Large-scale glaciotectonic-imbricated thrust sheets on three-dimensional seismic data: facts or artefacts?

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ABSTRACT

Imbricate reflections commonly occur in the glacigenic section of seismic profiles from the Bjørnøya Trough. This was the main drainage pathway for fast-flowing ice-streams from the former Barents Sea and Scandinavian ice sheets. Industry three-dimensional (3D) seismic data from the southern flank of the Bjørnøya Trough are used here to investigate these imbricate reflections. Integration of vertical seismic sections with 3D plan view images and attribute maps reveal that imbricate reflections at the SW Barents Sea Margin are mega-scale sediment blocks with a glacigenic origin. Imbricate reflections in two regions to the east of the survey appear on plan-view as well-developed lineations of U-shaped crescents; however, following detailed analysis of their location, geometry and relation to sailing direction during data acquisition, we can demonstrate that these are seismic artefacts. These artefacts are related to the straight parts of east–west-trending plough marks on the sea floor, having a dip direction that is directly related to the sailing direction of the ship during seismic acquisition. By analysing both real glacigenic imbrications and false imbrications or artefacts, we are able to demonstrate the critical distinguishing criterion.

INTRODUCTION

The emergence of three-dimensional (3D) seismic technology as a regional industry exploration tool in the 1990s has revolutionized seismic investigations. The main advantage of the 3D seismic method over the 2D seismic method is the dramatic improvement in lateral resolution. In 3D seismic acquisition, grid spacing is often 25 m or less, and with advanced 3D seismic migration algorithms accurate positioning of seismic reflections is obtained in all directions, and the Fresnel Zone can be collapsed in 3D. The result can be seen as impressive images of detailed stratigraphy and complex structures such as thrust-fault systems and salt domes (Cartwright & Huuse, 2005), mega-scale glacial lineations (Rafaelsen et al., 2002; Stokes & Clark, 2002; Andreassen et al., 2004; in press; Evans et al., 2005; O’Cofaigh et al., 2005) or carbonate build-up complexes (Elvebakk et al., 2002; Rafaelsen et al., 2003). However, it is important not to forget that they are time-images that may include artefacts.

In this study, 3D seismic technology is used to investigate seismic reflections that have the appearance of being glaciogenic features. These features occur commonly in the glacigenic section of 3D seismic data from the southern flank of the Bjørnøya Trough (Fig. 1a). There is a general consensus that the Bjørnøya Trough, the main cross–shelf trough in the Barents Sea, has been the focus of major ice streams draining the Scandinavian and Barents Sea–Svalbard Ice Sheets during the last glacial maximum (LGM; Fig. 1a). This is based on bathymetric considerations and ice-sheet geometry (Denton & Hughes, 1981), investigations of the Bjørnøya Trough Mouth Fan deposocentre of former ice streams (Fig. 1a; Vorren & Laberg, 1997), the observation of glacial flutes at several locations in the Bjørnøya Trough (Solheim et al., 1990; Elverhøi et al., 1993), 3D seismic studies of the outer Bjørnøya Trough glacigenic sediments (Andreassen et al., 2004) and is supported by ice-sheet modelling (Dowdeswell & Siegert, 1999).

2D seismic offshore investigations and a shallow borehole have documented that glaciogenic deformation is common at the northern flank of the Bjørnøya Trough (Sættem, 1994) as well as in the Russian SE parts of the former Barents Sea ice sheet (Gataullin et al., 1993, 2001; Gataullin & Polyak, 1997), involving un lithified glacigenic sediments and often also the upper part of the underlying consolidated bedrock. Recent field studies reveal the widespread occurrence and complex nature of glaciogenic thrusting on land in northern Russia associated with the Barents sea and Kara Sea ice sheets (Astakhov, 2001; Larsen et al., 2006).

Semi-regional industry 3D seismic data from the SW Barents Sea (Fig. 2a; 3D areas 1, 2 and 3) show that large-scale imbricate reflections commonly occur within the glacigenic sediments that are located at the southern flank of the Bjørnøya Trough (e.g. Fig. 3b). These data offer, with dense spatial sampling and advanced 3D computer inter-
pretation techniques, a fundamentally new method for studying such features. In this paper, we investigate these imbricate reflections and their 3D appearance. In 3D area 1, we discuss the imbricate reflections glaciological significance and relationship with other associated geomorphological features, and put constraints on their origin and formation. In 3D area 2 and 3, imbricate reflections may easily be mis-interpreted as glaciotectonic thrust sheets and thereby represent a pitfall for the interpreter. These imbricate reflections represent a 3D seismic artefact that has not been described before, and here we describe how this artefact appears in three dimensions. We also reveal how it is related to the geomorphology on the sea floor and the 3D seismic acquisition geometry.

