Glaciotectonic forms and structures on the Norwegian continental shelf: observations, processes and implications

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In the present work two glaciotectonic hill-hole pairs are recognized off Norway at 200 m and 300 m water depths. The structures are argued to be of Late Weichselian age. Displaced volumes are in the order of 1-1.7 km³ and one of the forms has a total length of more than 30 km. In the southwestern Barents Sea an area of possible repeated glaciotectonism is recognized; buried floes of sedimentary rocks and Quaternary sediments may occur in this area. The extensive glaciotectonism may be related to local glaciological conditions or geological conditions favourable for subsurface decollement. Formation and displacement of floes of subglacially consolidated layers resting on softer sediments are theoretically considered. Glaciotectonism has an influence on stratigraphy, morphostratigraphy and geotechnical conditions.

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The purpose of the present paper is threefold: (1) to discuss the genesis of two well-defined, glaciotectonic forms developed on the sea-bed in a deep continental shelf setting offshore Norway and to relate the forms to the glacial history of the respective areas; (2) to illustrate the possible presence of buried glaciotectonic forms by using the structures on the sea-bed as reference examples; and (3) to discuss a model for glaciotectonism particularly related to soft sediment areas typical for much of the Norwegian continental shelf. Some implications of the glaciotectonic forms and processes dealt with in the present paper are also addressed.

Descriptions of glaciotectonic processes and structures in onshore areas are abundant in the literature (Aber 1988). Examples from offshore deep water settings, however, are limited to ice-push influenced moraine ridges (e.g. Bugge et al. 1978; Solheim & Pfirman 1985; Boulton 1986; Solheim in press). Glaciotectonics is probably more common on previously glaciated continental shelves than the scarcity of literature might indicate. The present paper focuses on sea-bed forms in two deep water areas on the Norwegian continental shelf (Fig. 1), interpreted here as glaciotectonic hill-hole pairs (Bluemle 1970; Clayton & Moran 1974). The forms are recognized on bathymetric maps and shallow seismic profiles. The maps are constructed by IKU (Continental Shelf and Petroleum Technology Research Institute) based on soundings by the Hydrographic Office of Norway. The shallow seismic data are part of IKU’s regional seismic grid (Rise 1983, 1988).

Hill-hole pairs

A hill-hole pair (Bluemle 1970; Clayton & Moran 1974) is a distinctive glaciotectonic landform association which consists of a discrete hill of ice-shoved material (Quaternary sediment or consolidated pre-Quaternary sedimentary rocks) located immediately downglacier from a source depression. The hill and hole display similar morphology in terms of area, shape and volume. Typical dimensions of hills and associated holes are 1 km² to 100 km² and structural relief of 30 m to 200 m (Aber et al. 1989). According to Clayton
& Moran (1974) hill-hole pairs are formed subglacially in a zone near the glacier terminus where the ice was frozen to its bed. Their opinion of a subglacial formation of these structures is shared by several authors while, as reviewed by Aber (1982), others believe in a proglacial origin. The present work includes one proglacial example and one example that may have been formed in either of the two situations, but which has been later overrun by ice.

The ‘Horseshoe’

On the easternmost part of Trænabanken (Fig. 1), an arcuate hill informally named the ‘Horseshoe’ by King et al. (1987) rises about 100 m above the surrounding, smooth sea-floor, which is 300 m deep and dips gently eastwards (Fig. 2). The hill rests on Quaternary sediments which vary between less than 100 m to more than 175 m in thickness (King et al. 1987; Rise et al. 1988). It has a volume (above an assumed base following the regional bathymetric trend) of about 1 km³ and it covers an area of about 20 km². The hill is up to 2.5 km across and following its curvature it is about 15 km long. The front of the ‘Horseshoe’ points towards WNW (approx. 335°). Maximum average slope of the western hill front (from crest to base) is measured on the depth contours as approximately 12°, but may locally be steeper, and the dips measured on depth contours probably represent minimum values. The eastern slope of the hill is measured as 16° (corrected for slope strike) on sparker line B79–104 (Fig. 3). One 2.7 m long vibrocorer sample from the top of the ‘Horseshoe’ revealed a sediment interpreted as a till. The till is a dark grey, very sandy, silty, slightly gravelly clay, with undrained shear strength varying from about 10 kN/m² to about 90 kN/m². It is overlain by about 0.75 m of soft glaciomarine sediments and less than 5 cm superficial sand (unpubl. IKU data).

