JGS
Discussion
Journal of the Geological Society
Published online October 27, 2015; updated November 10, 2015
doi:10.1144/jgs2014-023 | Vol. 173 | 2016 | pp. 384–393

Discussion on 'Late Cenozoic geological evolution of the northern North Sea: development of a Miocene unconformity reshaped by large-scale Pleistocene sand intrusion', *Journal of the Geological Society*, 170, 133–145

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Received 18 March 2014; **revised** 3 July 2015; **accepted** 17 July 2015

In their recent paper, Løseth *et al.* (2013) propose a new model for the late Cenozoic evolution of the northern North Sea. They propose that during the early Pleistocene (*sensu* ICS 2013), large volumes of sand were ejected from the Paleocene through the Eocene–Oligocene Hordaland Group, and deposited both as extrusive sand on the Pleistocene seafloor and as intrusive sand within the Oligocene section, *c.* 180 m below the seafloor. The paper builds on two earlier studies: (1) that by Løseth *et al.* (2012) in which the Pleistocene extrusive sand is presented in more detail; (2) that by Rodrigues *et al.* (2009) in which an experimental model related to such sand deposition is presented.

The model of Løseth *et al.* (2013) is illustrated by a seismic section in their figure 12, showing intrusive sands within the Oligocene and extrusive sands within the Pleistocene. Details of this model, such as feeder dykes and blowout fissures that create ditches, are shown in their figure 8 (Visund Field) and figure 11 (Snorre Field). The geological events are summarized in their figure 16. As illustrated on a stratigraphic scheme (their figs 2 and 15), Løseth *et al.* interpret the Oligocene sands as being injected from a Paleocene parent sand. They propose that the mounds at the top of the Hordaland Group resulted from forced folding over the sand injectites, as exemplified in their figure 11. Furthermore, Løseth *et al.* interpret escarpments on the Top Hordaland Group Unconformity as cliff sections similar to those of southeastern England today and claim that the northern North Sea was subaerially exposed during a 10 myr Miocene time span.

Løseth *et al.* (2012, 2013) not only challenge our previous turbiditic interpretation of the Pleistocene sand (Eidvin & Rundberg 2001), but also much of our explanation of the post-Eocene evolution of the northern North Sea (Rundberg & Eidvin 2005, Eidvin & Rundberg 2007) by introducing a model that we consider to be highly speculative.

We have revisited the Snorre and Visund areas and reinterpreted the post-Eocene strata using the same 3D dataset as Løseth *et al.* (2013). In addition, we have extended the area to include most of the northern North Sea between 61 and 62°N. Our conclusions from this new study are in disagreement with the model of Løseth *et al.* (2013) and we propose an alternative interpretation of the mounded Top Hordaland Group Unconformity (Fig. 1) in this area.

The 'extrusive' Pleistocene sand

The 'extrusive sand' of Løseth *et al.* (2012, 2013) is claimed by them to be the world's largest body of extrusive sand ever described. Although extrusive sands are documented in the geological record (e.g. Hurst *et al*. 2006), the large volume of sands (10 km^3) seems unrealistic. We believe that this sand rather represents gravity deposits belonging to the Pleistocene prograding system (Naust Formation equivalent) as described by Eidvin & Rundberg (2001). Our arguments are as follows.

(1) Sand distribution and setting. Our map of the underlying clinoform surface (i.e. the depositional surface of the sand; Fig. 2) shows that the sand is located within a northwestward-trending submarine paleo-valley in the northern North Sea, at the toe of the clinoform foresets. Mapping of this surface would yield interesting data on the basin configuration during progradation of the giant Pleistocene system. Løseth *et al.* (2012, 2013) do not present any data on the location of the sand within the prograding Pleistocene system.

The clinoform surface delineates a basin topography deepening towards the Møre Basin north of 62°N, similar to the situation presented by Ottesen *et al.* (2014) and comparable with the base of their Naust Unit B. Two east–west seismic sections (Figs 3 and 4) and one north–south seismic section (Fig. 5) provide an overview of the Pleistocene depositional system in this area. In the southern east–west transect through wells 34/7-5 and 34/7-10 (Fig. 3), the sand is well defined seismically as bottomsets in front of the Pleistocene clinoform. In the other transect through wells 34/7-4 and 34/7-9 (Fig. 4), crossing perpendicular to the Snorre mounds, the sand is completely disrupted by the central Snorre mound. Notably the sand thins above the mounds and thickens in the depressions between the mounds. In comparison Løseth *et al.* (2012, fig. 2) do not interpret this surface.

The Pleistocene sand is penetrated in a number of wells in blocks 34/4, 34/7 and 33/9. The approximate outline of the sand is shown in Figure 2 (western extent is uncertain owing to seismic resolution). It is present in wells 10 km up-dip (i.e. to the south) of the Snorre mounds; for example, in well 34/7-8, where it is 15 m thick. This up-dip sand is positioned *c.* 100 m shallower than the 'blowout fissures' in the model of Løseth *et al.* (2012, 2013). Although some post-depositional uplift has affected the basin floor area (towards the SW), and this must be corrected for, it is difficult to explain how these sands could have travelled up-dip from the Snorre mounds in their model.

In the log correlation diagram (Fig. 6), the sand is displayed in six wells: three wells to the south of the Snorre mounds, one of which is intersected by well 34/7-6, and three wells to the north and NW of the mounds. Seismic ties to four of these wells are shown in Figure 3 (wells 34/7-5 and 34/7-10) and Figure 4 (34/7-4 and 34/7-9).

(2) Many similar sands within the prograding Pleistocene system. In the immediately overlying progradational sequence similar sands are encountered in wells 37/4-5 and 37/4-10 in a basinal position at the toe of the progradational clinoform (surface

