

Initial observations of the shallow geology in Tannis Bugt, Skagerrak, Denmark

Matthew J. Owen, Nicky H. Witt, Ziad Al-Hamdani, Niels Nørgaard-Pedersen, Katrine J. Andresen and Jørgen O. Leth

During August 2017, as part of the habitat mapping of Natura2000 areas, a geophysical survey of a large area within the Skagerrak was undertaken by the Geological Survey of Denmark and Greenland. In this article, we use the acquired data to discuss the geology of Tannis Bugt (Fig. 1), a large shallow bay at the north-west coast of Vendsyssel. The bay extends 40 km between Hirtshals in the west and Skagen in the east forming the northern-most Danish Skagerrak coast.

Geological setting and glacial history

In northern Vendsyssel, the Late Quaternary succession is 250 m thick and underlain by Cretaceous or Triassic strata (Håkansson & Pedersen 1992). Tertiary sediments are assumed to be absent (Sandersen *et al.* 2009). Vendsyssel was subjected to several ice advances during the Saalian and Weichselian, which resulted in a succession that is generally dominated by marine to glaciolacustrine clay (Knudsen *et al.* 2009; Larsen *et al.* 2009a). The oldest Quaternary deposits in Vendsyssel are represented by the clay-rich Skærumhede Till Formation, which is followed by the marine Lower Skærumhede Clay Formation. The till units of the Brønderslev and Åsted formations of the Early to Middle Weichselian reflect a change to a colder environment. Boulders are found throughout the till units (Pedersen 2005; Knudsen *et al.* 2009; Larsen *et al.* 2009a; Larsen *et al.* 2009b). The changing climate resulted in ice retreat and the deposition of the marine sediments of the Upper Skærumhede Clay Formation, which gradually

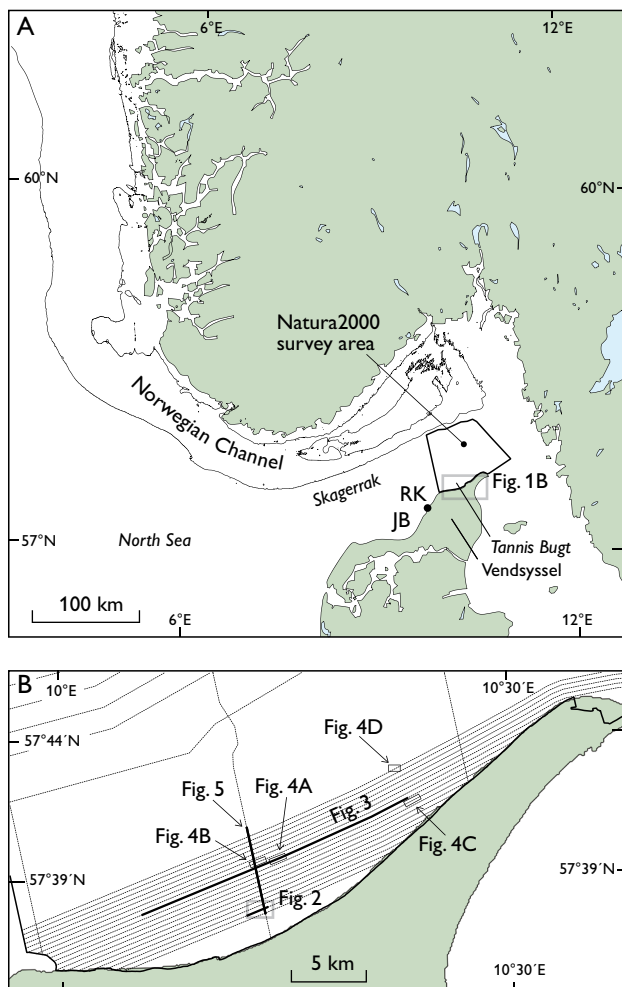


Fig. 1. Locality map. **A**: Regional setting of the study area. **JB**: Jammerbugt. **RK**: Rubjerg Knude. **B**: Tannis Bugt with location of data shown.

