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Late Jurassic to Late Cretaceous canyons on the Måløy Slope: Source to sink fingerprints on the northernmost North Sea rift margin, Norway

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The Måløy Slope is a key area for studying the connection between onshore and offshore geology of South Norway. It has functioned as an area of bypass, erosion and deposition between the Norwegian mainland source area and the offshore northern North Sea sink area since the Permian. The slope was faulted into N–S-trending rift fault-blocks through flexural down-bending during the large-scale extension and rapid rift basin subsidence in the Late Jurassic and Early Cretaceous. Mapping of 3D seismic data has revealed a profound network of E–W-oriented erosional submarine canyons. These canyons cut up to 500 m into the crystalline bedrock on the rift-related fault-block crests. We suggest that the canyons were first established prior to the faulting associated with late Jurassic rifting. The canyons may have been important feeders in the Oxfordian, Kimmeridgian and Tithonian like canyons in the Uer Terrace to the south, although we lack direct evidence for this. Further erosion and deepening of the canyons into the basement occurred during Cretaceous in a post-rift setting. The position of the main canyons sustained during recurring periods of erosion from the Late Jurassic until burial within the slope in the Late Cretaceous. By the aid of detailed bathymetric maps, the main canyons can be correlated with onshore faults and drainage systems (fjords and valleys). The evolution of the slope canyon system over time is controlled by both tectonic and isostatic movements and, as discussed in the text, can help understand when and where the pre-fjord drainage was established. Multiple incision events have been detected, and each of these express some correlation to regional tectonic events in (1) Late Jurassic–Earliest Cretaceous, (2) Late Aptian–Albian and (3) Turonian–Coniacian.

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Introduction

In source-to-sink systems, uplift and erosion of source areas are closely linked to subsidence and deposition in surrounding sinks. Modern 3D seismic data make it possible to map the preserved remains of such systems in rifted continental margins, providing important links between onshore topographic and exhumation history and basin subsidence. An example of a long-lived source-to-sink system has been detected between uplifted areas of southern Norway and the adjacent northern North Sea rift basin (Sømme et al., 2013a). Erosion and drainage of the Norwegian mainland (source) has led to deposition of sediments in the North Sea rift basin and Møre Basin (sinks) since the late Palaeozoic, and the offshore stratigraphy of the region has been linked to onshore paleo-topography (Sømme et al., 2013b). This study focuses on the transition between the source and sink in the northeastern margin of the northern North Sea rift, known as the Måløy Slope (Figs. 1 & 2). The Måløy Slope is bounded by the Sogn and Viking grabens in the west, the Norwegian mainland in the east and the Selje High and Møre Trøndelag Fault Complex in the north (Fig. 1).

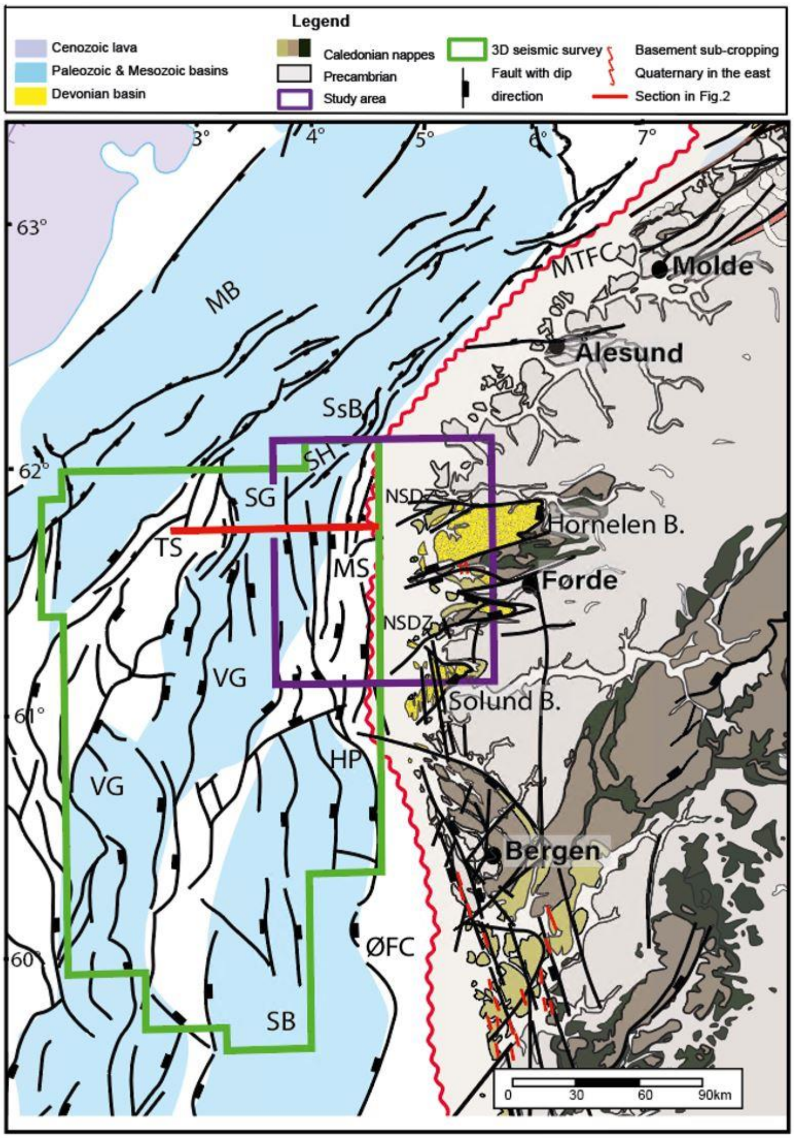

Figure 1. Simplified regional geology map of western Norway and the North Sea. The study area, shown with purple outline, covers the Måløy Slope (MS) which is bounded by the northern Sogn and Viking grabens (SG and VG) in the west, the Norwegian mainland in the east and the Selje High (SH) and Møre Trøndelag Fault Complex (MTFC) in the north. The outline of the 3D seismic dataset used in this study is shown in green. Red W–E line offshore shows the location of section shown in Fig. 2. Red lines onshore indicate location of observed Permian dykes. Abbreviations: SsB – Slørebotn Sub-basin, NSDZ – Nordfjord Sogn Detachment Zone, TS – Tampen Spur, HP – Horda Platform, MB – Møre Basin, ØFC – Øygarden Fault Complex, SB – Stord Basin.

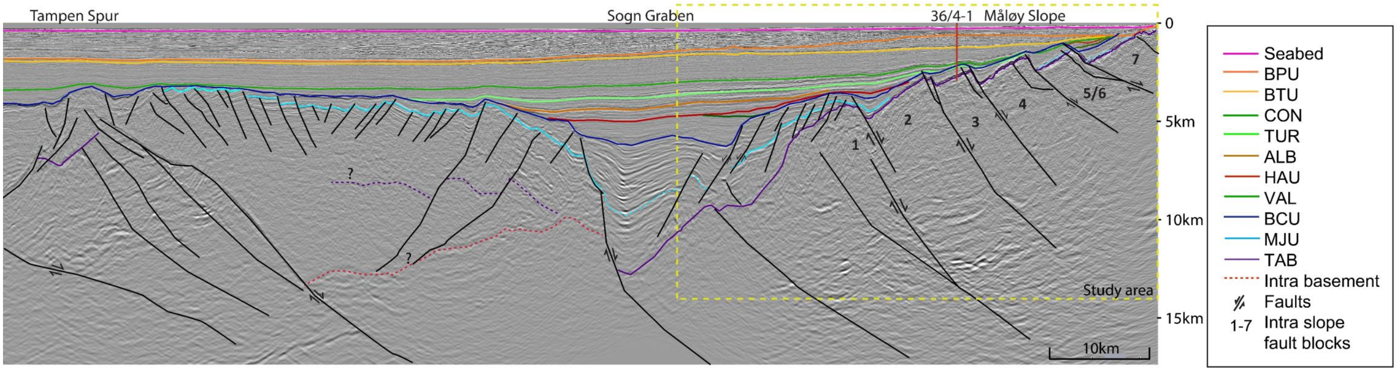

Figure 2. Seismic reflection line (Crossline 33147, depth) across the Tampen Spur, Sogn Graben and the Måløy Slope (see location in Figs. 1 & 3). The Måløy Slope defines the offshore part of the study area. Note the fault-blocks (see numbering in Fig. 3) of the Måløy Slope, bounded by easterly dipping faults. The interpreted horizons are described in the text and details are documented in Fig. 5. Abbreviations: TAB – Top acoustic basement, MJU – Middle Jurassic, BCU – Base Cretaceous Unconformity, VAL – Late Berriasian–Early Valanginian, HAU – Early Hauterivian, ALB – Top Albian sands, TUR – Turonian Unconformity, CON – Coniacian, BTU – Base Cenozoic Unconformity, BPU – Base Pleistocene Unconformity.

The coastal/inner shelf transition zone of the Måløy Slope is transected by incised canyons. Such canyons are described as feeders in source-to-sink systems, acting as conduits for deposits between onshore drainage systems by rivers and submarine depositional systems on the shelf (Bugge et al., 2001; Harris & Whiteway, 2011; Tillmans et al., 2021). Large canyons that incise into continental shelves can evolve into shelf valleys that have a direct connection to onshore fluvial systems (Harris & Whiteway, 2011) or they may form by deep-water currents.

Processes related to tectonics, isostasy, climate and global sea-level changes may play important roles in the source and sink areas as well as in the intervening transport system. Regional tectonics may cause rejuvenation of uplifted source areas. The associated erosion, also dependent on climate, may cause additional uplift due to the isostatic response to unloading. Rifting may cause margin uplift and enhanced erosion of the source area, together with subsidence and creation of accommodation space in the sink. Sediment loading in the sink lead to isostatic subsidence, while post-rift cooling leads to thermal subsidence.

The Måløy Slope is defined by a set of basement-rooted, N–S-trending fault-blocks where the metamorphic basement rock is overlain by Jurassic and younger strata. A set of W–E-trending canyons incise the fault-block strata and in certain places deep into the basement rocks. The incised canyons formed during repeated phases of erosion and have repeatedly acted as sediment feeders into the northern North Sea basin throughout Mesozoic and Cenozoic times.

The aim of the current study has been to explore the erosional canyon network using new 3D seismic data to better constrain the timing and relation to onshore structures and tectono-isostatic events in the region. Furthermore, the study is relevant to our understanding of hydrocarbon resources in the region, as both Upper Jurassic and Cretaceous deposits have been known to be good reservoirs for hydrocarbons. The Jurassic system is poorly understood as only patches are preserved due to erosion. The discovery of the Duva field shows that the Lower Cretaceous Agat Member sands have potential for hydrocarbon exploration. The work presented in the following is based on a NVG 3D seismic survey acquired in 2014–2015 (Fig. 1) combined with CGG's well-study.

Geological setting

Onshore (western south Norway)

The bedrock in western south Norway consists of the Proterozoic Baltic Shield represented by the Western Gneiss Region, separated from overlying Caledonian nappes and Devonian basins by major extensional shear zones (Fig. 1). The Precambrian bedrock of the Western Gneiss Region is dominated by quartzo-feldspatic gneisses with inclusions of eclogite, amphibolite and ultramafic rocks (Tucker et al., 2004). Caledonian allochthonous rocks comprising schists, greenstone, etc., were emplaced onto the Precambrian basement. The basal decollement was reactivated as a low-angle extensional detachment, followed by the development of W- to NW-dipping extensional shear zones linked to Middle Devonian supradetachment basins filled with conglomerates and sandstones (e.g., Hornelen and Solund basins; Seranne & Séguret, 1987; Osmundsen & Andersen, 2000; Vetti & Fossen, 2012; Fig. 1). The Nordfjord–Sogn detachment zone (Osmundsen & Andersen, 2000; Fig. 1) is the largest of these post-Caledonian extensional shear zones (Fossen, 2010; Fossen et al., 2014). The Nordfjord–Sogn detachment zone is folded into large-scale upright folds with W(SW)–E(NE)-trending axes that also affect Devonian basins in its hanging wall and the upper part of the Western Gneiss Region in the footwall (Krabbendam & Dewey, 1998).