Fig. 1. (a) Location and bathymetry of the SW Barents Sea. Possible glacier extent and directions of ice stream flow during Late Glacial Maximum (28–22 ka BP) and during the retreat of the ice sheet are indicated (modified from Andreassen et al., 2004). Red box indicates the position of Fig. 2a. (b) Seismostratigraphic section crossing the study area. Red box indicates three-dimensional (3D) area 1 and broken red boxes indicate the extrapolated position of 3D seismic areas 2 and 3. Not to scale. Approximate vertical scale is 1200 m. Modified from Vorren et al. (1990). (c) Seismic profile from 3D area 1.
Fig. 2. (a) Map of the sea floor (∼ 20 vertical exaggeration) revealing how the palaeo-ice flow could fit with the direction of the imbricate reflections dipping eastwards in three-dimensional (3D) area 2 and 3. Note the location of the 3D areas relative to large-scale elements on the sea floor. Black lines indicate palaeo-ice flow. Arrows indicate the main direction of the imbricate reflections. Depth is in kilometres below sea level and the grey circle shows the position of the light source. The map is a Statoil compilation of bathymetry based on seismic data, compiled by NGU/Eirik Mauring. A publication on details from the sea floor in the Barents Sea is presented in Andreassen et al. (2007). For location of map, see Fig. 1a. (b) Detailed map of the 3D-surveys 2 and 3 with the location, orientation, length and dip direction of the observed imbricate reflections. Note how the imbricate reflections in 3D area 2 occur in 4–10 km wide eastwards or westwards dipping belts.
PHYSIOGRAPHIC SETTING AND SEISMIC STRATIGRAPHY

The Barents Sea is an epicontinental sea characterized by relatively shallow banks separated by deep troughs, which have been excavated by glacial erosion. The bank areas have water depths of < 300 m, whereas the most pronounced trough, the Björnøya Trough, reaches depths of 500 m.

The Björnøya Trough ice stream developed in an area of strongly convergent ice flow from the Svalbard-Barents Sea and the Scandinavian ice sheets (Fig. 1a). It is modelled to have flowed at about 800 m a⁻¹ and produced about 30 km³ a⁻¹ of icebergs during full glacial periods (Siegert & Dowdeswell, 2002). The Björnøya Trough Mouth Fan, located at the mouth of this trough, acted during the Plio-Pleistocene as a main depocentre for ice streams that

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Fig. 3. (a) Root mean square (RMS) amplitude map from the lower part of unit GII showing the orientation of mega-scale glacial lineations (arrow) in the upper shaded (green) volume in (b) [three-dimensional (3D) area 1; Fig 1c]. The small black rectangle to the lower left represents the 3D seismic survey and the white rectangle within represents the area shown in this figure. (b) Seismic profile with thrust sheets on two stratigraphic levels within GII, where the green and blue colours represent the zones used when calculating the RMS amplitude maps. (c) RMS amplitude map with the position and size of the sediment blocks in the lower shaded (blue) volume in (b). The small black rectangle to the lower left represent the 3D seismic survey and the white rectangle within represents the area shown in this figure. Modified from Andreassen et al. (2007).
drained to the Bjørnøya Trough shelf break at glacial maxima (Fiedler & Fealle, 1996; Kuvaas & Kristoffersen, 1996; Vorren & Laberg, 1996; Andreassen et al., 2004).

Mega-scale glacial lineations are parallel-elongated groove-ridge structures and they occur in the study area on buried surfaces within the glacigenic succession (Fig. 4a; red, blue and purple arrows). The mega-scale glacial lineations in the study area have a relief of up to 10 m, widths from 50 to 360 m, length of 38 km and an elongation ratio of up to 105:1 (Andreassen et al., 2004). Such features are interpreted to have been formed subglacially in areas of fast ice flow (Stokes & Clark, 2002), and indicate the direction of palaeo-ice flow.