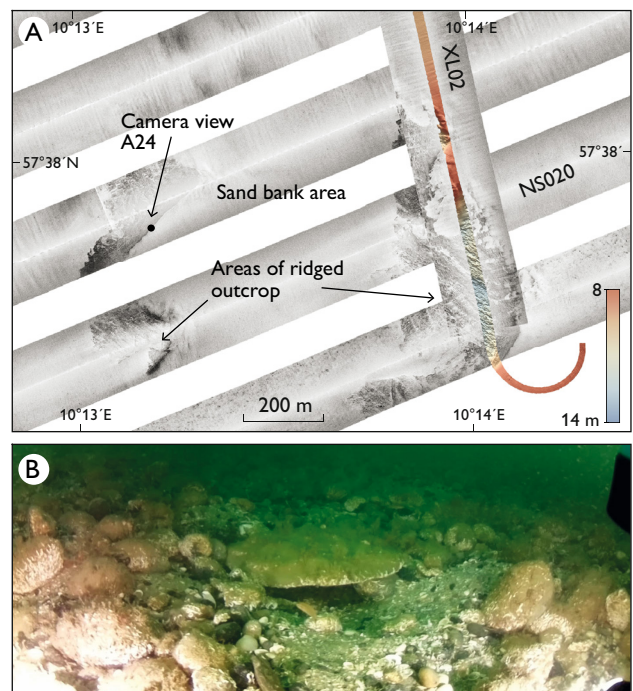


Fig. 2. **A**: Seabed morphology with location of Innomar lines XL02 and NS020 (shown in Fig. 4). **B**: Video view of the sea floor (A24).

developed into the glaciolacustrine Lønstrup Klint Formation, and the transition continues into terrestrial and glacial sediments of the Kattegat Till Formation. The Late Weichselian sediments consist of several phases of till and glaciolacustrine units. By *c.* 18 ka BP, as the ice retreated, large parts of Vendsyssel were inundated by the sea leading to the deposition of the marine Vendsyssel Formation.

Associated with the advance and retreat of ice sheets, the area was strongly influenced by isostatic rebound with a regression occurring from the Late Glacial to the present day.

Raised late-glacial shorelines are found up to *c.* 60 m above sea level (Richardt 1996). A number of glaciotectonic complexes have been mapped in northern Jylland (Fig. 1A) and tend to exhibit thrusting from the east or north-east (Pedersen & Boldreel 2015). The oceanographic setting has varied in response to the interplay between isostasy and eustasy. As such, the setting is inferred to have varied between an isolated embayment, extending from the Atlantic via the Norwegian Channel, to the present-day setting as a deep-water component of the North Sea.

