)*, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. *Lars Ole Boldreel* [lob@ign.ku.dk], *Department of Geosciences and Natural Resource Management (IGN)*, Copenhagen University (KU), Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. *Egon Nørmark* [en@geo.au.dk], *Department of Geoscience, Aarhus University, Høegh-Guldbergs Gade 2, DK-8000 Aarhus C, Denmark.*

Corresponding author: Lars Ole Boldreel.

Oscillations of the Scandinavian ice sheet and its associated deposition of outwash plains shaped large parts of the Danish landscape (Houmark-Nielsen 1987, 1999; Pedersen 2005, 2012). The three dominant advances during the Weichselian ice age are the Norwegian glacial advance 30–28 ka BP, the Swedish glacial advance 23–21 ka BP and the Baltic glacial advance 18–17 ka BP (Houmark-Nielsen & Kjær 2003; Pedersen 2005), named after their ice-accumulation source areas. These advances can be distinguished by their dominant ice flow directions from the north, north-east and southeast, respectively, and each of these glacial advances caused deposition of a glacial succession and glacial disturbance, i.e. glaciotectonic deformation.

In the Gribskov area in north-east Sjælland, the latest glacial advance formed the landscape and the Gribskov Ice Borderline (GIB) (Fig 1), which is a classic example of a glaciotectonic zone outlined by elongated parallel ridges (Milthers 1948; Houmark-Nielsen 1990). Information from a number of shallow boreholes (locations shown in Fig. 2) indicate a complex Quaternary succession. The northernmost wells show a pronounced offset of the pre-Quaternary, indicating significant faulting of the bedrock.

In the north-eastern part of Sjælland, the buried Esrum–Alnarp valley (EAV) is inferred (Sorgenfrei

1945; Adrielsson 1984; Konradi 1992). The valley trends along the SE–NW striking Sorgenfrei-Tornquist Zone and runs from Esrum in Denmark to Alnarp in Sweden (Fig. 3). The precise location of the valley is not well constrained, and it has been questioned if the valley is an inherited tectonic feature (Binzer & Stockmarr 1994). However, wrench-fault zones likely related to the Sorgenfrei-Tornquist Zone at the northern, middle and southern part of the Esrum Lake have been indicated on the map published by Håkansson & Pedersen (1992) (see Pedersen 1992).

It is well known that seismic data can reveal tectonic features such as thrusts and faults, and high-resolution vibro-seismic data may reveal the structures in the shallow underground in reasonable detail down to approximately 600 m (600 msec TWT). However, to obtain high-resolution seismic data on land requires that the ground coupling is good, as in areas such as lake shores where the water-saturated zone is located very shallowly. Recently, conventional reflection seismic data have been used to study the structure of glaciotectonic complexes in the North Sea (Bendixen *et al.* 2017; Pedersen & Boldreel 2017).

In this contribution, we use high-resolution vibro-seismic and well data, firstly, to show the presence of wrench-fault flower structures within the Pre-Quaternary succession along the Sorgenfrei-Tornquist

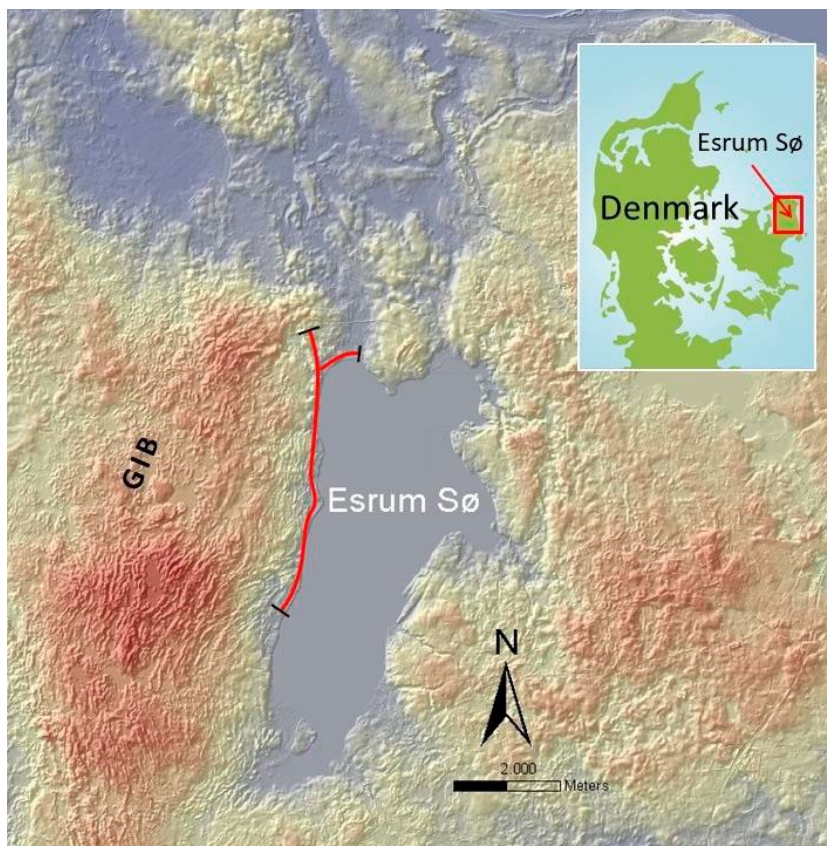


Fig. 1. Terrain elevation map of Esrum Sø and the surrounding area. Reddish colours indicate high elevation values and blue indicate low values. GIB indicates the position of the parallel-ridge landscape related to the Gribskov Ice Borderline. The two red lines along the western lake shore represent the locations of the two seismic profiles. Inserted map in the upper right corner shows the location of the study area in Denmark.

Zone and presenting the north-eastern delimitation of the EAV, and, secondly, to interpret the glacial deposits in the eastern margin of the EAV as comprising at least two glaciotectonic complexes that conceal the wrench-tectonic structures.

Geological Setting

The area studied is located in the northern part of Sjælland along the western bank of the second largest lake in Denmark, Esrum Sø (Figs 1, 2). The lake is located above part of the buried Esrum–Alnarp Valley (EAV) (Fig. 3) which is interpreted to be of geotectonic origin based on studies of wells (Sorgenfrei 1945; Schuldt 1981; Konradi 1992). The trend of the valley is

controlled by fault structures (Sorgenfrei 1945) and regarded as being related to the south-western branch of the Sorgenfrei-Tornquist Fault Zone (Håkansson & Pedersen 1992). The fault zone is an old tectonic weakness zone in the continental crust, located in the triangle between Denmark, Sweden and Norway, and comprises a former transform fault with a trend running from Bornholm in the Baltic Sea into south-western Sweden and then into Kattegat until it terminates at the Viking Graben in the North Sea (Ziegler 1990). In the Skåne–Øresund–south-east Kattegat region (Fig. 3), the tectonic element forms a large-scale half graben with Precambrian basement in the footwall block to the east and pre-Palaeogene sedimentary rocks in the hanging-wall block to the west (Erlström *et al.* 2018). Between Sweden and Jylland (Denmark) one of the most prominent fault zones in the Kattegat region is located; this is the Grenå-Helsingborg Fault Zone, a dextral strike-slip fault mainly active in the Upper Cretaceous to lowermost Palaeogene (Kamla *et al.* 2014) (Fig. 3). Post-glacial wrench-tectonic movements are still active along the zone, partly recorded by earthquake centres and sag-basin formation in the northern Kattegat area (Brandes *et al.* 2018).

In the Esrum Sø area, the uppermost pre-Quaternary units are Danian limestone and areas of Selandian clay, marls and glauconitic, arenitic limestone. A few wells penetrated the Selandian lithological unit which has a maximum thickness of *c.* 20 m (Fig. 5). The Danian limestone is recorded, but not penetrated, in many water-supply wells and often forms the base below the Quaternary successions. The thickness of the Danian limestone is known from two deep boreholes in the vicinity of Esrum Sø, namely the Lavø-1 drill hole (Sorgenfrei & Buch 1964) and the Karlebo-1A drill hole (Tethys Oil AB 2007) (Fig. 3). In both holes the thickness of the Danian limestone is recorded to be 122 m. Below the Danian limestone, the Upper Cretaceous chalk is more than 1.5 km thick, and the two units are generally referred to one big unit: The Chalk Group.

The EAV is about 60 m deep in the area of Esrum Sø, based on nearby wells (Fig 2), and its base is eroded down into the Danian limestone, which in this part of Denmark is interpreted to be the København Kalk Formation (Sorgenfrei 1945; Stenestad 1976; Binzer & Stockmarr 1994). The fill in the EAV comprises three elements. The Esrum diamictite lies on top of the pre-Quaternary surface at the bottom of the valley (Schuldt 1981; Houmark-Nielsen 1999). It is overlain by the Esrum sand, a thick succession of glaciofluvial sand. Above the Esrum sand an arctic marine deposit named Græsted clay occurs, which holds a foraminiferal assemblage related to the Middle Weichselian (Konradi 1992; Houmark-Nielsen 1999), correlated to the Skærumhede Series (Lykke-Andersen 1987). Limnic

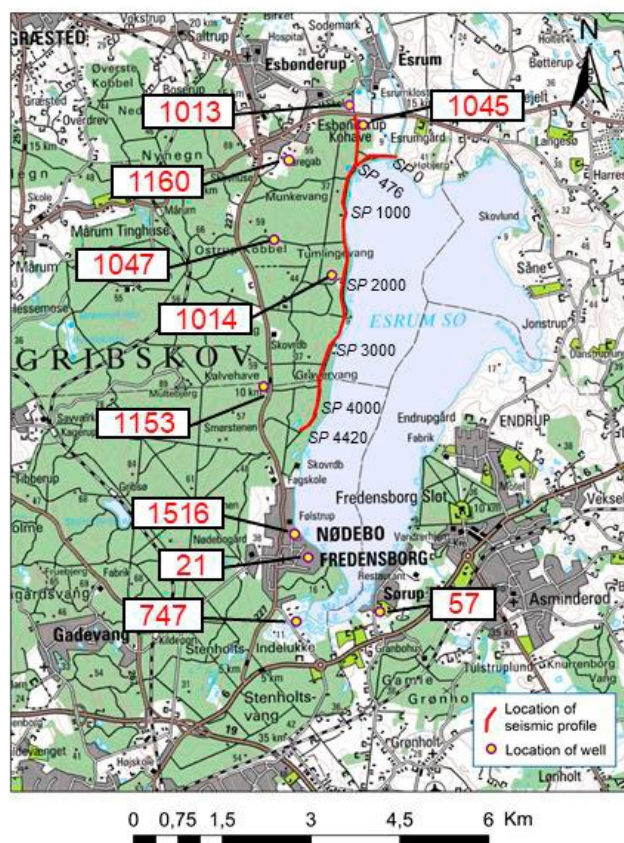


Fig. 2. Situation map of the study area located within the Gribskov forest, with the trend of the seismic sections along the western shore of Esrum Sø. The direction of the main seismic section is N–S, whereas the satellite section is W–E directed. Some annotations of the shot points (SP...) are given along the line. The locations of wells presented in Fig. 5 are indicated by yellow dots and identified by their Jupiter Database well-numbers without the prefix 187. Three local names of sites in the investigated area are presented, from south to north: Græstevang, Tumlingevang, and Munkevang.

deposits of Holsteinian age are identified in a borehole penetrating the EAV near Malmö in Sweden (Konradi 1992), and this implies that the Esrum–Alnarp valley could have been eroded out as early as Elsterian, a period when a large part of northern Europe was affected by deep valley erosion (Ehlers *et al.* 2004). On top of the fill in the EAV the Kattegat Till Formation conceals the valley.

The Kattegat Till Formation, formerly referred to as the ‘Norwegian Till’, is one of the three main tills which are present in this part of Denmark; it represents the Norwegian ice advance about 30–28 ka BP (Houmark-Nielsen 1987; Houmark-Nielsen & Kjær 2003; Pedersen 2005). Above the Kattegat Till Formation, the Mid Danish Till Formation occurs (Houmark-Nielsen 1987). This was formerly referred to as the ‘Swedish Till’ related to the Swedish ice advance of 23–21 ka BP (Houmark-Nielsen 1987, 2003, 2010). In the glaciodynamic succession, the two formations are separated by the proglacial deposits related to the Swedish ice advance. In the central part of Denmark, these outwash plain deposits are composed of a 20 m thick formation of glaciofluvial sandy sediments

named the Tebbestrup Formation (Larsen *et al.* 1977; Pedersen & Petersen 1997). In other parts of the country, the sand formation is missing, either due to a very rapid advance of the Swedish Ice, or erosion caused by the Swedish Ice. In north-east Sjælland, the sand has a variable thickness judged from the wells in the area, and a significant occurrence of proglacial, glaciolacustrine deposits appears here in contrast to the dominant outwash plain deposits elsewhere in the country. Finally, the Baltic ice advance occurred about 18–17 ka BP and caused the deposition of the Bælthav Till Formation (Houmark-Nielsen 1987; Richard *et al.* 1999; Krüger 2006). The glaciotectonic deformation of the proglacial, glaciofluvial deposits caused by the Baltic ice advance created the hilly landscape with elevation up to 80 m a.s.l. west of Esrum Sø. The composite, parallel ridges trend N–S with a tendency of a deflection towards NE. A glaciodynamic interpretation of this formation would be a hill-and-hole pair, where Esrum Sø represents the hole from where the material of the GIB was derived. However, this interpretation needs more support from future and more detailed work in the area of Gribskov and Esrum Sø.