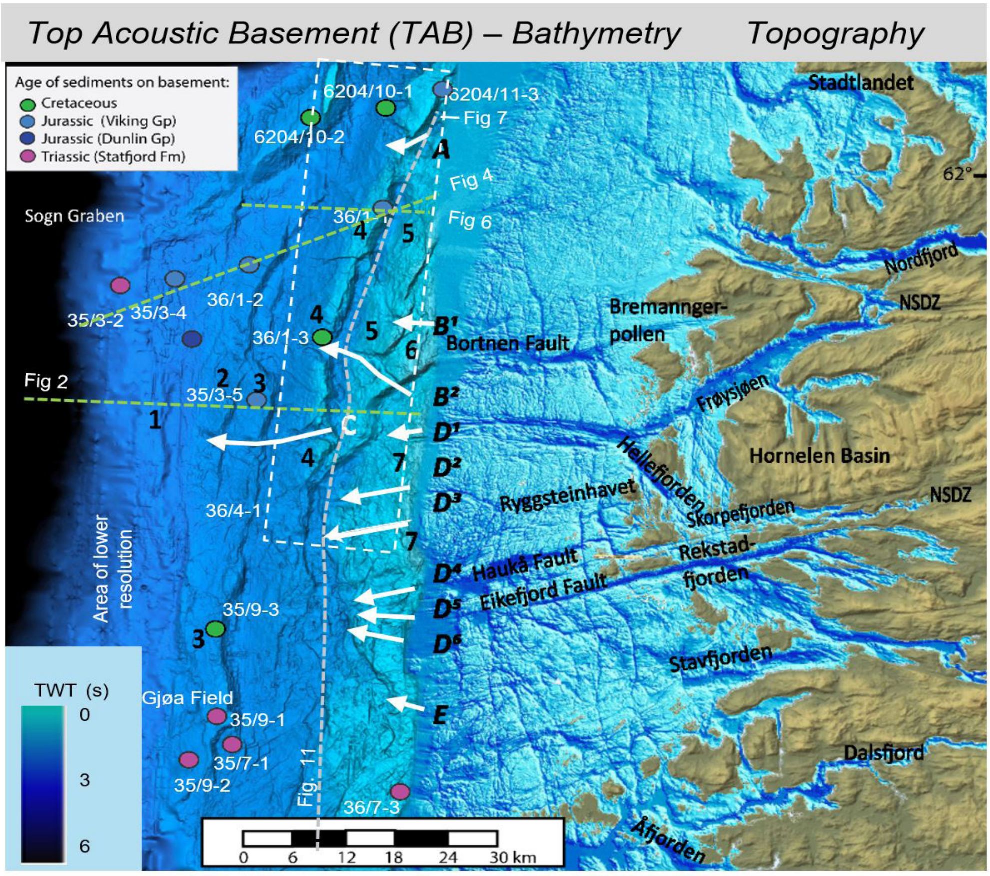

Figure 3. Structure map of the top acoustic basement of the Måløy Slope, juxtaposed with the present bathymetry and the topography of the Norwegian mainland. The top acoustic basement is seen at seabed in the east and down to 5 seconds and deeper in the west (area of lower resolution at basement level). Location of close-ups in Fig. 7 are shown in white dashed polygon. Location of seismic examples in Figs. 2, 4, 6 and 11 are shown in green dashed lines. The locations of basement wells are shown with the age of sediment found at this surface indicated by colour. Canyons A–E are shown with white arrows crossing the intra-slope fault-blocks 1–8. In the bathymetry the boundary where the top acoustic basement subcrops significant sedimentary units are clear (see location in Fig. 1). Abbreviations: SH – Selje High, NSDZ – Nordfjord Sogn Detachment Zone.

Coast-parallel Mesozoic dykes, faults and fractures overprint the Devonian extensional shear-zone structures and seem to correlate with the two main phases of rifting in the North Sea (Fossen et al., 2021 and references therein; Figs. 1 & 3). Several faults formed on the limbs of the large-scale folds, particularly north of Sognefjorden (e.g., Haukå, Eikefjord, Bortnen faults; Fig. 3) and the onshore fault pattern continues offshore, as seen from the near-shore bathymetric map (Fig. 3).

The onshore Mesozoic topography and geomorphology is not well known, but it is inferred that the coastline was located west of the present coastline in the Jurassic and farther east in the Cretaceous. In the Jurassic the onshore topography northeast of the study area is thought to have been elevated during the Late Jurassic rift phase, possibly reaching ~1600 m locally according to Sømme et al. (2013a), whereas in the Cretaceous the onshore topography was lower (<0.5 km; Sømme et al., 2013a).

Offshore (northern North Sea and Møre Margin)

The offshore basement in the study area has been entered by 15 wells. The basement is described as Precambrian and Caledonian. Seismic interpretations show that the offshore basement is folded with an E–W-plunging fold axis along the Måløy Slope, like what is observed onshore (Fazlikhani et al., 2017; Lenhart et al., 2019; Wiest et al., 2020).

Late Permian to Triassic

The northern North Sea basin was established in response to extensional rifting in the Late Permian–Early Triassic (Færseth, 1996; Bell et al., 2014; Phillips et al., 2019), setting up large, rotated fault-blocks and associated half-graben basins. Although documented onshore (Eide et al., 1997; Fossen et al., 2021), the impact of this first phase of rifting is less significant in the Måløy Slope than farther south on the Horda Platform. Regionally, this first phase of rifting was followed by thermal subsidence and sediment loading in the Triassic (Gabrielsen et al., 1990; Nøttvedt et al., 1995).

Early to Middle Jurassic

In the Early to Middle Jurassic the northern North Sea was part of a large shallow-marine sea, with deposition of shales and periods of large delta progradations from the south with deposition of the Brent delta (Helland-Hansen et al., 1992; Ravnås et al., 2000). The Early Jurassic was dominated by significant sediment delivery from the Norwegian mainland prior to and during deposition of the Brent delta (Husmo et al., 2003).

Middle/Late Jurassic to Early Cretaceous

The North Sea rifted for the second time in several Middle Jurassic–Early Cretaceous events (e.g., Ravnås et al., 2000; Bell et al., 2014; Phillips et al., 2019; Fig. 4). This modified the existing Permian–Triassic basin architecture and the main structural elements, with the formation of the Viking Graben (Fig. 1) and rotated fault-blocks on structural flanks (Færseth, 1996). The Sogn Graben also deepened during this period, flanked by the Tampen Spur and the Måløy Slope (Figs. 1 & 2). The latter has also been described as having formed as a result of flexural down-bending as sediments were deposited in the Sogn Graben (Bell et al., 2014). The down-bending set up several intra-slope fault-blocks with east-dipping bounding faults (Fig. 2). Rift flank uplift likely affected the entire eastern flank of the North Sea rift system during the Late Jurassic. Within the study area, the distance from the offshore rift axis in the Sogn Graben to the uplifted areas onshore is 70 km, in contrast to 120 km from the northern Viking Graben to Solund to the south (Gabrielsen et al., 1990, Nøttvedt et al., 1995; Fig. 1).

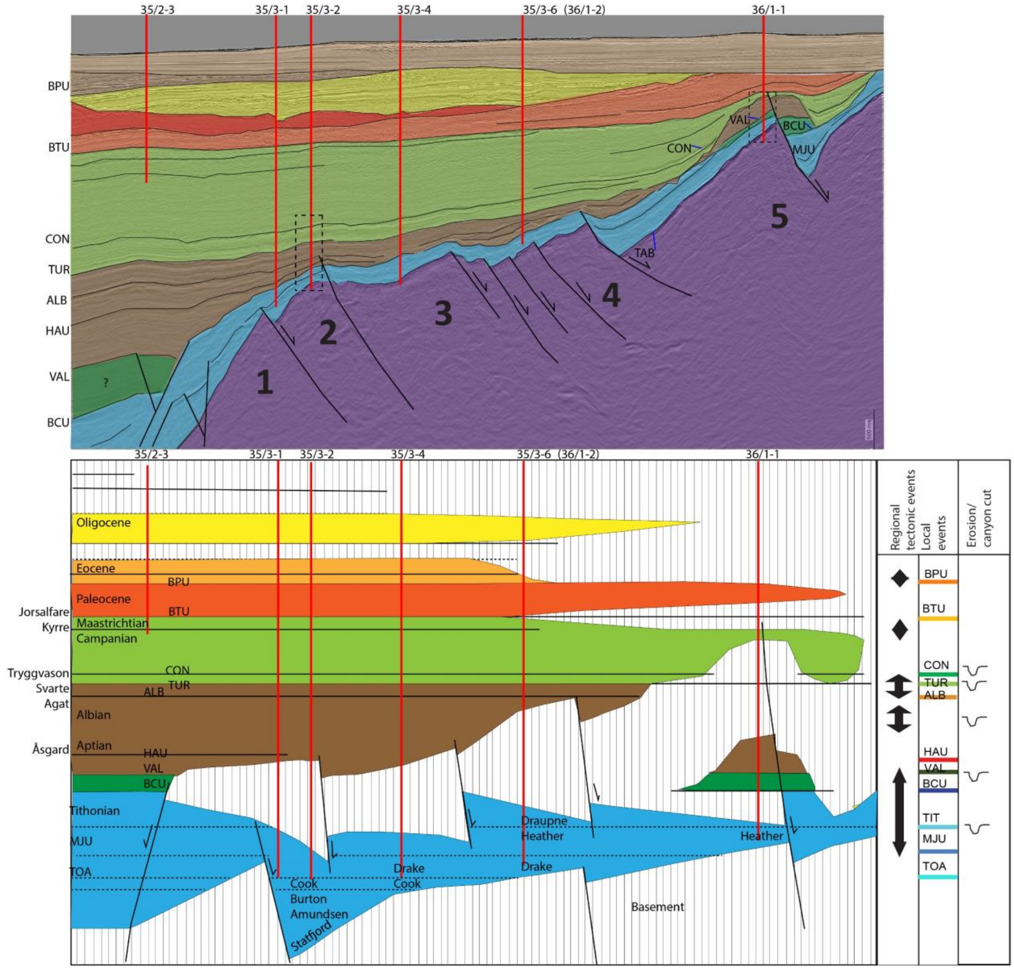

Figure 4. Interpreted random line, SW–NE through key wells in the Måløy Slope. The Wheeler diagram was made from the interpreted horizons and well information. Line location is shown in Fig. 3. The diagram indicates where sediments are deposited and preserved in relation to the fault-blocks of the Måløy Slope. Black squares indicate location of seismic used in seismic stratigraphy in Fig. 5. To the right the regional tectonic events and interpreted horizons and local incision events are shown. Abbreviation: TOA – the base of Toarcian–Aalenian sands. See Fig. 2 for more abbreviations.

During the Middle Jurassic–Early Cretaceous, mainly shales were deposited in the North Sea with periods of sand input (Steel, 1993; Ravnås & Steel, 1998). On the northern part of the Horda Platform (Fig. 1), the thick sandy Krossfjord, Fensfjord and Sognefjord formations were deposited at this time in coastal shallow-marine environments from drainage systems in the east (Patruno et al., 2014, 2015; Holgate et al., 2013, 2015). In the Måløy Slope (Fig. 3), the Oxfordian to Kimmeridgian setting was shallow marine with deposition of sand from the Norwegian mainland.