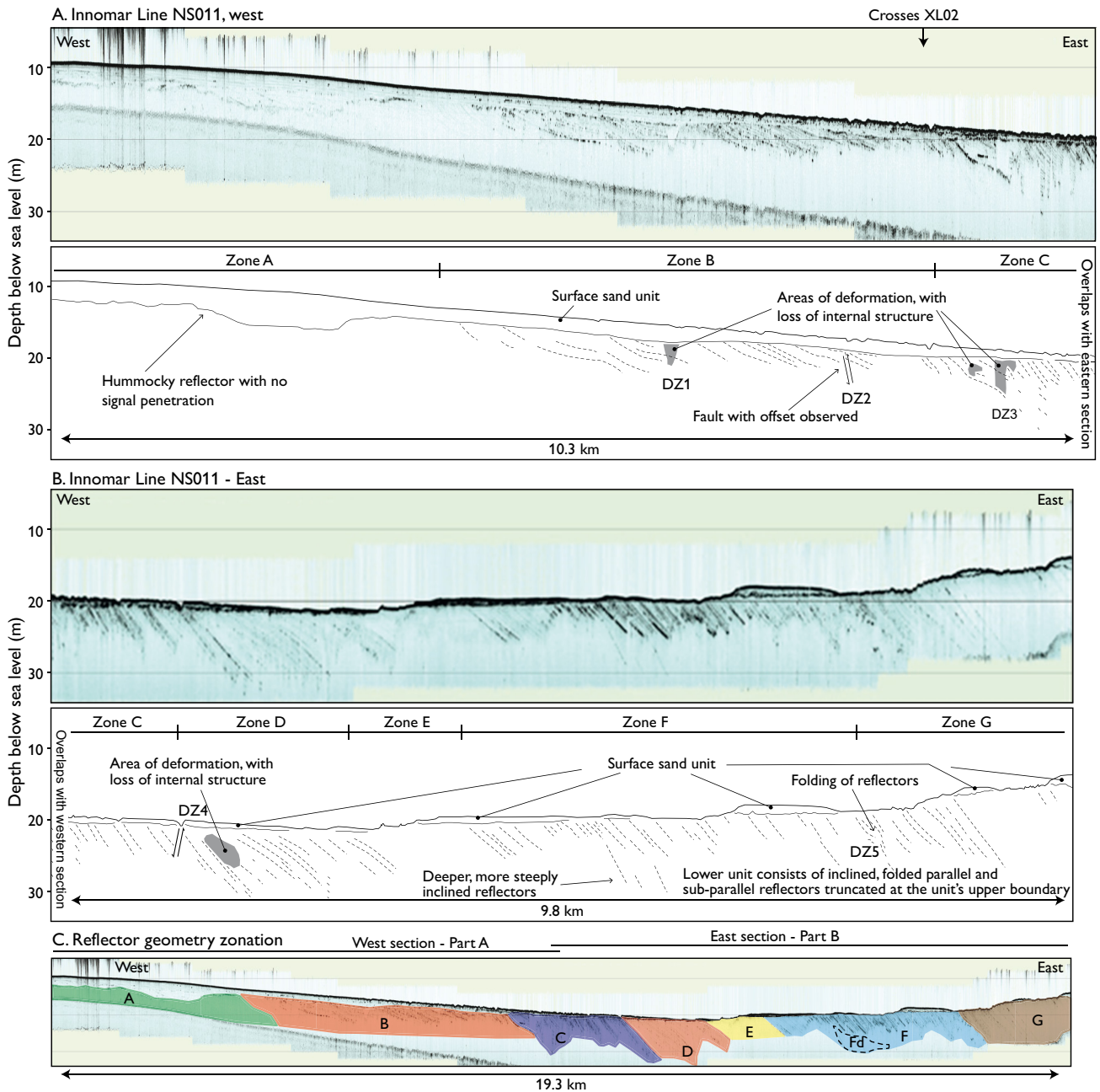


Fig. 3. WSW–ENE-orientated Innomar profile NS011. A: Western part. B: Eastern part. C: Full profile with zones described in Table 1. DZ: deformation zone. Vertical exaggeration 70 times.

Table 1. Summary of Innomar data shown on line NS011 (Fig. 3).

Zone	Length (m)	Facies characteristics	Representative reflector inclination
A	3270	Upper unit with a smooth and convex up upper boundary. The lower boundary shows undulation and a hummocky character. No Innomar penetration below.	NA
B	4650	Upper unit thins and pinches out eastward. The seabed becomes increasingly incised with small notches moving east. This unit rests unconformably on a lower unit characterised by northeastwardly dipping reflectors. Folded and offset reflectors are apparent (DZ1 and DZ2).	0.3°
C	2640	An upper unit is generally present, though it pinches out occasionally and is <1 m thick. Below, reflectors of the lower unit are inclined and appear to be more densely spaced, with deformation visible (DZ3). The upper surface of the lower unit becomes more irregular to the east.	0.9°
D	1800	Upper unit is present, though <1 m thick, in the west and pinches out and is absent in the east. Curvilinear, inclined reflectors characterise the lower unit, an apparent loss of internal structure is also visible (DZ4).	0.6°
E	930	Lack of penetration, cuesta-like scarps of ~1 m height visible on the seabed.	NA
F	4750	A semi-transparent upper unit with a lens-like morphology is intermittently present and <2 m thick. Below, densely spaced reflectors are inclined giving the seabed a cuesta morphology where they outcrop. Innomar penetration is variable. Area of folding in the east (DZ5).	0.9°
Fd		Deeper, more steeply inclined reflectors separate from the shallower units.	1.5°
G	2070	Intermittent upper unit, with a semi-transparent facies and lens-like morphology, resting unconformably atop of the irregular upper surface of the lower unit with inclined linear reflectors. The seabed shoals and Innomar penetration reduces in the east.	1.0°

Marine survey

The dataset obtained in the survey consists of multibeam bathymetry, side-scan sonar and Innomar sub-bottom profiler data. Some 2150 km of data were acquired using the vessel R/V *Aurora* (Fig. 1b), covering the northern coast of Vendsyssel between Skagen and Hirtshals. WSW–ENE-orientated nearshore lines were spaced at 300 m intervals and N–S-orientated crossing lines at 15 km intervals. In addition, 24 video views were made of the sea floor in the shallow-water area.

