UiT
THE ARCTIC UNIVERSITY OF NORWAY

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The Cenozoic pre-glacial sedimentary environment of the SW Barents Sea continental margin – Lofoten Basin

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Abstract

2D seismic data have been analysed to study the Cenozoic pre-glacial sedimentary environment on the southwest Barents Sea margin and the Lofoten Basin. Based on a seismic stratigraphic analysis and correlation to previous work in the area, the pre-glacial seismic unit G0 has been subdivided into four: The unit Te1 (Eocene age), unit Te2 (Oligocene age), unit Te3 (early-middle Miocene age) and the unit Te4 (late Miocene-early Pliocene). The four units have been described and discussed with regards to the geometry and internal seismic facies, and the sedimentary processes and depositional environment dominating during the deposition of the seismic units have been outlined.

Unit Te1 was deposited as prograding clinoforms in an intracratonic basin in the Vestbakken Volcanic Province (VVP). In the Lofoten Basin, turbidites infilled the irregular relief of the newly formed oceanic basement. Seismic unit Te2 was subject to tectonic movements and a reorganization in the spreading direction of the Mohns Ridge. This probably caused erosion and non-deposition of the unit, which is thin in the VVP area. Unit Te2 shows a similar infilling by turbidites of the high-relief oceanic basement as the unit Te1 in the Lofoten Basin. Deformation by compaction and subsidence caused disruption and probably polygonal faulting in parts of the study area.

Oceanic currents dominated the depositional environment on the middle continental from the Miocene, when contourite drift growth is observed in the southwest Barents Sea margin. At the same time, hemipelagic sedimentation is suggested to dominate in the Lofoten Basin. The contourite drift was deposited continuously during the deposition of units Te3 and Te4 and the overlying glacigenic unit GI. A change in the sedimentary environment occurred in the lower continental slope simultaneously to the drift growth, when the majority of unit Te4 was affected by downslope transport of sediments. The failures are suggested to be related to weak layers in the contourite drift deposits and rapid loading. Parts of the contourite drift was later eroded and is presently overlain by the seismic unit GII. A mega-failure located within unit GII truncates the mounded drift deposits, and the failure is probably related to weak layers in the drift deposits.

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Gert Vidar Høgseth

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Contents

1 INTRODUCTION

1.1 OBJECTIVES

The objectives of the thesis are:

1. To establish a seismic stratigraphic framework for the Cenozoic deposits of the SW Barents Sea margin and Lofoten Basin, including a subdivision of the pre-glacial seismic unit G0, and subsequently correlate this to the existing stratigraphic framework established along the southwest Barents Sea margin.
2. To perform a seismic facies analysis of the pre-glacial seismic units, and to describe the seismic facies and the external geometry of these units.
3. To reconstruct the sedimentary processes and paleo-environments at time of deposition.

The study is mainly based on 2D seismic data and information from wells located within the study area. In addition, a 3D seismic cube and a well outside the main study area was used to correlate the seismic stratigraphic framework to the area of study.

The master thesis is a part of the Research Centre for ARCtic Petroleum Exploration (ARCEx). The ARCEx is a national research centre with an overarching aim to create new knowledge about the petroleum resources in the Arctic, and to provide essential knowledge and methodology for eco-safe exploration. The Department of Geology at UiT - The Arctic University of Norway (UiT), is the host institution for the centre. Five other national universities and four research institutions are involved. The Research Council of Norway (NCR), eight industry partners and in-kind contributions are the funding sources for ARCEx (http://www.arcex.no/).

1.2 STUDY AREA

The study area includes the southwest Barents Sea continental margin and the Lofoten Basin and has an area extent of roughly 220 000 km^2 (Figure 1-1). The Barents Sea is an epicontinental sea located between Norway in the south, Svalbard in the north and Russia in the east. The western margin is located adjacent to the Lofoten Basin in the southwest. The Lofoten Basin is confined between the Vøring-Lofoten-Troms margin in the south-southeast, the southwest Barents Sea margin in the east, the Mohns spreading ridge in the northwest, and the Jan Mayen Fracture Zone in the west-southwest. The water depth of the Lofoten Basin is greater than 3000 m.

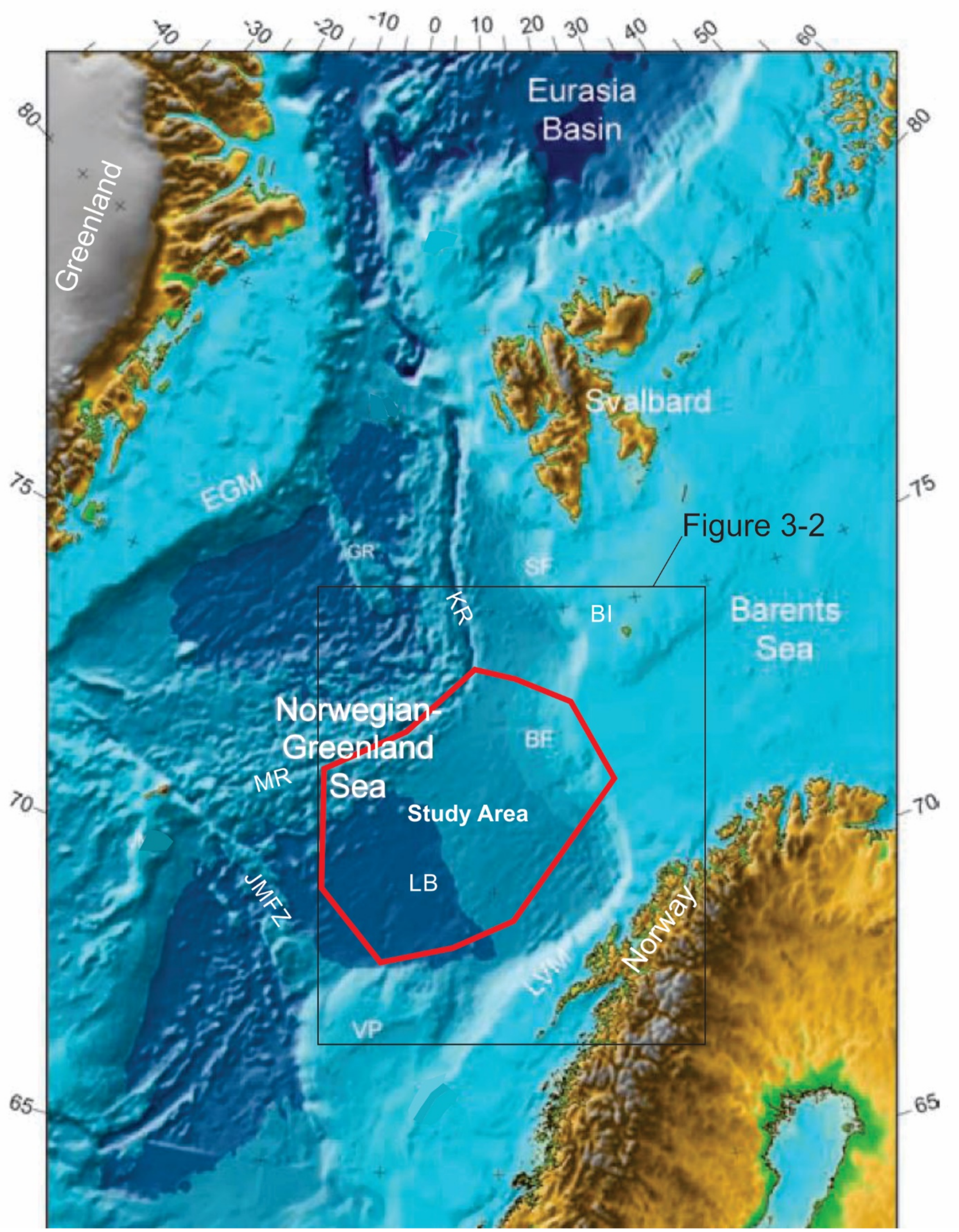


Figure 1-1: The study area is outlined in the Norwegian Sea in northern Atlantic Ocean. SF: Storfjorden Trough Mouth Fan, GR: Greenland Ridge, KR: Knipovich Ridge, MR: Mohns Ridge, BI: Bear Island, BF: Bear Island Trough Mouth Fan, LB: Lofoten Basin, EGM: East Greenland margin, JMFZ: Jan Mayen Fracture Zone, VP: Vøring Plateau, VM: Vøring margin, LVM: Lofoten-Vesterålen margin. The figure is modified from Faleide et al. (2008).

2 BACKGROUND

2.1 MARGIN MORPHOLOGY

2.1.1 NW Norway and SW Barents Sea continental shelf

The continental shelf along the passive western Norwegian-Barents Sea-Svalbard margins extends 2500 km from the North Sea, Svalbard (between 57°N and 80°N), and varies greatly with regard to width and depth. The shelf narrows from the wide Vøring Plateau SOUTHWEST of Lofoten down to a minimum of about 10 km on the Troms margin, offshore Andøya (70°N) (Dahlgren et al., 2005; Laberg et al., 2005b; Rise et al., 2013). This narrow part of the shelf comprises banks ranging in depths from 70-130 meters, and troughs ranging in depths from 80-515 meters (Rydningen et al., 2013). The shelf widens in the epicontinental Barents Sea north of Norway, and the Barents Sea shelf is one of the broadest in the world with a width of up to 1500 km (Vorren et al., 1998; Vorren et al., 2011). The Barents Sea shelf morphology is dominated by troughs up to 500 meters deep, bordered by shallower banks (Vorren et al., 1998). The Bear Island Trough is the most prominent feature with its length of 750 km and width of 150-200 km (Andreassen et al., 2008). Both underlying bedrock and structural trends, and the erosion and shaping of glaciers during Late Cenozoic glacials, influence the present Barents Sea shelf topography (Faleide et al., 1996).

2.1.2 The continental slope and the Bear Island Trough Mouth Fan

The continental slope along the Norwegian-Barents Sea margins is in general steepest off narrow shelves, and gentler beyond wider shelves (Vorren et al., 1998). Off Lofoten-Vesterålen and Troms, the average slope inclination comes up to 10° and 4-5°, respectively (Laberg et al., 2007; Rise et al., 2013). In the Bear Island Trough Mouth Fan (BITMF), beyond the Bear Island Trough on southwest Barents Sea margin, the slope inclination comes down to between 0,8-0,2°. A continental slope-rise transition is well defined off Lofoten-Vesterålen where the gradient change to 1° at ca 2500-2700 m depth, in contrast to the southwest Barents Sea, where no continental rise occurs (Eldholm et al., 2002; Rise et al., 2013).

TMFs occur on margins on both sides of the North Atlantic, and as far south as the British and Irish margins and on northern Barents Sea margin in the Arctic Ocean (Elverhøi et al., 1998; Vorren et al., 1998; Dahlgren et al., 2005). The Troms margin comprises the smaller Andfjorden, Malangsdjupet and Rebbenesdjupet TMFs (Rydningen et al., 2013), named North Norway Wedges by Dahlgren et al. (2005) (Figure 2-1).

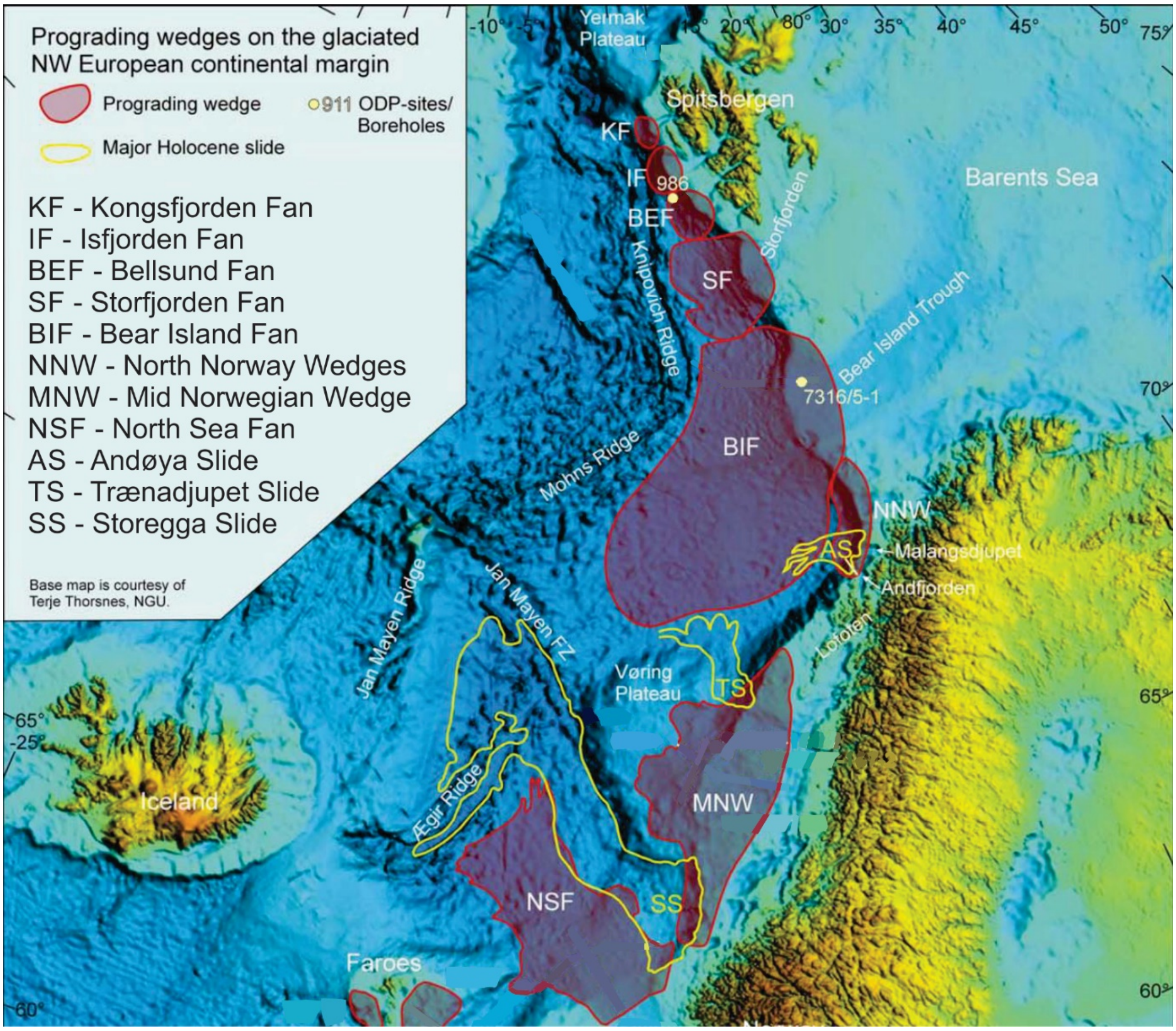


Figure 2-1: Prograding wedges and major Holocene slides along the Norway-Barents Sea – Svalbard continental margin. The figure is modified from Dahlgren et al. (2005).

The southwest Barents Sea margin comprises the largest of the Polar North Atlantic TMFs, namely the BITMF (Figure 2-1) (Andreassen et al., 2008). The BITMF covers most of the study area, also in Lofoten Basin, as it extends from the shelf break to depths of more than 3000 meters where it merges with the abyssal plain (Figure 2-1) (Laberg & Vorren, 1996a). The fan covers an area of ~280,000 km^2, and holds glacial sediments up to ~3.5 km thick, deposited on top of a pre-glacial sedimentary package (Faleide et al., 1996; Laberg & Vorren, 1996a). The total volume of sediments in the fan is estimated to be 595 000 km^3, whereof about 70% are glacigenic deposited during Late Plio-Pleistocene glacials, and the maximum discharge is expected to have occurred during mid-Pleistocene (Fiedler & Faleide, 1996; Elverhøi et al., 1998). Dahlgren et al. (2005) classified the BITMF as a mega fan, based on for example subsidence and tilting of the shelf, high sedimentation rates and long run-out distances of the gravity flows building the prograding wedges. The long run-out distances resulted in aggradation also in distal parts of the fan (Figure 2-2).

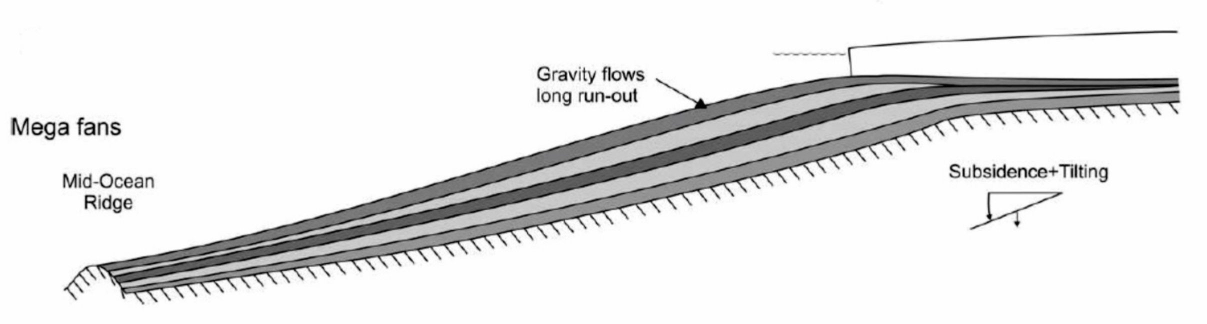


Figure 2-2: Mega fans are recognized by shelf subsidence, high sedimentation rates and long run-out distances of gravity flows, leading to aggradation also in distal parts. The figure is modified from Dahlgren et al. (2005).

Beside trough mouth fans, canyons and slide scars are important morphological features on the southwest Barents Sea and Troms margins, see for example Laberg and Vorren (1993); Laberg et al. (2000a); Rise et al. (2013) and Rydningen et al. (2015). Approximately 15 canyons along the margin northwest of Lofoten-Vesterålen have been documented. The Andøya Canyon northwest of Andøya is the largest, with an incision of up to 1100 m (Rise et al., 2013). Three slide scars left by major Holocene and Pleistocene slide events have a prominent relief on the continental slope between the Vøring Plateau in the south and the BITMF in the north. The Trænadjupet Slide in the south, the Andøya Slide on Troms margin and the Bjørnøyrenna Slide on southwest Barents Sea margin occurred from the upper continental slope or shelf break. The slides extend hundreds of kilometres downslope and into the Lofoten Basin. The Bjørnøyrenna Slide has a slide scar up to 400 m deep, and the Trænadjupet Slide have a headwall being 150 m high (Laberg & Vorren, 1993, 2000c; Hjelstuen et al., 2007).

2.1.3 Abyssal plain – Lofoten Basin

The present abyssal plain of the Lofoten Basin is deeper than 3000 meters. The distal part of the basin is a flat plain. However, the BITMF, comprising up to 70% of the sediments deposited in the basin, dominates the bathymetry with a broad bathymetric bulge along the southwest Barents Sea margin (Fiedler & Faleide, 1996; Hjelstuen et al., 2007).

2.2 SW BARENTS SEA MARGIN DEVELOPMENT

2.2.1 Pre-breakup evolution (Paleozoic – Early Cenozoic)

The western Barents Sea-Svalbard continental margin, and adjacent deep oceans, are the results of tectonic activity including rifting, volcanism, sea floor spreading and strike-slip movement since Paleozoic time. Multiple post-Caledonian rift episodes thinned and attenuated the crust prior to the final lithospheric break-up near the Paleocene-Eocene transition (ca. 56-54 Ma) (Eldholm et al., 2002; Faleide et al., 2008). Sediments deposited during rift episodes in Carboniferous-Permian-Triassic time are poorly preserved due to later tectonism and burial, but thick evaporates of Paleozoic age were deposited and are present in salt diapirs on the margin, for example in the Sørvestnaget Basin (Faleide et al., 2008). Sediments are better preserved in the deep Tromsø, Harstad, Bjørnøya and Sørvestnaget basins (Figure 2-3). They formed in response to the prominent northeast Atlantic-Arctic Late Jurassic-Early Cretaceous rift episode (Eldholm et al., 2002; Ryseth et al., 2003).

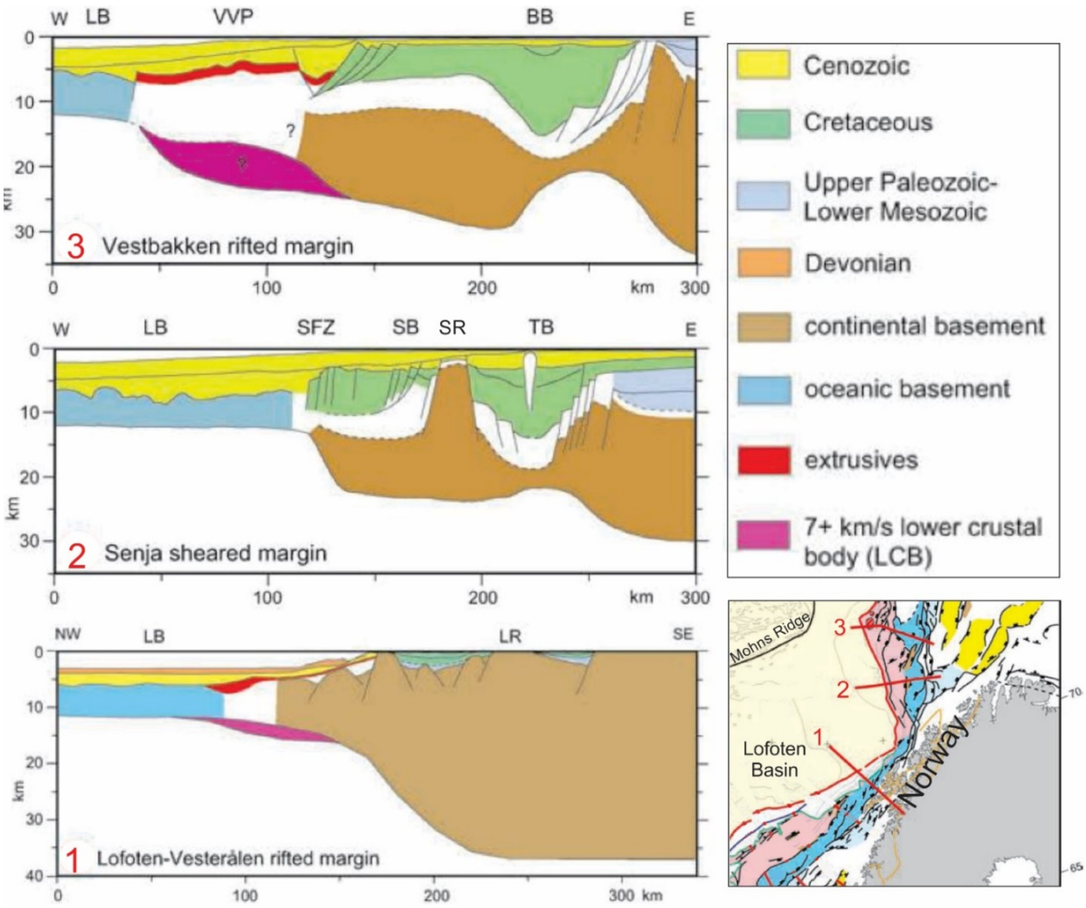


Figure 2-3: Crustal transects across the rifted Lofoten-Vesterålen margin (1), the sheared Senja margin (2) and the rifted Vestbakken margin are shown. Location of the three transects are shown in the location map. LB: Lofoten Basin, VVP: Vestbakken Volcanic Province, BB: Bjørnøya Basin, SFZ: Senja Fracture Zone, SB: Sørvestnaget Basin, SR: Senja Ridge, TB: Tromsø Basin, LR: Lofoten Ridge. The figure is modified from Faleide et al. (2008).

2.2.2 Cenozoic break-up and sea-floor spreading

An epicontinental sea existed between Fennoscandia, Greenland and Svalbard when the final lithospheric break-up occurred near the Paleocene-Eocene transition at ca. 56-54 Ma (Figure

2-4). Late Cretaceous-Paleocene extension changed to strike-slip movements/deformation within the De Geer Zone along the Svalbard-Barents Sea margin. Breakup initiated first in south, and progressed northward. Massive magmatic activity, lasting ca 3-6 m.y. followed the break-up and the onset of sea-floor spreading, and have left distinct extrusive and intrusive magmatic imprints on the margin segments (Faleide et al., 2008).

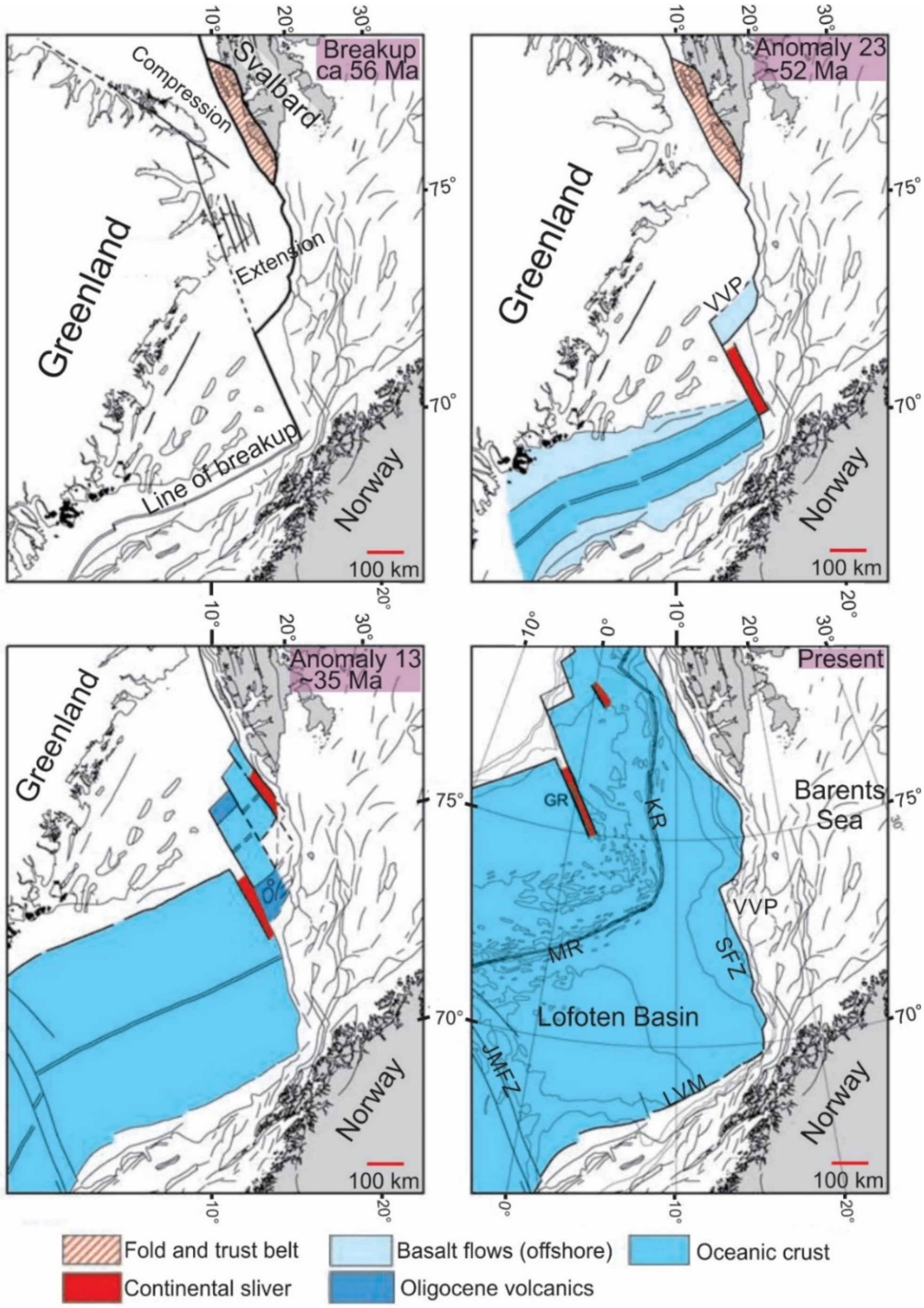


Figure 2-4: A four-stage model of the opening of Norwegian-Greenland Sea from ~56 Ma until present. VVP: Vestbakken Volcanic Province, SFZ: Senja Fracture Zone, GR: Greenland Ridge, KR: Knipovich Ridge, MR: Mohns Ridge. The figure is modified from Faleide et al. (2008).

The sheared southwest Barents Sea margin developed further during the Eocene opening of the Norwegian-Greenland Sea, and has been passive since Oligocene, with subsidence of the margin and deposition of a thick Neogene sediment succession (Figure 2-4 and Figure 2-3) (Ryseth et al., 2003; Faleide et al., 2008).

The present passive continental margin of western Troms and southwest Barents Sea holds three major structural segments; the northern rifted segment of the VVP, the central sheared Senja Fracture Zone (SFZ) on southwest Barents Sea margin and the rifted Lofoten-Vesterålen margin (LVM) in the south (Figure 2-4) (Ryseth et al., 2003; Faleide et al., 2008).

2.3 GLACIAL HISTORY

2.3.1 Paleogene and Miocene (66 Ma – 5.3 Ma)

The oldest ice-rafted debris (IRD) found in cores from the Lomonosov ridge in the Arctic Ocean are dated to about 46 Ma. Drifting sea-ice is suggested to be the main transport process of IRD into the Arctic Ocean at the time, but IRD from icebergs calved from continents surrounding Arctic Ocean cannot be excluded (Stickley et al., 2009). Moran et al. (2006) suggested that sea ice and icebergs also were present in Arctic Ocean later, in early Miocene, and resulted in increasing sediment rates and IRD dominated by dropstones. The amount of ice-derived sand started increasing significantly at ~14 Ma, along with irregular intervals of cold- to cool-water dinoflagellates, suggesting seasonal ice conditions (Moran et al., 2006).

Glaciers large enough to reach coastal areas around Iceland-Norwegian Sea during middle Miocene (~12.6 Ma) were suggested by Fronval and Jansen (1996) based on stable isotope stratigraphy and sedimentary methods on cores from Vøring Plateau west of mid-Norway. This coincided with a probable establishment of Atlantic water inflow, deep-water convection and intensification of North Atlantic Deep Water production at 12.5 Ma. IRD on Vøring Plateau further indicates gradual cooling of the Iceland-Norwegian Sea deep water from ~11 Ma – 6.4 Ma. Expansion of ice sheets around Iceland-Norwegian Sea at 7-6 Ma, inferred from increased IRD, represents the onset of small-scale Northern Hemisphere Glaciation (Fronval & Jansen, 1996).

2.3.2 Pliocene & Pleistocene (5.3 Ma – Last Glacial Maximum)

Small-scale ice sheets existed periodically between 6 and 3 Ma around the Iceland-Norwegian Sea (Fronval & Jansen, 1996). Individual and significant IRD peaks from 5.5 Ma to 3.5 Ma, and a series of smaller IRD peaks from 2.8 Ma to 2.57 Ma, document the early development of glaciation at high northern latitudes (Jansen & Sjøholm, 1991; Fronval & Jansen, 1996). A two - three order of magnitude increase in IRD flux at 2.57 Ma indicate a much smaller ice extent in the period up to the onset of Northern Hemisphere Glaciation (NHG) (Jansen & Sjøholm, 1991). Fronval and Jansen (1996), Ravelo et al. (2004) and Eidvin et al. (2014) suggested the onset of NHG to have taken place at ~2.74-2.75 Ma, while Thiede et al. (1989) and Jansen and Sjøholm (1991) suggested that the onset took place at 2.6 Ma and 2.57 Ma, respectively.

Knies et al. (2009) proposed a new glaciation model for the Barents Sea ice sheet from 3.6 Ma, including three phases of ice growth: the initial growth phase, the transitional growth phase and the final growth phase. The three phases of Knies et al. (2009) will be further described below. Their work was based on a revised chronostratigraphy and a compilation of borehole data from Yermak Plateau, Fram Strait and western Barents Sea.

2.3.2.1 Phase 1 - the initial growth phase – the onset and termination of NHG (3.6 – 2.4 Ma)

Mountainous to coastal style glaciations on an exposed Barents Sea are inferred from IRD and mineralogical data between 3.6 and 2.4 Ma (Figure 2-5). Short-term glacial expansions beyond the coastline at ~2.7 Ma on northern/western Barents Sea and in northern Greenland/Canada are concomitant with the global ice volume increase at the time, and implies a circum-Atlantic-Arctic response to climate deterioration during Late Pliocene (Knies et al., 2009; Rebesco et al., 2014a). This marks the onset for glacially derived deposits on the continental slope, and the formation of the R7 reflector (Section 2.6.2) (Faleide et al., 1996; Knies et al., 2009).

2.3.2.2 Phase 2 - the transitional growth phase (~2.4-1.0 Ma)

The Barents Sea Ice Sheet developed to a moderate size during the transitional phase (Figure 2-5). Somewhat less glacial activity from 2.4 – 1.6 Ma is inferred from reduced IRD input in the Fram Strait and circum-Atlantic (Knies et al., 2009). Butt et al. (2000) found that glaciers did not reach the shelf break until 1.5 Ma in northwest Barents Sea and along western Svalbard margin. Rebesco et al. (2014a) suggested that this event occurred even later, around 1.3 Ma, with the formation of reflector R4a. This implies an ice sheet that reached the shelf break first in northern Barents Sea, second in the southwest Barents Sea from R5 time at ~1.5 Ma, and finally west of Svalbard from R4a time at ~1.3 Ma (Andreassen et al., 2007a; Knies et al., 2009; Laberg et al., 2010; Rebesco et al., 2014a). The sub-aerially exposed Barents Sea was dominated by glacio-fluvial drainage, supplying the western Barents Sea-Svalbard margin with sediments at a relatively high sedimentation rate during this time (Butt et al., 2000; Laberg et al., 2012).

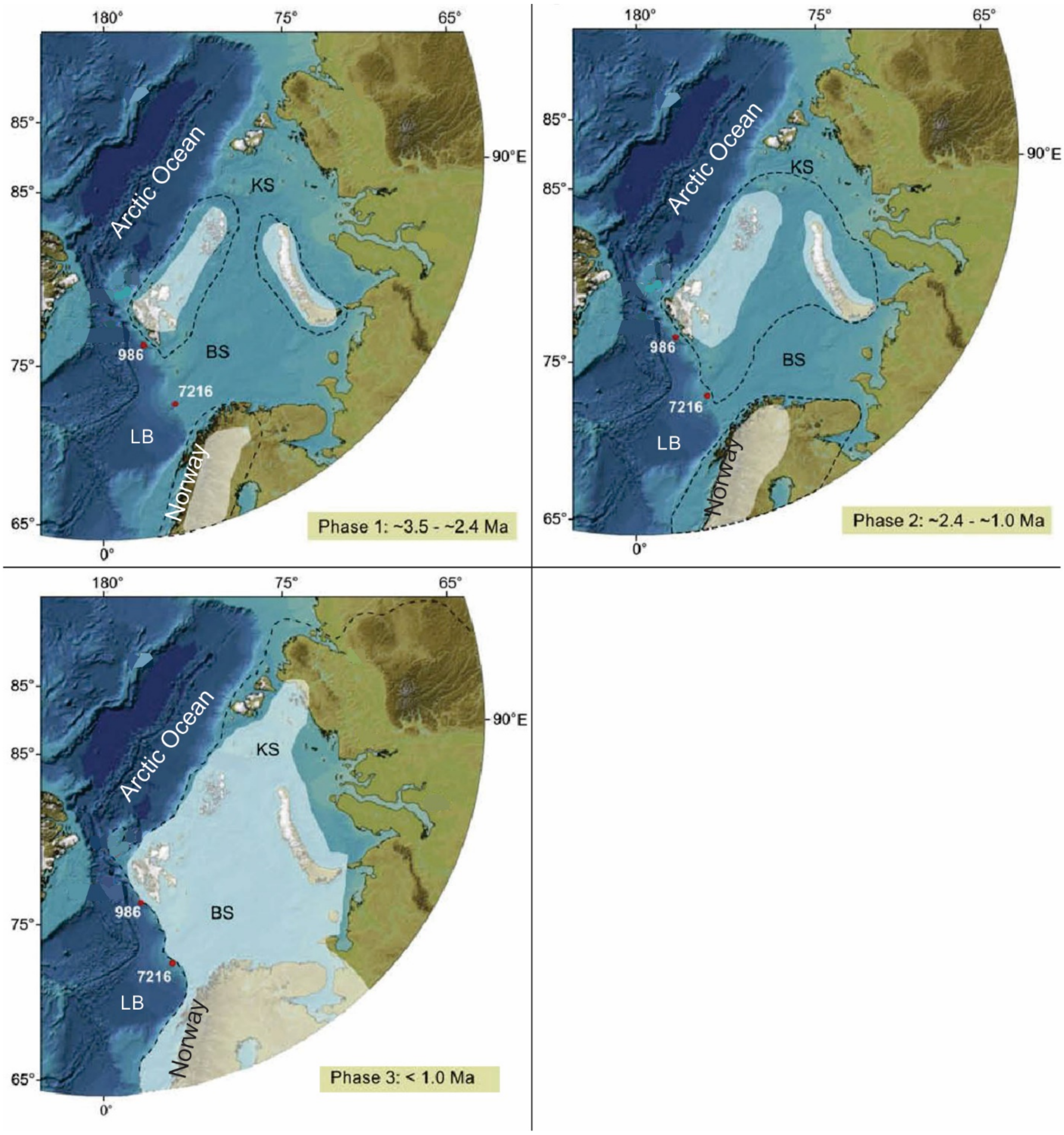


Figure 2-5: The three growth phases of the Barents Sea Ice Sheet as presented by Knies et al. (2009). The ice sheet may have varied in extent between the two extremes indicated (black dashed lines indicates maximum, white shaded areas indicates the minimum extent) several times during Phase 1 and 2. During Phase 3, the Barents Sea was completely covered by the Barents Sea Ice Sheet at several occasions. Phase 3 is here represented by the reconstruction of the Saalian glacial (the maximum extent, outlined with black stippled lines) and the Last Glacial Maximum (LGM) (the minimum extent, indicated with white shaded areas). BS: Barents Sea, KS: Kara Sea, LB: Lofoten Basin. Red spots indicate locations of borehole 986 and well 7216/11-1S. The figure is modified from Knies et al. (2009).

Enhanced IRD supply to the Fram Strait and acoustic and sedimentological data from the western Svalbard-Barents Sea margin indicate that a grounded ice sheet extended to the shelf break at ~1.5 Ma. (Andreassen et al., 2004; Andreassen et al., 2007a; Knies et al., 2009). Together with the presence of the prominent reflector R5, this supports a presumption of a transition from a land-based ice mass on an emergent Barents Sea shelf during Late Pliocene, to a fully developed ice sheet with glaciers delivering sediments directly at the shelf edge during early Pleistocene, around ~1.5 Ma. (Knies et al., 2009). Though ice sheets covered the entire shelf periodically from 1.5 Ma, the troughs were probably still not fully developed on the shelf to confine the ice streams, with the result that larger areas were affected by smaller ice streams. Rebesco et al. (2014a) proposed that the onset of growth of trough mouth fans on Svalbard-Barents Sea margins occurred after R4a time, and that this probably reflected the full development of glacial troughs and ice streams eroding them.

2.3.2.3 Phase 3 - the final growth phase (~1.0-0.01 Ma)

The final growth phase is dominated by the large-scale intensification of glaciation in the Barents Sea at ~1.0 Ma (Knies et al., 2009). The majority of the Barents Sea shelf had become submarine at ~1.0 Ma (Butt et al., 2002). This may have contributed to the intensification and resulted in a maximum ice sheet configuration (Figure 2-5) (Knies et al., 2009). Ice sheets covered the entire Barents Sea shelf several times during the last 1 myr. The development of troughs proceeded during this time. Erosion on the shelf affected mainly the trough-areas after 0.7 Ma (Laberg et al., 2012).

Shelf edge glaciations have been documented by the presence of imprints of former ice streams on the shelf (Andreassen et al., 2007a; Andreassen et al., 2008; Ottesen et al., 2008). Other indications on shelf-edge glaciations are the occurrence of Mesozoic sediments from the Barents Sea shelf in massive meltwater pulses from disintegrating ice sheets on the shelf edge (Knies et al., 2009) and the remobilization of slope sediments in the form of glacigenic debris flows and large-scale slides, (Laberg & Vorren, 1993, 1996a; Hjelstuen et al., 2007; Knies et al., 2009). Though ice sheets covered the Barents Sea shelf during several periods also the past 150 ka, areas in southwest Barents Sea may also have been ice-free for episodes lasting tens of thousands of years (Mangerud et al., 1998; Svendsen et al., 2004).

2.3.3 The last glacial maximum and the deglaciation

The Barents Sea Ice Sheet coalesced with the Fennoscandian Ice Sheet in the south, the Kara Ice Sheet in the east and the Svalbard Ice Sheet in the north during the LGM (Figure 2-6)

(Svendsen et al., 2004; Ottesen et al., 2005; Andreassen et al., 2008; Knies et al., 2009). Svendsen et al. (2004) suggested that an ice divide with an ice thickness of about 1000 meters was located over central parts of the Barents Sea at 20 Ka, and inferred a further increased in ice thickness to between 1500 and 1800 meters prior to the initiation of deglaciation (Svendsen et al., 2004).

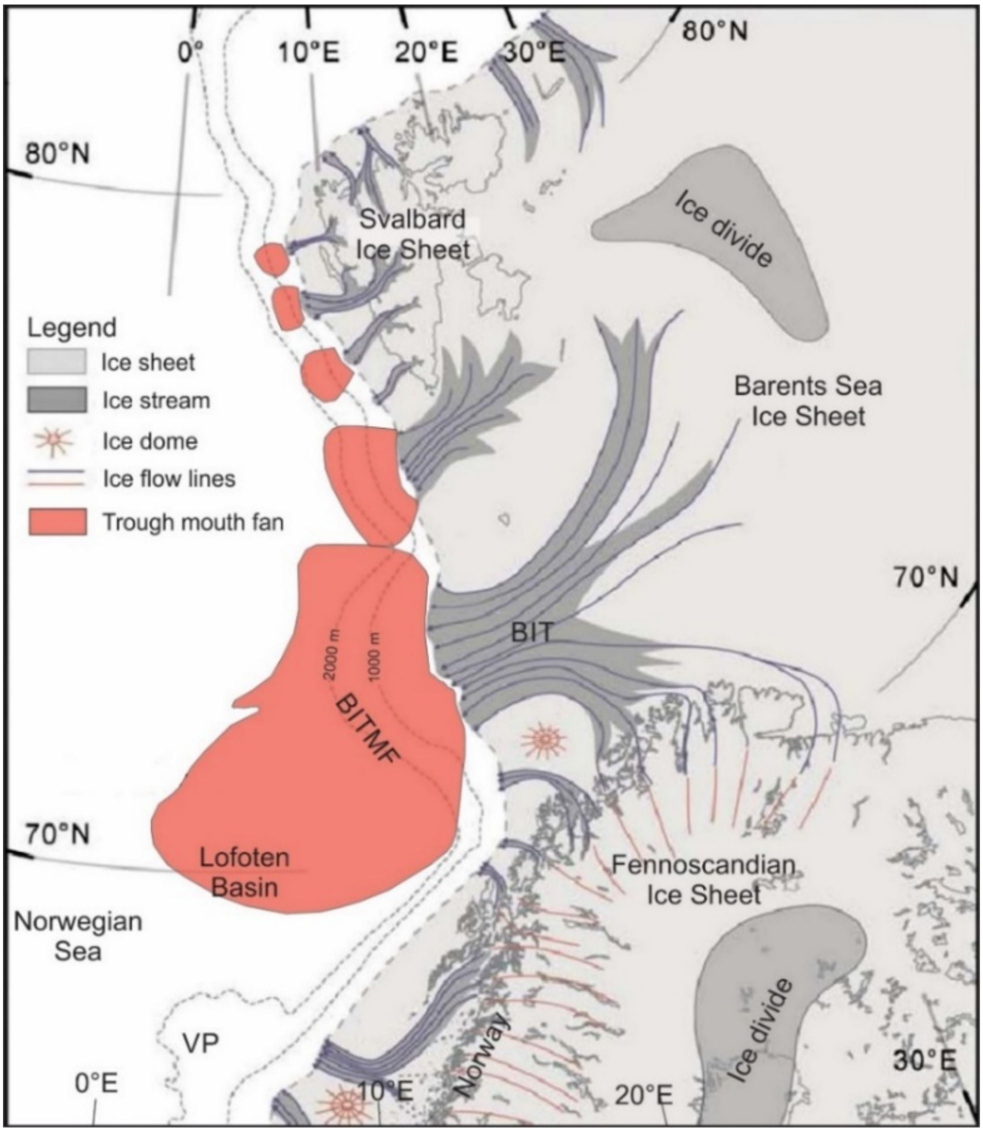


Figure 2-6: Map showing the ice sheet extent during the last glacial maximum. Ice flow lines and the trough moth fans of the western Barents Sea – Svalbard ice sheets are indicated. The trough mouth fan outlines are reconstructed from Vorren & Mangerud (2008). The figure is modified from Ottesen et al. (2005).

Glacial landforms formed by the Fennoscandian (FIS) and Barents Sea Ice Sheet (BSIS) during the Late Weichselian and the subsequent deglaciation have been preserved throughout the Troms and Barents Sea shelf, see for example Ottesen et al. (2005); Andreassen et al. (2008);

Ottesen et al. (2008); Winsborrow et al. (2010); Rydningen et al. (2013); Andreassen et al. (2014); Bjarnadóttir et al. (2014) and Rebesco et al. (2014a).

Flow sets of mega scale glacial lineations (MSGL) in troughs document the presence and dynamics of fast flowing ice streams draining the ice sheets (Figure 2-6) (Rydningen et al., 2013; Andreassen et al., 2014). End moraines and grounding zone wedges locally overprint the MSGLs. Such larger grounding zone systems represent the maximum extent of the ice stream at last glacial maximum, and/or halts or readvances during overall retreat of the ice sheet (Rydningen et al., 2013; Bjarnadóttir et al., 2014). Many smaller transverse ridges, and absence of MSGLs, on the banks, suggest a slower flowing or stagnant part of the ice sheet here (Ottesen et al., 2008; Rydningen et al., 2013).

Iceberg scours occur both in the troughs and on the banks, however, more frequent on the banks and along the trough-flanks (Andreassen et al., 2008; Ottesen et al., 2008; Rydningen et al., 2013). Lateral moraines and lateral shear zone moraines occurs at the transition between banks and troughs, and represents the border zone between fast ice flow and stagnant or sluggish ice flow (Ottesen et al., 2005; Rydningen et al., 2013).

Winsborrow et al. (2011) suggested an initial retreat of the Barents Sea Ice Sheet after 19 cal ka BP. The ice sheet grounding line in the BIT retreated rapidly during the following 2000 years, separated by periods of relative ice margin stability, and within 16 cal ka BP, much of BIT was ice-free. About 1000 years later, the ice margins had retreated onshore (Winsborrow et al., 2010). Reconstruction models for the deglaciation of the BSIS have been proposed by for example Winsborrow et al. (2010), Andreassen et al. (2008) Andreassen et al. (2014), Bjarnadóttir et al. (2014) and Rebesco et al. (2014a).

2.4 OCEANOGRAPHY AND OCEANIC CURRENTS

In the earliest parts of the Cenozoic, the ocean circulation in the North Atlantic was restricted. From the Late Oligocene to mid-Miocene it evolved to the present-day pattern following the opening of the Fram Strait (northern) and Faroe Conduit (southern) gateways. An early Neogene massive increase in contourite drift formation in the North Atlantic and the Norwegian – Greenland Sea is probably related to the opening of the gateways (Laberg et al., 2005a; Rasmussen et al., 2007; Hjelstuen & Andreassen, 2015). As a response to the ocean circulation development, slope-parallel bottom-currents dominated the Neogene sedimentation on the mid-Norwegian margin from ~12 Ma to ~3-4 Ma, (see 2.5.1). (Laberg et al., 1999; Laberg et al., 2001; Bryn et al., 2005; Laberg et al., 2005a; Rebesco et al., 2014b). Subsequently, glacially derived sediments dominate on the margin from R7 time (Faleide et al., 1996; Knies et al., 2009).

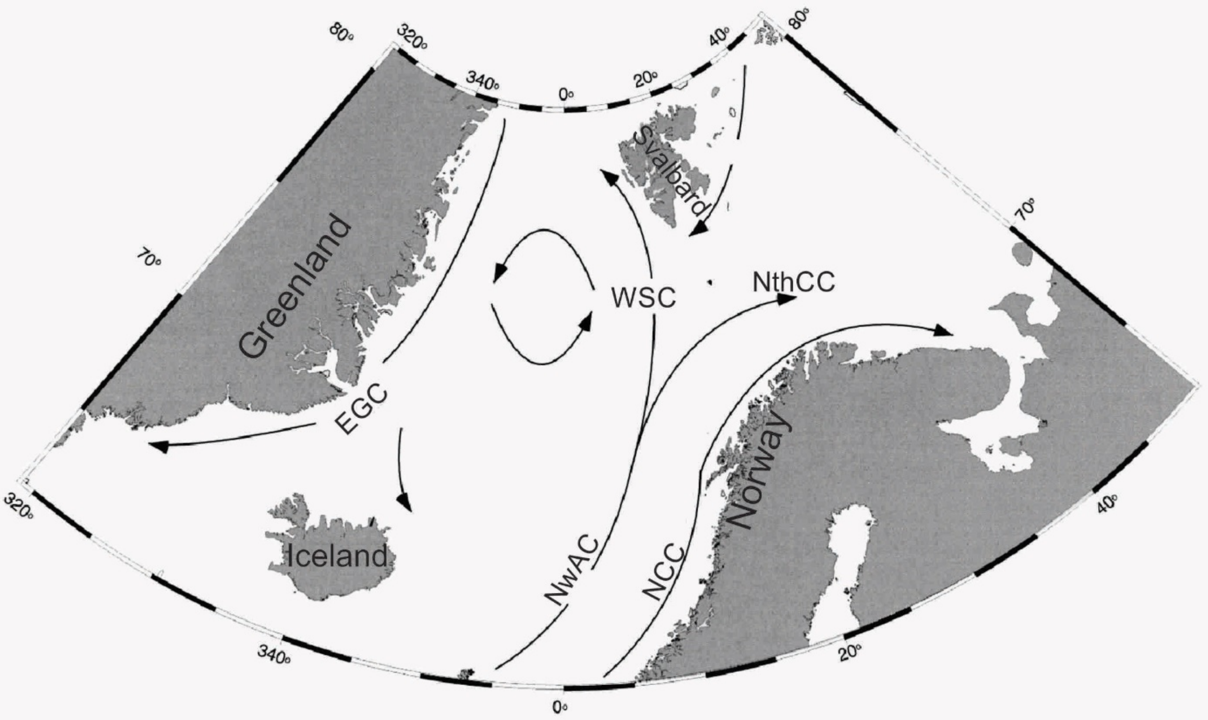


Figure 2-7: A simplified, modern oceanic circulation pattern in the northeast Atlantic is shown with the NwAC flowing along Norwegian margin, and subsequently splits into three branches north of Lofoten Basin. WSC: Western Spitsbergen Current, NthCC: North Cape Current, EGC: East Greenland Current, NwAC: Norwegian Atlantic Current, NCC: Norwegian Coastal Current. The figure is modified from Butt et al. (2000).

The modern oceanic circulation in the Norwegian – Greenland Sea includes the Norwegian Atlantic Current (NwAC), bringing warm, saline surface and intermediate water northwards, and as a response, cold, dense water is flowing south into the North Atlantic along east Greenland (Hansen & Østerhus, 2000). The NwAC is the northeast branch of the North Atlantic Current (NAC) and dominates the upper 500-700 meters of the water column. The Norwegian Sea Arctic Intermediate Water flows below the NwAC aligned with the large-scale bottom topography (Hansen & Østerhus, 2000; Bryn et al., 2005). The northward flowing NwAC fills the entire Lofoten Basin and resides there for a longer time before continuing northwards. North of the Lofoten Basin, the NwAC splits into three branches: one branch flows eastward into the Barents Sea and subsequently northward into the Arctic Ocean, the Western Spitsbergen Current flows west of Spitsbergen/Svalbard and enters the Arctic Ocean, and the third branch flows west across the Fram Strait and enters the southward flowing East Greenland Current (Mauritzen, 1996). NwAC cools and sinks to form Norwegian Sea Deep Water (Figure 2-7) as it approaches colder conditions northward. Returning cold and dense, intermediate and deep-water flows south into the North Atlantic via deep-water passageways (Bryn et al., 2005; Laberg et al., 2005a).

2.5 SEDIMENTARY PROCESSES

2.5.1 Along-slope processes

Alongslope sedimentary processes are related to oceanic currents and their ability to erode, transport and deposit sediments on continental margins. Erosion may lead to unconformities, and deposition may result in the formation of contourite drifts, see for example Laberg et al. (2005a), Nielsen et al. (2008) and Rebesco et al. (2014b). Contourites are “sediments deposited or substantially reworked by the powerful action of bottom currents” (Rebesco et al., 2014b).

Nielsen et al. (2008) described important characteristics for contourite drift deposits, including seismic elements of different scales (Figure 2-8). The large-scale elements reflect the long-lasting, stable conditions required to form a large contourite drift. The medium scale elements reflect smaller fluctuations like composition, homogeneity and bedding, causing variations in the sediment characteristics. Small-scale elements include internal seismic facies.

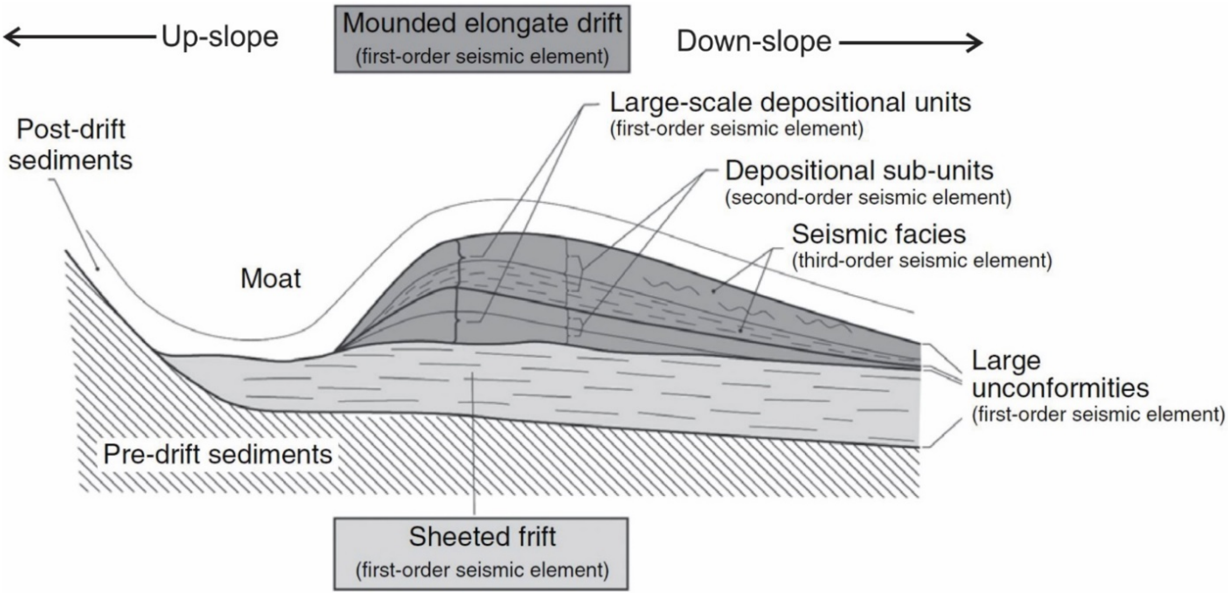


Figure 2-8: The principal seismic characteristics of a contourite drift deposit is shown. The alongslope flowing current would flow and erode within the moat depression in this setting. The down-slope deposition would construct the mounded external geometry. The figure is modified from Nielsen et al. (2008).

The sediments may hold a continuous and relatively high-resolution sediment record. They are found for example on continental slopes and in adjacent basins, and range in size from a few tens to several hundred thousand square kilometres (Rebesco et al., 2014b). They are up to 2 km thick with a relief of up to 1.5 km. Their morphology and overall geometry depends on for example the bathymetric setting, current conditions, sediment availability and interaction with other depositional processes (Rebesco et al., 2014b). Different drift types have been identified, and examples of mounded, elongated and infilling drifts are shown in Figures 2-8 and 2-9.