A depression partly surrounded by the ‘Horseshoe’ covers an area of about 35 km². Its volume is measured as approximately 0.7 km³ (volume between the sea-floor of the depression and an assumed pre-existing surface following the general bathymetric trend). Shallow seismic sections (Fig. 3) and side-scan sonograms reveal a rough morphology both on the hill and at the base of the depression. This indicates a thin cover of soft sediments. King et al. (1987) mapped a limited occurrence of glaciomarine/marine clay on the ‘Horseshoe’ and within the depression.

Steinbitryggen–Sopphola

On western Fugløybanken (Fig. 1) a hill complex rises 90 m above the surrounding sea-bed, which is 210 m below present sea level and dips gently westwards (Fig. 4). The hill is bounded to the southeast by a closed depression which reaches down to a water depth of more than 290 m. Among fishermen the hill is known as Steinbitryggen, and the depression is known as Sopphola. These names are informally used here. Steinbitryggen covers an area of about 58 km² and has a volume of about 1.6 km³. The hill has rather irregular slopes, which in places have dips of up to 16°. The depression, Sopphola, covers about 56 km² and has a volume of about 1.7 km³. Its central part consists of three smaller basins with flanks dipping in excess of 8° measured on the depth contours. The larger part of Steinbitryggen has an ‘arrowhead’ shape in plan view pointing towards the NW. At the tip of the ‘arrowhead’
The "Horseshoe" depression is found to be comparable to the volume of the hole and is interpreted to have been formed by a glacier front pushing sediments from the hole area into the observed ridge form. The inferred ice flow (towards NNW) compares well with the trend of linear ridges on the sea-bed (Lien 1983). Profile sections shown in Fig. 3 are indicated.

The hill axis turns towards the west. The hill then becomes lower but can still be traced for another 24 km (Fig. 4). The thickness of Quaternary sediments in the area is rather uncertain, but possibly exceeds 250–300 m. Sediment samples are not available from Steinbitryggen, but samples from the region typically comprise rather fine-grained glacigenic diamicton. The Tromsøflaket diamicton (Vorren et al. 1978) is sampled at several locations not far from Steinbitryggen and has a typical clay content of >18% and a sand content of <45%. This may be representative also for Steinbitryggen.

**Interpretation and comparison of the hill-hole pairs**

Both the sea-bed form associations described above are interpreted herein as glaciological hill-hole pairs (Bluemle 1970; Clayton & Moran 1974). This is to the author's knowledge the first recognition of such structures on a deep continental shelf setting.

The bathymetric depression associated with 'Horseshoe' has a moderate overdeepening (a maximum of approx. 20 m), although the infilling of soft sediment is less than a few metres. The
excavation of the depression seems to have cut progressively deeper into the subsurface towards the northwest, and then terminated abruptly. The steep distal side of the 'Horseshoe' and its abrupt northwestern boundary towards a smooth seafloor (Figs. 2, 3) would probably not have been preserved if ice had advanced across the 'Horseshoe' once it was formed. I therefore suggest that the structure was formed at the front of the last ice advancing to this point. Limbs of the 'Horseshoe' extend up-ice along the flanks of the source depression. Similar forms in Schleswig-Holstein are interpreted to have been created on the flanks of glacier tongues advancing in a fashion termed 'blockbewegung' (Stephan 1985). The 'Horseshoe' was probably formed in a similar way during the advance of a glacier tongue only a few kilometres wide in the front. The main body of the 'Horseshoe' was pushed at the snout of the ice tongue, while the parallel up-ice limbs could have been formed by combination of lateral squeeze up along the flanks of the tongue and escape around the corners of the advancing, bulldozing tongue front (cf. Sugden & John 1976, pp. 219 and 252). Moderate undrained shear strength (10 kN/m² - 90 kN/m²) was measured on the
Fig. 4. Local bathymetry of the Steinbitryggen–Sopphola area. The hill Steinbitryggen is interpreted to consist of sediments glaciotectonically displaced from the bathymetric depression Sopphola. The volume of Sopphola is subequal to that of the ridge, which is partly shaped into a westerly trending streamlined form. Possible bathymetric expression of boundaries between individual thrust masses is shown. Isolated depressions and a possible remnant of a glaciotectonic hill associated with the depression southwest of Sopphola are also indicated.