Camera view at site A24 – The site is located at a water depth of 12 m in an area characterised by a high-amplitude, irregular, acoustic seabed facies, in a depression adjacent to a low-amplitude shallow-banked area (Fig. 2A). To the east an adjacent depression is characterised by a similarly high-amplitude acoustic facies, but traversed by NW–SE-orientated linear ridges. When visible, the apparent strike of the bedding is generally SE, though in some instances a NE strike is also visible. The camera view (Fig. 2B) shows a mixture of coarse gravel, cobbles and boulders. The larger clasts appear to be sub-rounded to well rounded.

Innomar data – Figures 3 to 5 show a selection of the Innomar data from Tannis Bugt. The facies visible in these figures are representative of those observed across the site. The W–E-orientated Innomar profile NS011 (Fig. 3) shows a semi-transparent upper unit, which is intermittently present. It overlies a deeper unit with reflectors that dip to the north-east. An additional deeper unit, with more steeply

inclined reflectors, is occasionally visible. To aid description the data shown in Fig. 3 are divided into zones A to G from west to east (Table 1).

At least five zones of deformation (DZ1–DZ5; Fig. 3) are apparent in the Innomar data. Indications of deformation include folding, offset reflectors and loss of structure. Some of these complex features are shown in more detail in Fig. 4. Innomar examples (4A–C) show deformed reflectors, areas of lost structures and apparent faults. The side-scan example (Fig. 4D) shows an area of wave-like bedding outcropping at the seabed.

Figure 5 shows the N–S-orientated Innomar line XL02, which crosses the profile NS011 shown in Fig. 3 as well as the area shown in Fig. 2. As with the data shown in Fig. 3, an upper semi-transparent unit rests unconformably on a unit with truncated dipping reflectors. In the southern half of the profile, the upper unit thickens, where it is associated with large sand banks. The reflectors of the lower unit show steeper inclination in the northern third of Fig. 5, where inclination of 1.8° is found. Near the crossing of NS011, shown in Fig. 3, DZ3 (Fig. 3, Table 1) is visible and marks a divide between the more steeply inclined reflectors farther north and the more gently inclined reflectors to the south, where inclinations of 0.7° are measured.

At the far south, reflectors outcrop at the seabed with an inclination of 0.5°. Blanking of the Innomar data is particularly apparent in Fig. 5 north of DZ3; here reflectors are clearly cut by blanking zones rising from depth. South of DZ3 penetration ends abruptly and is variable. Some deformation is visible in Fig. 5 (folded reflectors below the thickening surface unit and some loss of structure at DZ3), though it is less apparent than in the data shown in Figs 3, 4.