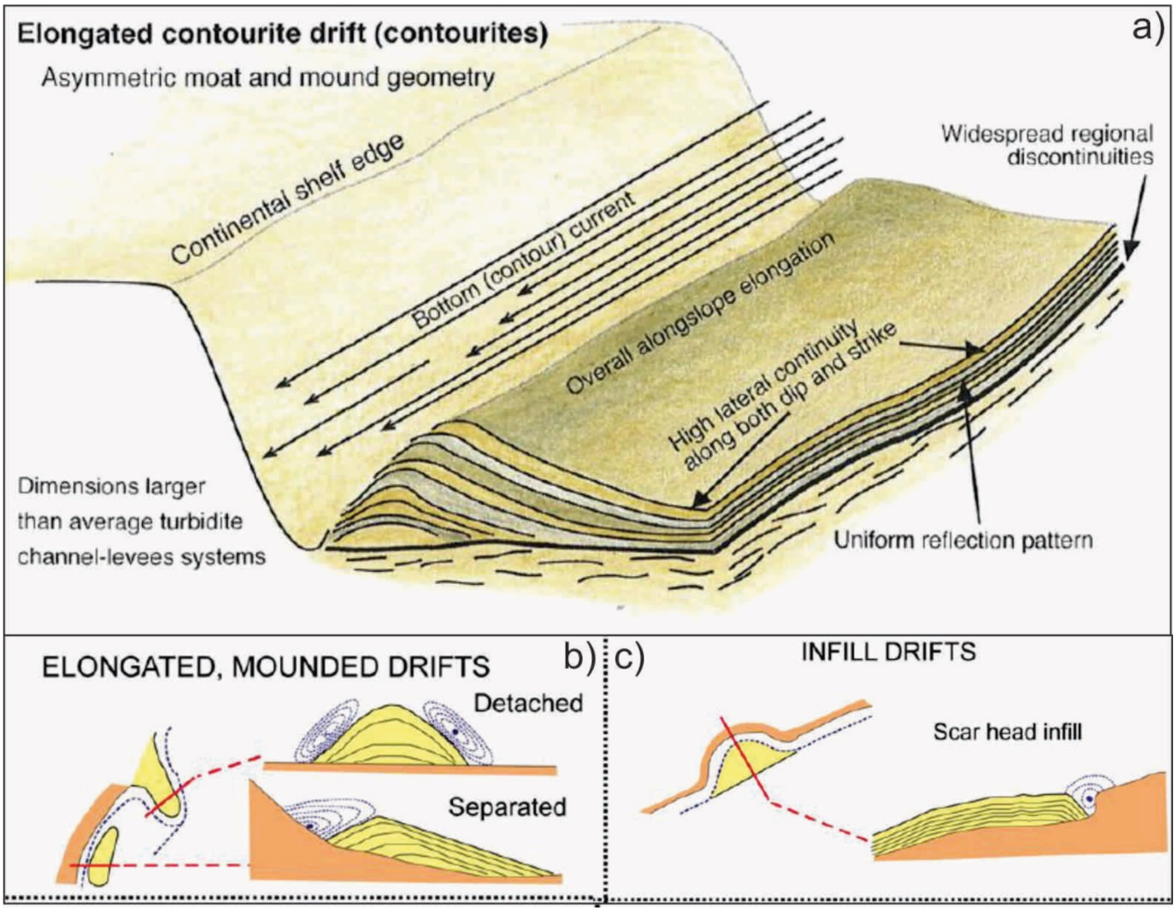


Figure 2-9: Examples of elongated (a), (b) and infilling (c) drifts. Sediment accumulations are indicated with yellow, and bottom-current path indicated in circular lines in b) and c). The figure is modified from Rebesco et al. (2014b).

Not much literature have been published regarding alongslope processes on the western Barents Sea margin. However, alongslope processes and contourite deposits are documented for the western Spitsbergen margin, e.g. Hustoft et al. (2009) and Rebesco et al. (2014a), and mid-Norwegian margin north to Lofoten, see for example Laberg et al. (1999); Laberg et al. (2001); Laberg et al. (2005a) and Bryn et al. (2005). Laberg et al. (2001) sums up four drift accumulations on the northern Norwegian margin, including the mounded, elongated, upslope accretion Lofoten, Vesterålen and Nyk drifts, and the infilling Sklinnadjupet Drift. Alongslope processes are shown in a larger context in a conceptual model in Figure 2-10.

2.5.2 Downslope processes

Downslope processes are gravity driven processes responsible for the re-sedimentation of sediments on the continental slope or in the deep-sea basin (STRATAGEM Partners, 2003). The transport mechanisms include creeping (semi-continuous), sliding, slumping, debris flows (lasting from minutes to hours) and turbidity currents (lasting from hours to days) (STRATAGEM partners, 2003). Downslope processes have been important agents for the shaping and outbuilding of the BITMF since ~1.0 Ma, and deposits related to downslope processes are inferred to dominate the BITMF from this time (Laberg & Vorren, 1996a; Dahlgren et al., 2005; Hjelstuen et al., 2007). A conceptual model for alongslope and downslope processes is shown in Figure 2-10.

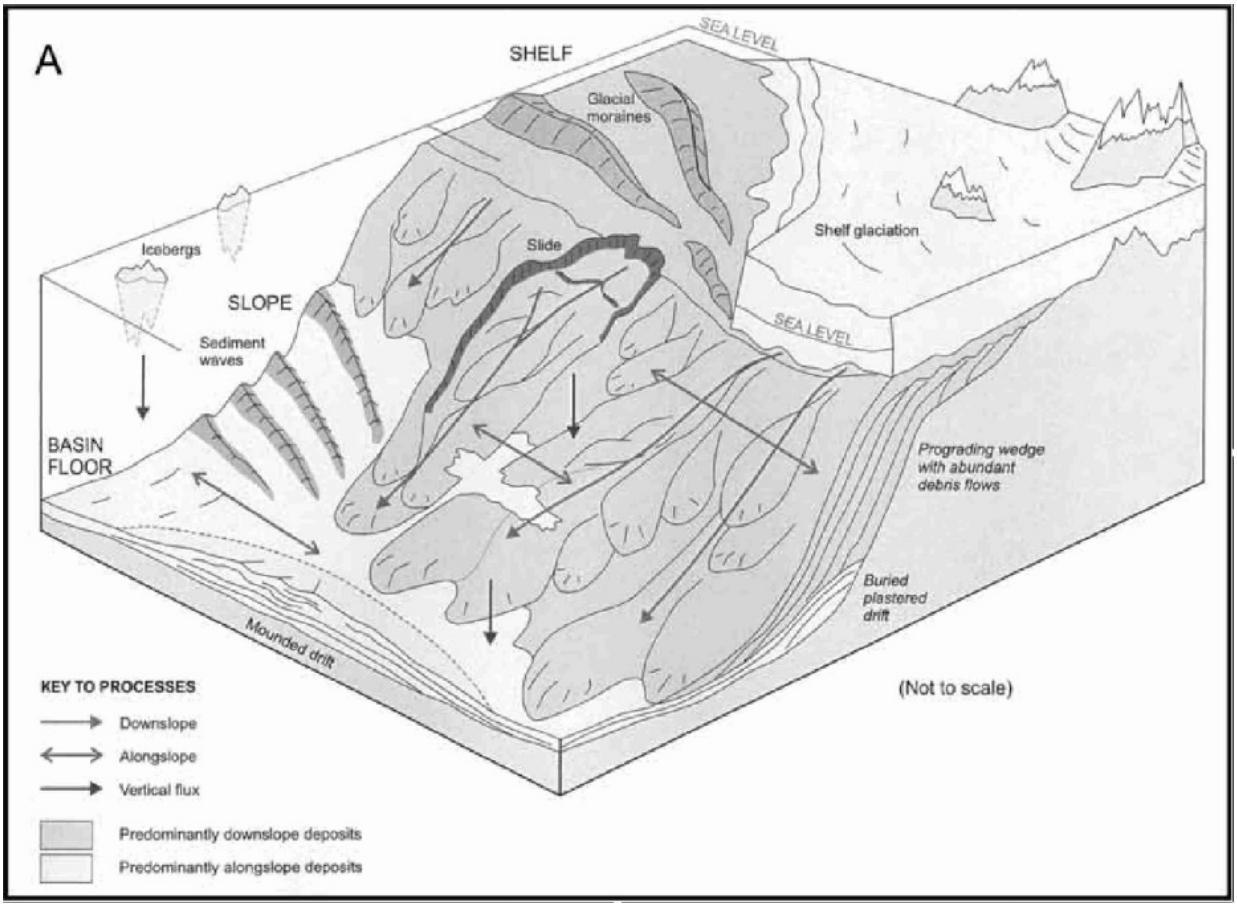


Figure 2-10: A conceptual model for alongslope and downslope processes on a glaciated margin. The figure is modified from Dahlgren et al. (2005), originally published by STRATAGEM Partners (2002).

Canyons and channels have not been described on the BITMF. However, the Lofoten Basin Channel (see for example Dowdeswell et al., 1996; Vorren et al., 1998; Laberg et al., 2000a and Haflidason et al., 2007) and the INBIS Channel (Vorren et al., 1998) have been described on the Troms margin and for the intra-fan area between the BITMF and Storfjorden TMF, respectively.

According to Hjelstuen et al. (2007), more than thirty large slides have been identified on Norway-Barents Sea margin. Nine of them have occurred in or adjacent to the study area (Figure 2-11). All of them are of Plio-Pleistocene age and most are younger than 1 Ma. Safronova et al. (2015) documents at least five large-scale submarine slide debrites located on the NW Barents Sea continental margin. The slides formed between 2.7 and 2.1 Ma, and probably pre-dates the shelf-edge glaciation in the area.

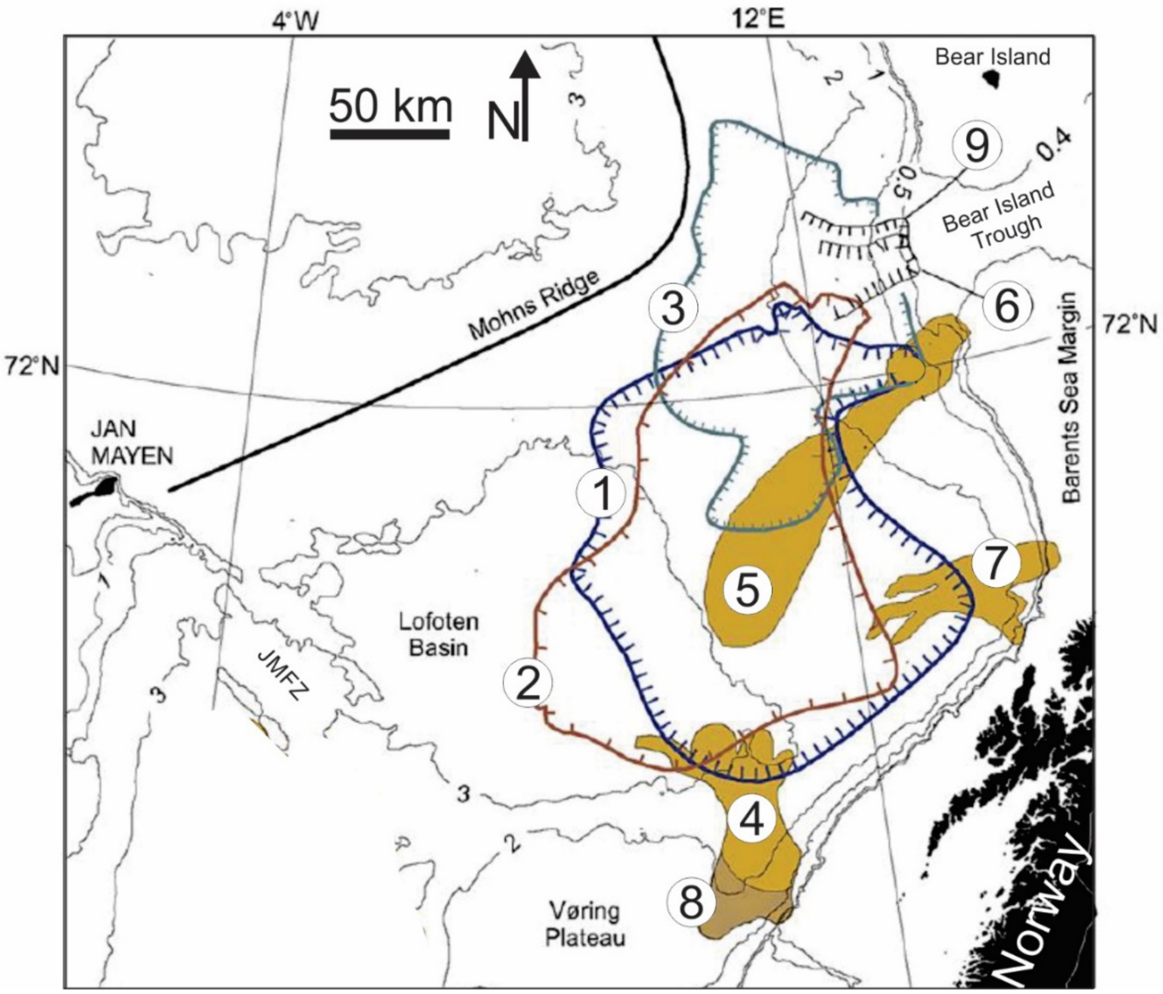


Figure 2-11: Location of large-scale slides depositing in Lofoten Basin and adjacent margins. 1) BFSC II; 2) BFSC I; 3) BFSC III; 4) Trænadjupet Slide; 5) Bjørnøya Slide; 6) Slide A; 7) Andøya Slide; 8) Nyk Slide; 9) Slide B. Contour lines show depth in 1000 meters. The figure is modified from Hjelstuen et al. (2007).

The three large Storegga, Trænadjupet and Andøya slides occurred on the mid- to northern Norwegian margin during Holocene. The latter two runs into southern Lofoten Basin (Laberg et al., 2000a; Hjelstuen et al., 2007). Six large-scale slides have been pointed out on the BITMF: Slide A (0.5-0.6 Ma), Slide B (0.5-0.6 Ma), Bjørnøya Slide (0.2-0.3 Ma) and Bjørnøya Fan Slide Complexes (BFSC) I (0.5-0.78 Ma), II (0.78-1.0 Ma) and III (0.2-0.5 Ma) (Laberg & Vorren, 1993, 1996a; Laberg et al., 2000a; Hjelstuen et al., 2007). Hjelstuen et al. (2007) suggested that increased loads of rapidly deposited glacigenic sediments on a softer substratum along with a trigger mechanism, probably an earthquake, provided slope failure conditions for the BFSC I-III to happen. Similar causes for Bjørnøya Slide were suggested by Laberg and Vorren (1993), and Solheim et al. (2005) reports that seven large slides mapped within the Storegga Slide complex probably were related to the shifts between fine-grained marine hemipelagic deposition and rapid glacial deposition of tills and debris flows. Contourite deposits have also been linked to slope failures, as described by for example Bryn et al. (2005) and Bull et al. (2009a, 2009b).

Laberg and Vorren (1996a) described eight seismic units outlining the evolution of BITMF since TeE time of Vorren et al. (1991), corresponding to R1 time of Faleide et al. (1996), and thus corresponding to seismic unit GIII. The eight units are dominated by a chaotic seismic signature on the upper fan, and a mounded seismic facies further downslope, indicating deposition of large submarine debris flows on the lower fan. They suggested that oversteepening of the slope, build-up of excess pore water pressure and/or seismic activity led to sediment failure on the upper slope and transport downslope as GDFs (Laberg & Vorren, 1996a).

2.6 SEISMIC STRATIGRAPHIC FRAMEWORK

A Cenozoic seismic stratigraphic framework has been established for the entire western Barents Sea – Svalbard continental margin. The framework includes one pre-glacial seismic unit, named G0 (oldest), and three prograding, glacigenic seismic units, named GI, GII and GIII (youngest), forming the BITMF in front of the BIT (Figure 2-12) (Vorren et al., 1989; Faleide et al., 1996; Fiedler & Faleide, 1996; Hjelstuen et al., 1996). The seismic units are bounded by the oceanic or continental crust at the base and the sea floor surface at the top. Seven regionally correlatable reflectors, the R7 (oldest) – R1 (youngest) are included in the framework. The R7 reflector (separating the G0 and GI units), the R5 reflector (separating the GI and GII units) and the R1 reflector (separating the GII and GIII units) separate the seismic units while reflections R6, R4, R3 and R2 are significant internal reflectors within the different main seismic units (Figure 2-12) (Vorren et al., 1991; Faleide et al., 1996).

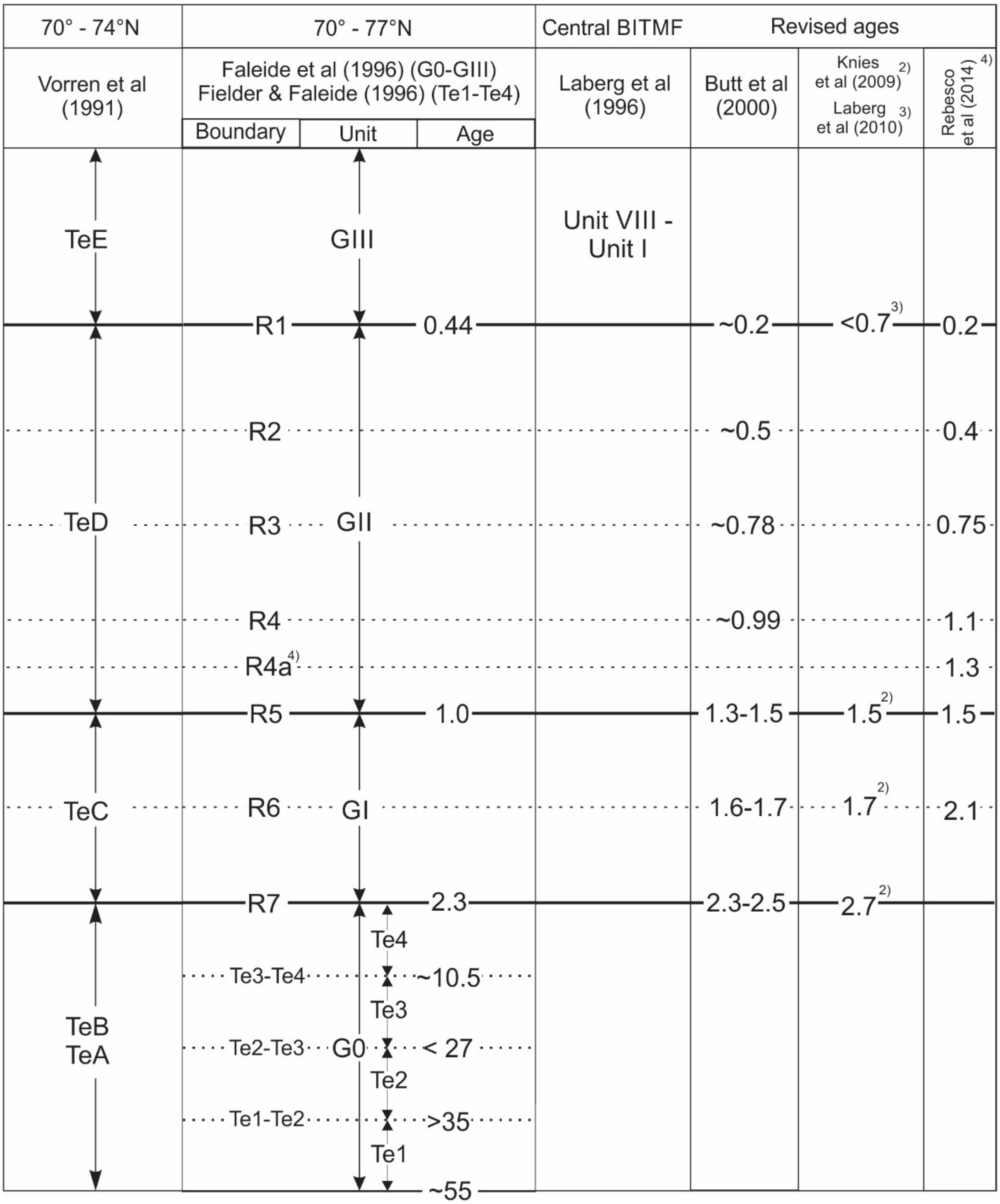


Figure 2-12: The main seismic units, unit boundaries and age ranges for Cenozoic sediments on the western Svalbard - Barents Sea margin as presented by Vorren et al. (1991), Faleide et al. (1996), Fiedler and Faleide (1996), Laberg and Vorren (1996), Butt et al. (2000), Knies et al. (2009), Laberg et al. (2010) and Rebesco et al. (2014a).

The seismic units and reflectors R7-R5 and R1 correspond to previously identified units and reflectors documented by other authors in the western Barents Sea, see for example Eidvin and Riis (1989); Vorren et al. (1991); Sættem et al. (1992); Eidvin et al. (1993); Knutsen et al. (1993); Richardsen et al. (1993) and Sættem et al. (1994). Vorren et al. (1991) defined the seismic units TeA (oldest) to TeE in Egga Basin on western Barents Sea margin. TeA-TeB corresponds to G0 of Faleide et al. (1996) and Fiedler and Faleide (1996). The base of TeC corresponds to R7, and seismic units TeC-TeA corresponds to seismic units GI-GIII of Faleide et al. (1996) and Fiedler and Faleide (1996). Based on high resolution seismic sparker data, Laberg and Vorren (1996a) sub-divided seismic unit GIII of Faleide et al. (1996) and Fiedler and Faleide (1996) and seismic unit TeE of Vorren et al. (1991) into the eight subunits I-VIII, comprising Middle and Late Pleistocene sediments. The subdivision of unit GIII by Laberg and Vorren (1996) made use of data with higher resolution than the data available in this study.

The nomenclature on the main seismic units and the regionally correlatable reflectors by Faleide et al. (1996) and Fiedler and Faleide (1996) will be adapted in this study, but some of the ages of the unit boundaries have been adjusted to more recent studies (Figure 2-12).

2.6.1 Pre-glacial sediments - seismic unit G0 (oceanic basement to R7)

The distribution of pre-glacial sediments along the Barents Sea margin and in the Lofoten Basin is closely related to the marginal tectonic evolution, and uplift and erosion in the Barents Sea (Fiedler & Faleide, 1996). Faleide et al. (1996) and Fiedler and Faleide (1996) subdivided the pre-glacial sediments in seismic unit G0 into four sequences, Te1 (oldest) to Te4. Seismic unit G0 have a total thickness of 1.0 s (twt) in the Lofoten Basin, but its maximum thickness occurs close to the ocean-continent transition at approximately 72°N (Fiedler & Faleide, 1996; Hjelstuen et al., 2007).

The irregular basement relief of the Lofoten Basin is commonly draped by the pre-glacial sediments. The sediments show a mounded pattern and sequence pinch-out, implying they might be affected by alongslope processes. Frequent small-offset faults interpreted to be polygonal faults appear in the pre-glacial sediments (Hjelstuen et al., 2007). The G0 unit in the BITMF, deposited during a time span of more than 50 Ma, have an average a thickness of 1182 m in the Lofoten Basin and a maximum thickness of up to 3500 m close to the continent-ocean boundary (COB) (Fiedler & Faleide, 1996). This is less than half of what was deposited the last ~2.7 Ma in the BITMF (Faleide et al., 2008).

The initiation of sea floor spreading at the Paleocene-Eocene transition gives the sea floor in Lofoten Basin, and sediments deposited on top of it, a maximum age of approximately 55 Ma (Fiedler & Faleide, 1996). The crustal age in the Lofoten Basin was set based on the known age of magnetic anomalies in the crust. Dating of the sediments was mainly based on downlap of sediments onto the oceanic basement. Sediments were assumed an age somewhat younger than the maximum age of the oceanic basement. This was due to the basement relief where the anomalies appears which would prevent immediate deposition close to them (Fiedler & Faleide, 1996). The magnetic anomaly map and the sequence pinch-out of the pre-glacial seismic units in the Lofoten Basin have been adapted from Fiedler and Faleide (1996) to this study, see section 4.2.2.

Sequence Te1 (Eocene age)

Sequence Te1 was deposited on oceanic basement in the Lofoten Basin south of anomaly 13 (Figure 4-4). Anomaly 13 have an age of 35 Ma, and the sea floor south of the anomaly has an age of from 35 Ma to the time of onset of sea floor spreading (Fiedler & Faleide, 1996).

Sequence Te2 (Oligocene age)

North of 72°N, sequence Te2 covers oceanic basement of Oligocene age (Figure 4-4) (Fiedler & Faleide, 1996). The Te1-Te2 sequence boundary is a strong reflection with high amplitude and variable continuity. Sequence Te2 terminates close to anomaly 13 and thins and pinches out southward in the Lofoten Basin. The Te2 sequence in the Lofoten Basin has an Oligocene age (Fiedler & Faleide, 1996).

Sequence Te3 (early-middle Miocene age)

The Te3 sequence has a strong base reflection with high amplitude and good continuity. The Te2/Te3 sequence boundary terminates close to anomaly 7 (25 Ma), and the sequence has been assigned a maximum age of about 27 Ma (Figure 4-4) (Fiedler & Faleide, 1996). The base Te4 erodes into the Te3 sequence, an event that may be correlated to a hiatus and sea level fall which ended at 10.5 Ma. The Te3 sequence has therefore been assigned an age of early-middle Miocene (Fiedler & Faleide, 1996).

Sequence Te4 (late Miocene - early Pliocene (R7) age)

The Te3-Te4 sequence boundary terminates between anomalies 6 (20 Ma) and 5 (10 Ma), giving sequence Te4 a maximum age of 13 Ma (Figure 4-4). Because of the above mentioned hiatus, the Te4 sequence has been suggested to have a late Miocene-early Pliocene age (Fiedler & Faleide, 1996).

The pre-glacial sequences from Faleide et al. (1996) are adapted to this study. However, the sequences will be referred to as units, to have a similar designation as will be used for other seismic units mapped and described in the thesis.

2.6.2 Reflector R7 and seismic unit GI

Seismic unit GI is bounded by reflectors R7 at its base and R5 at the top. Reflector R7 is interpreted to represent the onset of extensive continental shelf glaciations and deposits dominated by glacially derived sediments along the margin in the northern Barents Sea (Faleide et al., 1996; Fiedler & Faleide, 1996; Knies et al., 2009). The reflector has an erosive character and marks a pronounced unconformity on the lower slope and in Lofoten Basin, but is less distinct higher up on the continental slope (Hjelstuen et al., 2007). R7 was initially assigned an age of approximately 2.3 Ma by Faleide et al. (1996). The age of R7 has later been revised; Butt et al. (2000) assigned an age of 2.3-2.5 Ma for R7 in the ODP site 986 on the western Svalbard Margin (location indicated in Figure 2-1). Knies et al. (2009) assigned an age of 2.7 Ma for R7 on western Barents Sea Margin.

Seismic unit GI has a wedge-like geometry in cross-section, and holds parallel and continuous, medium- to high-amplitude reflections in the Lofoten Basin. It pinches out to the east on the shelf due to truncation by the Upper Regional Unconformity (URU), and terminates westwards by downlapping onto oceanic basement (Fiedler & Faleide, 1996; Hjelstuen et al., 2007; Laberg et al., 2010). The internal seismic signature on the slope is predominantly acoustically laminated, including continuous reflections downlapping and onlapping R7 (Figure 2-13). The paleo-slope has a gentle relief, dominated by erosional channels increasing in width in upper parts of the unit (Laberg et al., 2010). Laberg et al. (2010) suggested a paleo-environment of glaciers terminating on land and glaciofluvial transport of sediments to the paleo-coastline during deposition of the unit. During regressive periods (relative sea level fall), the shelf edge may have prograded 20-40 km during the deposit of seismic unit GI (Vorren et al., 1991).

2.6.3 Seismic unit GII (R5-R1)

Seismic unit GII is bounded by reflector R5 at the base and R1 at the top. Reflectors R4, R3 and R2 are prominent intra-GII reflectors. Reflector R5 have an erosional character, and truncates underlying clinoforms on the continental slope and Paleogene strata east of the Senja Ridge and in the area of the Senja Fracture Zone (Faleide et al., 1996). R5 is suggested to represent a hiatus resulting from a significant change in sedimentation pattern, caused by a climatic change (Faleide et al., 1996). The reflector is inferred to represent the onset of glacial expansion in the Barents Sea region, with repeatedly full glacial conditions on the shelf since ~1.5 Ma (Butt et al., 2000; Knies et al., 2009; Laberg et al., 2012).

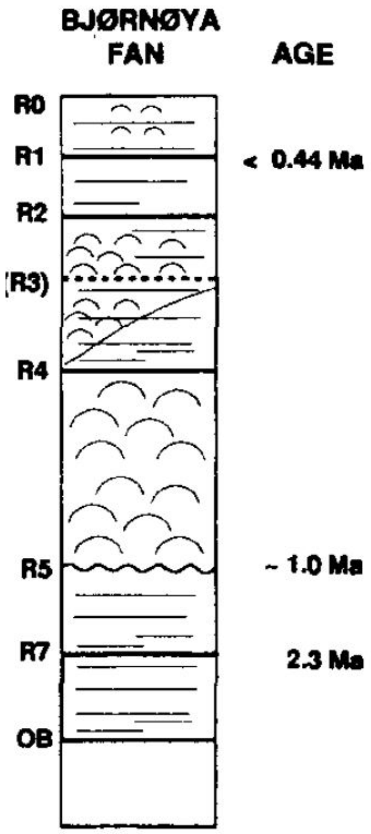


Figure 2-13: Seismic stratigraphic framework on BITMF with the main internal reflection patterns varying from stratified to chaotic (convex-up half circles) indicated. OB: Top oceanic basement. Ages are shown as they were initially assigned the reflectors by Faleide et al (1996), see Figure 2-12 for revised ages. The figure is modified from Faleide et al (1996).

Seismic unit GII thins eastwards due to truncation by the upper regional unconformity, and thins westward by downlapping onto oceanic basement (Fiedler & Faleide, 1996). Increased sediment supply to the outer shelf and subsequently mass movement caused by an unstable sediment configuration influence the seismic expression. Irregular to chaotic intervals dominate, but acoustically laminated and mounded facies exist, the two latter inferred to represent paleo-slide scars and glacigenic debris flows (GDF's), respectively (Figure 2-13) (Faleide et al., 1996; Laberg et al., 2010). Channels, interbedded with slide scars, GDFs and sediment blocks derived from the shelf dominate the paleo slope morphology (Laberg et al., 2010). A high sedimentation rate environment consisting of subglacial deformation till and channelized meltwater discharge depositing glaciomarine sediments dominated on the margin, with subsequent remobilization on the upper slope to form the earliest GDFs on the margin (Laberg et al., 2010).

2.6.4 Seismic unit GIII (R1-Sea floor)

Seismic unit GIII is bounded by reflector R1 at the base and the sea floor surface on the top. A change in net erosion to net accumulation of sediments that may be related to changes in glacial regime, sediment supply and differential subsidence in the outer continental shelf formed reflector R1 (Faleide et al., 1996). The R1 has been correlated to the URU on the southwest Barents Sea shelf (Fiedler & Faleide, 1996). The URU is an erosional surface separating prograding strata consisting of pre-glacial sedimentary rocks below from aggrading strata consisting of a horizontal glacigenic sequence above. It developed initially through fluvial erosion, and was later modified by glacial activity on the Barents Sea shelf (Vorren et al., 1989; Faleide et al., 1996).

Assuming a p-wave velocity of 2000 m/s in the sediments, the glacigenic sequence above URU/R1 is 0-300 meters thick in the shelf proper, and thickens to up to 900-1000 meters at the shelf break (Vorren et al., 1989). Sættem et al. (1992) suggested an age of 0.44 – 0.2 Ma for R1 based amino acid analyses and the deposit`s paleomagnetic properties. Later studies do not conclude on an exact age, and suggestions for the R1 age includes both less restrictive and more restrictive age estimates of the reflector. Butt et al. (2000) and Knies et al. (2009) suggested an age for R1 of 0.2 Ma at ODP site 986 and along western Barents Sea margin, respectively, while Laberg et al. (2010) suggested an age of R1 of younger than 0.7 Ma in southwest Barents Sea.

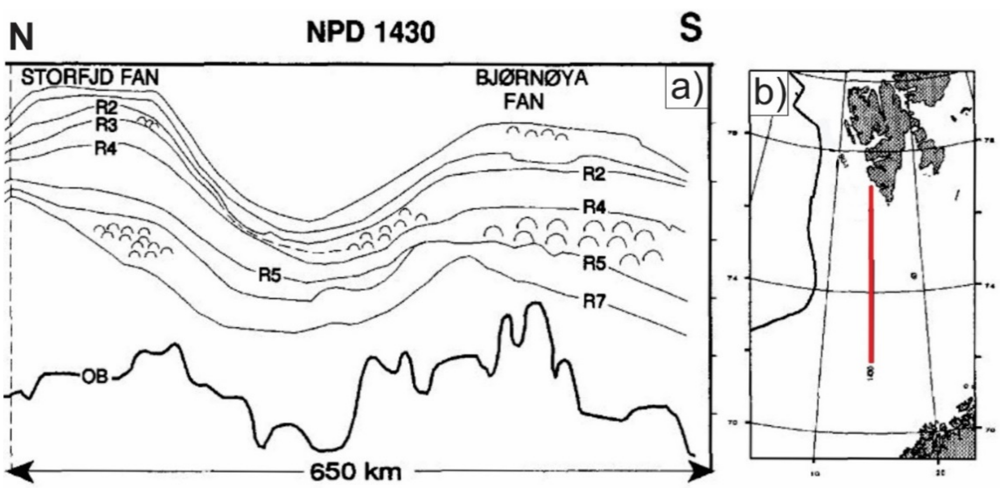


Figure 2-14: a) A composite geoseismic line showing the lateral and vertical distribution of seismic units along western Svalbard-Barents Sea margin, with chaotic reflection patterns indicated with convex-up half-circles. OB: Oceanic basement. The location of the composite seismic line is indicated with the red line in b). The figure is modified from Faleide et al (1996).

Laberg et al. (1996) subdivided seismic unit GIII into eight subunits, where the base of unit I corresponds to the R1. The two upper units are of Weichselian age, and the top of unit VIII corresponds to the sea floor surface. A chaotic seismic signature characterize the eight units on the upper slope, and mounds with a transparent internal seismic signature dominates further downslope (Figure 2-13). The mounds are interpreted to be large, submarine debris flow deposits, deposited during full glacial conditions. The eight units were separated by thin (< 10m.) draping and subparallel, acoustically laminated units inferred to have been deposited during interstadial and interglacial phases. Together, the eight units and the laminated layers reflect eight cycles of shelf-edge glaciations and interstadials/interglacials with ice-sheet retreat during deposition of seismic unit GIII (Laberg & Vorren, 1996a; Laberg et al., 2010).

3 DATA AND METHODS

3.1 SEISMIC DATA

The study is primarily based on seven regional 2D multichannel seismic lines in dataset HB-96 (Table 1), extending from the southwest Barents Sea continental margin and into the Lofoten Basin (Figure 3-2). The seismic lines have a total length of about 2180 km. In addition, three other multichannel 2D datasets (Table 1), one 3D data set (Table 1) and two wells (Section 3.3) on the Barents Sea shelf close to the shelf break have been applied or evaluated to correlate seismic stratigraphy from previous work on the margin to dataset HB-96 (Figure 3-2).

Table 1: Overview over seismic data sets used or evaluated in the study.

Data type	Name	Number of available lines in survey	Gathered by	Year
2D seismic	HB-96	7	Norwegian Petroleum Directorate (NPD)	1996
2D seismic	NBR11	51	TGS-Nopec	2011
2D seismic	NBR12	30	TGS-Nopec	2012
2D seismic	NPD-BJV1 & BJV2	33	NPD	1986
3D seismic	NH9803		Norsk Hydro / Statoil	1998

All seismic data were processed and ready to use in Petrel when received for this study. The polarity and phase applied to the seismic data during processing was determined by looking at the seismic signal across the sea floor surface. Different conventions for phases and polarities are applicable, for example the conventions of Badley (1985) and the SEG (Society of Exploration Geophysicists) standard of Sheriff (2006). In data set HB-96, the increase in AI contrast for the sea floor surface reflection is represented by a wavelet trough (represented by a red reflection in Figure 3-1 b)). The AI contrast increase thus implies a Zero-phase, reverse polarity using the SEG convention, (Figure 3-1 a)) or a Zero-phase, normal polarity using the Badley (1985) convention (Andreassen, 2009a).

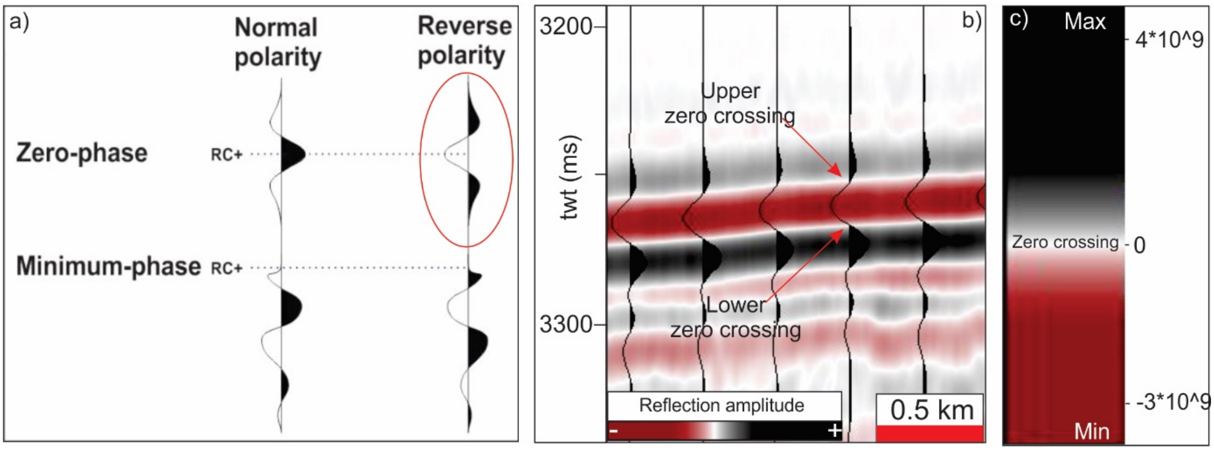


Figure 3-1: The polarity conventions used for the seismic data available to this study may be the Zero-phase, reverse polarity of Sheriff (2006), (red circle in a), or Zero-phase, normal polarity of Badley (1985). b) An example of the seismic reflection from the sea floor in data set HB-96, with the red colour reflection representing the AI decrease from water column down into the sediments. Upper and lower zero crossing indicated with red arrows. c) The reflection amplitude values as output in Petrel. Black is the positive maximum value, red is the negative maximum value. The reflection amplitude colour legend and values used in the study have been modified to as seen in b). a) is modified from Sheriff (2006).

3.1.1 2D seismic survey HB-96

The seismic data have a good quality appearance in the Petrel software, but the overall coverage of seismic lines on the southwest Barents Sea continental slope and in the Lofoten Basin is generally sparse. Seismic lines HB-2 to HB-6 have their orientation aligned in the approximate direction of inferred sediment input of the BITMF, running between ~ESE-NNW to northeast-southwest from the shelf break and downslope into the Lofoten Basin. Seismic line HB-1300 is aligned transverse to, and across, all the five other seismic lines on the continental slope (Figure 3-2). Seismic line HB-1 terminates close to the foot of the northern Vøring Plateau. Three of the seismic lines cross each other on the shelf break close to well 7316/5-1, and several of the seismic lines cross each other on the slope. Only seismic line HB-2 intersects with well 7316/5-1 (Figure 3-2).

3.1.2 Other 2D seismic surveys

A composite 2D seismic line combining four seismic lines from the surveys NBR11, NBR12, NPD and HB-96, was constructed in order to tie the Cenozoic stratigraphy from well 7216/11-1S to well 7316/5-1 (Figure 3-2). Other seismic lines from the surveys have been evaluated in the correlation process. The location of the evaluated seismic lines are shown in Figure 3-2.

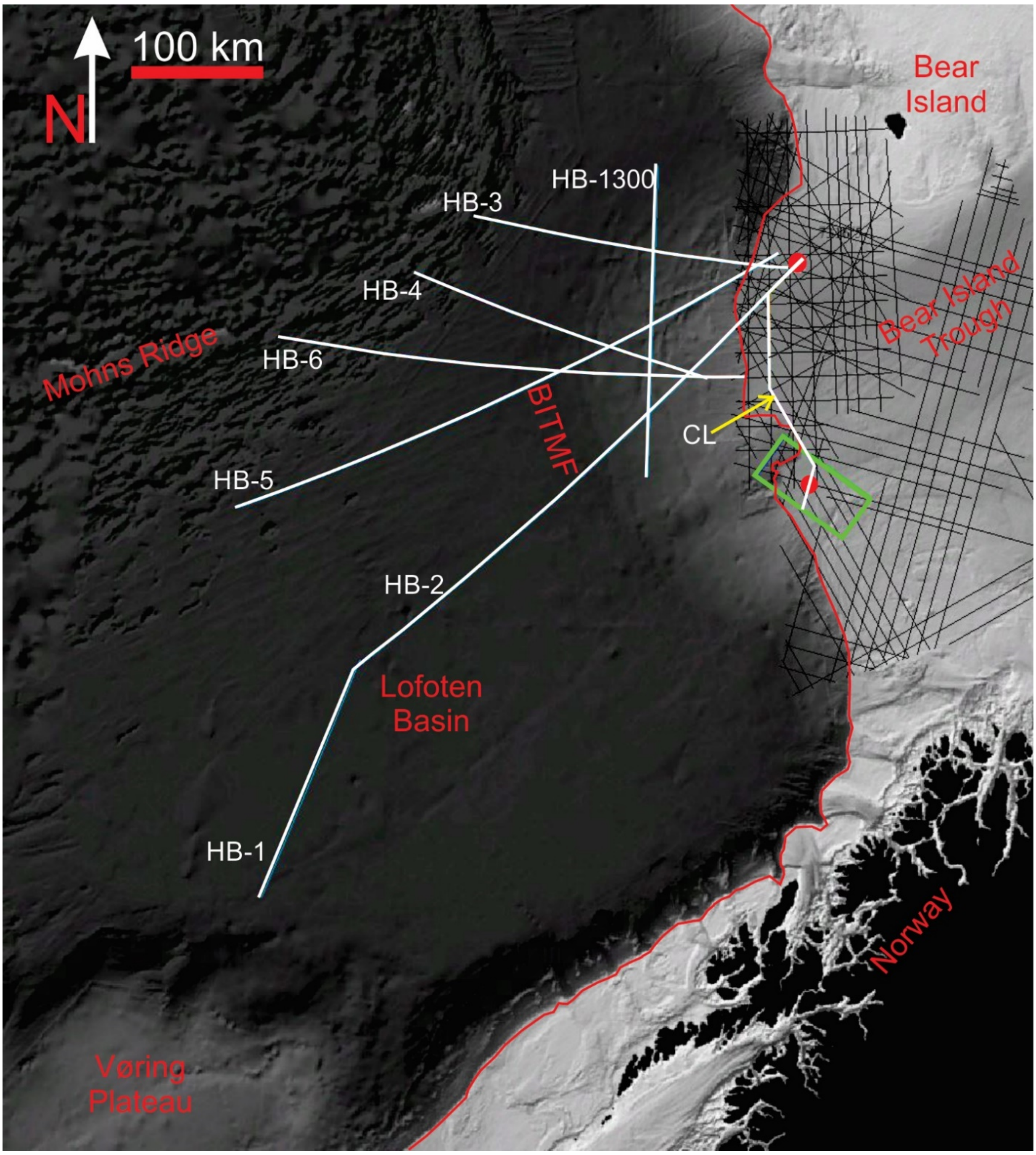


Figure 3-2: An overview of the study area with the location of the seismic lines from data set HB-96 and the composite line (CL) (white lines) along the shelf break (indicated with a red line). Black lines indicate location of seismic lines in other surveys used/evaluated in the study. Red dots indicate wells 7216/11-1S (in the south) and 7316/5-1 (in the north). Green rectangle indicates 3D data set NH9803. BITMF: Bear Island Trough Mouth Fan. The location of the figure is indicated in Figure 1-1.

3.1.3 3D seismic survey NH9803

The 3D seismic data set is located at the shelf break in the southwest Barents Sea (Figure 3-2). The survey covers an area of about 2000 km^2 and well 7216/11-1S is located in the central parts of the data set. The data set was used to construct parts of the stratigraphic framework that was correlated to well 7316/5-1. Previous work in the area includes Ryseth et al. (2003); Andreassen et al. (2007a); Knies et al. (2009) and Safronova et al. (2012); (2014)

3.2 SEISMIC RESOLUTION

Seismic resolution is the ability of the seismic data to separate two features that are close together. The resolution may be calculated for the vertical and horizontal dimension, and both are dependent on the dominant wavelength (λ), given by the ratio of P-wave sound velocity (V) and frequency (f) of the seismic signal (Equation 1). Both the P-wave velocity and the frequency are modified with depth, and as a product of those two, the wavelength will increase with dept. (Figure 3-3). (Badley, 1985; Brown, 1999; Andreassen, 2009a).

EQUATION 1 – WAVELENGTH:

$$\boldsymbol{\lambda = \frac{v}{f},}$$

(λ = dominant wavelength (m), v = velocity (m/s), f = frequency (Hz))

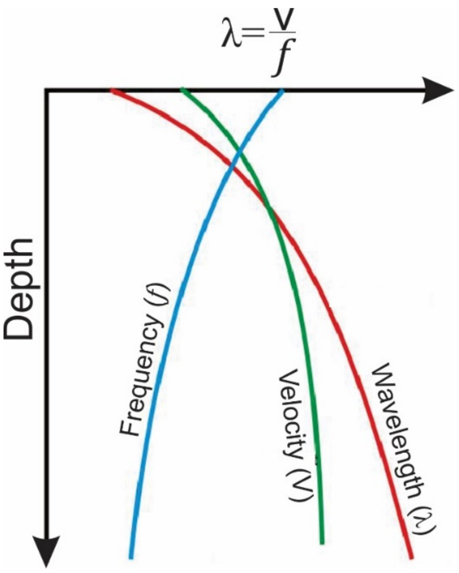


Figure 3-3: The wavelength of the seismic signal increase with depth, as a product of the velocity and frequency, resulting in poorer resolution. The sketch is modified from Brown (1999).

3.2.1 Velocity calculations for seismic units G0-GIII

The interval velocity of a seismic unit is needed in order to calculate the vertical resolution. Fiedler and Faleide (1996) suggested interval velocity numbers for the sediments in the BITMF based on a large number of seismic refraction profiles on the margin (Table 2). The average velocities were determined from the average thickness of each seismic unit and the velocity gradient. The velocity variations were found to be limited in a lateral dimension, thus, one average velocity-depth gradient was assumed to be sufficient for the calculations.

Table 2: Interval velocities for seismic units in the Bear Island Trough Mouth Fan, as proposed by Fiedler and Faleide (1996).

Unit	Average interval velocity (m/s)
GIII	1970
GII	2160
GI	2400
GI-GIII	2200
G0	2680

3.2.2 Vertical resolution

The vertical resolution is the minimum thickness of a sedimentary layer in order to stand out as one layer in a seismic section, with the upper and lower boundaries represented by individual seismic reflections. The formula for the vertical resolution is given in Equation 2. When the layer thickness equals or exceeds ½λ, two separate reflections are produced, representing the upper and lower boundary of the layer. Below ½λ layer thickness, the two reflections will interfere and overlap. At ¼λ layer thickness, the two reflections interfere perfectly to produce one single, anomalously high amplitude reflection. Thus, a unit in a seismic section should equal or exceed ½λ to show the upper and lower boundary of the unit.

The reflection amplitude decreases when the layer thickness decreases from ¼λ to 1/30λ, which is the lowest layer thickness possible to resolve in a seismic system (Andreassen, 2009a). A high acoustic-impedance wedge embedded within lower acoustic-impedance shale exemplifies the interference (Figure 3-4).

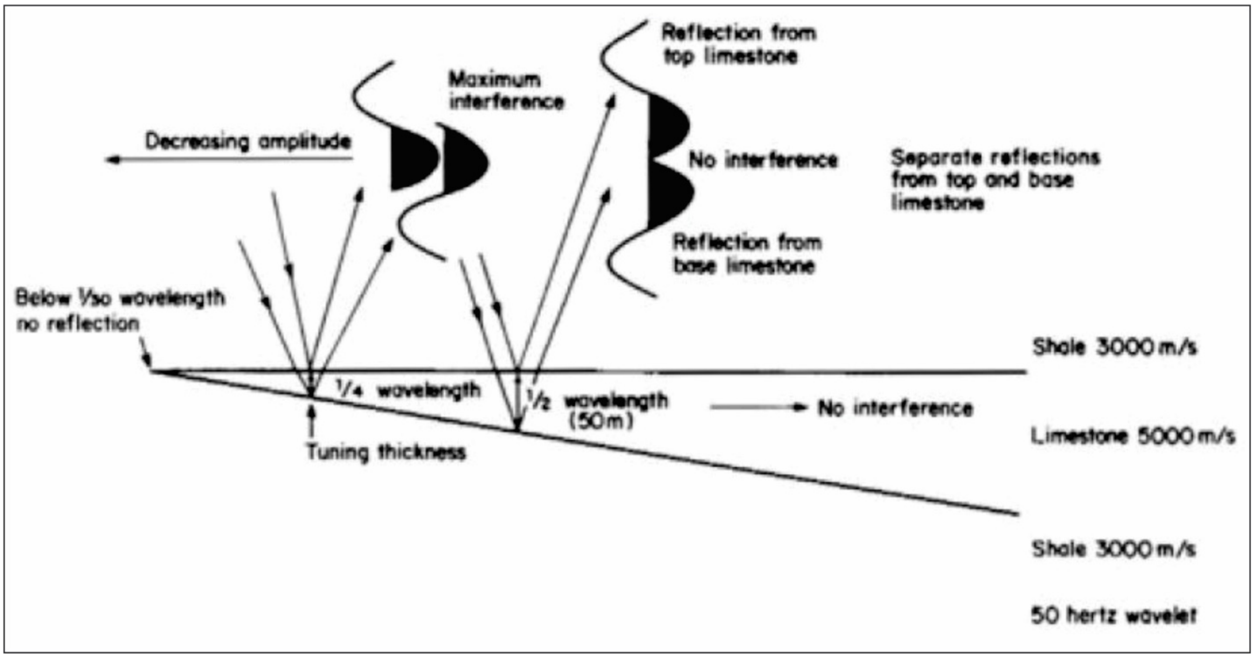


Figure 3-4: Interference effects associated for a high acoustic-impedance wedge embedded in a lower acoustic-impedance shale. The figure is modified from Andreassen (2009a).

EQUATION 2 – VERTICAL RESOLUTION:

$$\boldsymbol{Vr = \frac{\lambda}{4},}$$

(Vr = vertical resolution (m) and λ = dominant wavelength (m))

As seen from Equation 1 and 2, the vertical resolution will decrease with increasing depth. This is because the needed thickness of a layer to be visible increases with depth along with the increasing wavelength (Badley, 1985; Brown, 1999; Andreassen, 2009a). Equation 2 shows that to fulfil the demand of ½λ to show the upper and lower boundary of a unit, 2 x Vr is needed.

To obtain the Vr in the study area, the maximum peak frequency of the seismic data was measured from different locations in the study area using the “Inspector” in the Petrel software. The measurements where recorded manually from where the frequency started to drop in the frequency graph. The vertical resolution for the G0 seismic unit on the upper slope and in the Lofoten Basin was calculated using Equations 1 and 2. The results in Table 3 show that the vertical resolution decreases with depth in the seismic section.

Table 3: The measured maximum peak frequencies recorded in shallow and deep areas on the VVP and in the Lofoten Basin in the seismic unit G0. The measurements were recorded for the seismic line HB-2. The resulting vertical resolution (Vr) numbers are given in the right-hand column. LB: Lofoten Basin.

Location	Max peak frequency	Vr
Upper slope (deep)	~30 Hz	22,3 m
Upper slope (shallow)	~40 Hz	16,8 m
Lower slope / LB (deep)	~25 Hz	26,8 m
Lower slope / LB (shallow)	~29 Hz	23,1 m

3.3 WELL DATA

3.3.1 Well 7216/11-1S – Sørvestnaget Basin

The well was drilled in 2000 by Norsk Hydro on coordinates 72° 0' 56.72" N, 16° 36' 22" E at a water depth of 361 meters. The location is at the crossing of InLine A at shotpoint 2940 and X-Line A 4882 in NH9803 3D data set (Figure 3-2). The true vertical depth of the well is 3709 meters, but due to deviation of the well path, the total depth is 4215 mMSL (meters below mean sea level). The well penetrates through the Nordland Group and into the Sotbakken Group in the Torsk Formation where it terminates in rocks of Early Paleocene age (Ryseth et al., 2003; NPD, 2015).

3.3.2 Well 7316/5-1 – Vestbakken Volcanic Province

The well, operated by Norsk Hydro, was drilled in 1992 about 150 km southwest of the Bear Island in the VVP (Figure 3-2). It penetrates ~3.5 km through the Cenozoic Nordland Group (top) and Sotbakken Group (Torsk Formation) and terminates in the Cretaceous Nygrunnen Group (Kveite Formation) at a depth of ~4027 meters (Eidvin et al., 1994; Ryseth et al., 2003; NPD, 2016). The seismic line HB-2 intersects with the well, and the seismic lines HB-3 and HB-5 terminate close to the well (Figure 3-2).

3.4 SOFTWARE

3.4.1 Petrel

Petrel, version 2014.1 (64-bit), by Schlumberger is the seismic interpretation software used in this study. The main focus has been 2D seismic interpretation.

3.4.1.1 Volume attribute

The Volume attribute "Graphic equalizer" was used to show the stronger positive and negative signals of the seismic data. The attribute lets the positive and negative signals show with a higher contrast, and thus enhance the frequency component of the signal. The result was a seismic signal of slightly improved contrast between positive and negative amplitudes.

3.4.2 CorelDraw X6

CorelDraw is a graphic design software that has been used to generate and modify figures included in the study. New figures have been generated from Petrel, and figures from published articles and books have been modified to fit in the study.

3.5 EXTERNAL MAPS

Fiedler and Faleide (1996) constructed maps that shows the distribution of magnetic anomalies and pre-glacial strata in the Lofoten Basin. The adaption of their findings to this thesis includes the pinch-out map (Figure 3-5), which is the basis for the correlation of the pre-glacial seismic unit boundaries (Section 4.2.2).

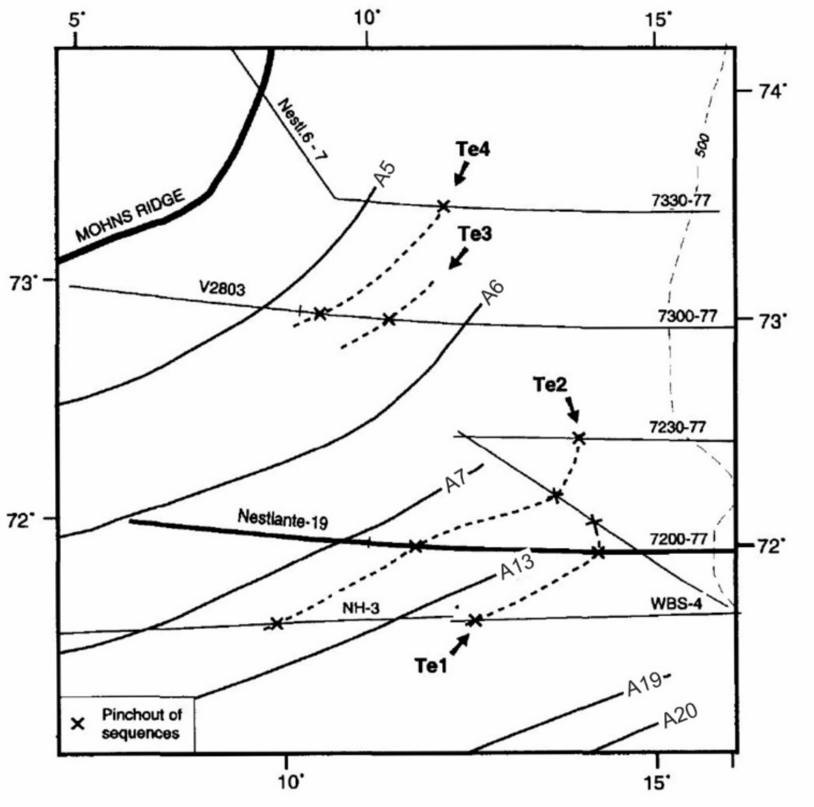


Figure 3-5: Pinch-out of the main pre-glacial seismic units as presented by Fiedler & Faleide (1996). A5= 10 Ma, A6= 20 Ma, A7= 25 Ma, A13= 35 Ma. See Figure 4-4 for the adaption of the pinch-out map to this thesis. The figure is modified from Fiedler & Faleide (1996).