Isolated depressions within Sopphola are bounded by escarpments in all directions (Fig. 4). This probably indicates that material was removed as more or less intact bodies that were lifted from the depressions and stacked together to form Steinbitryggen. The local topography on Steinbitryggen may indicate that the hill is composed of several stacked bodies bounded by thrust planes (Fig. 4). This suggests that the material in Steinbitryggen was of greater shear strength than the material in the ‘Horseshoe’. The stratigraphy of the displaced sediment (see below) suggests that it was overconsolidated and hence had a high shear strength when the structure was formed. A frozen state of the sediment would therefore possibly not be a necessary prerequisite for partly en masse displacement.

The westward termination of Steinbitryggen on Fugløybanken takes the form of an elongated, streamlined tail. I infer that the western, narrow part of this hill is the result of subglacial deformation of the hill subsequent to the initial formation of the hill-hole pair. It is not possible, however, to determine whether the structure was initially formed subglacially or proglacially.

Isolated depressions and buried glaciotectonic structures on Fugløybanken

Several other sea-bed depressions in the Fugløybanken area (Figs. 4, 5) have a size comparable to Sopphola. They too have a fairly rough topography and rather steep margins, but associated
hills are lacking or present only as erosional remnants. Ruszczynska-Szenajch (1976) has given examples of glaciotectonically formed depressions where the displaced material is not preserved as associated positive landforms. It is suggested here that the isolated depressions at Fugløybanken may also have a glaciotectonic origin.

On several shallow seismic profiles in the Fugløybanken area a similar relief, as seen across the hill-hole pair and the isolated holes (Fig. 5), is revealed by irregular reflections at several levels in the subsurface (Figs. 6, 7). This relief was assumed by Rise (1983) to represent buried over-deepened troughs caused by erosion associated with glacial events. Vorren et al. (1990) describe these forms as a series of buried troughs up to 14 km wide and 100 ms deep. The depressions are often sub-circular but occasionally elongate with a preferred northwesterly–westerly orientation (Vorren et al. 1990). The seismic grid, however, is insufficient to determine their detailed shape (9 km E–W profile spacing and scattered crossing profiles). Vorren et al. indicate, in accordance with Rise (1983), an origin by glacial erosion and suggest that subglacial meltwater may have initiated the erosion. The similarity on seismic records between the buried depressions and the better documented forms on the sea-bed (Fig. 4) may suggest that the erosion is more specifically related to glaciotectonism. In one case pre-Quaternary sedimentary rocks have probably been affected (Fig. 7). The bedrock in this case is possibly Eocene tuff (Rise 1983).

**Ice flow**

The present interpretation of the hill-hole pair at Trenabanken implies an ice flow towards WNW. This flow direction is perpendicular to the neighbouring Norwegian coast, where glacial striations...
Fig. 6. Depressions of suggested glaciotectonic origin. A. Expressed on the sea-bed, B. Buried paleodepression. Location of the profiles is shown in Fig. 5. Reflector B1 probably corresponds to the base of unit 1 comprising the ridge-forming deposits mapped by Vorren & Kristoffersen (1986), and Fig. 6B suggests a wider extent of these accumulations than mapped by Vorren & Kristoffersen (1986).
with similar orientation are found on the outer islands (Andersen et al. 1982). It also corresponds closely to the trend of small, parallel, linear ridges that occur on the sea-bed in this area (Fig. 2), suggested by Lien (1983) to have been formed along the flanks of tabular icebergs pushed in a NW direction by a rapidly advancing (surging?) grounded ice shelf. The inferred flow direction during formation of the 'Horseshoe' is consistent with Lien's (1983) explanation of the ridges. The ridges may, however, also have been formed in cracks in the base of grounded ice.