Three main sediment packages, GI, GII and GIII (Fig. 1b), have been identified and correlated along the western Barents Sea–Svalbard margin (Faleide et al., 1996; Butt et al., 2000). ODP Site 986 west of Svalbard (Fig. 1a) is a key borehole for age constraints of the seismic stratigraphy of this area (Forsberg et al., 1999; Butt et al., 2000); additional chronological constraints come from exploration wells (Eidvin et al., 1993, 1998) and shallow borings (Sættem et al., 1992, 1994). It is, however, a problem that biostratigraphic data used for age estimates are often retrieved from drill cuttings, where sediment collapse in the borehole adds younger material to the samples. In addition, glacigenic sediments may contain high amounts of older reworked material.

The regional seismic reflection, R7, which can be followed from ODP Site 986 southward along the margin to the base of sediment package GI of the Bear Island Trough Mouth Fan (Fig. 1b), has an age estimate of 2.3 Ma (Forsberg et al., 1999). Reflection R5, at the base of package GII (Fig. 1c), represents the first documented occurrence of grounded glaciers reaching the Bjørnøya Trough shelf break (Andreassen et al., 2004), and is given the interpolated age estimate of 1.6–1.7 Ma from ODP Site 986–data (Butt et al., 2000), whereas Faleide et al. (1996) suggested a likely age of about 1.0 Ma. Amino acid analysis of R1, at the base of GIII, indicates an age younger than 440 ka (Sættem et al., 1992), whereas the extrapolation of calculated sedimentation rates in piston cores on the Svalbard margin has given an approximate age of 200 ka (Elverhøi et al., 1995). A likely age of R1 is thus between 440 and 200 ka.

An upper regional unconformity (URU; Fig. 1b) developed over the entire Barents Sea shelf as a result of repeated glacial erosion (e.g. Solheim & Kristoffersen, 1984; Vorren et al., 1986; Lebesbye, 2000; Raafaelsen et al., 2002). It most likely represents the erosional base for several continental shelf glaciations; however, the seismic stratigraphy suggests that the last major erosion down to the level of the URU occurred at the SW Barents Sea shelf at R1 time, and that the sediments overlying the URU in this area are younger than 440 ka (Faleide et al., 1996; Kuvaas & Kristoffersen, 1996). The URU on the shelf represents a change from an early erosional glacial regime to a later aggradational regime, whereas the stratigraphy above indicates that ice sheets have reached the SW Barents Sea shelf edge at least five times (Vorren et al., 1991) since the URU was formed.

3D SEISMIC DATA

This study is based on three industry 3D seismic data sets located at the southern flank of the Bjørnøya Trough (Fig. 2a; 3D areas 1, 2 and 3), covering a total of 4000 km². The data sets are located at water depths of 150–400 m. The surveys were acquired in 1998 with a line spacing of up to 37.5 m (Table 1). The dominant frequency of the data is around 40 Hz at the studied depths. The theoretical vertical resolution of the data, using 1750 m s⁻¹ as an average velocity of the glacigenic sediments, is therefore around 10 m (~1/4 of the dominant wavelength). In practice, the occurrence of thin beds and associated interference effects can subtly distort the relief of two-way time picks. In addition, 3D seismic horizons represent an average response over at least 1/4 of a wavelength, possibly up to half a wavelength (Bulat, 2005), giving a vertical resolution of 10 m (1/4 of the dominant wavelength) to 20 m (1/2 of the dominant wavelength).

The theoretical lateral resolution is defined by the width of the Fresnel zone, which, after 3D migration, is also around 1/4 of the dominant wavelength (Brown, 2005), i.e. 10 m. Errors in migration may reduce the practical resolution to 1/2 the dominant wavelength (Brown, 2005; Bulat, 2005). The spatial sampling of the seismic volume is the primary control of horizontal resolution (Cartwright & Huuse, 2005), as the spatial sampling is generally coarser than or equal to the dominant wavelength of the signal (Bulat, 2005). In this study, the bin spacing and therefore the horizontal resolution is up to 37.5 m. 2D seismic lines and wells have been used for stratigraphic correlation with other work in the area.