Cretaceous

For the most part, the Cretaceous (Fig. 4) was dominated by subsidence, transgression and burial of the Late Jurassic rift topography (Gabrielsen et al., 2001; Fig. 2). The northern North Sea basin and the Sogn Graben functioned as depocentres (Sømme et al., 2013a, b, c; Sømme & Jackson, 2013). Several episodes of increased sediment input have been described in the Cretaceous, such as Hauterivian, Barremian, Aptian, Cenomanian, Turonian and Coniacian (Skibeli et al., 1995; Sømme et al., 2013c; Figs. 4 & 5). It has been suggested that these episodes were related to late pulses of tectonic activity and short periods of regression within a general transgressive period (Bugge et al., 2001; Figs. 4 & 5).

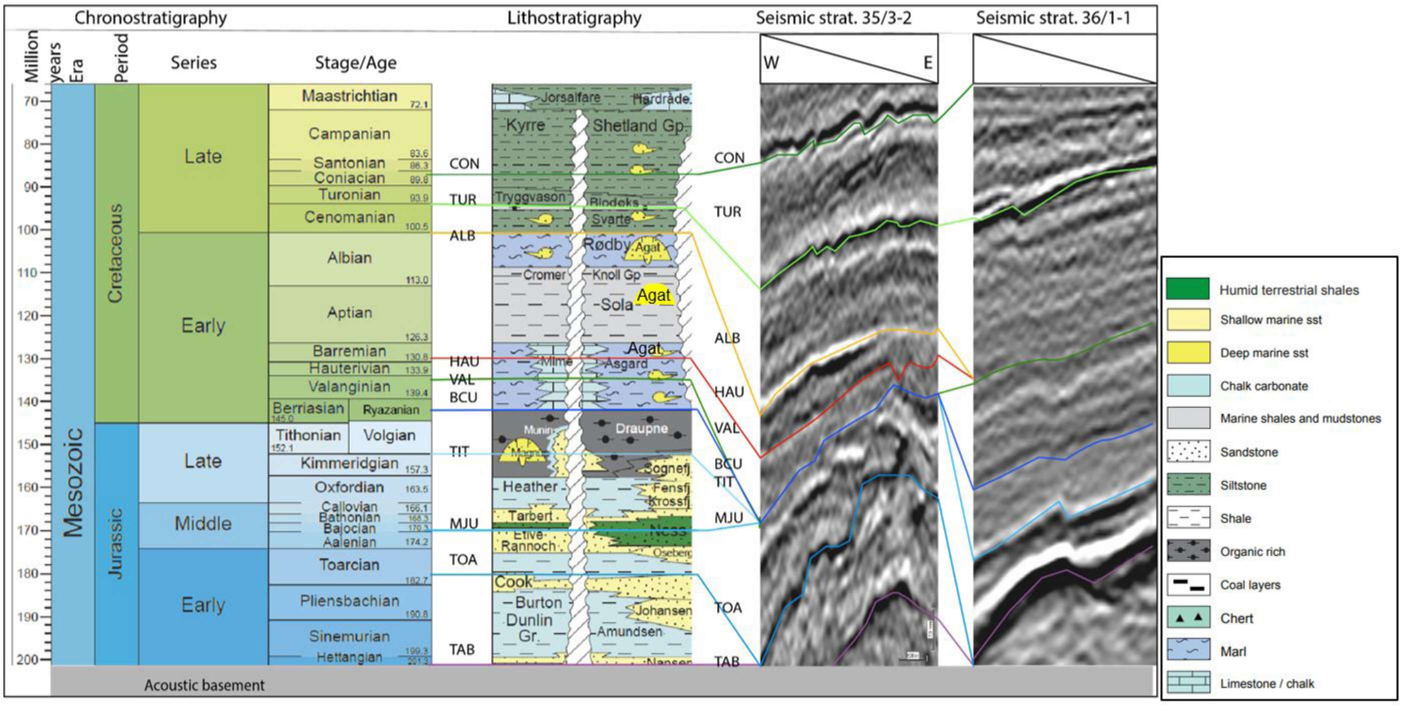

Figure 5. Stratigraphic framework of the Måløy Slope with the chronostratigraphic scheme from Gradstein et al., (2012) to the left and a lithostratigraphic scheme based on Gradstein et al. (2010), Færseth (1996), Martinsen et al., (2005), Jackson et al., (2008) and Sømme et al., (2013c). The seismic section goes through wells 35/3-2 and 36/1-1 (see well position in Fig. 3 & 4) and shows the interpreted horizons of this study. See Fig. 2 for abbreviations.

The Early Cretaceous Cromer Knoll Group consists of fine-grained marine sediments with pulses of limestone and sandstone deposits. The oldest part of the stratigraphy is represented by the Åsgard Formation (Barremian), which was deposited in the Sogn Graben and in local half-graben basins to the east (Fig. 3). The Måløy Slope was in general an area of bypass in this period (Bugge et al., 2001).

In the Barremian–Early Aptian, the main NE Atlantic rift system was centred on an axis running from the Rockall Trough through the Møre and Vøring basins offshore mid-Norway to the SW Barents Sea (Faleide et al., 1993). The major extension was much more focused and nearly reached continental breakup along the deep rift basins. Onshore, in the northwestern part of South Norway, uplift occurred in response to the lithospheric thinning (Sømme et al., 2013a, b) and associated heating along the inner flank of the adjacent SW–NE-trending rift system in the Møre Basin. The Late Aptian–Albian was a tectonic quiet period and deposition of deep- to shallow-marine claystone of the Sola Formation and mass-flow sand-deposits of the Agat Member (Copestake et al., 2003; Vergara et al., 2010; Fig. 5). The Agat Member is of interest for hydrocarbon exploration and has been the subject of several studies (Skibeli et al., 1995; Martinsen et al., 1999; Bugge et al., 2001; Martinsen et al., 2005). The Agat Member sands are tens of metres thick and the grain size is coarse. They are interpreted to have been deposited by turbidity currents during short periods of regression in E–W-oriented paleo valleys (Bugge et al., 2001; Martinsen et al., 2005).

Extension, rapid subsidence and filling of the Møre Basin in the Late Cretaceous may be associated with a new phase of uplift of adjacent onshore areas (Brekke, 2000). The top of the shaly Svarte Formation is a pronounced unconformity that can be interpreted across the Måløy Slope, marking a pronounced boundary to a period from Turonian to Coniacian with increased sand input to the basin. This unconformity coincides with the maximum eustatic sea-level reached in the earliest Turonian at 92 Ma (Haq et al., 1987; Haq, 2014).

Since the Santonian there has been only minor influence from the Late Jurassic–Early Cretaceous rift topography offshore (Gabrielsen et al., 2001). The fault relief on the Måløy Slope was filled during the Late Cretaceous by the Tryggvason Formation (Early–Middle Turonian; Fig. 5) and the Kyrre Formation (Late Turonian to Campanian). These formations consist mostly of shales, interrupted by few regional episodes of increased input of sands in the Turonian to Coniacian in the Måløy Slope and the Slørebotn Sub-basin (Sømme & Jackson, 2013; Sømme et al., 2013c). Such Turonian to Coniacian sands can be hydrocarbon reservoirs and are found along large parts of the Norwegian margin, for example as the Lysing Formation, in the Halten Terrace (Sømme et al., 2013c).

Methods

Seismic interpretation

Most of the offshore part of the study area is covered by a regional 3D seismic dataset acquired in 2014 and 2015, part of the CGG NVG 3D (Figs. 1 & 2). These data form the basis of the work presented in this study and are supplemented by an updated well database and detailed bathymetry data near shore and in the fjords.

The CGG NVG 3D seismic data used in this study are part of a regional broadband acquisition. The data were acquired in the N–S direction, with line spacing 12.5 m and recorded down to 9 seconds TWT corresponding to about 20 kilometres. The data have zero-phase and frequencies range from 0 to 240 Hz. The streamer length is 8200 m. Positive signal corresponds to an increase in acoustic impedance and is shown in black in the seismic sections. The dataset is pre-stack depth migrated (PSDM), with well calibration. Depth conversion uncertainty is estimated to be up to 10% down to top basement, based on known depths from the wells drilled in the area. Uncertainty increases with depth below the top basement. The PSDM depth data are shown in the figures and are used for estimation of sediment thickness and depth of canyons.

Well data

Fifteen exploration wells have reached the top of the basement surface within the study area (Fazlikhani et al., 2017; Lenhart et al., 2019; Fig. 3). In the Norwegian quadrants 35, 36 and 6204, 10 wells were used to identify episodes of erosion (35/3-2, 35/3-5, 35/9-1, 35/9-2, 35/9-3, 36/1-1, 36/1-2, 36/4-1, 36/7-2 and 6204/10-1). The well logs were included in a CGG well-study that followed the seismic acquisition project. In this study, the wells were preconditioned, velocities were updated, and new biostratigraphy descriptions and dating were made. The wells are tied to the seismic, which make the work with the many unconformities more reliable. In addition, two extra wells, 35/2-3 and 35/3-6, with original NPD tops, were used in the Wheeler diagram (Fig. 4). During this work the Presto (36/1-3) and Schweinsteiger (6204/11-3) exploration wells were drilled targeting the Krossfjord Formation and Åsgard Formation, respectively. The preliminary results from these were incorporated in the review process and biostrtigraphy was analysed by CGG Robertson to check the age of sediments on basement in the Presto well.

Seismic stratigraphy

The seismic stratigraphy with interpreted successions and boundaries is shown in Figs. 4 & 5. Despite its importance, the lack of preserved stratigraphy obscures the interpretation of timing of the

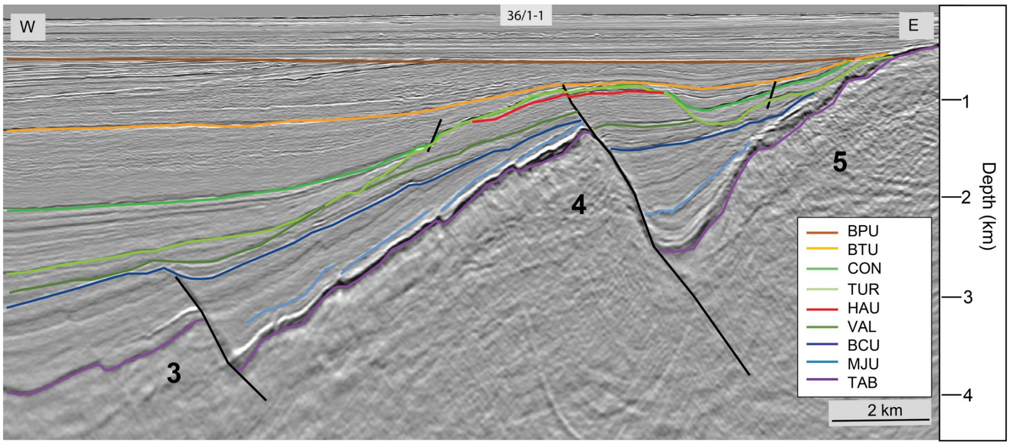

Figure 6. PSDM Depth-section, Crossline 35073, across fault-block 5 where well 36/1-1 was drilled. Note the thickness variations of the Jurassic deposits from the fault-block crest to the intra-slope basin.

incision. Consequently, the interpretation commencing with adjacent wells with preserved stratigraphy is fundamental. Locally, thick units of stratigraphy do not tie directly to well data, and correlation of seismically similar panels have therefore been used. This introduces some uncertainty; however, the presence of thick stratigraphic units most likely represents similar intervals as tested in key wells such as 36/4-1, 36/1-1 and 35/3-2 (Figs. 4, 5 & 6).

In most of the seismic data from the Måløy Slope, the top of the acoustic basement (TAB) can be clearly seen as a strong peak (purple horizon in this study; Fig. 5). It represents a change from Mesozoic sedimentary strata of low acoustic impedance to basement units of high acoustic impedance. Top acoustic basement here includes: 1) gneiss belonging to the Western Gneiss Region, 2) Caledonian allochthons and possibly 3) Devonian sediments differentiated on their acoustic properties. The strong amplitude associated with the top basement surface is less prominent westward, probably due to the increase in overburden thickness.