The Steinbitryggen–Sopphola hill-hole pair (Fig. 4) must have been formed during a NW ice flow, whereas the later streamlining of the hill occurred during westerly ice flow. The latter flow direction could reflect the influence from assumed west-flowing ice the broad trough Bjørnøyrenna to the north. On the other hand, if an ice fed by flow from the SE extended across the hill-hole pair to the shelf break and the position of the grounding line depended on the increase in water depth there, a distal ice flow directed perpendicular to the N–S trending depth contours would be expected. In both cases it may be argued that, if grounded ice or an ice shelf existed in western Bjørnøyrenna when Steinbitryggen and Sopphola were formed, this ice was not a sufficient barrier to hinder a NW flow of the ice on western Fugloybanken at that time.

Age of the structures and some implications in the reconstruction of glacial history

The 'Horseshoe'. The sea-bed on eastern Trænabanken corresponds to the surface of the Upper Till of King et al. (1987). On one seismic line (Fig. 3) there is a reflection which apparently extends the sea-floor trend underneath the base of the 'Horseshoe'. Provided that this reflection is not an artefact caused by side-echo from the hill, it suggests that the hill was formed subsequent to the deposition of the Upper Till. Furthermore, a sea-bed depression which occurs within the Upper Till (King et al. 1987; Enclosure 4) is inferred here to be the source for the sediments in the hill. Hence, the 'Horseshoe' belongs stratigraphically to the Upper Till and not to the underlying Middle Till, as suggested by King et al. (1987). According to Mogensen (1986) the
youngest part of the Upper Till of King et al. (1987) may correlate with the Haltenbank moraine farther south (Bugge 1980). This moraine is dated to be Late Weichselian in age, and might possibly be as young as 12,300–12,400 BP (Bugge 1980), although the minimum age of the Haltenbank moraine seems contradicted by some later ages obtained in the Norwegian coast summarized by Svendsen & Mangerud (1987). A minimum age of the ‘Horseshoe’ is given by a radiocarbon age of 13,420 ± 170 BP obtained on shell fragments on the neighbouring Norwegian coast (Andersen et al. 1981). The oldest reconstructed ice margin position in this area is the A-event, which is suggested to be about 12,300 ± 200 years old, and definitely older than about 11,700 BP (Andersen et al. 1981). The ‘Horseshoe’, located 80–90 km farther to the west, must have been formed prior to this. Based on the correlation with the Haltenbanken moraine (Bugge 1980), it cannot be ruled out, however, that the ‘Horseshoe’ may have been formed during an ice advance between 13,420 BP and 12,300 BP.

*The glaciotectonics at Fugløybanken.* The possible buried glaciotectonic structures (Figs. 6, 7) occur within the ‘older drift’ of Rokoengen et al. (1977, 1979) and correspond to local thickness maxima of seismic units 1W and 2W of Vorren et al. (1990). These sediments are undated, but Rokoengen et al. (1979) found it likely that they are older than 18,000 BP.

Steinbitryggen and the possible erosional remnants of sediments displaced from the isolated sea-bed depressions probably also originate from the ‘older drift’, but rest on a major unconformity on top of the ‘older drift’. This unconformity (corresponding to reflector B1 in Fig. 6B and reflector R in Fig. 7) is assumed to be glacial in origin, but the erosion has not noticeably affected the topography within the depressions. Hence, the glaciotectonics expressed on the sea-bed must be younger than the unconformity. Seismic correlations by the present author and co-workers suggest that this glacial unconformity corresponds to the base of the late Weichselian unit b4 of Hald et al. (in prep.). As glacial erosion is intraformational (King et al. 1987) the unconformity may have been created by the same ice as deposited unit b4 of Hald et al. (unpubl.), and a late Weichselian age cannot be excluded.

The glaciotectonic forms on the sea-bed all have an irregular ‘fresh’ topography, and this may indicate that they are all fairly recent in age. A sparker profile across Sopphola indicates that the soft sediment infill in less than 10 m thick in places (although the seismic resolution is limited). The sub-equal volumes of Steinbitryggen and Sopphola also support the impression that the sea-bed depressions are moderately infilled with soft sediments, although they are expected to be effective sediment traps. It is therefore concluded that the described hill-hole pair is a young form, probably of Late Weichselian age. If this age is correct, the Steinbitryggen–Sopphola hill-hole pair provides kinetostratigraphic evidence (Berthelsen 1973) that a Late Weichselian ice cover extended across Fugløybanken to a calving margin within a few kilometers of the continental shelf edge. This contradicts the maximum Late Weichselian ice extent suggested by Vorren & Kristoffersen (1986) who, in contradiction to views regarding ice extent in the area held by, for example, Rokoengen et al. (1977, 1979) and Andersen (1981), tentatively suggested that a complex of ridges on eastern Fugløybanken (Fig. 5) represents the position of the maximum Late Weichselian ice extent. A seismic profile section across ridge ‘G’ of Vorren & Kristoffersen (1986) (Fig. 6B), however, indicates that this ridge is not an isolated form but rather a thickening of the sediments above reflector B1, which extend farther westwards.