DIPPING REFLECTIONS IN 3D SEISMIC AREA 1

The glacigenic sediment packages GII and GIII contain more than 900 m of palaee–shelf sediments due to subsidence in 3D area 1. Long chains of megablocks and rafts, buried in thick till units between glacially eroded horizons, occur commonly within the shelf units of the sediment packages GII and GIII in 3D area 1 at the Barents Sea margin (Fig. 1c). These sediment blocks have previously been documented by Andreassen et al. (2004, 2007), and are shown here in Figs 3 and 4. Sediment blocks larger than 1 km² are classified as medium-sized mega-blocks whereas those smaller than 1 km² are termed rafts (based on Aber et al., 1989). Elongated groove-ridge structures, termed mega-scale glacial lineations, have a relief of up to 10 m, widths from 50 to 360 m and lengths exceeding 38 km (Andreassen et al., 2004). High-amplitude seismic anomalies, interpreted as mega-blocks with different acoustic properties than the surrounding sediments, are
Fig. 4. Small black rectangle in the upper left corner represents the three-dimensional (3D) seismic survey and the white rectangle within represents the area shown in that figure. (a) Shaded relief map of an intra GIII horizon (see Fig. 1c) underlying the sediment blocks in (b). Note the mega-scale glacial lineations (yellow arrows) oriented southwest/northeast (blue arrow). The position of the light source is shown by the grey circle. (b) Seismic profile with mega-scale glacial lineations. (c) Volumetric Root Mean Square map (RMS; shaded volume) with chains of sediment blocks from intra GIII (see Fig. 1c). Note that the orientation of the sediment chains is similar to that of the mega-scale glacial lineations in a. Modified from Andreassen et al. (2004). (d) Seismic profile reveals related thrusts. (e) RMS amplitude map (b) draped on top of the shaded relief map (a) showing two generations of mega-scale glacial lineations (1 and 2) combined with the sediment blocks. Modified from Andreassen et al. (2007).
Glaciotectonic thrust sheets: facts or artefacts?

Table 1. Parameters used in the 3D seismic acquisition

<table>
<thead>
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<th>3D area 1</th>
<th>3D area 2</th>
<th>3D area 3</th>
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<td>Very good</td>
<td>Very good</td>
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<tr>
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<td>3 Hz–18 dB/oct</td>
<td>3 Hz–18 dB/oct</td>
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<td>180 Hz–72 dB/oct</td>
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Time-variant filters have later been applied to the 3D surveys, significantly reducing the high-cut frequency values displayed here during the subsequent processing of the data.

3D, three dimensional.

observed at the base of GII (Fig. 3). Root mean square (RMS) volumetric attribute maps show a lateral distribution of sediment blocks and the appearance of mega-scale glacial lineations (Fig. 3a), whereas seismic profiles show their stacked glaciotectonic nature (Fig. 3b). The mega-scale glacial lineations indicate the direction of palaeo-ice flow (Fig. 3a).

On the interpreted seismic horizon Intra GIII, and in seismic profiles, mega-scale glacial lineations are evident (Fig. 4a and b). They are oriented in the same direction as the chains of sediment blocks (Fig. 4c and d). The chains of mega-blocks and rafts are aligned in over 50-km long chains that are 1–2 km wide (Andreassen et al., 2004) and have the same NE-trending orientation as the observed mega-scale glacial lineations.

Seismic profiles parallel to the orientation of the sediment chains and the inferred ice flow indicate, where the vertical resolution is good enough, that the mega-scale blocks consist of back-tilted sub–horizontal sediment slabs that have been displaced from the NE along a series of shear planes (Figs 3b and 4d), parallel to the inferred ice-stream flow. An image, obtained by calculating the RMS attribute for a volume that includes the horizon from Fig. 4a and the sediment blocks (Fig. 4b; shaded zone), has been draped over the interpreted shaded relief map (Fig. 4a) and reveals the relationship between the glacial lineations and mega-blocks (Fig. 4e). This combined attribute/shaded-relief image of Fig. 4e shows that the sediment blocks have been cut by two sets of mega-scale glacial lineations, suggesting that ice streams have eroded the already detached mass of sediment blocks after they were deposited.

Thrust faults related to the mega-blocks and rafts disturb the upper or entire section of the sediments between more pronounced seismic horizons above URU. These stacked mega-blocks dip towards the NE (Figs 3 and 4), indicating a glacier movement towards the south-west, as documented by Andreassen et al. (2004).