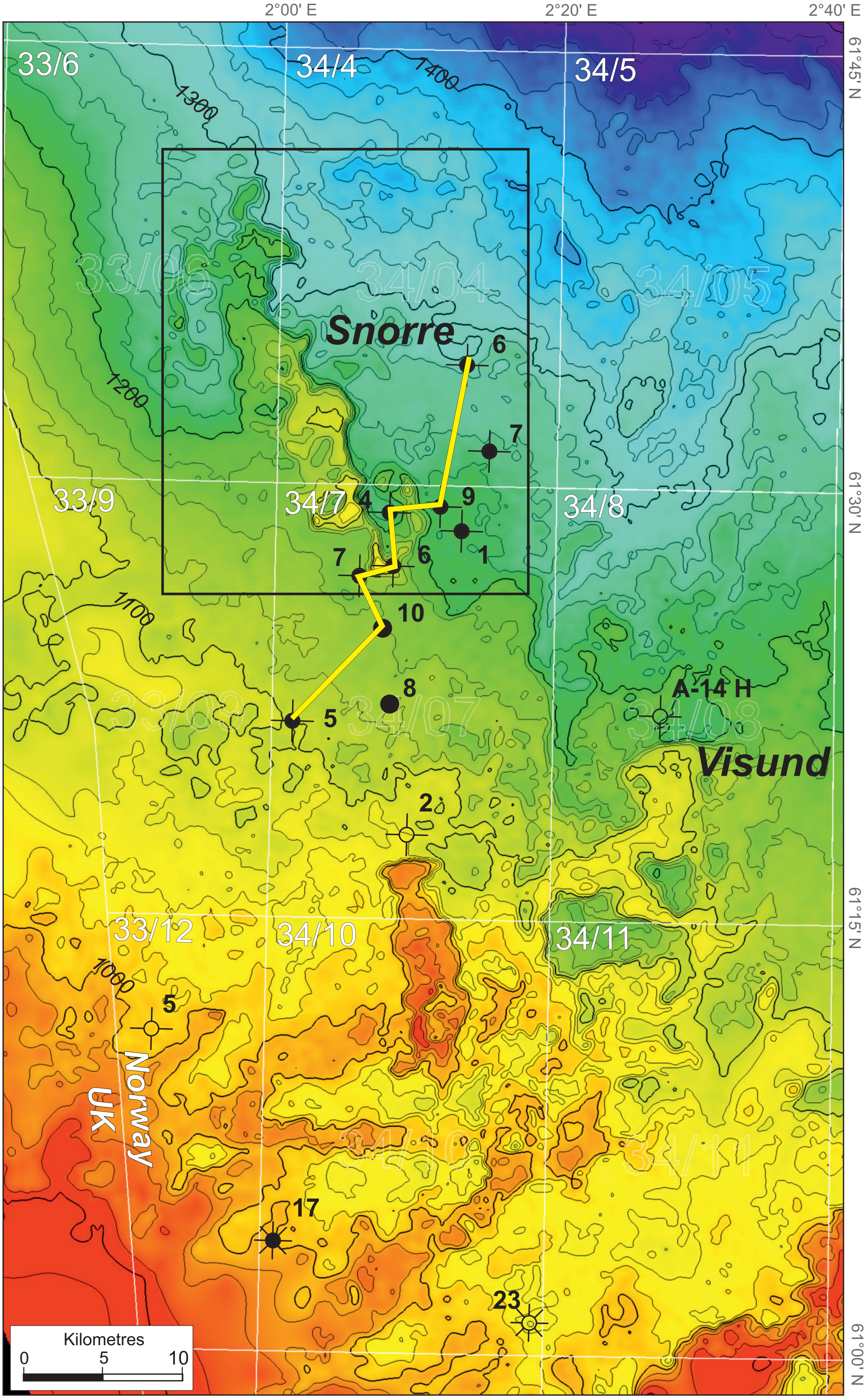

Fig. 1. Map of Top Hordaland Group Unconformity in the northern North Sea (time); contour interval 25 ms. Yellow line connects wells in log correlation (Fig. 6).

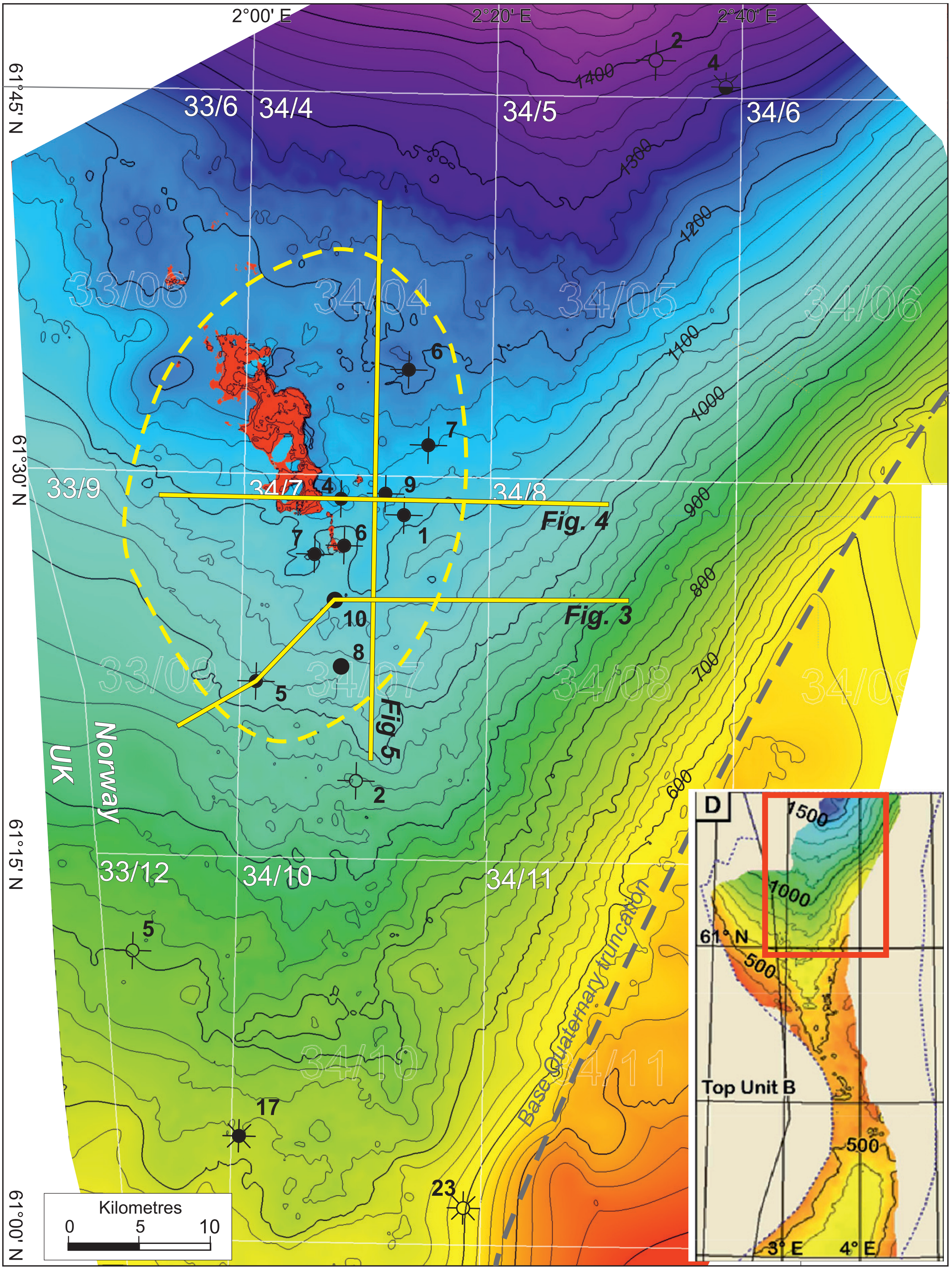

Fig. 2. Map of Pleistocene clinoform surface 1 with approximate outline of Pleistocene sand unit (yellow dashed line). Red area shows mounds at the Top Hordaland Group surface in the Snorre area that cut the base of the sands. Inset map (from Ottesen *et al.* 2014) represents approximately the same surface.