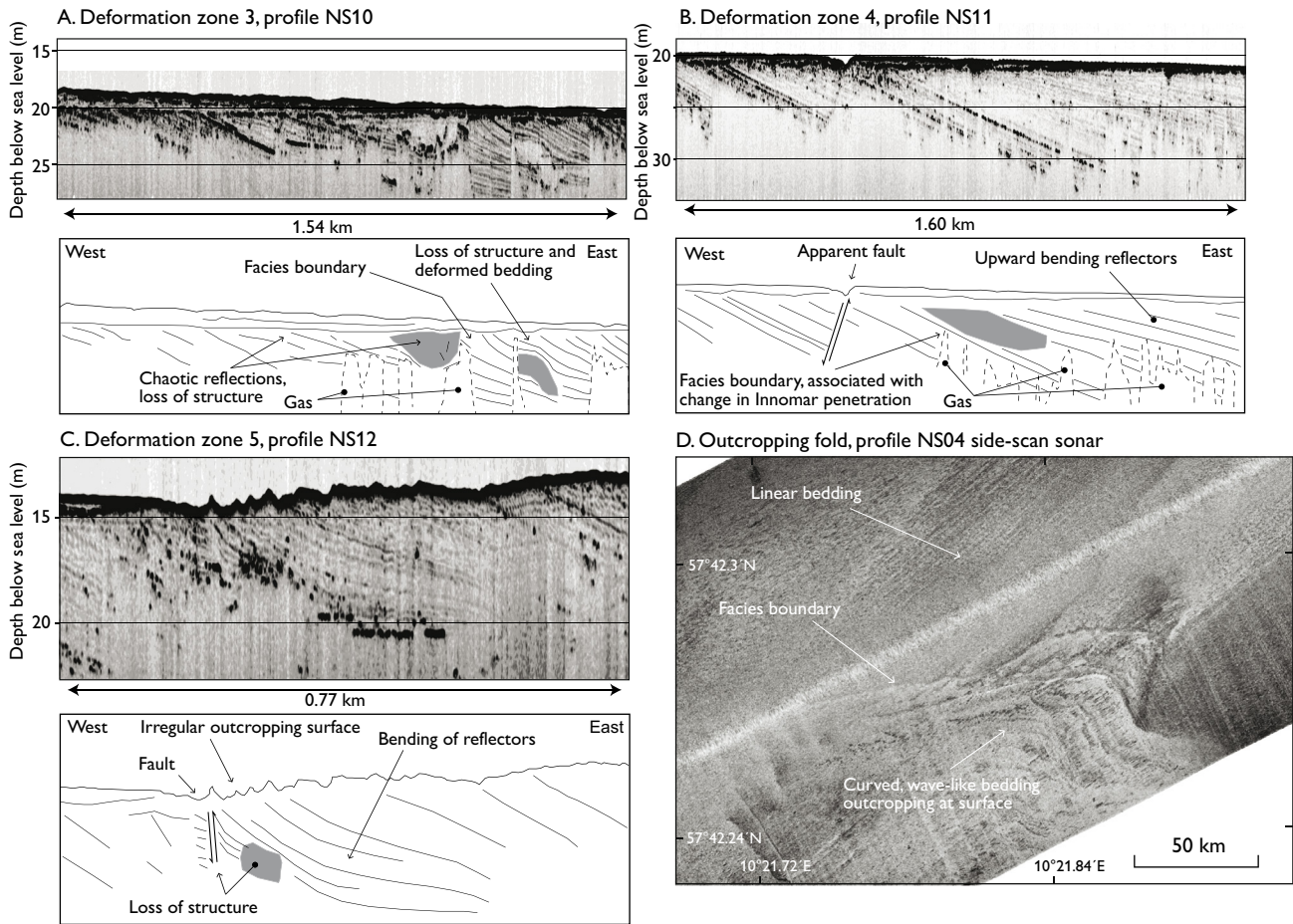


Fig. 4. Examples of deformations within Tannis Bugt. A–C: Innomar data shown with a vertical exaggeration of 28 times. D: Side-scan sonar data.

Discussion

Interpretation of Innomar and video data – The upper units visible in the Innomar data are interpreted as Holocene marine sand and gravel. Interpretation of the deeper unit is complicated by limited penetration from the Innomar system and no ground control. However, as indicated by the zoning in Figs 3 and 5, and the facies characteristics outlined in Table 1, there is a clear variation in reflector geometry, and we make some provisional observations.

One of the most striking aspects of the Innomar data is the inclined nature of the reflectors, representing bedding planes, and the truncated, often irregular upper surface. As shown in Table 1, inclination (as distinct from angle of dip due to the oblique orientation of the survey lines with respect to direction of dip) is low and measures between 0.3° and 1.5° within the W–E-orientated NS011 profile; it is generally greater in the east. Measured inclinations from the N–S-orientated XL02 profile (Fig. 5) are greater, with 1.8° . There is also clear variation in angle between zones B–D, F and G (zones A and E do not show inclined reflectors).