Wells show that the top acoustic basement surface is overlain by Jurassic and/or Cretaceous deposits in the northern part of the study area (north of the Gjøa Field; Fig. 3). From the wells that identify Jurassic strata directly on the top acoustic basement, only two (35/3-5 and 35/3-2; Fig. 3) have proven Lower Jurassic strata (Amundsen Formation). Four other wells (Fig. 3) have Upper Jurassic (Heather Formation) on the top acoustic basement.

In well 35/3-2, the base of Toarcian–Aalenian sands (TOA) shows a possible hiatus (Fig. 5). In the same well, a significant hiatus from Top Aalenian to Callovian is noticed (MJU), where the Brent Group is missing. The TOA and MJU events are shown for reference in some of the figures.

In general, the Upper Jurassic Heather Formation represents syn-rift deposits (Færseth et al., 1995; Ravnås & Bondevik, 1997). The formation consists mainly of grey silty claystone with streaks of limestone and local sandstones. In the area of the Gjøa Field (Fig. 3), two unconformities are recognised at the Jurassic/Cretaceous transition, the Tithonian and the Base Cretaceous Unconformity (Jackson et al., 2008; Sømme et al., 2013c; Sømme & Jackson, 2013; Jackson et al., in press; Tillmans et al., 2021).

The Tithonian Unconformity (TIT) is seen as an increase in acoustic impedance, produced by a change from the Draupne Formation with low acoustic impedance to the underlying Heather Formation with higher acoustic impedance. The deposition of the Draupne Formation represents a transgressive event, drowning the northern North Sea. In the study area, the base of this event is to a large degree eroded by Cretaceous processes.

The Base Cretaceous Unconformity (BCU, dark blue horizon in this study, Fig. 5) is picked on a soft seismic event representing a decrease in acoustic impedance from Cretaceous sediments to the Draupne Formation. Where the Jurassic is not eroded, the Cretaceous deposits are conformable with the underlying Jurassic deposits.

The Lower Cretaceous consists of deep marine shale and marl deposits of the Åsgard, Sola and Rødby formations (Fig. 5), interrupted by turbidity currents depositing sands locally. The sands are referred to as the intra Åsgard and Agat Member (Fig. 5). Within the Åsgard Formation, we have interpreted two soft events; Late Berriasian–Early Valanginian (VAL, dark green horizon in this study; Fig. 5) and early Hauterivian (HAU, red horizon in this study; Fig. 5). Both represent a decrease in acoustic impedance from shales with high carbonate content, to sands. The early Hauterivian sands are only locally preserved, as in well 36/1-1.

The Aptian to Albian and Turonian to Coniacian deposits are present in a larger area, documented in well 35/3-2 (Fig. 5). During the Aptian and Albian new pulses of sands were deposited, referred to as the Agat Member. The base of this member is an unconformity that represents erosion into the marine shales of the Åsgard Formation (Fig. 5). The base of late Aptian marks a major erosional event and the corresponding unconformity is seen as an increase in acoustic impedance (ALB, dark orange horizon in this study; Fig. 4). The Agat Member sands are seen as soft events locally in the deepest part of the basin.

The top of the Svarte Formation marks the Turonian unconformity (TUR, green horizon in this study; Fig. 5), a local unconformity seen in the Måløy Slope, Slørebotn Sub-basin and adjacent areas. It is represented by an increase in acoustic impedance giving rise to a strong peak in the seismic data. It marks the base of the Tryggvason Formation sands.

In the Coniacian (CON, spring green horizon in this study; Fig. 5) the base of the Kyrre Formation has many pulses of sands deposited, clearly seen in the seismic data.

The base Cenozoic (Tertiary) unconformity (BTU, orange horizon in this study; Fig. 5) is picked on a hard event, representing an increase in acoustic impedance from the Rogaland Group to the Upper Cretaceous Jorsalfare Formation.

The base Pleistocene unconformity (BPU, yellow horizon in this study; Fig. 5) can be recognised regionally as a soft event where the overlying succession consists of glacial material.

Results

Basement fault-blocks

The 3D seismic data allow detailed regional mapping of the top acoustic basement (TAB in Fig. 5) as seen in the structure map of this surface in Fig. 3. The map shows a high level of detail in the basement surface west of the coastal area. To visualise this surface in relation to the onshore bedrock structures it was juxtaposed with Norwegian mainland topography and near-shore bathymetry. The nearshore seafloor is covered by only thin Quaternary deposits, therefore the basement structures and the present offshore canyon systems outside the fjords of Norway are apparent (Fig. 3).

In the eastern flank of the Sogn Graben a set of faults lies parallel to the graben. These E to SE-dipping faults define a set of fault-blocks that dominate the morphology of the Måløy Slope. In the following, these fault-blocks are numbered 1–8 from west to east (Figs. 2 & 3). The faults of blocks 1–5 have a NNE–SSW strike and easterly dips (Fig. 3). The bounding fault of fault-block 6 is NE–SW striking with a southeasterly dip and can be correlated with the Bortnen fault at Bremangerlandet (Fig. 3). When tracing this fault toward the southwest, it merges into fault-blocks 4 and 5. Fault-block 7 is different from the other fault-blocks; there is no bounding fault to the east within the 3D area. In the west, it is bounded by a minor west-dipping fault forming a small graben with the fault bounding block 4.

The fault throws generally decrease southwards and terminate near the offshore continuation of the Haukå Fault (Fig. 3). Fault-block 3 continues southwards to the Gjøa Field (see well 35/9-3 in Fig. 3).

Intra-slope basins

Between the described fault-blocks, Jurassic stratigraphy is preserved (Figs. 4 & 5). A direct tie is not possible as these Jurassic layers are preserved only locally. From the wells drilled into the basement, the deposits onlapping basement are younger northeastward (Fig. 3). These observed deposits are conformable with the top basement surface and were deposited prior to faulting.

Canyons

From the basement interpretation (Fig. 3) the intra-slope fault-blocks are incised by canyons with a dominant E–W orientation, indicated by white arrows in Fig. 3. The canyons are identified by their erosional base, as seen in N–S sections (Fig. 7). In this work, we have interpreted these canyons based on angular relationships, younger stratigraphy onlapping older stratigraphy, at their erosional base. In addition, erosional surfaces observed in wells are used. In this area, there were many episodes of erosion at several parts of canyon incisions.

Our interpretation, based on well data and regional interpretation, is that the canyons were active during time intervals represented by missing stratigraphy. Based on the 10 CGG wells, we identify the following unconformities: Toarcian (TOA), Bathonian (MJU), Callovian, Oxfordian, Kimmeridgian, Tithonian (TIT), Berriasian (BCU), Valanginian (VAL), Barremian–Hauterivian (HAU), Aptian (APT), Albian (ALB), Cenomanian, Turonian (TUR) and Coniacian (CON). We have focused on the preserved Jurassic deposits and their relationship to the Cretaceous erosional events.

Based on the erosional features observed at the basement surface, the study area is subdivided into canyons A–E (Fig. 3). It is apparent that the canyons have eroded into basement at the fault-block crests (Fig. 7; Line X and Line Z), but in the deepest parts of the intra-slope basins the top acoustic basement is not eroded (Fig. 7, Line Y). In the following, areas A–E will be described spatially from north to south.

Canyons A and B

Three random lines are shown in Fig. 7 to examine the differences in erosion between the fault-block crests and the intra-slope basins. Canyon D^1 (Fig. 7, Line X) shows erosion into the TAB below the MJU. We also observe Early Cretaceous erosion into the BCU at canyon C. North of the Bortnen fault, along the crest of fault-block 5 (Fig. 7; Line X), two canyons have eroded into the basement. These are canyons B^1 and B^2. Note that the Base Cenozoic Unconformity (BTU) seems to follow the topography of canyon B^2 in fault-block 5 (Fig. 7; Line X). Canyon A is not covered by the 3D seismic at this fault-block.

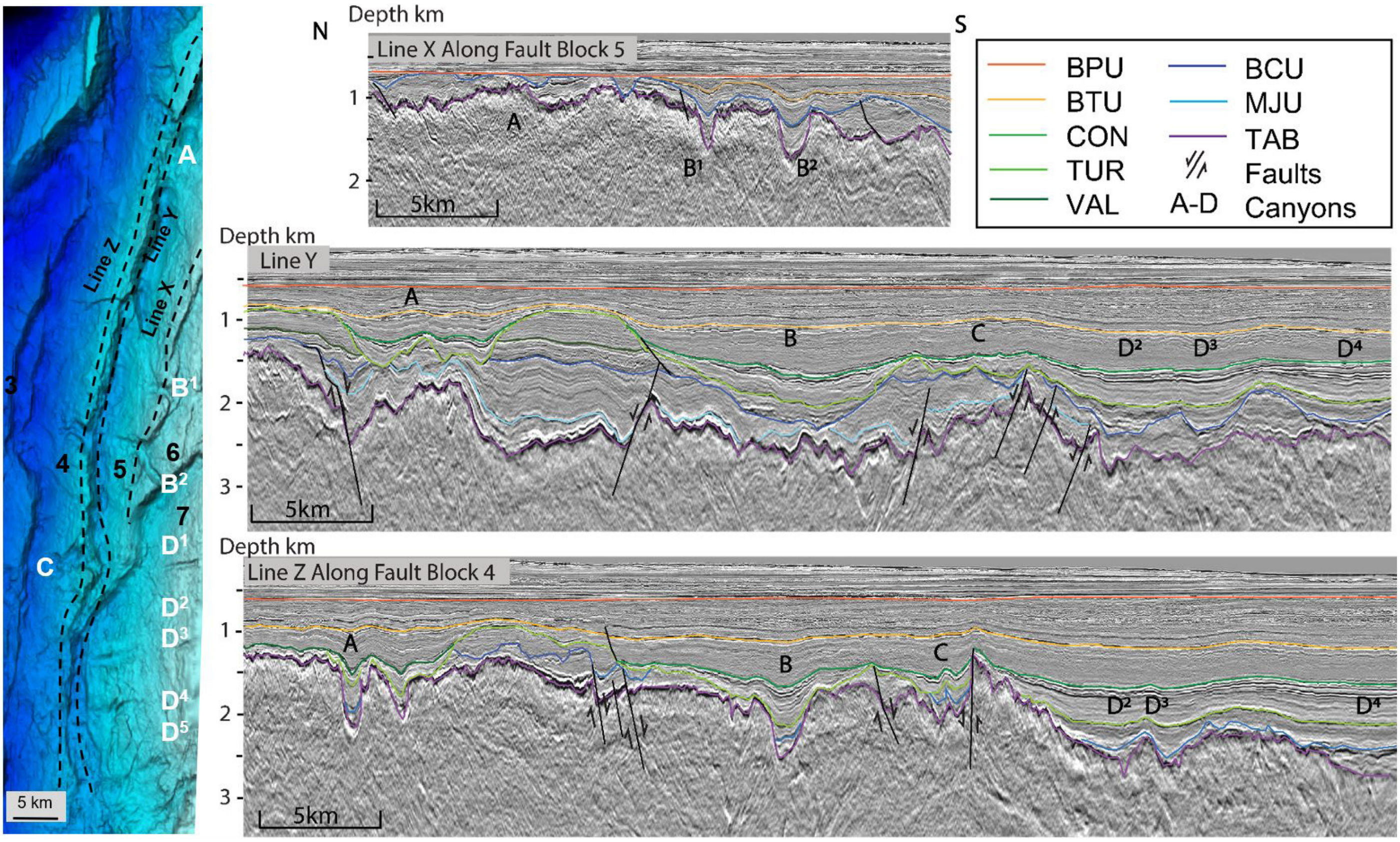

Figure 7. Three random PSDM Depth-sections along fault-blocks 4 and 5, positions indicated on the TAB map to the left (see location in Fig. 3). Line X goes along the crest of fault-block 5. This fault-block is incised by canyons B¹ and B², merging toward the next fault-block to the west. Note the depressions following the Cretaceous canyon seen at the BTU level. Line Y shows a parallel line in the intra-slope basin upflank and shows the Cretaceous canyons incising Jurassic strata, but not reaching the basement. Line Z goes along the crest of fault-block 4, and shows that the basement is incised by canyons A and B. See Fig. 2 for abbreviations.