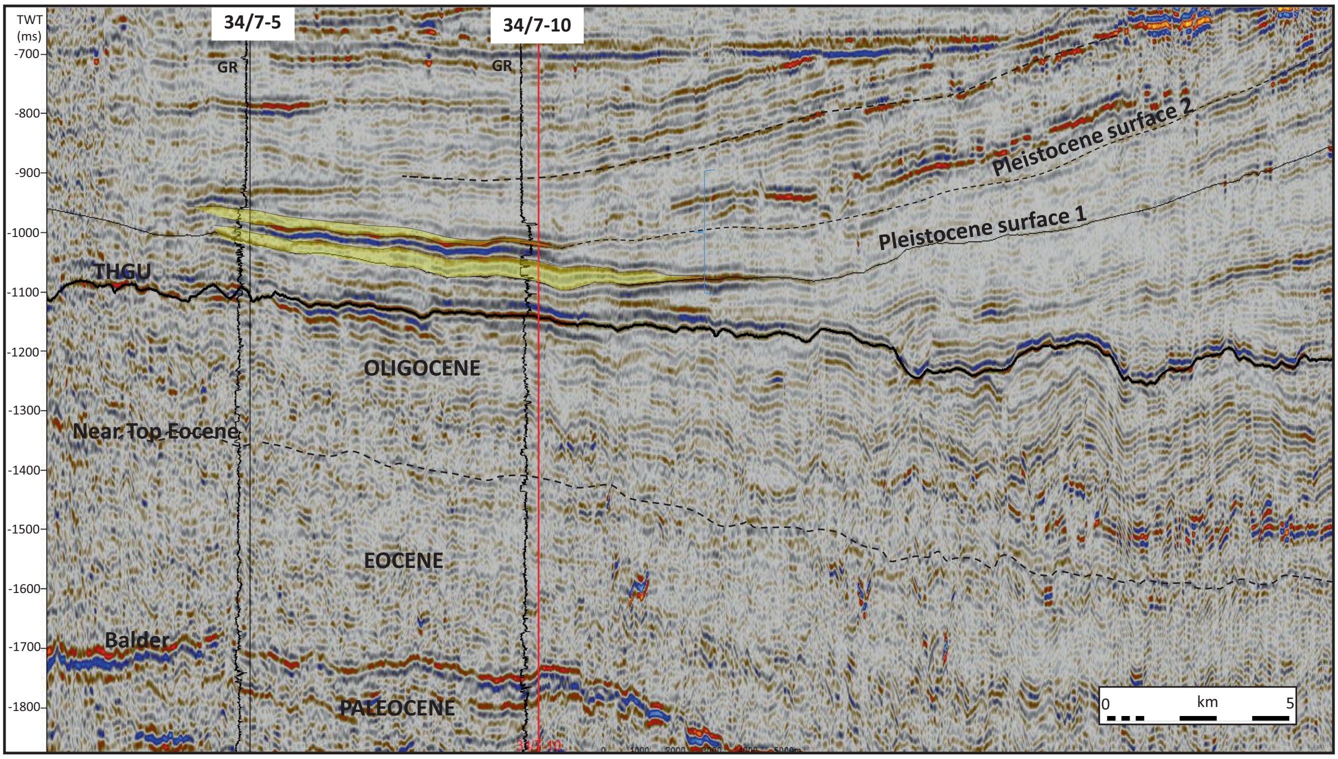

Fig. 3. East–west composite seismic section through wells 34/7-5 and 34/7-10 showing Pleistocene sands (yellow shading) interpreted as turbiditic deposits at the toe of clinoformal surfaces 1 and 2. The Oligocene sandstone in both wells (on GR logs) and the erosional character of the Top Hordaland Group Unconformity (THGU) should be noted. Location of profile is shown in Figure 2. TWT, two-way travel time.