The parallel bedding appears to have undergone deformation (folds and faults are visible in Figs 3, 4) in the centre and east of the site. Some deformation is apparent in Fig. 5, though it is less clear. Areas of deformation separate zones B and C, C and D, and F and G. The reflective facies within the zones are distinct and display features indicative of further deformation. Shown in Fig. 5, there is a clear reduction in bedding inclination between zones C and B. Innomar penetration is reduced by a factor of three in zone B compared to zone C and blanking cuts the bedding within zone C (indicating gas migration), whereas it does not in the more depth-limited imaging of zone B. This indicates a change in lithology between zones, with zone B potentially consisting of a less permeable and more dense material. Referring to Fig. 3, the reflectors in zone D display a lower angle of inclination and appear folded. Zone E is characterised by no sub-surface penetration and the presence of cuesta-like scarps on the seabed. Gas does not appear to be present in this location and the surface unit is thin or absent, therefore the lack of signal could be due to the presence of a massive or more dense unit.

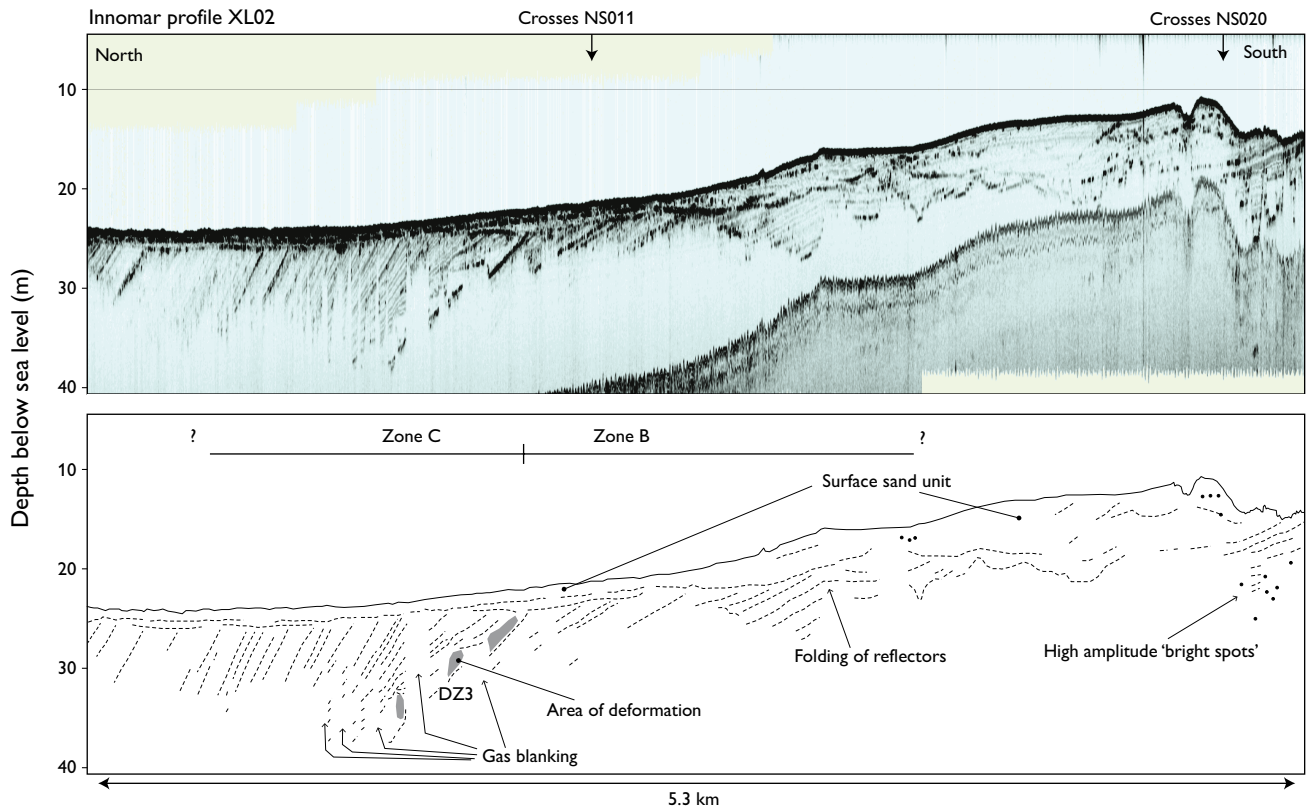


Fig. 5. N–S-orientated Innomar profile XL02. See Fig. 2 for location. Vertical exaggeration 40 times.