A geo-referenced map was created using the International Bathymetric Chart of the Arctic Ocean (IBCAO) resources available on the internet. The created map (Figure 3-2) is the background map used to show the location of the seismic lines and additional information used in the study.

3.6 INTERPRETATION METHOD

Mitchum et al. (1977) outlined an approach to the establishment of a seismic stratigraphy and the stratification patterns interpreted from seismic reflection terminations and configurations. Their approach involves:

1. A seismic sequence analysis, including a subdivision of the seismic section into packages of concordant reflections separated by surfaces of discontinuity, and interpreting them as depositional sequences.
2. A seismic facies analysis, including analysis of reflection parameters like configuration, continuity, amplitude, frequency and interval velocity of seismic reflection patterns within seismic sequences.

3.6.1 Seismic sequence analysis

Mitchum et al. (1977) defined a seismic sequence as a depositional sequence identified on a seismic section. Reflection terminations at sequence boundaries, for example erosional truncation, onlap, downlap and toplap, are the principal criteria for recognition of seismic sequence boundaries (Figure 3-6). Reflection terminations marks the top and base of the sequence boundaries which are interpreted to be unconformities, or their correlative conformities. Each sequence consists of relatively conformable successions of reflections which are interpreted to be genetically related strata (Mitchum et al., 1977).

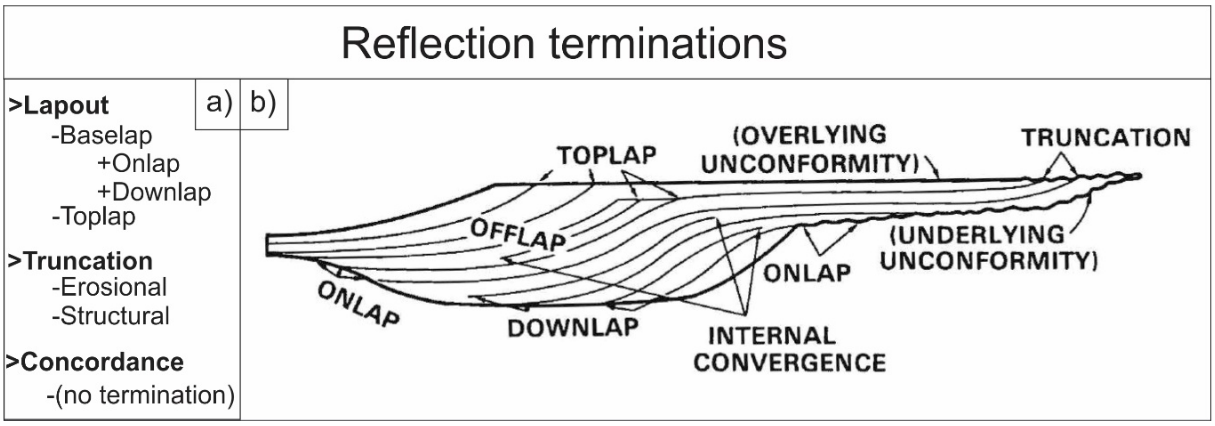


Figure 3-6: Reflection terminations types at sequence boundaries are listed in a) and illustrated diagrammatically in b). The figure is modified from Mitchum et al. (1977).

For top-discordant relations, erosional truncation and toplap are the terminations considered. Erosional truncation implies deposition and subsequent removal of strata along an erosional surface (Figure 3-7 a). Interpretation of the erosional surface depends on the angularity of the reflections to the erosional surface and how the erosional surface appears in the seismic section. Toplap occurs from non-deposition (sediment by-pass) and minor erosion, and is the termination of reflections interpreted as strata against an overlying surface (Figure 3-7 b) (Mitchum et al., 1977). In the case of concordance (Figure 3-7 c), the interface and substratum are deformed in the same manner, but the concordant surface may represent a large time gap (Veeken & Moerkerken, 2013b).

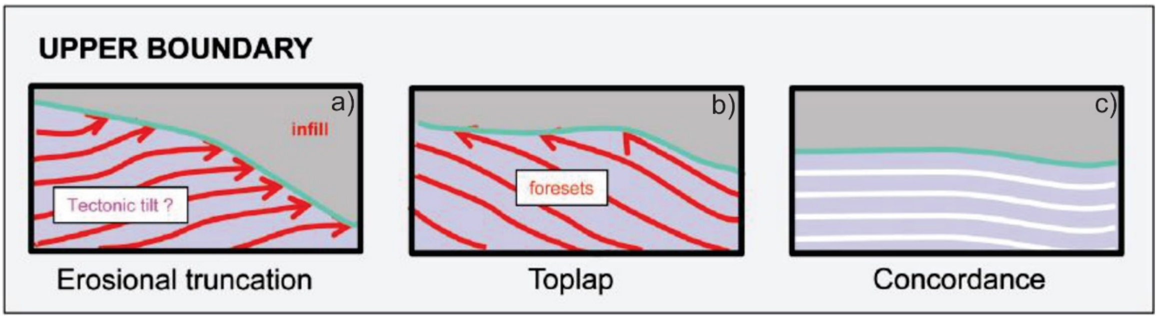


Figure 3-7: Erosional truncation (a), toplap (b) and concordance (c) illustrated for reflection terminations at unconformities, considering the sub-stratum. Red arrows indicate reflection terminations against an unconformity surface (coloured green). The sketch is modified from Veeken and Moerkerken (2013).

For base-discordant relations, onlap and downlap are the significant reflection terminations. Onlapping seismic reflections (Figure 3-8 a) are interpreted as initially horizontal strata terminating progressively against an initially inclined surface, or inclined strata terminating progressively updip against a surface of greater inclination.

Where initially inclined strata downdip on initially inclined or horizontal strata, downlap is the correct term (Figure 3-8 b). The younger strata pinch out in the distal direction (Mitchum et al., 1977; Veeken & Moerkerken, 2013b). The wider term baselap may be used in the case that onlapping and downlapping strata cannot be distinguished from each other (Mitchum et al., 1977). Concordance will be the case if overlying sediments show the same deformation as the separating interface and the underlying unit (Figure 3-8 c) (Veeken & Moerkerken, 2013b).

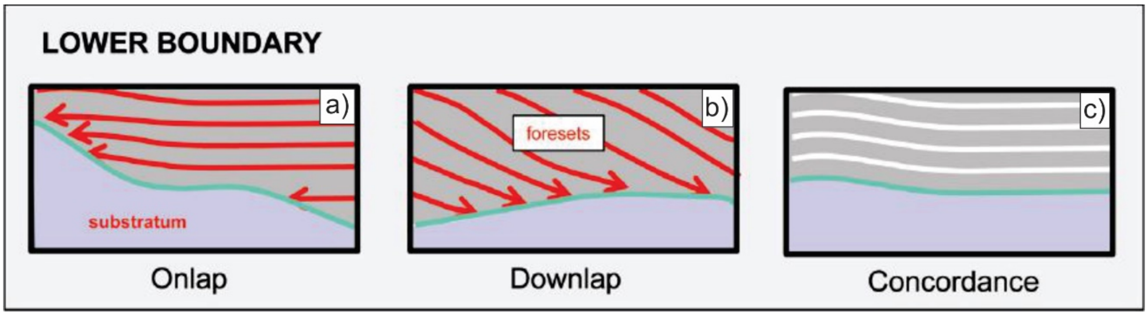


Figure 3-8: Onlap (a), downlap (b) and concordance (c) illustrated for reflection terminations at unconformities, considering the upper sequence. Red arrows indicate reflection terminations against an unconformity surface (coloured green). The sketch is modified from Veeken and Moerkerken (2013).

3.6.2 Seismic facies analysis

The seismic facies analysis consists of recognition and mapping of seismic facies units within depositional sequences, and includes the description and geologic interpretation of seismic reflection parameters. Seismic facies units are mappable, three-dimensional seismic units composed of groups of seismic reflections whose parameters differ from those of adjacent facies units (Mitchum et al., 1977). Mitchum et al. (1977) listed the following seismic facies parameters and their associated geologic interpretation:

Table 4: The seismic facies parameters and their associated geologic interpretation adapted to this study. The table is adapted from Mitchum et al. (1977).

REFLECTION TERMINATIONS (AT SEQUENCE BOUNDARIES)	REFLECTION CONFIGURATIONS (WITHIN SEQUENCES)		EXTERNAL FORMS (OF SEQUENCES AND SEISMIC FACIES UNITS)
LAPOUT	PRINCIPAL STRATAL CONFIGURATION		
BASELAP	PARALLEL		SHEET
ONLAP	SUBPARALLEL		SHEET DRAPE
DOWNLAP	DIVERGENT		WEDGE
TOPLAP	PROGRADING CLINOFORMS		BANK
TRUNCATION	SIGMOID		LENS
EROSIONAL	OBLIQUE		MOUND
STRUCTURAL	COMPLEX SIGMOID-OBLIQUE		FILL
CONCORDANCE	SHINGLED		
(NO TERMINATION)	HUMMOCKY CLINOFORM		
	CHAOTIC		
	REFLECTION-FREE		
	MODIFYING TERMS		
	EVEN	HUMMOCKY	
	WAVY	LENTICULAR	
	REGULAR	DISRUPTED	
	IRREGULAR	CONTORTED	
	UNIFORM		
	VARIABLE		

3.6.2.1 Reflection configurations

Each internal reflection parameter provides information on the geology of the subsurface. Reflection configuration reveals the main stratification patterns from which depositional processes, erosion and paleotopography may be interpreted. Parallel and subparallel reflection configurations (Figure 3-9) are common in sheet, sheet drape and fill units (Figure 3-11) and the pattern suggests uniform rates of deposition on a uniformly subsiding shelf or stable basin plain setting. Divergent reflection configuration (Figure 3-9) is characterized by a wedge-shaped unit (Figure 3-11), and suggest lateral variations in the rate of deposition, or progressive tilting of the depositional surface (Mitchum et al., 1977).

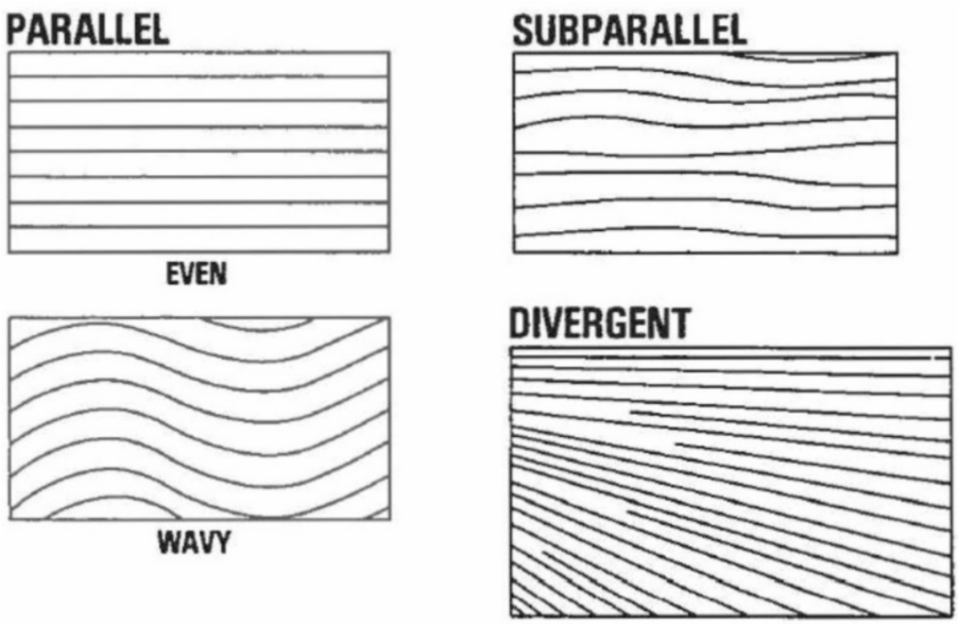


Figure 3-9: Illustrated parallel (even and wavy), subparallel and divergent reflection configurations. The sketch is modified from Mitchum et al. (1977).

A chaotic reflection configuration (Figure 3-10) is discontinuous, discordant reflections suggesting a disordered arrangement of reflection surfaces. Their origin may be either strata deposited in a variable, relatively high-energy setting, or initially deposited as continuous strata which have been deformed, and may for example represent volcanic rocks, overpressured shales, channel fills, slumped deposits and contorted zones (J. Mitchum, R. M. et al., 1977; Veeken & Moerkerken, 2013b).

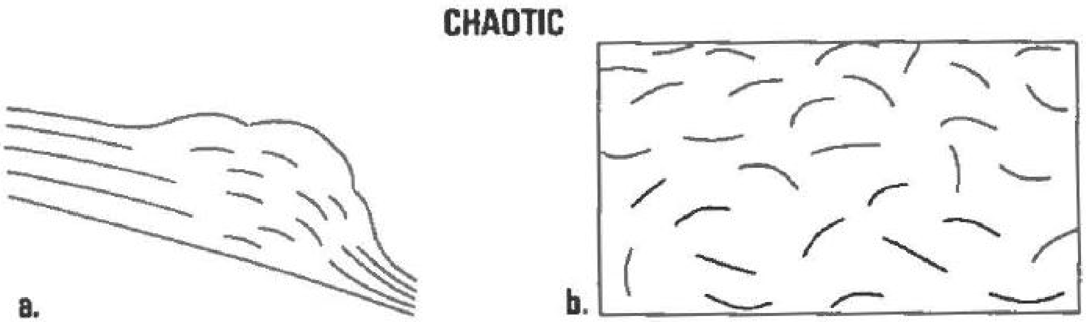


Figure 3-10: Chaotic reflection configurations in a) represents a pattern which may be interpreted as initial stratal features, while the chaotic pattern in b) cannot be interpreted in any recognizable stratal pattern. The sketch is modified from Mitchum et al. (1977).

Reflection free or transparent areas in seismic data are missing or have low acoustic-impedance contrast. They can be for example homogenous, non-stratified and highly contorted geologic units representing large igneous masses, salt features or thick, seismically homogenous shales or sandstones. Reflection free areas may also be caused by automatic gain control as an artefact from the software used in the processing of the seismic data (Mitchum et al., 1977; Veeken & Moerkerken, 2013b).

3.6.2.2 External forms of seismic facies units

In addition to the internal reflection configuration, also the external form of seismic facies units must be described to be able to understand the geometric interrelation and depositional setting of the facies units. Sheets or sheet drapes represents uniform sedimentation conditions in basins. Sheet drapes commonly consist of parallel, sub-parallel or wavy reflections interpreted as strata draped over underlying topography in a pattern suggesting uniform, low-energy, deep-marine sedimentation from suspension (Mitchum et al., 1977; Veeken & Moerkerken, 2013b). Wedges represents a gradual differentiation in the environment of deposition and a lateral change in sedimentation rate, and indicate a sudden break in sedimentation pattern (Veeken & Moerkerken, 2013b). Mounds and fills represents seismic forms derived from strata with diverse origins, forming prominences or filling depressions on depositional surfaces. The diverse origin of mounds give them diverse external shapes and internal stratal configurations. Deep-sea fans, lobes, slump masses and contourite deposits may have a mounded external form (Figure 3-11) (Mitchum et al., 1977).

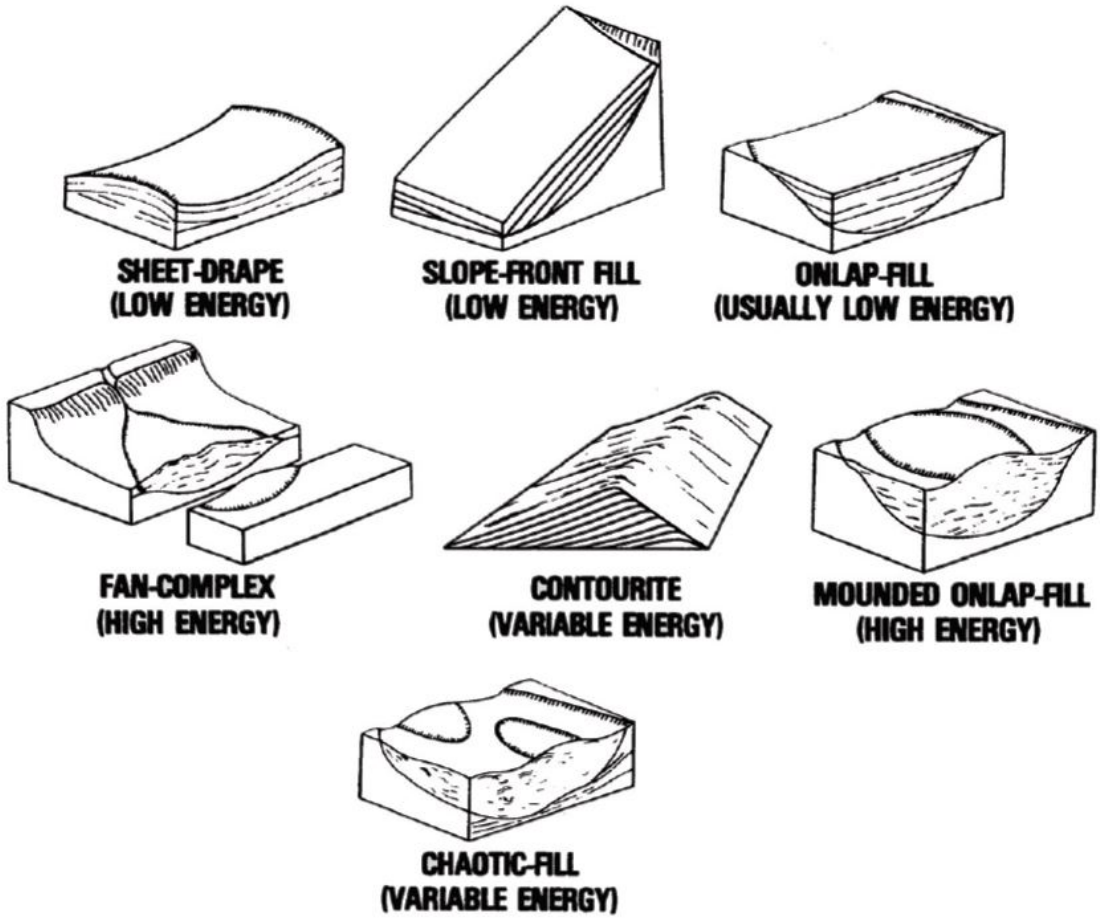


Figure 3-11: External forms of seismic facies units on the slope and in basins. The sketch is modified from Veeken and Moerkerken (2013).

4 RESULTS

4.1 INTRODUCTION

The correlation of the established seismic stratigraphic framework of the western Barents Sea continental margin to the seismic stratigraphy of this thesis the will be described in section 4.2. Next, the established seismic stratigraphic framework on the continental slope in the VVP and in the Lofoten Basin in this thesis is described in section 4.3, while section 4.4 deals with the seismic facies analysis of the seismic units Te1 – Te4. Depositional subunits related to alongslope and downslope processes will be described in section 4.5.

The study area has been subdivided into four main areas based on the present oceanic basement relief and the shape and sediment distribution in seismic unit G0 in the study area (Figure 4-1): 1) The area where the seismic unit G0 is deposited on top of volcanic flows in the VVP area will be referred to as the upper continental slope. 2) The lower continental slope is referred to as the area located downslope the inferred COB. 3) The proximal Lofoten Basin is located in the north-eastern part of the Lofoten Basin, while 4) the distal Lofoten Basin is located in the south-southwestern part of the Lofoten Basin.

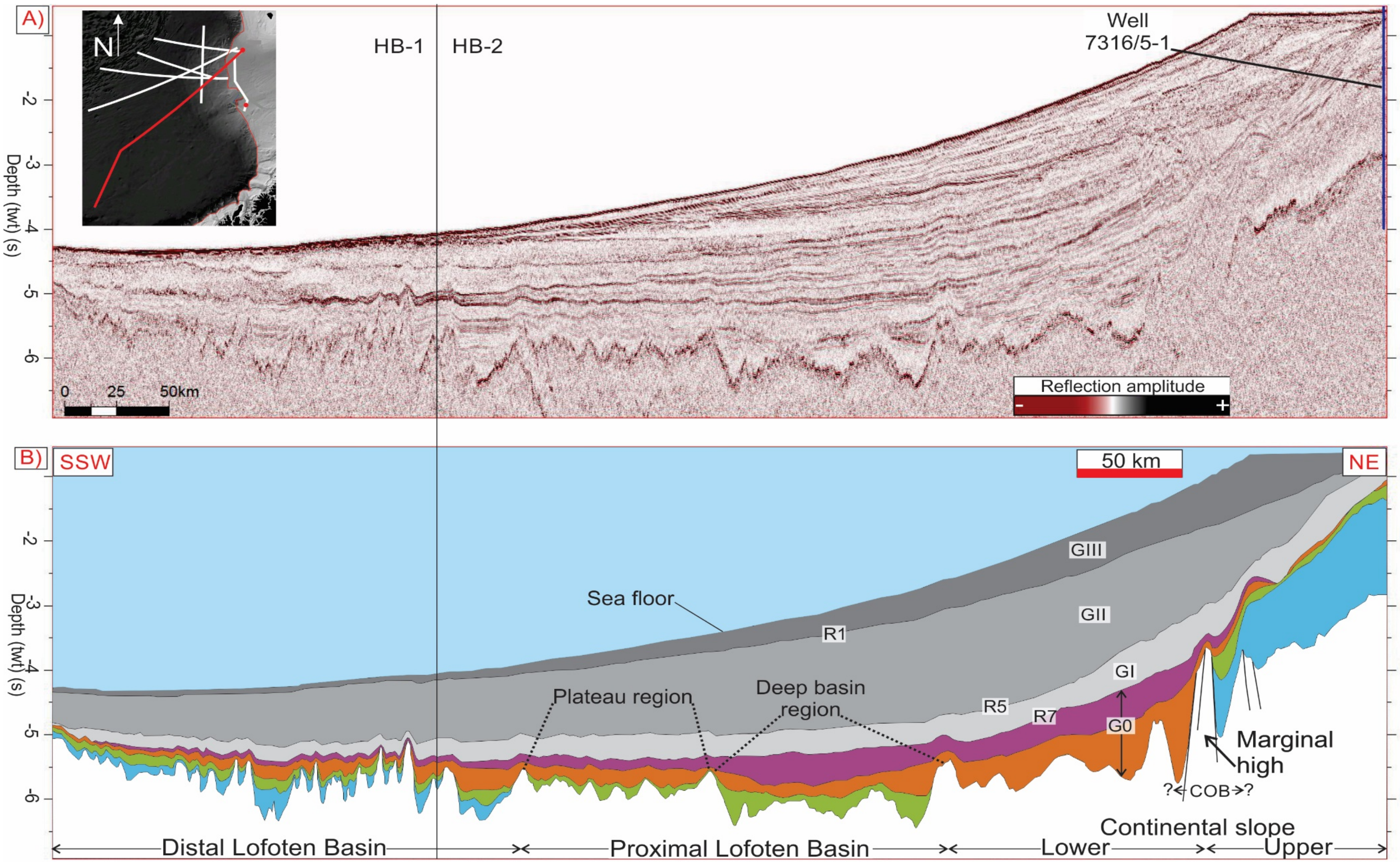


Figure 4-1: A) Seismic section from the VVP area across the Lofoten Basin. B) The main seismic units and the pre-glacial units outlined in a geoseismic section. See colour legend in Figure 4-2. The location of the seismic section is shown with a red line in the location map in A).

4.2 CORRELATION TO PREVIOUS WORK

4.2.1 Correlation to the established seismic stratigraphic framework

Colour codes have been assigned for the correlated reflections and seismic units in the thesis (Figure 4-2):

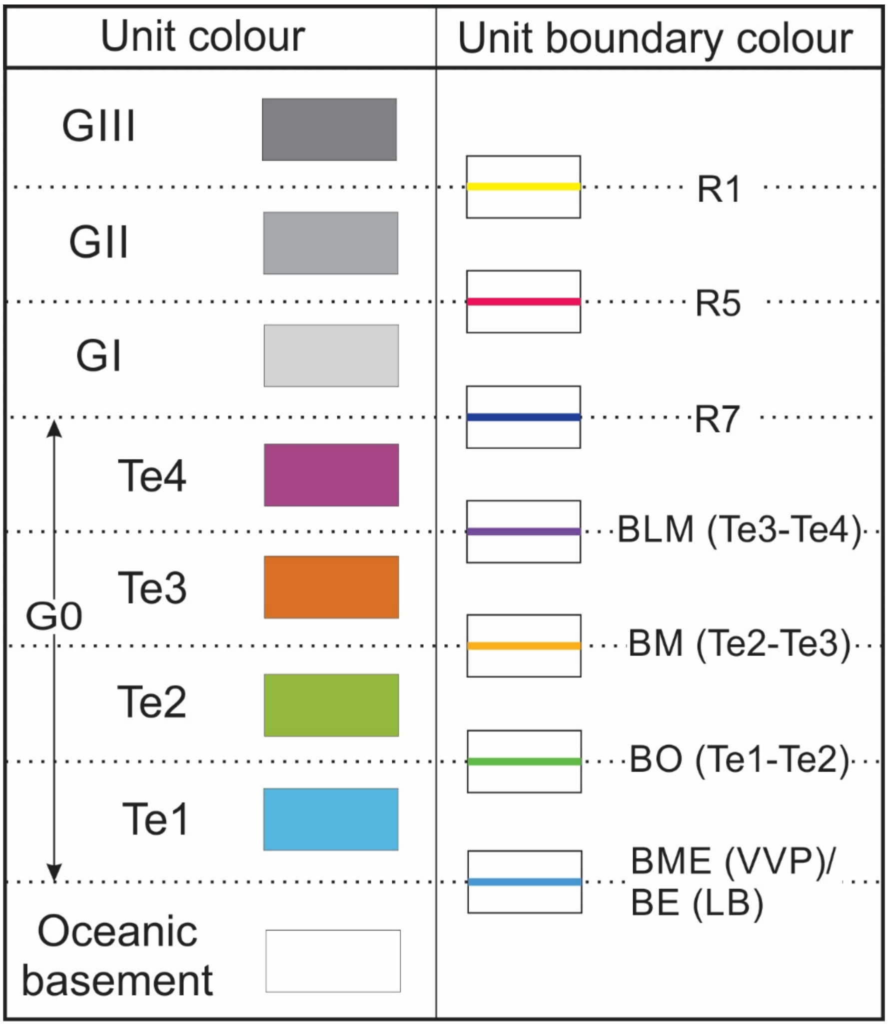


Figure 4-2: The colour codes assigned for the seismic units and the related unit boundaries correlated to this thesis. See Figure 2-12 for the previously established stratigraphic framework. LB: Lofoten Basin, BE: base Eocene, BME: base middle Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene.

The seismic stratigraphic framework in this study has been established based on the correlation of the pre-glacial unit boundaries in seismic unit G0, and reflectors R7, R5 and R1, which bound the glacial seismic units GI-GIII (Figure 4-3). In the VVP area, the pre-glacial unit boundaries and the depths where they intersect well 7316/5-1 were identified using previously published results from the area (Ryseth et al., 2003; Eidvin et al., 2014).

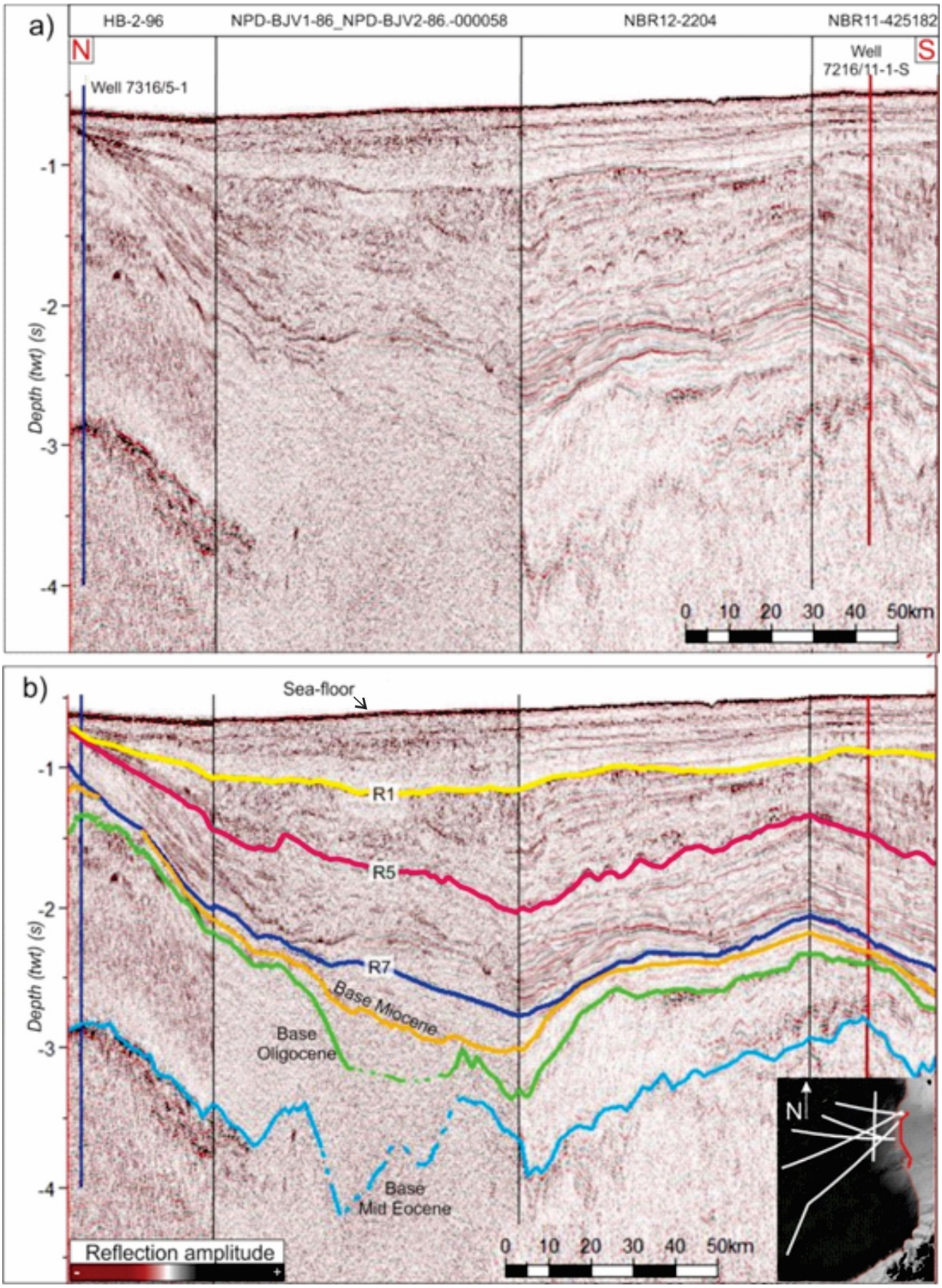


Figure 4-3: A seismic section composed of sections from four 2D seismic lines is shown without interpretations in a) and with the interpretation of the main seismic unit boundaries in b). The composite seismic line is located close to and running parallel to the shelf break between well 7216/11-1S in Sørvestnaget Basin and well 7316/5-1 on the VVP. The location of the seismic line is indicated with a red line in the location-map in b).

The unit boundaries were then correlated southwards to well 7216/11-1S following Ryseth et al. (2003). Reflectors R7, R5 and R1 were correlated from well 7216/11-1S northward to well 7316/5-1 in the VVP area. Then all the unit boundaries were traced downslope from the VVP area into the Lofoten Basin.

Seismic unit Te1 has been correlated to the Eocene unit of Ryseth et al. (2003) and Eidvin et al. (2014) in the VVP area. The unit rests on early Eocene lava flows in the VVP area, giving the sediments a maximum age of middle Eocene here (Faleide et al., 1988; Ryseth et al., 2003; Eidvin et al., 2014).

The base of the Oligocene sediments in unit Te2 (the Te1-Te2 boundary) has been correlated to the base Oligocene unit boundary of Ryseth et al., (2003) and Eidvin et al., (2014) in the VVP.

The base of the early-middle Miocene sediments in unit Te3 (the Te2-Te3 boundary) has been correlated to the base Miocene unit boundary of Ryseth et al., (2003) and Eidvin et al., (2014) in the VVP.

Unit Te4 holds sediments of late Miocene-early Pliocene age (Fiedler & Faleide, 1996). The base of the unit (the Te3-Te4 boundary) could not be correlated to any previous work. The boundary will be termed base late Miocene in this study, to have a similar designation as the other pre-glacial unit boundaries.

4.2.2 Correlation to magnetic anomalies in the Lofoten Basin

The onlapping relationship of the pre-glacial seismic units onto the oceanic basement (and their ages from magnetic anomalies) in the Lofoten Basin will be described in the following. In the Lofoten Basin, the oceanic basement gets progressively younger in a northerly direction towards the present location of the spreading ridge (Figure 4-4). Fiedler and Faleide (1996) presented maps locating the unit pinch-out boundaries of the pre-glacial units Te1-Te4 and magnetic anomalies of known age in the basin (Figure 3-5). Here, their approach has been followed. Uncertainties in these age estimates includes the accuracy of the maps presented by Fiedler and Faleide (1996). In particular, this relates to two areas that have relevance for the study (and that have been marked with question marks on the map (Figure 4-4);

1) The location of the unit Te2 pinch-out boundary (the Te2-Te3 unit boundary in Figure 4-4) in the east, close to the COB. If the boundary was moved more toward N, seismic lines in the area might cross the COB onto oceanic basement of Oligocene age (Figure 4-4). Studies of the

sediments in line HB-6 close to the COB show very similar reflection amplitude and configuration in unit Te3 as in the same unit beyond the COB a bit to the north in line HB-2. Therefore, the line HB-6 is also interpreted to cross the COB where the oceanic basement is covered with sediments of Miocene age (Figure 4-4).

2) The location of the unit Te4 pinch-out boundary (the Te3-Te4 unit boundary) in the north. Here, the northern part of line HB-1300 might be comprise unit Te4 sediments if the Te3-Te4 unit boundary was turned more to the east (Figure 4-4). It is difficult to give a good evaluation in this area because of the northward termination of line HB-1300, and the location of the Te3-Te4 boundary in this area remains uncertain. The location of this boundary, however, has little importance for the following part of this study.

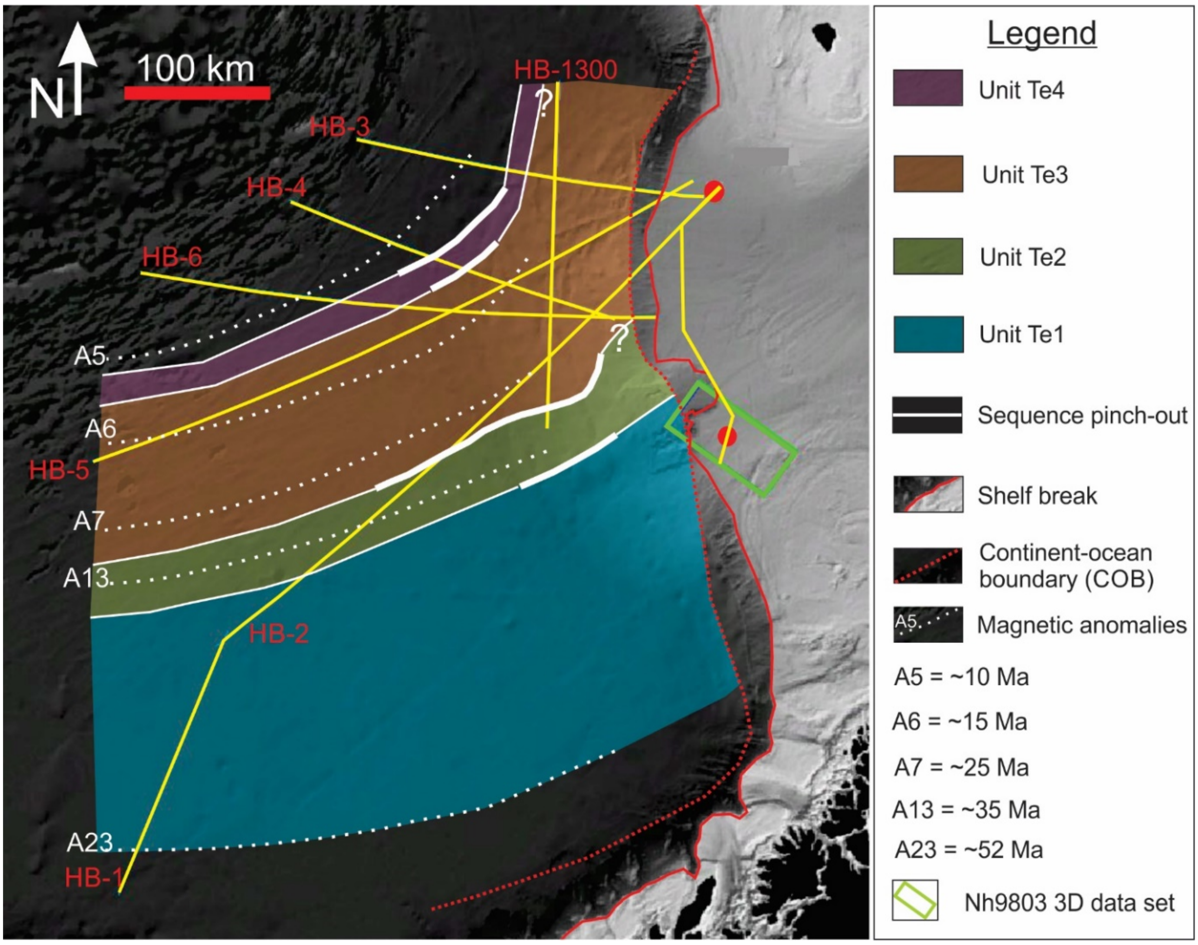


Figure 4-4: The magnetic anomalies and unit pinch out of pre-glacial seismic units in the Lofoten Basin as adapted from Fiedler and Faleide (1996). Bold, white lines represent the unit pinch-out boundaries adapted from Fiedler and Faleide (1996). Thin, white, lines are interpolations from the bold lines. Question marks indicate areas of uncertainty with regards to the pinch-out lines, as discussed in the text above. See the original seismic lines overview map in Figure 3-2.

All the seismic lines in the study area that cross the COB (lines HB-2, HB-3, HB-5 and HB-6), cross the boundary where the oceanic basement is covered with sediments of Miocene age (Figure

4-4). It is only line HB-1 and the southwestern part of line HB-2 that crosses sediments of Eocene age.

4.3 THE MAIN SEISMIC UNIT BOUNDARIES

4.3.1 Pre-glacial seismic unit boundaries

4.3.1.1 The base middle Eocene (BME) reflection in the Vestbakken Volcanic Province

In the VVP area, sediments of middle Eocene age rest on volcanic flows (Faleide et al., 1988; Fiedler & Faleide, 1996; Ryseth et al., 2003; Eidvin et al., 2014) (Figure 4-5). The base middle Eocene reflection is an intra-G0 boundary, and it defines the lower boundary of the stratigraphically deepest sediments on the continental slope that will be considered in this study.

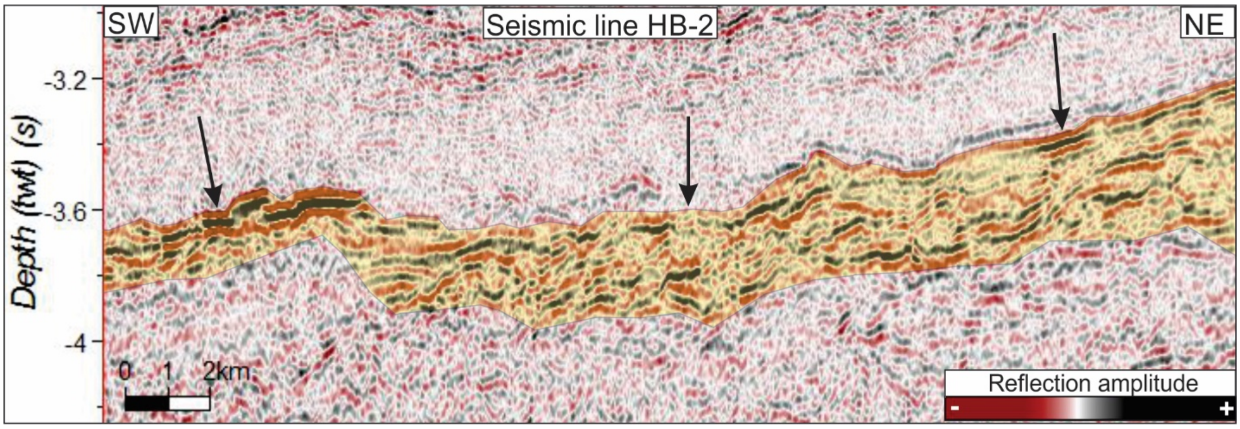


Figure 4-5: An example of the boundary between Early Eocene volcanic flows and the base of middle Eocene sediments on the VVP. Black arrows indicate the base of the middle Eocene sediments. Shaded yellow colour indicate Early Eocene volcanic flows. The location of the seismic section is indicated in Figure 4-6.

The boundary between the early Eocene volcanic flows below and the base middle Eocene boundary on top occurs at a depth of 2800-2850 ms (twt) in well 7316/5-1 (Figure 4-6). The boundary is characterized by a change from low- to medium amplitude and discontinuous to continuous reflection at the base middle Eocene boundary, to high-amplitude, discontinuous reflections from the volcanic flows below (Figure 4-5). The interval of volcanic flows has a thickness of tens to hundreds of milliseconds (twt), and the boundary between volcanic flows below and sediments on top is easy to follow downslope except for in the area close to the COB. Here, the boundary dips down in a deep, local basin where it becomes less distinct and is uncertain (Figure 4-6). It is however interpreted to onlap a prominent high in the COB area. The prominent high will be referred to as a marginal high in the following, as it separates the continental crust from the oceanic basement.

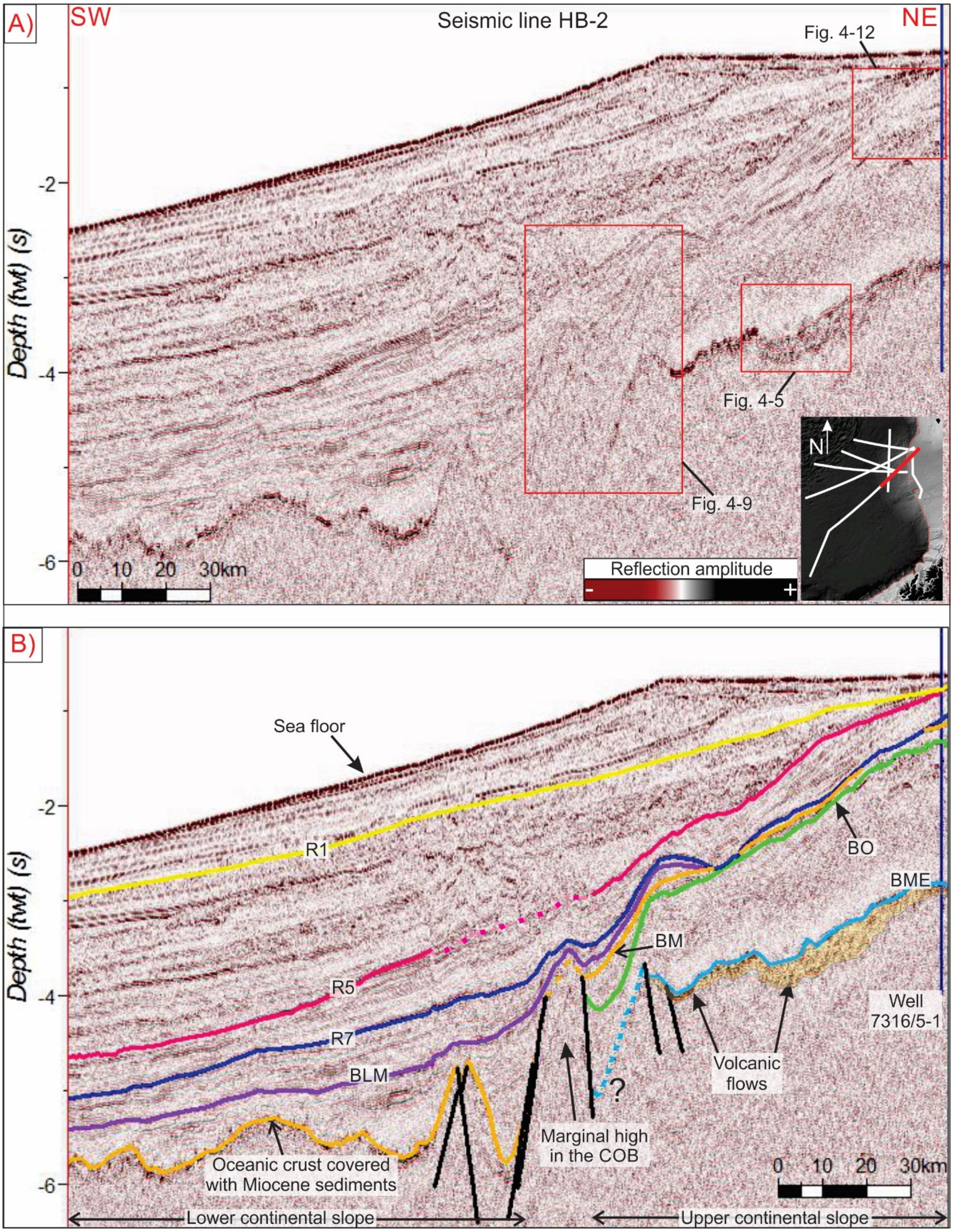


Figure 4-6: An un interpreted seismic section from the seismic line HB-2 across the VVP is shown in A), and the same section, including the interpreted main seismic unit boundaries, is shown in B). The uncertain location of the base middle Eocene boundary in the local deep basin up-slope the marginal high is indicated with a dashed, blue line. The location of the seismic section is shown with a red line in the location-map in A). BME: base middle Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. COB: Continent-Ocean boundary.

4.3.1.2 The oceanic basement

The north – south extent of the marginal high is unknown. However, it does not appear in seismic sections to the north of that shown in Figure 4-6. This may have implications for the downslope transport of sediments in the area, as will be discussed later. In the lower continental slope, downslope of the marginal high in the COB, the oceanic basement forms the base of all sediments deposited in the Lofoten Basin since the opening of the Norwegian-Greenland Sea.

The upper part of the lower continental slope (Figure 4-1) consists of a deep local basin immediately downslope the marginal high. Basins and highs of progressively lower relief dominates the basement morphology downslope (Figure 4-8). The boundary between the oceanic basement below and sediments on top of it is a moderate to high-amplitude, continuous to discontinuous reflection (Figure 4-7). The oceanic basement has an irregular appearance in the Lofoten Basin, where it creates basins separated by highs. The highs appear as both symmetric to asymmetric peaks and rotated fault blocks in the seismic sections (Figures 4-7 and 4-13).

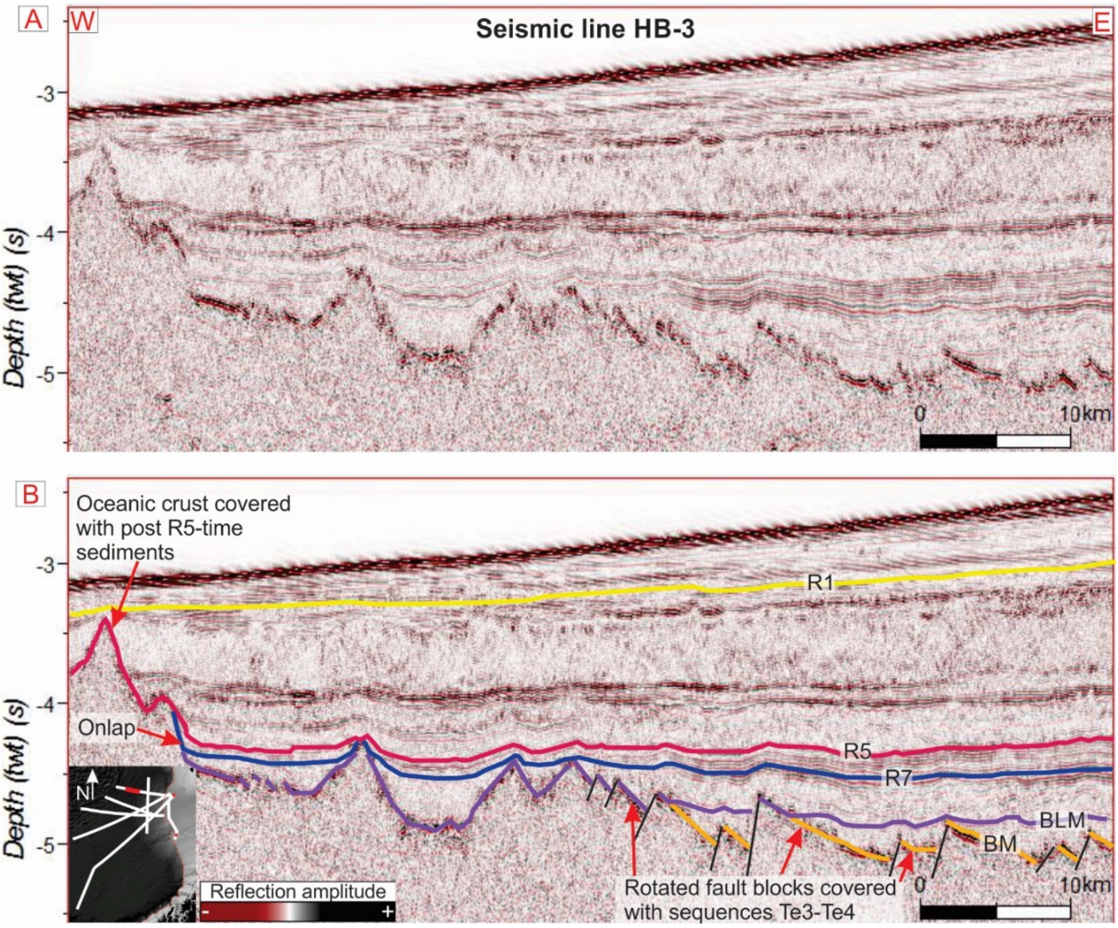


Figure 4-7: An example of the oceanic basement reflection appearing with rotated fault blocks in the northern Lofoten Basin is shown in seismic line HB-3. BM: base Miocene, BLM: base late Miocene. The location of the seismic section is shown with a red line in the location map in B).

The crust appears more irregular in the south-west than in the northeast, following lines HB-1 and HB-2 (Figures 4-8 and 4-10).

The proximal Lofoten Basin region morphology is dominated by two prominent sub-regions; a wide area of deep basins in the proximal part, referred to as the deep basin region, and a wide area which is elevated relative to the deep basin region and appears as a plateau, referred to as the plateau region (Figure 4-1 and Figure 4-8). The deep basin region is about 110 km wide and has a generally low relief compared to the prominent highs in the area. The depth of the oceanic basement increases about 1000 ms (twt) (1300-1400 meters) toward the southwest within the deep basin region relative to surrounding areas. The plateau region is about 90 km wide and has an irregular but low relief and generally even depth (Figure 4-8).

The dominating morphology in the distal Lofoten Basin is the variation between the high and narrow peaks separating narrow basins, and creating a very irregular oceanic basement relative to the other parts of the study area (Figure 4-8). In the south-west, the crust rises toward the Vøring Plateau with a gradually lower relief. The abrupt change in irregularity from seismic line HB-2 in the northeast to seismic line HB-1 in the southwest may partly be related to the alignment of the seismic lines to the direction of sea floor spreading. Seismic line HB-2 is aligned with an inclined angle to the spreading axis, while the seismic line HB-1 cross the spreading axis nearly perpendicular (Figure 4-4).

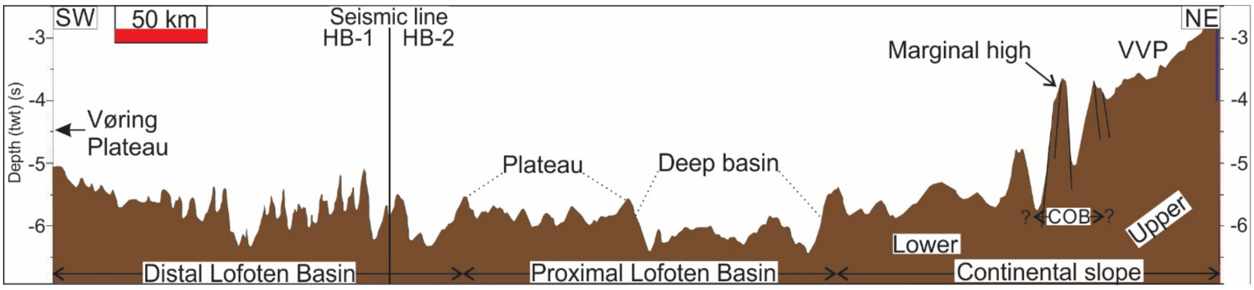


Figure 4-8: The oceanic basement morphology (brown colour) is shown for the lower continental slope and the Lofoten Basin. The upper continental slope is included in the sketch, where the volcanic flows define the top of the brown coloured area. The location of lines HB-1 and HB-2 is indicated in Figure 3-2.

4.3.1.3 The base Eocene (BE) in the Lofoten Basin

Seismic unit Te1 is probably deposited in the distal Lofoten Basin (Figure 4-10). The inferred transition from a crust covered with Oligocene sediments (unit Te2) to a crust covered with Eocene sediments (unit Te1) occurs in a relatively deep and wide local in the southwest of the plateau region (Figure 4-10 and Figure 4-11). The oceanic basement south and southwest of this transition is entirely covered by unit Te1.

4.3.1.4 The base Oligocene (BO) reflection

The Eocene-Oligocene unit boundary occurs in well 7316/5-1 at a depth of 1300-1350 ms (twt) in the VVP area (Figure 4-6). The boundary was interpreted along a positive seismic reflection that has a high amplitude in the VVP area, but faulting has affected the reflection continuity here. The amplitude generally decreases downslope and varies between low and high, while the reflection continuity increases. The reflection has an erosional character in the upper slope (Figure 4-12) and upslope the marginal high in the COB (Figure 4-9). Downslope, the reflection on-laps the marginal high in the local basin (Figure 4-9).