The Nordvestnaget Drift (Fig. 5) was interpreted by Rokoengen et al. (1979) to represent the extent of a glacier readvance occurring not earlier than 13,310 ± 110 BP. From Fig. 5 it appears that this happened after the Steinbitryggen–Sopphola glaciotectonic event, although Rokoengen et al. (1979) regarded their stratigraphy as provisional in areas with sparse profile coverage (Rokoengen et al. 1979, fig. 1), and a wider extent of the Nordvestnaget Drift readvance cannot be excluded. Vorren & Kristoffersen (1986) considered the ridge complexes on eastern Fugløybanken (Fig. 5) not to be formed during a surge from a comparison with the Bråsvellbreen surge moraine (Solheim & Pfirman 1985). However, offshore ice-push forms – for example, Viknaryggen off Mid-Norway (Bugge et al. 1978), the Bråsvellbreen surge moraine (Solheim & Pfirman 1985; Solheim in press) and the ‘Horseshoe’ – show a variety in size and shape, and glaciotectonism has played an important role in forming moraine ridges in the low
relief North American interior (Moran 1971; Bluemle & Clayton 1984). This fact, and arguments regarding the last deglaciation of the Fugløybanken area presented herein, point to the possibility that also the ridges described by Vorren & Kristoffersen (1986) as marginal moraines may be ice-pushed forms created during a temporary ice margin readvance.

Possible conditions favouring repeated glaciotectonism in the Fugløybanken area

Existing models. The present interpretation of exposed and buried glaciotectonic structures suggests that glaciotectonism may have occurred repeatedly on Fugløybanken and hence that there may have been local factors favouring this process. Aber et al. (1989) argued that high horizontal stresses generated by vertical ice load pressure may develop along the margin of a glacier and that the horizontal stress will increase with increased ice surface gradient. A steep ice surface on Fugløybanken would probably require a frozen base ice sheet, as a wet based ice as described by Boulton & Jones (1979) (or at least an ice with a net melting base) would create a soft, deforming bed resulting in a low gradient ice. Bodies of subglacial debris may be incorporated into the glacier by oscillations in the boundary between frozen and freezing glacier base (Weertman 1961). The physiographic setting of Fugløybanken (the bank is bounded by troughs or deep water areas in almost all directions) may have favoured temporary local existence of fairly passive ice, with a frozen base, possibly with development of subglacial permafrost. Salt structures at depth (e.g. Rønnevik et al. 1975) may have caused local heat flow variations affecting permafrost distribution. Changes in relative sea level or increased ice supply from up-ice source areas could have resulted in temporary and local changes in glacier surface gradient, acceleration of the ice flow and thus instability of boundaries between thermal zones at the glacier base.

Bluemle & Clayton (1984) concluded that most studied glacial thrust features in North Dakota are located over discrete aquifers. A similar relationship of Fugløybanken would lead to the expectation of several local buried aquifers in the area. Gallagher et al. (1989) suggested from a study on the mid-Norwegian continental shelf that isolated sand bodies may occur within buried iceberg ploughmarks, and argue that these bodies may form shallow gas reservoirs. Any presence of gas or gas hydrates could have contributed further to local instability (e.g. Bugge 1983). Gas migrating into a confined aquifer under high pressure conditions beneath an ice cover could provide a particular failure triggering mechanism during ice retreat as high pressure could be maintained when the ice retreated, resulting in a very low effective stress.

