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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In their recent paper, Loseth *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 Loseth *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 Loseth *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 diaches, 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), Loseth *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, Loseth *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 10myr Miocene time span.

Loseth *et al.* (2012, 2013) not only challenge our previous tectonic–sedimentologic 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 Loseth *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 Loseth *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 Loseth *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 (10km³) 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. Loseth *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 Loseth *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 10km 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 Loseth *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.
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.

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).

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 blow-out 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.

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.
Discussion

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 Loseth 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 erosive 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 Loseth et al. (2013) find support in both experimental modelling (Rodrigues et al. 2009) and previous work on possible Eocene injections 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 Loseth 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 Loseth 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 Loseth 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 Loseth 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’S and 61°30’S. This sandy system represents the first three of sandy phases that are associated with the Oligocene—Miocene compresional 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 mound ed 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 (Rykkveld & 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 mound ed 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 shallowening of the basin during the late Oligocene—Miocene, but there is no clear evidence of subaerial exposure. Biostratigraphical investigations of the shallow basin and 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 basin equivalent—Utsira Formation boundary or at the basin 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 placktonic 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 sea-way 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 turbidite 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).

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Knowledge of small sand injection is far from new (Murchison 1827; Hurst et al. 2011) but that intrusive and extrusive bodies of sand can be more than 100 m thick and extend for kilometres is considered unlikely by Rundberg & Eidvin (2015), who discuss our paper (Løseth et al. 2013). Their discussion disagrees with our interpretation of the origin of these sand bodies and instead favours their previously proposed models (Eidvin & Rundberg 2001; Rundberg & Eidvin 2005). They claim that (1) the early Pleistocene sandstones are turbiditic sands deposited at the toe of the glaciomarine shelf clinoform foresets and not extrusive sands; (2) the Oligocene sandstones, located below mounds at the top Hordaland Group Unconformity, are in situ deposits representing turbiditic gravity sands shed from the Shetland Platform and not intrusive sands; and (3) the top Hordaland Group Unconformity in the northern North Sea was formed by submarine erosion and not during subaerial exposure. We have studied rock properties of Eocene to Pleistocene claystones and sandstones (Øygarden et al. 2015), carried out detailed seismic and well studies in the North Sea (Løseth et al. 2003, 2012, 2013), studied the physical processes of injection, extrusion and depletion of sand in analogue experiments (Rodrigues et al. 2009), and studied outcrops of intrusive sandstones through sand injection research consortia (e.g. Hurst et al. 2006, 2011; Vigorito et al. 2008; Cartwright 2010; Scott et al. 2012). Our seismic and well observations above the Snorre and Visund fields were in conflict with existing geological models and therefore we proposed new models. This reply builds on knowledge of how the seismic expression of sandstone varies with the type of embedding claystone. Øygarden et al. (2015) showed that the top of a brine-saturated sandstone corresponds to a soft kick (downwards decrease in acoustic impedance) in glaciomarine claystones, a hard kick in low-density but stiff Lower Miocene and Upper Oligocene ooze-rich claystones, and close to zero amplitude reflection in Eocene and Lower Oligocene smectite-rich clays. These seismic interpretation rules must be obeyed except where pore content and/or cement locally change the rock properties of the sandstone. Below we answer the claims of Rundberg & Eidvin (2015).

Extrusive or toe of slope sand

The arguments why the sand is extrusive have been given by Løseth et al. (2012) and are not repeated here. Rundberg & Eidvin (2015) claim (1) states that we do not present data on the location of the Pleistocene sandstone but Løseth et al. (2012) showed both in writing and their figure DRIE that the sandstones are located at the toe of the 500 m high shelf clinoforms. We also document well ties, time thickness and distribution of the sandstone around the mounds, so none of the observations in their discussion are new to us. Rundberg & Eidvin (2015) also state that it is difficult to explain how the 15 m thick sandstone in Well 34/7-8 can be located at a depth 100 m shallower than the blow-out fissures 10 km to the north. This area was tilted regionally 0.3° to the north after the sand was deposited. Thus, the elevation is reduced to 50 m at the time of blow-out. Such a height is no more than that from the base to the rim of the interpreted blow-out craters (Løseth et al. 2012, figs 1B, 2 and DR1D). An additional point, not mentioned in our previous papers, is that warm water erupting into higher density cold arctic water will form an upward directed current in the more than 500 m deep sea. Sand grains already in the water column may be further elevated by such currents before being deposited from lateral gravity currents as suggested by Ross et al. (2011).