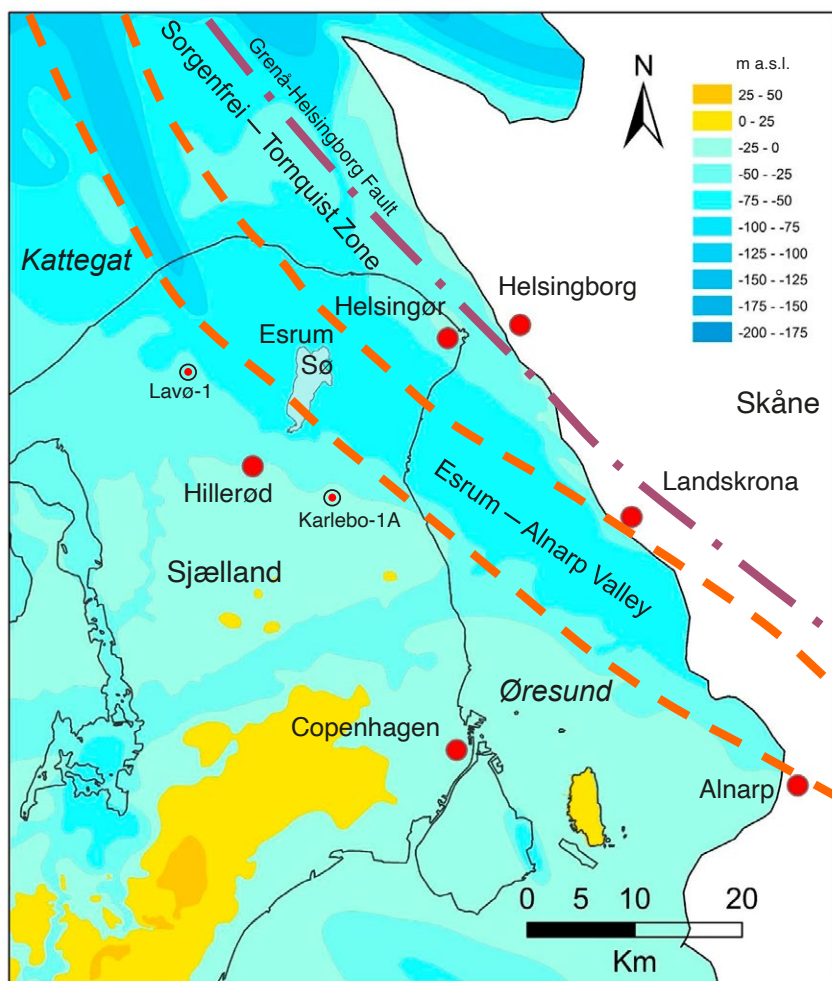


Fig. 3. The outline of the buried Esrum–Alnarp valley shown on a map of the pre-Quaternary topography. The colours showing the depth to the pre-Quaternary surface indicate a depression trending from Kattegat toward Øresund across northern Sjælland and including Esrum Sø. The location of the valley boundaries is based on Adrielsson (1984). The Esrum–Alnarp valley is parallel to the Sorgenfrei–Tornquist Fault Zone trending NW–SE from Kattegat, north of Helsingør and through the southern part of Sweden. Selected towns are marked with red dots.

Methods

Concepts of structural complexes relevant to this investigation

Two very different structural frameworks are recognized in the investigation of the seismic section along the west bank of Esrum Sø: the structural framework of wrench-fault tectonics, and the structural framework of thin-skinned thrust-fault tectonics related to proglacial glaciotectonics. The wrench-fault deformation affected dominantly the pre-Quaternary bedrock below the Quaternary successions, whereas the glacial thrust-fault tectonics affected the Quaternary, mainly glacial deposits.

The challenge in the interpretation of the seismic section along the west bank of Esrum Sø is the number of irregular structures due to superimposed deformation. For the understanding of the architecture of these structures, the concept of glaciodynamic sequence systems is applied. The concept states that a glaciodynamic sequence is a lithostratigraphic grouping of a glaciogeological succession that acquired its final form during a major glacial advance including glaciotectonic deformation (Pedersen 2012, 2014).

Wrench-fault tectonics

According to the definition of the principal elements of wrench-fault tectonics, the Sorgenfrei-Tornquist Zone classifies as a wrench-fault zone. The principal elements are: (1) en échelon dome folds; (2) conjugate strike-slip faults; (3) the main wrench faults are parallel to the wrench zone; and (4) normal faults or tension joints are oriented perpendicular to the fold axes (Wilcox *et al.* 1973). Furthermore, three block-displacement styles are recognized: (1) parallel wrenching (strike-slip) with blocks moving parallel to the wrench faults; (2) convergent wrenching (transpression) with blocks moving obliquely towards the wrench faults; and (3) divergent wrenching (transtension) with blocks moving obliquely away from the wrench zone Harding

(1974). The transpression and transtension structures are recognized in cross sections as respectively positive and negative flower structures (Mogensen & Korstgård 2003; Fossen 2010).

Glaciotectonic complexes

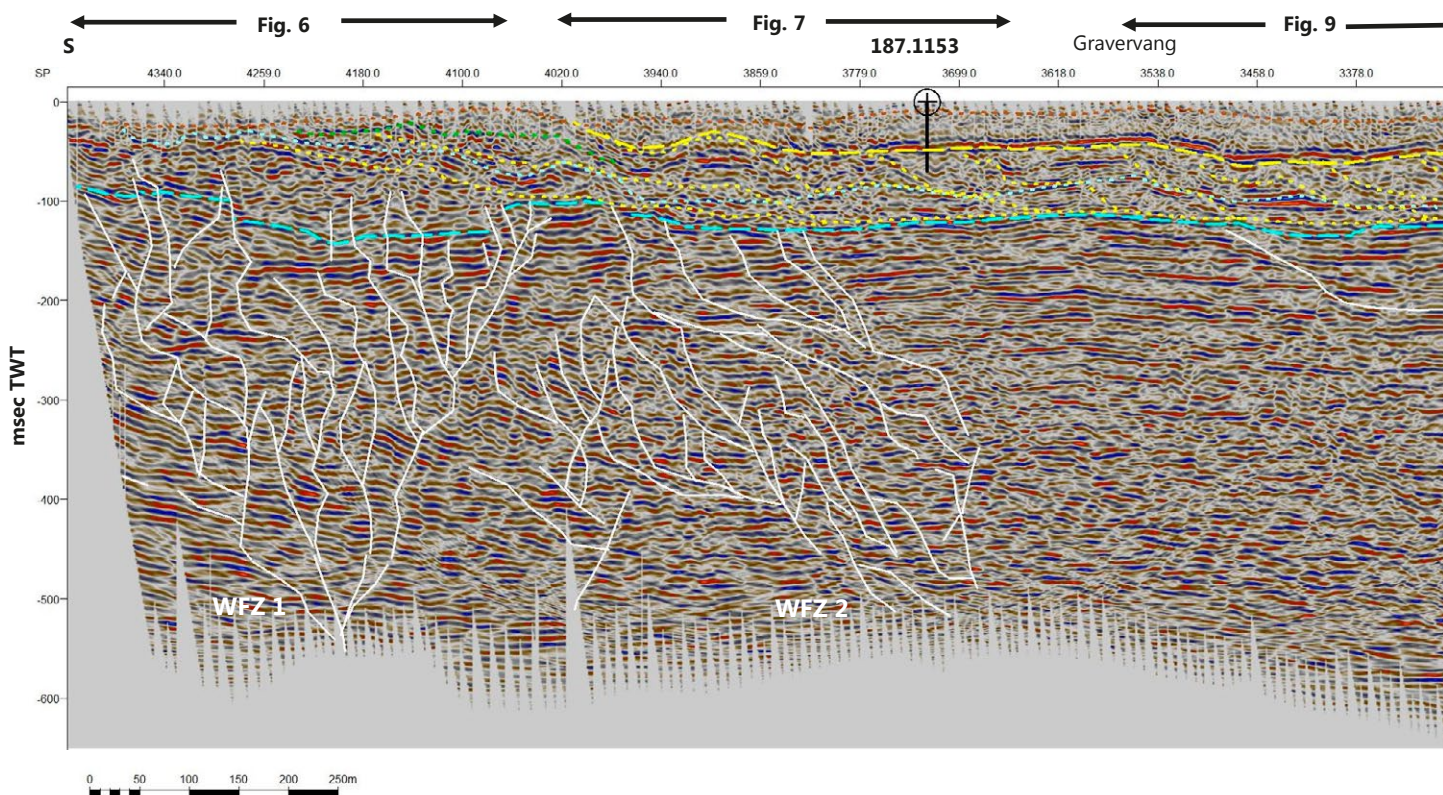
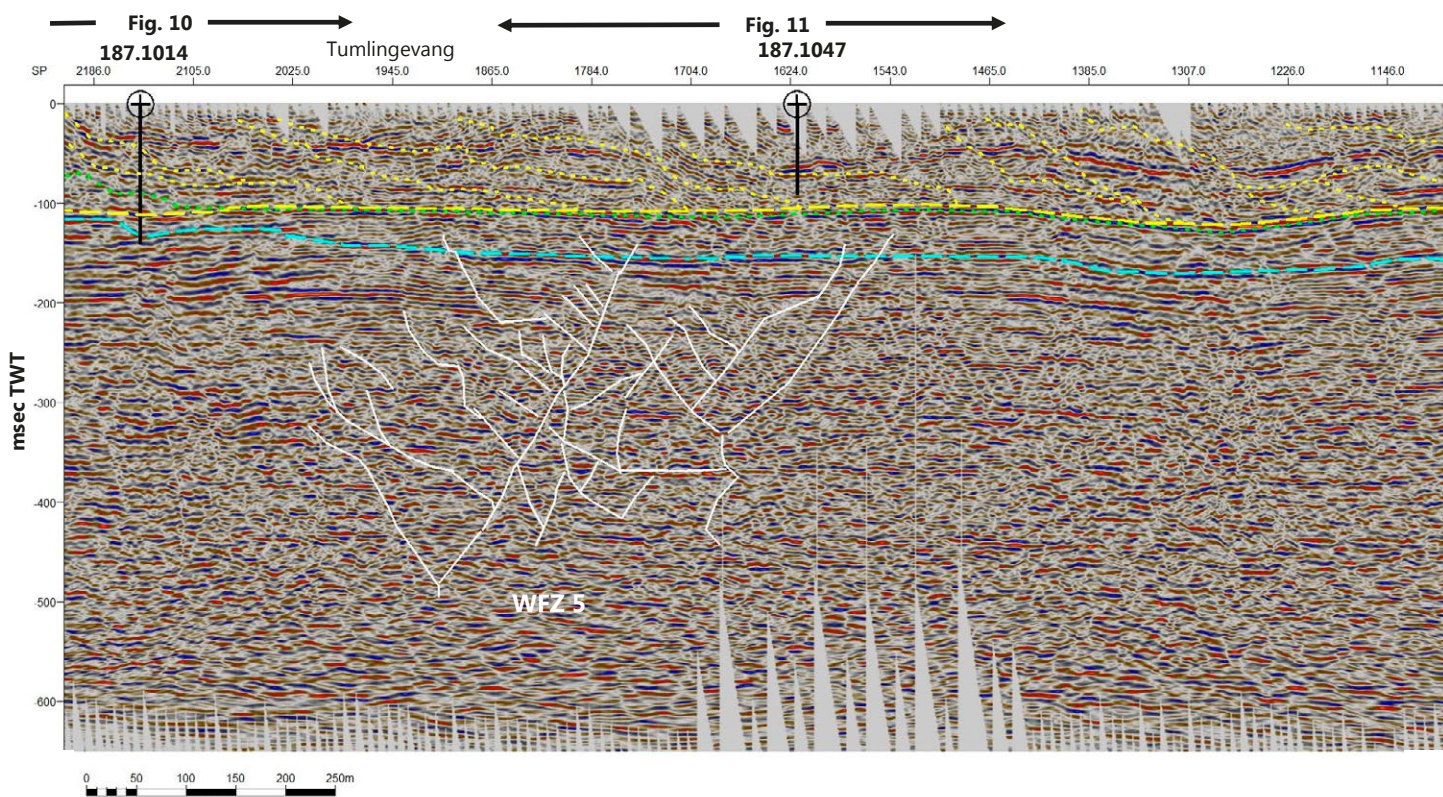
A glaciotectonic complex is categorized into four orders of architectural surfaces (Pedersen 2014). The three mentioned below are used for the interpretation of the upper part of the seismic sections in this study.