A model for glaciotectonism related to a consolidated sediment layer caused by subglacial freezing. It is, as yet, unknown whether the structures in the Fugløyenbanken area were formed proglacially or subglacially, and whether the parent sediments of the buried structures were soft or well consolidated at the time of the inferred glaciotectonism. In the following, a model is presented for subglacial creation of conditions favourable for glaciotectonic en masse displacement of initially soft, homogeneous, fine-grained sediments – an initial condition which is common for ice sheet advance into the marine environment.

Lien (1983) describes relict iceberg ploughmarks where the rim of ploughed-up material comprised 3–5 m thick blocks of sediments. One of Lien’s explanations for this was that the sediments had been temporarily loaded by ice, consolidating the sediments to a certain depth (Lien 1983). The base of a consolidated layer in otherwise lithologically homogeneous sediments is expected to represent a preferential glaciotectonic decollement level, but a consideration of the possible consolidation process is appropriate.

Ice load consolidation is related to increase in effective load (vertical stress caused by the ice load less the water pressure at the base of the ice) forcing pore water to drain away from the sediment (Mathews & Mackay 1960). The degree of consolidation is dependent on the ability for pore water drainage (e.g. Harrison 1958; Mathews & Mackay 1960; Laprade 1982). Laprade (1982) found effective preconsolidation stresses of the Lawton Clay in Seattle corresponding to less ice thickness than suggested by geologic evidence, but further found a close relationship between the degree of consolidation and the distance to the nearest sand layer. In situations where a low-gradient ice sheet rests on
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A substratum composed of several tens of metres of fine-grained sediments the drainage conditions are extremely poor. The flow path length for lateral drainage of excess pore water may be in the order of 100 km. In such conditions the consolidation of the substratum will be very slow, and will stop completely if basal melting balances the drainage from the ice-bed interface. The subglacial sediments will then remain soft and may be further softened by meltwater being admixed to the substratum (Boulton 1979; Boulton & Jones 1979; Boulton & Hindmarsh 1987; Jones 1979; Menzies 1981; Alley et al. 1987). Under such conditions an increasing part of ice load will rest on pore pressure, and Blankenship et al. (1986) estimated for example the water pressure at the Upstream B camp in Antarctica to be more than 99% of the total ice pressure.

A local pore water sink at the top or base of a layer being consolidated will reduce the flow length for excess pore water by four to five orders of magnitude and increase the consolidation potential. In the following, a drainage mechanism related to subglacial freezing is considered. In periglacial environments, consolidation during ground freezing is a well-known process. The consolidation is caused by migration of pore water towards a freezing front and formation of isolated ice lenses. This is illustrated theoretically, experimentally and in the field in cold regions (e.g. Williams 1966; Sutherland & Gaskin 1973; Chamberlain et al. 1978; Takashi et al. 1980; Chamberlain 1981; Førland et al. 1988). Freezing at the base of a glacier or at the base of a subglacial permafrost zone may offer a drainage mechanism which is the reverse of the substratum softening process related to basal melting. Menzies (1981) addressed the possibility of pore water migration towards an advancing subglacial freezing front, and also considered that pore water expulsion could occur in front of an advancing freezing front. It is considered here that consolidation may occur below a freezing front at or beneath the base of an ice cover if the thermal and hydrological conditions are such that ice lenses are formed. (A net-freezing glacier base may be regarded as an ice lens in this context.) This will occur regardless of whether the freezing front is advancing or not. Pore water expulsion caused by freezing, however, is related to the volumetric expansion as water freezes to ice (Menzies 1981), and can therefore only occur if the freezing front advances. Aquifers or a gradual downward increase in permeability can maintain high pore pressure (and low effective stress) at depth while an upper layer may be consolidated beneath a net freezing base ice. Fragments of a crust of consolidated (but not necessarily frozen) sediments created as described above may be dragged along by a moving ice and slide upon a softer substratum, and the result may be a complex mixing and remoulding of glaciotectonically displaced and sheared sediments. A similar glaciotectonic dislocation of frozen substratum floes was suggested by Boulton (1979).