Their argument (2) is that several other sandstones exist at the toe of the slope in the North Sea and that they therefore have to be deposited by gravity flows. Løseth et al. (2013, fig. 13) documented that sandstones exist in the lower part of the Pleistocene succession above both the Snorre and Visund fields and we are aware of sandstones in similar positions above the Gullfaks Field and along the flanks of a mound in the Tordis Field (Well 34/7-2). We interpret these sandstones to be extrusive. The toe of the prograding clinoforms is the preferred position for sands erupting to the seafloor (Fig. 1). The situation in the North Sea at the time of sand eruption is one of prograding glaciomarine sediments with very high sedimentation rates. Nygård et al. (2007) reported glacial sedimentation rates up to 80–100 m ka⁻¹ from the North Sea, which also are significantly higher than the high rates (12 m ka⁻¹) at Site U1324, south of the Mississippi River, Gulf of Mexico (Flemings et al. 2008). Here, rapid differential loading causes fluid pressure build-up and lateral fluid flow in sands below the mudstones (Flemings et al. 2008). Hjelstuen et al. (1997) discussed a similar process in the Norwegian Sea. We therefore expect build-up of fluid pressure in sands below or within the very low permeability smectite-rich Hordaland Group clays (Mondol et al. 2008; Marcussen et al. 2009). The fluid pressure within the parent sand may first exceed lithostatic pressure at the toe of the slope, where the lithostatic pressure is lowest owing to the thin overburden. Hydraulic fractures, initiating in the overpressured parent sand, will fracture the overburden and the fractures will finally reach the seafloor. The large volume of extrusive sand (10 km³), which
Rundberg & Eidvin (2015) claim is unrealistic, can erupt where the volume of available parent sand is large and the pressure generation mechanism can support fluid flow over sufficient time to transport such sand volumes to the surface. The North Sea was in an ideal place for fluidization, intrusion and extrusion of sand during short periods of the Quaternary.

Rundberg & Eidvin (2015) point (3) is that the extrusive sand cannot come from the sands in the Hordaland Group because both the composition and maturity are different. We do not agree. Sand analyses from cores from Well 34/8-A-14 H and thin-section analyses from Well 34/7-18 (see below) show large ranges in both maturity and composition. The extrusive sand was also deposited during a period of high background sedimentation of glaciomarine sediments that would mix into the sands. We expect the content of background sediments in the sand to be small close to the blow-out position and to gradually increase with increasing distance until they are the dominant sediments. Well 34/4-7 is located 5 km to the NE of the closest blow-out fissure and background sediments are interpreted to have mixed with the extrusive sand (Løseth et al. 2012, fig. 3; Rundberg & Eidvin 2015, fig. 7a). Apart from that we see no significant composition or maturity difference between the extrusive sand analysed in Well 34/4-7 and those in the underlying Hordaland Group.

Rundberg & Eidvin (2015) point (4) is an alternative interpretation of the ditches and ridges of our blow-out fissures for sand. They 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 sea floor, 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.’ They use a combination of three separate and co-occurring processes to explain the observations, but still their model does not explain the interpreted sand feeder dykes going from the intrusive sand body up to the base of the ditch (Løseth et al. 2012, fig. DR1C).

Regarding their comment (5) that there is no evidence of the flysch-type agglutinating benthic fauna typical of the Eocene and Paleocene deposits, to our knowledge such sands typically hold small volumes of fossils and therefore this result is expected.