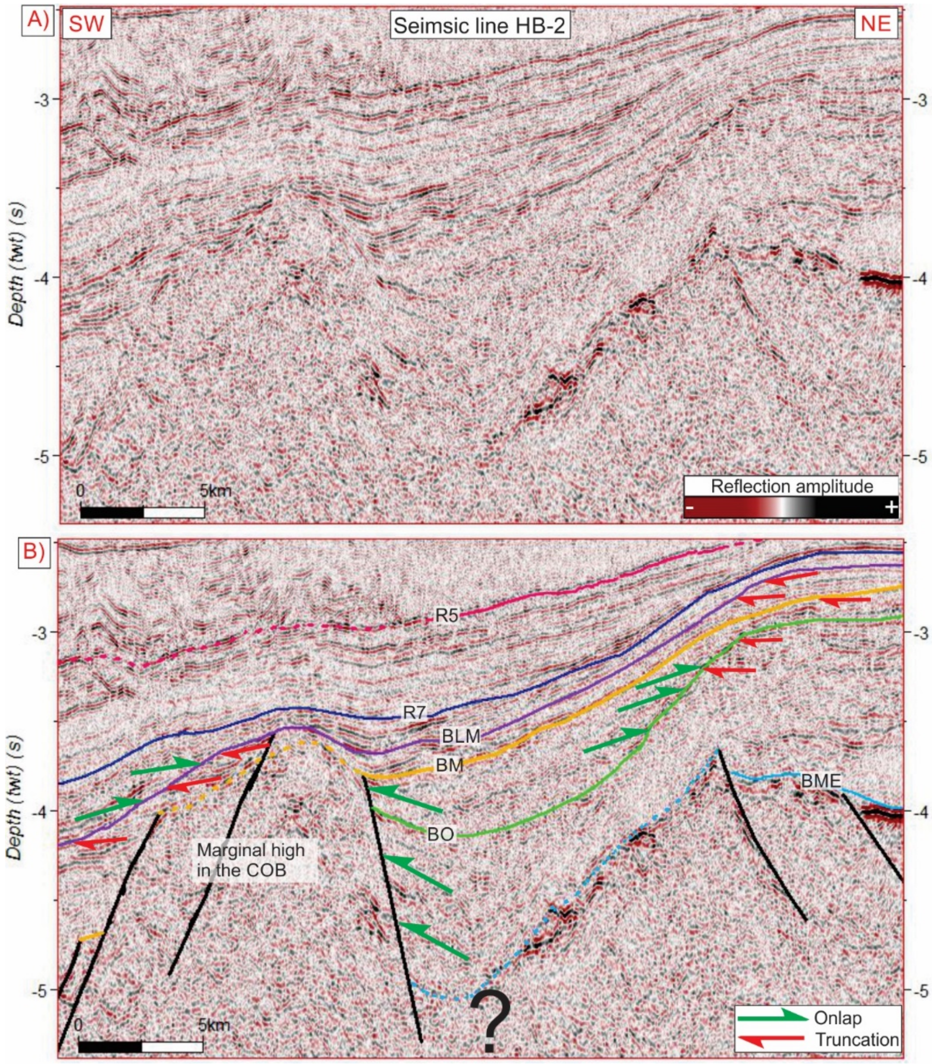


Figure 4-9: The figure shows truncation by the base Oligocene and base late Miocene of underlying strata, up-and down-slope of the prominent high in the continent-ocean boundary (COB). BME: base middle Eocene BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is indicated in Figure 4-6.

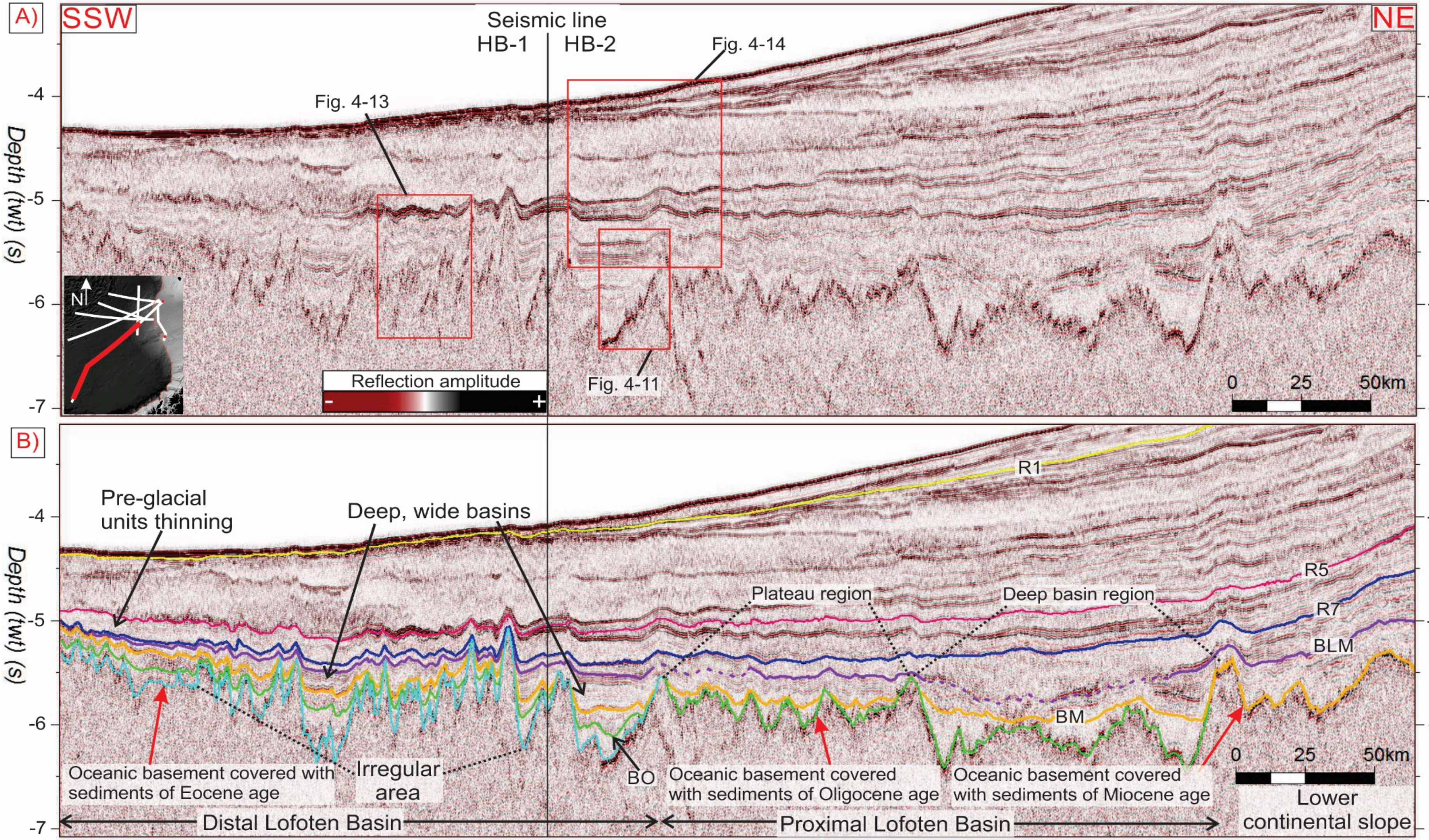


Figure 4-10: The seismic stratigraphy is shown in a seismic section from the lower continental slope and the Lofoten Basin, where A) is an un-interpreted version. B) shows the inferred locations of the different units resting on the oceanic basement and the location of the base Oligocene (BO), base Miocene (BM), base late Miocene (BLM) and reflections R7-R1. The location of the seismic section is shown with a red line in the location-map in A).

The sediments deposited on the oceanic basement in the lower continental slope are inferred to be of Miocene age (Figures 4-6 and 4-10). In the Lofoten Basin, sediments of Oligocene age first appears in the transition from the lower continental slope to the proximal Lofoten Basin (Figure 4-10). The Oligocene sediments are here interpreted to constitute the base of the G0 seismic unit deposited onto the oceanic basement (Figure 4-10). In the central part of the Lofoten Basin, the transition of the base Oligocene reflection to an intra G0 unit boundary occurs where the unit overlies the Te1 unit (Figures 4-10 and 4-11).

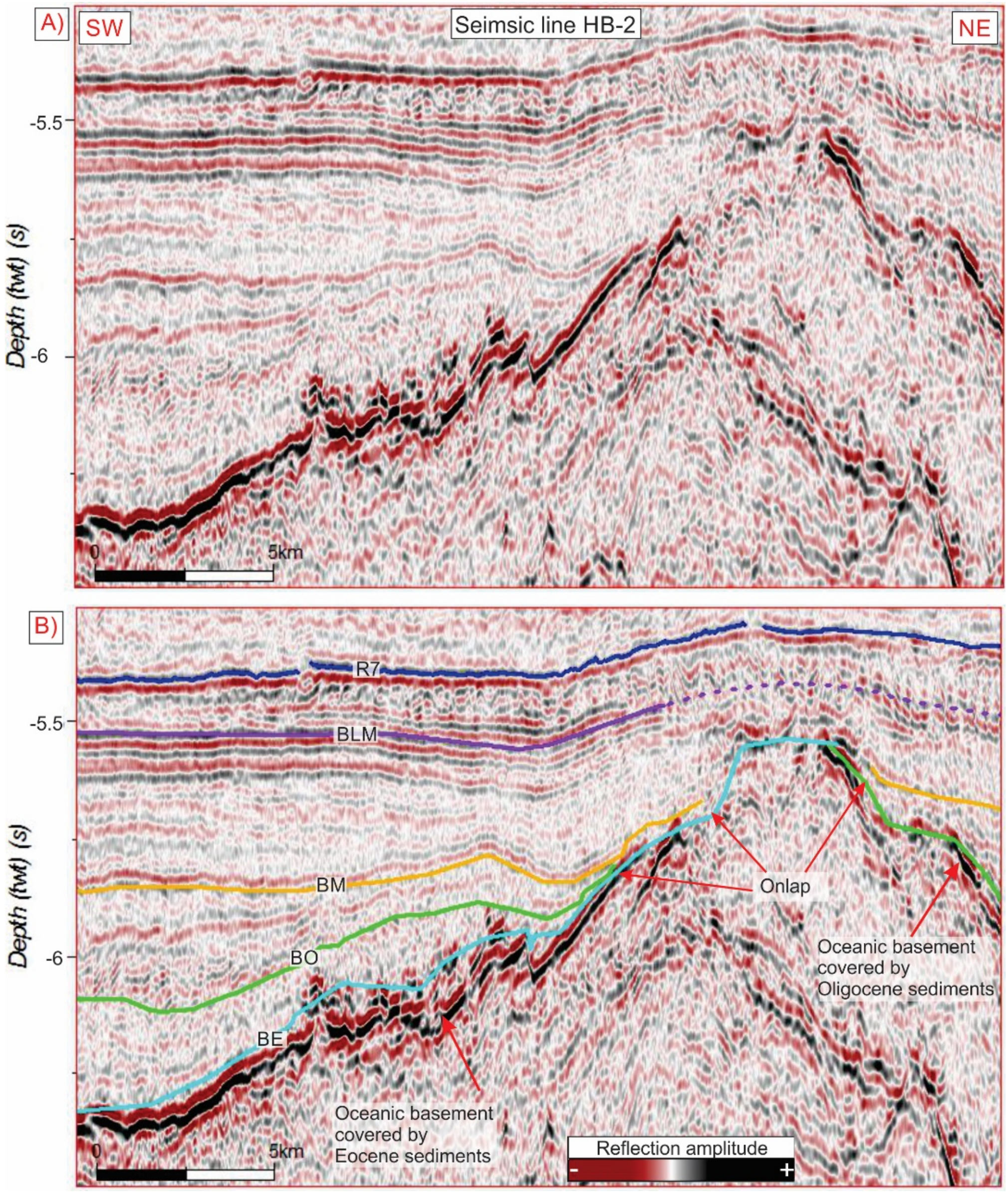


Figure 4-11: Pre-glacial unit boundaries shown in a seismic section from the central parts of the Lofoten Basin. The base Oligocene is interpreted to transit from the base of G0 unit in the northeast, to an intra G0 unit boundary toward the south-west, where Eocene sediments are interpreted to cover the oceanic basement and make out the base of unit G0. BE: base Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is shown in Figure 4-10.

The intra G0 base Oligocene reflection is discontinuous with a low to medium amplitude here (Figure 4-13). The reflection onlaps most of the basement highs in the irregular Lofoten Basin, but examples where the reflection overlies highs of lower relief have also been observed in the southwest (Figure 4-13). The reflection is easiest to follow in the local basins. Here, the difference in facies between the seismic units is commonly clear (Figure 4-13).

4.3.1.5 The base Miocene (BM) reflection

The base Miocene reflection was interpreted along a discontinuous, positive seismic signal of low to medium amplitude in the VVP area. It appears in well 7316/5-1 at a depth of ~1150 ms (twt) (Figure 4-12). The Miocene succession is overlain by the glacial deposits from R7 time with an erosional contact, and the base Miocene has been locally truncated on the continental slope (Figure 4-12). Downslope, the base Miocene reflection possibly onlap the marginal high in the COB, and a thin part of unit Te3 possibly drapes the high (Figures 4-6 and 4-9). The base Miocene forms the base of seismic unit G0 in the lower continental slope downslope of the marginal high (Figures 4-6 and 4-9).

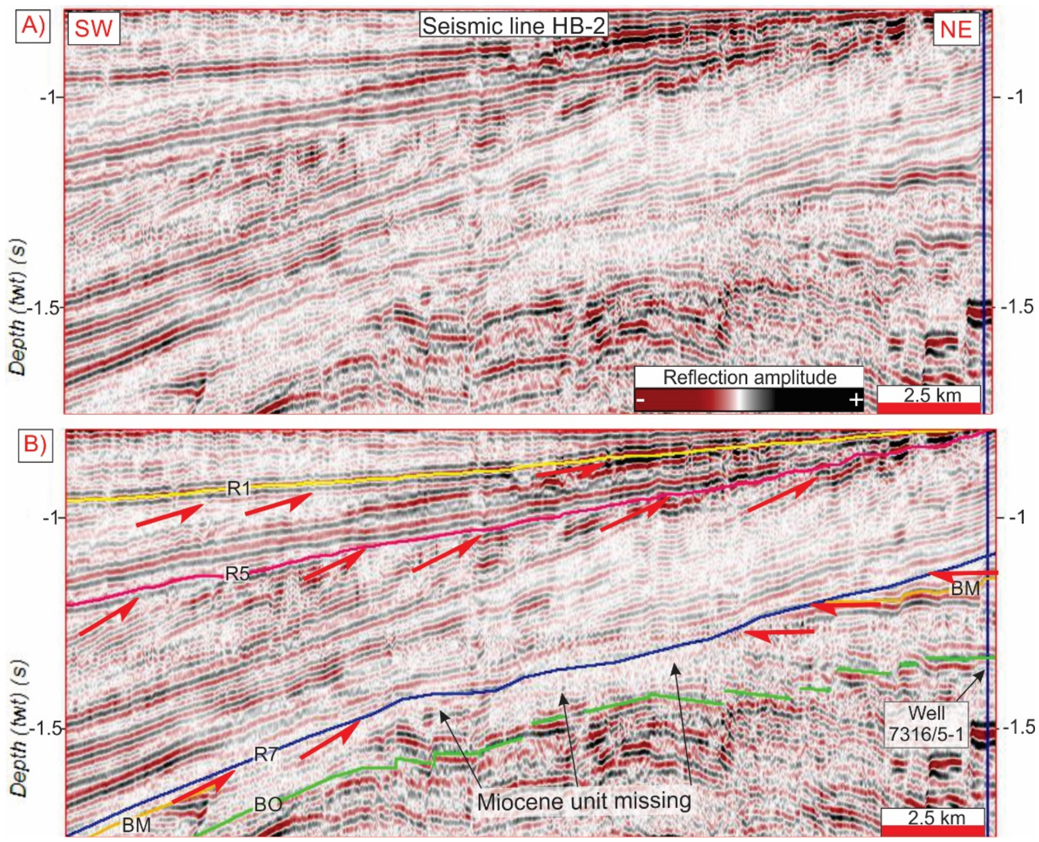


Figure 4-12: The seismic unit boundaries from base Oligocene to R1 are shown in the upper slope in the VVP in seismic line HB-2. Red arrows indicate truncation. BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is indicated in Figure 4-6.

The intra unit Te3 overlies the Oligocene unit Te2 in the proximal Lofoten Basin (Figure 4-10). The base Miocene reflection is discontinuous and of low amplitude here. The reflection character changes gradually toward the southwest into the Lofoten Basin to a continuous, medium- to high amplitude reflection in the distal parts. The base Miocene reflection onlaps the most prominent highs in the Lofoten Basin, but occasionally drapes highs of lower relief (Figure 4-11 and Figure 4-13).

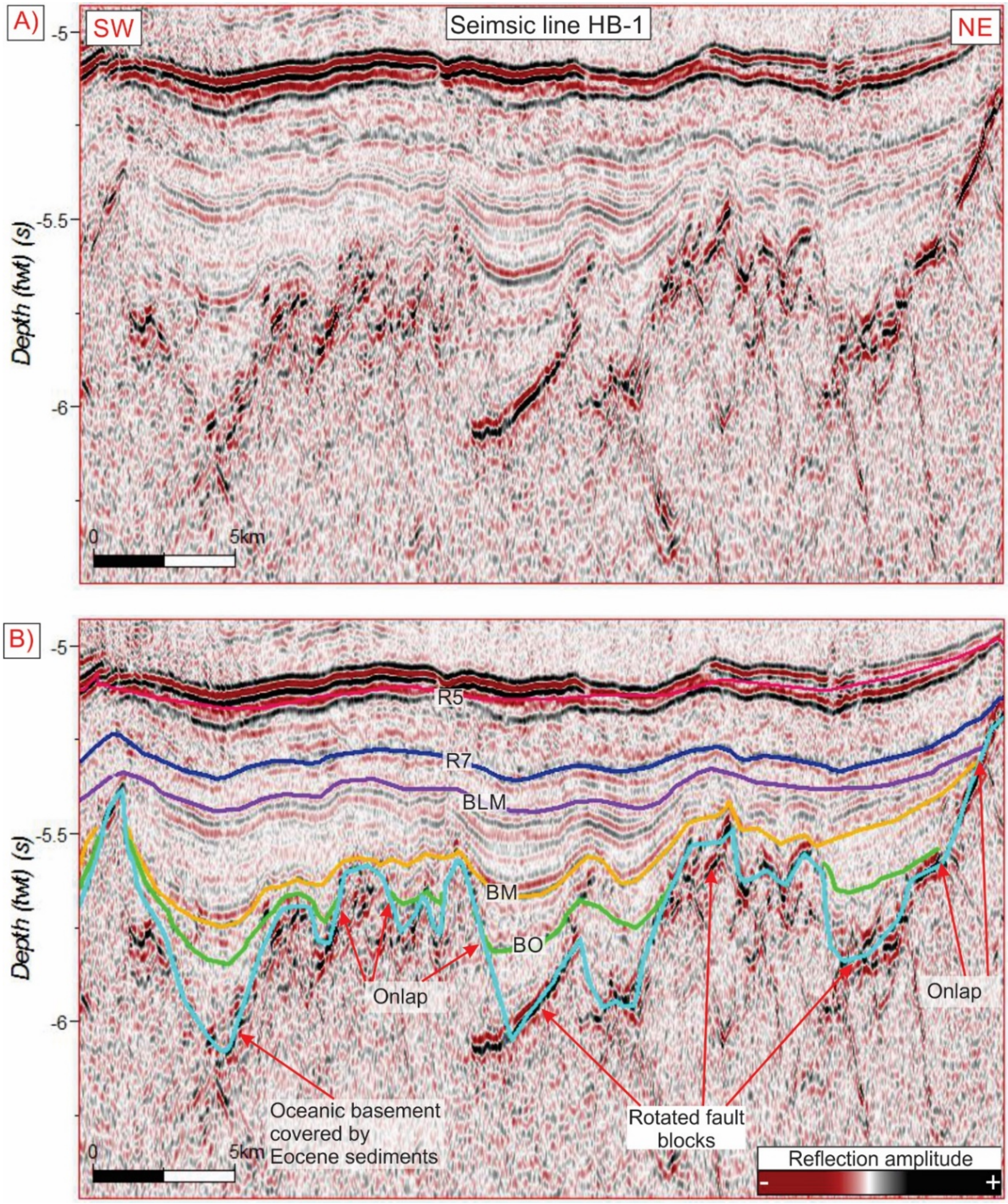


Figure 4-13: The pre-glacial unit boundaries are in a section from the distal Lofoten Basin. The area has lower relief peaks between higher relief peaks. Rotated fault blocks and the onlap of sediments within units Te2 and Te3 to the highs are indicated. BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the figure is shown in Figure 4-10.

4.3.1.6 The base late Miocene (BLM) reflection

The base late Miocene reflection is not present on the upper part of the upper continental slope, but appears in the middle part of the area (Figure 4-6). The continuous to discontinuous reflection has been interpreted along a positive seismic signal of medium amplitude. The reflection has an erosional character downslope the marginal high where it truncates the underlying unit Te3 (Figure 4-9).

In the Lofoten Basin, the reflection has been difficult to follow in areas where the reflection is discontinuous. By analysing the seismic facies above and below, the boundary has been tentatively located and marked with a stippled line (Figures 4-10 and 4-11). The continuity and amplitude of the base late Miocene reflection increases toward the southwest. Here, the reflection onlaps two prominent highs. Apart from those two highs, the reflection overlies all the highs (Figures 4-10 and 4-13).

The base late Miocene reflection is difficult to follow where the oceanic basement rise toward the Vøring Plateau in the southwest. Seismic units Te3 and Te4 are thin here, and it is difficult to determine whether the Te4 unit is present between the Te3 unit and reflector R7 or not (see description of the units in Section 4.4.4).

4.3.2 Glacial seismic unit boundaries

4.3.2.1 R7

Reflector R7 intersects well 7316/5-1 at a depth of ~1075-1100 ms (Figure 4-12). It has been interpreted along a positive seismic signal of low to medium amplitude, and it is discontinuous on the upper half of the continental slope. The erosive character of R7 is easiest to identify on the upper slope, were R7 truncates the strata in rotated blocks. In some parts of the slope, the entire Miocene has probably been eroded (Figure 4-12). On the middle to lower slope, the R7 reflection differs between an erosive and a conform appearance. The conform appearance increases downslope and the reflection is generally conform to the over- and/or underlying strata in the Lofoten Basin (Figure 4-13 and Figure 4-14). The continuous and medium amplitude characters follow the reflection toward the southwest in the Lofoten Basin where the reflection commonly separates units with different internal seismic characteristics (Figure 4-13). Reflection R7 drapes all the highs in the Lofoten Basin and has a smooth appearance relative to the irregular oceanic basement below (Figure 4-10 and Figure 4-13). In seismic lines in the northern Lofoten Basin, reflection R7 downlaps the oceanic basement close to the Mohns Ridge (Figure 4-7).

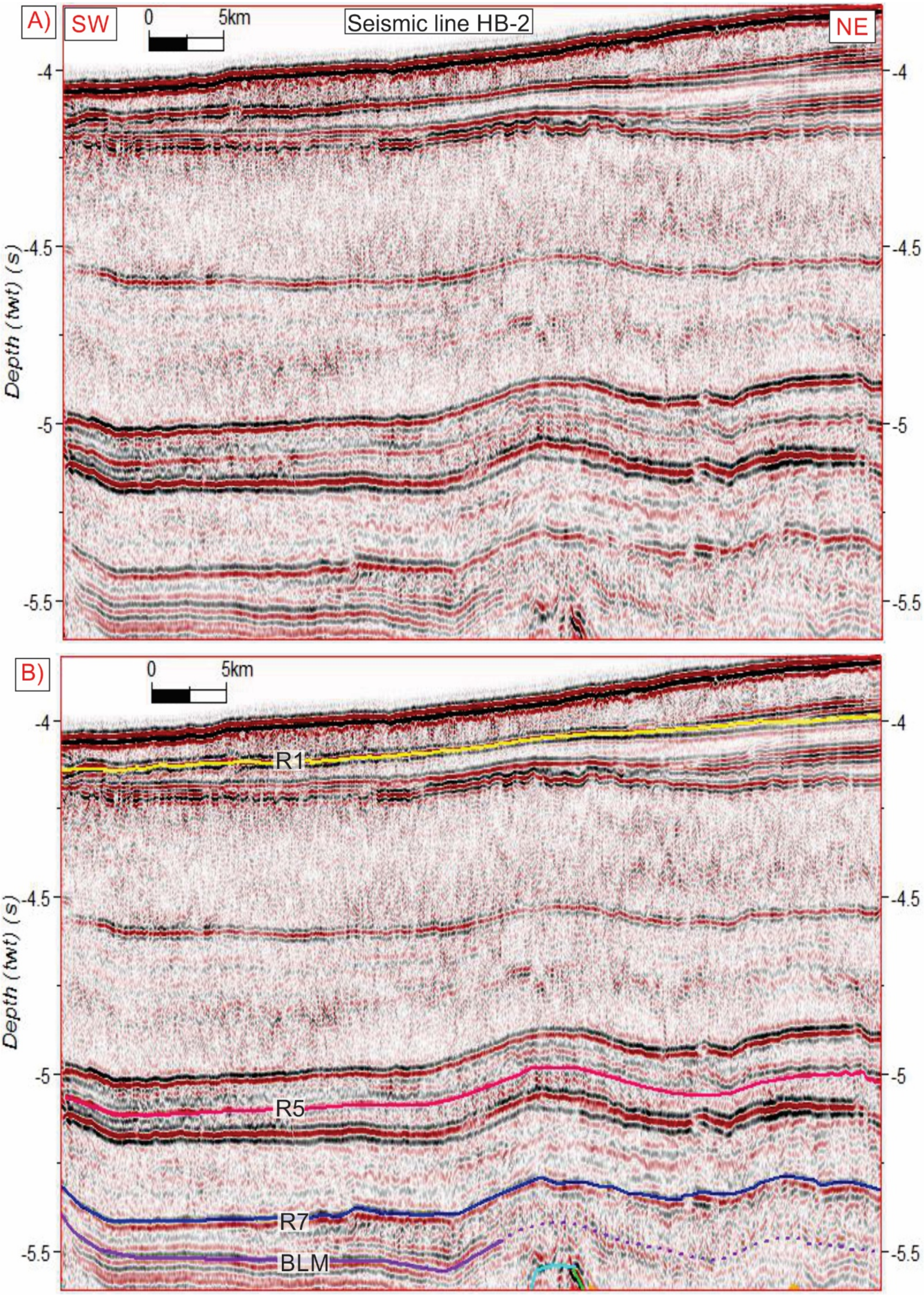


Figure 4-14: The location of BLM, R7, R5 and R1 is shown for the central part of the Lofoten Basin in seismic line HB-2. The R7 separates partly chaotic and partly stratified reflections below from chaotic reflections above. R5 separates chaotic reflections, while R1 separates chaotic reflections above from partly transparent and partly stratified reflections below. BLM: base late Miocene. The location of the seismic section is shown in Figure 4-10.

4.3.2.2 R5

Reflection R5 intersects with well 7316/5-1 at a depth of 775-800 ms (twt). It has been interpreted along a negative seismic signal. The reflection has a medium to high reflection amplitude and appears continuous on the continental slope (Figure 4-12). The paleo shelf-break of R5 time is easy to point out on the upper slope due to the change from the truncation of underlying strata on the paleo shelf to where the reflection dips down the paleo slope (Figure 4-6). Several intervals of truncation of underlying strata is observed downslope (see for example Figure 4-12). In the Lofoten Basin, the R5 reflection varies between low and high amplitude, and appears continuous to discontinuous. It is relatively easy to identify, because it often separates units with internal chaotic seismic signature (Figure 4-14). In the north, R5 downlaps oceanic basement close to the Mohns Ridge (Figure 4-7).

4.3.2.3 R1

Reflection R1 intersects with well 7316/5-1 at a depth of 750-775 ms (twt) (Figure 4-12). The reflection was interpreted along a continuous to discontinuous positive seismic signal of low to medium amplitude downslope. R1 truncates underlying strata on the paleo-shelf. It is easy to follow downslope due to its clear difference in appearance from the overlying and underlying strata. This is because the reflection commonly separates units of chaotic facies with higher reflection amplitudes below from varying seismic facies with lower amplitudes above. The downslope location of the R1 reflection in this study does not coincide exactly with that of Hjelstuen et al. (2007), as they located R1 somewhat lower on the middle slope in seismic line HB-2. The basis for the location of the R1 reflection in the VVP here was the inferred location of the R1 in the Sørvestnaget Basin, and its location in the composite seismic line shown in Figure 4-3. The interpretations for the R1 reflector are the same for this thesis and for that of Hjelstuen et al. (2007) for the Lofoten Basin. The R1 reflection truncates underlying strata on the lower continental slope, until it is conform to the over- and underlying strata further out in the Lofoten Basin. The reflection in the Lofoten Basin changes gradually to a continuous and medium to high amplitude reflection (see for example Figure 4-14).

4.3.2.4 The sea floor surface

The sea floor surface has a negative, high-amplitude and continuous seismic signal (Figure 4-14).

4.4 SEISMIC UNIT G0

The description of seismic unit G0 will start on the upper continental slope (Section 4.4.1) followed by the lower continental slope (Section 4.4.2), the proximal Lofoten Basin (Section 4.4.3) and the distal Lofoten Basin (Section 4.4.4). The glacial seismic units GI-GII will be briefly described in Section 4.5.

4.4.1 The upper continental slope

4.4.1.1 General description of seismic unit G0

Seismic unit G0 has a uniform thickness in the upper continental slope (Figures 4-1 and 4-17). The overall geometry is dominated by several prominent features downslope, including: a mounded feature (convex up in the upper stratigraphy), a deep local basin (convex down shape) and the marginal high downslope the local deep basin in the COB (Figure 4-16). The lower part of unit G0 thins across a threshold below the mounded unit, and subsequently fills the deep local basin in the COB. Most of the unit onlaps the marginal high downslope and only a thin part of the unit overlies it (Figure 4-16).

4.4.1.2 Seismic unit Te1

The lower part of unit Te1 is dominated by an interval of reflection-free internal seismic facies. The internal reflections in the middle and upper part of the unit have a trend of increasing amplitudes and continuity both up in the stratigraphy and downslope. On the upper slope, these deposits form rotated fault blocks with internal reflections of medium to high amplitude. Some of the faults terminate within the unite Te1, while others extend up into the unit Te2 (Figure 4-15).

A divergent reflection configuration exhibiting a westerly dip is observed downslope (Figure 4-17) until it changes to sub-parallel toward the threshold. The sub-parallel reflections are subsequently truncated by the base Oligocene reflection above the threshold (Figure 4-9). Here, the Te1 unit is thinnest. However, it thickens downslope in the deep local basin where the unit has a convex-down shape and the internal reflections onlap the marginal high (Figure 4-9 and 4-17).

Interpretation

A reflection free interval occurs in the lower part of unit Te1 (Figure 4-17). Reflection free zones may be the result of for example homogenous gross lithology like a massive reef build-up or thick seismically homogenous shales or sandstones (Mitchum et al., 1977; Veeken & Moerkerken, 2013b). According to Veeken and Moerkerken (2013a), automatic gain control (AGC) in the seismic processing sequence may also result in artificial reflection free zones where the signal generated on top of a unit is so strong that it dominates the amplitude normalization process. The reflection free area in the lower part of the Eocene unit appears immediately above where the acoustic-impedance (AI). The contrast is expected to be high across the sediment-volcanic flow interface, and this area is therefore interpreted to be the result of seismic processing rather than a homogenous gross lithology.

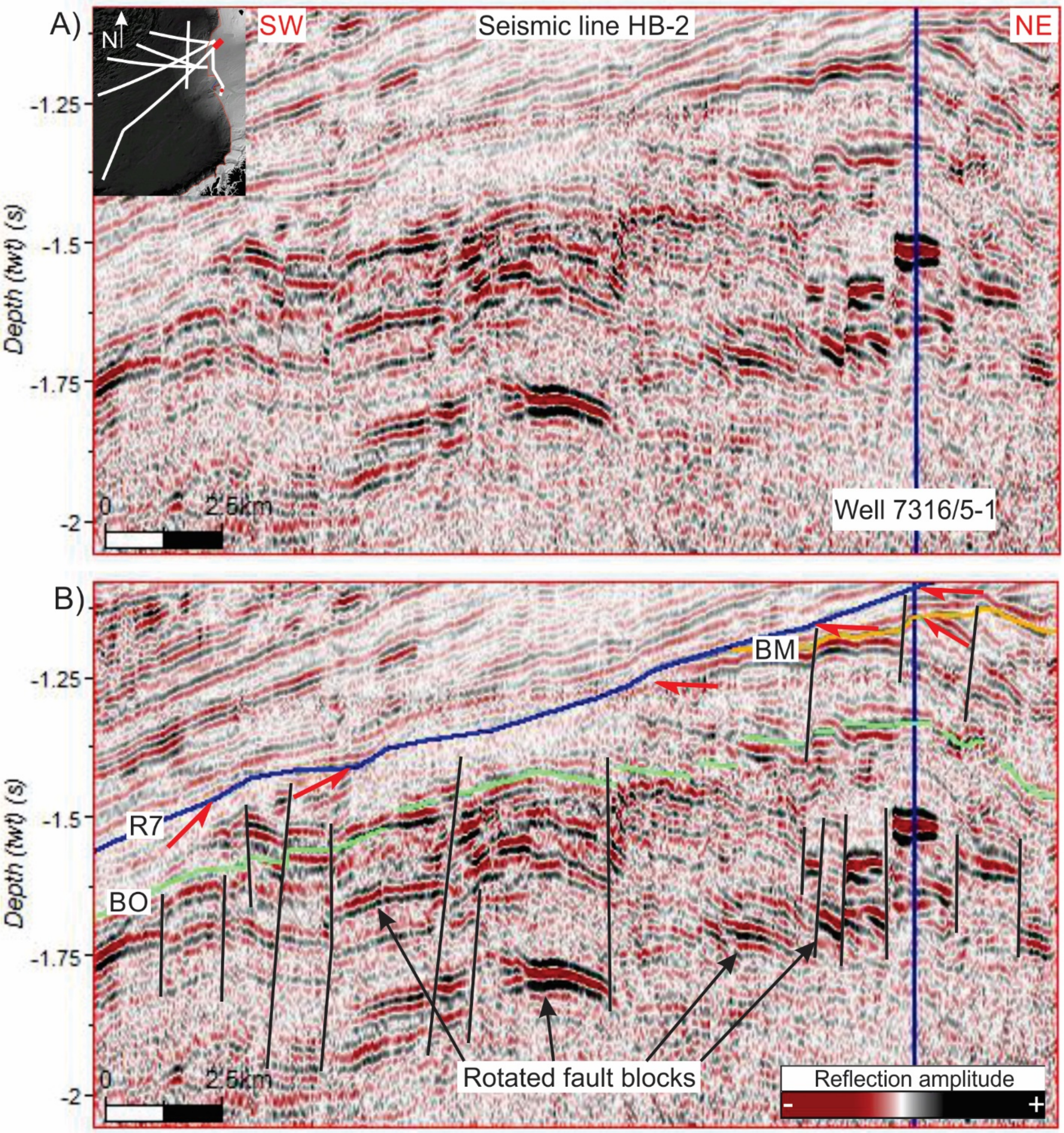


Figure 4-15: Rotated fault blocks and the truncation of units (red arrows) in the upper continental slope in the VVP area. The location of the seismic section is shown with a red line in the location map in A).

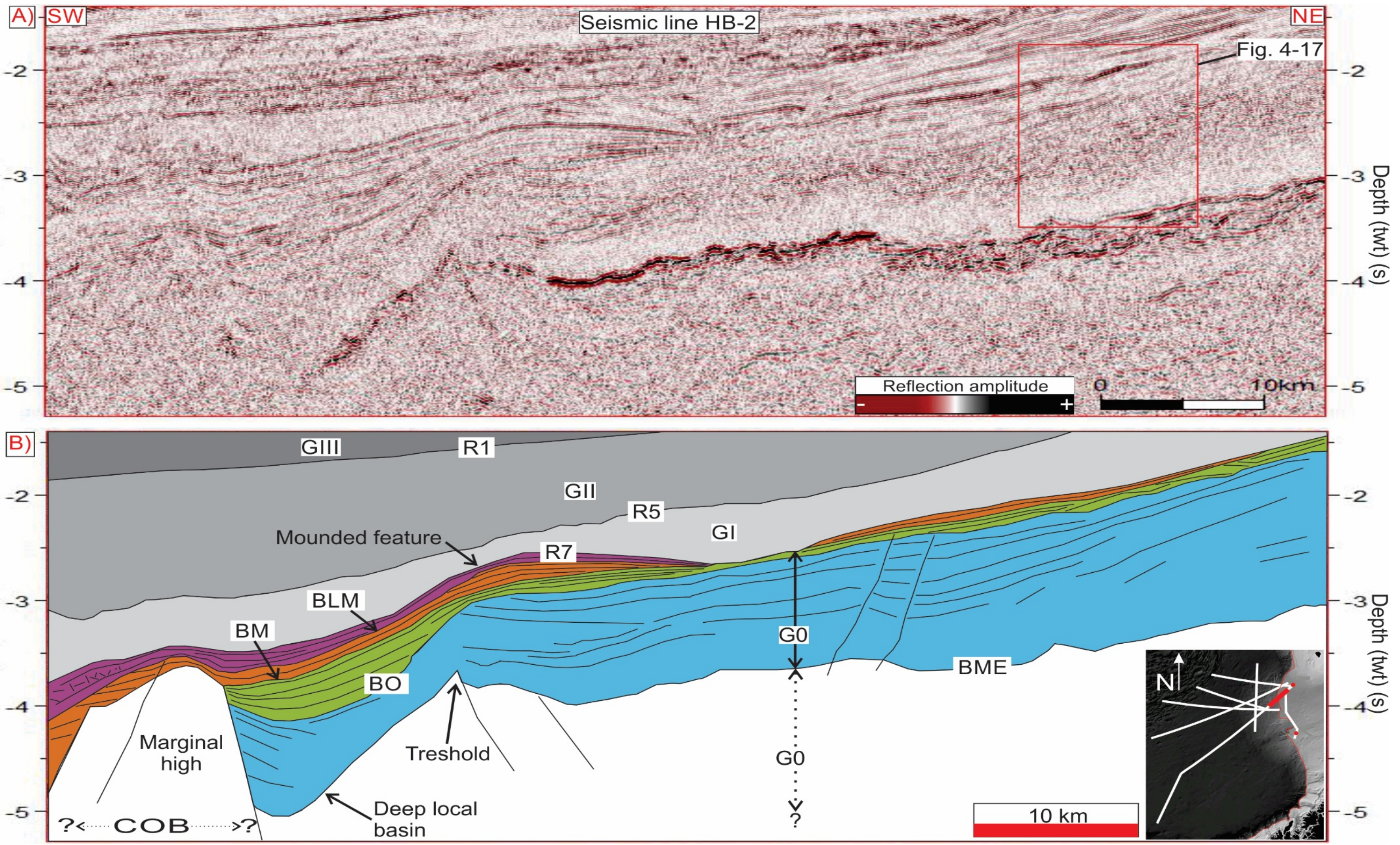


Figure 4-16: The seismic unit G0 on the upper continental slope including the different pre-glacial units outlined. BME: base middle Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is indicated in the location map in B).

The rotated fault blocks indicate tectonic movements in the area. Faults both terminating within the unit and extending into the overlying unit indicate that the area has been subject to tectonic movements in both the Eocene and the Oligocene.

The high amplitude reflections observed in rotated fault blocks close to well 7316/5-1 are located in an area where a gas column was proven (Eidvin et al., 1998). An increased amplitude within a small, rotated fault block was interpreted to be a "bright-spot" in relation to the gas column. The high-amplitude reflections appearing within rotated fault blocks described in this thesis are suggested to have a similar origin to that described by Eidvin et al. (1998), with gas trapped in the fault blocks appearing as "bright-spots" in the seismic section.

The divergent reflections dipping westerly are interpreted to represent prograding clinoforms deposited in a marine environment. The dip toward west indicate a source of these sediments located to the east of the area. However, due to the lack of controlling seismic lines holding Eocene sediments on the upper slope, the exact progradational trend is difficult to point out. No topset nor bottomset have been observed in the unit. Divergent reflection configuration may indicate a lateral variation in the sedimentation rate or progressive tilting of the depositional surface (Mitchum et al., 1977). The downslope change to parallel to sub-parallel reflections may indicate a more uniform sedimentation rate (Mitchum et al., 1977).

Reflections onlapping the marginal high with inclined reflections may represent post-depositional deformation. The pre-glacial sediments in the Lofoten Basin have been subject to massive overload by subsequent deposition, especially the past ~2.7 Ma, e.g. Vorren et al., 1991; Faleide et al., 1996; Fiedler & Faleide, 1996 and Hjelstuen et al., 2007. Compaction and changes in geometry of pre-late Neogene deposits are suggested to be caused by the deposition of the thick glacigenic succession on the Norwegian margin (Hjelstuen et al., 2004). A similar cause for deformation is suggested to be possible for the infilling Eocene deposits. A subsequent deformation by overloading may have caused subsidence of the deposited infilling units in the basin. The onlapping reflections to the sides may have been tilted during this process.

4.4.1.3 Seismic unit Te2

Seismic unit Te2 is generally thin on the upper continental slope, but thickens downslope in the local basin upslope the marginal high (Figure 4-16). Close to well 7316/5-1 and downslope, the unit is dominated by rotated fault blocks comprising internal reflections of low to medium amplitude, interbedded with low-amplitude discontinuous reflections. The faults extending into the unit from the unit Te1 below appear to terminate within unit Te2. Some faults probably extend from unit Te2 and up into unit Te3 (Figure 4-15). The overlying unit Te3 and unit GI truncates the rotated fault blocks (Figure 4-15 and 4-18).

The internal seismic character changes into sub-parallel reflections of low to high amplitudes in a uniformly thin unit downslope toward the mounded feature. Below the mounded unit, unit Te2 has a parallel to divergent reflection configuration. Above the threshold, the unit thins where it is truncated by the overlying unit Te3 (Figure 4-9). The unit terminate by onlap to the marginal high in the basin upslope the high (Figure 4-9 and 4-17). The reflections in the local basin upslope the high appears disrupted and of low amplitude, partly similar to the facies seen in unit Te1 below.

Interpretation

The faults terminating within the unit indicate tectonic movement during the Oligocene. However, it is possible that the unit was subject to tectonic movements also during the early-middle Miocene as faults probably extend across the base Miocene boundary. The truncation of rotated fault blocks in the upper continental slope and close to the well indicate erosion of the unit here. This is in agreement with the findings of for example Eidvin et al. (1998) and Ryseth et al. (2003). Inclined reflectors located downslope may represent intact sediment blocks that have been transported downslope as part of a submarine landslide (Figure 4-17). Similar events have been reported by Laberg et al. (1993) for the Pleistocene Bjørnøyrenna Slide. However, the low thickness of the unit complicates the understanding of the inclined blocks and the varying seismic facies in the area.

Truncation of the unit across the threshold indicates erosion also here (Figure 4-9 and 4-17). Thickening of the unit in the local deep basin between the threshold and the marginal high, and onlapping relations to both the upslope and downslope flanks of the basin, indicate compaction and deformation of the unit due to rapid loading after the deposition, as described also for the unit Te1 previously. The observed change up in the stratigraphy to less convex down shape of the reflections may indicate that the basin was filling in (Figure 4-16) and sediments may have bypassed the basin.

4.4.1.4 Seismic unit Te3

Rotated fault blocks occur also within unit Te3 close to well 7316/5-1. As noted above, a few faults probably extend from the unit below and into unit Te3 (Figure 4-15). The unit has a wedge-shape here, and pinches out toward the west where it is truncated by the overlying seismic unit GI.

A thin unit re-appears downslope. Here it includes low-amplitude and discontinuous reflections (Figure 4-17), and is again truncated where the R7 reflection creates a depression up-slope the mounded feature (Figure 4-16). Within the mounded feature, unit Te3 has a divergent reflection configuration with medium amplitude and continuous, parallel to sub-parallel reflections. Some of the internal reflections downlap the base Miocene reflection. The unit shows a wedge shape as it pinches out upslope where it is truncated by the overlying unit GI (Figure 4-16). Downslope the mounded unit, the base of the unit truncates the underlying unit Te2, and is also probably truncated by the overlying unit Te4. The unit remains thin toward the lower continental slope (Figure 4-16).

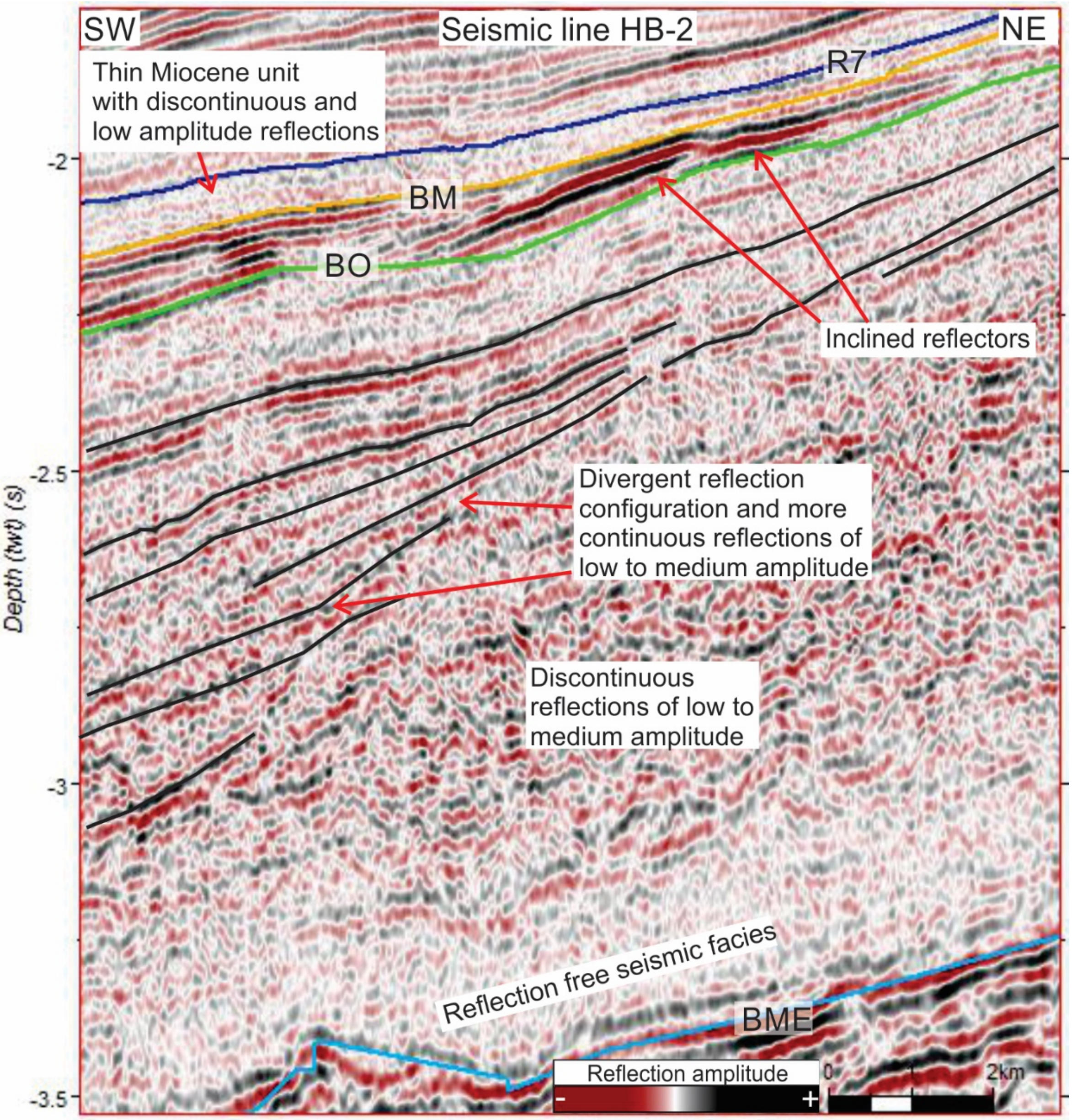


Figure 4-17: The vertical change of seismic facies on the upper continental slope is shown in a seismic section from seismic line HB-2. BME: base middle Eocene, BO: base Oligocene, BM: base Miocene. The location of the seismic section is indicated in Figure 4-16.

Interpretation

The observation of rotated fault blocks in unit Te3 indicates that tectonism also influenced this unit. The unit is however thin and only a small part of the unit is present in the seismic section here (Figure 4-15), making the interpretation complicated. The truncation of the unit by the overlying glacial unit GI and the pinch-out toward the west indicate that the unit was eroded and is absent in parts of the continental slope. The thin unit Te3 in the VVP-slope area has been discussed by Eidvin et al. (2014). They suggested that the unit is condensed and/or eroded in the area.

The observed upslope pinch-out of the unit and the internal reflections downlapping the base of the mounded unit, in addition to the depression located upslope the mounded unit, are characteristic for contourite drift deposits (Nielsen et al., 2008). The unit Te3 is here interpreted to represent the lower sub-unit of a contourite drift with an associated moat located upslope the drift, in the sense of Nielsen et al. (2008). The contourite drift is inferred to extend into the seismic unit GI. The complete description of the contourite drift is therefore given in Section 4.5.1.

The uniform unit thickness and parallel to sub-parallel internal reflections downslope the contourite drift and across the marginal high may reflect a relatively stable sedimentary environment during the deposition of the unit here (Mitchum et al., 1977). Possible onlap of the lower part of the unit to the upper part of the marginal high may represent the final infilling and the termination of subsidence or opening of the local basin upslope the high. The sediments deposited downslope the mounded contourite drift deposits may also have been deposited by alongslope processes and probably represent a part of the contourite drift, see Section 4.5.1.

4.4.1.5 Seismic unit Te4

The first downslope observation of the unit Te4 in the upper continental slope is within the mounded unit. The unit here has a wedge-shape as it pinches out upslope. An internal divergent reflection configuration is observed, and reflections downlap the base of the unit, similar to the within the underlying unit Te3 (Figure 4-16). The unit is thin and has sub-parallel discontinuous reflections of low to medium amplitude downslope the mounded unit toward the lower continental slope. The unit here truncates the underlying unit Te3.

Interpretation

The absence of unit Te4 in the upper continental slope indicates erosion of the unit. This observation and interpretation is in consistency with the findings of Ryseth et al. (2003) and Eidvin et al. (2014), as mentioned also for the units Te2 and Te3. The unit has a similar external shape and internal reflection configuration as the unit Te3 in the mounded unit, and unit Te4 is therefore interpreted to represent a sub-unit within the contourite drift deposit (see Section 4.5.1.). An even unit thickness and sub-parallel internal reflections downslope the contourite drift deposits may represent a relatively stable sedimentary environment (Mitchum et al., 1977). These deposits are suggested to be related to the along-slope processes that deposited the contourite drift (Section 4.5.1.)

4.4.2 The lower continental slope

4.4.2.1 General description of seismic unit G0

The G0 seismic unit thickens substantially downslope of the marginal high where the deepest basins occur, and the unit is here up to 1800 ms thick (twt), indicating about 2400 meters of sediments. The overall thickness of the unit decreases to around 500-800 ms (twt) toward the Lofoten Basin concurrent with the general decrease in the relief of the oceanic basement (Figure 4-18).

4.4.2.2 Seismic unit Te3

Unit Te3 is inferred to cover the oceanic basement in the lower continental slope. The unit thickens in the basins (up to ~1200 ms (twt)) and thins substantially across the highs (down to ~300 ms (twt)) (Figure 4-18). A major change in thickness is observed from the marginal high and downslope. Here, an abrupt increase in thickness, from ~100 ms above the marginal high to ~1200 in the deep, local basin downslope the high (Figure 4-18).

The reflections in the local basins are chaotic to transparent in the lower part, and change up to transparent and discontinuous to continuous reflections (Figure 4-19). The reflections within the basins onlap the highs, while the reflections that are located close to the level of the highs, and above, drape the highs (Figure 4-19 and 4-21).

Toward the lower part of the slope, unit Te3 drapes the low-relief basement floor with continuous to discontinuous sub-parallel reflections of low amplitude. The unit thins where it crosses the prominent high in the transition to the Lofoten Basin, and the reflection configuration changes to discontinuous above the high (Figure 4-20).

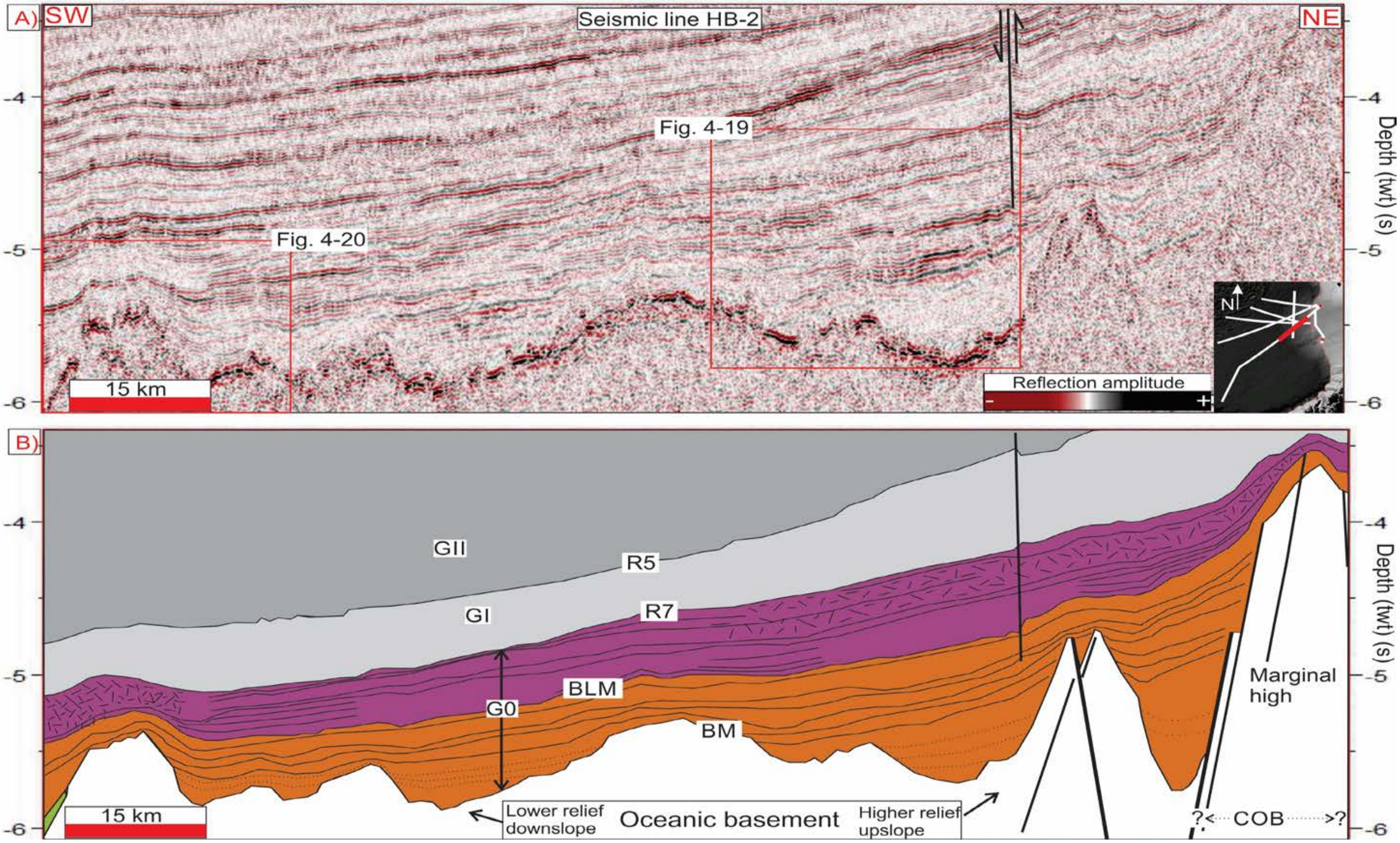


Figure 4-18: The distribution of the seismic units within G0 are shown in the lower continental slope. BM: base Miocene, BLM: base late Miocene. The red line in location map in A) shows the location of the seismic section.

Interpretation

The chaotic to transparent seismic facies observed in the local basins in the lower continental slope are interpreted to represent sediments that have been deformed by downslope movement of sediments. According to Mitchum et al. (1977), chaotic to transparent seismic facies could indicate seismically homogenous units. Slumps and slides may disintegrate downslope to various gravity flows, for example debris flows and turbidity currents (Lee et al., 2007). The downslope disintegration causes deformational homogenization represented by a transparent seismic facies. Gravity flow deposits represented by chaotic to transparent or reflection free seismic facies, located along the western Barents Sea margin, have been described by for example Laberg and Vorren (1993, 1995); Safronova et al. (2015).

The sediments transported downslope fill the lower part of the local basins downslope the marginal high. The increase in thickness beyond the marginal high indicate that these sediments bypassed the marginal high during transport.

The mainly parallel to subparallel and continuous to discontinuous reflections of varying amplitude indicate a relatively stable sedimentary environment with hemipelagic deposition of sediments. Because of the contourite drift deposit located upslope, it is suggested that alongslope sediments probably are interbedded with hemipelagic. The draping of oceanic basement by the upper part of the unit supports the interpretation that the sediments are deposited by alongslope and hemipelagic processes.

4.4.2.3 Seismic unit Te4

Unit Te4 thickens immediately downslope the marginal high, and subsequently thins downslope toward the Lofoten Basin (Figure 4-18). The unit is dominated by internal seismic facies varying both laterally and vertically. Seismic facies in the unit includes chaotic reflections and sub-parallel reflections with varying reflection amplitudes and continuity (Figure 4-19).