In the intra-slope basin down-flank/east of fault-block 4 (Fig. 7; Line Y), the canyons A and B are wide, and between them are thick units of Jurassic and Early Cretaceous stratigraphy, tested by well 36/4-1. The wide canyons represent the Turonian to Coniacian erosion, which in canyon A has eroded into the BCU and VAL. In canyon B², the BCU and TUR can be recognized. The canyons associated with the Turonian erosion may overprint the Early Cretaceous canyons. Similarly, the Early Cretaceous erosion may overprint Late Jurassic erosion. The exact age of sediments deposited in the canyon B are found to be Late Aptian (Sola Formation) in well 36/1-3.

In the crest of fault-block 4 (Fig. 7; Line Z), canyons B¹ and B² merge into one canyon B. The canyons A and B cut up to 800 m into the basement. They are narrow (2.5–4 km wide), U-shaped at the base and represent erosion at the BCU level. Canyons A and B were eroded in (at least) two different periods (Early Cretaceous and Turonian to Coniacian), where the latter represents a 12 km-wide valley in canyon B². The thickness of sediments between the top acoustic basement and the Base Cretaceous Unconformity varies within the study area (Figs. 6 & 8) due to the presence of syn-rift deposition, erosion and infill of rift topography. From the thickness map of the Jurassic (Fig. 8A), we observe thick Jurassic strata preserved along (at least) four intra-slope faults (3, 4, 5 and 7) between canyons B² and C (Fig. 8B), whereas the strata are missing in the line along canyon C (Fig. 8C). The red horizon represents the base of the Lower Cretaceous canyon events in the Hauterivian–Barremian. The map

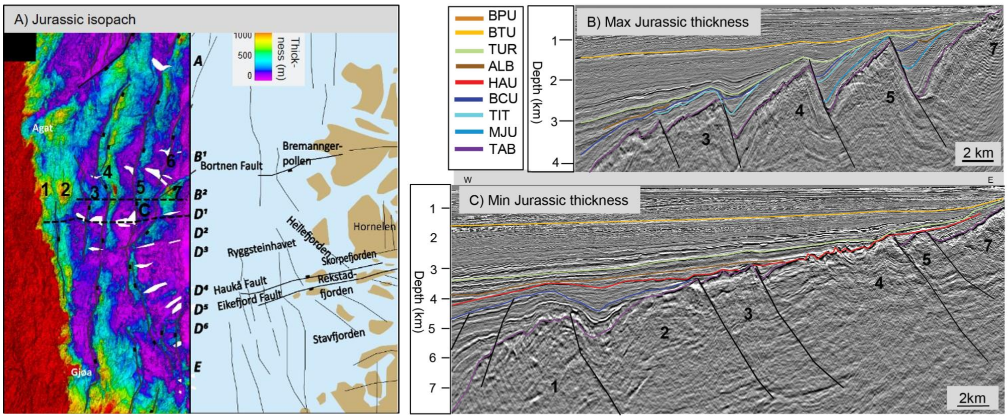

Figure 8. (A) Isopach map of the interval between the top acoustic basement and the Base Cretaceous Unconformity. This shows that the Jurassic thickness is varying both due to rifting and significant erosion. For reference see the intra-slope fault-blocks 1–8 and canyons A–E in Fig. 3. Red areas show where the top acoustic basement is incised. NSDZ – Nordfjord–Sogn Detachment Zone. Location of the Agat discoveries and Gjøa Field is indicated. (B) Cross-section across intra-slope fault-blocks 3, 4 and 5 showing erosion of the top of the Jurassic deposits. Dashed line in Fig. 8A shows the location of this cross-section. (C) Cross-section along the deepest part of canyon C, see location in Fig. 8A. The erosive base of the canyon, shown in red marks the base of the Agat Member and is of Late Albian–Early Aptian age. Note that the canyons incise fault-blocks 2, 3, 4 and 6 and Jurassic sediments in the basins between these. Toward the west the canyon incises Early Cretaceous sediments. The base of the canyon marks the base of the Agat Member sands.

(Fig. 8A) also shows thickness variation across the fault-blocks representing both syn-rift deposition and erosion at the uplifted part of the fault-blocks. More specifically, the preserved Mesozoic deposits between canyons A and B² probably represent the local thickness of this succession prior to incision. The Jurassic deposits are on average 200 m thick at the top of the fault-block 4 (Fig. 6) and up to 1000 m thick in the intra-slope basin (Fig. 6).

The Turonian Unconformity (TUR) is well preserved in the west (Fig. 9A). In the east, the thickness of the sediments between the TAB and TUR is thin and the uncertainty of timing is large, therefore the TAB is displayed here. The mapped TUR surface can be interpreted as representing a slope setting with abrupt uplift that led to erosion of unstable deposits. The canyons on this slope followed the existing topographic lows. From the flat shelf in the east, sets of gullies merge into larger incisions. Note that the canyons are guided by the basement fault-blocks until they reach an established incision (Fig. 9). From this point, the erosion progressed along the older established canyon to the deeper part of the slope in the west. The edge of the shelf shows scarps where instable deposits have been transported down the slope. Between the Selje High and fault-block 4 there was a NNW–SSE-trending drainage barrier where the trend of canyons/gullies split in two new directions: northeast into the Slørebotn Sub-basin and southwest into the Sogn Graben. A close-up of the structure map is shown without interpretation overlain in Fig. 9B.

In relation to Turonian erosive canyons (Figs. 9 & 10) there are large side-wall collapses, interpreted as slumps. These are 1–2 km wide, 200–300 m thick, have little internal reflectivity and the primary sedimentary layering is disturbed. The base of the slumps has a concave-up shape (Fig. 10).

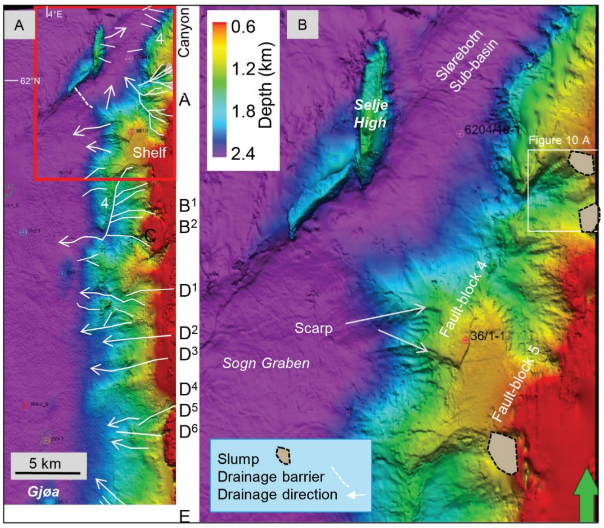

Figure 9. (A) Structure map of the Turonian Unconformity as seen in Fig. 5. In the east, the paleoshelf is represented by a relatively flat surface. Westward this surface is eroded, and we observe numerous gullies, see white lines and close-up. These gullies merge and find common routes through the remnant rift topography. Note scarps along this shelf edge. Between the Selje High and the shelf edge in the east a barrier is seen where canyons lead toward the south or the north. The locations of canyons A, B1–2, C, D1–6 and E and the intra-slope fault-blocks are shown. Note that the fault-blocks in the west (1, 2, 3) are buried, but that fault-block 4 has influenced the path of the canyons. (B) This is a close-up of the northern part shown in Fig. 9A with the details interpreted.

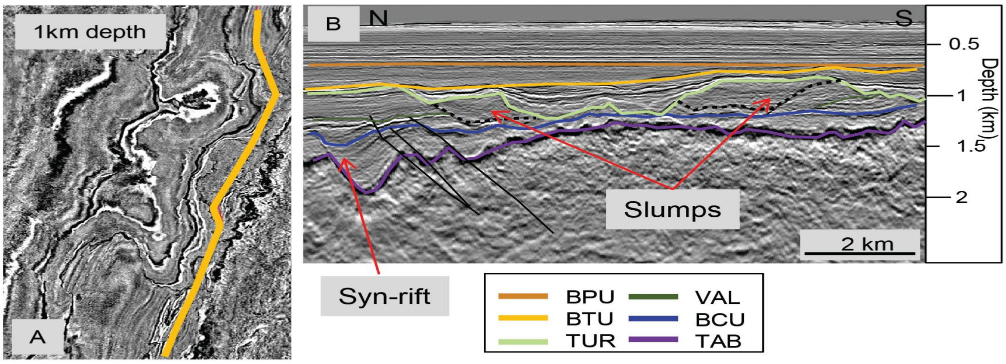

Figure 10. (A) Depth slice at 1 km at the where canyon A is observed, see location in Fig. 9B. (B) Seismic section across canyon A, see orange line in Fig. 10A for location. The section shows large slumps in relation to the Turonian canyons.

Canyons C–E

Canyon C is seen from fault-block 4 and westward (Fig. 3). A random line along the main canyon is shown in Fig. 8C, where the base of the canyon is marked with a red line. The interpreted base of the canyon has incised fault-blocks 2, 3, 4, and 6, making this the most erosive canyon identified in this study (Fig. 11). It has also eroded sediments of the Åsgard Formation (HAU) in the deeper basin in the west and the flanks of the Jurassic deposits in the intra-slope basins. The canyon is infilled with Cromer Knoll deposits, and was active in the Barremian.

West of Florø, canyons $D^{1–6}$ erode into fault-block 7 over a 25 km-long area (Figs. 3 & 12). The basement surface is incised by at least five canyons. Canyons D^1, D^2 and D^3 are ~1 km wide, up to 300 m deep, U-shaped and can be seen over a length of 12 km. Canyons D^4, D^5 and D6 are closer spaced, each canyon is 1 to 1.5 km in width and has eroded 350 m into the basement. Between the canyons, there are remnants of Jurassic pre-rift deposits (Fig. 8A).

Between canyon D^6 and E there are Late Aptian–Albian canyons cutting into the Jurassic sediments, but not into the basement. Canyon E is found in the southeasternmost corner of the study area. Here, several WNW-trending Late Aptian–Albian canyons cut into the basement in a limited area.

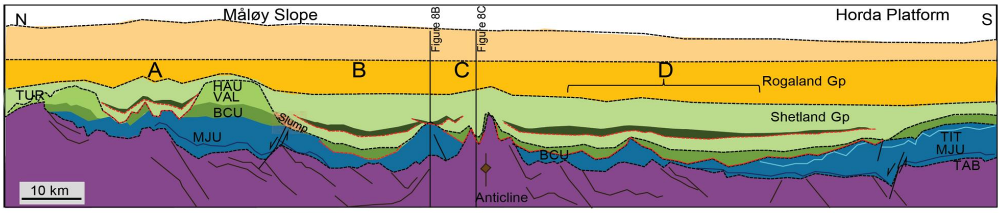

Figure 11. Interpreted line-drawing along a central intra-slope basin (see location in Fig. 3). The canyons discussed in the text can be seen here, the two major periods of active erosion and deposition and the intra-basement structures observed in seismic are indicated. Colouring as in Fig. 2. Note the anticline in the basement below canyon C. The thinning of the Jurassic deposits toward the position of canyon C is apparent.