The chains of sediment blocks are parallel to mega-scale glacial lineations and the inferred flow of ice streams.

The common occurrence of mega-scale sediment blocks and rafts within sediment packages GII and GIII suggests that glaciotectonic erosion, transport and deposition by ice streams accounts for the high sediment flux from the Barents Sea to the shelf break and the Bear Island Trough Mouth Fan since the early Pleistocene.

IMBRICATE REFLECTIONS IN 3D SEISMIC AREAS 2 AND 3

The glacigenic sediments in 3D seismic areas 2 and 3 are separated from underlying dipping, consolidated sediments by the URU (Fig. 1b). In this area, the thickness of the glacigenic sediments is up to 150 m. The glacigenic sequence is commonly disturbed by imbricate reflections that occur over large parts of these two 3D areas. They occur on vertical seismic profiles as dipping reflections that are stacked obliquely in an imbricated manner (Figs 5a and 6a, c). The dipping reflection segments are each 200–300 m wide (Figs 5b, c and 6b, d), 300–850 m long, 22–100 m in vertical extent and inclined between 2.5° and 22° (mainly 8°–12°). They occur in patches that reach a total length of 0.5–5 km. The imbricate reflections reach down to URU or more frequently the horizon just above URU (Figs 5a and 6a, c).

The integration of vertical seismic sections with map-view images shows that the imbricate reflections run parallel to the straight parts of the flanks of east–west-trending plough marks on the sea floor (Fig. 7). The dip directions of the imbricate reflections are mainly towards the east (Figs 2b and 6a; totally 70 structures) or west (Figs 2b and 6c; totally 76 structures). In some instances less distinct, almost semi-transparent/lower-amplitude areas have been observed on the seismic profiles on the stoss-side of the imbricate reflections (Fig. 8a). The observed structures have been mapped on all glacigenic horizons within 3D areas 2 and 3.

The imbricate reflections observed in 3D surveys 2 and 3 appear on time slices (Figs 5b, c and 6b, d) and horizon
Fig. 5. (a) Seismic profile from three-dimensional (3D) area 2 with imbricate reflections that sole out along a decollement zone above the Upper Regional Unconformity (URU). (b–c) The time slices show the characteristic smooth U-shape and the linearity of the imbricated thrust lineations. A slight increase in size of the U-shape with depth can be measured using the interpretation software, but is difficult to observe with the naked eye. The small black rectangle in the lower left corner represents the 3D seismic survey and the white rectangle within represents the area shown in that figure.

Fig. 6. (a and c) Seismic profiles from three-dimensional (3D) area 2 with east dipping (a) and west dipping (c) imbricate reflections in the upper part of the glacigenic succession. The thickening of the sequence in (c) may in 2D appear to be related to the imbricate reflections, but they are genetically unrelated to each other. (b and d) Time slices illustrating their imbricated horizontal appearance. The small black rectangle in the upper right corner represents the 3D seismic survey and the white rectangle within represents the area shown in that figure.
Glacial megablocks and rafts are common in formerly glaciated areas, and may be aligned in chains (Aber et al., 1989). The occurrence of cupola hills buried within a till unit have been documented at the northern flank of Bjørnøya Trough by Satttem (1994) in a unit that correlated with the very upper part of sequence GIII. One of the cupola hills consisted of a 15–25-m-thick block of Cretaceous sedimentary rock, buried in the Pleistocene till. A cupola hill has a glaciotectonic origin and has an overall dome-like morphology shape (Aber et al., 1989).