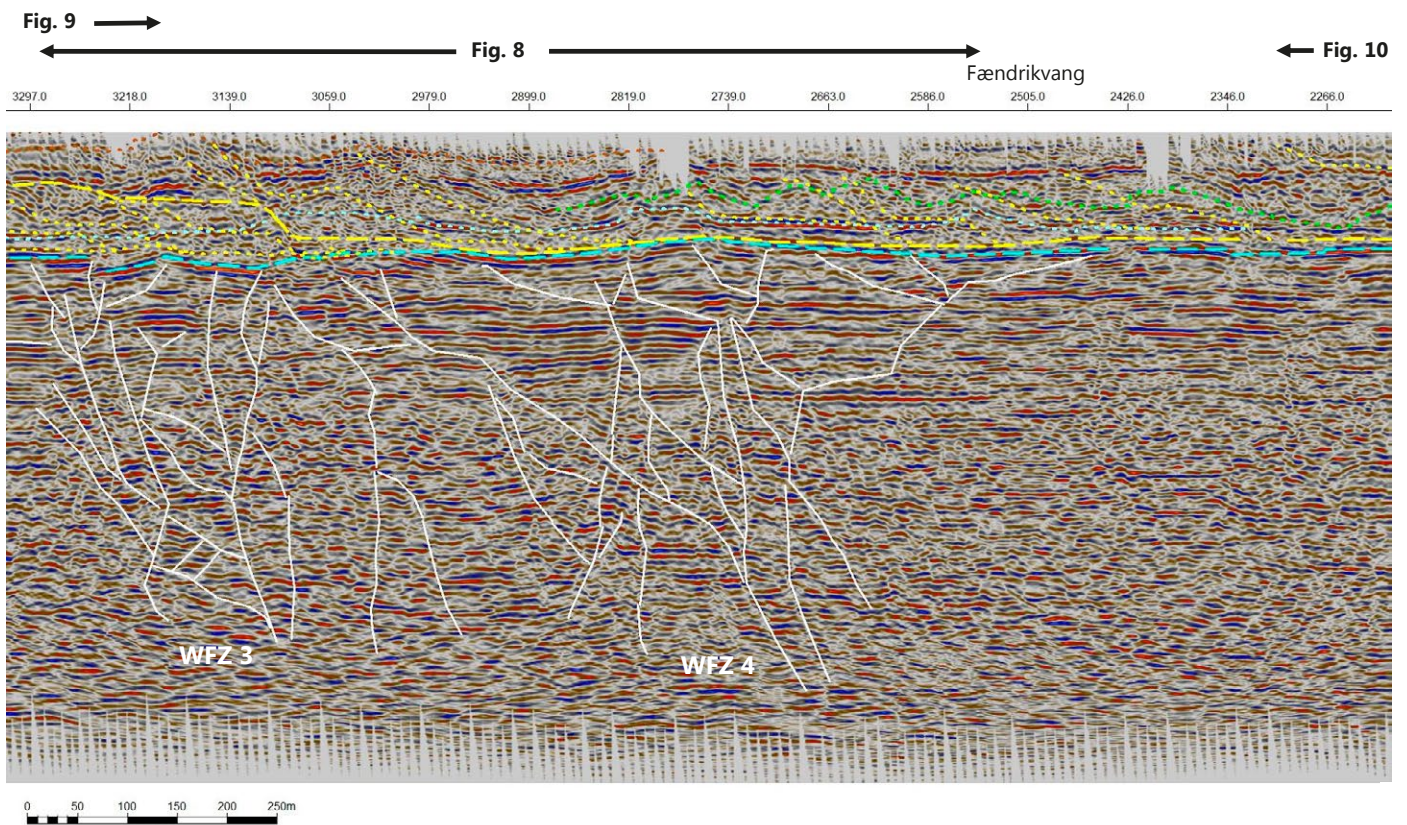
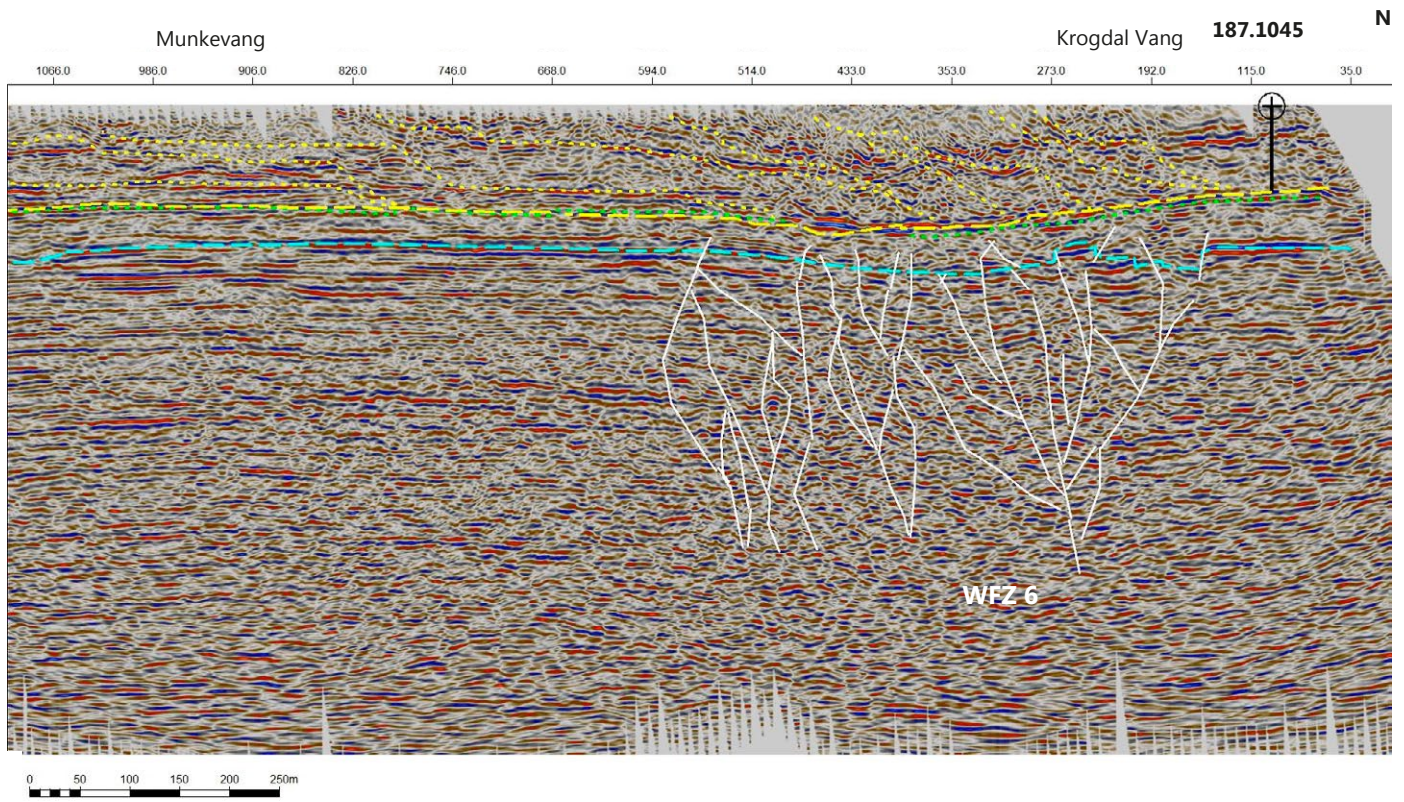
A first-order surface bounds the glaciotectonic complex at its base by a décollement surface that separates the complex with internal deformations from the planar sediments below. The upper boundary of the glaciotectonic complex is also a first-order surface, a truncation surface formed by the shear at the base of the overriding basal till.

The second-order surfaces are the thrust faults that form the boundaries of each individual segment building up the complex. These boundaries are defined as ramps and flats. The ramp is the fault that cuts the bedding in the footwall, causing seismic reflections to show termination against the ramp. In the hanging wall the parallel bedding is bent and occurs inclined parallel to the ramp (Pedersen 2014). Ramp angles typically range between 10° and 35° and rarely exceed 45° (Suppe 1983; Pedersen 2005, 2014). The flat is a displacement surface that is parallel to the bedding. There are several structures found in the second order surfaces, e.g. stacked thrust sheets which are caused by ramp collapse when the various segments propagate across one another. This provides contorted seismic reflections with horizontal terminations, down-lapping and top-lapping against other segments.

The third order surfaces are the folded bedding planes forming synclines and anticlines, in particular the hanging-wall anticline, which forms as one segment propagates across another. Here the front of the propagated segment forms the frontal dipping limb of a hanging-wall anticline, and its bedding down-laps onto the underlying footwall segment. The signifi-

► **Fig. 4.** The main seismic section N–S along the western bank of Esrum Sø. The figure illustrates a cross-section on a scale almost 1:1 through the geological successions down to a depth of 500–600 m. The numbers on the vertical scale are two-way-travel times (TWT) which, with a depth conversion velocity of 2000 m/s, represent also the depth in metres. The horizontal scale is given by the bar in the lower left corners. Locations along the cross-section are referred to the shot points (SP). Locations of the five local place names and nearby wells are shown, as well as the locations of Figs 6–11. The lines of interpretation represent traces of fault surfaces. The white lines are wrench faults, which are assembled in six wrench-fault complexes and annotated WFZ1, WFZ2 ... WFZ6. The blue dashed line is the interpreted top of the Chalk Group, which is also the erosional unconformity surface of the bedrock, which mainly consists of Danian limestone. The dotted blue line marks the top of the zone, where rafts of limestone may be present. The green dotted line is the top of the parautochthonous or allochthonous Selandian clay and marl. The yellow, short-dash lines are glaciotectonic thrust-fault surfaces (first and second order architectural surfaces according to the classification of Pedersen 2014). The yellow dashed line is the glaciotectonic décollement zone. The orange dotted line represents the top of a significant glaciolacustrine unit mainly occurring in the southern half of the seismic section.





cance of hanging-wall anticlines in the interpretation of glaciotectonic thrust-fault settings has also been shown by e.g. Thomas & Chiverrell (2007), Brandes & Le Heron (2010) and Pedersen & Boldreel (2017).

Data and methods of interpretation

Data from the study area constitute a 6.3 km vibro-seismic main profile oriented N–S (Fig. 4) and a 0.7 km vibro-seismic satellite profile oriented E–W. The two profiles intersect each other in the northern part of the study area. In addition, wells from the Jupiter database are used (Fig. 5; <https://www.geus.dk/produkter-ydelsler-og-faciliteter/data-og-kort/national-boringsdatabase-jupiter/>).

Seismic data

The seismic profiles were acquired in August 2014. The main seismic profile is located on a dirt road along the north-western bank of Esrum Sø (Figs 1, 2). The road runs N–S and is very straight and the change in elevation along the road is small. The road is situated mostly 5–10 m west of the lake, and the road level is mostly about 1–2 m above the water level in the lake. The satellite profile was acquired on a dirt road along the northern bank of Esrum Sø (Figs 1, 2). This profile starts at the intersection of the main profile at SP 668 and ends at a small wooden bridge. The road conditions are similar to those of the main profile. The subsoil along the roads was close to being water saturated at the time, which ensured a very good coupling for the geophones, leading to high quality data. The data is 2D reflection seismics acquired by use of a vibro-seismic truck from the Department of Geoscience, Aarhus University, Denmark. The streamer consists of 72 geophones with a separation of 2.5 m which were mounted on small metal sledges to ensure that the geophones can easily be dragged when the vehicle is moved and that they are oriented upright and not tilted. The streamer was towed behind the vibro-seis truck, and before recording data at each position the streamer was stretched out and all the geophones were tested for signal and coupling to the ground. Data was collected every ten metres, and the vibro-seis made four sweeps for four seconds before being moved to a new position. The recording depth of the data is 2000 msec TWT (Two Way Traveltime). The raw vibro-seis data were sorted into common midpoint (CMP) gathers, and normal moveout corrections (NMO) were performed. Data were then stacked, filtered for noise and corrected for amplitudes using automatic gain control (AGC) before being migrated. The 0-stratum level for the seismic section is situated about 10 m above sea level. After the processing, the data was output as

Seg-Y and loaded onto a workstation using Petrel as interpretation software. The near subsurface is not recorded continuously due to the spacing of the geophones, and the upper part of the seismic profile shows ‘holes’ which are intervals where data is not present due to the stacking (Figs 4, 6–12). From approximately 35 msec TWT depth the data coverage is complete (Fig. 4). For interpretation purposes, reflections to approximately 650 msec TWT depth were used (Fig. 4). In order to correlate the seismic profile with intersecting wells, the seismic data has been depth converted with a velocity of 2000 m/s. For the interpretation of the seismic data in a structural geological context, the length:depth relation is 1:1, obtained using the velocity of 2000 m/s.

Interpretation of reflection seismic profiles in glaciotectonic complexes is a challenging task due to e.g. thrusting and repetition of stratigraphic successions. In this study, we have used the seismic stratigraphic interpretation technique of Mitchum *et al.* (1977) and the approach described in Pedersen & Boldreel (2017), i.e. identifying thrust-fault ramps and small seismic units that have the same internal pattern, reflecting the original deposition. Likewise, it is important to identify pronounced reflectors such as the top Chalk Group as they serve as marker horizons outlining the original near-horizontal deposition. Furthermore, we have used attribute analysis (instantaneous phase, structural smoothing, second derivatives and chaos attribution), which is applied for extracting additional information from the seismic data.

Well data

A number of wells all reaching a depth of more than 50 m are located in the study area and their locations are shown in Fig. 2. The wells are projected into a well-log profile parallel to the trend of the main seismic section (Fig. 5). All well numbers are prefixed with ‘187’, which is the region number in the Jupiter database but is omitted in the following.

Well 1013 is located approximately 100 m north of the main seismic profile, whereas wells 1045 and 1014 are almost crossed by the main profile. Wells 1160, 1047 and 1153 are located about 600 m west of the main profile, and wells 1516, 21, 747 and 57 are located south of the profile. Lithological boundaries in the wells are compared to the depth-converted seismic profiles and the acoustic impedance contrast (i.e. the reflections) and in this way a correlation between the geological layers and the seismic reflections are established. The locations of wells 1045, 1047, 1014 and 1153 are shown on the seismic profiles (Figs 4, 7, 10, 11).