Inclined reflectors are again apparent in zone F, sub-surface penetration varies and is generally limited. Outcropping bedding is apparent in zone G, matching the acoustic facies visible on the side scan record: where outcropping strata are visible as ridges (Fig. 2A).

Cobbles and boulders visible in camera view A24 (Fig. 2B), where Innomar data show high amplitude seabed in an area with outcropping strata, appear to have two possible origins: either a winnowed deposit from a Quaternary till or drop-stone unit, or eroded pre-Quaternary bedrock. The density of the clasts visible would require a large, though not impossible, initial thickness of till to yield such a high number of clasts. The presence of pre-Quaternary geology would be unexpected; however, shown by the bedding visible in Figs 3 and 5, outcrop in the location of camera site A24 is stratigraphically older than the lithological units located north and eastward, which extend for up to 20 km.

Origin and contributing geological processes – One of the more puzzling aspects of the geology of Tannis Bugt is the difference to the onshore data which show a succession of till, glaciomarine and lacustrine units that are incised by tunnel valleys covered by a thick succession of Late Glacial and Holocene marine deposits (Larsen *et al.* 2009a; Sandersen

et al. 2009). Whilst the change in facies observed in the Innomar data could occur due to transitions between till and glaciomarine or lacustrine units, the bedding inclination is not so simple to explain.

It is possible that the deeper facies could represent cross-bedding associated with the development of the Skagen spit, or palaeo-Skagen spit(s), with marine transgressive erosion surfaces noted on the north-western coastline of the present spit, which is migrating eastward (Nielsen & Johannessen 2009). However, the observed facies are too deep and, due to the regressive nature of the shoreline, would have been significantly deeper prior to the early Holocene (Richardt 1996).

The inclination and north-eastward dipping of the beds in Tannis Bugt could indicate deposition within a prograding system during the development of the shallow-water area off Vendsyssel, which extends some 20 km from the coastline. The truncated, inclined facies shown in Figs 3, 5 are similar to a delta facies which may undergo deformation via gravity-driven processes (Postma 1995; Patruno *et al.* 2015). However, if a delta complex is present in Tannis Bugt, the age and sediment source are unknown. Early Quaternary deltaic units are present in the central and southern North Sea (Lamb *et al.* 2018), but these dip in a westerly direction. If deltaic, the NE–SE-direction of dip observed in Tannis Bugt

would indicate progradation into the Skagerrak and Norwegian Channel. This suggests that the inclined bedding could represent subaqueous shelf-prism clinoforms (Patruno *et al.* 2015), deposited within the Skagerrak embayment during low stands (producing the observed SW–NE-orientated strike) and as a consequence of the stronger south-west flow from the North Sea during high stands (producing the SW–NE-orientated strike).

Glaciotectonic activity is documented near Tannis Bugt, with complexes at Rubjerg Knude (Pedersen 2005) and in Jammerbugt (Pedersen & Boldreel 2017; Fig. 1), and could also cause the observed facies. Tannis Bugt has a dip geometry (to the north-east) that is similar to Jammerbugt, though the measured reflector inclination of *c.* 1–2° is less than the *c.* 6° thrust plane dip seen in the proximal part of the Jammerbugt complex (Pedersen & Boldreel 2017). The lower angle of inclination could be due to limited penetration of the Innomar data not revealing the unit's true geometry, or it could represent a low-angled thrust component, such as a flat (Pedersen & Boldreel 2015). However, it is perhaps more likely that the facies are a result of the combined processes of clinoform deposition, causing the observed inclination, and glaciotectonic activity causing the deformation.

If the deformation in Tannis Bugt is glaciotectonic, it is unclear whether it is part of a larger Tannis–Jammerbugt complex, or whether there are two separate complexes. In any case, their geographical proximity and similar direction of dip indicate that they could be formed by a similar process such as an advance from the Norwegian Channel ice stream.