**Intrusive or in situ turbiditic gravity sand**

On normal polarity seismic data, both top and base of sandstones embedded in Upper Oligocene ooze-rich claystones are well expressed as relatively high-amplitude peak and trough reflections, respectively (Løseth et al. 2012, fig. DR1B and C; Løseth et al. 2013, figs 7a, 8a and 11b). However, the reflections are not always continuous where crosscutting various layers and where dips are high (e.g. Øygarden et al. 2015, fig. 6). Intrusive sands typically cut stratigraphic layers whereas depositional sands follow layering (Cartwright et al. 2008). The main reason why we do not interpret the sandstones as in situ deposits representing turbidite gravity sands (Rundberg & Eidvin 2005) but as intrusive is that they crosscut the reflections from the layered host rocks (Løseth et al. 2012, fig. DR1B; Løseth et al. 2013, fig. 7a). Rundberg & Eidvin (2015) claim (1) states that the lack of Paleocene parent sand is an argument against our intrusive model. We agree that the parent sand for the Oligocene intrusive sand is not proven. Only carbonate-cemented sands are visible in the smectite-rich Hordaland Group whereas most sandstones, including deposits and depositional sands, are not visible on conventional P-wave seismic data (Øygarden et al. 2015). The reasons for suggesting Paleocene and/or Eocene deep marine sands as the source for the Oligocene sands are as follows.

(a) The base of underlying cone-shaped sand injectites, visible owing to carbonate cement as ‘V-brights’ on seismic sections, is
located immediately above the top Balder Formation and in the Lower Eocene Hordaland Group (Hause & Mickelson 2004, figs 4 and 8; Løseth et al. 2013, fig. 12). The parent sand of these injections is below the cones; that is, Paleocene and Lower Eocene.

(b) The northern termination of these ‘V-brights’ coincides with the northern extent of the distinct mounds at the top Hordaland Group Unconformity in the Visund area.

(c) Experiments show that sand layers can deplete to a weld (Rodrigues et al. 2009, fig. 13) and the massive intrusive and extrusive sandstones in the study area must come from heavily depleted parent sand(s). Wells show irregular distributions of thin Paleocene sandstones in this area (Ahmadi et al. 2003), as experiments predict for a heavily depleted parent sand.

Rundberg & Eidvin (2015) claims (2) and (3) state that the mounds at the top Hordaland Group Unconformity are ‘distinct compaction relief’ above ‘turbiditic channel systems, with major and minor bifurcations’. The top and base of sandstone embedded in the Oligocene ooze-rich claystones are imaged on seismic data but internal reflections normally do not exist owing to the homogeneous sandstone displaying a typical blocky gamma-ray pattern (Løseth et al. 2013, figs 13 and 14). Rundberg & Eidvin (2015, figs 3, 4 and 8) must interpret the top and base sandstone reflections instead of simply indicating a yellow zone that does not follow any reflection in order to show where their claimed sand channels are located. Figure 5 of Løseth et al. (2013) shows that the mounds are linear in several directions above the Gullfaks Field, and are irregular but mainly connected above the Visund Field but totally isolated above the Snorre Field. All these mounds have underlying sandstones with zigzag-like tops and bases that cut reflections from layered host rock claystones, and for these reasons we interpret them as intrusive in origin. It has not been possible to prove whether some or all of these sandstone bodies have Paleocene–Lower Eocene or shallower Eocene–Lower Oligocene parent sands, because such sandstones are not visible on seismic data.

Rundberg & Eidvin (2015) claims (3) and (4) state that the mounds are the result of differential compaction, implying that the claystone along the flanks is more compacted than the sands in the mounds. Øygarden et al. (2015) showed that the suggested compacted claystone is rich in low-density silica ooze (around 1.8 g cm−3), and is characterized by a stiff framework and a neutron porosity of 66%. Assuming no compaction of the sand and 150 m compaction of a 300 m thick clay, which is required to obtain the observed 150 m relief, the pre-compaction porosity of the oozey claystone was 84%, which is too high a porosity for a claystone buried to 150 m (Mondol et al. 2007). Fifty per cent differential compaction of the claystone above the mounds should appear as thinning of intra-clay layering towards the mounds. We do not observe this, but instead note identical thickness of the oozy claystone above and on the flank of the mounds (Løseth et al. 2013, figs 7, 8, 11, 12 and 13). Restoring a seismic section to a pre-injection situation by removing the sand gives a layered succession with nearly parallel but polygonally faulted reflections both above and below the sand (Løseth et al. 2013, figs 7b and 13b). We therefore maintain that the sandstones in the upper Oligocene succession in the northern North Sea are of intrusive origin.