The well reports reveal an alternating succession of clay, silt, sand, and till layers superposed on the pre-Quaternary unconformity. In the southern part

of the well-log profile (Fig. 5), the unconformity constitutes an erosional surface in the Danian limestone. Stepwise to the north, the Selandian deposits and Danian limestone subside, and towards the central part of the investigated line (at Tumlingeving area), the subsidence resulted in preservation of the thickest unit (about 30 m) of Selandian clay and marl (Fig 5). In the northern part of the well-log profile the bedrocks are elevated again and the erosional surface has only left less than 10 m of Selandian clay and marl in the area of Krogdal Vang (Figs 2, 5).

Results and interpretation

Because of the strongly contrasting structural styles displayed in the seismic section above and below the 100 msec TWT level (Fig. 4), the shallow and deep parts of the section are interpreted separately. The interpretation of the seismic data is carried out on the main profile and in specific circumstances; the satellite profile is used to support the interpretation. The uninterpreted main profile is shown in the supplementary file to this article.

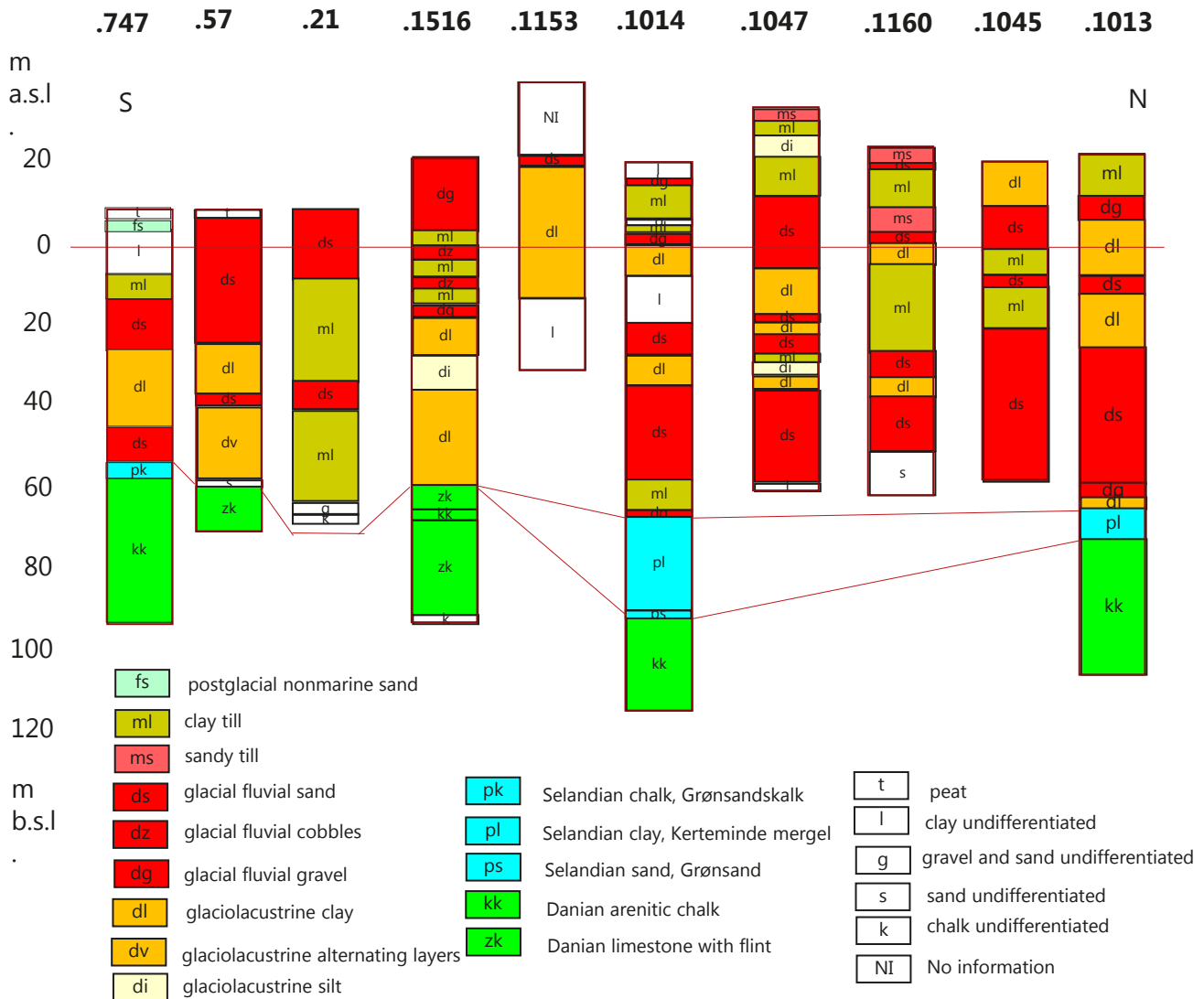


Fig. 5. Well logs showing the lithologies in the boreholes near the west bank of Esrum Sø. The Jupiter Database well numbers are shown without their prefix '187.'. The locations of the wells are shown in Fig. 2, and they are here projected onto a S–N profile line parallel to the trend of the main seismic section. The wells penetrate at least 50 m into the ground. The variation of the thicknesses and lithologies indicates a complex framework of the Quaternary successions ranging in thickness from 50 to 80 m. Note that the presence of Selandian clay and marl in well .1014 supports the interpretation of transtension subsidence along the fault zones in the area.

Wrench-fault complexes

At middle depths in the seismic section (the interval 100–c. 300 msec TWT), the main seismic architecture displays parallel-bedded geological layers representing Upper Cretaceous chalk and Danian limestone. These more or less horizontal layers are displaced by moderately to steeply dipping faults, which are grouped in flower-like wrench-tectonic frameworks (Fig. 4). The structures extend from the deepest levels of the recorded seismic reflections, about 200–300 m below the top of the Danian limestone, and up into the base of the Quaternary layers (Fig. 4). Positive as well as negative flower structures are recognized by the appearance of normal and inverse fault offsets. There is a tendency of the wrench-tectonic faults to be re-used as ramps in the glaciotectonic architecture, where the faults in the top of the flower splay zone are in contact with the Quaternary succession. Towards the deeper parts of the flower structures, the faulting develops into an anastomosing fault pattern with rhombohedral fault segments.

The wrench-fault flower structures are grouped into six wrench-fault complexes. These are annotated WFZ1, WFZ2, ...WFZ6 and are here described from south (WFZ1) to north (WFZ6).

Wrench-fault complex 1

The southernmost wrench-fault complex, WFZ1, is located in the subsurface beneath Gravervang (Figs 4, 6). This is near the end of the seismic section that ends at SP 4400. The interpretation of the reflection pattern at the south side of the structure indicates that the block to the south is a footwall block (Fig. 4). The lithologies in the wells show pronounced offsets in the stratigraphy (Fig. 5). In the block on the north side of the structure another flower structure occurs (WFZ2). As we have no indications of the strike of the faults, it is uncertain whether we are looking at structures perpendicular to the strike or a more oblique cross-section of the complex.

WFZ1 is concealed by 50–100 m glacial deposits emplaced by glaciotectonics. The main framework constitutes a negative flower structure, which is dominated

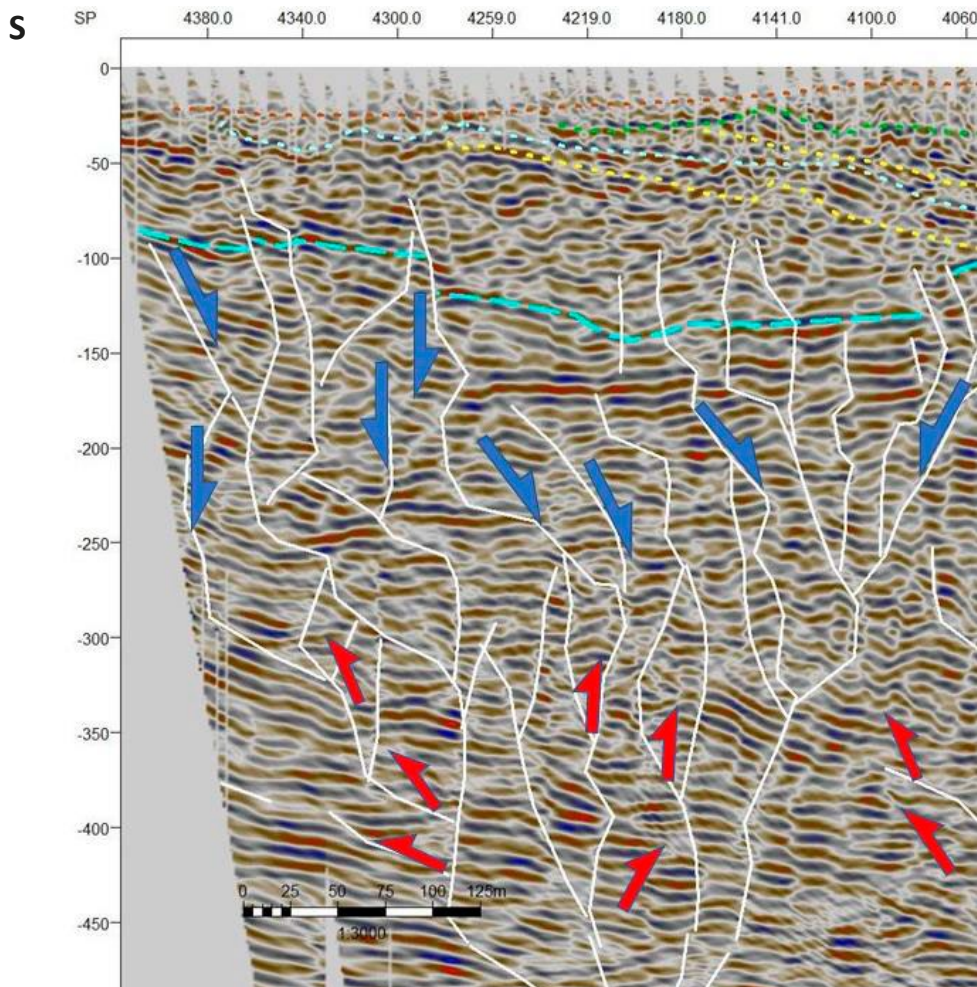


Fig. 6. The WFZ1 wrench-fault flower structure. Red arrows indicate reverse faulting and inversion tectonics. Blue arrows indicate normal fault movements related to the latest phase of deformation in the negative flower structure. The top of the structure is interpreted to be the top of the Chalk Group marked by the blue, dashed line. For description of the structure see text. The yellow dashed lines outline the glaciotectonic décollement zone (the lowest) and two additional thrust faults. Note that the ramp on the décollement zone is parallel to one of the prominent normal faults. The green dashed line is interpreted to represent dislocated Selandian clay and marl.

by syntectonic deposition in the subsiding centre. The internal fault framework comprises steeply dipping to vertical fault segments creating an anastomosing fault pattern. In the deeper part of the flower complex, reverse faulting and updoming appear in the formerly deposited lenses of the chalk in the interval c. 300–350 m below surface (Fig. 6). These features are regarded as inversion structures in a positive flower structure related to an early phase of transpression. In the top of the flower structure, the subsidence in the centre resulted in a 20 m deep, vertical displacement which trapped the Selandian marl. Unfortunately, there are no wells to confirm the presence of the marl in the centre of the flower structure, but 1.5–2 km south of Gravervang the Selandian beds occur in wells, e.g. 187.747 at about 60–70 m below surface where the Selandian is represented by sandy, glauconitic limestone (pk in Fig. 5).

Wrench-fault complex 2

In the northern part of the Gravervang location (SP 4000–3700), wrench-fault complex WFZ2 occurs below a cover of c. 120 m glacial deposits and glacial rafts.

This fault zone is interpreted as a southern delimiting fault that limits a graben or half-graben feature. The trace of the main fault system dips c. 45° N. In the upper part of the structure, the faults are listric, normal faults with drag along the footwall block as well as in the hanging-wall blocks (Figs 4, 7). This part of WFZ2 forms a listric-normal-fault imbricate fan (Fig. 7), and the accumulated vertical displacement of the hanging-wall block is in the order of 50 m. Towards the deeper parts of the fault zone, the faults are more steeply-dipping, and the number of branching listric faults decreases.

The main hanging-wall block is almost undeformed for about half a kilometre from the northern part of Gravervang to the southern part of Fændrikvang (SP 3780 to SP 3300). Here it is delimited by the appearance of wrench-fault complex WFZ3.

Wrench-fault complex 3

The wrench-fault complex WFZ3 is a relatively narrow fault zone comprising a number of steeply northerly-dipping normal faults. The complex is located in the southern part of the area Fændrikvang (Fig. 4).