Discussion. It is uncertain to what extent the different conditions and mechanisms above were involved in the formation of the glaciotectonic structures described herein. The ‘Horseshoe’ is interpreted as formed by rapid push in homogeneous sediments of moderate stiffness, possibly without any preferred level of decollement. The described structures on Fugloybanken are, however, interpreted to have been formed by thrusting along planes of decollement. Sufficient driving stresses may have been caused by episodic high ice flow velocities following periods of more passive ice (partly frozen base?). The buried structures may have been displaced along decollement planes at the base of consolidated layers formed as outlined above. This could correspond to sand layers if such were present. The depressions on the sea-bed cut down below an erosional surface into sediments expected to be overconsolidated by earlier sediment burial, and sand layers may be the most likely decollement zones.

Implications

The ‘Horseshoe’ and Steinbitryggen have been interpreted above as glaciotectonically formed ridges, and it is also suggested there that the ridges on eastern Fugloybanken described by Vorren & Kristoffersen (1986) may be ice-pushed forms created during a temporary ice margin readvance similar to Viknaryggen off Mid-Norway (Bugge et al. 1978) and the Brasvellbreen surge moraine (Solheim & Pfirman 1985; Solheim in press). This suggests that many of the so-called moraine ridges on the continental shelf may be partly glaciotectonic in origin. Despite their large sizes, they may therefore reflect short, temporary ice advances with high rates of erosion and transportation, rather than existence of major long-lasting ice margin positions. Interpretation of the
significance of such forms should therefore be supported by stratigraphic evidence.

The observations and the theoretical model presented above suggest that glaciotectonics results in a complex stratigraphy. Large floes of Quaternary sediments and pre-Quaternary rocks may be expected in areas where glaciotectonism has occurred. Such floes may comprise sediments similar to or different from the parent rock. In the former case the floes may be particularly difficult to recognize (Aber 1985). In an offshore setting recognition is further hampered by lack of exposure, and seismic data may be rather poor due to inhomogeneous and tectonized sediments. Glaciotectonic structures are therefore potential sources or error in stratigraphic work. Displaced rafts may be different from the parent rock in soil mechanical properties (stiffer or softer) and complex variations in geotechnical conditions are probably associated with glaciotectonics.

Conclusions

Two described sea-bed forms on the Norwegian continental shelf are considered by the author to be glaciotectonic hill-hole pairs. The ‘Horseshoe’ off mid-Norway (10°40’E, 66°15’N) at 300 m present water depth was formed by ice push in front of the last ice advancing to this point. Steinbitryggen on Fugльйбanken in the SW Barents Sea (18°30’E, 71°10’N), at about 200 m present water depth, may have either a proglacial or a subglacial origin. This ridge, however, has been overrun by ice and is reshaped by the ice flow. Both structures are probably composed of more or less tectonized glacigenic sediments.

The ‘Horseshoe’ is determined on stratigraphic evidence to be of Late Weichselian age. A 14C dating obtained on the neighbouring Norwegian coast indicates a minimum age of 13,420 ± 170 BP, but at present it cannot be ruled out that the structure was formed during an advance between 13,420 ± 170 BP and the A-event of Andersen et al. (1981) dated to 12,300 ± 200 BP.

The age of Steinbitryggen is at present not determined, but a probable Late Weichselian age is suggested here. Glacier ice has extended to within 10 km of the shelf edge after the formation of the ridge. The Late Weichselian ice extent in the area is debated, but at present no conclusive data exist. From the apparent limited infill of soft sediments in the depression, Sopphola, it is argued that little sediment redistribution has occurred in the area since Steinbitryggen was formed, and hence that the structure was probably formed by a Late Weichselian ice of wider extent than favoured by Vorren & Kristoffersen (1986). The moraine ridges mapped by Vorren & Kristoffersen (1986) are suggested here to be local (ice push?) accumulations within a sediment extending farther westwards. The resemblance between the glaciotectonic structures on the seabed and buried morphology on Fugльйбanken, may suggest that this has been an area where repeated glaciotectonism has taken place.

A particular type of glaciotectonism could develop within a consolidated layer, possibly formed by basal freezing, resting on softer substrata. This process has been theoretically considered and is expected to effectively remould and mix soft sediments. The model further predicts particularly high subglacial consolidation beneath a net freezing base ice sheet.

Large buried or subcropping floes of Quaternary sediments and pre-Quaternary rocks may be expected in areas where glaciotectonism has occurred. Such floes may be difficult to recognize, but may cause large variations in subsurface geotechnical conditions and are also potential sources of error in stratigraphic work.

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