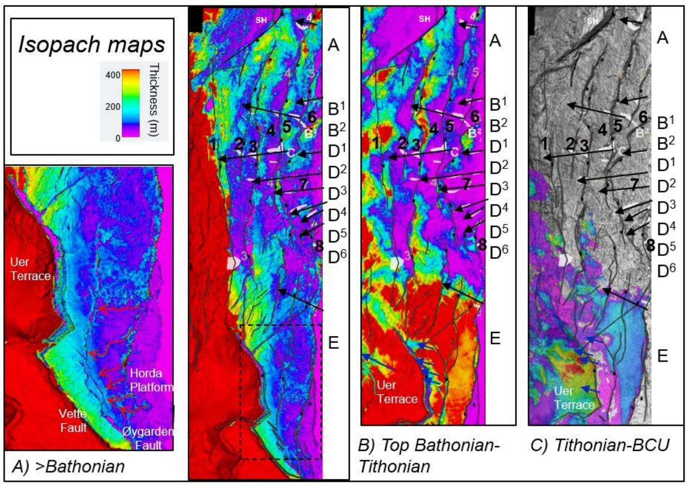

Figure 12. Stratigraphic isopach maps from three Jurassic intervals. All maps show the basement incisions in white polygons, with the canyons shown in the results indicated (A–E). The colour-bars are adjusted to show the small accumulations (0–400 m thick). (A) Isopach map of the TAB–MJU shows the preserved stratigraphy below the MJU (Bathonian). The image to the left is a zoom of the stapled area on the figure to the right to focus on a channel-system on the Horda Platform with sediment transport away from the faults in the east toward the west (red arrows). In the Måløy Slope we see an uneven distribution of the Bathonian (and older) sediments. (B) Isopach map of the MJU–TIT showing the distribution of Heather Formation and intra Heather sandstones. Purple color is where this interval is not present. The upper Jurassic canyons on the Uer Terrace are clearly eroding this interval (blue arrows). This map show how the Heather Formation is unevenly preserved on the Måløy Slope. (C) Isopach map of the TIT–BCU in the south and Basement map in black/white in the background. This map shows the Tithonian deposits filling the canyons in the Uer Terrace. It also shows the lack of good regional consistent reflectors from Upper Jurassic in the Måløy Slope.

Isopach maps

We have not studied the Late Jurassic Unconformities in the Måløy Slope, but we have interpreted the MJU (Bathonian), the TIT (Tithonian) and the BCU (Berriasian) horizons where evident (Fig. 11). The map in Fig. 8A shows the total thickness of the Jurassic sedimentary sequences between BCU and TAB. It demonstrates how the Jurassic stratigraphy is preserved between the fault-blocks and between the canyons. There are also thickness variations across the fault-blocks indicating some syn-rift deposition in the Jurassic, but some of these are also due to erosion on the crest as seen in well 36/4-1 (Fig. 4). To explore the details of the Jurassic depositional and erosional configuration, the Jurassic strata were divided into three units (Fig. 12). The purple colour indicates lack of strata. Fig. 12A shows the thickness between TAB and MJU (Bathonian). In the south and west this includes Triassic deposits, but across the Måløy Slope it represent uniformly deposited Lower Jurassic strata decreasing in thickness on the middle of the slope and onlaps the basement surface from north and south. This indicates that this part of the slope has been elevated compared to the surrounding parts. We can see some canyons incising the basement surface at the Horda Platform in the south (see close-up red arrows in Fig. 12A).

The isopach map from MJU (Bathonian) to TIT/BCU (Fig. 12B), indicates that significant deposited strata are preserved in patches across the slope. This would include the undefined intra Heather formations such as Krossfjord, Fensfjord and Sognefjord formation equivalents. The lack of confident interpretaton of the TIT unconformity leaves some uncertainty in the isopach map of the Tithonian–Berriasian in Fig. 12C. Therefore, a TAB structure map in grey shading is shown in this area. The map shows infill of the large Tithonian Jurassic canyons across the large fault bounding the Uer Terrace south of our study area. Northward (adjacent to canyon E) there are several incisions at the west-dipping faults.

Discussion

In the following section, the observed canyons are discussed in relation to the source area and paleo-topography from the Late Jurassic until the Late Cretaceous. We also discuss the locations of canyons in relation to near-shore bathymetry, fjords and valleys — as well as basement structures. Correlations with regional tectonic events and related structures are discussed in relation to potential processes that may have contributed to vertical motions causing uplift of source area(s) onshore and subsidence in the sink(s) offshore.

Source to sink evolution

In this work, we have shown that the intra-slope basins of the Måløy Slope have an up to 1000 m-thick, succession of Jurassic strata (Figs. 6 & 8). Disregarding thickness variations across faults, we observe a thinning (due to erosion) of the Jurassic stratigraphy toward canyon C (Fig. 8C), from both the north and the south. This indicates that this area was the most elevated part of the Måløy Slope during the many periods of erosion.

In the northern North Sea, several intra Heather Formation (Middle–Late Jurassic) sandstones have been documented. They are of mainly Middle Jurassic (the Bathonian Krossfjord Formation and Callovian Fensfjord Formation) and Upper Jurassic (the Oxfordian–Kimmeridgian Sognefjord Formation and the Tithonian 'Hardangerfjord unit') age. There are also systems of turbidites related to these established formations.

On the Måløy Slope, there are a few wells where the Bathonian and Callovian sands are present. Well 36/1-2 (Fig. 3) has Bathonian sand deposits overlying weathered granite or gneissic basement deposited in the distal part of a delta in a northwesterly direction on a NW-dipping paleo-slope. The direction could indicate a source area in the Førdefjord region (Fig. 3). Adjacent, 35/3-5 has 11 m of Bathonian Krossfjord equivalent sand, while 35/3-2 suggests 9 m of attenuated Callovian intra Heather Formation. Intra Heather proximal sands of Bathonian and Callovian age are also reported in 36/1-1, while siltstone of late Callovian age is suggested (uncertain) in 36/4-1 from the composite log. We suggest that a similar setting was valid at the Måløy Slope in the Middle Jurassic with a possibility of sand deposition close to the shore and turbidite depositions in the shallow-marine sink.

Apart from three wells with Oxfordian strata (17 m mudstone in 36/4-1, 60 m marls and sand in 36/1-2 and hints in the log of 35/3-4), the Late Jurassic stratigraphy of the slope is not well constrained. We have therefore applied learning from recent studies in the proximal south, where Late Jurassic drainage systems and incising canyons were described by Sømme et al., (2013c), Jackson et al., (in press) and Tillmans et al., (2021). It is generally assumed that in the Oxfordian, the major onshore relief was located far inland, 120 km from the coast, near the inner part of the present Sognefjorden, without being too influenced by the rifting in the northern North Sea (Sømme et al., 2013c). The Sognefjord

Formation was deposited on the Horda Platform, west of Sognefjorden. A time-equivalent unit to the Sognefjord Formation is observed in the deeper parts of the Måløy Slope and in the Sogn Graben, but the source area of this sand deposit is not known (Sømme et al., 2013c). A similar but slightly younger (Kimmeridgian–Tithonian) system was deposited west of Hardangerfjorden, 'the Hardangerfjord unit' (Sømme et al., 2013a).

Furthermore, in well 6204/11-2 (in the Slørebotn Sub-basin), another time-equivalent Sognefjord Formation deposit was discovered. Evidence of ocean-currents from north to south (Patruno et al., 2014) indicates that these deposits were not sourced from the Sognefjord region.

The amount of coarse sediment deposited in the Sognefjord Formation (Oxfordian) and later in the 'Hardangerfjord unit' (Kimmeridgian to Tithonian), suggests that the topography may have been as high as 1500–1600 m for a longer period in the Late Jurassic, according to Sømme et al., (2013c). These authors also suggest a shift of the onshore drainage from the Sognefjord region toward the Hardangerfjord region in the Oxfordian to Kimmeridgian. At this time, the Måløy Slope was covered by shallower waters and was probably also more prone to erosion by turbidity currents. The source for the Upper Jurassic deposits on the Måløy Slope was probably either transported from local highs or from the mainland in the east.

The onshore topography was lower but still significant in the Early Cretaceous. The Sogn Graben was getting deep in the Berriasian, while the fault-blocks that formed during rifting were elongated islands and barriers on the Måløy Slope (Gabrielsen et al., 2001).

The observed canyons incised into the basement at the fault-block crests, but not in the intra-slope basins, as demonstrated in Figs. 3 & 8. In the intra-slope basins, only the Late Jurassic–Early Cretaceous deposits are eroded. The episode of deep erosion into the basement of the fault-block crests must have occurred after the Late Jurassic phase of rifting. The canyons are E–W oriented regardless of the existing fault-block barriers (Fig. 3), therefore the energy level must have been high. The significant required difference in elevation between the source and the sink indicates that the major period of basement incision was before the Early Cretaceous transgression and subsidence of the source area.

Once established, the system was re-used repeatedly. This was particularly important in the Aptian–Albian, when the Agat Member sands were transported across the Måløy Slope, as demonstrated in Fig. 13A–E. At the base of the stratigraphic interval (Fig. 13B) there was a major transport route westward from Canyon B[1]. This seems to represent a well-defined route for high-energy sediment transport. Fig. 13B also shows increased amplitudes and lobe shapes west of canyons A, B, C and E. Similar trends are seen in Fig. 13C–E, where all attribute maps show lobe- and channel-shaped features across the Måløy Slope. The lobes seen in relation to canyon A seem relate to the deposition of the Agat Member sands.

The global eustatic sea level rose in the Late Cretaceous and reached its maximum of ~240–250 m above present-day mean sea level in the early Turonian (Haq, 2014). The coastline was probably located close to its present position, with the highest onshore topography in the Møre area (Sømme et al., 2013a, c). The water depths were shallow into the North Sea basin, and the rift topography at the slope was less prominent than in the Early Cretaceous (Gabrielsen et al., 2001).

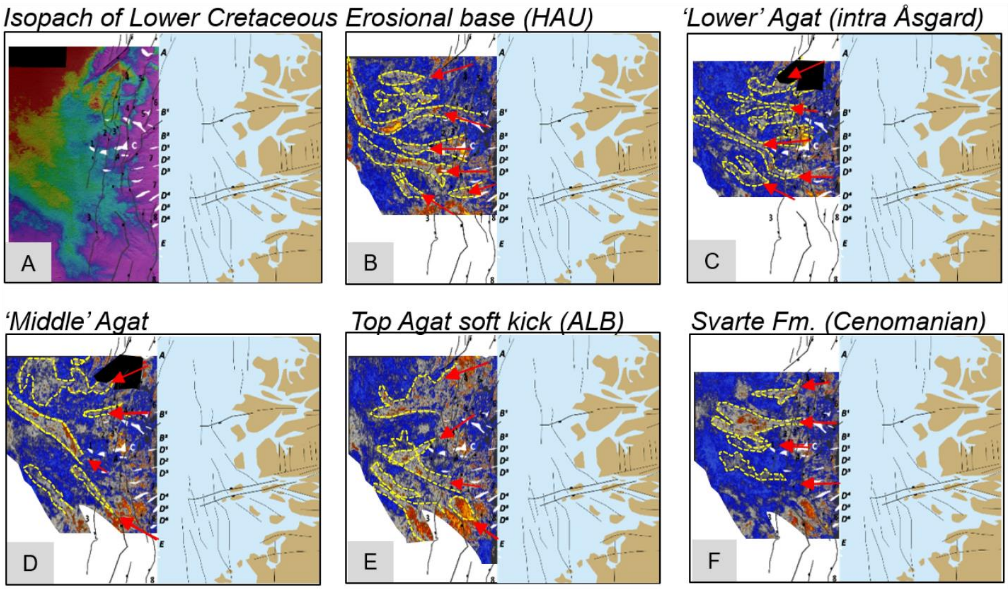

Figure 13. In background a simplified onshore map shows Norwegian mainland in beige and some faults (from Fig. 3). The basement incisions are shown by white filled polygons and red arrows where we note the different canyons have been active. The sweetness attribute is interpreted, see yellow stippled lines. (A) Isopach map of the Lower Cretaceous deposits. Purple represents not present. Note the thickness increase toward the NW. (B) Sweetness attribute of Barremian erosional event (HAU). This is a peak reflector in the seismic and may represent more than one event. (C) Sweetness attribute of 'Lower' Agat event intra Åsgard Formation. (D) Sweetness attribute of a 'Middle' Agat event intra Åsgard Formation. (E) Sweetness attribute of the top Agat soft kick (ALB). (F) Sweetness attribute of the top Svarte (Cenomanian).