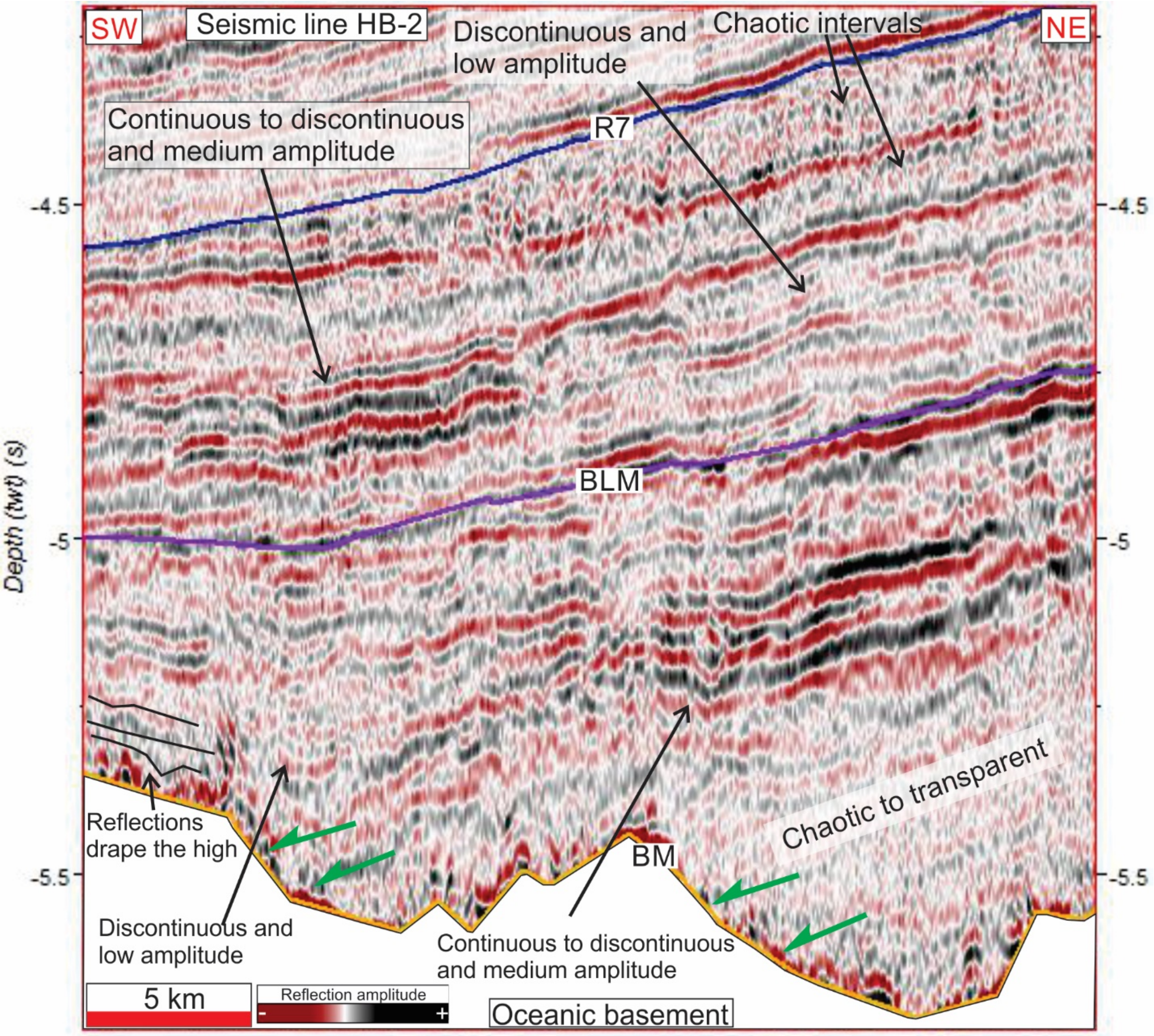


Figure 4-19: Lateral and vertical changes in the seismic facies in the lower continental slope is shown in a seismic section. BM: base Miocene, BLM: base late Miocene. Green arrows indicate reflections onlapping highs. The location of the seismic section is indicated in Figure 4-18.

Continuous and sub-parallel to parallel reflections of medium amplitudes dominate unit Te4 on the lower slope toward the transition to the Lofoten Basin. The facies terminates abruptly and changes to a chaotic seismic facies that continues into the proximal part of the Lofoten Basin (Figure 4-20).

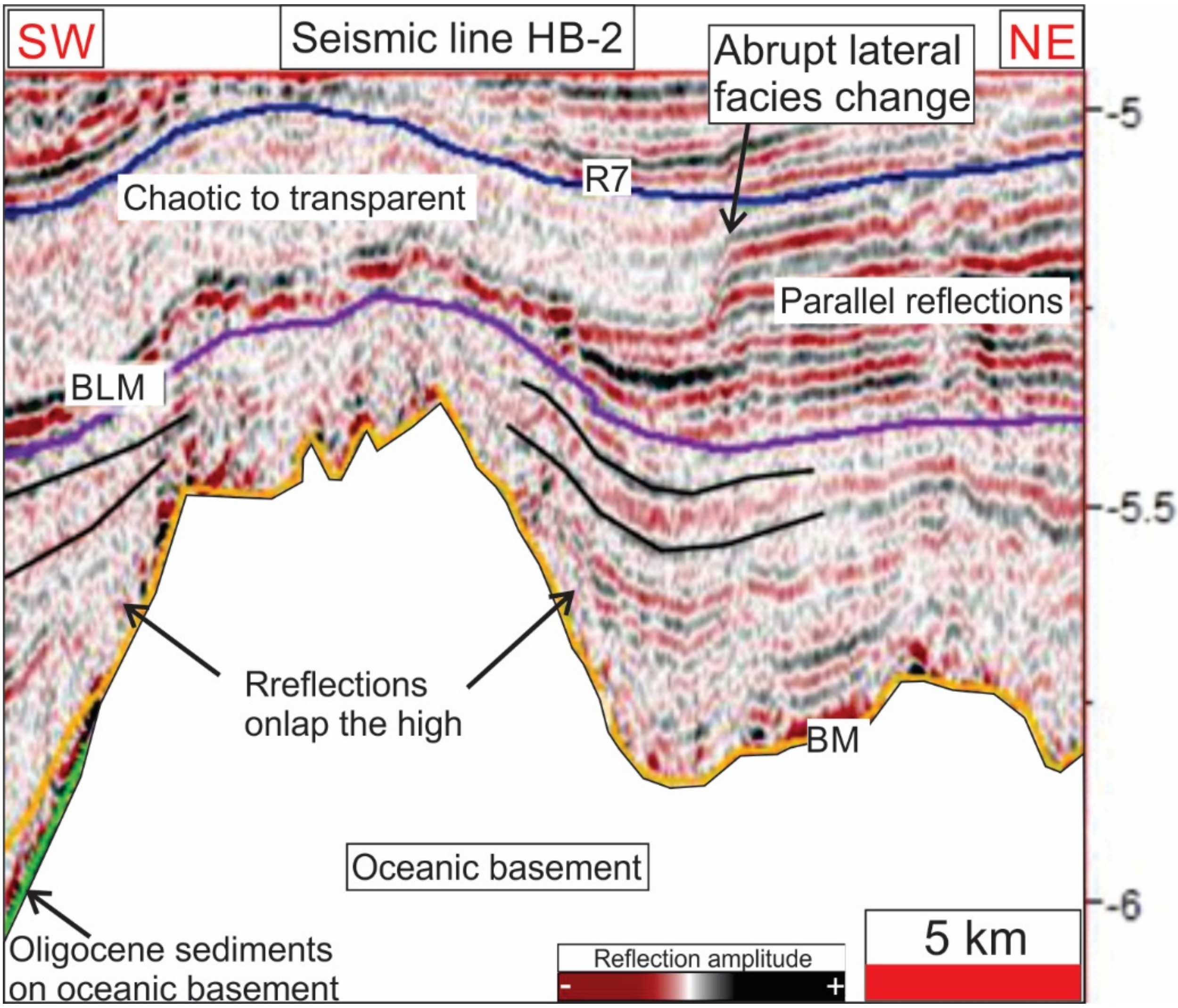


Figure 4-20: Lateral changes in seismic facies in the transition from the lower slope to the proximal Lofoten Basin in both the Te3 and Te4 units. BM: base Miocene, BLM: base late Miocene. The location of the seismic section is indicated in Figure 4-18.

Interpretation

The parallel and continuous reflections interbedded with the chaotic facies indicate an unstable slope setting in a depositional environment dominated by hemipelagic and alongslope sedimentation and downslope transport and deposition of sediments. Large parts of the sediments within unit Te4 on the lower continental slope are interpreted to be influenced by small scale and larger scale mass transport. A more detailed study of unit Te4 is given in Sections 4.5.3.1 and 4.5.3.2.

4.4.3 The proximal Lofoten Basin

4.4.3.1 General description of seismic unit G0

The unit G0 has a very varying thickness and shape in the proximal Lofoten Basin. The lower part of the unit infills the irregular oceanic basement, while the upper boundary of the unit, reflector R7, overlies the area sub-horizontally. Unit G0 contains sediments of up to 1300 ms thickness (twt) in the deep basin region (Figure 4-21). In the plateau region, the thickness of the unit exceeds 600 ms (twt) only in the deepest local basin.

4.4.3.2 Seismic unit Te2

Unit Te2 is inferred to cover the oceanic basement in the proximal Lofoten Basin region (Figure 4-22). The Oligocene unit is thickest in the deep basin region, where it fills the local basins and thins across the local highs (Figure 4-21). In the plateau region, the unit is much thinner. The unit commonly infills the basement relief, however, drapes some of the lower relief highs, and for example not the prominent highs bordering the plateau to the northeast and southwest (Figure 4-21 and Figure 4-23). According to the inferred age of the oceanic basement (see the magnetic anomaly map, Figure 4-4), the oceanic basement in the plateau region in the southwest is older than within the deep basin region, and could thus have received sediments for a longer time.

A chaotic to transparent seismic facies dominates the unit in the deep basin region (Figure 4-22). Though chaotic to transparent facies dominates the unit, onlap to the prominent highs flanking the deep basin region is observed (Figure 4-22). The onlapping reflections appear to tilt up toward the sides of the highs.

A possible displacement along an inferred fault plane indicated by disrupted reflections have been observed in one of the local basins in the deep basin region (Figure 4-22). Above the displacement, the deposited sediments form a wedge with internal reflections onlapping the adjacent high. Similar wedge-shaped units possibly related to subsidence or rotation of basement blocks have been observed also in the distal Lofoten Basin.

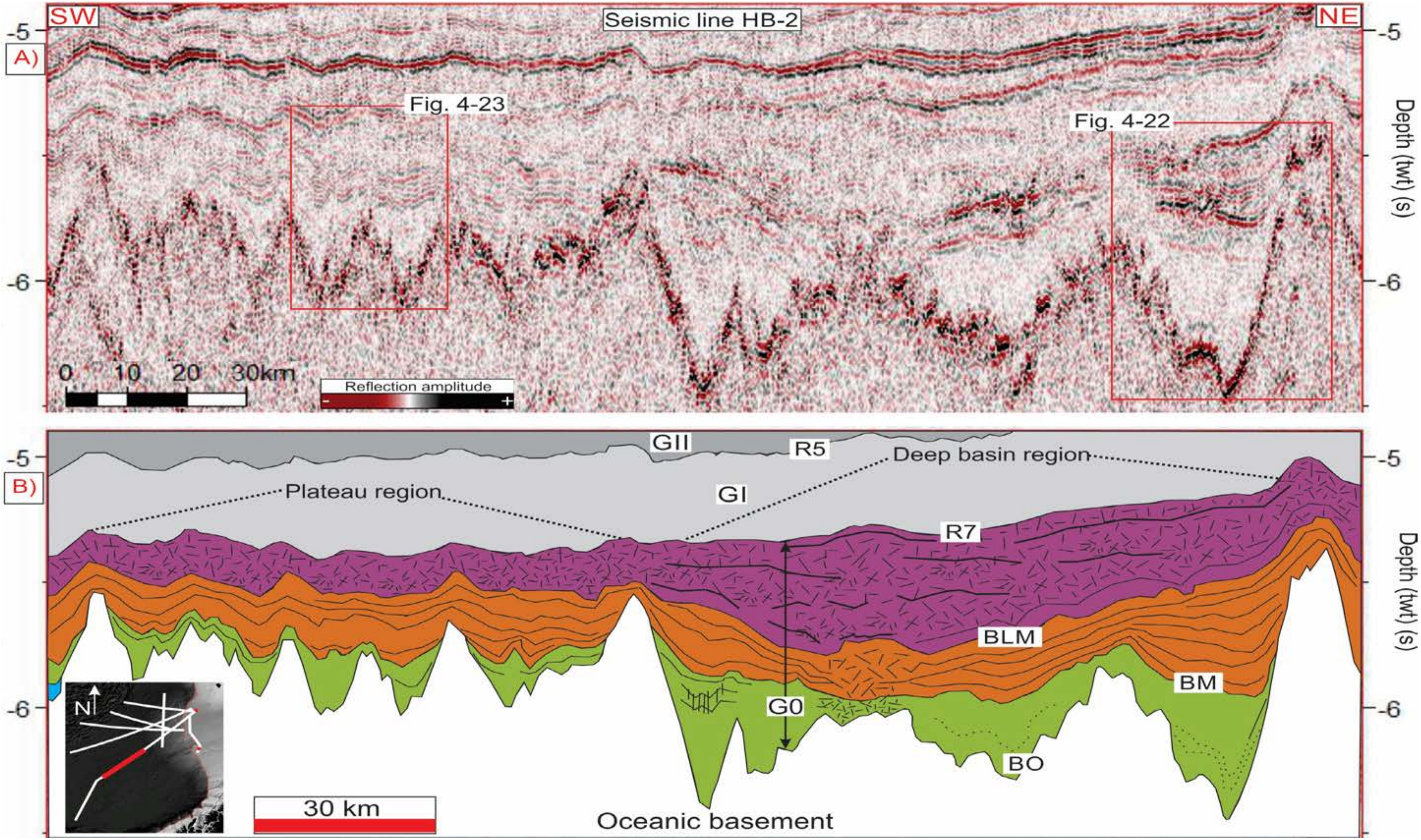


Figure 4-21: The distribution of the seismic subdivisions of unit G0 in the proximal Lofoten Basin. BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. Possible Oligocene small-offset faults are indicated with vertical lines in the deep basin region. The location of the seismic section is shown in the location map in B).

Small-offset faults, indicated in Figure 4-21, may be present in the southwest part of the deep basin region. Here, medium amplitude, disrupted reflections appear in the upper part of the unit. Similar structures appearing more clearly have been observed in unit Te2 further toward the southwest in the distal Lofoten Basin.

The chaotic to transparent seismic facies dominates also in the smaller, local basins in the plateau region (Figure 4-23). However, discontinuous to continuous, laminated reflections with low to medium amplitude also appears frequently in the unit here.

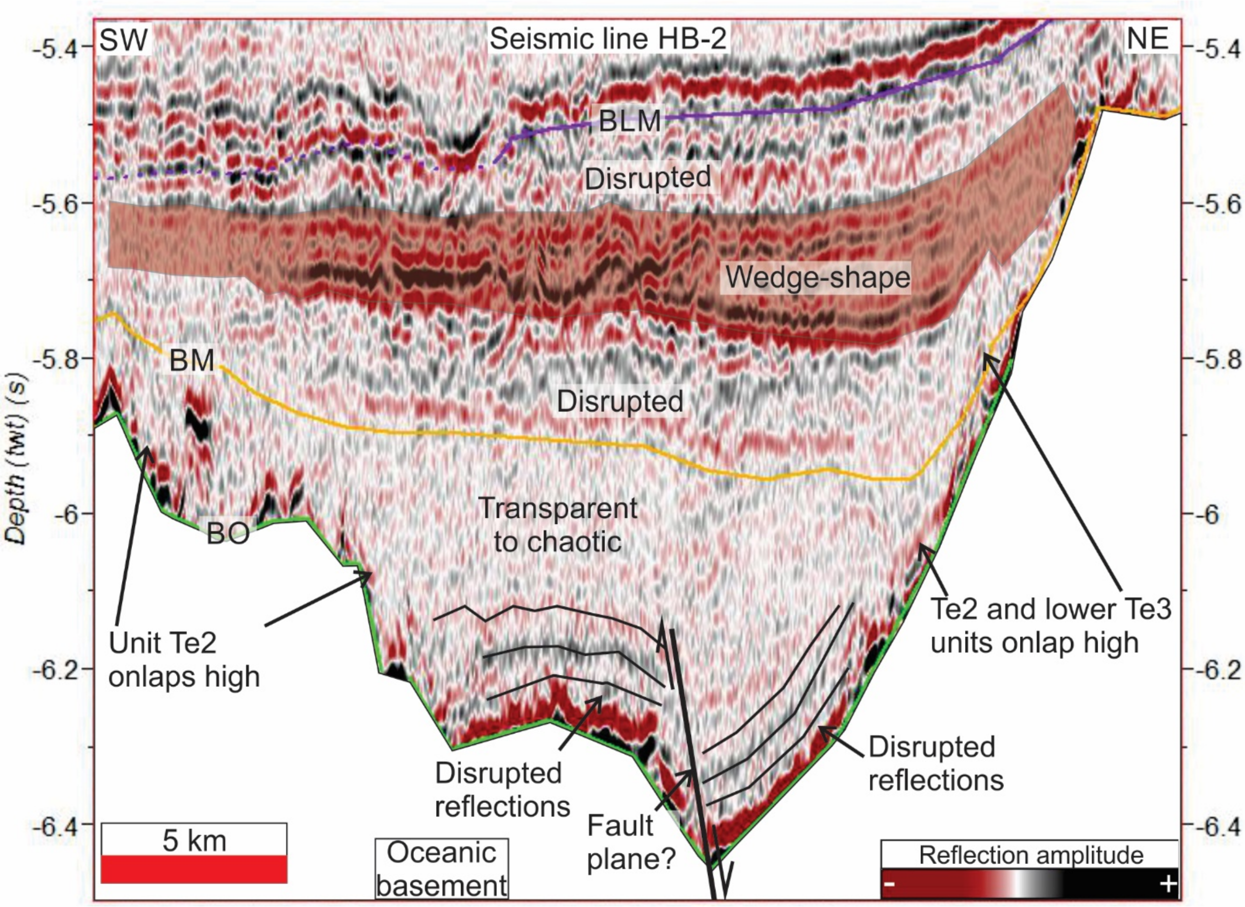


Figure 4-22: Seismic facies and reflection configurations of unit Te2-Te3 infilling parts of the deep basin region of the proximal Lofoten Basin. The wedge-shaped depositional unit is highlighted (red transparent colour). Possible direction of movement along fault plane is indicated. BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the figure is indicated in Figure 4-21.

Interpretation

The relatively thick unit Te2 in the younger deep basin region compared to that in the older plateau region indicates that the deep basin region acted as a sediment trap during the Oligocene, and that unit Te2 filled the lower part of this region. The domination of chaotic to transparent seismic facies favours the interpretation that downslope processes deposited these sediments. It is inferred that the chaotic to transparent facies is caused by deformational homogenization during downslope movement, as interpreted also for unit Te3 on the lower continental slope. Due to the chaotic to transparent character in the unit, the sediments are suggested to be deposited by gravity flows like debris flows or turbidites. According to Laberg and Vorren (1993), the downslope change from chaotic/discontinuous to acoustically transparent pattern may represent the transition from slide/slumping to various gravity flows.

The chaotic to transparent seismic facies in the plateau region indicates that gravity flows dominated in this area as well, however, in a smaller scale than for the deep basin region. This is because of the reduced thickness of the unit here. The laminated reflections found especially in the southwestern area of the plateau region may represent less deformed turbidites.

Inclined reflections onlapping the highs in both the deep basin region and the plateau region indicates post-depositional deformation of the sediments due to compaction and subsidence. Similar structures and processes were described in unit Te1 in the upper continental slope. It is also possible that the onlapping reflections are syn-depositional structures, where the sediments were deposited with an inclined angle to the side of the basins. This could be the case if the energy in the depositing processes was high enough to deposit sediments along the flanks of the local basins. The inclined reflections are suggested to be a result of compaction and subsidence or syn-depositional structures.

The medium amplitude disrupted reflections appearing as small-offset faults observed here (indicated in Figure 4-21) are suggested to be deformed sediments due to loading and compaction. Small-offset faults have been related to for example the deformation of fine grained sediments in abyssal plains, gravitational loading and gravity sliding/collapse in marginal slope settings (Cartwright et al., 2003; Hjelstuen et al., 2004). Such faults have been referred to as polygonal faults (Cartwright et al., 2003). The small-offset faults observed here does not show very clear offset and are not interpreted to represent polygonal faults. However, the observation of polygonal faults in Oligocene sediments in the Lofoten Basin (Hjelstuen et al., (2004; 2007), indicate that the structures observed here may be the result of a similar deformational process.

4.4.3.3 Seismic unit Te3

Relative to in the lower continental slope, the unit Te3 thickens substantially in the deep basin region, and the thickness is similar in the plateau region. This is different from unit Te2 below and unit Te4 above, which both are thicker in the deep basin region compared to in the plateau region

(Figure 4-21). The upper part of the unit drapes most of the low-relief highs in both the deep basin region and the plateau region, but the lower part of the unit usually onlaps the prominent highs (Figure 4-21 and Figure 4-23). Both tilted reflections (Figure 4-22) and sub-horizontal reflections have been observed to onlap highs in the plateau region. In the deep basin region, tilted reflections onlaps the highs flanking the region (Figure 4-23).

Unit Te3 has an irregular shape in the deep basin region, varying from a wedge-shape in the northeast (Figure 4-22) to an almost even shape in the central parts, a mounded shape above a local high, and a lens-shape in the south-west end of the deep basin region (Figure 4-21).

The internal reflection configuration in the deep basin region is dominated by continuous and disrupted reflections varying from medium to high amplitudes, interbedded with more transparent and discontinuous reflections. Though appearing disrupted, many of the reflections may be followed at longer distances (Figure 4-22). A slight change to more continuous reflections in the upper part of the unit is observed.

In the plateau region, discontinuous to continuous reflections of low amplitudes/transparent reflections dominate the lower part of the unit. These sediments fill the low relief in the area and reflections onlap the sides of the highs (Figure 4-23). A distinct change occurs in the middle of the unit, where the upper part is dominated by continuous and parallel reflections of medium amplitude. These reflections drape the oceanic basement (Figure 4-23).

Interpretation

The more or less even thickness of unit Te3 in the deep basin region and the plateau region indicate a relatively stable sedimentation rate in the proximal Lofoten Basin at the time of the deposition.

The wedge-shaped part of the unit in the northeast and the lens-shaped part of the unit in the southwest of the deep basin region (Figure 4-21) are interpreted to relate to asymmetric subsidence of the underlying unit. A possible subsidence of parts of the underlying oceanic crust in the area may further have given the asymmetric shape of the unit, as indicated in (Figure 4-22).

The continuous/disrupted character of unit Te3 in the deep basin region (see for example Figure 4-22) does not show displacement in the same character as seen for the small-offset faults observed for example in the distal Lofoten Basin (Figure 4-24). Due to the wide distribution of small-offset faults interpreted to be polygonal faults in the Miocene deposits along the margin (Berndt et al., 2003; Cartwright et al., 2003; Hjelstuen et al., 2007; Hjelstuen & Andreassen, 2015), the discontinuous reflections within unit Te3 in the deep basin region are suggested to be the result of a similar process. The small offset may be due to a less developed process.

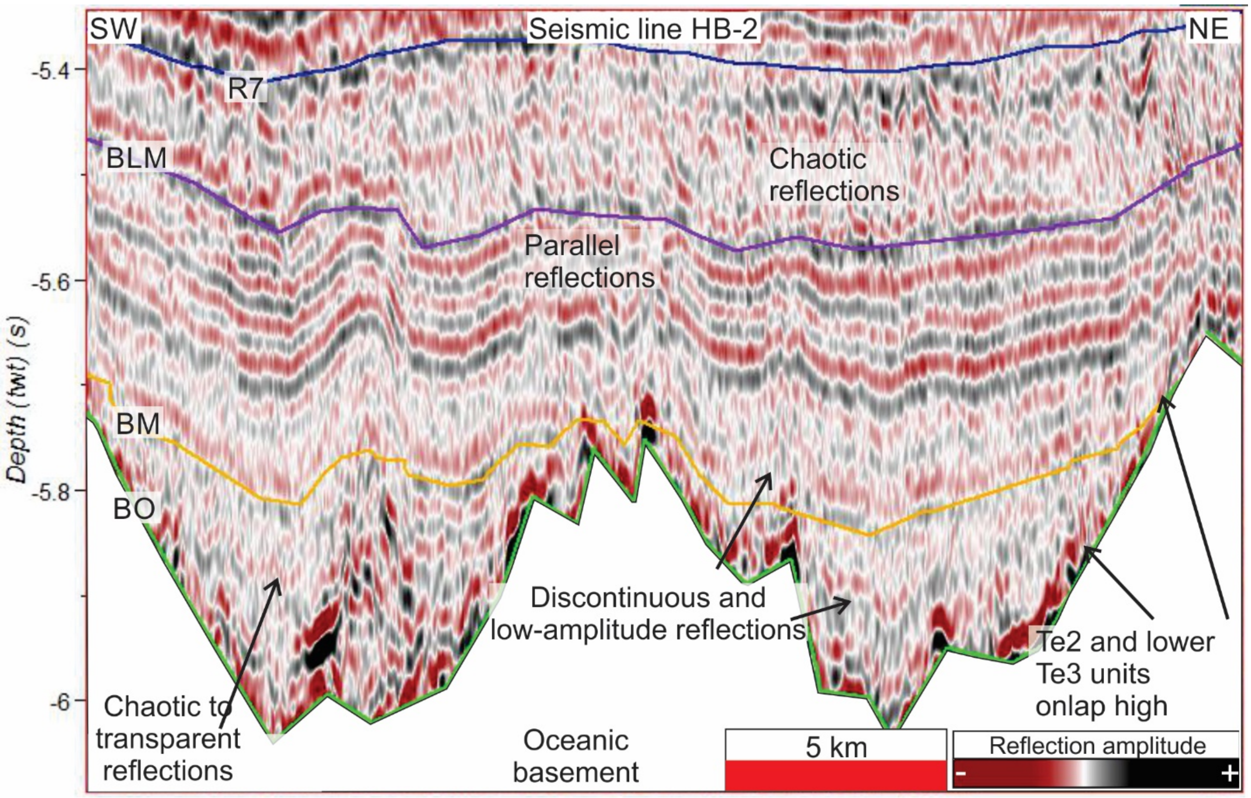


Figure 4-23: Seismic facies and reflection configuration shown for units Te2-Te4 in the plateau region. Parallel reflections in unit Te3 mirror the oceanic basement topography. BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is shown in Figure 4-21.

The discontinuous to continuous lower part of the unit in the plateau region shows a similar transparency as seen in unit Te2, however, increasing continuity (Figure 4-23). It is suggested that the sediments, which fill the local basins, are deposited by gravity flows as in the unit below. The increasing continuity may indicate less deformation of the sediments during deposition of this part of the unit.

The parallel and continuous reflections in the upper part of the unit are interpreted to represent a change to a domination of hemipelagic sedimentation. The draping of the underlying relief supports this interpretation. Hjelstuen et al. (2007) suggested hemipelagic sedimentation in the Lofoten Basin during the Miocene. Sættem et al. (1994) suggested that distinct acoustic stratification to represent a lateral continuity and vertical variation of the depositional environment. The upper part of unit Te3 is thus suggested to represent vertical variations with regards to sedimentation rate in an otherwise stable sedimentary environment.

4.4.3.4 Seismic unit Te4

Unit Te4 shows the greatest thickness variation of the pre-glacial seismic units between the deep basin region and the plateau region in the proximal Lofoten Basin. The unit thickens substantially in the deep basin region and is relatively thin in the plateau region. The unit develops from having a distinct convex down shape at the base to being sub-horizontal at the top in the deep basin region. In the plateau region, the unit thins progressively toward the southwest (Figure 4-21).

Unit Te4 is dominated by a chaotic reflection configuration in the entire proximal Lofoten Basin region (Figure 4-21). In the deep basin region in the northeast, the reflections generally varies from low to medium amplitudes, and individual, sub-horizontal irregular reflections can be followed at longer distances within the unit here. The reflections that are possible to follow stands out with generally higher amplitudes than the surrounding more chaotic reflections. The chaotic reflection configuration within the unit possibly terminates above or past a major basin to the south-west in the distal Lofoten Basin region (Figure 4-24).

Interpretation

The total domination of chaotic reflections favours an interpretation that downslope processes deposited the sediments. The increasing thickness of the unit in the deep basin region relative to the surrounding areas suggests increasing accommodation space in the area during deposition of unit Te4. As discussed for unit Te3, the area was probably subject to subsidence. The subsidence of the area has probably continued during the deposition of unit Te4.

However, the thickest part of the unit is close to the center of the region, which is very different from the units below, which are thickest in the local basins. The location of the thickest part may indicate that the increasing space mainly arose here rather than uniformly across the deep basin region or adjacent to the prominent highs along the flanks. The extensive mass transport suggested to have taken place here is studied in more details in Section 4.5.3.3.

4.4.4 The distal Lofoten Basin

4.4.4.1 General description of seismic unit G0

All the pre-glacial units Te1-Te4 are inferred to be present in the distal Lofoten Basin (see overview in Figure 4-1). The upper unit boundary, the R7 reflection, mimics to some degree the underlying oceanic basement relief. The reflection is elevated where prominent peaks rise higher than the common stratigraphic location of the R7 (Figure 4-25). The thickness of unit G0 varies between a few tens of ms (twt) across the most prominent highs to ~1000 ms (twt) in the deepest basin (Figure 4-25).

4.4.4.2 Seismic unit Te1

The unit Te1 covers the oceanic basement in the distal Lofoten Basin, from the transition between the proximal and the distal Lofoten Basin and toward the southwest (Figure 4-24). The unit has an uneven thickness varying with the depth of the local basins. The unit is generally thin or absent across the basement highs, and increases in depth in the local basins where it reaches up to about 350 ms (twt) thickness. The difference in unit thickness decreases in the rise to the Vøring Plateau in the southwest where the basement relief is lower (Figure 4-26). Here, a thin unit commonly overlies the highs.

A chaotic to transparent seismic facies dominates the unit, but discontinuous reflections with low amplitude may be followed close to the basement at some instances, and in particular in the deepest basins (for example Figure 4-24 A). Internal reflections commonly onlap the highs with reflections that are tilted up toward the sides of the highs. The level of the onlapping reflections is observed to be similar on both sides of the highs (Figure 4-24 and Figure 4-25).

Interpretation

The dominance of chaotic to transparent seismic facies in unit Te1 indicates that the unit was deposited by gravity flows. It is suggested that the chaotic to transparent facies reflects a high grade of deformation during transport and deposition, as also described previously for units Te2 and Te3. The confinement of unit Te1 to within local basins in most of the Lofoten Basin indicates that the turbidites filled the local basins during the deposition. The draping of the oldest part of the Lofoten Basin in the southwest may be due to the lower relief here. The generally even thickness of the unit across the distal Lofoten Basin indicates an even sediment input to the area.

The onlapping reflections to the local highs in the Lofoten Basin indicates that the unit Te1 was subject to post-deposition deformation from compaction and subsidence due to loading, or that the sediments were deposited up along the sides of the highs initially, as described for unit Te1 in the upper slope and unit Te2 in the proximal Lofoten Basin.

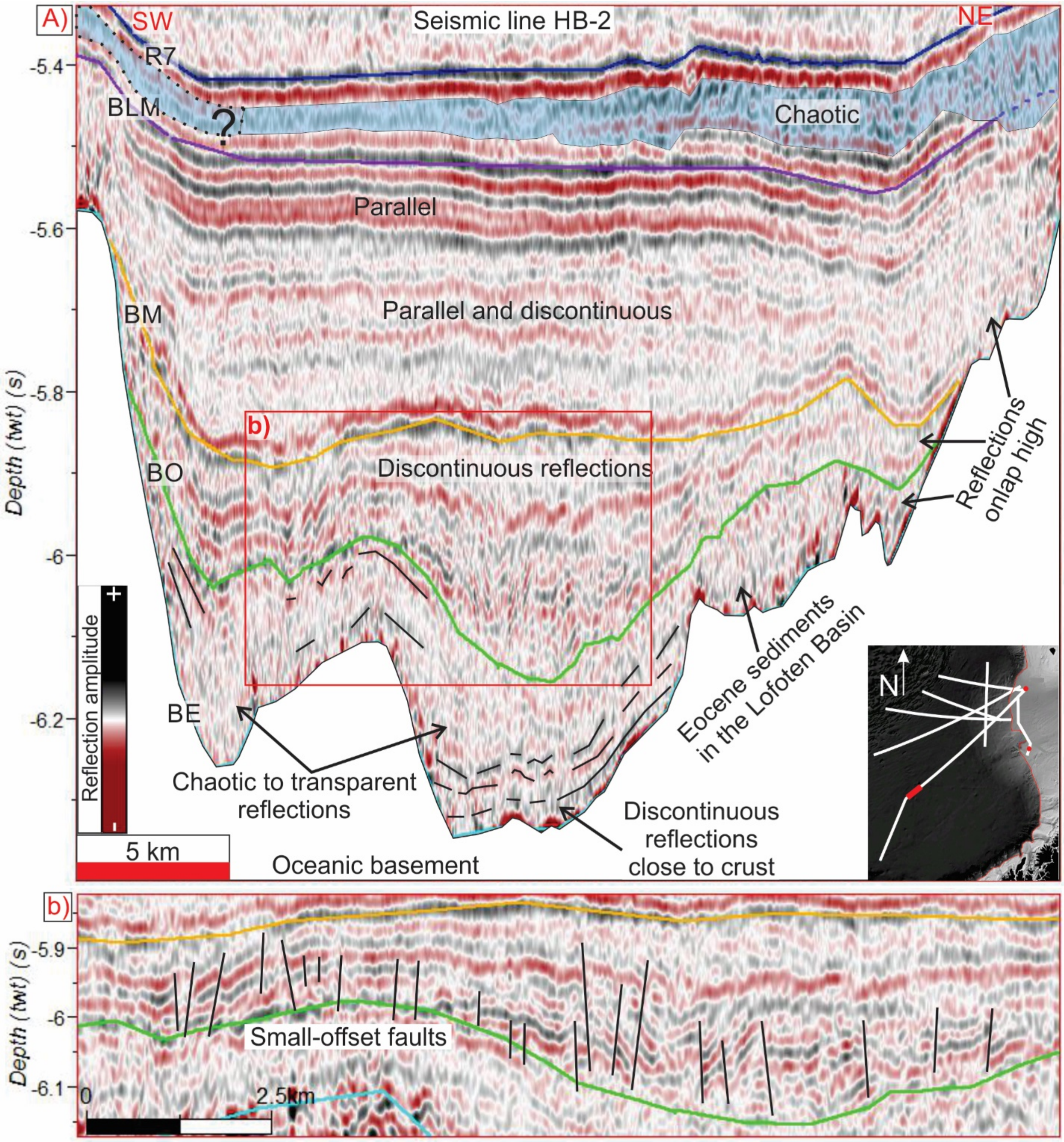


Figure 4-24: A): Prominent, vertical changes in seismic facies in a deep and wide basin in the Lofoten Basin are highlighted. The shaded blue area in unit Te4 represents chaotic seismic facies extending across the proximal Lofoten Basin. Uncertain continuation is indicated with a dashed outline of the unit. B): Small-offset faults within the Oligocene unit are shown in a zoomed-in part of A). BE: base Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene.

4.4.4.3 Seismic unit Te2

The thickness of unit Te2 is relatively uniform and usually less than 300 ms (twt) in the distal Lofoten Basin. The unit fills the local basins in the area, and the reflections onlap the local highs with inclined reflections. Parts of the unit occasionally drapes the lower relief highs (Figure 4-25). The internal reflections varies between a low amplitude/transparent character to medium amplitude, and are discontinuous or disrupted in most of the region. The discontinuity/disruption often seems to be caused by small-offset faults (Figure 4-24 and Figure 4-25). A more chaotic and chaotic to transparent reflection configuration is observed within the unit where the oceanic basement rise toward the Vøring Platea in the south-southwest (Figure 4-26).

Interpretation

The infilling of the high-relief distal Lofoten Basin continues from the Eocene into the Oligocene, with the deposition of unit Te2. The inclined onlapping of the reflections to the sides of the highs are suggested to represent post-depositional deformation from compaction and subsidence due to subsequent loading, as described for the previous units and areas.

The disrupted/discontinuous reflections, often appearing as small-offset faults, are interpreted to represent post-deposition deformation of the unit. Similar character of the reflections within unit Te2 and Te3 was observed in the proximal Lofoten Basin. The offset of the small faults is however observed to be larger in some places within unit Te2 in the distal Lofoten Basin (Figure 4-24). These small-offset faults are interpreted to represent polygonal faulting. The cause for the deformation is suggested to be related to the same processes that caused the inclined onlapping reflections - the deformation of the unit from compaction and subsidence due to loading.

The seismic facies within unit Te2, dominated by discontinuous/disrupted reflections of varying amplitudes, is suggested to represent a depositional regime dominated by turbidity currents. However, frequent occurrences of the discontinuous/disrupted reflections, probably initially deposited as continuous, indicate that the sediments were less deformed during transport or deposition of the unit. The less deformation may be due to the already smoothed out oceanic basement by the underlying unit.

The chaotic reflection configuration observed in the near-slope area in the southwest (Figure 4-26) may be related to the deposition of sediments transported downslope. Chaotic and chaotic to transparent seismic facies have previously been interpreted to represent downslope transport and deposition of sediments (Laberg & Vorren, 1995; Lee et al., 2007; Bull et al., 2009b, 2009a; Safronova et al., 2015). The chaotic seismic facies here is suggested to represent slide or debris flow deposits.

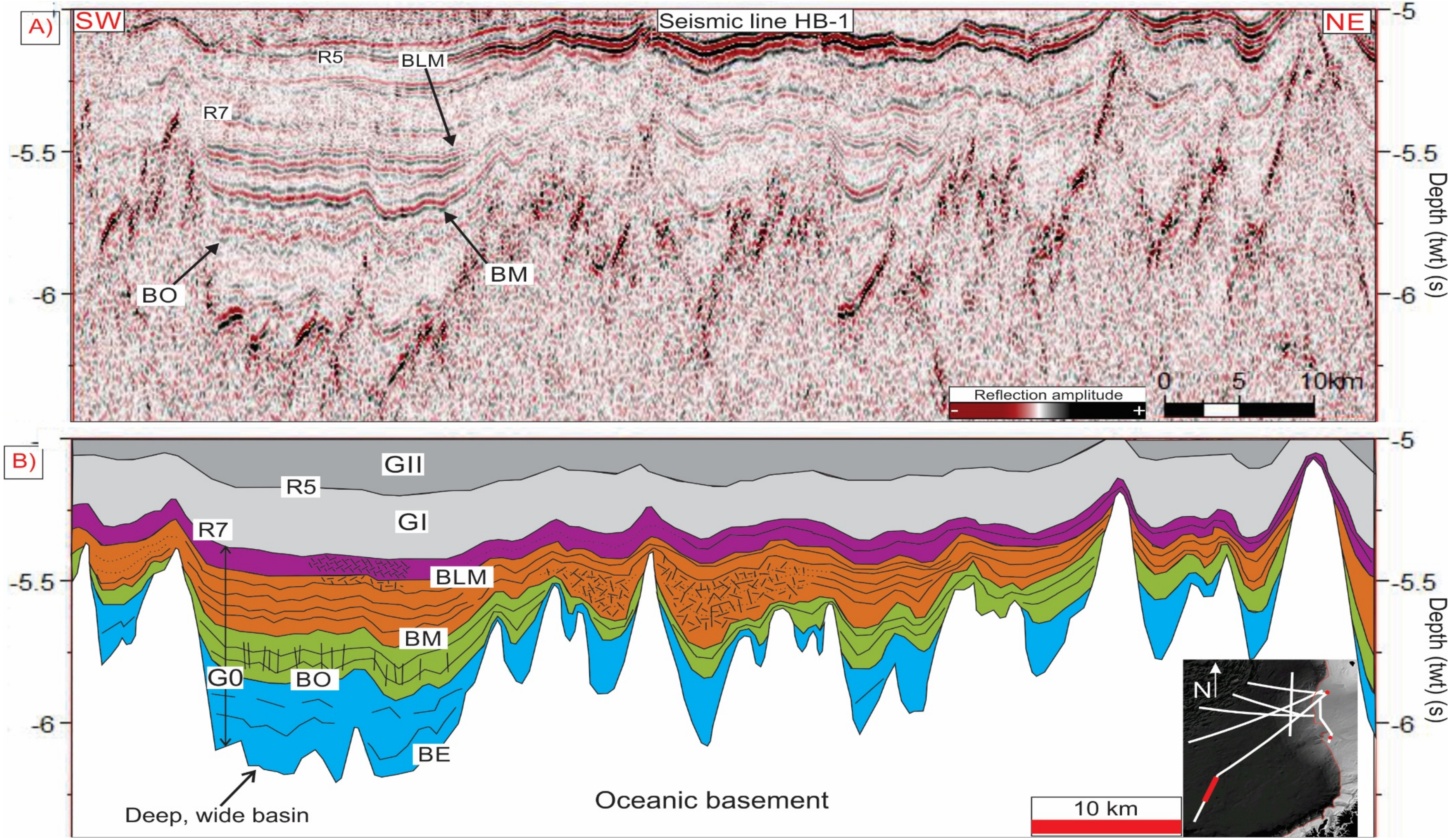


Figure 4-25: The distribution of pre-glacial sediments in the central part of the Lofoten Basin. Possible small-offset faults in unit are indicated in the deep and wide basin in the south-southwest. BE: base Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is indicated in the location map in B).

4.4.4.4 Seismic unit Te3

Unit Te3 is up to ~400 ms (twt) thick in the deep and wide basin in the north-northeast (Figure 4-24 A), and thins gradually toward the southwest where it is around 100 ms (twt). The lower part of the unit fills the local basins, and the internal reflections of this part of the unit onlaps a few prominent highs in the north-northeast of the distal Lofoten Basin. Toward the south-southwest, the unit drapes the basement highs (Figure 4-25).

The unit has distinct different facies compared with the units below (Figure 4-24A and 4-26). Continuous, parallel and sub-parallel reflections dominate in most of the distal Lofoten Basin region, and the reflection amplitude generally varies between low and medium. A distinct vertical facies change is observed within the unit in the northeast of the area (Figure 4-24), where the lower part of the unit is transparent/low amplitude and the upper part of the unit is medium amplitude. The facies change may be observed in local basins toward the southwest but becomes less distinct here.

Interpretation

The unit Te3 in the distal Lofoten Basin has similar characteristics as observed in the proximal Lofoten Basin. The lower part of the unit fills the local basins, with internal reflections onlapping the highs. The upper part of the unit drapes the irregular oceanic basement with continuous reflections. A similar interpretation for the distal Lofoten Basin as was given for the proximal Lofoten Basin is thus suggested. The lower part of the unit is probably deposited by infilling turbidity currents, while the upper part of the unit is suggested to mainly consist of hemipelagic deposits. The laminated strata are suggested to represent a lateral stable environment with vertical variations, probably related to variations in the sedimentation rate.

The gradual thinning toward the southwest, and probably pinch-out of the unit in the rise toward the Vøring Plateau (Figure 4-26), is suggested to reflect an increasing distance from the source area.

4.4.4.5 Seismic unit Te4

Unit Te4 is thin across the distal Lofoten Basin area, about 100 ms (twt) or less (Figure 4-24 and 4-26). The thickness is even in the area, in contrast to the units below. Parts of or the entire unit drape all highs in the distal Lofoten Basin (Figure 4-25).

The internal seismic reflections changes laterally from continuous to discontinuous with low to medium amplitudes in the north-northeast of the region, to more discontinuous and low-amplitude reflections in the south-southwest toward the Vøring Plateau.

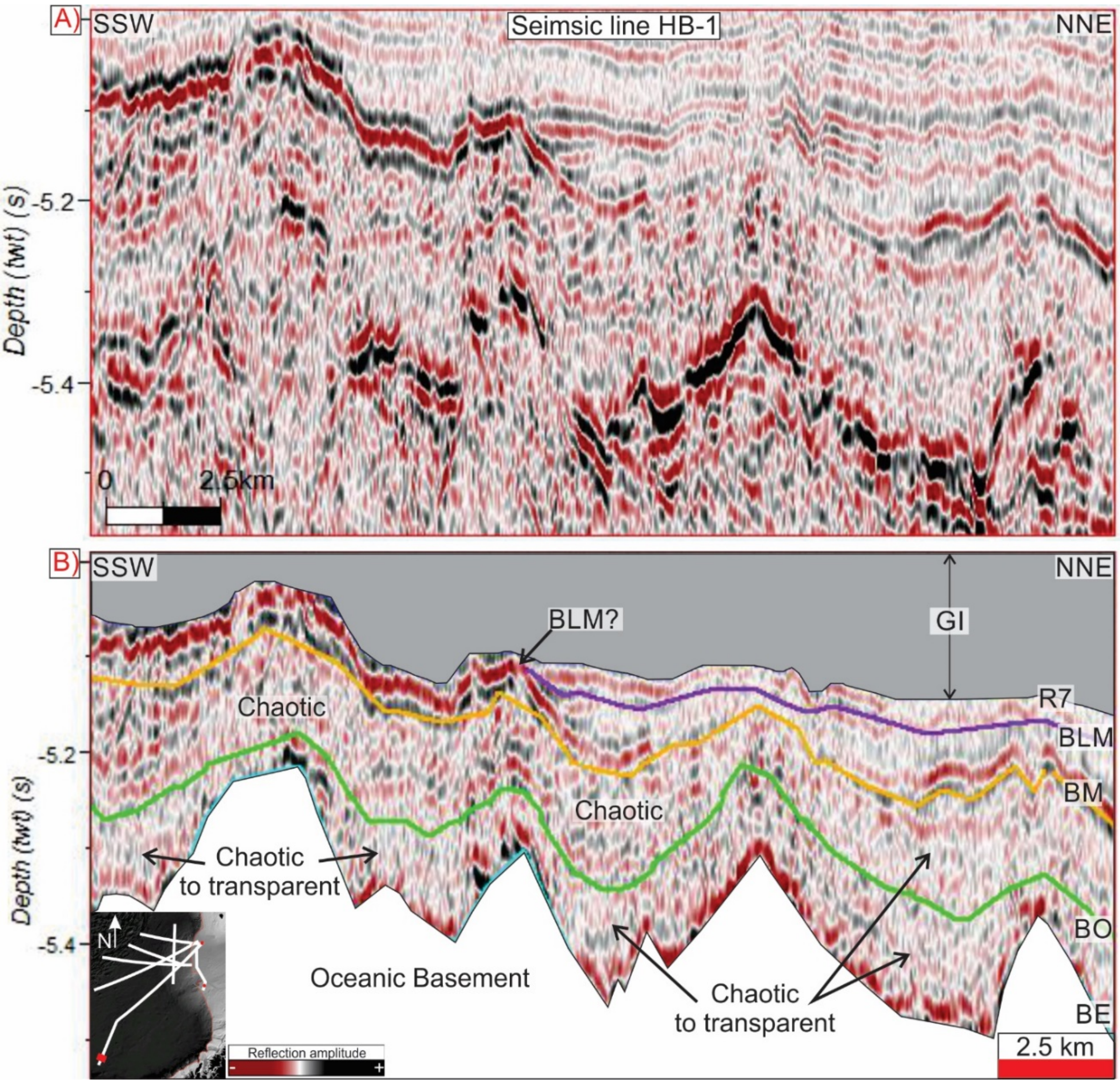


Figure 4-26: The distribution of pre-glacial sediments is shown where the oceanic basement rise toward the Vøring Plateau in the south-southwest. Uncertain termination of the BLM reflection, and chaotic and chaotic to transparent intervals are indicated. BE: base Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The location of the seismic section is indicated in the location map in B).

Unit Te4 thins and possibly pinches out toward the south-southwest where the oceanic basement rise toward the Vøring Plateau (Figure 4-26).

Interpretation

The uniform thickness of the unit, and the draping of the entire distal Lofoten Basin, indicate that the unit is deposited by hemipelagic processes. The pinching out toward south-southwest indicates an increasing distance from the source area toward the south-southwest.

4.5 DEPOSITS RELATED TO ALONG-SLOPE AND DOWN-SLOPE PROCESSES

The focus of this chapter is to address the sediments inferred to be deposited by alongslope and downslope processes on the continental margin and in the Lofoten Basin in more details.

First, the mounded unit, shortly presented in section 4.4.1, will be described (section 4.5.1). The description includes the pre-glacial units Te3 and Te4, and the seismic unit GI, as the contourite drift is inferred to extend into this unit. Next, a large depositional feature on the middle continental slope, inferred to be affected by downslope mass transport, will be described (section 4.5.2). The feature is located within seismic units GII. It is located directly above reflection R5 in an area where R5 is inferred to represent an erosional boundary affecting the mounded unit. Finally, three areas all located in the seismic unit Te4 and inferred to comprise downslope mass transport deposits will be described (Section 4.5.3).

4.5.1 Contourite drift

The contourite drift and the associated moat are located within the G0-GI units below the present shelf break, at a depth in the seismic section of about 2500 – 3000 ms (twt) (Figure 4-27). The contourite drift may have a downslope extent of several tens of kilometres, but due to the erosion of the upper part of the drift, and no detectable lateral limit of the drift deposits downslope, no exact downslope extent can be inferred. The thickness of the mounded drift is up to around 600-700 ms (twt), indicating around 800-900 meters. However, the thickness is inferred to be a minimum estimate due to erosion of the upper part of the drift (Figure 4-27).

The contourite drift consists of continuous reflections of medium to high amplitude interbedded with lower amplitude reflections. The continuous reflections separate smaller sub-units within the drift. The sub-units pinches out upslope toward the moat. Internal, lower amplitude reflections within the sub-units show a divergent reflection configuration and often downlap to the continuous reflections (Figure 4-28). A continuous, particularly high amplitude reflection located immediately above the R7 reflection apparently subdivides the drift deposits in two main units; the lower main unit consists of the two units Te3 and Te4, and the upper main unit consists of GI sediments (Figure 4-28).

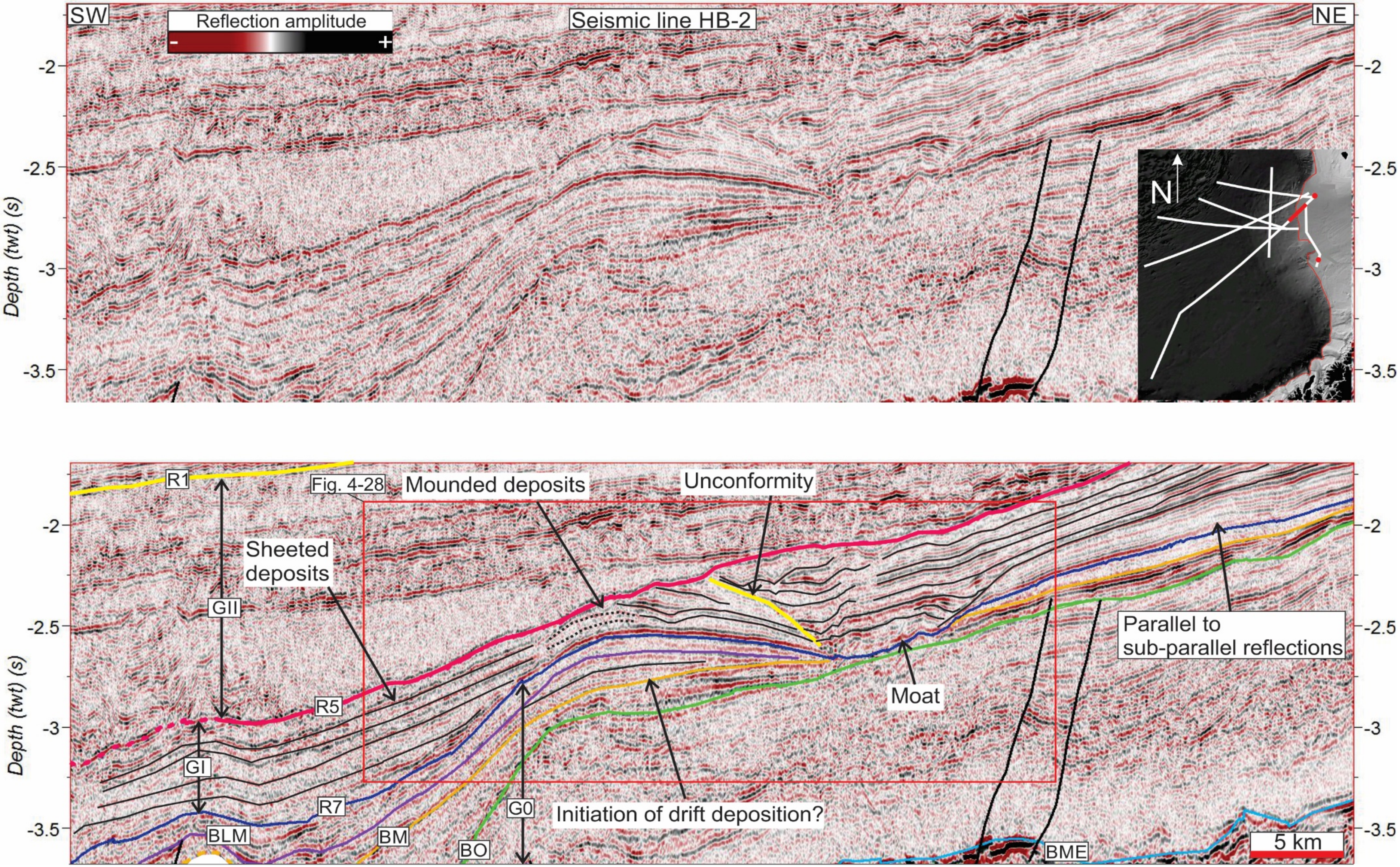


Figure 4-27: The contourite drift on the continental slope as displayed in seismic line HB-2. Mounded and sheeted deposits and moat are indicated.

A reflection in the upper part of the contourite drift represents a lateral change in the seismic facies, from the reflections inferred to be a part of the drift deposits below/downslope, to a wavy reflection configuration within the moat above/upslope (Figure 4-28). The reflection represents an angular unconformity in the top of the drift deposits, as the wavy reflections located within the moat upslope the boundary onlap it (Figure 4-28). The reflections within the moat upslope the top unconformity have a wavy reflection configuration. They have a low to medium amplitude and are continuous to discontinuous. The reflection configuration within the moat can probably not be related to the stacking pattern within the drift deposits downslope, because of the lateral boundary that separates the moat infill from the drift deposits.

The mounded unit changes its external shape downslope the crest of the contourite drift (Figure 4-28). Here, the lower main unit dips relatively steep down, and fills the upper part of the local deep basin upslope the marginal high. The upper main unit dips at a lower angle downslope. Internal reflections within the upper main unit onlap the lower main unit updip (Figure 4-28). The onlapping reflections within the upper main unit are here continuous and parallel, and interbedded with lower amplitude reflections. The external geometry of the upper main unit downslope is flat (Figure 4-27 and 4-28).

The overlying seismic unit GII truncates the contourite drift above the crest of the drift (Figure 4-28). Downslope the crest, the base of unit GII is aligned parallel to the underlying upper main unit of the contourite drift (Figure 4-27).

The contourite drift deposits are difficult to map along the margin (in a north-south trend) because of the low grid density, and no deposits inferred to be a part of the mounded drift deposits have been observed in other parts of the continental slope. However, seismic reflections with a wavy appearance are observed in seismic unit GI in the northern part of the study area at a depth of ~2700 – 3200 ms (twt) (Figure 4-29). A possible unconformity is observed below and up-slope the wavy reflections (Figure 4-29). Here, sub-parallel reflections upslope the contact dips down and possibly terminate where the amplitude decrease along the inferred unconformity. The wavy reflections have similar characteristics as for the moat reflections seen further south (Figure 4-27), and show a progressive upslope accretion to the unconformity (Figure 4-29). No mounded deposits in the same character or scale as seen in the south have been found down-slope the wavy reflections in the north. An up-slope vertical and lateral migration of the wavy reflections along the inferred unconformity is observed (Figure 4-29).