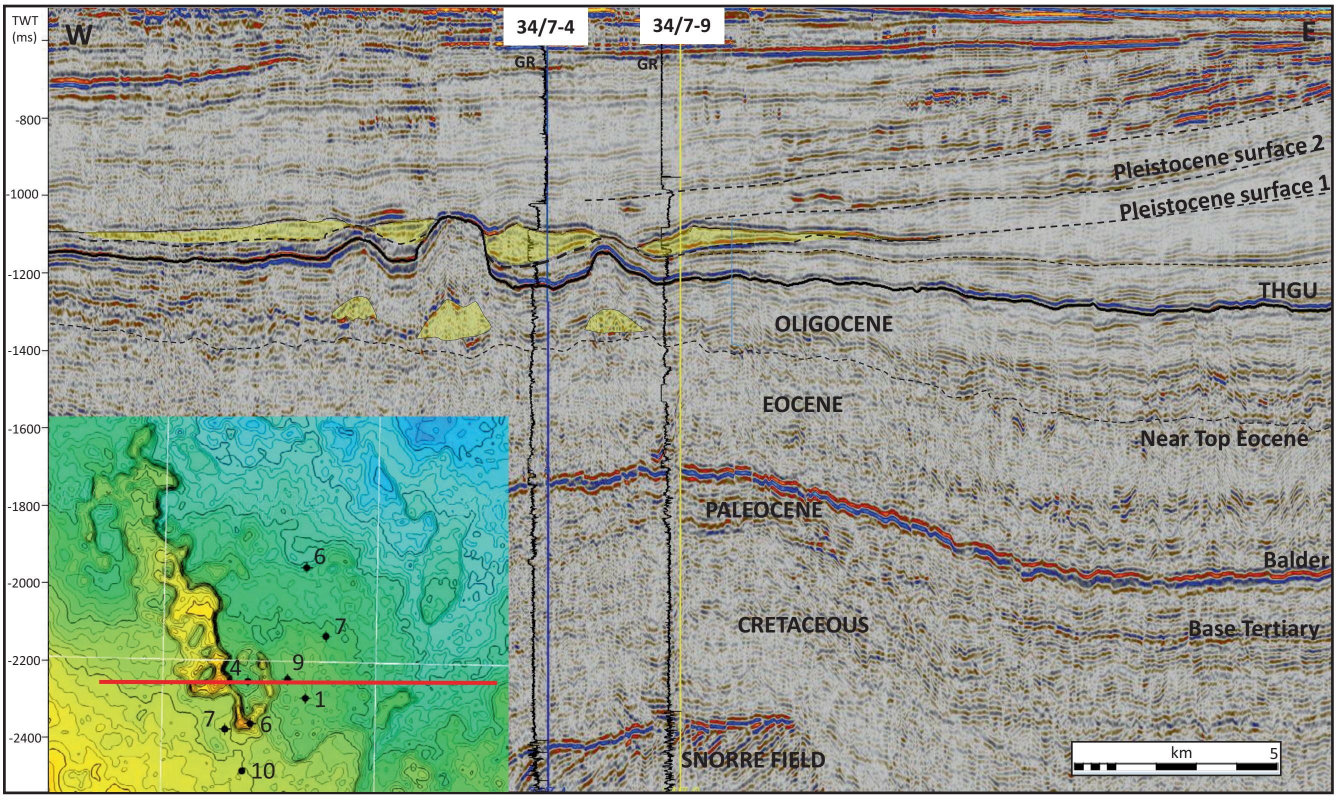

Fig. 4. East–west seismic section through wells 34/7-4 and 34/7-9 illustrating the Cenozoic stratigraphy above the Snorre Field. The Oligocene sands, high-relief mounds at the Top Hordaland Group Unconformity and disrupted Pleistocene sand unit should be noted. Also noteworthy is the local erosional upper surface of the sand (referred to as ditches by Løseth *et al.* 2013) and the relation to the overlying clinoform surface 2. Location of profile is shown on the inset map (10 ms contour interval) of the Top Hordaland Group Unconformity and also in Figure 2.

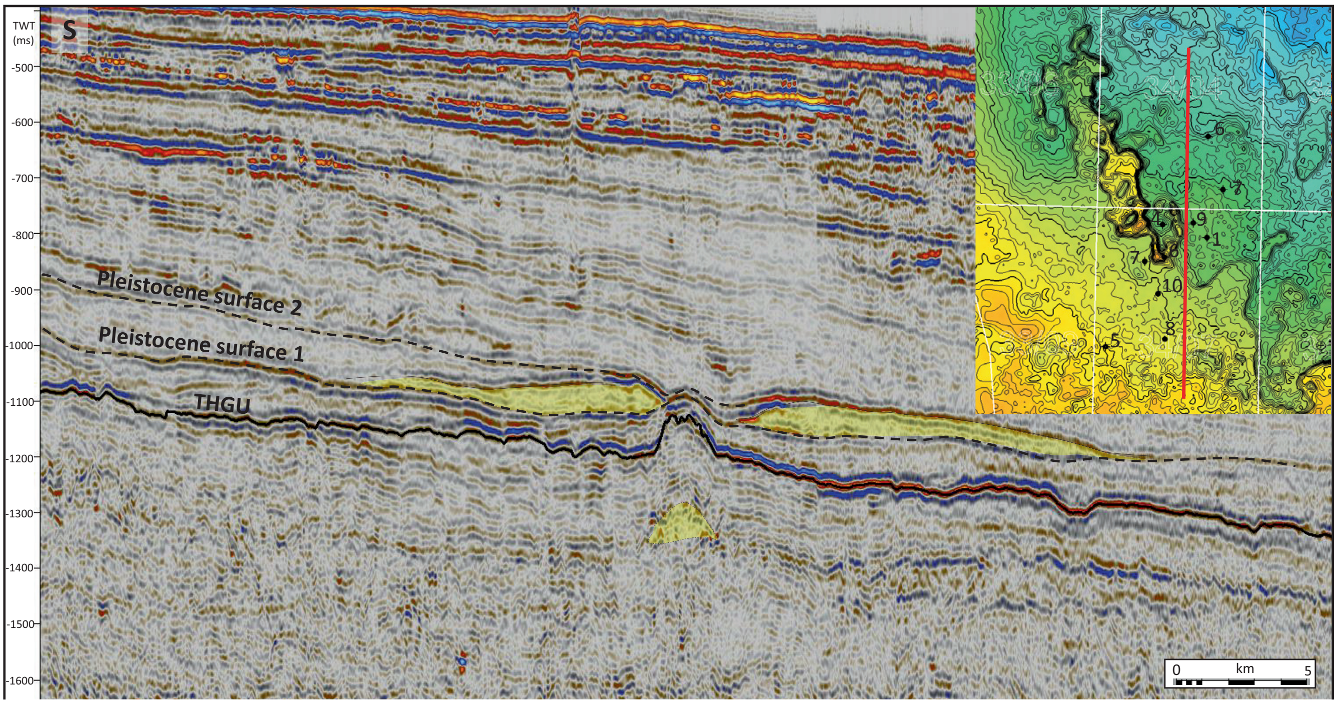

Fig. 5. North–south seismic section illustrating Pleistocene sand unit. Location of profile is shown on the inset map (10 ms contour interval) of the Top Hordaland Group Unconformity and also in Figure 2.

2, Fig. 3). Further to the north, seismically similar sands are present at the toe of younger Pleistocene clinoform foresets. One such sand, which is penetrated in wells 34/2-2 and 34/2-4 (Eidvin & Rundberg 2001; Eidvin *et al.* 2013), extends to the north of 62°N. To the south, wells 34/10-17 and 34/10-23 encountered thick Pleistocene gravity sands belonging to an older Pleistocene prograding unit (Rundberg & Eidvin 2005, fig. 8). Similar sands were also recorded in the basal Pleistocene from the Tordis Field area (Eidvin 2009). The Snorre Pleistocene sand is thus one of many toe-of-foreset sands within the prograding Pleistocene system. It is one of the thickest and most extensive Pleistocene sands found in the northern North Sea.

(3) Sand composition. We have analysed the composition of the Pleistocene sand from ditch cuttings and one sidewall core in three wells from the Snorre area (34/4-7, 34/4-6 and 34/7-1; Fig. 6) and one well further north in the Tampen area (34/2-4). The sand, which Løseth *et al.* (2013) postulate to be extrusive, is found by us to have a rather immature composition with a high abundance of angular quartz grains and angular grains of crystalline rocks (Fig. 7a and b; see also Eidvin & Rundberg 2001; Eidvin *et al.* 2013). Such a grain composition points to mechanical weathering and erosion typical for glacial environments.