Canyon locations

The canyons were created by gravity flows that initiated when sediments from the rivers onshore reached the sea (Harris et al., 2011; Tillmans et al., 2021; Fig. 3). The locations of the rivers in the east are influenced by structures in the underlying bedrock. As known from onshore mapping, the basement is lithologically and mechanically heterogeneous (Krabbendam & Dewey, 1998; Tucker et al., 2004; Fossen, 2010; Fig. 1). Heterogeneities that may influence the drainage pattern and the position of rivers onshore include dipping or vertical structures such as faults, lithological contacts, foliations and shear zones. It is known from basement wells in the area (Fig. 3) that the transition from crystalline basement to sediment can be gradual in some areas due to weathering (Lenhart et al., 2019). Weathered basement will be more prone to erosion, hence the deposition of sediments on the basement surface will be influenced by the basement structures. It is believed that the positions of several of the present fjords and their offshore continuations (Fig. 3) are controlled by ancient rivers (Nesje, 2010). However, the basement in the Måløy Slope was covered by Jurassic sediments prior to rifting and the basement influence of the canyons was less important then.

From onshore towards the west, the rivers were linked with submarine canyons that transported the sediments farther westward (Jackson et al., 2008; Sømme et al., 2013a; Sømme & Jackson, 2013; Jackson et al., in press; Tillmans et al., 2021). When the positions of such canyons are stable, and the energy level is high, the sediment transport is restricted to these positions and can further erode down into the underlying rocks.

The basement structures of the Måløy Slope and onshore are dominated by upright E–W-trending Devonian folds, seen as a set of synforms and antiforms (Lenhart et al., 2019). These basement structures have influenced the faults observed on the slope. The offshore basement was buried by sediments prior to the establishment of the deeply eroding canyon system, and the orientations of the canyons were directed toward the deep basin in the west, and not influenced by bedrock structure. However, the onshore part of the drainage systems was more directly influenced by basement structures. In order to examine the onshore-offshore connection we discuss some bedrock/canyon relationships in the following. Canyons A and B^1 are located at faults on the southern flanks of Devonian antiforms (Fig. 7), while canyon B^2 is observed on a basement synform. Canyon C is observed on top of a basement antiform (Fig. 11). Canyons $D^{1–6}$ follow the southern flank of a large basement antiform. To summarise, the foliation of the basement rocks seems to coincide with the direction of the paleo sediment transport. The erosion into the basement rocks is observed at the flanks of large antiforms and synforms.

A possible connection to the fjords seen in the east and in the bathymetry is discussed from north to south in the following. The bathymetric data linking the onshore and the area covered by the seismic (Fig. 3) indicate that the onshore Bortnen fault extends offshore (Fig. 3), where it has reactivated the flank of a basement antiform. Our interpretation indicates that it was active in the Early Cretaceous during deposition of the Åsgard Formation. The sediments were routed along the fault while it was active, until the accommodation space was filled, at which point the canyons were again led westward in the already established E–W trend of canyon C.

In the north, the bathymetric continuation of Nordfjord diminishes westward and is covered by sediments before reaching the seismically mapped basement (Fig. 3). We can therefore not evaluate any potential connection between the inshore Nordfjord and canyon A. A modern bathymetric canyon is not seen in relation to canyon B^1. Farther south, the submarine extension of Bremangerpollen may correlate with canyon B^1, despite a gap in the seismic coverage of sub-sedimentary fault-block 6 (Fig. 7). The B^2 canyon is almost at a 90° angle to the Bortnen fault and does not correlate with any specific bathymetric feature.

The canyons seen in the bathymetry of Frøysjøen merge with Hellefjord (Fig. 3) to a prominent bathymetric canyon west of the Hornelen Basin. It has the same E–W trend as seen in canyon C (Fig. 3). We do not see incisions on the basement crest of fault-block 6 here. The erosion has intersected the offshore continuation of the Bortnen fault, resulting in canyon C.

South of the Eikefjord and Haukå faults, the bathymetry shows clear influence of N–S-oriented faults and submarine canyons, in contrast to the area north of Frøysjøen (Fig. 3). Canyon D^4 can be correlated to Skorpefjorden and Rekstadfjorden, which follow the trend of the Haukå and Eikefjord faults (Fig. 3). Canyon E is located west of Dalsfjorden and Åfjorden (Fig. 3) representing the southernmost canyon conveying deposits into the Agat depositional system (Copestake et al., 2003; Vergara et al., 2010; Fig. 14). The locations and orientations of the canyons coincide with the trend of Åfjorden (Fig. 3).

In summary, the observed positions of canyon incision in the basement fault-blocks correlate well with the positions of major present-day fjords and near-shore extensions of these. After the early Turonian erosion, the canyons never reached the basement surface in the area covered by the 3D seismic survey. The locations of the canyons seem to be the same in the Cenozoic, including the glacial periods.

Timing of incision

In this study, at least three major periods of incision are identified: (1) Late Jurassic–Earliest Cretaceous (Fig. 14A), (2) Late Aptian–Albian (Fig. 14B) and (3) Turonian–Coniacian (Fig. 14C). We will discuss timing below in relation to recent work/papers. The first two periods can be difficult to separate while the third is better expressed on the seismic sections (Figs. 6 & 11), probably due to it being the most recent of the three and thus eroding the previous erosional features.

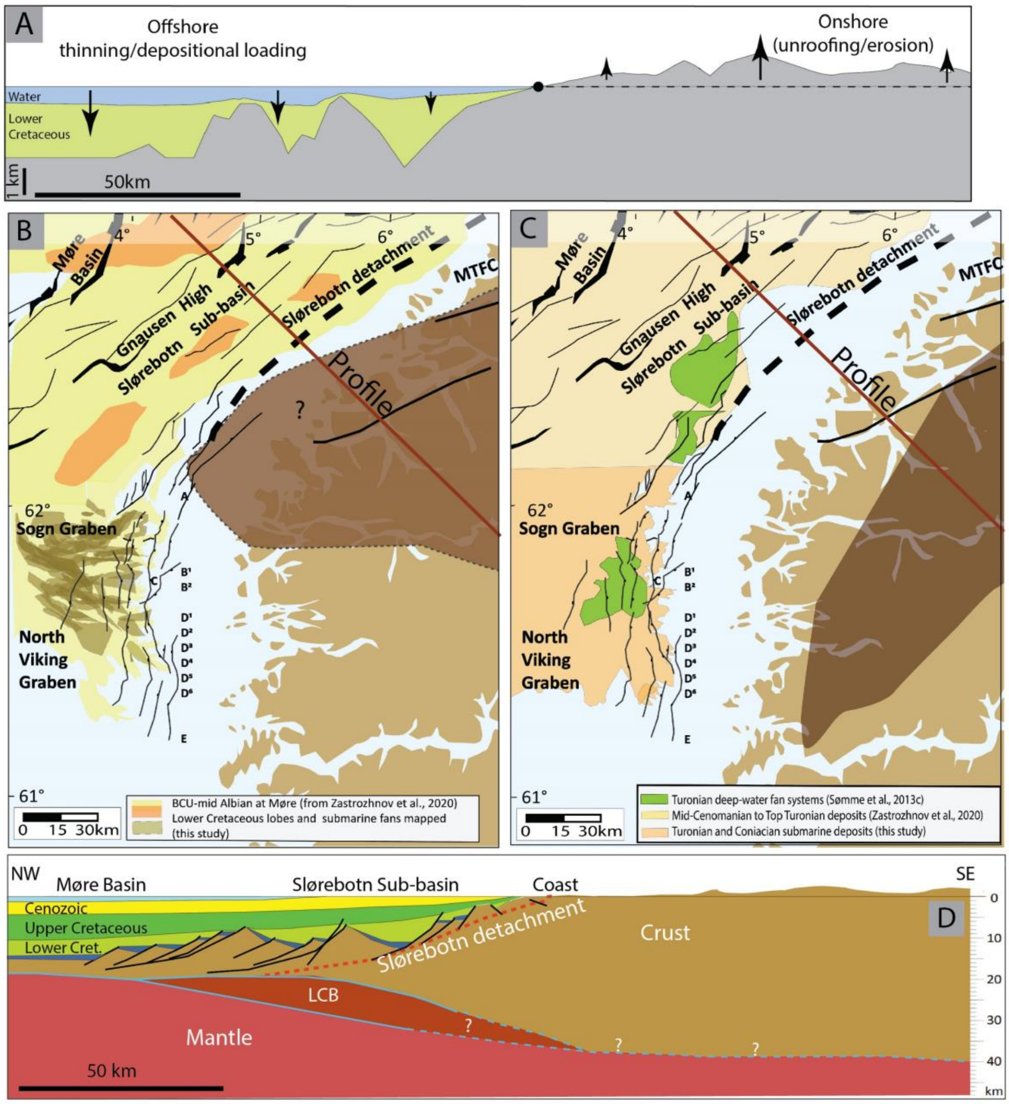

Figure 14. (A) Profile from the Møre Basin, across the Slørebotn Sub-basin, Møre–Trøndelag Fault Complex (MTFC) and the Norwegian mainland, representing a source-to-sink setting at mid-Cretaceous time. The location of the profile is shown in Fig. 14B, C. The intention of the figure is to show the long wavelength (flexural) response to unloading of the source area, leading to uplift onshore (black arrows pointing up) and loading and subsidence the offshore (black arrows pointing down). We suggest that most uplift is expected close to the coast in the Early Cretaceous, due to tectonic activity along the Slørebotn detachment and the MTFC. Black dot indicates hinge point. The subsidence increases away from the hinge point (black dot) toward the Møre Basin that also experienced crustal thinning and associated tectonic subsidence in the Early Cretaceous. (B) Regional map extended outside the study area to show the Early Cretaceous setting. The sediment distribution of the interval from BCU to Albian in the study area is from Fig. 13 while similar interval from Zastrozhnov et al., (2020) in the North. We propose elevated near-shore topography bounded by the northern part of NSDZ and the transition toward the Slørebotn detachment fault and MTFC. (C) The distribution of the Turonian and Coniacian interval from this study and Zastrozhnov et al., (2020), while the green polygons show submarine fan deposits as described by Sømme et al. (2013c). The onshore topography is also from Sømme et al. (2013a). (D) Crustal profile from the Møre Basin, across the MTFC to the Norwegian mainland, representing present setting. Profile location is seen in the maps in Fig. 14B, C. Sedimentary units in the basin are from Osmundsen & Péron-Pinvidic 2018; pre BCU (dark blue), Lower Cretaceous (bright green), Upper Cretaceous (green), Cenozoic (yellow), water (blue). Crust is beige, faults are black and Slørebotn detachment is red stippled line. The depth of Moho/Mantle and Lower Crustal Body (LCB) is from published data from profile2 in Kvarven et al., (2014). Uncertainty regarding the depth to Moho is indicated by blue stippled line.

In the southern part of the study area, the Middle–Late Jurassic erosional features and deposits are preserved, and recent literature (Tillmans et al., 2021; Jackson et al., in press) has described Late Jurassic unconformities and canyons here. The earliest recorded canyon mapped by Tillmans et al., (2021) is late Oxfordian. They also describe Kimmeridgian and Tithonian unconformities. Koch et al., (2018) described the two intra-Heather episodes of increased sand input in the Bathonian and Oxfordian. Jackson et al., (in press) describe the first canyons as Kimmeridgian, with reuse in the Aptian–Albian and Cenomanian. Based on the observed patches of Jurassic stratigraphy seen locally on the Måløy Slope (Figs. 8 & 12), our interpretation is that the slope was covered by Jurassic sediments prior to the Late Jurassic uplift and erosion. The canyons were first formed in the Late Jurassic, during similar setting and timing as seen in the proximal south, with patches of Upper Jurassic sediments deposited.