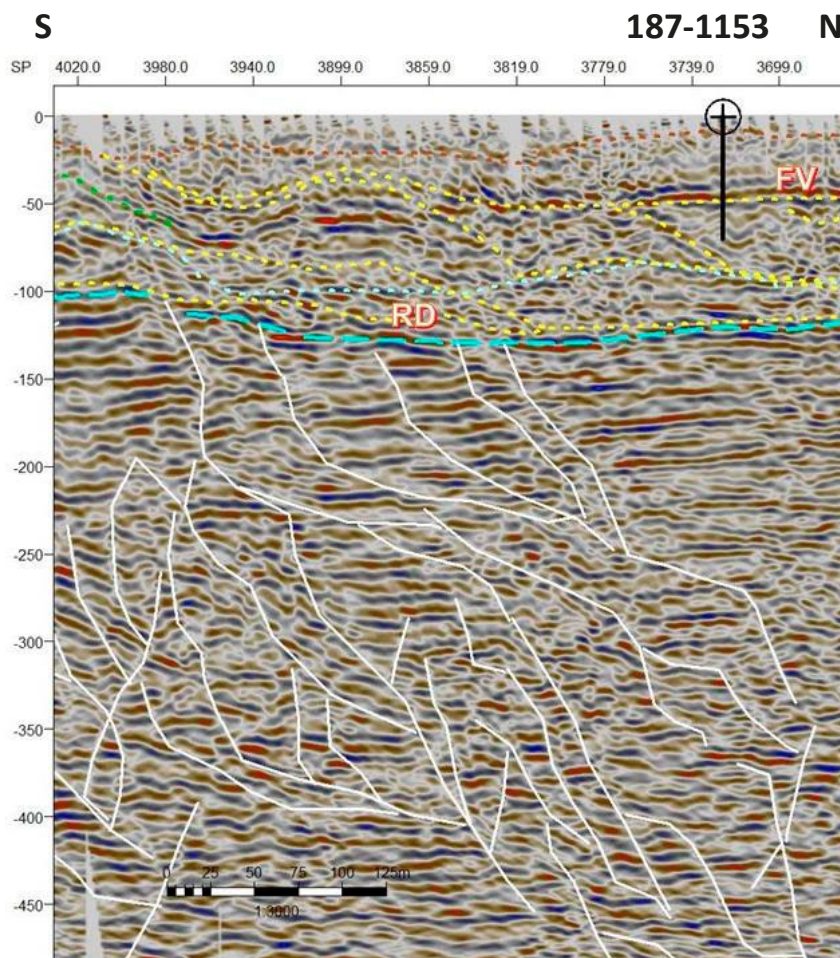


Fig. 7. Wrench-fault zone WFZ2, characterized by the occurrence of a listric-normal-fault imbricate fan. This imbricate fan appears in the interval from c. 100 to 250 msec TWT. Below the upper normal-fault imbricate, indications of earlier-formed normal-fault imbricates occur. Note that the glacioteclonic décollement zone (lower yellow dashed line) is ramping c. 25 m up along the top of the southern boundary fault, location marked with RD (Ramping of the Décollement zone). The position of the well 187.1153 confirms the lithological characteristics of the marked parallel reflections in the upper half of the glacial deposits, which we refer to as the Frændrikvang bed, marked with FV (compare to Fig. 4).

Evidently, some of the faults are older faults, which are truncated by chalk sedimentation (Fig. 8). In the deeper part of the complex, about 250–300 m below surface, the intensity of deformation is high and a number of roll-over anticlines appear (Fig. 8). This indicates that this level was a surface-near deposit during a major deformation event in the Upper Cretaceous. The root of the complex is an almost vertical master fault located at SP 3139. In the uppermost part of the chalk succession, minor displacements (about 10 m vertical separation) took place along inherited fault traces in the southern side of the complex.

Wrench-fault complex 4

The intensive fault deformations in the interval 250–300 m met with in WFZ3 are also recognized in wrench-fault complex WFZ4. In the deeper parts of the complex (below 250 m depth), the architecture can be characterized as an asymmetric, negative flower structure. Similar to WFZ3 a number of roll-over anticlines occur (Fig. 8). These indicate sequential development of displacements with smaller jumps along the master fault over a minor time span. After this event the carbonate platform represented by the Chalk Group was downthrown to the north. The last significant displacement in the complex occurred along a 45° N-dipping fault extending from the top of the Chalk Group in the northern part of the WFZ3 complex and downwards into the lower part of the Cretaceous chalk layers to a regional master fault, the stock of the flower structure in WFZ4 (Fig. 4).

Wrench-fault complex 5

In relation to the southern limiting fault of a graben feature mentioned under WFZ2, the wrench-fault complex WFZ5 is regarded as representing the northern limiting fault of the graben. The upper level of the master fault in the complex appears at SP 1750 (Fig. 4). The master fault dips about 50°–60°S. Possibly, the dip is more to the SW judged from the regional geology, but we have no data supporting the exact strike of the fault planes. North of the master fault, a smaller number of satellite synthetic faults are present. The hanging-wall block on the south side of the fault is characterized by a number of antithetic faults. The displacements along this framework of faults are responsible for a complex reflection pattern.

Wrench-fault complex 6

From WFZ5 and northwards, the seismic section displays preservation of continuous layers of the Chalk Group. The almost undeformed carbonate platform succession extends for more than a kilometre until the wrench-fault complex WFZ6 appears at the northernmost end of the section in the area Krogdal Vang (Fig. 4). The Maastrichtian chalk is covered by c. 100 m of Danian limestone and Selandian clay and marl, which is overlain by 100 m of glacial deposits. The main part of WFZ6 is a negative flower structure displacing all of the chalk succession with separation of 25 m along individual fault branches. South of the flower structure, five minor, steeply dipping faults are present. The framework of these and their relation

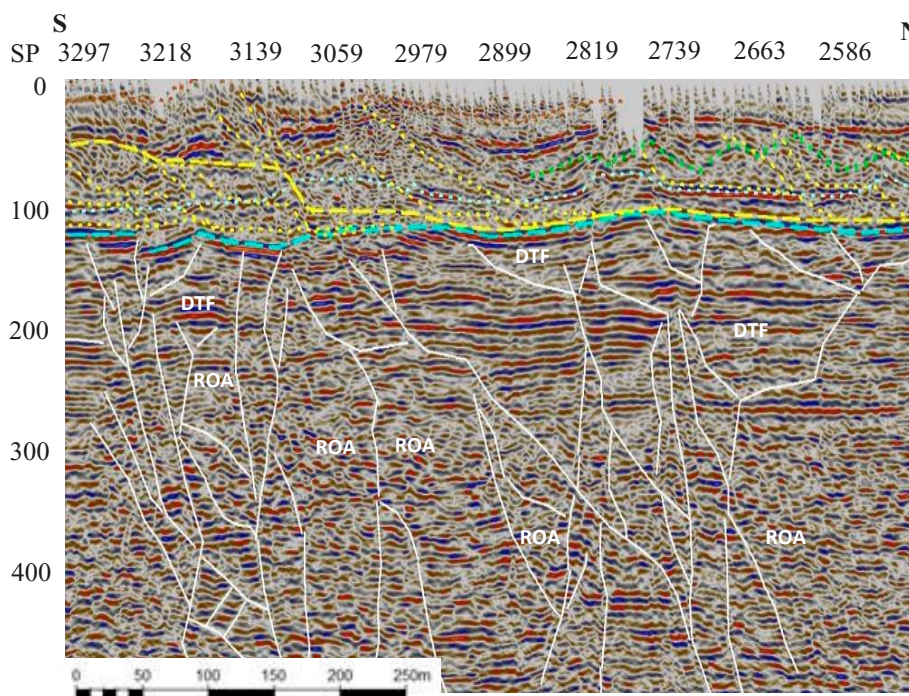


Fig. 8. Wrench-fault zones WFZ3 and WFZ4, annotated to show selected rollover anticlines (ROA) and deposits truncating earlier faults (DTF). For further descriptions, see text. Note the relatively steeply dipping glaciotectionic shear zone occurring between two ramp-thrust-faults (yellow dashed lines) at SP 3139. This marked glaciotectionic structure also forms the transition from the distal zone to the central zone. The segment between SP 3139 and SP 2819 represents the southern part of the central zone of the glaciotectionic complex. The southern boundary of the central zone is large shear zone occurring at SP 3139, where the northern part of the Fændrikvang bed translates up over a 40°N-dipping ramp.

to the flower structure is not fully understood. The complex pattern of the fault segments in the 250–350 m depth interval could be interpreted as inversion-related reverse faulting due to early transpression.

Because it is possible to correlate faults in WFZ6 on the N–S line to faults recognized in the short satellite W–E line, the WFZ6 can be estimated to strike NNW–SSE, as discussed below. There is no obvious information on the general strike of the other five wrench-fault systems.

Glaciotectonic deformation

Throughout the more than 6-km-long seismic section and the satellite seismic section, thin-skinned thrust-fault structures characterized by ramps and flats occupy the uppermost *c.* 100 m. The investigation and mapping of these thrust-fault structures indicate that more than 40 thrust sheets are present. The décollement zone and thus the first order surface of the glaciotectonic architecture coincides typically with the top surface of the Chalk Group, except for the places where the Selandian marl occurs at the 100 m depth level.

The key to understanding the differentiation of the glaciotectonic complex into two glaciodynamic sequences is the significant strong reflections appearing in the upper part of the seismic section between SP 3840 and SP 2400 (Figs 4, 7, 8, 9). According to the correlation with drill hole 187.1153 located at SP 3730 (Fig. 7), these marked reflections represent a more than 25 m thick succession of glaciolacustrine clay (Fig. 5). We refer to this unit as the Fændrikvang bed. The lithostratigraphic position of this bed will be addressed in the discussion below. The base of the Fændrikvang bed truncates the top of the thrust-fault structures in the lower part of the glaciotectonic complex. Thus, a glaciotectonic thrust-fault event took place before the formation of a relatively large lake and the deposition of a thick glaciolacustrine succession. At the same time, the southern part of the Fændrikvang bed is displaced up along a ramp (SP 3860–3830 in Fig. 7), which traces back to a thrust-fault flat below the bed as well as to inherited displacements along thrust-fault duplex-imbricates in the lower complex (SP 3860–3100 in Figs 4, 7, 8). In the northern part of the complex, the Fændrikvang bed vanishes, partly due to decreased thickness, but mainly because of a number of thrust-fault displacements. In the central part of the Fændrikvang bed, internal contraction is documented by the appearance of minor ramp-collapse features (at SP 3458–3218 in Fig. 9) similar to the structures described by Pedersen (2005, p. 74–75). Therefore, we advocate the presence of two glaciodynamic sequences separated by the base of

the Fændrikvang bed. Almost all reflections showing dipping ramps indicate a glaciotectonic push from a northerly direction. This of course rises the question: are the two glaciodynamic sequences formed by oscillations from the same ice advance direction, or do they indicate two different glaciodynamic events, one during the Norwegian advance superimposed by one during the Swedish advance. This question is further treated in the discussion below.

For the description of the overall architecture of the glaciotectonic complex below the west bank of Esrum Sø, the complex is divided into a distal zone, a central zone and a proximal zone following the architectural concept of Pedersen (2014). The distal zone is situated between SP 4360 and SP 3139, which includes the geographical area Gravervang (Figs 2, 4). The thrust faults here are shallow-dipping, and the about 30 m thick thrust sheets have a length of 300–600 m. The central zone occupies the space between SP 3139 and SP 2300, crossing the areas of Fændrikvang and southern Tumlingeang (Figs 2, 4). This zone is characterized by shorter, less than 200 m long, thrust sheets, imbricate thrust sheets and moderately dipping ramps. The proximal zone is located in the northern half of the seismic section from SP 2300 to the starting point for the seismic recording (Figs 2, 4). This zone passes over the northern Tumlingeang, Munkevang and Krogdal Vang areas. The zone is the most chaotic zone in the complex with duplex features and erosional elements in a former tectonic depression in the hinterland-near area, and possibly with rafts of long-distance transported bedrock.

The distal zone – glaciotectonic cross-section of Gravervang and the southern limit of Fændrikvang (SP 4360 to SP 3139)

The framework of this zone is a typical distal thrust-fault architecture. The boundary tip line for the front of the thrust-fault complex almost coincides with the southern end-point of the seismic cross-section. From this point the thrust sheets extend northwards, resting on gentle northward-dipping thrust faults (Figs 4, 6). From SP 3900 towards south the décollement surface steps up along a ramp from a depth of about 125 m below baselevel (125 ms TWT) to a décollement level at 100 ms TWT. The ramp between SP 3900 and SP 4000 dips nearly 20°N and seems to follow the dipping bedding in the tilted bedrock in the top of WFZ2 in Gravervang. The décollement level continues along an almost horizontal level, with only one minor ramp jump, southwards to the southern margin of WFZ1. Here it steps up along a *c.* 45° steep ramp, which is parallel to the normal fault features at the southern edge of the footwall shoulder of wrench-fault zone WFZ1 (Fig. 6). From the elevated level of 75 ms TWT,

the décollement zone trends towards the terrain surface along a gently-dipping thrust fault, and based on a simple construction it should crop out about 200 m south of the end point of the seismic line.

The southernmost three thrust sheets in the fringing part of the distal zone are relatively long, up to about 500 m, but with some minor internal side-branching (satellite) thrusting. At SP 3859 a 30°N-dipping ramp can be correlated with a hanging-wall anticline marked by a series of strong reflections (Fig. 7). With a back-stripping of the beds to the décollement level at the lower hinge point of the ramp, these beds correspond to the upper part of the bedrocks in the northern margin of WFZ2. We therefore interpret the reflections in the hanging-wall anticline as representing dislocated chalk rafts. The north-dipping limb of the hanging-wall anticline controls the orientation of the thrust sheets displaced above the hanging-wall anticline, and at the top of the cross-section, the structures demonstrate that inherited thrusting occurred, resulting in the displacement of the Fændrikvang

bed. A displaced chalk raft probably also appears as the strong reflections between SP 4100 and SP 4000 (Figs 4, 6).