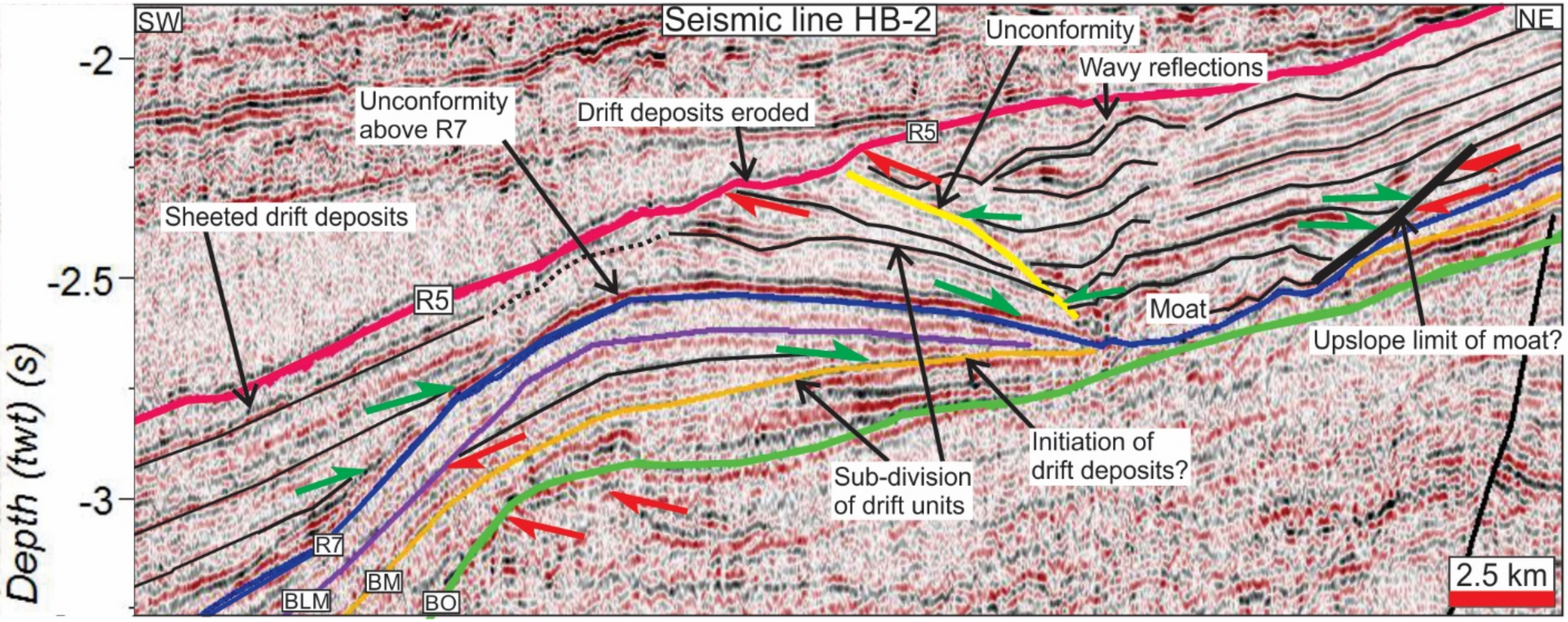


Figure 4-28: A detailed overview of the upper part of the contourite drift deposits and the adjacent moat. A subdivision of the drift units is suggested, and the lateral boundary between drift deposits and the up-slope moat is shown by the yellow line. Red arrows indicate reflection truncation, green arrows indicate reflection onlap. BO: base Oligocene reflection, BM: base Miocene reflection, BLM: base late Miocene reflection. The location of the seismic section is shown in Figure 4-27.

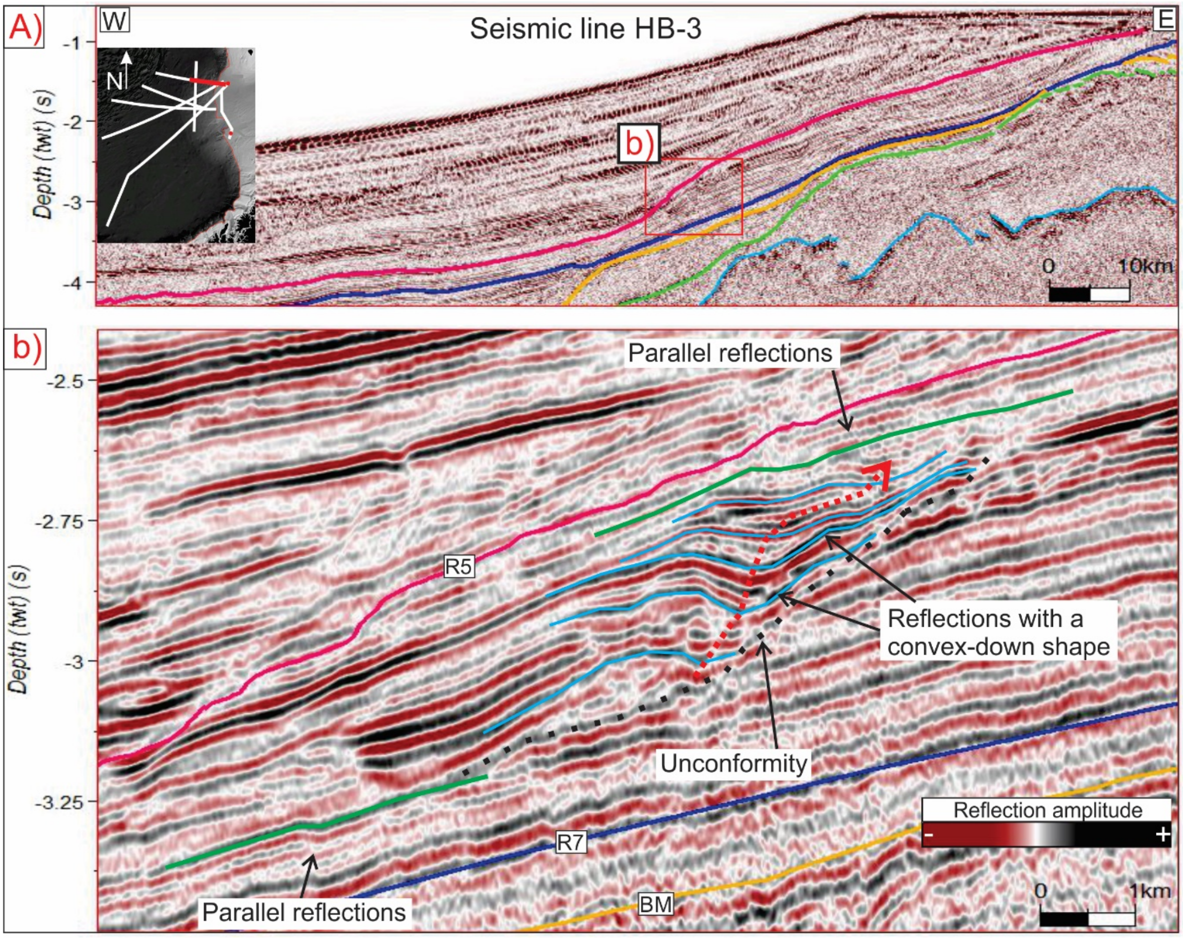


Figure 4-29: The continental slope in the northern part of the study area. Here the reflections are partly characterized by a convex down shape (indicated with blue lines), similar characteristics as the reflections within the moat further south (Figure 4-28). A possible lateral and vertical migration of the convex-down reflections is indicated with a red, dashed arrow. The green lines indicate the lower erosional boundary and the top of the feature. The black, dashed line indicates an unconformity. BM: base Miocene.

Interpretation:

The change from current dominated to non-current dominated depositional style above and/or downslope the mound (Nielsen et al., 2008) cannot be observed as it has been eroded. However, the major change in seismic facies that the unconformity produces (Figure 4-28) may though indicate that this is the upper bounding reflection of the contourite drift in the sense of Nielsen et al. (2008). The truncation of the boundary by the unit GII implies that the sediments deposited above and upslope the lateral boundary, are older than the sediments deposited below and downslope the lateral boundary (Figure 4-28).

Continuous reflections within the drift, sub-dividing the drift deposits into sub-units, may represent minor and major variations in the current strength and/or sediment supply. These variations may have led to shifts between erosion and deposition (Nielsen et al., 2008). Such shifts are indicated where the continuous reflections truncate the underlying strata (Figure 4-28).

The high-amplitude reflection immediately above reflection R7, sub-dividing the drift deposits into the lower and upper main unit, is interpreted to represent a major change in the depositional environment. This change is reflected in the angular unconformity that the reflection represents downslope the crest of the mounded drift deposits. Here, parallel reflections located within the upper main unit onlap the unconformity up-dip at a distinct angle (Figure 4-28).

The parallel reflections in the upper main unit cannot be traced with certainty from upslope the crest of the mounded unit and downslope across the crest. A chaotic interval above the crest in the upper main unit complicates this. However, the similar stacking pattern and internal seismic signature within the mounded unit upslope the crest and within the parallel unit downslope the crest (Figure 4-28), leads to the suggestion that these two areas of deposits are related.

The base of the moat is inferred to be located where the R7 reflection truncates underlying units upslope the mounded drift deposits (Figure 4-28). The wavy reflections that occur in the moat-area may represent the focus of the current flow at different times, indicated by the migration of the moat.

The wavy reflections observed in the north of the study area (Figure 4-29) diverges from those observed in the south in that no clear moat or mounded unit have been observed. The unconformity pointed to here is suggested to represent a slide scar due to the lateral facies change and the downslope and upslope termination of reflections to the unconformity. The wavy appearance of the reflections and termination upslope to the unconformity are interpreted to represent a contouritic infilling of a paleo slide scar deposited by alongslope flowing oceanic currents. Similar infilling drift deposits have been reported by for example Laberg et al. (2001) and Safronova et al. (2015).

4.5.2 Mega-failure above the contourite drift deposits

On the continental slope, a large area within seismic unit GII appears with reflection free and chaotic to transparent internal reflections (Figure 4-30). The feature has an extent of several tens of kilometres both downslope and alongslope, and has been mapped on all seismic lines on the continental slope in the study area. Changes in seismic facies that define the inferred boundaries of the feature are generally easy to outline (Figure 4-30 and Figure 4-31). In the south, the feature terminates high up on the slope and is poorly covered in the seismic lines in this area.

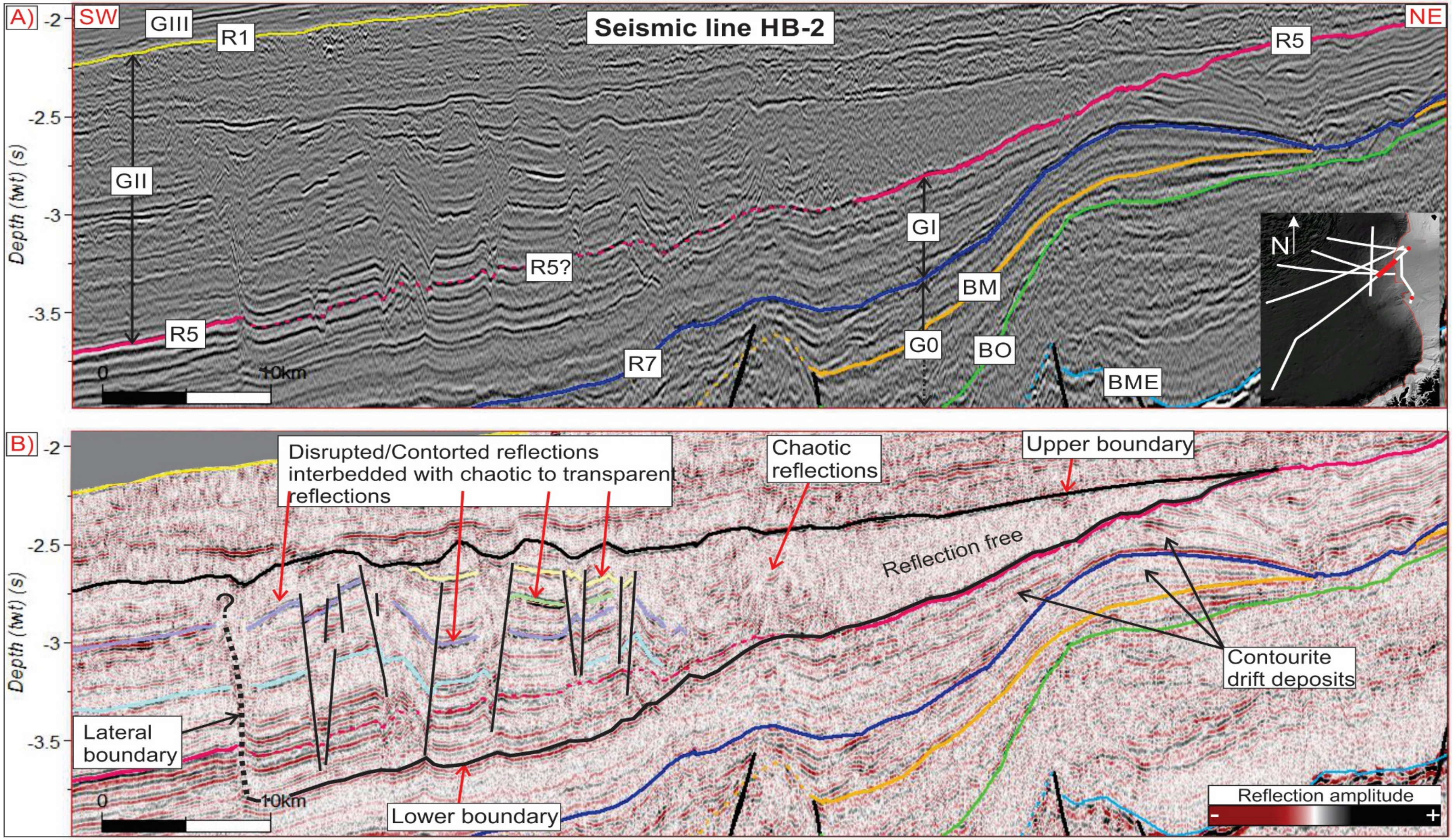


Figure 4-30: A seismic section is shown in grey-scale in A) and with red-white-black seismic reflections including the outline of the mega-failure in B). The inferred upper and lower boundaries of the feature is marked with solid, black lines, while the inferred lateral downslope boundary is marked with dashed, black line. Reflection free, chaotic and contorted/disturbed reflections are indicated.

The area of interest appears above the R5 reflection on the upper slope below the present shelf break, just above the inferred moat and contourite drift deposits mapped in the south (Figure 4-30). This is where the R5 reflection erodes through the upper part of the contourite drift deposits (Figure 4-28). The feature has a wedge-shape, due to a continuous downslope increase in thickness of the affected area (Figure 4-30). Further north, a slide scar is observed at the upslope termination of the feature (Figure 4-31 B).

At the lower boundary of the feature, the seismic facies changes from continuous and parallel reflections below reflection R5 to reflection free seismic facies above it. The change is bounded by a continuous reflection parallel to the underlying strata, coinciding with the R5 reflection (Figure 4-30 and Figure 4-31 B). Downslope, the lower boundary has been outlined based on the grade of deformation of the sediments. The suggested lower boundary defines the lower level of dislocated contorted/disrupted reflections. Here, the lower boundary is inferred to be located slightly below or at the same level as the R5 reflection (Figure 4-30 and 4-31).

The upper boundary of the feature is observed by distinct facies change across the boundary. The facies commonly changes up to chaotic reflections (Figure 4-30) or discontinuous high amplitude reflections interbedded with chaotic reflections (Figure 4-31). A more irregular and disrupted appearance of the upper boundary is observed downslope (Figure 4-30) and in a N-S trend (Figure 4-31 A).

The seismic facies in the upper slope appears reflection free, changing gradually downslope to a more chaotic appearance (Figure 4-30 and Figure 4-31B). The chaotic seismic facies shows different characteristics, including for example dislocated, thrusted and folded reflections of medium to high amplitude, interbedded with transparent reflections (Figure 4-30 and Figure 4-31). An increase in dislocation and disruption of reflections is observed downslope, while the amount of interbedded transparent/reflection free reflections increases up in the stratigraphy (Figure 4-30 and Figure 4-31).

The contorted/disrupted reflections interbedded with chaotic to transparent facies terminate abruptly downslope, where the facies changes to non-disrupted parallel, continuous reflections interbedded with chaotic to transparent reflections. The downslope termination of the lower part of the feature is marked by a sub-vertical area of highly deformed/disrupted reflections (Figure 4-30). Here, the feature has a thickness of ~1400 ms (twt).

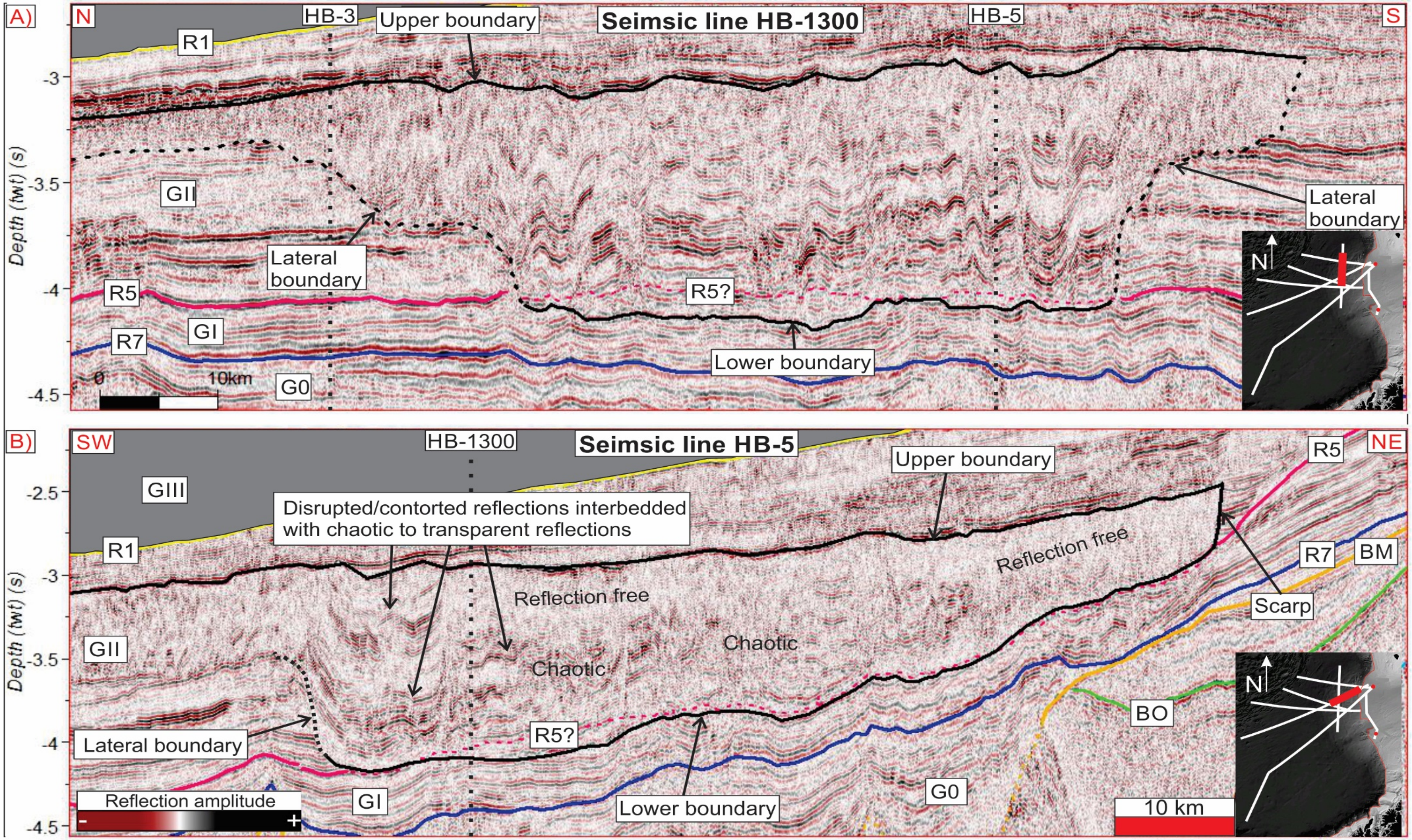


Figure 4-31: The mega-feature on the continental slope is outlined in the seismic lines HB-1300 (A) and HB-5 (B). Black lines indicate top and base of the feature, and black, dashed lines indicate lateral boundaries. Black, vertical, dashed lines indicate crossing seismic lines.

This indicates a maximum thickness of the affected sediments of about 1500 meters, using an average velocity of 2160 m/s for the GII seismic unit (Fiedler and Faleide (1996)).

The upper part of the feature continuous downslope toward the Lofoten Basin. The continuation is clearest in the central part of the area (Figure 4-31 B), however, the feature probably extends downslope toward the Lofoten Basin also in the southern part (Figure 4-30). The southern and central extent of this continuation is not possible to map due to the oblique angle of the relevant seismic lines to the feature. In the north, a thin “arm” of the unit with chaotic seismic facies extends toward the north. The chaotic seismic facies here terminates about 10 km north of the termination of the seismic section in Figure 4-31 A.

The northern part of the feature, where it is crossed by line HB-3, is probably related to the Bear Island Fan Slide Complex III, documented by Hjelstuen et al. (2007). The slide extends downslope into the Lofoten Basin. A headwall or sidewall scarp exists here, located just upslope the transverse seismic section (Hjelstuen et al., 2007). The possible relation between the mega-failure and the BFSC III has not been studied any further here.

Interpretation:

The chaotic and reflection free seismic facies together with the nature of the upper and lower boundaries observed in the identified mega-feature are commonly related to the deposition of remobilized sediments. Similar features have previously been described by Solheim et al. (2005); Hjelstuen et al. (2007) and Bull et al. (2009b). According to Lee et al. (2007), the downslope movement of sediments on a planar surface is defined as a translational slide.

The distinct lower boundary on the upper continental slope is suggested to represent a glide plane or a basal shear surface (BSS) that formed at the base of sediments being transported downslope. Similar glide planes or BSS occurring as basal boundaries parallel to the sub-strata and defining distinct facies changes have been reported and described by for example Bryn et al. (2005); Rise et al. (2005); Solheim et al. (2005) Bull et al. (2009a) and Safronova et al. (2015). Based on the bounding reflections, the basal shear surface acting as glide plane and the internal seismic signature, the mega-feature is interpreted to represent slide deposits.

The upper boundary of the deposits has probably been removed by subsequent slides. This is particularly noticeable in the south, where no headwall scarp is present (Figure 4-30). The lateral, upslope boundary observed further north (Figure 4-32 B) is interpreted to be a headwall scarp in the sense of Bull et al. (2009a).

The lateral boundaries oriented obliquely across the BITMF (the downslope boundary indicated in Figure 4-30 and Figure 4-31 B) are interpreted to represent the southbound lateral margin of the slide deposits. Thus, the lateral boundary indicated in the south in the transverse seismic section (Figure 4-31 A) is the same lateral margin. Downslope and close to the base, the folded and disrupted reflections probably represents in situ deformation or only short downslope transport of the sediments. The suggestion is based on the possibility to trace medium-high amplitude reflections and complete seismic facies across the lateral boundaries, especially in the south (Figure 4-30). The increasing amount of chaotic to transparent facies, including folded and thrusted reflections, up in the stratigraphy indicates a higher degree of deformation here. Unfortunately, no seismic lines cross the slide deposits straight downslope in the central, deepest part, and thus, the downslope termination may not be mapped for the deeper part.

Based on the characteristics observed, the slide deposits are interpreted to represent the remobilization and subsequent deposition of large volumes of sediments on the continental slope. The reflection free and chaotic to transparent seismic facies in the upper part of the unit indicate a higher degree of deformation, and this part of the unit extends downslope into the Lofoten Basin.

4.5.3 Mass transport deposits in unit Te4

Chaotic and transparent seismic facies, sometimes interbedded with discontinuous and/or transparent reflections, dominate in large areas in seismic unit Te4. For better insight in the dominating processes during the deposition of unit Te4, a more detailed study of the northern part of the lower continental slope (Section 4.5.3.1), central-southern part of the lower continental slope (Section 4.5.3.2) and proximal Lofoten Basin (Section 4.5.3.3) will be conducted here. An overview of the location of the main figures that form the basis for the following description and interpretation is shown in Figure 4-32.

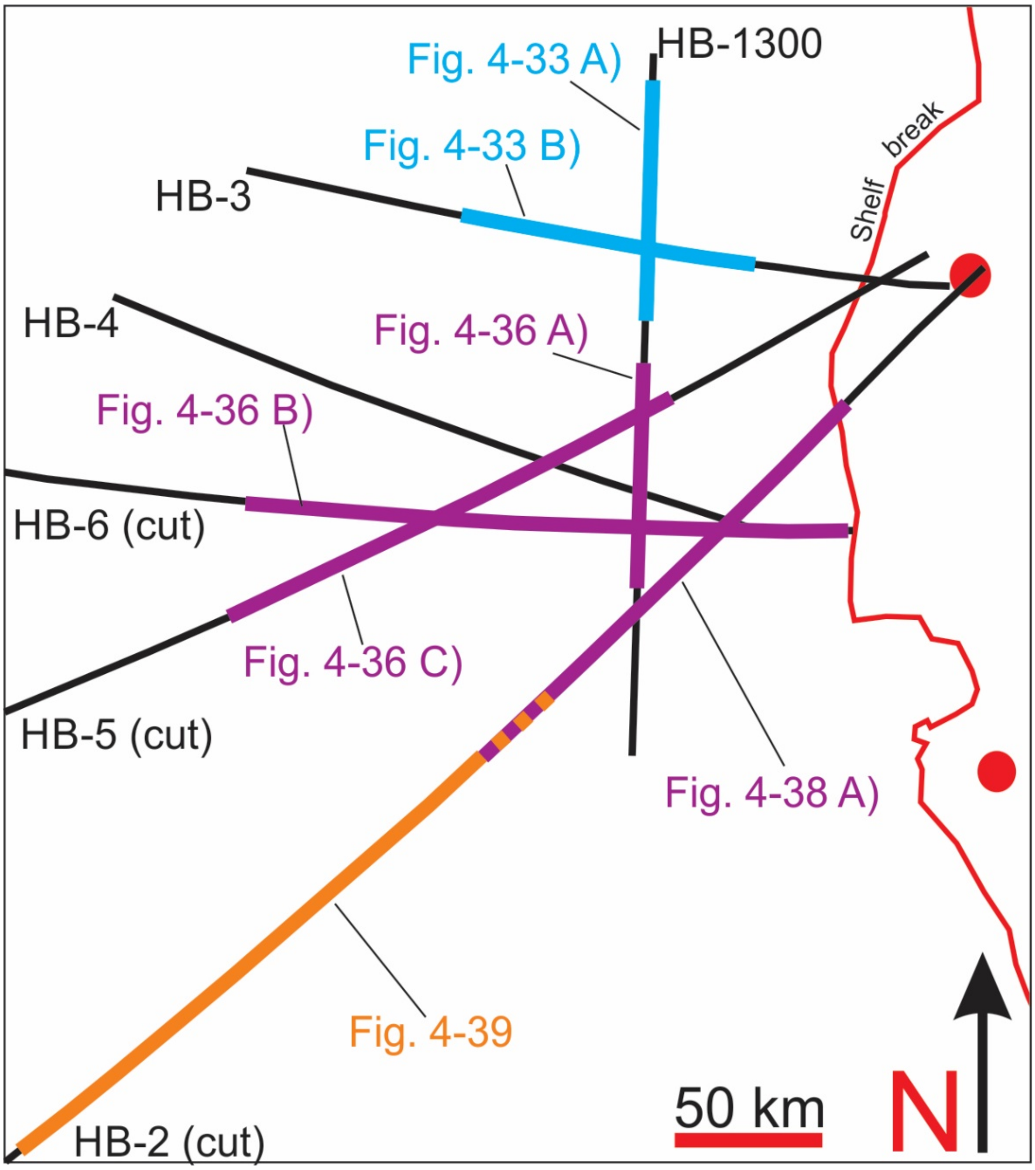


Figure 4-32: Location map for the main figures in the study of mass transport deposits. Red dots: Well 7316/5-1 (in the north) and well 7216/11-1S (in the south). Black lines: seismic lines. Coloured lines indicate the seismic sections shown in the main figures. The seismic lines HB-6, HB-5 and HB-2 are cut in this view, see Figure 3-2 for the complete location map.

4.5.3.1 Mass transport depositional units uN1 – uN6 in the northern Lofoten Basin

Six depositional units, uN1 (oldest) – uN6 (youngest), (N = North), have been mapped in unit Te4 in the northern part of the study area (Figure 4-33 A and B).

The six units have been mapped based on their internal seismic facies, mainly consisting of a chaotic or chaotic to transparent signature. Discontinuous reflections have also been identified within the units. The units stack directly on each other or are separated by continuous reflections (Figure 4-33).

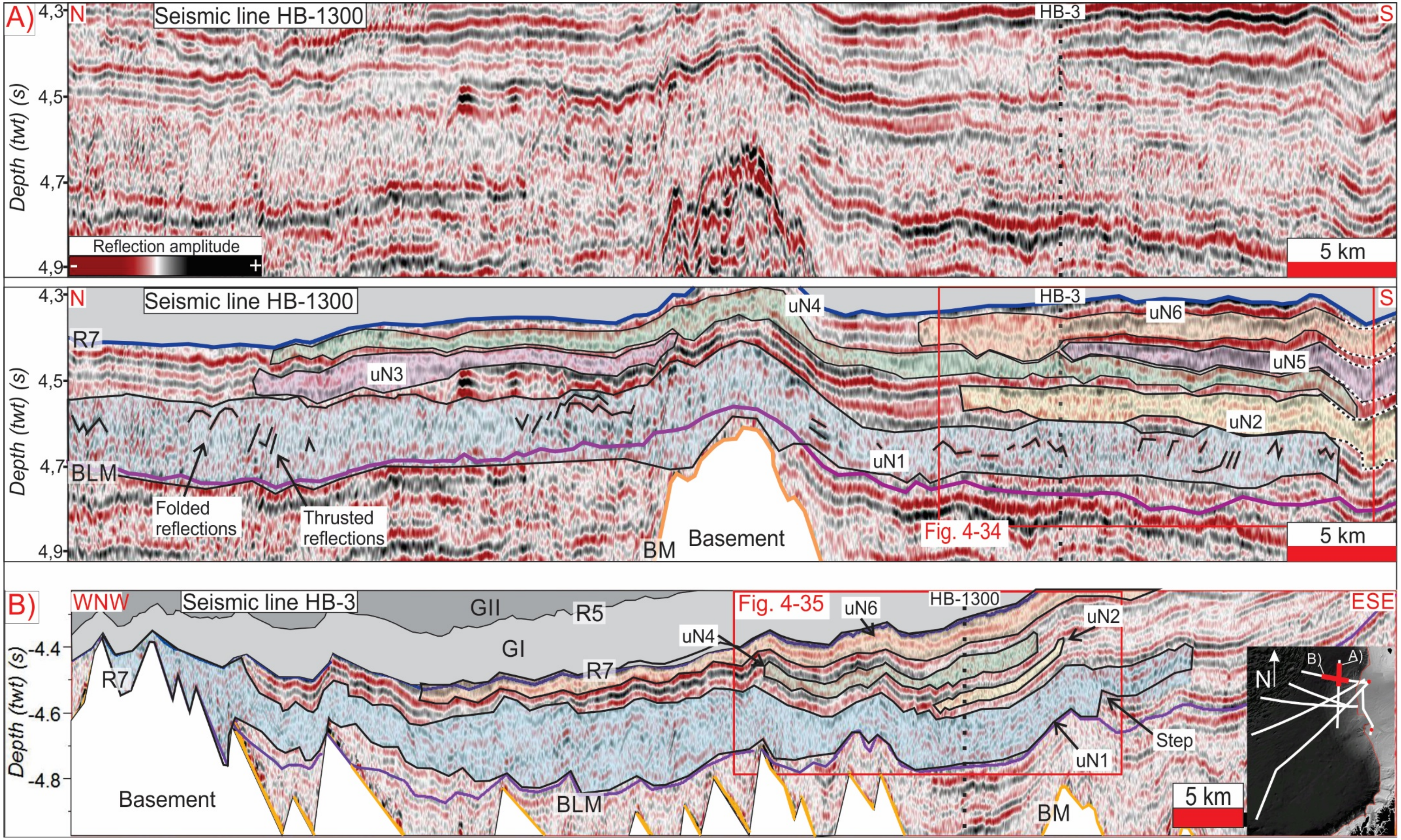


Figure 4-33: The subdivision of the unit Te4 into uN1 to uN6 in the northern part of the study area in (A) and B). Black lines within the unit represent possible intact blocks. The location of the seismic sections shown in A) and B) is indicated in the location map in B).

Lateral boundaries of the units, where observed, occurs as lateral changes from the mentioned internal reflections to parallel and continuous reflections, for example the northern boundaries of units uN2, uN3 and uN6 (Figure 4-33 A) and the up-slope boundaries for units uN1, uN2 and uN4 (Figure 4-33 B). No southbound lateral boundaries have been identified for units uN2, uN5 and uN6. These units follow a stratigraphically stable configuration southward toward the area described further south in next section.

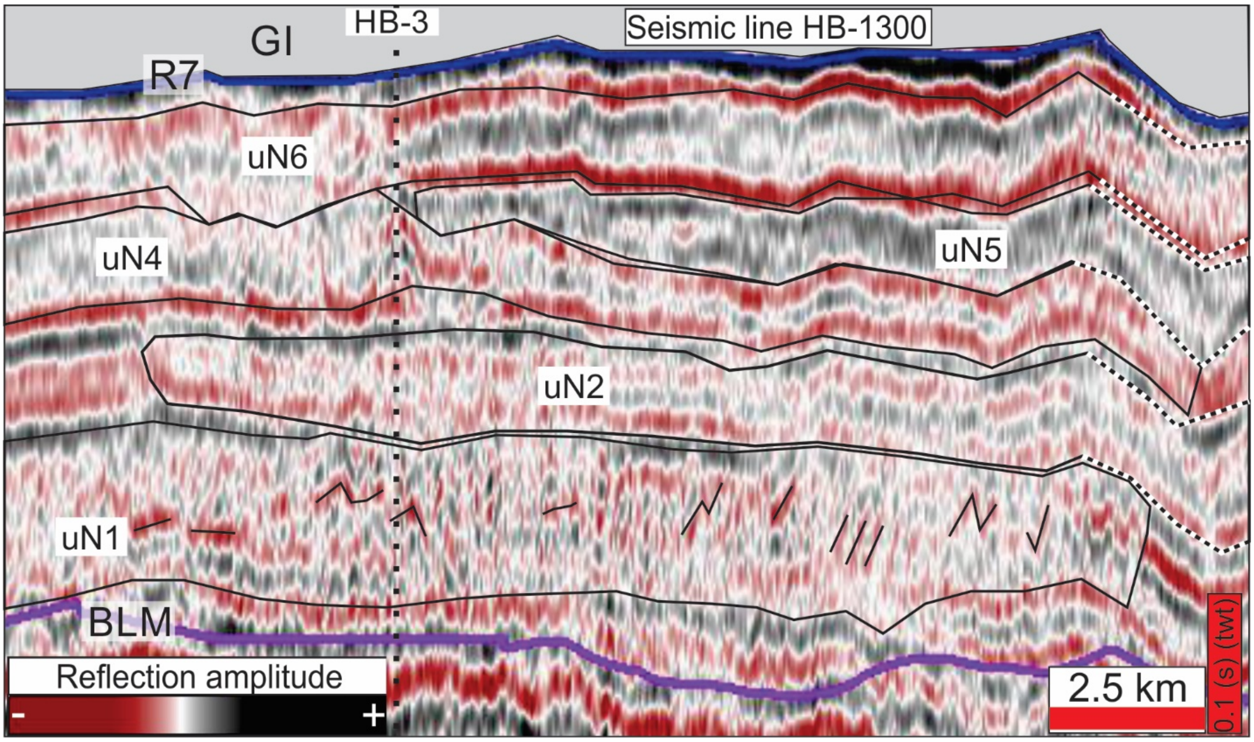


Figure 4-34: Details of units uN1-uN6 is shown in a transverse view. Black lines within unit uN1 indicate intact blocks. The location of the section is shown in Figure 4-33 A).

The units range in width from more than 20 km, where uN1 and uN4 have a greater lateral extent than the other units (Figure 4-33 A). Unit uN1 has a width of about ~70 km, but this is a minimum estimate as the unit continues northward beyond the termination of seismic line HB-1300. The units range in thickness from about 50 to 200 ms (twt), indicating thicknesses between ~60 – ~260 meters (Figure 4-34). The individual units have a relatively uniform thicknesses and appears to have a flat or sheeted external shape in transverse view (Figure 4-33 A). They commonly thin and pinch out downslope. The exception is the larger unit uN1, which thicken downslope where it deposits on top of a basement high (Figure 4-33 B).

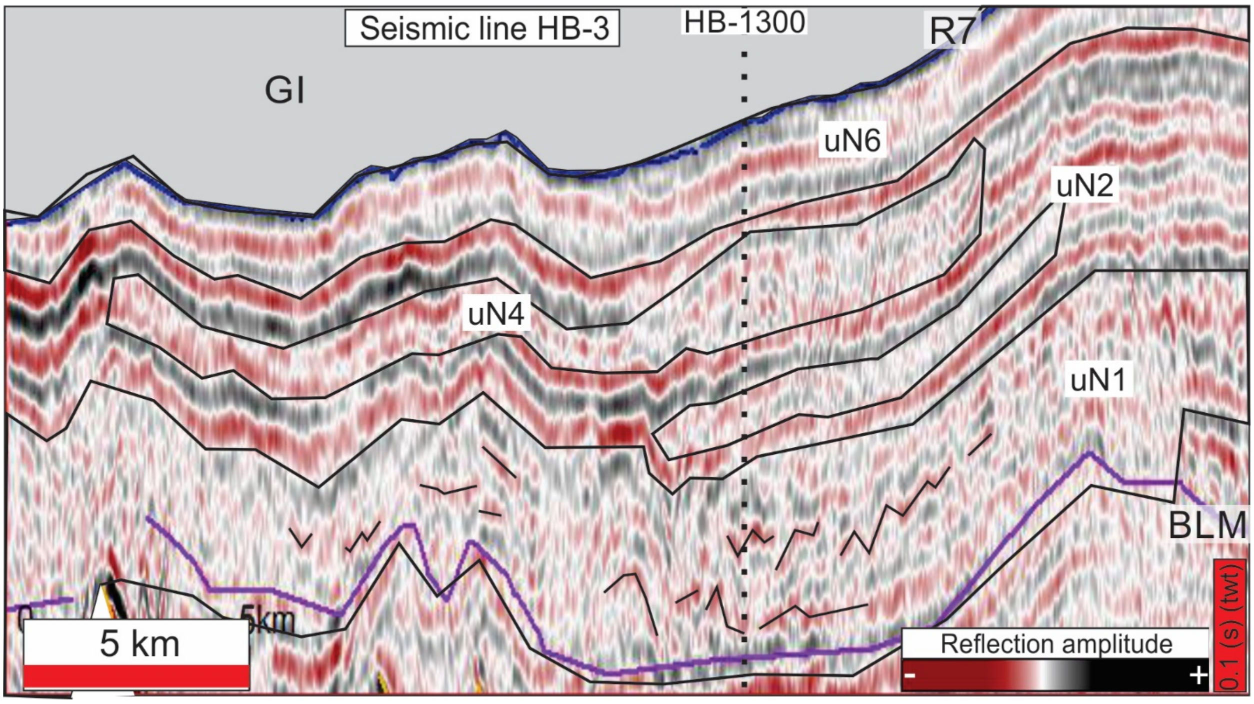


Figure 4-35: Details of units uN1, uN2, uN4 and uN6 in a section from line HB-3.Black lines within unit uN1 indicate intact blocks. The location of the section is shown in Figure 4-33 B). .

Unit uN1 is dominated by a chaotic internal seismic facies including discontinuous reflections of medium-high amplitude, and which are folded or inclined (Figure 4-33 A and 4-35). The unit extends a minimum of 80 km downslope (Figure 4-33 B). However, the termination of the unit in the Lofoten Basin is not clear and the unit may extend some tens of km further toward the west. The unit uN1 basal boundary largely follows the lower Te4 unit boundary (BLM), and this boundary changes from being irregular in the northern part to more even in the southern part (Figure 4-33 A). The unit is deposited across a prominent basement high in central parts, and it is possible that the unit is deposited directly onto the high (Figure 4-33 A). Continuous reflections below the base of the unit onlap the sides of the high and the chaotic facies within the unit lies directly on the top of the high. Erosion into sediments below the BLM is observed on both sides of the high, where the outline of the unit is drawn below the BLM (Figure 4-33 A).

The upper boundary of unit uN1 appears more irregular than the base. The lateral boundary toward the south is inferred to be present at a distinct change in the seismic facies, from chaotic within the unit uN1 to sub-parallel and continuous reflections outside the unit (Figure 4-34). Similar abrupt facies change is seen in the upslope part of the unit, changing from parallel and continuous upslope to chaotic downslope across a sub-vertical boundary. Here, also a step-like pattern probably is present at the upslope termination of the unit (Figure 4-33 B).

The internal seismic facies in units uN2 - uN6 are slightly different from that observed within unit uN1. These units are dominated by frequent, lateral changes between transparent, chaotic and discontinuous reflections. They extend downslope from 10 km (uN2) to ~65 km (uN6) (Figure 4-33).

Interpretation of units uN1-uN6:

The depositional units uN1 – uN6 are interpreted to represent mass transport deposits on the lower continental slope. The interpretation is based on the continuous to discontinuous and irregular upper and lower boundaries of the units, and the internal seismic facies dominated by chaotic or chaotic to transparent reflections. Similar deposits have been reported by for example (Laberg & Vorren, 1995; Lee et al., 2007; Bull et al., 2009b, 2009a; Safronova et al., 2015).

The folded and thrusted blocks found in unit uN1 may represent intact sediment blocks transported downslope within the masses. Such features may relate to the toe domain of the mass transport deposits (Bull et al., 2009a; Safronova et al., 2015). Step-like patterns as seen in the upslope termination of unit uN1 have also been reported by for example Hjelstuen et al. (2007) and Bull et al. (2009a). They related the step-like patterns to a retrogressive failure development, and a similar explanation is suggested here.

The less clear lateral extent of the units uN2-uN6, and the internal variations in seismic facies in each of the units, complicate the interpretation of some of them. This accounts especially for units uN5 and uN6 where the chaotic to transparent facies dominates. The thickness of the units may play a role in the expression of the internal seismic facies of the units as they range around the ½λ thickness. However, chaotic reflections are commonly observed where the units are thickest and above ½λ thickness, for example unit uN6 in the north (Figure 4-33 A).

The appearance of chaotic seismic facies within the units leads to the interpretation that also these units may represent the deposition of masses transported downslope, though the units appear with another facies where they are thinner. In addition, the overall setting with frequent appearance of chaotic seismic facies in unit Te4 in the area favour this interpretation. Together, units uN1-uN6 are interpreted to represent stacked mass transport depositional units located in the lower continental slope and the Lofoten Basin.

4.5.3.2 Mass transport depositional units uS1 – uS3

Three depositional units, uS1 (oldest) – uS3 (youngest), (S = South), have been mapped within unit Te4 in the central and southern part of the study area.

Unit uS1 is dominated by a chaotic to transparent seismic facies, with continuous to discontinuous internal reflections of medium amplitude that are possible to follow through parts of the unit (Figure 4-36 A) and B), 4-37 and 4-38). The unit has a N-S extent of about 32 km (Figure 4-36 A), but the unit probably extends more than 10 km further south where it is crossed by seismic line HB-2 (Figure 4-38).

The unit is bounded by the BLM reflection at the base and by a continuous to discontinuous reflection at the top, which is interpreted to also represent the uS2 basal boundary. The unit has a thickness of up to ~350 ms (twt), indicating about 470 meters. In an along-slope view, the unit appears thin in the upper part and thickens downslope (Figure 4-36 B). No headwall scar has been identified at the up-slope termination, and the initiation of the unit is suggested to be located where the unit uS2 basal boundary diverge downslope from the BLM reflection (Figure 4-37 A). The unit extends downslope for about 85 to 100 km (Figure 4-36 B and 4-38A). Sub-vertical faults affect the unit in the Lofoten Basin (Figure 4-36 B) and 4-37B). The unit terminates toward a basement high in the Lofoten Basin (Figure 4-37 B).

Unit uS2 has an alongslope width of about 65 km (Figure 4-36 A). Chaotic reflections dominate within this unit, but continuous reflections of medium amplitude are possible to follow in some areas (Figure 4-36 A and B) and Figure 4-38). The thickness is around 150-200 ms (twt), indicating a thickness of around 200-270 meters.

The unit has a uniform alongslope thickness, downslope and in the Lofoten Basin the thickness varies from about 200 ms (twt) to about 50 ms (twt) (Figure 4-36 B) and C) and Figure 4-38). Unit uS2 extends for more than 100 km from the continental slope and into the Lofoten Basin. It probably terminates beyond a basement high (Figure 4-36 B), and by thinning and pinch-out (Figure 4-36 C and 4-38). The unit is interpreted to by-pass basement highs on the lower continental slope (Figure 4-36 C).

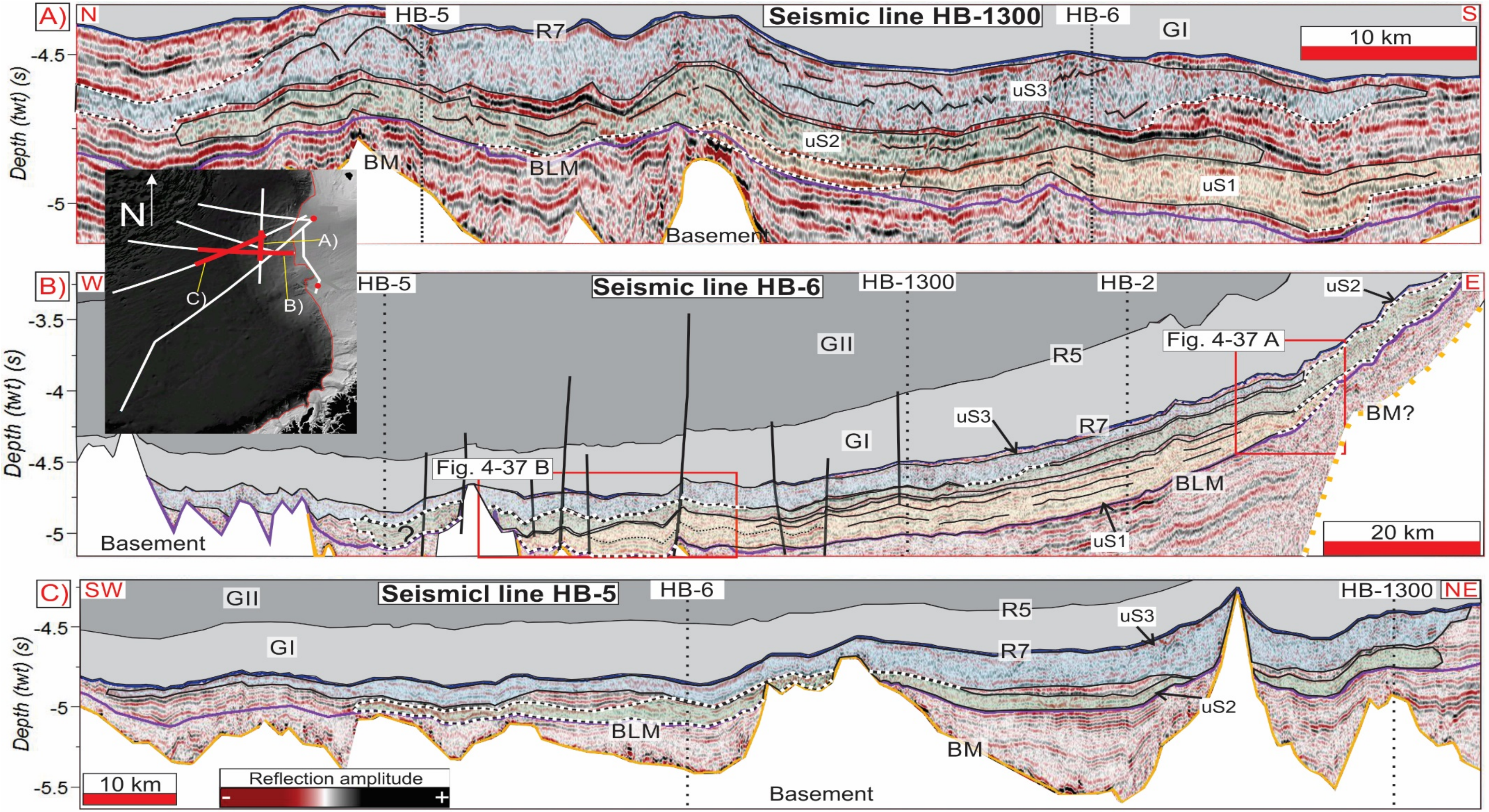


Figure 4-36: Seismic sections from three crossing seismic lines are shown with the units uS1 – uS3 outlined. Location of the crossing seismic lines are indicated with vertical, dashed lines in the individual sections. Black lines appearing within the individual units represent possible intact blocks. White dashed lines indicate uncertain unit boundaries. BLM: base late Miocene reflection, BM: base Miocene reflection. The colours for depositional units uS1 – uS3 in this and the following figures have no relevance to the colours used to describe the depositional units uN1-uN6 mapped in the north (Figure 4-33). The locations of the seismic sections are indicated in the location map in A)/B).

In the south, the unit first appears on the downslope side of the marginal high (Figure 4-38). The unit thins abruptly on the lower continental slope where unit uS3 first appears (Figure 4-38). A medium to high amplitude, irregular seismic reflection appears on top of the thinned unit uS2 downslope, and another area of chaotic reflections is observed on top of it (Figure 4-38 B). This chaotic area on top of the thinned unit uS2 is interpreted to be another depositional unit, the uS3.

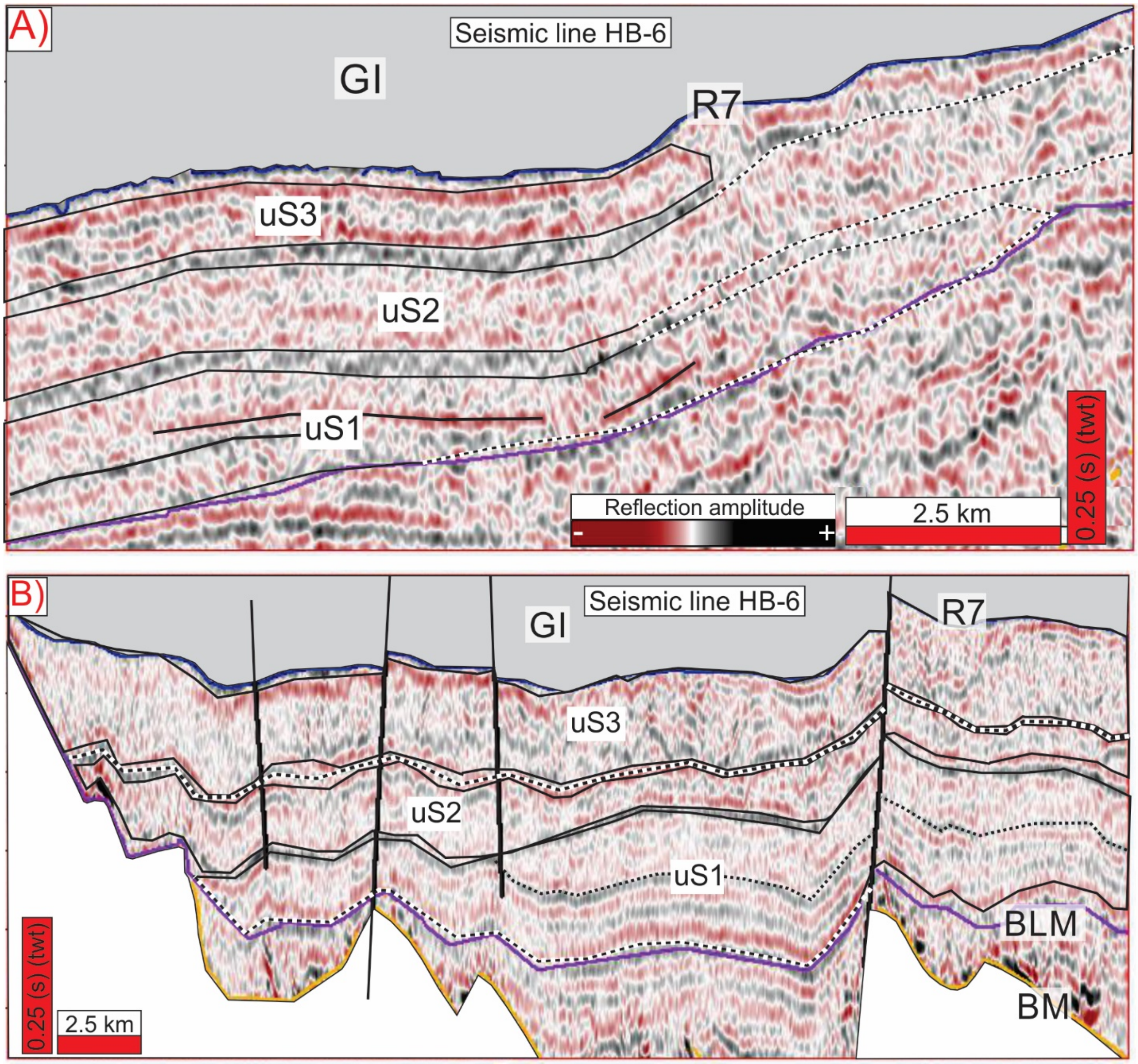


Figure 4-37: Sections from the continental slope (A) and the Lofoten Basin (B) showing details regarding the internal reflections within the units and the possible termination of units uS1 and uS2 toward a high in the Lofoten Basin. Black lines within the units represent continuous to discontinuous reflections. White dashed lines indicate uncertain unit boundaries. The location of the figures are indicated in Figure 4-36 B).

Unit uS3 has an alongslope width of about 50 km and a thickness of around 250 – 300 ms (twt) (Figure 4-36 A). The thickness is uniform in most of the unit, but the unit thins on both flanks.

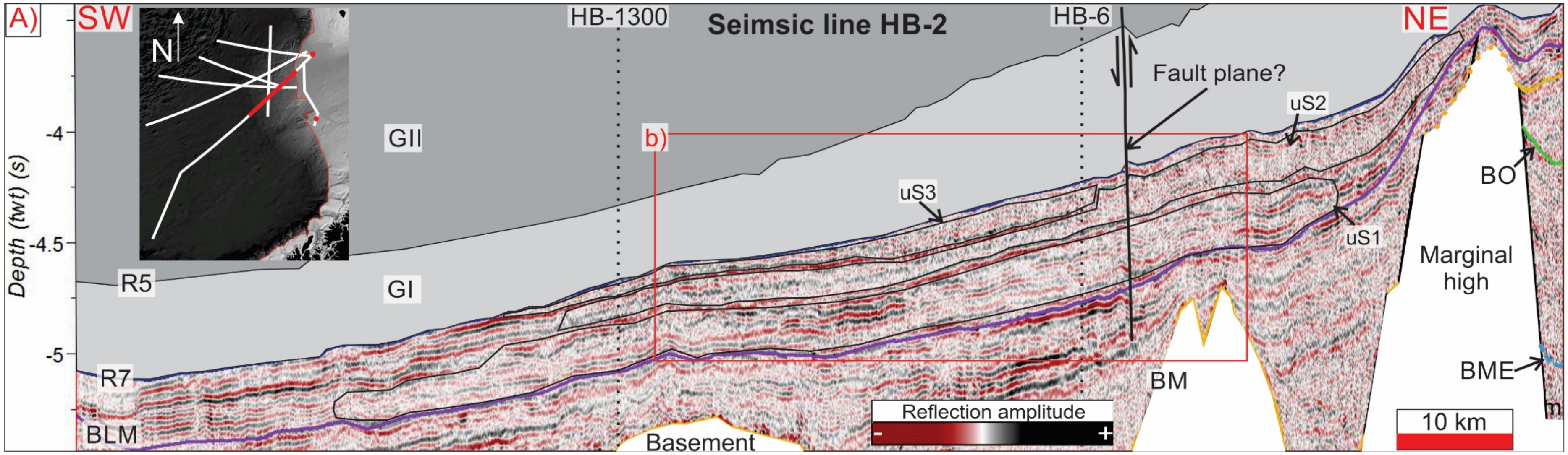
Chaotic seismic facies dominates, represented by three different appearances: In the northern part, reflections with a mounded shape appears along with chaotic reflections just north of the crossing with seismic line HB-5. A more transparent chaotic seismic facies appear in the central part, and in the southern part, the chaotic seismic facies have higher amplitudes (Figure 4-36 A). Both seismic lines HB-6 and HB-5 cross the unit uS3 in seismic line HB-1300, and the unit extends more than 140 km downslope into the Lofoten Basin (Figure 4-36 B and C).