3D seismic images of the buried surfaces are within sediment packages GII and GIII in 3D area 1 characterized by mega-scale glacial lineations that extend for over 38 km over the entire survey area. The dominant orientation of these lineations is generally north-easterly (Figs 3a, c and 4a, e), which is consistent with orientation of ice streams draining out the Bjørnøya Trough (Fig. 1a). Imprints from ice streams that drained to the shelf edge during the LGM are clearly visible on the large-scale shaded relief image of the SW Barents Sea seafloor (Fig. 2a). The mega-scale sediment blocks and the other thrust-features observed in 3D area 1 (Figs 3 and 4) are, from their orientation between glacially eroded surfaces and from their internal structural consistency with mega-scale glacial lineations, interpreted to have been subjected to deformation by glaciers draining out the Bjørnøya Trough. Andreason et al. (2004) suggested this was most probably due to fast-flowing ice streams. The detached sediment blocks are interpreted to have been picked up, transported and deposited by glaciers. Transportation of glacial mega-blocks is normally interpreted to be formed by basal freezing onto the base of the glacier (Aber et al., 1989). Andreasen et al. (2004) propose that palaeo-ice streams draining through the Bjørnøya Trough could have undergone periods of basal freezing near their margins, caused by a fast downward advection of cold surface ice. The frozen sediment blocks are interpreted to have been entrained by the glacier and transported along thrust planes before being re-deposited at the margin. Basal freezing is known to cause over-consolidation of sub-glacial sediments and can produce a rheological contrast between the frozen sediments at the ice base and the less-consolidated sediments with depth. This may focus the thrust deformation at the transition between the over-consolidated and less-consolidated sediments.

Large-scale glaciotectonic thrust sheets similar to those described from 3D area 1 have been described from former glaciated areas on land in NW Europe and North...
America (Clayton et al., 1980; Aber et al., 1989; Huuse & Lykke-Andersen, 2000). In Denmark, cliff-exposures on land have allowed detailed sedimentological and structural studies of such thrust sheets (Pedersen, 1987, 2000; Klint & Pedersen, 1995). At Mons Klint the thrust sheets are ca. 100 m thick and 1 km long, and at Lønstrup Klint the stacked imbricated thrust sheets are ca. 4.5 km long. Imbricated glaciotectonic structures from push-moraines have been described from Svalbard (Van der Wateren, 1995; Boulton et al., 1999). Elsterian/Saalian glaciotectonic thrust structures from marine areas, studied in two dimensions using 2D seismic data, are 200 m long, 100–250 m thick and interpreted to have been formed by gravity spreading in front of advancing ice sheets (Huuse & Lykke-Andersen, 2000; Andersen et al., 2005). 2D seismic and shallow boreholes have been used for the identification of a glaciotectonized bedrock surface (Søttem et al., 1992) and glaciotectonic structures such as hill-hole pairs (Søttem, 1990). Also, glaciotectonic features imply strong glacial erosion of glacigenic sediments (Gataullin et al., 2001; Larsen et al., 2006) and Mesozoic rocks in the eastern Barents Sea (Gataullin et al., 1993).

Fig. 8. (a) Vertical seismic profile showing several kilometres of well-developed imbricate reflections dipping towards the east [three-dimensional (3D) area 3]. The blue line indicates the location of the time slice in (b). The seismic profile has been filtered, post-stack, with a low-cut of 40 Hz. (b) Time slice at 572 ms TWT with U-shaped imbricated thrust lineations. The small black rectangle in the upper right corner represents the 3D seismic survey and the white rectangle within represents the area shown in that figure. (c) Constructed model of 3D appearance of the glaciotectonic imbricated features.
The imbricate reflections of 3D areas 2 and 3 (Figs 5–7) show many of the same characteristics as those of 3D area 1. They appear in map view as crescentic U-shaped features (Figs 5b, c, 6b, d and 7a, c, d), a characteristic that has been described for both large- and small-scale glaciotectonic ridges (Aber et al., 1989). The geological history of the study area with repeated glacials/inter-glacials since the formation of URU has directed us towards a glaciotectonic origin for the observed imbricated features.

Decollement zones, in connection with glaciotectonics, are primarily dependent on lithology (Pedersen, 1996). Marine clay can act as a decollement zone for the thrust sheets and, because of increased pore pressure, be plastically deformed (Pedersen, 1987; Huuse & Lykke-Andersen, 2000). A duplex of imbricate thrust sheets develop as the sediments are deformed and overthrust, which are among characteristic structures produced by gravity spreading (Pedersen, 1987). This may occur when faults form thrust blocks underneath and in front of a glacier and place them in an imbricated relation to each other (Pedersen, 2000). In this way, imbricated structures are constructed (Fig. 10) in which proximal thrust blocks

Fig. 9. Illuminated shaded relief map of a buried horizon above the upper regional unconformity in three-dimensional (3D) area 3 showing imbricate reflections and mega-scale glacial lineations. Note how the imbricate reflections here crosscut the direction of the mega-scale glacial lineations. The upper encircled structure is shown in the seismic profile on Fig. 11a. The grey circle shows the position of the light source. The small black rectangle in the upper right corner represents the 3D seismic survey and the white rectangle within represent the area shown in the figure.