The thrust sheets in the trailing end of the distal zone are shorter, up to about 200 m, with a thickness of about 25 m. They appear as thrust-fault imbricates displaced up along a 30°N-dipping ramp and translated along horizontal intermediate flats. Between SP 3538 and SP 3458 the bend of the Fændrikvang bed demonstrates renewed displacement along inherited thrust faults (Fig. 9). The whole 900 m long sheet comprising the Fændrikvang bed and an overlying c. 15 m glaciofluvial sand bed was translated on top of the earlier-formed thrust-sheet imbricates. At the distal ramp (at SP 3850, Fig. 7), the Fændrikvang sheet was bent and the uppermost thin units were deformed as the ramp collapsed towards the monoclinial flexure (Fig. 9). At the transition from the distal zone to the central zone (SP 3139 Fig. 4) a large shear zone occurs with chaotic ramp-thrust-fault framework including duplexes and rafts (Fig. 8).

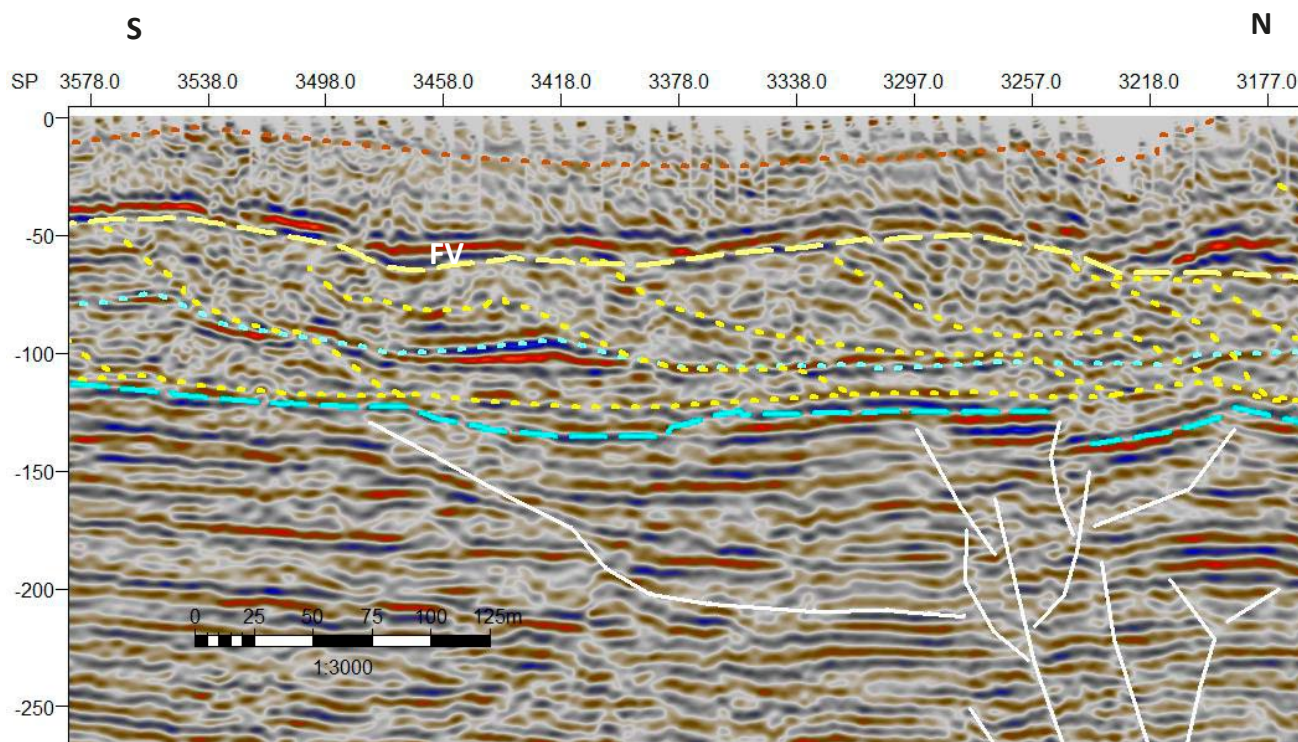


Fig. 9. The translation of the Fændrikvang bed (FV) is here illustrated by the seismic-section segment from SP 3177 to SP 3578. The imbricate thrust sheets of the lower glaciotectionic complex are clearly truncated by the Fændrikvang bed. The yellow dashed line indicates the décollement zone at the base of the Fændrikvang bed. Above this décollement surface, the Fændrikvang bed is almost unbroken, but the succession above the bed (and below the orange dotted line) is strongly deformed by ramp-collapse imbricates. A gentle ramp formed over an underlying dipping thrust sheet occurs at SP 3500. Another gentle ramp occurs in the northern part of the segment (SP 3230), which mirrors a step along a fault in WFZ3. The dotted yellow lines are significant thrust faults. The blue dashed line indicates the top of the Chalk Group. The dotted, blue line marks the top of the zone where rafts of limestone may be present, which is inferred by the erosional surface that truncates the gently dipping beds in the top of the Chalk Group. White lines mark the faults in the top of WFZ3.

The central zone – glaciotectionic cross-section of the main part of Fændrikvang to southern Tumlinge­vang (SP 3139 to SP 2300)

The transition from the distal zone to the central zone is well defined by the large shear zone at SP 3139 (Fig. 8). Moreover, a very irregular deformation pattern appears, including folding at various scales. In the central zone, a 500 m long northern part of the Fændrikvang bed occurs almost unbroken. Where this sheet disappears to the north (SP 2300), we define the transition to the proximal zone (Fig. 4).

The depth to the décollement surface in the centre of the zone is slightly less deep than in the distal zone, about 115 m at SP 2739. The long thrust sheet above this point has a 200 m long trailing end resting on the décollement level. Due to arguments originating from the interpretation of the proximal zone (see below), we interpret this as a chalk sheet resulting in a velocity pull-up of the décollement surface. Two more thrust sheets further to the north contain 100-m-long trailing ends. Judged from the displacement of the frontal part of the thrust sheets over the ramps, the lateral translation of the trailing end must be more than 150 m. On a broad scale, this indicates a source area for

the thrust sheets to be in the depression above the wrench-fault zone WFZ5 in the proximal zone of the glaciotectionic complex.

The proximal zone – glaciotectionic cross-section of Tumlinge­vang, Munkevang and Krogdal Vang (SP 2300 to SP 0)

The northern part of the seismic section covers the proximal part of the glaciotectionic complex. The proximal zone superposes the tops of two wrench-fault zones, WFZ5 in the southern part of the zone and WFZ6 in the northern part of the zone. Thus, the proximal zone involves superimposed glaciotectionic structures related to the first of the four defined categories of superimposed deformations in glaciotectionics (Pedersen 2000).

Along the northern end of Esrum Sø, where the short satellite seismic section trending W–E intersects the main seismic section, the correlation of structures between the satellite section and the main section has supplied important data for the orientation of the glaciotectionic thrust faults. The lithostratigraphy of the successions in the proximal zone is firmly supported by the three wells 187.1014, 187.1045, 187.1047

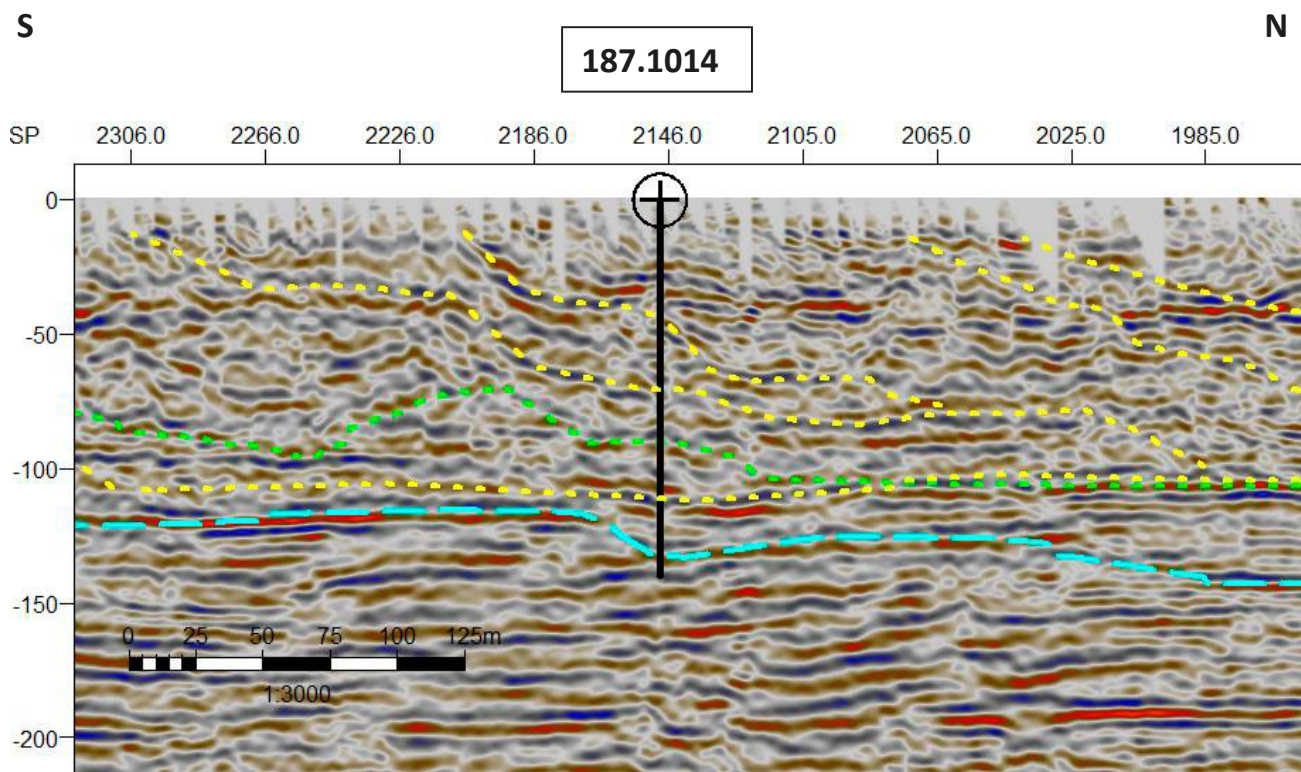


Fig. 10. The southern part of the proximal zone of the glaciotectionic complexes (SP 2300–SP 2025) comprises three thrust sheets, which form an antiformal stack complex. The chaotic pattern in the thick lower thrust sheet indicates a number of duplex sheets to be present, and the structures are probably to be characterized as duplex stacks similar to the structures in the proximal part of the Rubjerg Knude Glaciotectionic Complex (Pedersen 2005). The yellow dotted lines are thrust faults. The thick blue dashed line is the top Chalk Group unconformity. The top of the Selandian clay and marl is marked with a green dotted line.

and 187.1013 (Figs 2, 4, 5). The latter of these is located just north of the northern end of the seismic line, wherefore it is not tied in on the seismic section.

The southern part of the proximal zone (SP 2300–SP 2025) comprises three thrust-sheet complexes with chaotic internal patterns that qualify them to be characterized as duplex stacks similar to the structures in the proximal part of the Rubjerg Knude Glaciotectonic Complex (Pedersen 2005). In Fig. 10 the interpretation of the duplexes is illustrated. However, the number of smaller duplex segments in a densely deformed duplex stack cannot be expected to be accurately traced out in the seismic section.

The well 187.1014 is located at SP 2150, where it penetrates two till horizons interlayered by a thin glaciolacustrine unit. The upper till appears 10 m above the 0-level of the seismic section (according to the top-terrain-base of the well: 22 m a.s.l.). We interpret the clay and till units below the upper till as corresponding to the strong reflections at a depth of 30–40 m. This till and the overlying clay are evidently dislocated during a later glaciotectonic phase. An almost 50 m thick succession of glaciofluvial sand and

clay occurs below the second till. This glaciofluvial unit superposes a glaciectonite breccia (dg overlain by ml at -60 m, see Fig 5) and the bedrock, which here comprises Selandian marl and clay. This unit is about 20 m thick and rests on the Danian limestone. The structural location of well 187.1014 is not far from the southern margin of WFZ5. According to the reflection patterns, the well penetrated a rather complex unit of bedrocks, more or less displaced by the glaciotectonic décollement zone at the level of about 120 m b.s.l. (Fig. 10). The ramp appearing at the top of the limestone at SP 2150 may be the source for dislocated rafts displaced further to the south towards the central zone.