Unit uS3 is thin high up on the continental slope (Figure 4-36 B) and thickens gradually downslope where it bypasses basement highs (Figure 4-36). The unit subsequently thins into the Lofoten Basin where it pinches out in the southwest (Figure 4-36 C) and probably terminates against a basement high in the west (Figure 4-36 B). Irregular, internal reflections may be mapped within the unit in the southern part (Figure 4-36 A). The unit pinches out on the lower continental slope in the south where the extent of the unit appears to be minor compared to the northern areas (Figure 4-38).

Interpretation of units uS1 – uS3:

The interpretation of the units uS1-uS3 is similar to that of units uN1-uN6 in the northern part of the study area. The interpretation of these deposits as mass transport depositional units is based on the continuous to discontinuous upper and lower boundaries of the units, and the internal seismic facies dominated by chaotic or chaotic to transparent reflections. Laberg and Vorren (1995); Lee et al. (2007); Bull et al. (2009a; 2009b) and Safronova et al. (2015) have previously described similar deposits.

The frequent lateral variations in seismic facies between chaotic, transparent and continuous to discontinuous reflections within unit uS1, leads to the suggestion that this unit is complex and composed of several deposits of small-scale mass transport events. Also unit uS2 shows similar variations, especially at the lateral margins where the unit thins. Single, continuous reflections of low-medium amplitude overlain by chaotic seismic facies are interpreted to represent the base of individual small-scale events of downslope transport and deposition of sediments. The internal subdivision of events in each of the depositional units has not been given priority in the study due to the complexity of the units and the low grid density of seismic lines in the area.



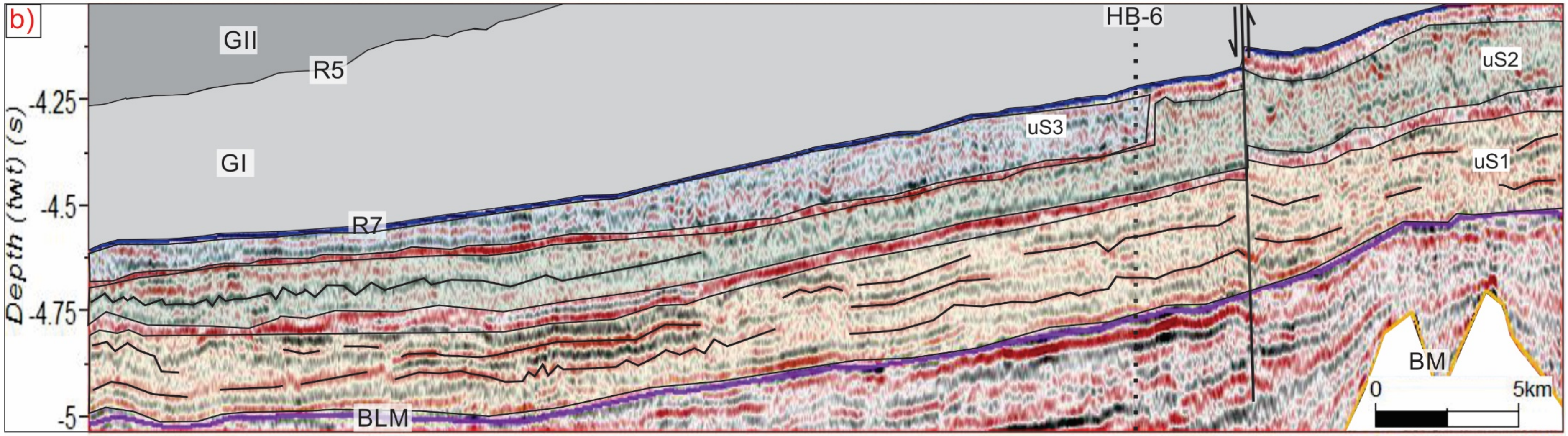


Figure 4-38: The location of the depositional units uS1 – uS3 on the lower continental slope. Dashed, vertical lines indicate the location of crossing seismic lines. White dashed lines indicate uncertain unit boundaries. BO: base Oligocene reflection, BLM: base late Miocene reflection, BM: base Miocene reflection. The location of A) is indicated in the location map in A).

The domination of chaotic seismic facies within the larger unit uS3 favours the suggestion that this unit is composed of one or a few larger-scale events. Irregular, discontinuous reflections traced within the unit (Figure 4-36 A) and 4-38) may favour the latter suggestion. The unit is interpreted to have partly eroded the top of unit uS2. As the unit is larger toward the west and the north, the scar where unit uS3 cuts down into unit uS2 (Figure 4-38) is interpreted to represent a headwall scarp. Units uS1-uS3 are interpreted to represent small- and larger scale stacked mass transport depositional units located in the lower continental slope and the Lofoten Basin.

4.5.3.3 Mass-transport complex in the proximal Lofoten Basin, BLM – R7 unit

A vast area dominated by chaotic and chaotic to transparent seismic facies within the BLM-R7 unit has been observed in the lower continental slope and the proximal Lofoten Basin. The area has been subdivided in three sub-areas: 1) the area up-slope the deep basin region in the northeast, 2) the deep basin region in the central part, and 3) plateau region toward the southwest (Figure 4-39).

1) In the area up-slope the deep basin region, unit Te4 has a uniform thickness of about 250 meters (~200 ms (twt)), and both the base (BLM) and top (R7) reflections of the unit follow the overall topography down the slope. The seismic facies in the unit on the lower continental slope changes abruptly downslope from sub-parallel and continuous to a chaotic to transparent seismic facies. The change occurs abruptly at a sub-vertical boundary, and is clearly seen in the seismic section (Figure 4-39 b). The change in seismic facies occurs up-slope the basement high that flanks the deep basin region in the northeast. The chaotic to transparent seismic facies continues downslope across the basement high and follows the BLM-R7 unit into the deep basin region.
2) In the deep basin region, the BLM reflection dips down from both the northeast and the southwest toward the centre of the region, and is here located about 700 meters (500 ms (twt)) lower than it is above the high in the northeast. Unit Te4 doubles in thickness in the area (Figure 4-39 A). The interpretation of the BLM reflection in the deep basin region is uncertain because the reflections in the area are discontinuous and contorted. The location of the BLM reflection is based on the change in facies across the inferred BLM in the area and have been dashed in the illustrations (Figure 4-39 A). Unit Te4 is dominated by chaotic reflections, interbedded with continuous to discontinuous irregular reflections appearing sub-horizontal. Both the amplitude strength and grade of chaotic seismic facies increase laterally from northeast toward the southwest.

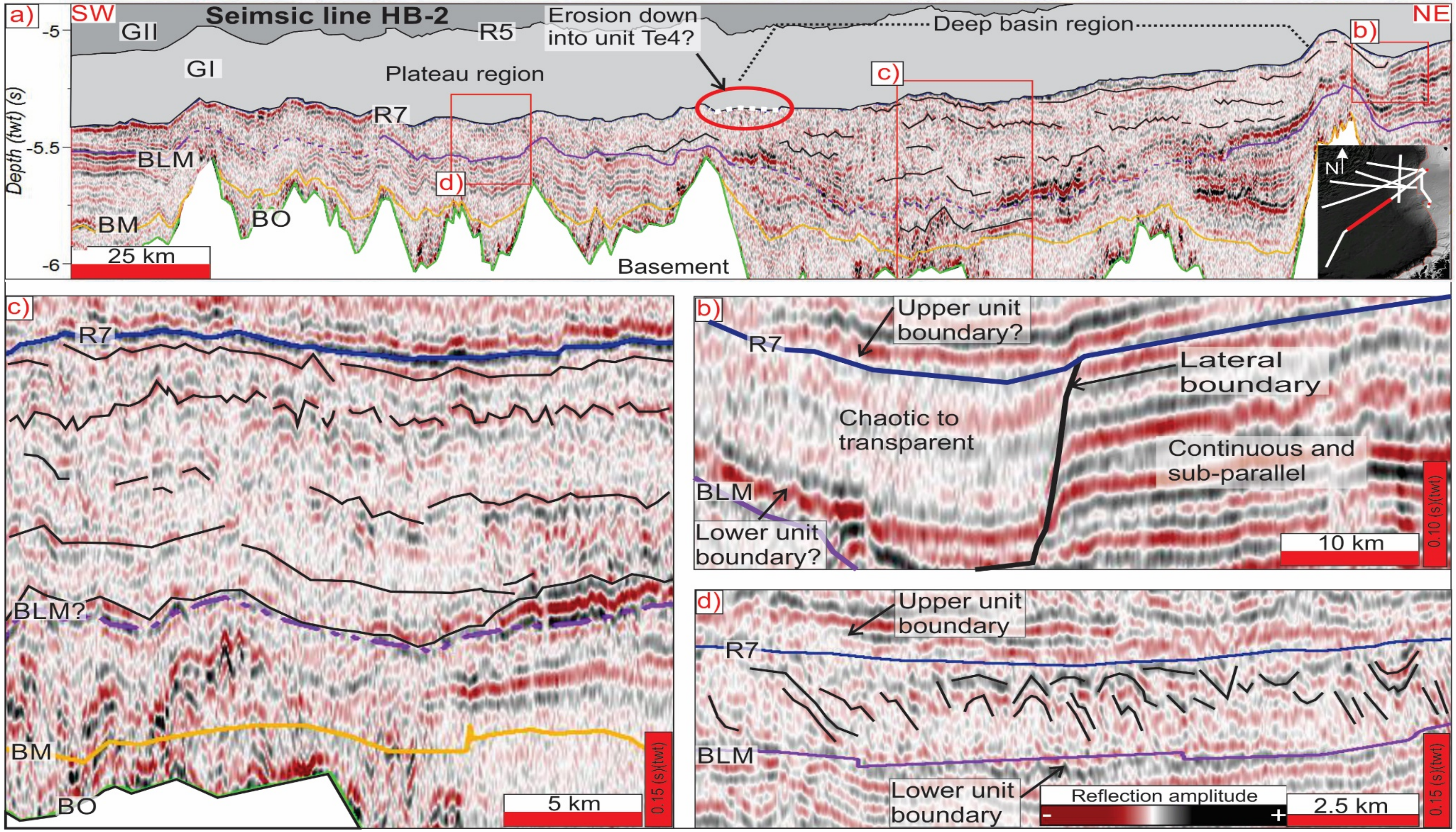


*Figure 4-39: **a):** A mass transport complex in the proximal Lofoten Basin. Black lines in indicate discontinuous to continuous reflections that may represent boundaries between sub-units in unit Te4. The location of the seismic section in A) is indicated in the location map. **b):** The lateral, distinct change in seismic facies is marked with a black, sub-vertical line. The upper and lower boundaries of mass-transport unit are indicated. **c):** Details of central part of the area with irregular and continuous reflections within the unit marked with black lines. **d):** Intact, inclined and folded blocks appearing in unit Te4 further toward southwest in the Lofoten Basin. The inferred upper and lower boundaries of the mass transport unit are indicated.*

The increasing chaotic seismic facies toward the southwest makes the mapping of internal reflections more difficult. The most continuous reflections have been mapped, showing a possible vertical subdivision of depositional units within the area. However, the lateral extent of these sub-units is difficult to point out due to a high grade of chaos and no clear lateral terminations of the subdivisions (Figure 4-39 c).

3) The complete unit Te4 is dominated by the chaotic seismic facies in the southwest part of the proximal Lofoten Basin (Figure 4-39 A). The chaotic seismic facies changes laterally between chaotic reflections with no systematic structures, to chaotic seismic facies that includes inclined/thrusted and folded (both convex and concave geometry) reflections (Figure 4-39 D). Unit Te4 thins gently toward the southwest, and the chaotic seismic facies terminates by pinch-out where the BLM-R7 unit is thin above a deep basin in the central parts of the Lofoten Basin (Figure 4-24 A). The BLM-R7 unit here continues toward the southwest as a thin unit comprising horizontal and continuous reflections. Possible disturbance of sediments below the BLM boundary have been observed above highs in the plateau-region. A possible erosion of the overlying R7-R6 unit down into the BLM-R7 unit have also been observed (marked with red circle in Figure 4-39 A).

Interpretation of mass-transport complex:

As noted in Section 4.4.3, the complete dominance of chaotic seismic facies within unit Te4 in the proximal Lofoten Basin indicates that this area has been subject to massive input of sediments transported downslope as summarized below. This represents a major change in the depositional environment in this part of the Lofoten Basin, from the hemipelagic sedimentary environment inferred to dominate in unit Te3 below, to the dominance of mass transport deposits in unit Te4.

1) The abrupt lateral change in seismic facies in the northeast probably represents a lateral or headwall margin, defining the boundary between undisturbed sediments upslope and mass transported sediments downslope. The suggestion here is that the boundary represents a lateral margin. This is due to the oblique angle of the seismic line (trending northeast southwest) to the probable slope dip and sediment transport direction downslope (toward the west), and the low gradient where the boundary is located. The probable source for the mass transported sediments would thus be to the southeast of the area mapped (Figure 4-39 A). The lateral margin is probably related to the mass transport complex in the proximal Lofoten Basin. However, the exact relation between the two areas, other than the continuous chaotic facies between them, is uncertain.

2) The partly continuous and irregular sub-horizontal reflections marked within unit Te4 in the deep basin region, (Figure 4-39 A) and C)), are interpreted to represent bounding reflections representing the separation of different mass transport events. Similar irregular basal reflections have been reported both for glacigenic debris flows (Laberg & Vorren, 2000b) and large slides (Rise et al., 2006). The setting here is somewhat different as the area is located in the transition between the continental slope and the abyssal plain, and the deposited units appear to be confined within a morphological low. However, the subdivision of the unit from continuous reflections implies that several events of mass transport deposition have occurred in the region. The full extent of mass transport events in the area is complicated to infer due to the complexity and the lack of lateral boundaries to limit single events laterally.

   It has not been possible to map the deposits within the deep basin region relative to the surrounding areas due to the low grid density. However, assuming that the sediments were transported from an east-southeast direction, the western flank of the region would act as a threshold or barrier for the sediments deposited there (Figure 4-39 A). Repeated mass transport events from the east-southeast could result in increased deformation of the sediments in the west toward the lateral margin of the deep basin region. This could thus explain the generally increasing amount of chaotic facies in unit Te4 toward the southwest in the deep basin region.

3) The dominance of chaotic seismic facies in the plateau region, bounded mainly by the BLM reflection at the base and the R7 reflection at the top, indicates that downslope-transported sediments affect also this part of the proximal Lofoten Basin. The domination of chaotic seismic facies throughout the unit in most areas favors the interpretation that this part of unit Te4 is composed of one single slide event extending far into the Lofoten Basin. Folded and thrusted reflections observed in the unit have been related to the toe domain of slide deposits (Bull et al., 2009a; Safronova et al., 2015). The unit identified in the plateau region is probably part of the upper part of the mass transport complex in the deep basin region. However, the exact relation between this part of unit Te4 and the mass transport complex and the lateral margin in the northeast is not clear because of the chaotic nature of the reflections in the area. The lack of a clear termination of the chaotic facies in the unit in the southwest (Figure 4-24), until the thickness decreases to below ½λ indicates that the slide unit extends beyond this point and probably a little further into the distal Lofoten Basin.

5 DISCUSSION

This chapter comprises a discussion on the sedimentary processes and the paleoenvironment during the deposition of the seismic units Te1-Te4. The discussion will start with the oldest deposits in the study area, the Eocene succession. A similar discussion follows for the Oligocene and Miocene deposits. Then, the continuation of contourite drift growth into during GI time and the mega-failure in the central part of the BITMF will be discussed.

5.1 EOCENE SEDIMENTARY PROCESSES AND PALEO ENVIRONMENT

The VVP was located in the western flank of a fault bounded terrace during the deposition of unit Te1 (Eidvin et al., 2014). The land masses of Fennoscandia, Greenland and Svalbard were located adjacent to each other (Faleide et al., 2008), and an epicontinental sea was present in the area until early Eocene (Sættem et al., 1994). Marine conditions probably prevailed in the VVP area throughout the Eocene (Sættem et al., 1994; Eidvin et al., 1998; 2014). The sedimentary environment in the rifted VVP area, which was an intracratonic pull-apart basin in a tectonically complex area, has probably been quite different from the young Lofoten Basin, developing to a deep-sea basin in the south.

5.1.1 The unit Te1 in the Vestbakken Volcanic Province

The prograding clinoforms on the continental slope, dipping in a westerly direction, indicate that the VVP area received sediments from the east during the deposition of unit Te1. The length of the clinoforms, covering several kilometres, indicates that unit Te1 represent shelf-margin clinoforms rather than deltaic clinoforms (Johannessen & Steel, 2005). The westward progradation of the clinoforms gradually filled the local basin. The eastern source of the sediments deposited in the VVP area is probably the uplifted Stappen High to the east. Tectonic movements along the margin during the Eocene caused uplift of the Stappen High (Sættem et al., 1994). Simultaneously, the rifted setting in the VVP area resulted in downfaulting and rapid subsidence in the area and allowed for the formation of local basins west of the Stappen High (Sættem et al., 1994; Faleide et al., 2008).

The Stappen High was suggested as the source area for sediments deposited in the VVP area by Sættem et al. (1994) and Faleide et al. (1993). This is in consistency with the observed westerly prograding pattern in unit Te1. No other eastern nor southern plausible source to these sediments was present in the margin at the time. A source from the west is also not likely here, since a western source would result in clinoforms with a more easterly dip, which have not been observed. The results presented here and in previous studies favour the Stappen High as the sediment source for the deposition of unit Te1.

The deposition of shelf-margin clinoforms indicates an open marine depositional environment during the deposition of unit Te1. Eidvin et al. (1998) suggested that much of unit Te1 in the VVP was deposited in relatively deep and open marine environment. The interpretation was based on studies of microfossils in well 7316/5-1. Muddy sediments dominated, and they suggested an outer to middle shelf environment for the deposition of the unit, including a shallow marine environment for the upper part (Eidvin et al., 1998). The suggested marine conditions in the area have been supported by for example Nøttvedt et al. (1988), Sættem et al. (1994) and (Ryseth et al., 2003). The shallower marine environment toward the end of the period may be due to the infilling of the basin of the thick unit Te1.

The faults and rotated of fault blocks in the VVP area are suggested to relate to tectonic activity. Faults appearing both in unit Te1 and across the Eocene-Oligocene boundary indicate that the formation of these structures occurred during both the Eocene and the Oligocene. The rotated fault blocks may be related to the differential stress that have been applied to the VVP area. Fault zones bounding the VVP terrace to the west have been active during the Eocene-Oligocene (Faleide et al., 1993; Sættem et al., 1994). The extensive downfaulting of the VVP area during the Eocene (Faleide et al., 1993; Sættem et al., 1994) and subsequent reorganization in the spreading direction in the Eocene-Oligocene transition (Faleide et al., 1993; Sættem et al., 1994) may have caused faulting and rotation of the fault blocks.

Eidvin et al. (1998) interpreted the deposits in well 7316/5-1 in the VVP to be of middle Eocene age. The upper middle Eocene and the upper Eocene sediments are missing, representing a hiatus. They found the unconformity to be related to uplift and rotation. The sediments in the area were raised above the wave base, and erosion and non-deposition dominated. The hiatus is suggested to have an age of 45-34 Ma (Eidvin et al., 1998). This indicates that the sediments in unit Te1 are of middle Eocene age. However, due to the prograding pattern in the unit, the sediments deposited toward the west are younger than those deposited close to the well. The angular unconformity and the missing Upper Eocene succession may be related to the downfaulting and rotation of fault blocks during the plate tectonic reorganization in the Early Oligocene (Eidvin et al., 1998), as will be discussed in the Oligocene section.

Summary – sedimentary environment:

The prograding clinoforms in the VVP area were deposited on top of Early Eocene lava flows during the middle Eocene, and g filled the local pull-apart basin. The sediments were sourced from the Stappen High to the east, and were probably deposited in a marine environment varying between outer and middle shelf. The water depth may have changed from deeper water in the lower part of the unit to more shallow conditions in the upper part, and the shallowing may be related to the gradual infilling of the basin. Tectonic movements during Eocene-Oligocene along with the change in spreading direction in early Oligocene probably contributed to faulting and rotation of the small fault blocks in the upper continental slope. The upper middle Eocene and upper Eocene sediments are missing in the VVP. The missing upper part of the Eocene unit is probably related to tectonic movements in the area during the Eocene-Early Oligocene, which resulted in erosion and non-deposition. The suggested sedimentary environment during the deposition of unit Te1 in the VVP area is shown in Figure 5-1.

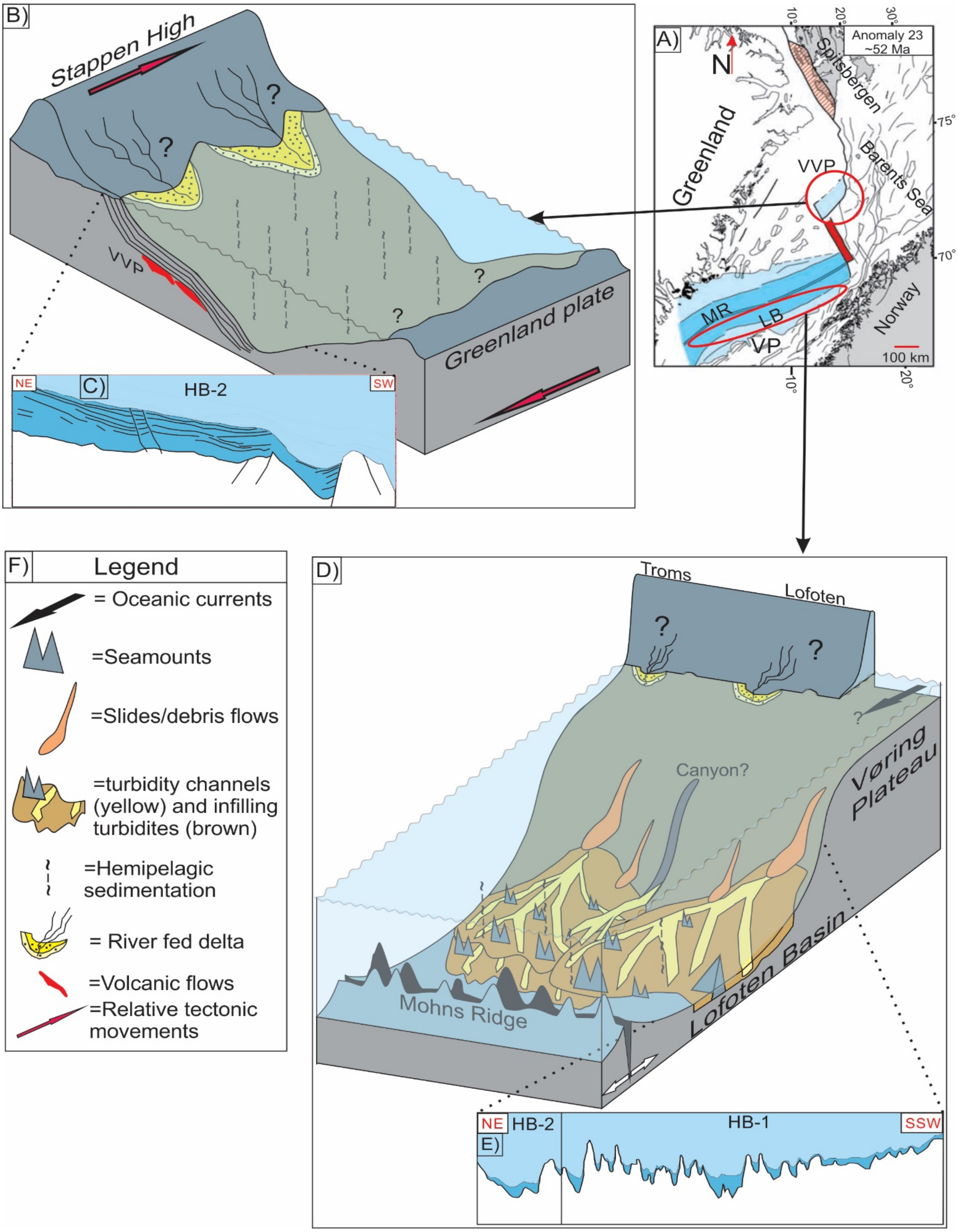


Figure 5-1: The sedimentary environment inferred to dominate during the deposition of unit Te1. The location and extent of the VVP area and the Lofoten Basin are shown in A). The dominating sedimentary environment is shown in B) for the VVP area and D) for the Lofoten Basin. Question marks indicate uncertainties regarding relative sea level and potential terrestrial processes. The respective geoseismic profiles are shown in C) and E). A legend is shown in F). VPP: Vestbakken Volcanic Province, MR: Mohns Ridge, LB: Lofoten Basin, VP: Vøring Plateau. A) is modified from Faleide et al., (2008).

5.1.2 The unit Te1 in the Lofoten Basin

The seismic data available do not cover the COB of the southern part of the study area. The sea floor spreading in this area initiated with an opening of the southernmost part of the Lofoten Basin (Figure 5-1 A). As the spreading proceeded, the width of the Lofoten Basin increased in the direction of spreading while the eastern termination of the Mohns spreading ridge moved in a north-northwest direction along the Senja Fracture Zone (Faleide et al., 1993). The location of the Lofoten Basin relative to the VVP area during the Eocene rules out the VVP area and the Stappen High as a sediment source for the Lofoten Basin during the Eocene (Figure 5-1 A). Sediments transported southward from the Stappen High were probably trapped in the Sørvestnaget Basin. The interpretation that turbidites dominate unit Te1 in the (Eocene) Lofoten Basin indicates that these sediments were derived from the surrounding margins.

Gravity driven mass flow deposits are suggested to have deposited on the southern part of the Lofoten Basin first. In the near-slope areas, slides and debris flow deposits may have accumulated, interpreted from the transparent character of unit Te1 also in the south of the Lofoten Basin. An acoustically transparent seismic signature caused by deformational homogenization often characterizes debris flow deposits (Laberg & Vorren, 1995; Lee et al., 2007). Therefore, mass flow events like debris flows are more likely to be the origin of these sediments rather than slides. Slides are commonly related to the movement of more rigid, internally un-deformed masses (Lee et al., 2007).

As the low-relief southern part of the Lofoten Basin was infilled, turbidity currents could flow further northward into the Lofoten Basin without being obstructed by the relief of the basement. Turbidity currents may flow up to hundreds of kilometres and deposit sediments on the abyssal plain while debris flows generally have shorter run-out distance and commonly deposit in more proximal areas to the sediment source (Lee et al., 2007). Laberg and Vorren (2000b) stated that debris flows in the BITMF were transported up to 200 km downslope and deposited in the abyssal plain. However, these debris flows moved down a low-gradient slope, less than 1°, with a very small gradient in the transition to the abyssal plain. The southern margin of the Lofoten Basin has, in contrast, a relatively steep slope with up to 10° inclination and a more abrupt transition to the rise and abyssal plain.

Turbidity currents are thus suggested to be the origin of the sediments deposited in the distal areas of the Eocene Lofoten Basin, while the more proximal areas may contain sediments deposited from various mass flow processes. Turbidites may disintegrate from the mass flow events occurring closer to the margin (Lee et al., 2007). Disintegration of slides and debris flows have been reported by for example Bryn et al. (2005b) and Safronova et al. (2015). The disintegration of a slide into debris flow and turbidity current is shown in a concept model in Figure 5-2.

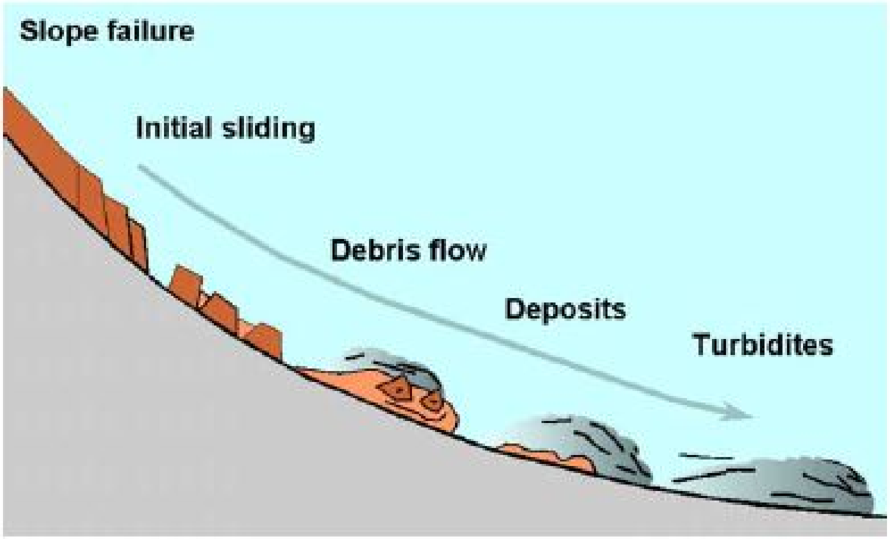


Figure 5-2: The disintegration of a slope failure, from slide to debris flow, and last to turbidity current that deposits turbidites, is shown in a concept sketch. The sketch is from Bryn et al. (2005b).

Dependent on the strength and pattern of the ocean circulation in the area during this period, suspended material from the Greenland continental margin might have reached the Lofoten Basin during the Eocene. The circulation pattern in the area is however uncertain. Laberg et al. (2005b) concluded that the Paleogene ocean circulation system in the area of the Vøring Plateau southwest of the Lofoten Basin was interbasinal or intrabasinal. They could not discriminate between the two options of the interbasinal circulation being restricted to the Norwegian-Greenland Sea, or if an intrabasinal circulation was somehow connected to the North Atlantic Ocean. They found however that the Eocene sedimentation in the Vøring Plateau was influenced by ocean currents.

The narrow shelf along the southern margin of the Lofoten Basin resulted in a short transport distance for sediments from the terrestrial Lofoten-Troms margin to the shelf break and the continental slope. The sea level relative to the margin off Lofoten-Troms during the Eocene is not known. A low relative sea-level could enhance the sediment transport from the shore to the shelf break as river borne sediments might bypass parts of or the entire shelf, and erosion of shelf deposits might be possible (Safronova et al., 2015). The combination of a steep, terrestrial Lofoten-Troms hinterland, a short transport distance across the continental shelf and the steep continental slope favours a relatively high influx of sediments to the shelf-slope system, and may have developed conditions favourable to mass flow events to occur.

According to Lee et al. (2007), tectonic activity may represent an external trigger to slope failures. Seismic activity has been suggested to be the external trigger for slope failures along the Norwegian-Barents Sea margin (for example Hjelstuen et al. (2007) and Safronova et al. (2015)). The nearby Mohns spreading ridge may have caused tectonic activity that triggered slope failures along the Lofoten margin.

The high relief of the Mohns spreading ridge would probably prevent sediments transported down the northeast Greenland continental slope from crossing the spreading ridge and accumulate in the Lofoten Basin. Thus, the most likely source for sediments deposited from downslope processes would be the southern margin of the Lofoten Basin, the Lofoten-Troms margin. As the spreading ridge moved north along the Senja Fracture Zone, sediments might have been shed into the eastern part of the Lofoten Basin from the very southwest Barents Sea margin.

The Eocene sediment distribution in the Lofoten Basin, showing deposits of similar level and similar seismic appearance on both sides of the highs indicates that the highs generally are single seamounts rather than ridges. Ridges transverse to the direction of sediment transport would probably leave the lee-side of the ridge with less sediments and possibly other seismic expression here, as other processes would dominate.

Even though the oceanic current system in the area probably was restricted during the Eocene, sediments in the area were probably affected by oceanic current flowing north. Ocean-current influenced sedimentation probably prevailed on the outer part of the Vøring Plateau during the Eocene (Laberg et al., 2005b). The current flowed north past the area and probably entered the Lofoten Basin to the north. Shallow marine conditions probably existed on the inner Vøring Plateau (Laberg et al., 2005b). The shallow marine conditions and the north-flowing current may have contributed to the deposition of sediments on the northern slope of the Vøring Plateau. The Vøring Plateau area may thus have acted as a source to sediments during the Eocene.

A number of canyons with an incision up to 1100 meters cut the modern southern margin of the Lofoten Basin (Haflidason et al., 2007; Rise et al., 2013; Rydningen et al., 2015). Thick units of submarine slides and fan deposits interbedded with hemipelagic and turbidite deposits are deposited at the continental rise at the outlet of the canyons (Haflidason et al. 2007). The development of the canyon systems is inferred to have initiated during middle Miocene (Rise et al., 2013). The formation of canyon systems on the southern margin of the Lofoten Basin shows that the margin had potential for slope failure and subsequent deposition of mass flow transported sediments in the Lofoten Basin.

Summary – sedimentary environment:

Sediments deposited in the Lofoten Basin during the Eocene was infilling the high relief of the irregular oceanic basement. The infilling of theses sediments was mainly driven by the downslope transport of sediments, probably disintegrating from slides and debris flows in the near-slope areas to turbidites in the more distal parts. Turbidity currents have distributed the sediments across the Lofoten Basin. The sediments were mainly sourced from the southern margin of the Lofoten Basin, the Lofoten-Troms margin. Oceanic currents were present in the Vøring Plateau southwest of the Lofoten Basin. North-flowing oceanic currents may have eroded sediments in the Vøring Plateau area and transported these to the southern margin of the Lofoten Basin. The suggested sedimentary environment during the deposition of unit Te1 in the Lofoten Basin is shown in Figure 5-1.

5.2 OLIGOCENE SEDIMENTARY PROCESSES AND PALEO ENVIRONMENT

By the beginning of the Oligocene, the Mohns spreading Ridge had not yet migrated north-northwest-wards the full length of the Senja Fracture Zone south of the VVP (Faleide et al., 1993). A major plate tectonic reorganization took place during early Oligocene, when the orientation of the relative motion between Greenland and Norway changed from a NNW direction to WNW direction (Faleide et al., 1988). The tectonic reorganization was followed by the onset of formation of oceanic crust north of the VVP (Faleide et al., 1993; Faleide et al., 2008). The location of the Mohns Ridge indicates that the Lofoten Basin was not directly connected with the VVP during the early Oligocene as shown by the seismic data available, where Oligocene sediments are interpreted not to be present beyond the COB (Figure 4-16).

5.2.1 The unit Te2 in the Vestbakken Volcanic Province

Unit Te2 is thin on the continental slope. The base Oligocene reflection represents a regional, prominent boundary along the southwest Barents Sea margin and has been suggested to reflect the reorganization of spreading poles during the early Oligocene (Faleide et al., 1988; Ryseth et al., 2003; Eidvin et al., 2014). The erosion of the underlying unit Te1 is most easily observed downslope the mounded contourite drift deposits across the threshold where unit Te1 thins (Figure 4-16). Eidvin et al. (2014) commented that the base Oligocene in the VVP area east of well 7316/5-1 (and east of the termination of the seismic data in this study) represents an angular unconformity where it truncates the underlying strongly faulted and folded Eocene sequence. The erosional character of the base Oligocene observed downslope the drift deposits is suggested to reflect the mentioned reorganization of plate motion during early Oligocene. The erosional character is probably related to the sub-aerial exposure of the area from the early Oligocene, caused by tectonic uplift (Sættem et al., 1994) and a probable fall in the global sea level (Sættem et al., 1994; Eidvin et al., 2014). The lowering of the global eustatic sea level followed growing ice sheets in the Antarctica and possibly in Greenland (Eidvin et al., 2014). Eidvin et al. (1998); (2014) suggested that the late Oligocene – early Miocene succession was eroded and/or condensed, and that the lowering of the global eustatic sea level may have played a role in the deposition/non-deposition or erosion of the Oligocene unit. The increasing influence of oceanic currents along the Norwegian margin (Davies et al., 2001; Laberg et al., 2005b and Hjelstuen et al., 2007) may also partly be related to the thin and eroded unit. However, the influence of oceanic currents in along the southwest Barents Sea margin during the Oligocene is uncertain.

Unit Te2 thickens in the local basin upslope the marginal high, which may indicate deposition of eroded sediments here. As mentioned earlier, the marginal high described in the area is not observed to continue as a high toward the north, and the southern extent is unknown. A passageway for the eroded Eocene sediments north or south of the marginal high could be possible. However, the possibility of a northern route would depend on the location of the spreading ridge at the time. The southern route might lead to the northeast part of the progressively opening Lofoten Basin.

Faults extending across the Eocene-Oligocene boundary and interpreted to terminate within unit Te2 indicate an Oligocene age of many of the faults in the area. Following the plate tectonic reorganization in the early Oligocene, the VVP was subject to renewed downfaulting and regional subsidence (Faleide et al., 1988).

Summary – sedimentary environment:

The VVP was subject to renewed tectonic movements with downfaulting, subsidence and rotation during the Oligocene. The tectonic movements are reflected in faults and rotation of fault blocks on the upper slope around well 7316/5-1. The thin unit Te2 has been eroded, and may also be condensed as suggested by Eidvin et al. (2014). Erosion during the Oligocene was probably due to the lowering global eustatic sea level and sub-aerial exposure of the area from early Oligocene. Downslope the mounded contourite drift deposits, erosion of the underlying Eocene sediments across a threshold occurred during the Oligocene. The Eocene eroded sediments were probably transported downslope, possibly past the marginal high and deeper into the intracratonic basin. The suggested sedimentary environment during the deposition of unit Te2 in the VVP area is shown in Figure 5-3.

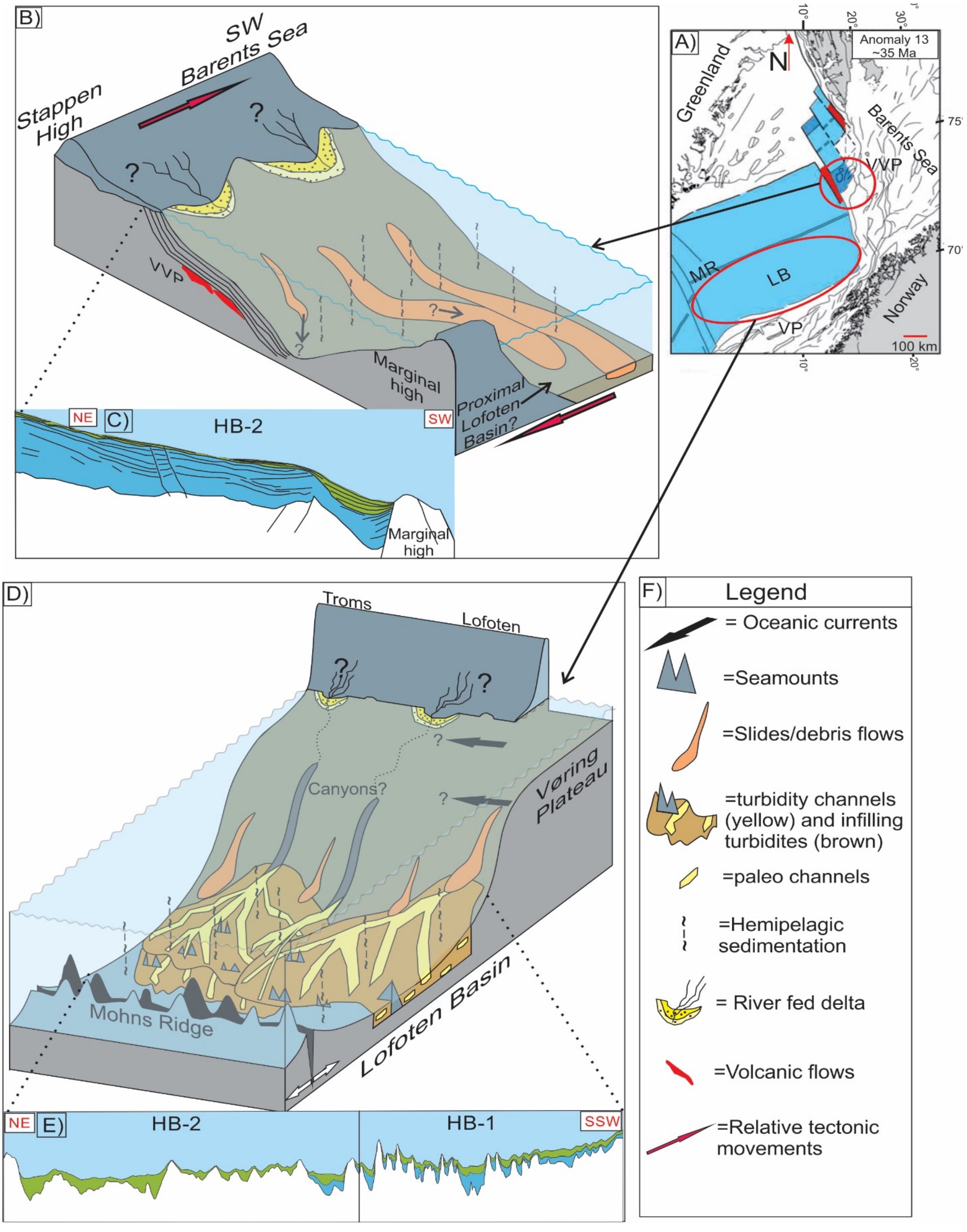


Figure 5-3: The sedimentary environment inferred to dominate during the deposition of unit Te2. The location and extent of the VVP area and the Lofoten Basin are shown in A). The dominating sedimentary environment is shown in B) for the VVP area and D) for the Lofoten Basin. Question marks indicate uncertainties regarding relative sea level and potential terrestrial processes. The respective geoseismic profiles are shown in C) and E). A legend is shown in F). VPP: Vestbakken Volcanic Province, MR: Mohns Ridge, LB: Lofoten Basin, VP: Vøring Plateau. A) is modified from Faleide et al., (2008).

5.2.2 The unit Te2 in the Lofoten Basin

The seismic facies dominating in unit Te2 in the distal and the proximal Lofoten Basin show some variations. While the seismic facies in the distal Lofoten Basin varies laterally between generally chaotic to transparent and discontinuous reflections, the seismic facies in the proximal Lofoten Basin is dominated by chaotic to transparent seismic facies. Though the seismic facies differs, a similar depositional environment for the two areas is suggested, as will be discussed below.

After the infill of Eocene sediments in the distal Lofoten Basin, only the higher peaks were still above the paleo sea floor. All the lower relief highs had been smoothed out by the Eocene sediments. The subsequent infilling is suggested to have been less influenced by the relief, therefore the Oligocene unit was deposited as mainly continuous unit in the distal Lofoten Basin. The subsequent loading by thick deposits have probably resulted in post-depositional deformation and disruption of the Oligocene reflections to discontinuous, sometimes appearing as polygonal faults, as discussed previously.

The seismic facies in unit Te2 in the proximal Lofoten Basin shows a similar character as seen in unit Te1 in the distal Lofoten Basin. The chaotic to transparent reflections indicates that these sediments were deposited by downslope processes. A high grade of deformation of the deposited sediments is suggested due to the chaotic to transparent seismic character, related to the downslope disintegration from slides/slumps and debris flows to turbidity currents (Laberg & Vorren, 1995; Lee et al., 2007; Safronova et al., 2015). Thus, turbidity currents are inferred to dominate also the proximal Lofoten Basin during the Oligocene.

Although unit Te2 in the distal Lofoten Basin probably was deposited as a continuous unit initially, the clear infilling of local basins where the relief increases toward the northeast supports the suggestion above that these sediments were deposited in a regime dominated by gravity driven processes, mainly turbidites, as also discussed for the Eocene unit. In all of the Lofoten Basin, the same tilted onlapping reflections to the highs appear here as in unit Te1 below, and the infilling deposits generally show a convex down shape. The tilted onlapping relations and the convex down shape is inferred to represent subsidence of the unit due to post-depositional loading and deformation. Polygonal faults were observed in the deep basin region of the proximal Lofoten Basin, probably also representing post-depositional deformation due to rapid loading and compaction.

Unit Te2 in the proximal Lofoten Basin is thick in the deep basin region and thin in the plateau region. The sub-horizontal upper boundary of unit Te2 remains little affected relative to the basement morphology in both regions, supporting the suggested infilling style of deposition. The morphological setting, with a plateau and a deep basin located adjacent to each other, may explain the difference in the unit thickness in the two areas. Due to the inferred domination of gravity flows, a higher sedimentation rate is suggested to have existed in the deep basin region relative to the plateau region. This is because gravity flows would seek to the lower areas.

In addition to the dominating gravity flow deposits, increasing oceanic current circulation during the Oligocene may have affected the sediments deposited. A mounded reflection pattern related to alongslope processes have not been observed in unit Te2. However, Hjelstuen et al. (2007), with other datasets available, suggested that the pre-glacial sediments in the Lofoten Basin possibly were affected by alongslope processes. The observations of Laberg et al. (2005b), that interbasinal or intrabasinal circulation systems were present in the Vøring Plateau area from the Eocene and a current flowing north at the time must be taken into account. In addition, Davies et al. (2001) indicated that the initiation of deep-water circulation between the Norwegian-Greenland Sea and the North Atlantic occurred already during the early Oligocene. Thus, the possibility that ocean currents have affected the Oligocene sediments in the Lofoten Basin cannot be ruled out.

The main source of sediments deposited in the abyssal distal Lofoten Basin is still suggested to be the Lofoten margin south of the Lofoten Basin. The slight thinning of the unit in the deep, wide basin in the transition between the distal and proximal Lofoten Basin as mentioned above, is suggested to reflect an increasing distance from the southern sedimentary source. The turbidites deposited in the proximal Lofoten Basin are suggested to be sourced from the southwestern Barents Sea margin and the Troms margin. The long distance to the Lofoten margin probably does not discriminate the area as a source to sediments deposited here. As no seismic lines are available for the southern / south-eastern Lofoten Basin, the morphology of the oceanic basement in that area is difficult to predict, and the extent of the deep basin region and plateau region in that direction is unknown. The slope gradient was probably steeper than that of today, as the massive sediment input during Plio-Pleistocene and the following progradation of the shelf and slope had yet not started (Vorren et al., 1991 and Faleide et al., 1996). The margins located closer to the proximal Lofoten Basin are favoured as source areas because of the shorter distance.

Summary – sedimentary environment:

The sedimentary environment in the dep marine Lofoten Basin was dominated by gravity flows. The infilling of the Lofoten Basin relief continued during the Oligocene, where turbidity currents probably dominated the depositional environment. However, oceanic currents are expected to increase their influence during the Oligocene and may have played a role in the deposition of the unit. This is best reflected in the distal Lofoten Basin, where (inferred) initially continuous reflections are suggested to represent an interaction between turbidity flows and ocean currents. The continuous reflections were later deformed by compaction to discontinuous/disrupted, including polygonal faults. Similar deformation of reflections that initially were deposited continuously was also observed in the deep basin region.

The Troms margin and southwest Barents Sea margin are expected to dominate as source areas for the sediments deposited in the proximal Lofoten basin in the northeast, while the Lofoten-Troms margin in the south probably still sourced the distal Lofoten Basin in the south-southwest. A particularly deep area, the deep basin region, was interpreted to act as a sediment trap and contains a thick Oligocene unit compared to the rest of the Lofoten Basin. The suggested sedimentary environment during the deposition of unit Te2 in the Lofoten Basin is shown in Figure 5-3.

The sedimentary processes inferred to have dominated in the Lofoten Basin during the Oligocene is different from that suggested by Hjelstuen et al., (2007), i.e. that the glacial successions in the Lofoten Basin rests on Miocene-Oligocene hemipelagic oozes.

5.3 EARLY – MIDDLE MIOCENE SEDIMENTARY PROCESSES AND PALEO ENVIRONMENT

During the Miocene, the Mohns Ridge had migrated north past the study area and a continental margin with a shelf-slope-basin setting was developed along the entire western Barents Sea. The oceanic current system is inferred to have developed to the present during the Late Oligocene-Middle Miocene, and this is suggested to have initiated the massive increase in contourite drift formation in the Norwegian-Greenland Sea.

5.3.1 The unit Te3 in the continental slope

Unit Te3 is observed to be eroded on the upper continental slope where it is penetrated by well 7316/5-1 (Figure 4-15). A thin unit is observed downslope until again truncated by the overlying seismic unit GI. The erosion west of the well location and thickening of the unit toward the east gives the unit a wedge-shape.

Unit Te3 represents the lower of several sub-units composing a mounded drift, and the base Miocene reflection is suggested to represent the initiation of contourite drift growth. A sketch showing the initiation and early development of the contourite drift is shown in Figure 5-4. The timing of this is in consistency with other studies south of the study area (Laberg et al., 1999; Bryn et al., 2005; Laberg et al., 2005a). The contourite drift located in the Vestnesa Ridge northwest of Svalbard have an assumed age of post late Miocene (Hustoft et al., 2009). No other contourite drifts have previously been described for the western Barents Sea continental margin. The age of the unit Te3 sediments in the contourite drift is not known.

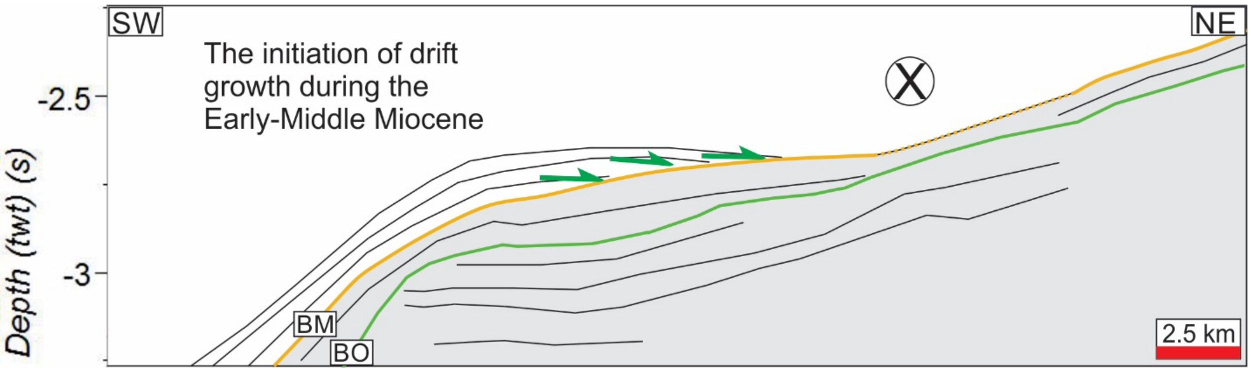


Figure 5-4: The sketch illustrates the initiation of drift growth during the early-middle Miocene, with internal seismic reflections downlapping to the base Miocene reflection. Green arrows indicate downlapping. Circle with an X indicates flow direction away from reader.

The age of the contourite drift cannot be estimated based on the dating of sediments in well 7316/5-1, as no reflections can be mapped downslope to within the contourite deposits due to the erosion of the unit on the slope. A middle Miocene age for the initiation of drift growth is therefore suggested based on the estimated ages for the initiation of drift growth described from the Mid-Norway - Lofoten margin (middle Miocene; Bryn et al., 2005; Laberg et al., 2005a)) and the Vestnesa Ridge area (post late Miocene; Hustoft et al., 2009)), i.e. south and north of the study area, respectively.

On the lower continental slope, downslope the marginal high, a vertical shift in the seismic facies was observed close to the level of the local highs in the area (Figure 4-19). The seismic facies in the deeper local basins favoured an infilling style of deposition, suggested to be dominated by gravity mass flow deposits like debris flows and/or turbidites, as discussed also for the older units Te1 and Te2 in other areas. This was found to be possible because the marginal high does not extend to the north, thus allowing for downslope transport of sediments which infilled the basins. At the level of the local highs in the lower continental slope, the facies changed up to more continuous and parallel reflections. This facies was suggested to represent hemipelagic sedimentation and/or sediments deposited by alongslope flowing oceanic currents.

It is suggested here that the change in seismic facies downslope the marginal high reflects the change from a domination of mass flow deposits in the lower part and up to sediments deposited by alongslope and hemipelagic processes. The facies change thus also represents the onset of drift growth recorded higher up on the slope. This implies that the chaotic to transparent sediments in the lower continental slope are older than the contourite drift, and that they thus were deposited in an environment dominated by downslope processes prior to the onset of drift growth. These sediments may have been derived by erosion from the upper continental slope due to the tectonic movement in the area and transported downslope, bypassed the marginal high and deposited as infilling mass flow deposits in the deeper areas of the oceanic basement. Subsequently, alongslope and hemipelagic processes dominated in the area and deposited on top of the mass flow deposits throughout unit Te3.

Eidvin et al. (1998) and Eidvin et al. (2014) has described erosion of sediments of Miocene age in the VVP area. They suggested that the truncation of the unit and the thickening of the unit toward the east were related to the tectonic movements in the area and to subsidence and deposition along fracture zones to the east. They also suggested condensing of the unit to be a possible explanation for the thin unit in the VVP area. Eidvin et al. (1998) further suggested that the Miocene sediments observed in well 7316/5-1 are of Lower Miocene age, and that they were deposited on the middle to outer shelf in open marine environments. Unit Te3 is observed to be of similar thickness and seismic appearance in the entire VVP area, and the extent of the unit is found to be too sparse to give a relevant discussion on other possibilities for the depositional environment than suggested by Eidvin et al. (1998) and Eidvin et al. (2014).

Summary – sedimentary environment

The sedimentary environment on the continental slope during the deposition of unit Te3 is suggested to be dominated by low sedimentation rate and non-deposition/erosion in marine conditions in a shelf setting. Sediments deposited in the VVP area and downslope towards the west may have been eroded and transported downslope past the marginal high to be deposited in the deeper parts of the newly forming oceanic basement here. Towards the middle Miocene, the erosion and the deposition of mass flow transported sediments decreased and the oceanic current circulation system increased in strength. Alongslope processes increased their influence of the depositional environment. This is indicated by the base Miocene, which is inferred to represent the onset of drift growth in the area. Alongslope and hemipelagic processes probably dominated the sedimentary environment in the continental slope throughout the early-middle Miocene. The suggested sedimentary environment during the deposition of unit Te3 in the continental slope is shown in Figure 5-5.