Fig. 10. (a) Schematic diagram illustrating continued displacement of inclined ice-marginal thrust blocks (4, 5, 6). (b) The older thrust blocks are probably eroded in the upper parts when the glacier overrides them (1, 2, 3). Not to scale. Modified from Aber et al. (1989).
(oldest) may be moved several kilometres, whereas the most distal (youngest) will move only a short distance (Aber et al., 1989). Thrust structures may also form englacially (Hambrey et al., 1997), but they are generally steeper (20°–35°) and less extensive (10–100 m wide and long) than those described from 3D area 2 and 3.

After a close examination of the 3D seismic data, an image of the 3D appearance of the imbricate reflections in areas 2 and 3 was constructed (Fig. 8c). The following observations may suggest that the imbricate reflections could be glaciotectonically formed: (i) the imbricate reflections occur with a varying angle to the inline direction (Fig. 2b), (ii) the reflections are only observed in the glacigenic succession, (iii) the imbricate reflections do not seem to be associated with the orientation of the acquisition (Fig. 2b), (iv) the imbricate reflections tend to die out along a decollement plane (Fig. 8a), (v) in some cases a thickening of the sequence related to the imbricate reflections is observed, as expected, due to compression (Fig. 6c). If the imbricate reflections represent compressed and more consolidated sediment than sediments surrounding them, it is possible that icebergs drifting with their keel down into the sediments, creating turning and bending plough marks, were sometimes pushed against imbricated features and forced to move along them until the prevailing wind and current direction changed or until it passed the imbricated features.

On the other hand, the following has puzzled the authors: (i) The geographical distribution (Fig. 2b) of imbricate reflections dipping towards the east (Fig. 6a) and
The occurrence of imbricate reflections with an easterly dip fits well within a model of glaciotectonic deformation in the convergence zone of fast-flowing ice streams draining out Ingoydjugupet and Bjornoya Trough, and is in consistence with imprints of mega-scale glacial lineations on the sea floor (Fig. 2a). The imbricate reflections with a westerly dip do not, however, fit into such a glacigenic setting and have been difficult to explain from a geological point of view. Also, the alternating zones of westerly and easterly dipping thrust sheets in 3D area 2 have been difficult to explain (Fig. 2b). (ii) There is no correlation between the orientation of imbricate reflections and mega-scale glacial lineations on buried surfaces (Fig. 9; Rafaelsen et al., 2002), the imbricate reflections crosscut the mega-scale glacial lineations. (iii) On map-view images, the smooth symmetrical appearance of the U-shape of the imbricate reflections (Fig. 5b and c), their amazingly even width of around 200–300 m persisting for up to 5 km length (Fig. 8b), and the extreme linearity of the stacked structure (Fig. 9) is much more organized and less rough and chaotic than expected. (iv) Significant disturbance of the sediments laterally and proximally of the structures is generally lacking. (v) The imbricate reflections occur along straight parts of the edge of east–west-trending plough marks, but disappear where the plough mark bends (Fig. 11), i.e. where the direction of iceberg transports change. In addition, the imbricate reflections never occur along the straight north–south-trending parts of plough marks (Fig. 11). The relationship between the straight parts of iceberg plough marks (Fig. 7) and imbricate reflections was not obvious until sea floor maps were combined with amplitude maps from below the sea floor (Fig. 11). (vi) On seismic profiles the imbricate reflections possess similar regular dips, regular spatial frequency and crosscut reflectors. (vii) In plan view the features appear with a regular spatial period and are very linear.

A breakthrough came when we discovered that there is a one-to-one correlation between the sailing direction during seismic acquisition and the dips of the imbricate reflections within both 3D area 2 (Fig. 12) and 3D area 3 (Fig. 13). This correlation indicates that the thrust features in 3D areas 2 and 3 are artefacts. One way to get an idea of the sailing direction during 3D seismic acquisition is to study the edges of the data set. To get full-fold within the area of interest, the ship must start acquisition before entering the area of interest. Therefore, more data normally occur on the eastern side of the survey when the ship sails westwards, and when the ship sails eastwards more data occur on the western side of the survey (Figs 12 and 13). However, 3D seismic surveys are in some cases cut at the edges showing only the area of interest and not the data without full fold, and in these cases this method cannot be used.