Further to the north in the proximal zone, the well 187.1047 is the next focus point (Fig. 11). Here we interpret the strong reflections at the level of 50–70 msec TWT at SP 1600 to be the glaciolacustrine unit penetrated in the well at 0–35 m. The discrepancy between the depths to the strong reflections and the clayey units in the well is explained by the uncertainty related to projection of a well 1.5 km away from the profile and the structural position of the clay unit, which is ramping up to a depth of only 10–30 m below

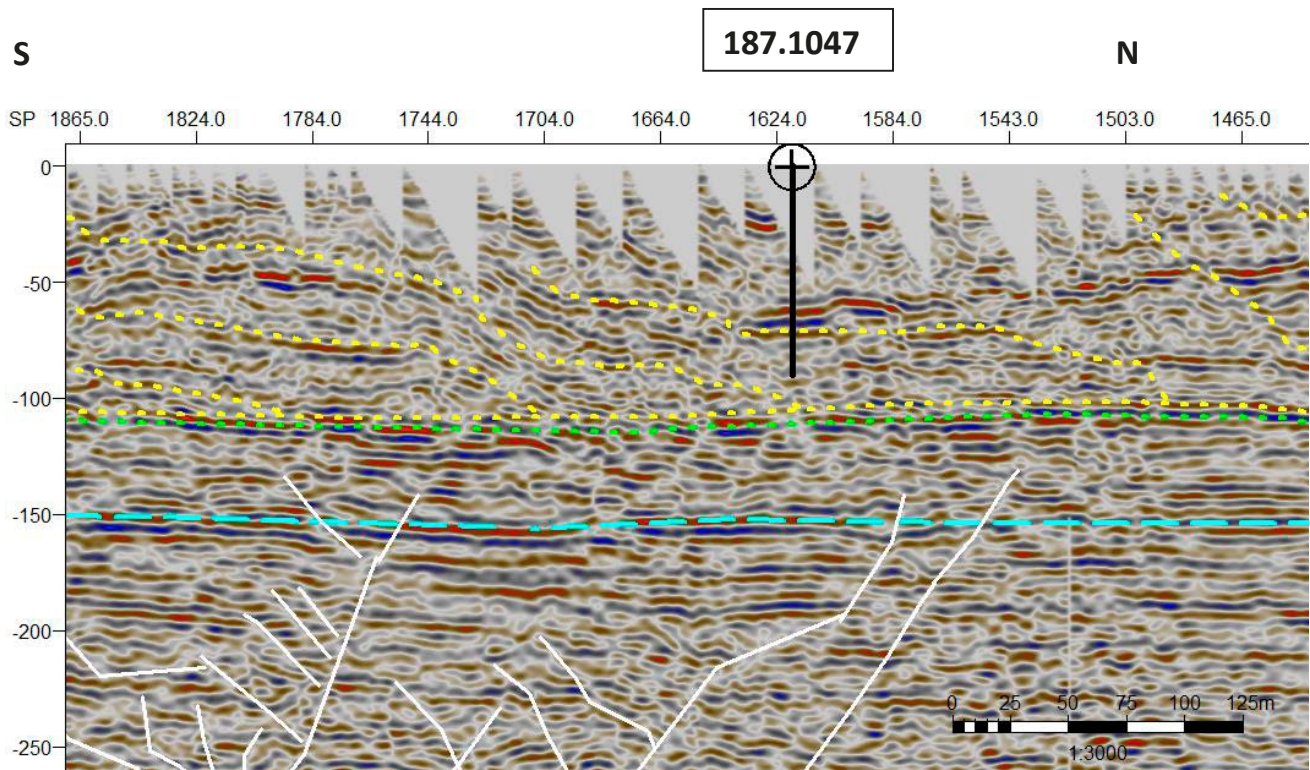


Fig. 11. Four big thrust sheets occupy the middle part of the proximal zone of the glaciotectonic complexes. According to the well 187.1047, the dominant lithology of the thrust sheets is glaciofluvial sand, mainly occurring in two 20 m thick units. The strong reflections in the middle of the succession are interpreted to correspond to the glaciolacustrine units in the well. Therefore, the thick sand unit (Fig. 5) is a repetition displaced to the south along a lower flat and an intermediate flat. The thrust sheet is more than 500 m long, and the displacement is in the order of 300 m. The blue dashed line is the top chalk unconformity. The green dotted line is the top of the Selandian clay and marl. The yellow dashed lines are décollement surface and thrust faults.

the surface about 50 m south of SP 1600. The strong reflection is very weak in the interval covered by the ramp, which is caused by diffusion of reflection signals from steeply dipping beds. Above and below the clayey unit weaker reflections represent glaciofluvial sand deposits. The lower glaciofluvial unit is about 20 m thick and rests on an undifferentiated clay horizon. This horizon is interpreted as a tectonite corresponding to a thrust fault rising from the décollement zone to form the lower hinge zone of a ramp. The unit may be either a local glaciolacustrine clay or Paleocene clay. According to the interpretation of the seismic architecture, we are inclined to suggest the latter.

The 20 m thick lower glaciofluvial unit identified in well 187.1047 (Figs 5, 11) is displaced to the south along a lower flat, a ramp and an intermediate flat. The thrust sheet is more than 500 m long, and the displacement is in the order of 300 m. Because the thrust sheet was first displaced over an underlying thrust sheet, it became secondarily monoclinaly bent due to the underlying thrust sheet's propagation over a similar lower ramp, which formed a long-displaced hanging-wall anticline, translating the upper sheet piggyback southwards. Below these two thrust sheets one more thrust sheet occurs, which is of nearly the same size and has the same structure with a trailing end resting on the décollement surface. From here it is displaced up along a lower ramp to an intermediate flat and then further along an upper ramp towards the foreland. These structures are not architecturally comparable to structures in the proximal part of an 'ordinary' glaciotectonic complex (see Pedersen 2005, 2014). Hence, we draw the attention to these structures in the context of a superimposed glaciotectonic complex with two glaciodynamic sequences (see discussion below).

North of the well 187.1047 the clay unit at a depth of about 30–40 m below terrain can be followed as a seismic marker horizon (Figs 4, 11). Although broken by smaller displacements along penetrating thrust faults, it can be traced from SP 1700 to SP 1000. In the northern part of the study area, it is possible to correlate the structures interpreted on the main seismic section with the structures on the satellite seismic section, so that a 3D interpretation is possible as the two profiles intersect almost orthogonally (Figs 12, 13). The interpretation of the structures in the trailing end of the thrust sheets depends very much on the correlation of the architecture from the northernmost part of the main S–N orientated section and the small W–E orientated satellite section (Fig. 13). Comparison of the two sections indicates that the décollement surface can be traced as a more or less horizontal surface above the limestone and a thin cover of Selandian clay and marl. These bedrock units are penetrated in well

187.1013 located less than 100 m north of the end-point of the S–N seismic section (Fig. 5). The top of the bedrock appears at about 75 m b.s.l., and in the seismic section it is seen how this surface descends from a northern located footwall block into a depression above the subsided hanging-wall block to the south at wrench-fault zone 6 (Figs 4, 11). The thrust faults traced in the S–N section dip moderately to the north. The same thrust faults traced in the W–E section display moderate dips to the east. The geometric correlation of these dips results in a dominant dip towards the north-east, which implies a push direction from north-east to south-west, corresponding to an advance of the Swedish ice (Fig. 13). Some irregularities immediately above the décollement surface suggest displacement of flat-lying duplexes deformed from north to south. However, the geometry of ramps and hanging-wall anticlines above the intermediate flat and to the top of the glaciotectonic complex evidently demonstrates a push from the north-east (Figs 12, 13).

In the northern end of the seismic section (SP 500–SP 35), we declined from tracing the details of the thrust fault framework and only the major thrust sheet units are outlined; the northernmost of these is counted to be thrust sheet 42. Note that the strong reflections in the upper part of this thrust sheet correlates well with the glaciolacustrine clay units recorded in well 187.1013. However, the internal thrust fault frameworks appearing in the northernmost part of the proximal zone form two categories: a lower thrust fault framework with duplexes, partly deformed into duplex stacks, and an uppermost framework dominated by minor thrust sheet imbricates (Figs 11, 12). In the entire framework, folding dominates. These folds formed due to minor-scale hanging-wall anticlines and superimposed folding related to ramp collapses in various flat-levels (compare with similar structures described by Pedersen 2005).

Glaciodynamic sequences and glaciodynamic development

Two glaciodynamic sequences are identified in this work: the Gravervang sequence and the Tumlingeving sequence, named after the areas with characteristic elements supporting the nature of each sequence. The main boundary between the two sequences is the base of the Fændrikvang bed. Thus, the Gravervang sequence comprises the décollement zone and the beds below the Fændrikvang bed. The glaciotectonic structures are thrust faults between the décollement zone and the glaciotectonic unconformity truncating the top of thrust sheets below the base of the Fændrikvang bed. The Tumlingeving sequence comprises the Fændrikvang bed superposed on the

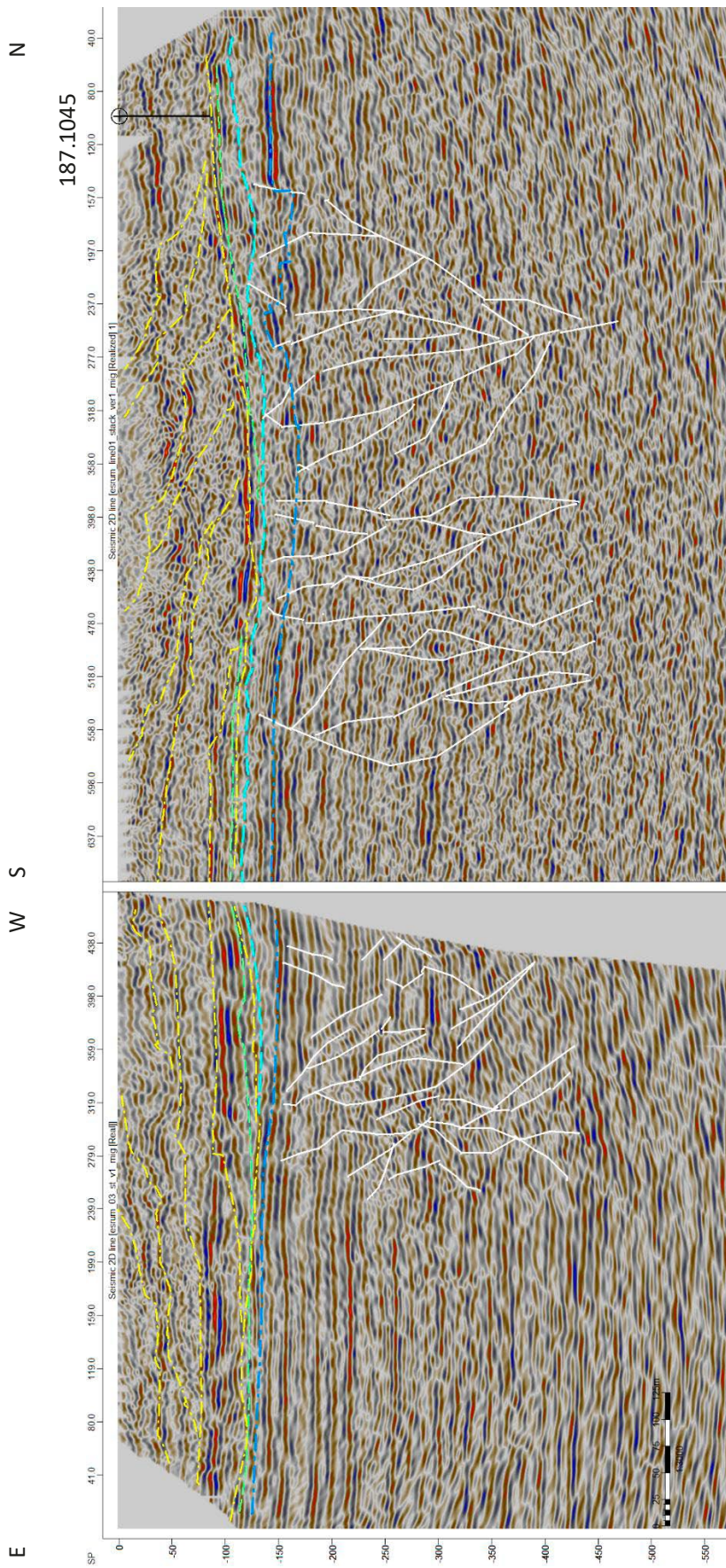


Fig. 12. The seismic satellite section trending E-W tied up to the main N-S trending seismic section. Note that the glaciotectonic thrust faults (yellow dashed lines) can be traced from one section to the other and the geometric constructions from this indicate an ice push from north-east. The correlation of the wrench faults (white lines) indicates that the strike of these fault probably trends NNW-SSE, which is also the reason for a much narrower wrench fault zone displayed in the E-W section than in the N-S section.

secondary décollement zone, which coincides with the glacioteconic unconformity on top of the Gravervang sequence. Above the Fændrikvang bed, an alternating succession of till and glaciofluvial sediments is present. The top of the Tumlingevang sequence is located above the ground level of the seismic section. Here we interpret it to coincide with the base of the Gribskov glaciodynamic sequence, which is responsible for the formation of the GIB.

The Gravervang Glaciodynamic Sequence

A rough estimate of the thrust fault displacements of Gravervang Glaciodynamic Sequence indicates a shortening of about 50%. The dominant lithology is glaciofluvial deposits. These deposits are interpreted as formed on an outwash plain accumulated on the pre-Quaternary bedrock unconformity in front of an ice advancing from the north. The glacioteconic deformation may well have started in the bog-dominated lowland 5 km north of the northern end of Esrum Sø. From here, the outwash deposits were displaced and translated towards the south. During the translation of the 30 m thick and probably 2–300 m long thrust sheets, more and more, steeper N-dipping, ramps developed, and imbrication of the proximal part of the complex occurred. Thus in the northern areas, the Munkevang and Krogdal Vang part of the seismic section, a glacioteconic depression formed. In

the southern, distal part of the complex, the shallow dipping décollement and thrust fault surfaces had their tip points more or less directly located above the southern limit of the wrench fault WFZ1 graben structure.

When the ice related to the advance forming the Gravervang Glaciodynamic Sequence finally melted back, the top of the sequence was probably truncated by a glacioteconic unconformity. It is expected that a basal till overlying a glacioteconite would have been present on the unconformity. On the surface left by the retreating ice a southerly-located hilly area showed up. Towards the north the unconformity became a depression area, resulting in the hill-and-hole pair configuration of the glacial landscape.