Conclusion

Inclined and deformed bedding planes dipping predominantly to the north-east have been identified in Tannis Bugt, off the north coast of Vendsyssel. A bouldery area, representing either winnowed glacial unit or eroded pre-Quaternary bedrock, has been identified near the coastline in the centre of the bay. If the inclined bedding represents a prograding sequence with an eroded upper surface then the outcrop long section could represent a unit of significant age, with the possibility of pre-Quaternary geology exposed at the seabed. If the inclination and deformation are the result of glaciotectonic deformation then the site represents a newly discovered glaciotectonic complex. Deeper penetrating multichannel

seismic data and geological samples will be required to fully understand the geology of Tannis Bugt and how it relates to the development of northern Denmark.

Acknowledgements

We thank the Danish Environmental Protection Agency for permission to publish data acquired during the survey of Natura2000 areas, the captain and crew of the R/V *Aurora* for their assistance during the survey and Orbicon A/S for the acquisition of video data.

References

- Håkansson, E. & Pedersen, S.A.S. 1992: Geologisk kort over den danske underground, map sheet. Copenhagen: Varv.
- Knudsen, K.L., Kristensen, P. & Larsen, N.K. 2009: Marine glacial and interglacial stratigraphy in Vendsyssel, northern Denmark: foraminifera and stable isotopes. *Boreas* **38**, 787–810.
- Lamb, R.M., Harding, R., Huuse, M., Stewart, M. & Brocklehurst, S.H. 2018: The early Quaternary North Sea Basin. *Journal of the Geological Society* **175**, 275–290.
- Larsen, N.K., Knudsen, K.L., Krohn, C.F., Kronborg, C., Murray, A.S. & Nielsen, O.L.E.B. 2009a: Late Quaternary ice sheet, lake and sea history of southwest Scandinavia – a synthesis. *Boreas* **38**, 732–761.
- Larsen, N.K., Krohn, C.F., Kronborg, C., Nielsen, O.B. & Knudsen, K.L. 2009b: Lithostratigraphy of the Late Saalian to Middle Weichselian Skaerumhedehede Group in Vendsyssel, northern Denmark. *Boreas* **38**, 762–786.
- Nielsen, L.H. & Johannessen, P.N. 2009: Facies architecture and depositional processes of the Holocene–Recent accretionary forced regressive Skagen spit system, Denmark. *Sedimentology* **56**, 935–968.
- Patruno, S., Hampson, G.J. & Jackson, C.A.-L. 2015: Quantitative characterisation of deltaic and subaqueous clinoforms. *Earth Science Reviews* **142**, 79–119.
- Pedersen, S.A.S. 2005: Structural analysis of the Rubjerg Knude Glaciotectonic Complex, Vendsyssel, northern Denmark. *Geological Survey of Denmark and Greenland Bulletin* **8**, 192 pp.
- Pedersen, S.A.S. & Boldreel, L.O. 2015: Thrust-fault architecture of glaciotectonic complexes in Denmark. *Geological Survey of Denmark and Greenland Bulletin* **33**, 17–20.
- Pedersen, S.A.S. & Boldreel, L.O. 2017: Glaciotectonic deformations in the Jammerbugt and glaciodynamic development in the eastern North Sea. *Journal of Quaternary Science* **32**, 183–195.
- Postma, G. 1995: Sea-level-related architectural trends in coarse-grained delta complexes. *Sedimentary Geology* **98**, 3–12.
- Richardt, N. 1996: Sedimentological examination of the Late Weichselian sea-level history following deglaciation of northern Denmark. In: Andrews, J.T. *et al.* (eds): Late Quaternary Palaeoceanography of the North Atlantic Margins. Geological Society (London), Special Publication **111**, 261–273.
- Sandersen, P.B.E., Jørgensen, F., Larsen, N.K., Westergaard, J.H. & Auken, E. 2009: Rapid tunnel-valley formation beneath the receding Late Weichselian ice sheet in Vendsyssel, Denmark. *Boreas* **38**, 834–851.

Authors' addresses

M.J.O., N.H.W., Z.A.-H., N.N.-P., J.O.L., *Geological Survey of Denmark and Greenland, C.F. Møllers Allé 8, DK-8000 Aarhus C, Denmark.*

E-mail: mow@geus.dk.

K.J.A., *Department of Geoscience, Aarhus University, Høegh-Guldbergs Gade 2, DK-8000 Aarhus C, Denmark.*