Rundberg & Eidvin (2015) claim (5) states that ‘No cores or sidewall cores have been taken in the Oligocene sands.’ This is not correct because Core 2 (1409–1427 m MD RKB) in Well 34/8-A-14 H drilled Oligocene sands (70% recovery). The Oligocene sandstone (porosity 34–35%), comprises mainly quartz (90%) and minor feldspar, illite–mica, chlorite, smectite, calcite, pyrite and amorphous material. The sandstone consists of clear to occasionally milky white quartz, occasionally yellowish brown, partly orange, translucent, very fine to medium grained, from subangular or angular to subrounded or rounded, medium sorted and glassy, and contains traces of glauconite. Thin-section analysis of a sandstone from the upper Hordaland Group in Well 34/7-18 (1239 m MD RKB) proves it to contain only 65% quartz. The sand resembles Palaeogene sands in the northern part of the North Sea. For instance, it contains the heavy mineral staurolite and quartz grains with red–brown dust rims and abraded quartz overgrowths inherited from older quartz-cemented sandstones (O. Walderhaug, pers comm.). Rundberg & Eidvin (2015) claim that this sandstone cannot have the same source as the extrusive Pleistocene sandstone. We do not understand this assertion, as their maturity and composition are comparable. Their micropalaeontological point (6) is discussed above.

The mounded shape of the top Hordaland Group Unconformity

Rundberg & Eidvin (2015) discuss the mounded shape of the top Hordaland Group Unconformity in a separate point. Our reply is mainly given above but they also claim that ‘the mounds already existed when the Utsira sands were deposited’ and that the Utsira sands ‘fill in depressions and onlap the mounds’. Above the Visund and Snorre fields the glauconitic Utsira Formation sand is around 50 m and 15 m, respectively (Eidvin & Rundberg 2001, fig. 4). The top of the glauconitic sand has no acoustic contrast (Øygarden et al. 2015) and we therefore do not understand how Rundberg & Eidvin (2015) can observe the infill around the mounds on seismic data. Significant erosional topography was present on the top Hordaland Group Unconformity before the glauconitic sand was deposited (Løseth et al. 2013, fig. 8a, green arrow). Reconstructing to a pre-mound situation by flattening on an intra-Hordaland Group horizon shows that significant erosion topography also existed above some of the mounds (Løseth et al. 2013, fig. 8b). This limits their suggested compaction period above the Visund Field to after the formation of the erosion unconformity and before the deposition of the Pleistocene sediments. Above the Snorre Field the lowest Pleistocene sediments, above the glauconitic sand, are force-folded by the mounds (Løseth et al. 2013, fig. 11b) and this limits the mounding to a short period during the Pleistocene before the pregrading shelf clinoform of the Naust Formation covered the area. We consider instant compaction during such a short time window highly unlikely.

Above the Snorre Field, Rundberg & Eidvin (2015) claim the presence of both gas chimneys and carbonate cementation but this is not supported by any documentation. Rundberg & Eidvin (2015) claim to use the same 3D dataset as Løseth et al. (2013) but the quality of their seismic figures appears noisier and with lower continuity. We have observed neither gas chimneys nor bright peak reflection anomalies related to carbonate cement.

Hiatus and subaerial exposure

The final claim of Rundberg & Eidvin (2015) is a discussion on whether the erosion at the top Hordaland Group Unconformity was formed sub-aequously by sea currents (Rundberg & Eidvin 2005) or subaerially as suggested by Løseth et al. (2013). A sediment record for a minimum of 10 myr is missing at the top Hordaland Group Unconformity above the Visund Field where the time gap is smallest (Eidvin & Rundberg 2001). Løseth et al. (2013, figs 3–7 and 9) presented the first images of elongated escarpments and isolated outliers with escarpments at the top Hordaland Group Unconformity. Because the escarpments resemble the east coast of England and we have found no publications describing similar submarine erosion shapes, our preferred interpretation is that they were formed by coastal erosion and that the northern North Sea was periodically subaerially exposed. If similar submarine erosion morphology can be proven we would change our interpretation. The 10 myr missing sediment record does not imply that the entire northern North Sea was a continuous land throughout; for example, the low central area between the escarpments was most
probably filled with seawater. Details of when the northern North Sea was a continuous land area and when and where seawater could pass are still open for debate. Further investigations on new high-quality 3D seismic data may give more details of the late Cenozoic geological evolution of the northern North Sea.

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