Similar immature sand composition is found in well 35/2-1 (Fig. 7c) in the Peon gas reservoir, which was deposited by subglacial rivers during the middle Pleistocene (Carstens 2005; Eidvin 2005), and also in a sidewall core from a Pleistocene sand from well 34/7-2 (Eidvin 2009) situated just north of the Tordis Field (Fig. 7d).

In contrast to the Pleistocene samples, sands from the underlying Hordaland Group are quartz-rich and mature, with a low content of lithic fragments (Rundberg 1991). Figure 7e shows Early Oligocene grains from a sandy unit in well 34/4-6 (Eidvin & Rundberg 2001; Eidvin *et al*. 2013). Most of the grains in this sample are subrounded and subangular. Figure 7f shows high-maturity and well-rounded sand grains from an Eocene sandy unit in well 33/12-5 (NPD 2015).

(4) Ditches and ridges. One of the arguments for an extrusive origin of this sand is the presence of ditches or depressions close to the mounds. Løseth *et al.* (2013) interpret these 'ditches' as blowout fissures from the sand eruption centre. There are two depressions starting from approximately the same position at the southern end of the mounds. Both are located at the eastern side of the mounded features and follow these in a down-dip direction; one is arcuate and the other slightly sinuous. We interpret these depressions as being formed by other local erosional processes, perhaps related to hydrocarbon gas or fluid seepage via the underlying Oligocene sands to the Pleistocene seafloor, combined with north-directed ocean bottom currents. In addition, the depressions appear to be augmented by the overlying lowstand system, which also incises into the top of the sand near the mounds to form ridges (Fig. 4). This younger erosional system becomes more apparent towards the north.

(5) Micropaleontology. Figure 7h shows a flysch-type benthic agglutinated foraminiferal fauna typical of Paleocene–Eocene sediments in the North Sea (King 1989; Gradstein & Bäckström 1996). The foraminiferal fauna is from the same sample as the sand grains in Figure 7f. No such foraminifera are recorded in any of the Pleistocene samples we have investigated, nor have we recorded any Oligocene to Lower Miocene index foraminifera from the Hordaland Group in these samples. On the contrary, in Pleistocene samples we have recorded calcareous benthic and planktonic foraminiferal faunas typical for such sediments, as in the sample from well 34/4-7 (Fig. 7g; Eidvin & Rundberg 2001; Eidvin *et al.* 2013).

The 'intrusive' Oligocene sand

Løseth *et al.* (2013) interpret the Oligocene sands to be injected from a Paleocene parent sand (their figs 2 and 15). They propose that the mounds at the top of the Hordaland Group resulted from forced folding over the sand injectites, as exemplified in their figure 11. The injected sands occur *c.* 180 m below the unconformity. We interpret the Oligocene sands to be *in situ* deposits representing turbiditic gravity sands shed from the Shetland Platform as described by Rundberg & Eidvin (2005). Our arguments are as follows.

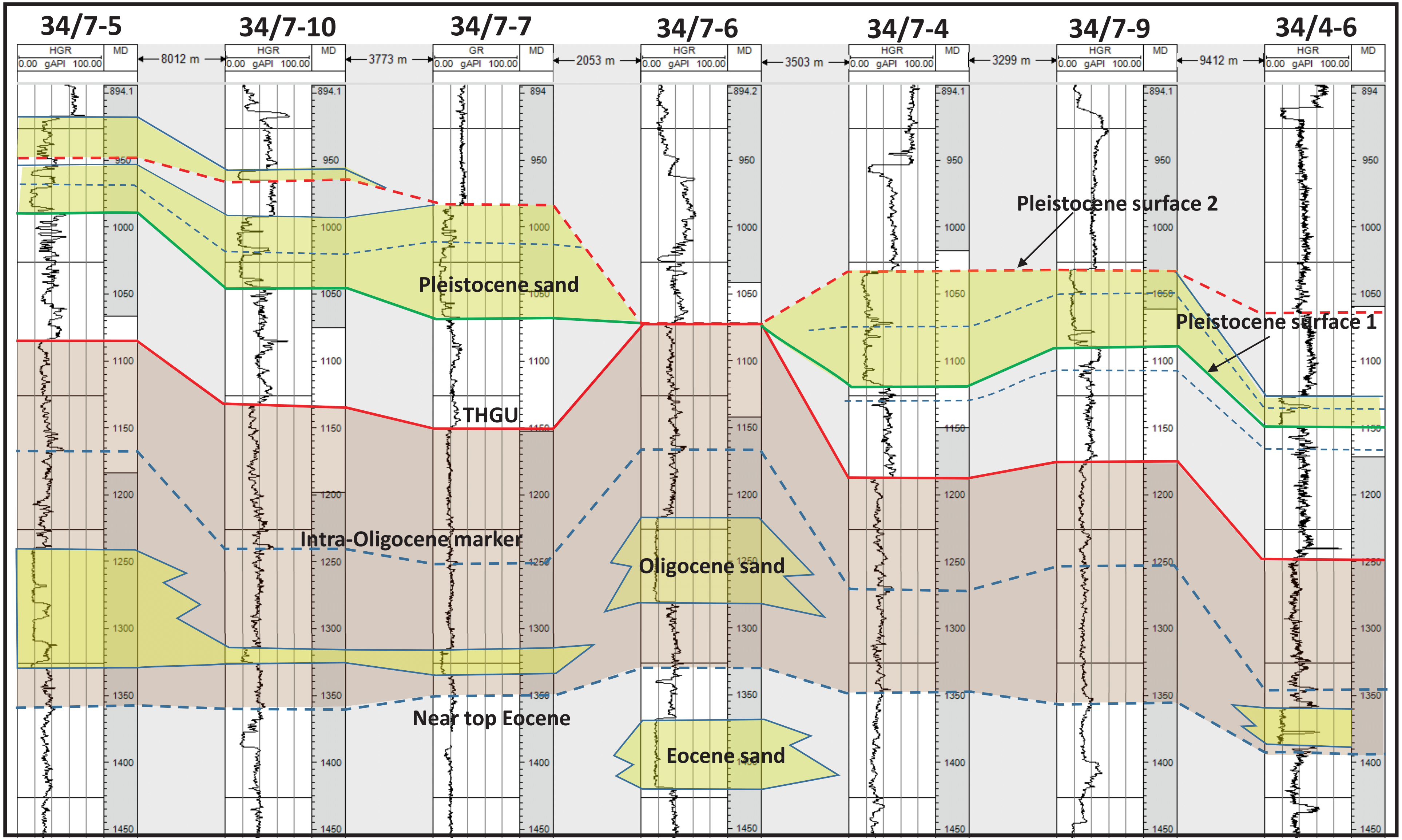

Fig. 6. Log correlation diagram of the Oligocene–Lower Pleistocene section in wells 34/7-5, 34/7-10, 34/7-7, 34/7-6, 34/7-4, 34/7-9 and 34/4-6. Flattened on depth.