Further investigations revealed that the red–white–black compressed colour scale used when viewing seismic profiles may cause the imbricated features to appear as soling out along a decollement zone, whereas grey-scale uncompressed images in some cases reveal that the features propagate further down beyond URU and into the Cretaceous and Triassic part of the succession before they weaken beyond detection (Fig. 14). Additionally, the smooth U-shape of the imbricated features widens slightly in plan view with depth (Fig. 5). These observations illustrate that the use of correct colour scale is important in the interpretation of seismic data, particularly 3D seismic data.

In relation to the sailing direction of the ship during acquisition, the imbricated features tend to occur on the 'lee-side' of plough marks (i.e. the opposite side from which the ship came; Fig. 11). In some cases, weak imbrication features also occur on the plough marks 'stoss-side' relative to the acquisition direction (Fig. 7c). The cause of this preferential occurrence is not clear.
The imbricate reflections in 3D areas 2 and 3 are based on the evidence above interpreted to be related to plough marks on the sea floor (Fig. 7). The imbricate reflections may represent aliased energies associated with the plough marks or diffraction hyperbolas set up by the edges of the linear parts of iceberg plough-marks parts. The fact that these imbricate reflections appear as U-shapes and not circles in time slices are unclear, but could be related to

Fig. 13. Time-structure map of the sea floor in three-dimensional (3D) area 3. Yellow arrows indicate the sailing direction of the vessel during acquisition. Black and white arrows show the orientation, dip direction and length of the imbricate reflections (black arrows indicate eastwards dip, white arrows indicate westwards dip). There is almost a 1:1 correlation between sailing direction during acquisition and the dip direction of the imbricate reflections.

Fig. 14. Vertical seismic profiles showing that the appearance of imbricate reflections depends on the display. The small black rectangle in the upper right corner represents the three-dimensional (3D) seismic survey and the white rectangle within represents the line shown in that figure. (a and c) Seismic profiles from 3D area 3 viewed with a compressed red–white–black colour scale. Note how the imbricate reflections appear to weaken and possibly sole out before reaching upper regional unconformity (URU). (b and d) The same seismic profiles, as in (a and c), are here viewed with an uncompressed grey-scale. The imbricate reflections extend deeper, even beyond URU, and do not to sole out.
the acquisition geometry or seismic processing. These artefacts are either difficult to remove during processing or not thoroughly dealt with as they are located in much shallower depths than the target depth of the 3D seismic surveys. These results reveal the importance of consulting the acquisition parameters when interpreting 3D seismic data.

CONCLUSIONS
Integration of vertical seismic transects with 3D shaded relief images of buried surfaces, volumetric attribute maps and time slices provides an excellent tool for detecting and imaging mega-scale thrust sheets, and for understanding the processes involved in glaciotectonic deformation.

Glaciotectonic features as mega-scale blocks and rafts are common within the upper two sediment packages GII and GIII in 3D area 1. These glaciotectonic features are parallel to mega-scale glacial lineations, which suggest erosion by fast-flowing ice streams during Pleistocene glaciations.

The level of detail in the 3D seismic images can, however, seduce the interpreter into treating the image purely as an aerial photograph (Bulat, 2005), and it is important not to forget that they are time-images that may include artefacts. The excellent correlation between shooting direction and dip of apparent thrust-sheet features in 3D areas 2 and 3 indicates that the apparent thrust features in these two areas are artefacts and not real. These dipping reflections are interpreted to be related to the flanks of iceberg plough marks on the sea floor. In plan view images such as time slices, and shaded relief images of interpreted horizons, they appear as lineations of smooth U-shaped crescents.

3D seismic data allow us to visualize large areas of the subsurface in unprecedented detail, and may reveal geological features that have not been described before. The data might, however, also contain 3D artefacts that have not been described before and which therefore may be difficult to recognize. Knowledge of the 3D seismic acquisition geometry and parameters used in the processing may help the interpreter to detect potential artefacts. Critical examination of the seismic data is essential before interpretation starts and the way the data are displayed can be critical with respect to identification of potential artefacts.

Knowledge of the artefact described in this paper may be of importance to those working with both seismic processing and seismic interpretation.

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B. Rafaelsen et al.


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