The Tumlingevang Glaciodynamic Sequence

The glaciodynamic development of the Tumlingevang Glaciodynamic Sequence started with the formation of an about 3–4 km wide, glacial lake in the depression left behind by the former glaciodynamic event. Here the Fændrikvang glaciolacustrine unit up to 30 m thick was deposited in the proglacial environment in front of the new ice advance interpreted to transgress the Esrum Sø area from the NE. When the ice margin approached the glacial lake, coarser-grained glacial sediments accumulated, and the material affected by glacioteconics became a mixture of clay, sand,

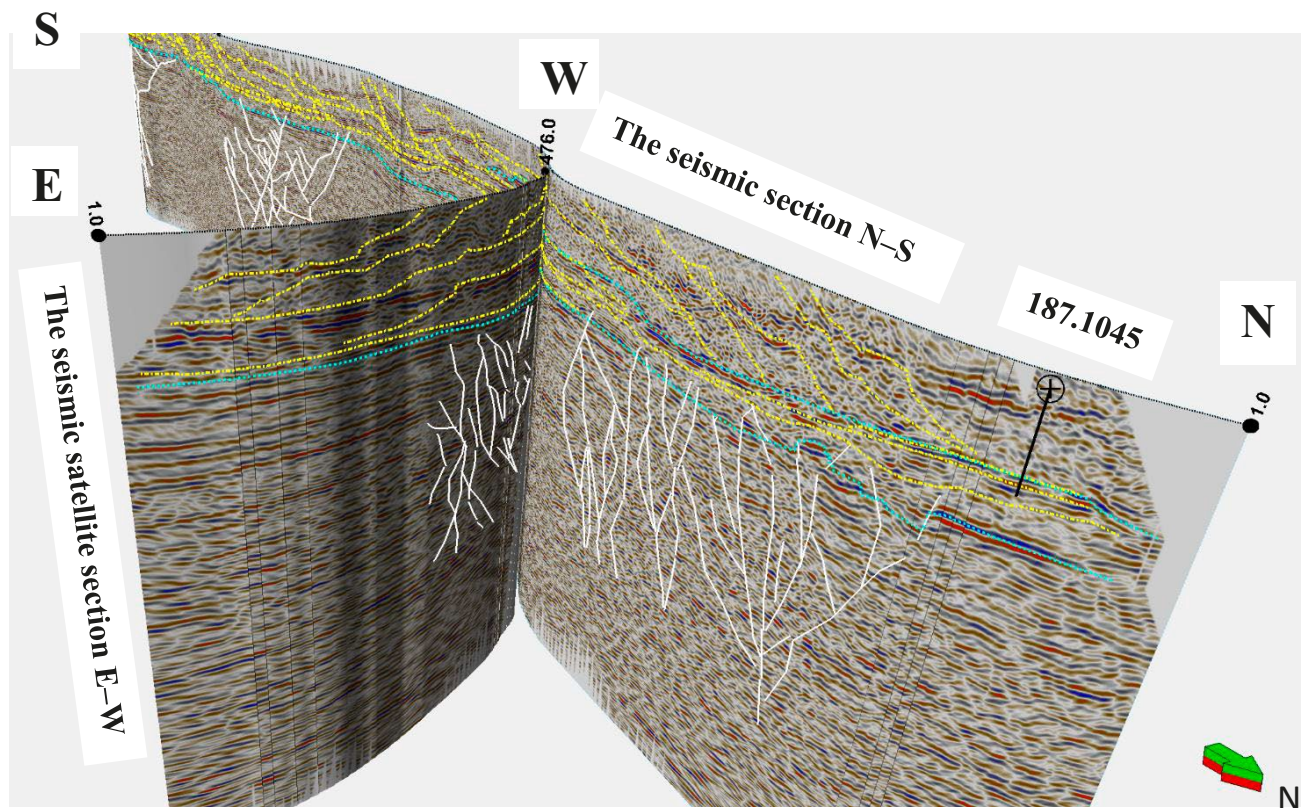


Fig.13. A 3D view of the main seismic section N-S and the satellite seismic section W-E.

gravel and rafts of bedrock marl and limestone. The new activated décollement zone stepped down into the Selandian marl, which occupies the depression in the top of the flower structure related to WFZ6. The compression in the proximal and central part of the complex amounts to more than 50%. However, the estimate is hampered by the inaccuracy caused by the oblique trend of the seismic section in relation to the strike of the thrust-fault ramps. The correlation between the wells 187.1014 and 187.1047 and the seismic section signifies that a till-horizon is deformed by a glaciotectonic event. We interpret this as the basal till deposited in the Gravervang Glaciodynamic Event and deformed during the Tumlingeving Glaciodynamic Event. The glacial sand and clay sediments are either reworked dislocated older deposits or proglacial deposits related to the Tumlingeving Glaciodynamic Sequence.

The 50% shortening of the complex in the hinterland-near part of the complex means that the translation in the central and frontal part of the complex approaches 1–2 km. The displacement took place along an upper flat, which served as a new upper-décollement zone for the distal part of the complex. The ramping of the décollement zone occurs close to SP 3100 (Fig. 4). North of this ramp the Fændriksvang bed was carried piggyback on the crests of the imbricate thrust sheets occurring in the Fændriksvang and Tumlingeving areas. South of the décollement-ramping zone the Fændriksvang bed was displaced along the upper décollement zone to the frontal part of the Tumlingeving Glaciodynamic Sequence, where a gently dipping ramp brings the displaced thrust sheet up to the ground level for the seismic section. During the translation the nearly 1 km long thrust sheet had to pass two additional ramps, namely one at SP 3230 and one at SP 3475 (Fig. 4). Between these two ramps, the compression in the glaciotectonic complex resulted in the formation of minor thrust-fault imbricate-fans. Furthermore, folding and small-scale thrusting deformed the c. 30 m thick succession of glaciofluvial sand above the Fændriksvang bed in the southernmost, distal part of the Tumlingeving Glaciodynamic Sequence. These structures are apparently similar to glaciotectonic structures in glaciolacustrine environment observed by Phillips & Evans (2019).

Discussion

Wrench-fault framework

The observed wrench-fault structures are an important new recognition in the Esrum Sø area. However,

the faults have only been recorded in the seismic profile along the west bank of Esrum Sø, and apart from the short satellite seismic section along the northern bank of the lake (Figs 12, 13), we have no data for mapping their lateral extension. The strike direction of the wrench fault zone WFZ6 judged from Figs 12 and 13 indicates a NNW–SSE trend, which implies that the widths of the wrench-fault zones are exaggerated in the S–N trending seismic section. The most prominent fault zone in the western margin of the Tornquist-Sorgenfrei Zone is the Grenå–Helsingborg Fault (Fig. 3), which strikes from the northernmost part of Øresund to the north-east corner of Djursland (Håkansson & Pedersen 1992). Along this fault, a number of en échelon faults and satellite faults were mapped from conventional seismic data in the southern part of the Kattegat Sea (Pedersen & Gravesen 2010; Kamla *et al.* 2014). The main strike of the faults is SE–NW. Therefore, the flower structures recognized in the Esrum Sø seismic section are most probably part of the wrench-fault framework located off the north coast of Sjælland. The wrench-fault framework was also identified in other seismic sections in the sea just north of Sjælland (Gunn Karine Sperling Opdal, personal communication 2019), and these faults extend towards the wrench fault system in the southern Kattegat Sea found by Kamla *et al.* (2014). We expect that the wrench faults identified on our seismic profile continue from the investigated site along the west bank of Esrum Sø and towards the south-east.

Glaciotectonic structures and glaciodynamic sequences

Age of the deformation

The emplacement of the investigated glaciotectonic complex pre-dates the deposits of the Gribskov Ice Borderline (GIB) because it occurs at a depth of about 50 m below this. The complex is thus older than the age of the Baltic ice advance (18–17 ka BP).

Two main middle–late Weichselian glaciodynamic events predate the Baltic ice advance in northern Sjælland: The Norwegian ice advance (30–28 ka BP) and the Swedish ice advance (23–21 ka BP, see Geological setting). The lithostratigraphic units representing these events are exposed in coastal outcrops along the north coast of Sjælland. These beds are glaciotectonically displaced from sources deeper than 50 m b.s.l., and these units are reasonable candidates for the Esrum Sø complexes.

Some early–middle Weichselian glaciodynamic events in eastern Denmark are represented by ice advances from the east or south-east (Houmark-Nielsen 1999, 2010; Houmark-Nielsen & Kjær 2003). As the

Esrum Sø complexes were deformed from northerly and north-easterly directions, they were not produced during the early–middle Weichselian events. Furthermore, there is no evidence and no need to consider that the Esrum Sø deposits represent earlier glacial periods (i.e. Saalian, Elsterian and older).

Identification of two glaciodynamic sequences

The differentiation of the glaciotectonic complex into two glaciodynamic sequences is based on the interpretation of superimposed glaciotectonic deformation. Four superimposed settings exist: 1) glaciotectonic deformation superimposed on pre-Quaternary deformed deposits; 2) glaciotectonic deformation superimposed on earlier-formed glaciotectonic structures in two or more glaciodynamic events; 3) glaciotectonic deformations superimposed sequentially within the same glaciotectonic unit in two or more phases of the same glaciodynamic event; and 4) neotectonic deformation superimposed on glaciotectonic structures (Pedersen 2000).

The first type of superimposed deformation is relevant for the interpretation of the structures in our seismic section. It is difficult to prove that normal faults caused by wrench faults are displaced by glaciotectonic thrust faulting. However, it is evident that some thrust-fault ramps formed over normal-fault slip surfaces.

The second type of superimposed deformation is the setting in focus. In the distal part of the glaciotectonic complex, the glaciotectonic unconformity and the Fændrikvang bed evidently separate the Gravervang and the Tumlingeving glaciodynamic sequences (e.g. Fig. 9). Towards the proximal part of the complex, the superimposed deformation increases and several thrust-fault ramps were re-used by the deformation during the Tumlingeving event. In consequence, the décollement surface in this part of the complex served as the translational surface for both glaciodynamic events. The glaciodynamic development is interpreted to be an ice advance from the north, followed by a re-advance from the north-east.

The third type of superimposed deformation is generally observed in structures that are too small to be identified in seismic section. However, the ramp-collapse structures resulting in minor-scale thrust-fault imbricates we interpret to be of this category.

Concerning the fourth type of superimposed deformation, it is uncertain if neotectonic displacements are observable in the complex deformation framework previously formed.

Geological development

The glaciotectonic complex in the subsurface below the western bank of Esrum Sø is interpreted to com-

prise two glaciodynamic sequences. The Gravervang sequence formed due to the Kattegat ice stream, which advanced from Norway over Kattegat between 30 and 28 ka BP (Houmark-Nielsen 2003). Prior to the deformation, an outwash plain was situated in front of the ice, and its glaciofluvial deposits became part of the glaciotectonic complex. The ice lobe and its ice borderline extended across northern Sjælland to Skåne in south-west Sweden, and the Gravervang Glaciodynamic Sequence formed in the marginal zone of the Norwegian ice. When the Norwegian ice melted back, a major lake basin formed in the glaciotectonic depression next to the proximal part of the glaciotectonic complex. The Tumlingeving Glaciodynamic Sequence comprises the glaciolacustrine deposits and related glaciofluvial sediments, which were thrust into a superimposed glaciotectonic complex by the main advance of the Swedish ice which affected northern Sjælland about 23 to 21 ka BP (Houmark-Nielsen & Kjær 2003). The translation of relatively thin and surprisingly extensive glaciolacustrine units for distances comparable to the length of the thrust sheet such as the Fændrikvang bed, is well documented in the distal zone of the Rubjerg Knude Glaciotectonic Complex (Pedersen 2005). Here a glaciolacustrine unit less than 20 m thick and about 50 m long is displaced about 500 m towards the foreland. We regard this as a reasonable model for the setting of the Fændrikvang bed and the Tumlingeving Glaciodynamic Sequence.

Conclusion

The interpretation of two high-resolution vibro-seismic sections, together with some boreholes, along the western bank of the lake Esrum Sø in northern Sjælland show that the upper part (down to 100 msec TWT) is characterized by two glaciotectonic complexes, whereas in the lower part of the seismic section (100–600 msec TWT) six wrench-fault structures are found. The wrench fault structures are recognized as flower structures, which displace the parallel-bedded Upper Cretaceous and Danian limestones and Selandian clay and marl in the depth interval 100–300 msec TWT. The strike of the northernmost wrench fault is determined, and the fault trends parallel to the eastern border of the buried Esrum-Alnarp Valley. This corresponds to the northernmost faults located at Esrum Sø shown in Håkansson & Pedersen (1992), which supports the fault-bound nature of the valley. The wrench faults are related to the Sorgenfrei-Tornquist zone. The wrench faults and the Esrum-Alnarp Valley are concealed by the about 100 m thick glaciotectonic complex.

The normal faults in the flower structures served as

ramps for the glaciotectonic thrust faulting during the glaciations in the late Quaternary, Weichselian time. Two glaciodynamic events formed the glaciotectonic complex: the first event comprises the Gravervang Glaciodynamic Sequence and is related to the Norwegian ice advance about 28 ka BP, and the second event comprises the Tumlingeving Glaciodynamic Sequence and is related to the Swedish ice advance about 23 ka BP.

Acknowledgements

We are grateful for the permission to use the vibro-seis truck of Aarhus University. Furthermore, we would like to acknowledge the team of people who have helped collect the vibro-seismic data: Emma Hald Boldreel, Irena Årberg Joensen and Vigdis Louise Jónsdóttir. Thanks are due to the Schlumberger company for issuing a University Grant, including Petrel software, to IGN. The reviewers and the editor L.M. Larsen are thanked for constructive comments and suggestions that led to improvement of the manuscript.

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