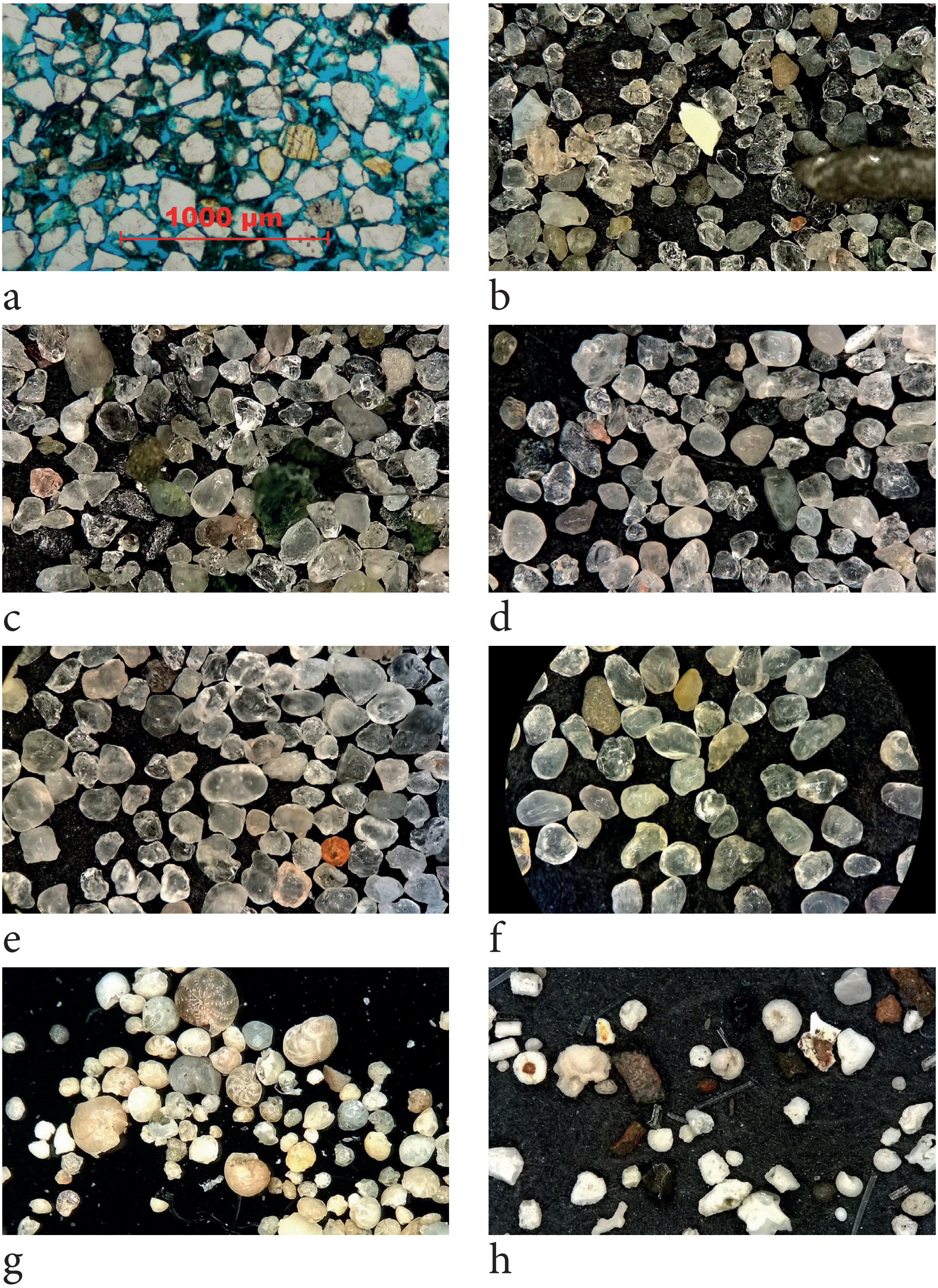

Fig. 7. Photomicrographs of samples from Pleistocene (**a**–**d**, **g**), Oligocene (**e**) and Eocene (**f**, **h**) sands in the northern North Sea. (**a**) Well 34/4-7, 1063 m, thin section from Pleistocene sand, sidewall core (photomicrograph provided by Statoil); (**b**) well 34/7-1, 1040 m, 0.5–0.1 mm fraction of ditch cuttings, Pleistocene sand; (**c**) well 35/2-1, 591 m, 0.5–0.1 mm fraction of ditch cuttings, Pleistocene sand, Peon gas discovery; (**d**) well 34/7-2, 1010 m, 0.5–0.1 mm fraction of a sidewall core, Pleistocene sand; (**e**) well 34/4-6, 1370 m, 0.5–0.1 mm fraction of ditch cuttings, Oligocene sand; (**f**) well 33/12-5, 1368–1362 m, 0.5–0.1 mm fraction of ditch cuttings, Eocene sand; (**g**) well 34/4-7, 1090 m, calcareous foraminiferal fauna picked from the 0.5–0.1 mm fraction of ditch cuttings, Pleistocene sand; (**h**) well 33/12-5, 1368–1362 m, flysch-type agglutinated foraminiferal fauna picked from the 0.5–0.1 mm fraction of ditch cuttings, Eocene sand.