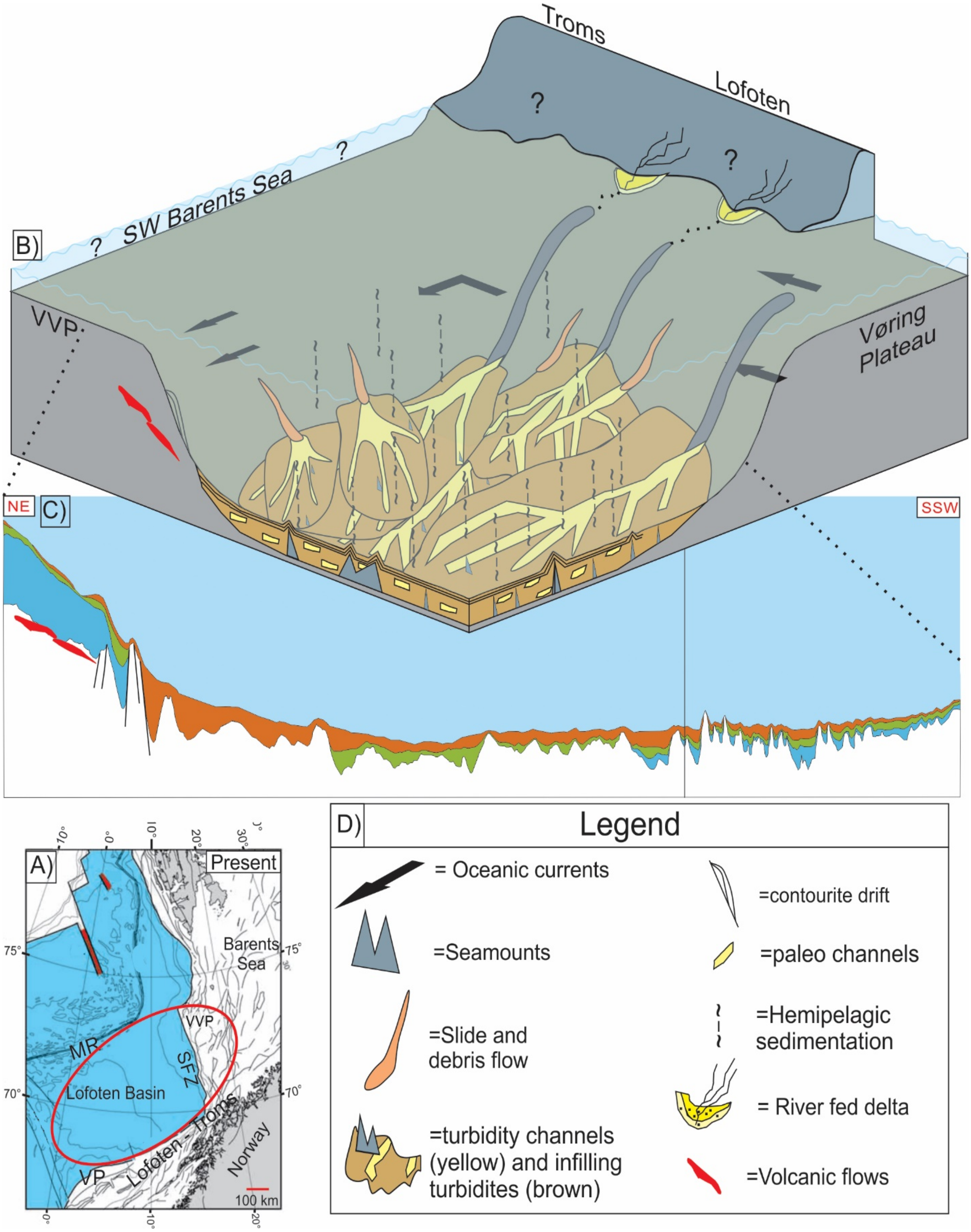


Figure 5-5: The sedimentary environment inferred to dominate in the SW Barents Sea margin – Lofoten Basin during the deposition of unit Te3. The location of the area is shown in A). The dominating sedimentary processes and depositional environment are shown in B) Question marks indicate uncertainties regarding relative sea level and potential terrestrial processes. A geoseismic profile from the SW Barents Sea margin to the Lofoten Basin is shown in C). The legend is shown in D). VVP: Vestbakken Volcanic Province, SFZ: Senja Fracture Zone, MR: Mohns Ridge, VP: Vøring Plateau. A) is modified from Faleide et al. (2008).

5.3.2 The unit Te3 in the Lofoten Basin

The unit Te3 has a relatively uniform thickness across the Lofoten Basin and is little affected by the underlying basement topography. However, it gradually thins toward the southwest. Two facies changes are observed to occur in unit Te3.

First, the facies change from the chaotic to transparent seismic facies in unit Te2, to the transparent facies with increasing continuity in the lower part of unit Te3 (Figure 4-23). This lower part of unit Te3 is observed to mainly infill the basement relief. The facies change is observed in most of the Lofoten Basin. Second, the facies change occurring internally in unit Te3, to dominating continuous reflections draping the underlying strata and basement highs in the upper part of unit Te3 (Figure 4-23). The internal unit Te3 facies change is observable across the entire Lofoten Basin, except in the rise to the Vøring Plateau.

It is suggested that the first facies change, across the boundary between unit Te2 and Te3, represents a change to less domination of mass flow deposits. The result is less deformed deposits and reflections that are more continuous. Deposition on top of the already smoothed relief may also have contributed to the decreasing deformation of deposits and increasing continuity of reflections in this part of unit Te3, as discussed also for unit Te2 where it overlies unit Te1 in the distal Lofoten Basin. This means that the influence of mass flow deposits decreased, and hemipelagic processes and bottom currents probably have had a greater influence in the depositional environment in the lower part of unit Te3 than for unit Te2.

IRD deposited in the Lofoten Basin might contribute to the laminated strata observed in the upper part of unit Te3. IRD dated to about 12.6 Ma were observed in cores from the Vøring Plateau. The IRD occurrences coincided with the intensification and reorganization of oceanic circulation patterns at the time and a general decrease in air temperature (Fronval & Jansen, 1996). Oceanic currents flowing north from the Vøring Plateau may potentially have brought icebergs to the Lofoten Basin. The eventual amount of IRD deposited here is however unknown.

The second facies change, occurring within unit Te3, is suggested to represent a major change in the depositional environment in the Lofoten Basin. The facies change is observed in all parts of the Lofoten Basin, often more distinct in wide and deep, local basins (Figure 4-24). The facies change is supplemented with a transition to draping of the basement relief and underlying strata, from the infilling style of deposition observed in the lower part of the unit, and in particular in most of units Te1 and Te2 in the Lofoten Basin. The internal seismic facies change within unit Te3 is suggested to represent a final transition from the domination of mass flow deposits in units

Te1 and Te2 to a sedimentary environment dominated by hemipelagic sedimentation in the upper part of unit Te3.

The inferred changes in the depositional environment may be a result of the increasing oceanic current circulation during the Miocene. As the oceanic currents increased in strength and developed to the present circulation pattern, more sediments were probably derived by erosion and winnowing of the shelf and upper slope, and more sediments may thus have been brought into suspension in the Lofoten Basin.

This is suggested to be related to the decreasing amount of mass flow deposits and increasing domination of hemipelagic and bottom currents as more sediments were brought into suspension along the margin during the early-middle Miocene. Laberg et al. (2005b) suggested that a period of non-deposition or erosion during the late Miocene-late Pliocene observed along parts of the Norwegian continental margin could be related to increasing ocean current erosion. They found that sediments may have been eroded from the outer shelf and upper slope, and were subsequently deposited in the lower part of the continental slope. It is suggested that this may be the situation here as well, however, somewhat earlier than suggested by Laberg et al. (2005b), i.e. during the middle Miocene. This is also reflected in the initiation of drift growth on the southwest Barents Sea margin, as discussed earlier. The removal of sediments from the outer shelf and upper slope may have affected the amount of gravity flows in the area. However, no seismic data has been available along the Lofoten-Troms continental shelf and upper slope, thus, the suggested cause for the facies change remains uncertain.

The discontinuous character of the seismic reflections and irregular shape of the unit within the deep basin region differ from the other parts of the Lofoten Basin at the time. The general trends observed in the Lofoten Basin during the early-middle Miocene, the facies changes and the generally even unit thickness as discussed above, are reflected also in the deep basin region. This favours an understanding that the sedimentary environment was similar in the deep basin region as in the other parts of the Lofoten Basin. Thus, local variations are suggested to cause the different appearance of the unit here.

The irregular shape of the unit is suggested to be related to differential subsidence of the basin during deposition. Displacement of reflections along a possible fault plane was observed close to the oceanic basement (Figure 4-22). Thus, the differential subsidence in the area have resulted in uneven accommodation space for the depositing sediments and a unit with a thickness varying laterally.

When it comes to the discontinuous character of the reflections, it was suggested in the interpretation that post-deposition deformational processes caused this. A probable cause for the compaction and deformation may be the inferred rapid deposition of the thick overlying unit Te4 and the subsequent deposition of seismic units GI-GIII. The discontinuous character of unit Te3 is confined to within the deep basin region where unit Te4 has an exceptionally thickness relative to other areas. Because of this limited lateral extent of the structures, it is suggested that the deposition of unit Te4 have played a role in the deformation of the unit below.

The thinning of the unit toward the southwest supports the thesis that less sediments were sourced from the southern margin and distributed via turbidity current. The main sedimentary source probably changed toward the southwest Barents Sea during the middle-Miocene.

Summary – sedimentary environment

A gradual change in the sedimentary environment from unit Te2 to unit Te3 has been indicated by a change to more continuous reflections in the lower part of unit Te3. The change is inferred to represent a gradual reduction of deformation and deposition of turbidites in the lower part of the unit. The internal, distinct facies change to parallel and continuous reflections, probably represents a major change in the depositional environment. The change probably takes place across the entire Lofoten Basin and represents the first occurrence of dominating hemipelagic and possibly bottom current processes in the pre-glacial sediments in the Lofoten Basin.

The change in depositional environment is suggested to be related to the increasing oceanic current circulation in the North-Atlantic – Greenland-Norwegian Sea. This again may have resulted in the gradual change from mainly mass flow deposition to a depositional environment dominated by hemipelagic and possibly bottom current deposits. The main source for sediments deposited in the Lofoten Basin probably changed gradually during the early-middle Miocene. A generally even sediments supply from the margins surrounding the Lofoten Basin is suggested to have fed the mass flow deposits composing the lower part of the unit across the Lofoten Basin. Toward the middle Miocene, along with the change to dominating hemipelagic processes, the main source probably changed to the southwest Barents Sea margin, reflected in the thinning unit toward the southwest. The increasing influence of oceanic currents along the margin may have induced the change of main sediment source. The suggested sedimentary environment during the deposition of unit Te3 in the Lofoten Basin is shown in Figure 5-5.

5.4 LATE MIOCENE–EARLY PLIOCENE SEDIMENTARY PROCESSES AND PALEO ENVIRONMENT

5.4.1 The unit Te4 in the continental slope

The absence of unit Te4 in the upper continental slope indicates erosion or non-deposition of the unit (Figure 4-15). Downslope, the unit makes out a sub-unit in the contourite drift (Figure 4-27), where it overlies unit Te3. A sketch showing the initiation and early development of the contourite drift is shown in Figure 5-6. A similar shape and internal reflection configuration is observed for unit Te4 as for Te3. The unit forms a sub-unit in the contourite drift, in the sense of Nielsen et al. (2008), and is observed to possibly truncate the underlying unit Te3 (Figure 5-6).

According to Nielsen et al. (2008), the presence of subunits and their internal reflection configuration in contourite drift deposits reflects smaller and commonly temporal fluctuations in the depositional environment. It is suggested that the reorganization and increasing influence of oceanic current circulation in the area may represent such fluctuations at the time. Uplift of the margin during the Miocene-Pliocene (Faleide et al., 1993; Sættem et al., 1994; Eidvin et al., 1998; Faleide et al., 2008) may also have influenced the deposition of the contourite drift.

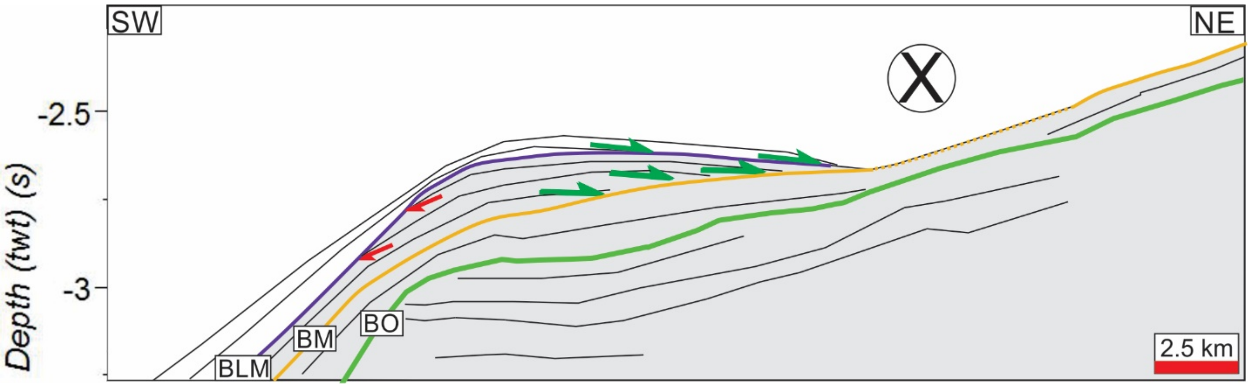


Figure 5-6: The sketch illustrates the continued drift growth during the deposition of unit Te4. Unit Te4 is thinner than unit Te3 in the contourite drift, however, also here internal reflections downlap the base of the sub-unit (BLM). Green arrows indicate downlapping, red arrows indicate truncation. Circle with an X indicate flow direction away from reader.

The unit Te4 thickens downslope the marginal high. A vertical and lateral variation between chaotic to transparent facies and continuous to discontinuous reflections dominates downslope the marginal high. Further downslope, the unit thins again towards the Lofoten Basin with increasing continuity of the internal reflections. Similarities with the below unit Te3 on the lower continental slope indicates a similar depositional environment, i.e. unit Te4is interpreted to be dominated by alongslope and hemipelagic processes.

The presence of small and larger-scale mass transport deposits distinguishes the unit Te4 from unit Te3 on the lower continental slope. Six depositional units in the north (Figure 4-33) and three depositional units in the central and southern part (Figure 4-36 and 4-39) of the study area were identified. The depositional units define a major change in the depositional environment from the Middle Miocene to the late Miocene-early Pliocene. The depositional units mapped in the north and in the central-southern part of the study area are probably representative for the entire unit Te4 in the lower continental slope. The units constitute the entire unit Te4 vertically, and have been mapped along almost the entire slope. The units extend into the Lofoten Basin in the northern parts of the study area. The extent of the units mapped in the central-southern parts of the study area is more uncertain because of the lack of seismic lines in the area.

The change in sedimentary processes, from the dominating alongslope and hemipelagic processes observed in unit Te3, to the domination of smaller and larger scale mass transport deposits in unit Te4, are suggested to reflect the increasing amount of sediments deposited by alongslope and hemipelagic processes in conjunction with an unstable slope setting and possibly external trigger.

A combination of factors promoting failure may increase the possibility for failure to occur (Laberg et al., 2000c; Lee et al., 2007; Safronova et al., 2015). The southwestern Barents Sea was subject to uplift during the Miocene-Pliocene, and the uplift was probably related to a regional event affecting larger areas of the Barents Sea shelf (Faleide et al., 1993; Sættem et al., 1994; Eidvin et al., 1998; Faleide et al., 2008). A high slope gradient (Lee et al., 2007) and earthquakes (for example Laberg et al., 2000c; Hjelstuen et al., 2007; Bull et al., 2009) resulting from the marginal uplift and general tectonic activity during the Miocene-Pliocene, and the increasing thickness of sediments deposited by alongslope processes (Bryn et al., 2005), are suggested to represent such promoting factors in the paleo slope setting during the late Miocene-early Pliocene.

The absence of the unit Te4 in the upper continental slope is in consistency with previous work in the area (Eidvin et al., 1998; Ryseth et al., 2003; Eidvin et al., 2014). The southwestern Barents Sea was subject to uplift during the Miocene-Pliocene, and the uplift was probably related to a regional event affecting larger areas of the Barents Sea shelf (Faleide et al., 1993; Sættem et al., 1994; Eidvin et al., 1998; Faleide et al., 2008). Erosion of the unit related to tectonic movements including uplift or non-deposition were presented as possible causes to explain the missing unit.

Laberg et al. (2005b) suggested that increasing ocean current erosion might explain the thin units during the Miocene. According to Rise et al. (2013), the present oceanic currents flowing northeast along the Lofoten-Vesterålen margin reach down to ~1000 meters depth, depending on seasonal variations. It has operated roughly like this since the early-middle Miocene with a winnowing effect along the shelf and upper slope (Laberg et al., 2005a) (Figure 5-7). The eroded sediments have been deposited (locally) in lower slope embayments and in slide scars (Laberg et al., 2005a).

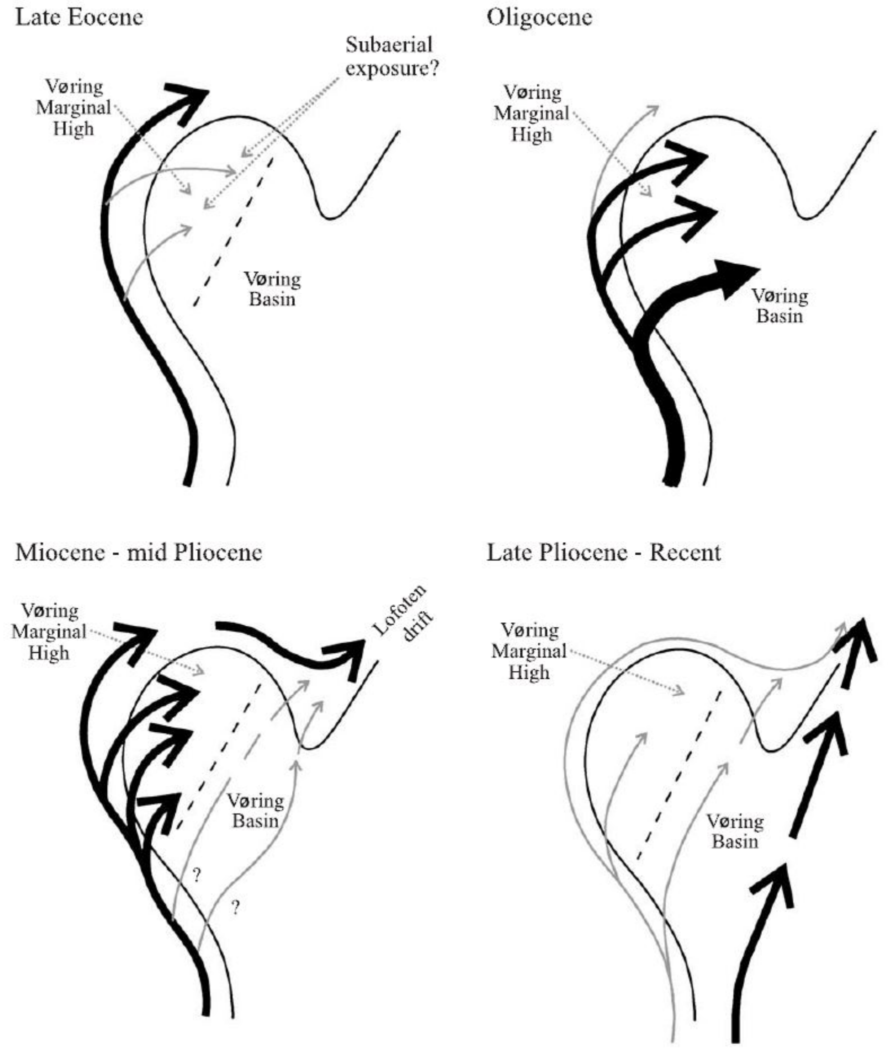


Figure 5-7: The evolution of the ocean circulation is shown for the Vøring Plateau area south of the study area, from the Eocene until present. The boldest arrows indicate currents with erosional effect, the bold arrows indicate main branches of the currents beneath which sediments were deposited, and the thin lines indicate location of minor current branches. The sketch is from Laberg et al., (2005b).

Summary – sedimentary environment

Tectonic movements and uplift of the southwest Barents Sea shelf and winnowing of the shelf and upper slope by increasing influence of oceanic currents are suggested to have caused the erosion of unit Te4 in the VVP area. Downslope, unit Te4 constitutes a sub-unit of the contourite drift in the continental slope. The sub-unit, including the truncation of unit Te3, indicates a slight, temporal reorganization in the depositional environment at the time. The increasing influence of oceanic currents at the time, possibly combined with a regional uplift, is suggested to have caused this reorganization. The unit Te4 shows a major change in the dominating sedimentary processes and depositional environment in the lower continental slope in the entire study area. The change is reflected in the dominating mass transport deposits, including both smaller scale and larger scale events. The mass transport deposits located in the northern part of the study area extends into the abyssal plain of the Lofoten Basin, while the southern extent of the depositional units is uncertain. The mass transport deposits are probably related to failures of weak layers within the contourite drift. The suggested sedimentary environment during the deposition of unit Te4 on the continental slope is shown in Figure 5-8.

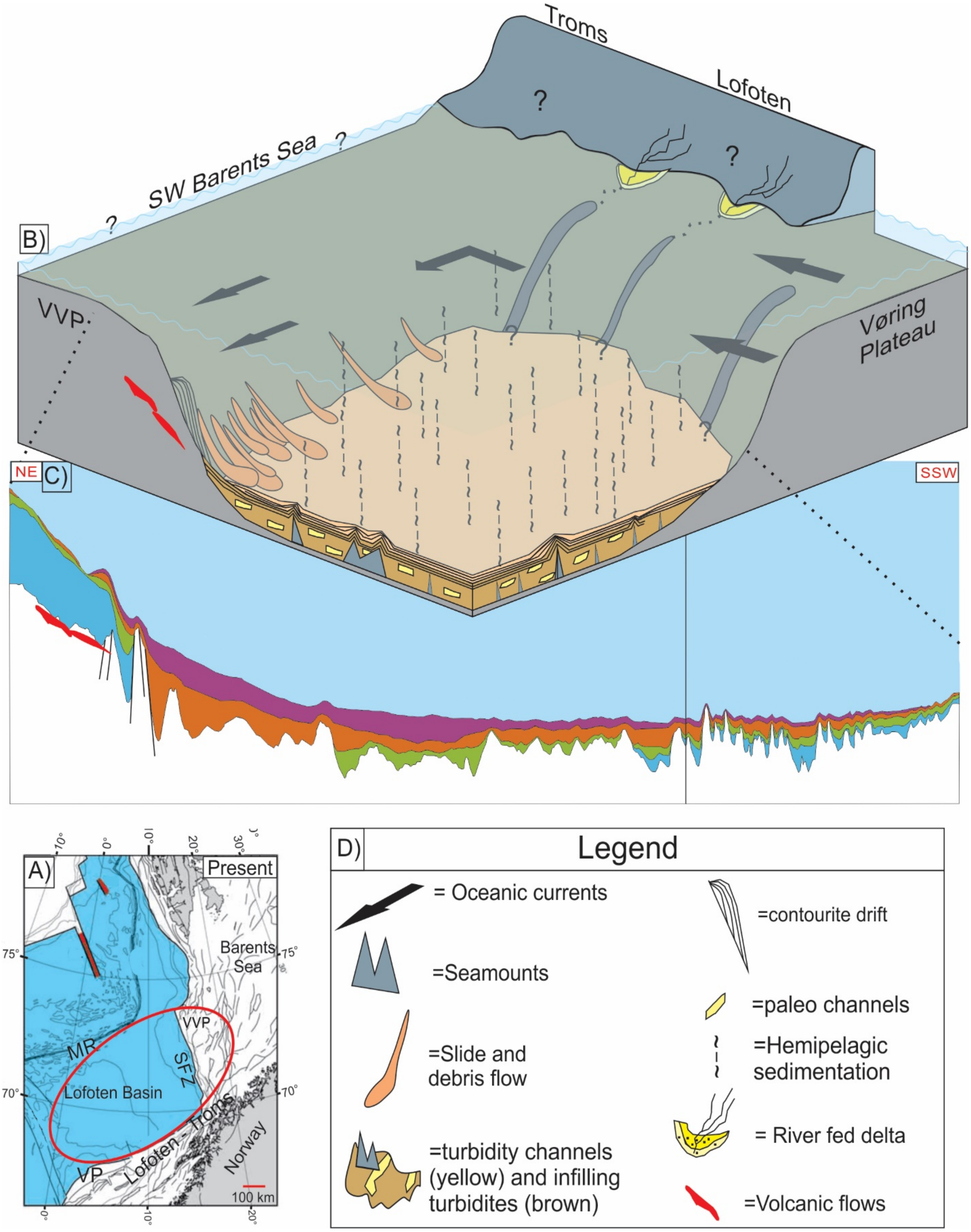


Figure 5-8: The sedimentary environment inferred to dominate in the SW Barents Sea margin – Lofoten Basin during the deposition of unit Te4. The location of the area is shown in A). The dominating sedimentary processes and depositional environment are shown in B) Question marks indicate uncertainties regarding relative sea level and potential terrestrial processes. A geoseismic profile from the SW Barents Sea margin to the Lofoten Basin is shown in C). The legend is shown in D). VVP: Vestbakken Volcanic Province, SFZ: Senja Fracture Zone, MR: Mohns Ridge, VP: Vøring Plateau. A) is modified from Faleide et al. (2008).

5.4.2 The unit Te4 in the Lofoten Basin

The base late Miocene boundary defines an even more pronounced facies change in the Lofoten Basin than for the lower continental slope. The area in both the deep basin- and plateau region is dominated by chaotic seismic facies (Figure 4-39). In the more distal areas, a thin, transparent unit is present until it probably pinches out at the rise to the Vøring Plateau (Figure 4-26).

The vertical facies change across the base late Miocene boundary in the deep basin region reflects an abrupt change in the depositional environment, from the continuous reflections in unit Te3 to the thick unit Te4 dominated by a chaotic seismic facies. Major differences are observed also for the shape of the units. The units below were thicker along the flanks and in small, local basins in the region. Unit Te4 thickens substantially from the flanks of the region toward the centre, and the upper bounding reflection (R7) is sub-horizontal.

It is uncertain why the unit has this overall shape. One possibility is that the surface of the underlying sediments already dipped toward the centre of the area when deposition of the unit Te4 sediments was initiated. Another, more likely, possibility is differential subsidence and compaction of the underlying units during deposition of unit Te4. However, it is uncertain if the differential subsidence and compaction could have formed the overall shape of unit Te4. The reason for the uncertainty is that the centre of the region, where unit Te4 is thickest, is underlain by a basement high. It does not seem plausible that the greatest subsidence should appear immediately above a basement high. A third possibility is that the mass transport events that compose unit Te4 may have eroded into the underlying strata. However, reflections in the upper parts of unit Te3 seems continuous and unaffected by erosion. Also, the area is probably already located in a morphological low, not favouring an erosional explanation as the eroded sediments must have been transported somewhere. It is suggested that differential subsidence and compaction is the most plausible cause for the unit shape. A combination with an already existing depression in the area is relevant to suggest, otherwise, the first mass transported deposits would probably have been distributed over a larger area. However, exactly how this occurred is not fully understood.

As already suggested in chapter 4, the probable direction of mass movement to the deep basin region was from the east or southeast. The lateral margin observed in the transition between the lower slope and the Lofoten Basin supports this. Since the transparent to chaotic seismic facies occurs downslope the lateral margin, the event that is related to the lateral margin must have a flow direction from the east or southeast. The lack of seismic data coverage here prevents a certain confirmation of this. Other options are, however, unlikely. A transport direction along the seismic line HB-2 is unlikely because of the lateral margin. A source to the north is not likely, as this is the northern part of the Lofoten Basin. Therefore, the source to these mass transported deposits are suggested to be located to the east or southeast of the seismic coverage in the study. It is therefore natural to discuss the possible setting to the south in relation to that described and discussed for the lower continental slope previously.

Small and larger scale mass transport deposits dominate the entire unit Te4 along the margin. The failures are probably related to the contourite drift. The southern extent of the contourite drift is not known. However, it is possible that the drift extends toward the south, and that the possible drift deposits to the south are related to the failures that led to the deposition of mass transported sediments in the deep basin region. It is thus suggested that the mass transport complex in the deep basin region reflects a similar slope setting and depositional environment to the south of the study area as already described and discussed for the study area. This is however a speculation, as neither the drift nor the deposits may be mapped in that direction. Also, the morphology of the deep basin region toward the south is unknown.

The interval entirely dominated by a chaotic seismic facies extending from the deep basin region toward the southwest across the plateau region (Figure 4-39) was suggested to represent a single slide event. The interval occupies the entire unit Te4 in the plateau region, and the R7 reflection is the upper boundary of the unit. Because of the chaotic nature of the seismic reflections in the deep basin region, it cannot be clarified if the slide unit runs across the deep basin region and continuous to the plateau region, or if the unit bypass the deep basin region and enters the plateau region from another angle. However, it is suggested that the unit represents an event sourced from the similar area and in a similar environment as discussed for the mass transport complex in the deep basin region. This is because it is unlikely with a source for this event located within the seismic data coverage as discussed for the mass transport complex above.

The thin and transparent unit Te4 observed in the distal Lofoten Basin has probably been deposited in similar environments as discussed for unit Te3 previously. However, the unit is thinner and is more transparent than unit Te3, and Te4 probably pinches out toward the southwest in the rise to the Vøring Plateau. Unit Te4 is therefore interpreted to represent a continuation of the relocation of main source area for the sediments deposited in the Lofoten Basin to the eastern margin. The uplifted southwestern Barents Sea margin have thus probably acted as the main sediment source for sediments deposited in the entire Lofoten Basin during the late Miocene-early Pliocene. The transparent character of the unit together with the pinch-out toward the southwest favours a domination of hemipelagic sedimentation of unit Te4 in this part of the study area. The continuous and transparent character indicate a stable and homogenous depositional environment (Sættem et al., 1994).

Summary – sedimentary environment

The major change in sedimentary processes and depositional environment in unit Te4, to a full domination of the deposition of mass transported sediments is reflected also in the proximal Lofoten Basin. A mass transport complex constitutes the entire unit in the deep basin region of the proximal Lofoten Basin. These sediments infilled the morphological low in the area. Differential subsidence and compaction in the deep basin region may have provided additional accommodation space for the mass transport complex. A single slide event, extending far beyond the underlying mass transport complex in the deep basin region, was deposited across the plateau region. In the distal Lofoten Basin further toward the southwest, hemipelagic sedimentation dominated. The thinning of the unit toward the southwest indicates that the southwest Barents Sea continued to dominate as the sediment source during the late Miocene-early Pliocene. The suggested sedimentary environment during the deposition of unit Te4 in the Lofoten Basin is shown in Figure 5-8.

5.5 THE CONTOURITE DRIFT AND ITS POSSIBLE RELATION TO THE MEGA FAILURE

5.5.1 The continuation of drift growth during the deposition of seismic unit GI

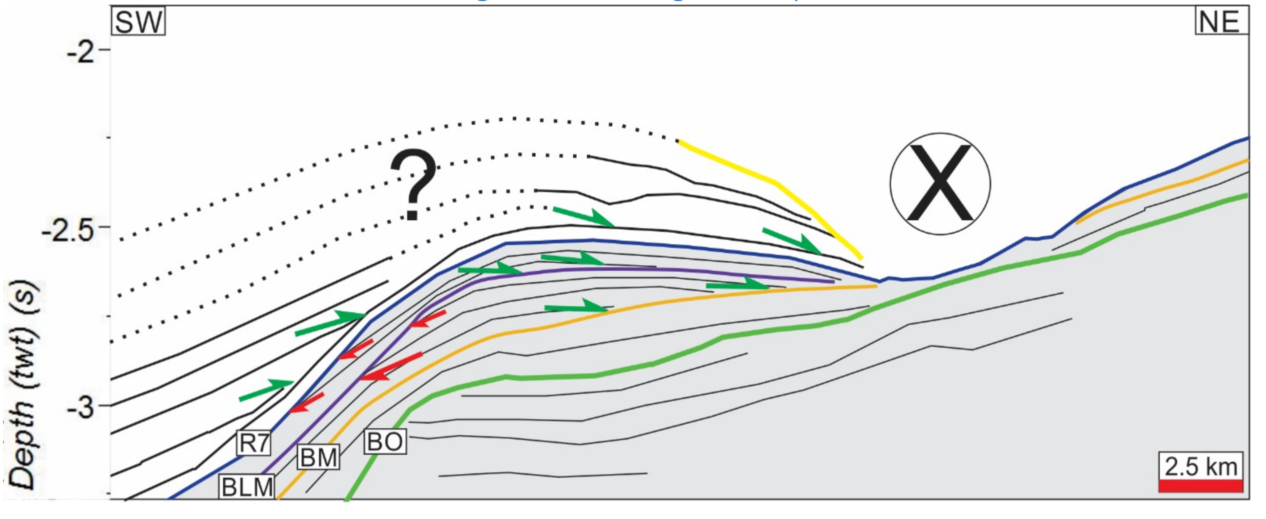


Figure 5-9: The sketch illustrates the continuation of drift growth during the deposition of seismic unit GI. The inferred shape of the drift deposits prior to termination of drift growth and subsequent infill of moat is indicated with dashed lines. Internal reflection onlap and downlap are indicated with green arrows. Red arrows indicate truncation. Circle with an X indicate flow direction away from reader.

The contourite drift growth is inferred to have continued during the deposition of seismic unit GI (Figure 5-9). The continuation of drift growth into seismic unit GI probably represents a major reorganization in the depositional environment at the time. The high amplitude reflection immediately above the R7 reflection forms an angular unconformity and defines a prominent change in the depositional regime in the area. The reflection is generally concordant to the underlying strata. However, the up-dip onlapping reflections to the unconformity (Figure 5-9) defines another depositional environment above the unconformity than within the mounded drift. It is suggested that increasing influx of sediments from the R7 time may have affected the deposition of the contourite drift.

The R7 reflection marks the onset of extensive continental shelf glaciations in the area (Faleide et al., 1996). From this time, the paleoenvironment in the Troms-Barents Sea shelf was dominated by periglacial processes, including fluvial/glaciofluvial erosion (Laberg et al., 2012; Rydningen et al., 2015b). The sediments settled on the continental slope mainly from meltwater overflows, resulting in the dominating laminated signature of the seismic unit (Laberg et al., 2010). The erosion of the Barents Sea shelf and the sedimentation rate in the continental slope to the west increased substantially relative to the average rates during the deposition of unit G0 (Vorren et al., 1991; Fiedler & Faleide., 1996; Laberg et al., 2012).

According to Fiedler and Faleide (1996), the average linear sedimentation rate during the deposition of seismic unit G0 was 2.2 cm/k.y. Laberg et al (2012) calculated the equivalent numbers for the seismic units GI-GII with the age of the regional reflectors adjusted to the latest publications. Based on the works of Vorren et al. (1991) and Fiedler and Faleide (1996), they found the average linear sedimentation rate in the period from 2.7-1.5 Ma (Unit GI) was 16 or 22 cm/k.y., respectively.

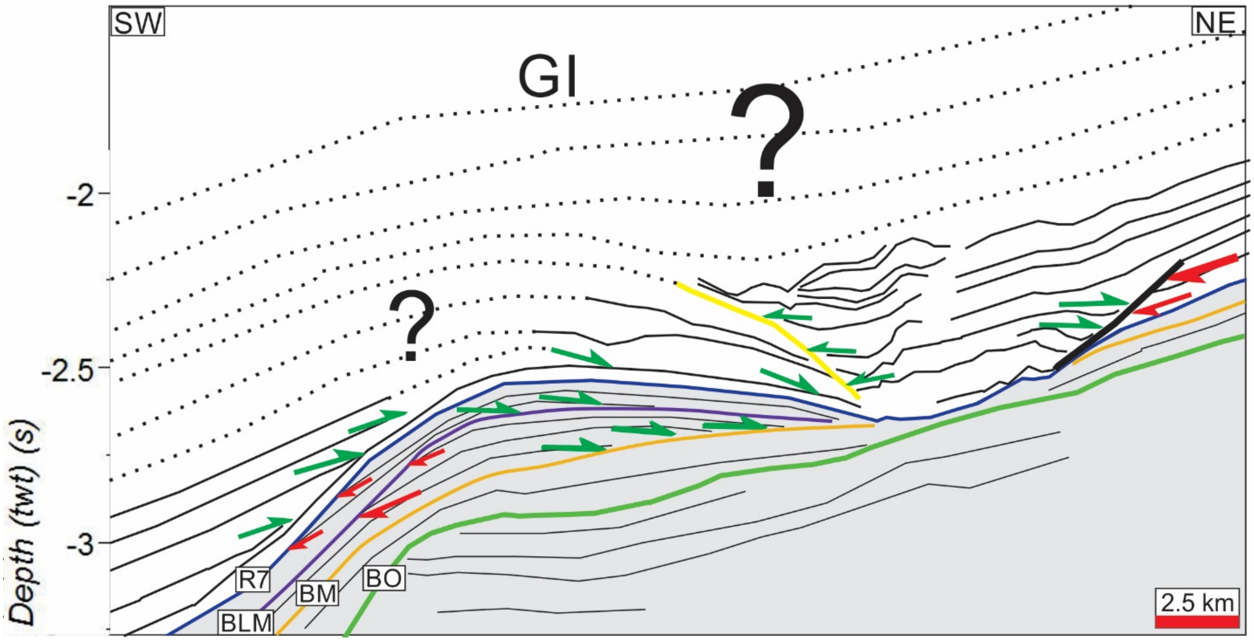


Figure 5-10: The sketch illustrates the inferred infilling of the moat and subsequent draping of the drift deposits after the termination of drift growth during GI time and prior to erosion by overlying seismic unit GII. Internal reflection onlap and downlap are indicated with green arrows. Red arrows indicate truncation. Yellow line indicates an angular unconformity representing the top of the drift deposits.

The increased influx of sediments to the continental slope during the deposition of unit GI may have affected the alongslope flowing currents. However, the formation of the contourite drift did not cease. It is suggested that the increasing sediment input during the GI time have affected the current system so that the formation of the contourite drift was reorganized. The reorganization is suggested to have caused the differing external shape of the drift deposits, to a sheeted shape downslope the crest of the mound, after the initiation of shelf glaciation (R7 time). The influence of the oceanic current may for example include a slight reorganization of flow direction along the slope or a relocation of the focus of the flow, for example up or down the slope. Since there is no seismic data coverage to the south of the observed contourite drift, a further study of this reorganization is prevented.

The formation of the contourite drift may have ceased, or the moat may have migrated, prior to the erosion of the upper part of the unit. The moat was filled with sediments before the erosional event. This is indicated where wavy reflections located upslope the inferred top unconformity of the drift fills the moat (Figure 5-10). The subsequent erosion occurs above the deposits filling the moat (Figure 5-11). The infilling sediments may represent infilling during migration of the moat, or infilling by hemipelagic sedimentation after the termination of drift growth. The wavy appearance of the infilling deposits favors an interpretation that the sediments represent infilling during migration of the moat.

The inferred infilling of the slide scar within seismic unit GI in the northern part of the study area (Figure 4-29) supports the suggestion that the alongslope processes continued the domination of the sedimentary processes along the margin also after the initiation of ice sheet growth on the continental shelf.

Summary – sedimentary environment

Alongslope processes on the continental slope dominated during the deposition of seismic unit GI. The contourite drift continued its growth during the deposition of the unit. The drift deposits within unit GI shows another external geometry of the drift deposits downslope the crest of the mound than for the sub-units below R7. The sheeted external shape and the up-dip onlap to the unconformity above R7 indicate a reorganization of the oceanic current at the time. It is suggested that the increasing influx of sediments during deposition of unit GI may be the reason for this reorganization. The increasing influx of sediments may have affected the current flow so that it changed the direction of flow and/or that it have migrated up or down the slope. The termination of the drift growth cannot be estimated because the upper part of the drift has been eroded.

5.5.2 The relation between the contourite drift and the mega-failure

The observation of a mega-failure located on the continental slope within seismic unit GII supplements Hjelstuen et al (2007), who described three mega-slides in the Lofoten Basin, the BFSC I-III. The possibility of a relation between the mega-failure described here and one of the BFSC I-III of Hjelstuen et al (2007) is uncertain due to the data coverage and is not the focus here.

The mega-failure was interpreted to include slide deposits and is located on the continental slope. The R5 reflection, which is the base of seismic unit GII, represents the base of the failed masses in parts of the area. These failed masses truncate the reflections within the upper main unit of the contourite drift (Figure 4-30 and 5-11). Downslope the crest of the mounded drift deposits, the R5 reflection lies parallel to the underlying inferred sheeted drift deposits. Thus, the mega-failure clearly cuts directly through the upper part of the contourite drift deposits, and has layer of the sheeted drift deposits as its glide plane downslope the crest.

According to Bryn et al., (2005a), the presence of contourite drifts on the continental slope are important for the slope instability of the glaciated margin of Mid-Norway (the Naust formation = GI – GIII on the western Barents Sea).

Other physical properties than the glacial deposits, a potential for build-up of excess pore pressure due to rapid loading from subsequent glacial deposits, a smoothing effect of the seabed and their great lateral extent are important properties of the drift deposits that make them prone to failure (Bryn et al., 2005a).

The Holocene Storegga Slide failure is inferred to be closely related to contourite drift deposits (Bryn et al., 2005b). Several major slides occurred in the same area the past ~500 k.y. They suggested that a generally increased sediment supply and cyclic variations in sedimentation rate and type, between glacials and interglacials, were closely related to the failures. They found that laterally extensive glide planes were located in marine clays of hemipelagic/contouritic deposits. Subsequent loading of sediments during glaciations caused compaction of the thick ooze deposits (hemipelagic/contouritic deposits) (Bryn et al., 2005b). The triggering of the slides was related to reactivation of fault systems in the area (Bryn et al., 2005b).

The sedimentary environment in the Mid-Norwegian margin shows similarities to the southwest Barents Sea margin. As noted in the previous section, the linear sedimentation rate in the BITMF increased substantially from seismic unit G0 to seismic unit GI with the onset of extensive shelf glaciations in the in the Barents Sea from the R7 time. The linear sedimentation rate increased even more to the seismic unit GII, with 64 cm/k.y. (based on Vorren et al., (1991)) or 50 cm/k.y. (based on Fiedler and Faleide (1996)). During the deposition of seismic unit GII, the southwestern Barents Sea shelf was glaciated repeatedly during full glacial conditions (Andreassen et al., 2007). This resulted in a varying sediment supply to the outer shelf and upper slope, fluctuating between direct supply of glacial deposits (deformation till) to the shelf break and upper slope during full shelf glaciation, and periods of lower sediment influx to the slope when the ice sheet was retreated from the shelf break (Laberg et al., 2010).

The sediments deposited from 1.5 Ma (seismic unit GII) were deposited on top of the sediments in the middle and lower continental slope dominated by alongslope processes since the Miocene. There was thus already a thick body of contouritic deposits, probably interbedded with hemipelagic sediments, in the area when seismic unit GII was deposited. From the R5 time, the fluctuating Barents Sea ice sheet has probably caused cyclic variations in the depositional environment in the continental slope, with periods of low sedimentation rates and periods of rapid loading of the underlying strata, probably quite similar to that reported by Bryn et al., (2005b) for the mid-Norwegian continental slope.

Hjelstuen et al. (2007) related the failure of BFSC I-III to the increased loads of rapidly deposited glacigenic sediments on top of a softer substratum in a continental slope setting. In addition, they suggested that an external trigger mechanism might have been required for the slides to occur, and this was most likely an earthquake. According to Safronova et al. (2015), seismicity related to the Knipovich spreading ridge represent a possible triggering mechanism for five larger scale slide debrites in the northwest Barents Sea continental margin.

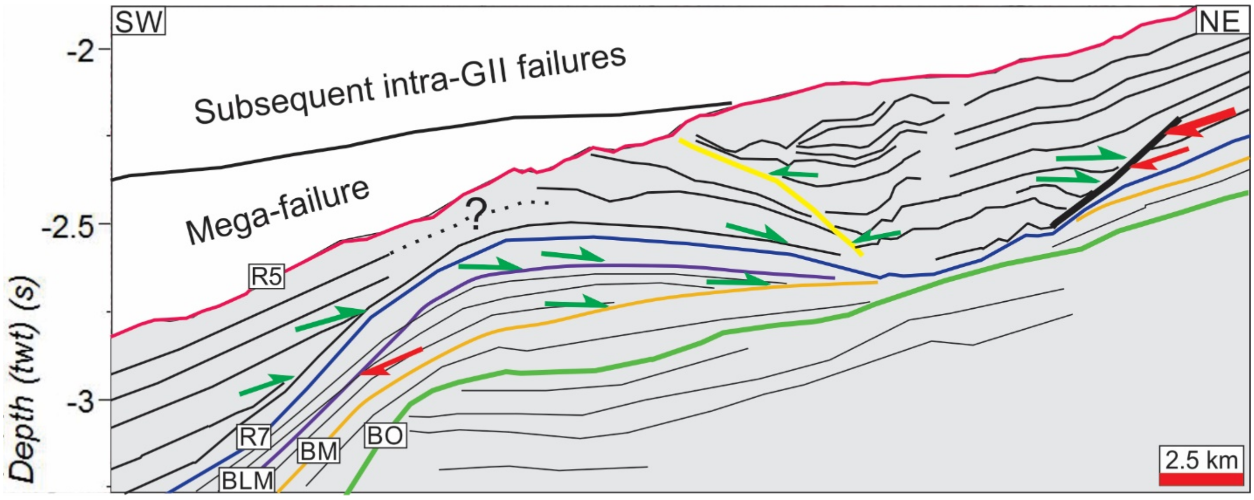


Figure 5-11: The sketch illustrates the erosion of the upper part of the contourite drift deposits by the mega-failure in seismic unit GII. Internal reflection onlap and downlap are indicated with green arrows. Red arrows indicate truncation.

It is suggested that the mega-failure described in this thesis occurred as a result of rapid loading of glacigenic sediments, possibly in a cyclic manner, on top of the dominating contouritic sediments in the middle-lower continental slope. The failed sediments eroded through the top of the contouritic deposits in the middle slope and probably moved downslope with a weak layer of the contouritic deposits functioning as a glide plane. A probable trigger mechanism for the failure in this area is an earthquake, as reported both by Hjelstuen et al., (2007) for the BITMF and Safronova et al., (2015) for the northwestern margin of the Barents Sea.

Summary – sedimentary environment

The mega-failure occurred during the deposition of unit GII on the continental slope. The base of the failure erodes through the upper part of the contourite drift deposits. Downslope the mounded drift deposits, the base of the failure is located conform to the underlying sheeted drift deposits. The sheeted drift deposits are inferred to have acted as a glide plane for the overlying failure. The mega-failure probably occurred as a result of rapid loading on top of softer sub-stratum within the drift deposits and cyclic variations in sedimentation rates, related to glacials and interglacials. As a result, a weak layer within the drift deposits have probably failed. An external trigger mechanism like earthquake may have triggered the failure to occur.

5.6 SUMMARY

From the opening of the Norwegian-Greenland Sea at the Paleocene-Eocene transition, the Lofoten Basin has developed to a deep-sea basin confined by very different boundaries: from the Mohns spreading ridge in the west and northwest and the steep Lofoten-Troms margin in the south-southwest, to the presently very low gradient continental slope of the western Barents Sea margin to the east. The sedimentary processes and the paleo-environment during the deposition of seismic units Te1-Te4 has changed along with the development of the Lofoten Basin and the oceanic current circulation system in the area. These changes have resulted in the varying depositional environment observed to dominate the different seismic units studied. The depositional environments and sedimentary processes observed to dominate during the deposition of seismic units Te1-Te4 are summed up in Table 5. The observations of the contourite drift formation during the deposition of seismic unit GI, and the mega failure that occurred during GII time, are also included.

Table 5: The summary table shows the seismic stratigraphic framework and the respective dominating depositional and sedimentary environment for each seismic unit. OcB: Oceanic basement, BE: base Eocene, BME: base middle Eocene, BO: base Oligocene, BM: base Miocene, BLM: base late Miocene. The asterisk (*) indicate information from the background chapter.

Unit boundaries, ages (Ma) and seismic units			**Continental slope**		**Lofoten Basin**	
			Dominating depositional environment	Dominating sedimentary processes	Dominating depositional environment	Dominating sedimentary processes
		GIII	Glacimarine*	Slides and GDFs*	Marine-Glacimarine*	Slides*
R1	0.7-0.2					
		GII	Glacimarine*	Slides* / mega-slides	Marine-Glacimarine*	Slides*
R5	1.5					
		GI	Glacimarine*	Contourite drift / slides*	Marine-Glacimarine*	Slides*
R7	2.7					
		Te4	Marine – slope setting	Along-slope / slides/MTDs?	Marine	Hemipelagic-MTC?
BLM	~10.5					
		Te3	Marine – slope setting	Along-slope / slides/MTDs?	Marine	Hemipelagic
BM	<27					
		Te2	Shallow marine?	Non-deposition / erosion	Marine	Turbiditic currents
BO	>35					
		Te1	Marine outer to middle shelf setting	Hemipelagic	Marine	Turbiditic currents
OcB/BE (BME)	~55 (~45)					

Unit Te1

An outer-middle marine shelf setting dominated the depositional environment in the VVP area from middle Eocene time. The sediments, sourced from the Stappen High to the east, were deposited as prograding clinoforms in a local pull-apart basin. A gradual infilling may have resulted in shallowing of the basin. Tectonic movements and reorganization of the sea floor spreading during Eocene-early Oligocene resulted in erosion and/or non-deposition, and this is probably the cause for the missing late Eocene sediments in the area.

Downslope transport and deposition of sediments is suggested to have dominated the depositional environment in the Eocene Lofoten Basin. Slides and debris flows may have dominated in the near-slope areas while turbidites dominate in more distal areas of the basin. The turbidites have probably infilled and gradually reduced the irregularity and partly high relief of the young Lofoten Basin. The sediments were probably derived from the southern margin of the Lofoten Basin, the

Lofoten-Troms margin. Oceanic currents flowing north across the Vøring Plateau may have transported sediments to the continental slope in the southwest of the Lofoten Basin where they subsequently were remobilised as gravity currents.

Unit Te2

The unit Te2 in the VVP area was probably deposited in a local basin that was continuously developing as the spreading ridge to the west migrated north-northwest past the area during the Oligocene. By the end of the Oligocene, a physical connection between the VVP area and the Lofoten Basin was established. The area was subject to tectonic movements and reorganization of the spreading poles in the early Oligocene. This probably caused erosion and/or non-deposition during the Oligocene, resulting in a very thin unit Te2. A low, global sea level during the Oligocene probably also influenced the deposition of the unit. Erosion of the upper part of the unit have been observed both in the upper continental slope and downslope.

The sedimentary environment in the Lofoten Basin was probably still dominated by gravity driven processes, mainly turbidity currents. The turbidites continued to fill in the high-relief oceanic basement. A smoother relief to the southwest may have resulted in less deformed deposits and more continuous reflections. These sediments were later deformed to disrupted and/or polygonal faults. The deformation was probably a result of compaction and subsidence of the unit due to rapid loading of subsequent deposits. The sediments were probably sourced from the southern Lofoten-Troms margin in the beginning of the Oligocene. However, increasing sediment input from the east is assumed as the spreading ridge migrated north-northwest. Sediments located in the proximal Lofoten Basin are suggested to have been sourced from the southwestern Barents Sea-Troms margin.

Unit Te3

Unit Te3 is thin on the entire upper continental slope, and the upper part of the unit is occasionally eroded. Low sedimentation rates and non-deposition/erosion in a marine shelf setting dominated the sedimentary environment in the VVP area during the early-middle Miocene. Sediments eroded from the continental shelf-upper continental slope may have been transported downslope to the lower continental slope. Here, sediments infilling the basement relief were probably deposited from gravity driven processes like debris flows or turbidity currents. The base Miocene is suggested to represent the onset of contourite drift formation along the southwestern Barents Sea margin, and an age of middle Miocene for the initiation of drift growth is suggested here. The drift deposits probably extend from the upper continental slope downslope beyond the marginal high where they overlie the infilling deposits on the lower continental slope, probably interbedded with hemipelagic deposits.

In the Lofoten Basin, unit Te3 probably represents a change in the depositional environment. The increasing continuity within the transparent seismic facies in the lower part of unit Te3 is suggested to represent less deformation during deposition of turbidites, possibly related to a smoother relief. A more distinct facies change occurs within unit Te3, to continuous reflections suggested to represent a domination of hemipelagic sedimentation. These reflections drape the peaks of the irregular oceanic basement still raised above the sea floor at the time. Increasing influence of alongslope processes along the entire margin from the Vøring Plateau to the southwest Barents Sea is likely during the early-middle Miocene. This have influenced the depositional environment along the margin, with increasing development of contourite drift deposits. The winnowing effect of the oceanic currents on the shelf and upper slope may have eroded and transported the sediments from this part of the margin and deposited the sediments further downslope. Along with the increasing oceanic currents, the main source for the sediments deposited in the Lofoten Basin probably changed to the east (the southwest Barents Sea). This is inferred from the observed thinning unit of the unit toward the southwest.

Unit Te4

The erosion of unit Te4 on the upper part of the continental slope is suggested to be related to uplift due to tectonic movements. In addition, the increasing influence of oceanic currents may have eroded the unit on the shelf and upper slope. Parts of these sediments may have been deposited as a sub-unit in the continuously growing contourite drift downslope. The drift deposits of Unit Te4 probably represents a temporal variation in the depositional environment, suggested to be related to the influence of oceanic currents at the time. On the lower continental slope, unit Te4 represents a major shift in the depositional environment with the small- and larger-scale events suggested to be responsible for the mass transport deposits observed. The deposits comprise the entire unit on most of the lower continental slope, and are suggested to be related to failures in weak layers of the growing contourite drift.

A similar cause for the mass wasting complex in the proximal Lofoten Basin is suggested. The entire unit here consists of inferred slide and/or debris flow deposits, probably derived from the continental slope south of the seismic coverage in the study. The mass transport complex fills a major morphological low in the area, while a single or a few sliding events overlie most of the failed sediments and extend further toward the southwest in the Lofoten Basin. The thinning of unit Te4 toward the southwest is suggested to be related to the inferred change in main sediment source to the southwest Barents Sea.

6 CONCLUSION

The Cenozoic pre-glacial sedimentary processes and depositional environments along the southwestern Barents Sea margin and in the Lofoten Basin have been studied using 2D seismic data. The pre glacial seismic unit G0 was sub-divided into four seismic units, units Te1 (Eocene age), unit Te2 (Oligocene age), unit Te3 (early-middle Miocene age) and unit Te4 (late Miocene-early Pliocene age). In addition, the contourite drift extending across the G0- GI boundary and the mega-failure occurring within seismic unit GII have been studied.

1. The sedimentary environment in the VVP area was dominated by a shallow to deep marine shelf setting during the deposition of unit Te1. A thick unit comprising prograding clinoforms sourced from the Stappen High were deposited in a local rift basin. The local basin was subsequently filling up, and the upper part of the Eocene unit was later eroded. The Lofoten Basin was dominated by gravity flows sourced from the Lofoten-Troms margin to the south. Turbidites distributed across the Lofoten Basin partly filled the irregular oceanic basement. Slides and debris flow deposits probably accumulated in the near-slope areas.
2. Tectonic movements occurred in the VVP area during the deposition of unit Te2, resulting in faulting and rotation of fault blocks. The tectonic movements, in addition to a low global sea level, probably caused erosion and/or non-deposition, resulting in a thin unit. Sediments eroded from the SW Barents Sea continental slope were deposited in the Lofoten Basin when the Mohns spreading ridge had migrated north of the VVP area. Turbidites continued to infill the high relief Lofoten Basin during the Oligocene. The turbidity currents were probably sourced from the entire Lofoten-Troms-SW Barents Sea margin toward the end of the Oligocene. Post-depositional deformation resulted in disrupted reflections and polygonal faults.
3. The oceanic circulation system increased its influence on the depositional environment in the Lofoten-Troms-SW Barents Sea continental margin during the deposition of unit Te3. This is documented by the initiation of drift growth at the time, inferred to start around the middle Miocene. Unit Te3 compose the lower sub-unit of a mounded contourite drift located in the middle continental slope and extending downslope. A change in the Lofoten Basin, from the infilling turbidites to draping hemipelagic sediments, is observed during the early part of the Miocene. The upper part of the unit drapes most of the remaining high relief. Disrupted reflections and polygonal faults indicate post-depositional deformation of

the unit. The main sediment source for the Lofoten Basin probably changed to the southwestern Barents Sea margin during the early-middle Miocene.

4. Unit Te4 is missing on the upper continental slope. The probable cause for this is the uplift of the region and increasing erosion on the shelf and upper slope from oceanic currents. Unit Te4 compose a sub-unit in the mounded contourite drift on the middle slope. A major change in the depositional environment is observed on the lower continental slope and the proximal Lofoten basin, where most of the unit consists of mass transported deposits. The change to mass transport deposits is suggested to be related to failures of weak layers within the contourite drift. The southwestern Barents Sea margin is the main sediment source for the Lofoten Basin during the early-middle Miocene.
5. The along-slope processes continued the domination on the middle continental slope during the deposition of unit GI. A reorganization in the deposition of the drift occurred after R7 time, inferred to be caused by increasing sediment influx from the shelf and upper slope. This resulted in the change to sheeted drift deposits downslope the mounded drift. The upper part of the contourite drift is eroded, and the timing of termination the drift is unknown. A mega-failure located within unit GII truncates the mounded drift deposits, and lies conformably to the sheeted deposits downslope. The mega-failure probably occurred because of rapid loading in a cyclic manner resulting in failure in a weak layer within the sheeted drift deposits. The failure was probably triggered by an earthquake.

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