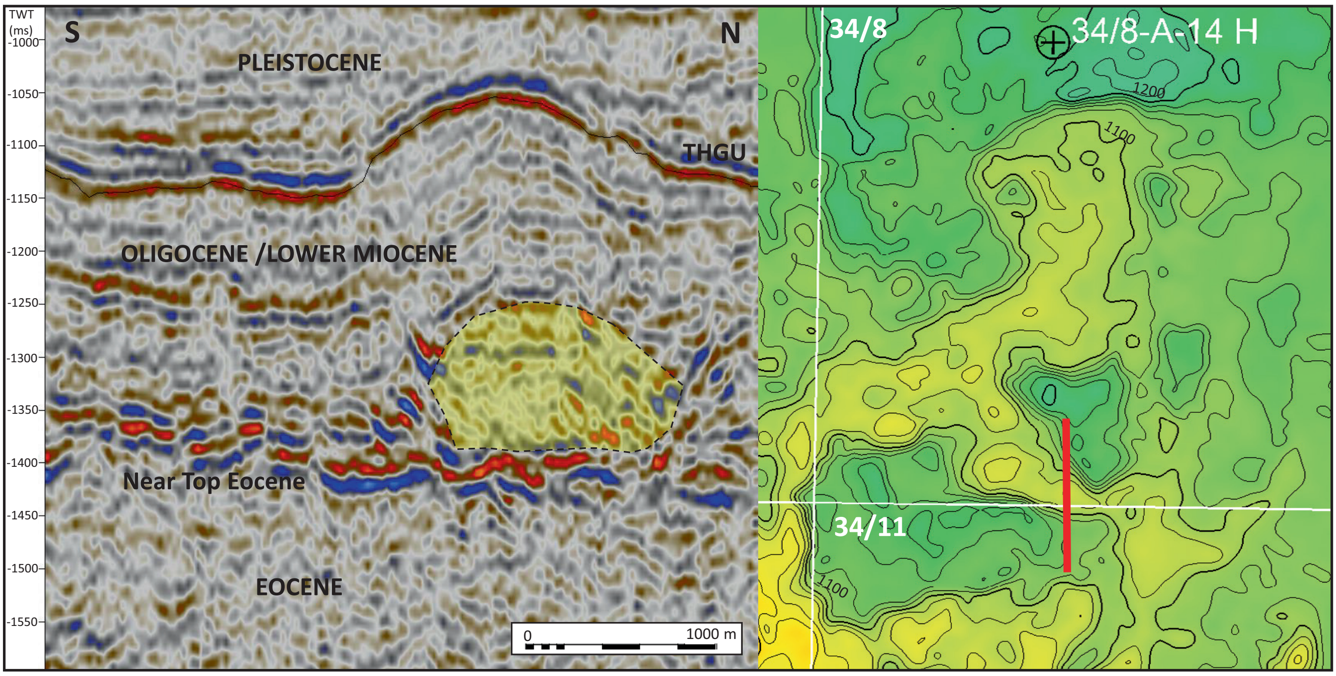

Fig. 8. Seismic section through mound at the Top Hordaland Group Unconformity in the Visund area. Top of Oligocene sand is interpreted at high reflective seismic interval *c*. 180 ms below the unconformity. The wing-like reflections at the margin of the sand should be noted. Map to the right shows mounded pattern at Top Hordaland Group Unconformity and location of line; contour interval 20 ms.

(1) Lack of parent sand. In the model of Løseth *et al.* (2013) the mounded shape of the Top Hordaland Group Unconformity in the Snorre and Visund areas is explained as resulting from a giant intrusive event that uplifted the seafloor. Their interpretation of a parent Paleocene sand that has almost completely disappeared through eruptive processes is hard to justify. In this area there is limited deposition of Paleocene sand (Ahmadi *et al.* 2003), and in all exploration wells drilled in blocks 34/4 and 34/7 Paleocene sands are either thin or largely absent. Although Løseth *et al.* (2013) find support in both experimental modelling (Rodrigues *et al.* 2009) and previous work on possible Eocene injectites in the area (Huuse & Mickelson 2004), their interpretation of the intrusive Oligocene sands underneath the Snorre and Visund mounds appears to lack a credible source for the volumes of sand mobilized.

(2) Mounds mimic underlying channel-belt sands. Our map of the Top Hordaland Group Unconformity (Fig. 1) shows that the mounded relief in the Visund area extends to the SW, towards the UK boundary. The mounded features are finger-like, more or less continuous, and extend in a SW–NE direction from the UK sector towards the Visund area. The pattern of the mounds mimics that of underlying turbiditic channel systems, with major and minor bifurcations. This is particularly seen in the Visund area (southern part of block 34/8), suggesting that the mounds here originate from differential compaction. As shown by Løseth *et al.* (2013, figs 13 and 14) the strongly deviated well 34/8-A-14 H encountered thick sand (145 m vertical thickness) below the Visund mound. A perpendicular cross-section through the southern arm of the Visund mounds (Fig. 8) also shows distinct compaction relief above a highly reflective sandy interval.

(3) Remobilization of Oligocene sands, Visund area. In favour of their model Løseth *et al.* (2013) describe an irregular zigzag pattern at the top of the Oligocene sand (their fig. 8) and claim this to be typical of injected sand bodies. Their seismic example is shown in a longitudinal direction along the sand body. A perpendicular cross-section through the southern arm of the Visund mounds (Fig. 8) shows distinct compaction relief above a highly reflective sandy interval. Locally, at the margin of the mound there are wing-like reflections suggesting remobilization and sand injection. Seismically, it resembles the near age-equivalent (Late Eocene) Alba sand where remobilization and injection are typical (Duranti & Hurst 2004). Although injection processes are indeed present, accompanied by small-scale faulting, the dominant signature of the area is the compaction relief.

(4) Compaction mounds in the Snorre area. Similarly, the mounded relief in the Snorre area to the north also appears to have initiated from differential compaction involving a turbiditic channel-belt system, although the situation here appears to be more complex. For example, the Snorre mounds occur as isolated features and there are no clear feeder channels expressed on the Top Hordaland Group Unconformity surface (Fig. 1). The mounds show a consistent pattern that has many of the characteristic features of underlying submarine channel-belt systems; all along the mounded system there are clear indications of sinuosity, which is typical in submarine slope and basin settings (e.g. Mayall *et al.* 2006) and suggests the presence of meandering channel sands. The width of the mounded system is of the order of 2–4 km and the length is 26 km (not 10 km as reported by Løseth *et al.* 2013). The mounds define a continuous feature with heights of up to 100 m. At the southern end of the mounded system there is a branch that can be interpreted as channel bifurcation.

(5) Well data. No cores or sidewall cores have been taken in the Oligocene sands. In well 34/7-A-14 H (Visund area), the 145 m thick sand displays a blocky gamma-ray (GR) log pattern with no interbedding of fine-grained sediments. Similarly, in well 34/7-6 (Snorre area), a 60 m thick sand displaying a blocky GR log profile is penetrated *c*. 150 m below the Top Hordaland Group Unconformity. In the well completion report (NPD 2015), this latter sand is described from ditch cuttings as medium grained and well sorted. This does not support a common source for the Oligocene and Pleistocene sands implicit in the papers by Løseth *et al.* (2012, 2013).

(6) Microfossil content. The foraminiferal fauna in a lower Oligocene sand in well 34/4-6 (1370–1390 m measured depth (MD)) consists of a sparse calcareous benthic foraminiferal fauna including Oligocene index fossils. The assemblage also contains

long-range Paleogene diatoms and radiolaria. There is no evidence of the flysch-type agglutinating benthic fauna typical of the Eocene and Paleocene deposits.

(7) Further comments on deposition and source area. We interpret the Oligocene sands to be *in situ* deposits, belonging to the sandy system that was sourced from the uplifted Shetland Platform during the Early Oligocene (Rundberg & Eidvin 2005). The approximate outline of this sandy system is shown by Rundberg & Eidvin (2005, fig. 7a), being mainly deposited between 60°30'N and 61°30'N. This sandy system represents the first of three sandy phases that are associated with the Oligocene–Miocene compressional tectonic phase (Rundberg & Eidvin 2005). These sands are unnamed in the current Cenozoic stratigraphic framework (Isaksen & Tonstad 1989), but have recently been proposed as the Ull Formation (Eidvin *et al.* 2013).

The mounded shape of the Top Hordaland Group Unconformity

Løseth *et al.* propose that a giant intrusive event during the Gelasian stage uplifted the seafloor and caused mounding of the Top Hordaland Group Unconformity. In our view, the mounds in the study area are a result of prolonged and complex processes that initiated from differential compaction of Oligocene channel-belt sands. In the Visund area and southwestwards (blocks 34/10 and 34/12; Fig. 1), the compaction relief (below the Top Hordaland Group Unconformity) comprises Oligocene and Lower Miocene strata. Locally, Lower Miocene strata are erosionally truncated by the Top Hordaland Group Unconformity. Above the unconformity, the oldest sediments (thought to be thin Utsira Formation sands) fill in depressions and onlap the mounds, whereas younger Pleistocene strata, inferred as deep-water deposits, drape the mounds, thus forming part of the compaction relief. Consequently, the mounds already existed when the Utsira sands were deposited. During the Late Miocene the relative height of the mounds therefore progressively increased owing to the effect of loading-induced differential compaction.

In the Snorre area, Utsira sands are absent, except for a glauconitic layer (Eidvin & Rundberg 2001). Here the oldest Pleistocene unit forms a drape over the smaller mounds (Fig. 4), and is apparently eroded around the central (main) Snorre mounds. The main Snorre mounds commonly display an asymmetric profile with steeper eastern than western slopes. Locally, and commonly at the highest elevations, gas chimneys, associated with chaotic seismic reflections, are present. It is likely that the mounds are affected by a high degree of carbonate cementation caused by hydrocarbon fluid seepage from Jurassic reservoirs and source rocks, via fault zones predominantly developed along the eastern channel-system margin, to the paleoseafloor. The steepness of the eastern slope could indicate the presence of carbonate structures (or pipes) that have stabilized the mound. Such structures have been identified above the Frigg Gamma discovery, further to the south (Rykkelid & Rundberg 2014).

During a long period of submarine exposure the height of the mounds was probably enhanced by a combination of erosional current activity, the influence of carbonate cementation processes and differential compaction. The mounded interval may also have undergone soft-sedimentary deformation as a result of faulting, the effects of degassing and probably some sand injection activity above the Oligocene sand body.

In their paper, Løseth *et al.* (2013) also discuss the hiatus in the northern North Sea and argue that the entire northern North Sea was subaerially exposed for a 10 myr period during the mid- to late Miocene. They present only vague evidence for this statement and no further outline of the exposed area, although it was schematically presented in an earlier publication (Løseth & Henriksen 2005). This question was discussed in the synthesis of Rundberg & Eidvin (2005), who concluded that there are a number of features that indicate a shallowing of the basin during the late Oligocene–Miocene, but there is no clear evidence of subaerial exposure. Biostratigraphical investigations of the basal Naust Formation equivalent and top underlying Utsira Formation in a number of wells from the Snorre, Visund and Tordis fields in the Tampen area show no evidence of subaerial exposure or shallow marine deposits at the basal Naust equivalent–Utsira Formation boundary or at the basal Naust equivalent–Hordaland Group boundary (Eidvin & Rundberg 2001; Eidvin 2009; Eidvin *et al.* 2013).

In the central area of the northern North Sea, which Løseth *et al.* (2013) claim was subaerially exposed, middle Miocene marine mudstones and Late Miocene shelf sands (Utsira Formation) are present (Eidvin & Rundberg 2007). More complete Neogene strata are preserved on the western basin margin at about 60°N (Eidvin *et al.* 2013; profile 6) and on the eastern basin margin at about 62°N (Rundberg & Eidvin 2005, fig. 18). Biostratigraphical investigations of a number of wells from the southern Viking Graben, Central Graben, Ringkøbing–Fyn High area and North German Basin show that planktonic deep-sea forms, which have their origin in the North Atlantic and the Norwegian Sea, have been brought by ocean currents through an open strait in the northern North Sea (the only seaway passage into the North Sea Basin during the Miocene) and into the central North Sea during the entire Serravallian, Tortonian and Messinian (about 14.5–4.5 Ma; Laursen & Kristoffersen 1999; Eidvin *et al.* 2013).

The paleogeographical interpretation of Løseth *et al.* (2013) is thus in conflict with our mapping. The interpretation of escarpments on the Top Hordaland Group Unconformity as representing coastal erosion similar to that of present-day southeastern England is highly questionable. We believe that these erosional escarpments were formed by vigorous current erosion during the late Miocene, at the outlet of the North Sea strait where strong currents operated and where the Utsira sands were deposited. Our model of late Miocene paleogeography, with the creation of a shallow seaway along the northern North Sea (the ‘Viking Strait’ of Galloway 2002), is presented elsewhere (Rundberg & Eidvin 2005).

In conclusion, we believe that the model of late Cenozoic evolution of the northern North Sea as presented by Løseth *et al.* (2013) is inconsistent with the geological data. The paleogeographical interpretations are in conflict with our observations and mapping, and we believe that the postulated ‘extrusive sand’ is better interpreted as turbiditic sand within the giant Pleistocene progradational system. In addition, we believe that there are other mechanisms (e.g. differential compaction) that can better explain the mounded shape of the Top Hordaland Group Unconformity than the intrusive sand model presented by Løseth *et al.* (2013).

Acknowledgements and Funding

We acknowledge reviewers T. Bugge and P. Haughton for constructive comments that greatly improved the initial draft of the paper. We thank J. Mouatt, R. Eastgate and E. Rykkelid (Svenska) and F. Riis (NPD) for valuable comments, R. Goa and T. Tjelta Hansen (NPD) for technical support, P. Taylor (Draftoil) for drafting assistance and R. Williams (NPD) for help with photomicrographic images.

Scientific editing by Quentin Crowley

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