An important deepening of the canyons took place in the Early Cretaceous. The Lower Cretaceous isopach map (Fig. 13A) shows how these deposits were fed through the established drainage system. As described in this paper, the incisions from this period are especially important in the Måløy Slope due to tectonic events described later in the discussion. The preservation of deposits from this period is limited in the slope itself, but the amount of sediments deposited in and toward the Sogn Graben indicate that these were active repeatedly during this period. The sweetness attribute maps presented in Fig. 13B–E are from stratigraphic horizons of the Lower Cretaceous. Fig. 13B shows the base erosional unconformity (peak) representing the base erosion below the HAU (Barremian–Hauterivian) event. Three soft events indicating lobe-shaped features indicate three levels of Agat Member sands (Fig. 13C–E), where the lower one is intra Åsgard Formation (Fig. 5). The maps show how the canyons were re-used as feeders of sediments across the slope to the basin in Barremian, Aptian, Albian, and Cenomanian times.

Canyon architecture

Can the shape and depth of the canyon incisions help explain details of lithology or relief onshore or the structural framework of the rocks into which they erode? The canyons incising into the basement are U-shaped and vary in depth and width. The first observed episode of incisions created canyons A, B and C, which are 2.5–4 km wide and incise up to 500 m into the basement at the crest of fault-block 4 (Fig. 7C). These incisions are very local, and their proximity to the onshore relief could indicate that the fault-blocks of the Måløy Slope were part of an uplifted area at or close to the shore in a narrow shelf setting. Canyon C likely marks the most uplifted part of this slope at that time. The Jurassic strata are thinning toward canyon C, as indicated by the dark blue horizon of Bathonian age onlapping the top acoustic basement both from the north and from the south in Fig. 11.

Canyons D^{1-6} are 1500 m wide and 100 m deep and incise into the basement for a length of up to 12 km. This area appears more like a large erosional area, where no large fault-block crest has functioned as a barrier for the sediment flow.

The deposits from the Turonian to Coniacian periods have slope-fan geometry (Bugge et al., 2001; Fig. 9). The details of the early Turonian structure map show that the thick sedimentary unit corresponding to the Blodøks and Svarte formations (Fig. 5) is deeply eroded, probably as a direct response of a relative rapid sea-level fall. The sediments deposited before this event were unstable and easily eroded and seem to have collapsed gravitationally (Figs. 9 & 10). Some of the described incisions, canyons A–C (Fig. 3), have acted as routes across the basement ridges where the sediments have passed toward deeper parts of the slope (Fig. 9). These canyons do not seem to further erode into the basement but use the already established basement incisions. These canyons can be ~200–500 m deep (Fig. 10), while canyons D^{4-6} and E are less influenced by the rift relief and therefore less prominent at this time. Canyons D^{1-6} seem to have been erosional at that time too.

Processes controlling vertical motions

In this study, we have presented evidence of a history of repeated canyon incisions in the Måløy Slope. What are the reasons for this repeated history of incision? Vertical movements of the mainland (Fig. 14A) and the changing depths of the basin have given rise to variations in the offshore slope gradient and dip of the onshore drainage channels through time. There may be both tectonic and isostatic reasons for such vertical motions. The close temporal correlation between incision events and deposition of submarine fans downslope (Fig. 14B, C) from the canyons and regional tectonic events indicates tectonic control on source-to-sink relationships, including rejuvenation of source areas by tectonic/isostatic processes. Tectonically controlled rift flank uplift is the main process, affecting the Måløy Slope in both the Late Jurassic and the Early Cretaceous (Færseth, 1996; Gabrielsen et al., 2001; Bugge et al., 2001; Bell et al., 2014; Jackson et al., in press). Tectonically driven rifting resulted in parallel subsidence of the rift basin and uplift of the rift shoulder (Fig. 14A, Ravnås et al., 2000). This gives elevated rocks prone to erosion and creates accommodation space in the rift basin (Fig. 14A, Gabrielsen et al., 1990; Nøttvedt et al., 1995). The isostatic response to erosion in the source area is more uplift and erosion (Ravnås & Steel, 1998). In the sink, depositional loading will contribute to increased subsidence (Fig. 14A). Another response to rifting is thermal subsidence and a drop in sea-level. The change in sea-level is also influenced by climate (Nielsen et al., 2009). The erosion rates, and consequently sedimentation rates, are also affected by changing climate through time (Nielsen et al., 2009). All these processes influence the topography both onshore and offshore. Furthermore, the sediment supply to the basin is controlled by the distance to the hinterland (Ravnås & Steel, 1998).

During the Late Jurassic–Earliest Cretaceous the entire North Sea rift system was active. In the northern North Sea, rifting was centred on the Viking Graben and Sogn Graben. Uplift of flanking areas are documented both on the Norwegian and UK sides (Nøttvedt et al., 1995; Bell et al., 2014; Phillips et al., 2019; Claringbould et al., 2020). The uplifted areas worked as source areas for a large depositional system draining into the northern North Sea (Fig. 14A). The known drainage systems were coincident with the present Sognefjorden and Hardangerfjorden, and there were others in the Måløy Slope, indicated by the maps in Fig. 12. The highest relief in the Late Jurassic was probably close to the coast of West Norway during the final stage of the rifting (Sømme et al., 2013b), and thus the distance from the source to the sink was shorter giving rise to large sediment supply. In the Aptian and Albian, the topographically highest region was probably located quite far west, close to the Slørebotn detachment and Møre Trøndelag Fault Complex (Fig. 14B). The elevation was slightly lower now than in the Late Jurassic (Fig. 14D).

The widespread (regional) Late Jurassic–Earliest Cretaceous extension gave rise to stretching of the upper crust, brittle faulting, rotation of tilted fault blocks, and deposition of growth-wedges towards the main faults. These structural and depositional styles are characteristic for both the northern North Sea and the Møre Margin rift systems (Osmundsen et al., 2016; Theissen-Krah et al., 2017; Phillips et al., 2019; Claringbould et al., 2020; Zastrozhnov et al., 2020).

In the Early Cretaceous, most of the North Sea rift had aborted and entered the post-rift stage, but the northernmost North Sea area was still tectonically active — linked to large-scale extension in the Marulk, Magnus and Møre basins as part of the NE Atlantic rift system extending from the Rockall Trough to the SW Barents Sea (Faleide et al., 1993). The Early Cretaceous extension affecting the Møre Basin, as part of the North Atlantic rift system, resulted in rapid differential subsidence in the Early Cretaceous and accumulation of thick Lower Cretaceous depocentrers. Large-scale extension caused significant thinning of the crust, accommodated on deep-seated low-angle detachment zones, while the upper crust shows little evidence of faulting (Zastrozhnov et al., 2020 and references therein). In this rift system, fault reactivation occurred repeatedly throughout the Cretaceous (Neocomian, Aptian–Albian, Cenomanian–Santonian, Campanian–Maastrichtian; Zastrozhnov et al., 2020).

The most severe thinning occurred in the Aptian–Albian when the Møre Basin crust evolved from a 'stretching mode' in the Late Jurassic–Earliest Cretaceous to a 'thinning mode' in the Aptian to (mid) Albian (see Zastrozhnov et al., 2020). The thinning mode was associated with displacements up to 20–30 km on west-facing low-angle detachment faults (see Osmundsen & Ebbing, 2008; Osmundsen & Redfield, 2011; Osmundsen et al., 2016; Péron-Pinvidic & Osmundsen, 2020). This resulted in a sharp/narrow crustal taper on the Møre Margin (e.g., Osmundsen & Redfield, 2011) where the crystalline crust thins from more than 35 km onshore (MTFC) to <10 km in the Møre Basin over a distance of <100 km (Fig. 14D, Kvarven et al., 2014; Theissen-Krah et al., 2017; Osmundsen & Péron-Pinvidic, 2018).

The Early Cretaceous thinning phase must be the main reason for the observed difference in present-day crystalline crustal thickness between the northern North Sea (10–15 km; Christiansson et al., 2000) and the Møre Basin (3–5 km; Kvarven et al., 2014), since these two areas share the Late Permian–Early Triassic and Late Jurassic–Earliest Cretaceous rift history. The significance of the Early Cretaceous thinning phase on the Møre margin is also manifested in the subsequent phase of Late Cretaceous rapid regional subsidence, which was likely associated with post-rift thermal cooling (Zastrozhnov et al., 2020).

This extreme thinning and associated movements on the detachments of Early Cretaceous age must have impacted the tectonic and geomorphic evolution of the hinterland (Fig. 14D), causing uplift of the area south and southeast of the MTFC that sourced the depositional system along the Måløy Slope/Sogn Graben (Sømme et al., 2013a). This uplift resulted in new pulses of coarser sediment input and further erosion of the established incisions (Fig. 13, Skibeli et al., 1995; Bugge et al., 2001).

The most important proximal normal fault is the combined Slørebotn detachment/main Møre boundary fault (MMF) and the offshore parts of the Møre–Trøndelag Fault Complex (MTFC) (Fig. 14, Osmundsen & Ebbing, 2008; Osmundsen & Péron-Pinvidic, 2018). The Slørebotn Sub-basin developed as a supra-detachment half-graben in the Late Jurassic (Osmundsen & Ebbing, 2008; Jongepier et al., 1996) and was active through the Cretaceous. This led to extreme thinning and basinward tapering of the crystalline crust. Thinning usually leads to subdidence, but here it was associated with increased temperatures, which also affected the adjacent basin flanks. As a result of this unroofing, a meta-morphic core complex developed in the footwall of the Møre Detachment and a broad area was uplifted, thereby affecting the drainage patterns (Osmundsen et al., 2010). Erosion onshore and sediment loading offshore amplified the source-to-sink relief in the Aptian. Supportive AFT cooling ages at the MTFC show significant uplift/erosion since mid-Cretaceous (Redfield et al., 2004, 2005).

The density and rheological character of the crust also influenced the height and the shape of the onshore escarpment (Redfield et al., 2005; Maupin et al., 2013). The inner Møre Margin (offshore-onshore), in the area of the Selje High and western Slørebotn Sub-basin, is underlain by a high-velocity/density lower crustal body, possibly associated with high-pressure metamorphic rocks buried to large depths during Caledonian collision (Kvarven et al., 2014, 2016; Theissen-Krah et al., 2017). Heating associated with the Cretaceous extension/thinning event may have caused a phase change due to shifting P–T conditions of the lower crustal body, making it lighter and hence contributing to increased uplift of a source area located close to our study area at the Måløy Slope. The same process has been inferred for the Early Cretaceous uplift of the Loppa High in the SW Barents Sea, which was in a similar tectonic setting at the flank of deep Cretaceous NE Atlantic basins (Indrevær et al., 2018).

From the Møre and Vøring basins, we know that the Cenomanian–Santonian (mainly Turonian–Coniacian) experienced increased subsidence and sediment input (Zastrozhnov et al., 2020). The basin topography was smoother and there was a redistribution of sediment fairways. Increased sediment load caused flexure and regional uplift/erosion of the basin flanks (both Norwegian and Greenland sides). The flexural response is long wavelength and dependent on the rheology and rigidity of the crust. The pronounced Turonian unconformity in the Måløy Slope show that this area has an important connection to the events observed in the Møre and Vøring basins. This led to the renewed tilting and differential subsidence on the Måløy Slope, the incision documented in this study (Fig. 9) and the deposition of sand-rich deep-water fans documented by Sømme & Jackson (2013).

Concluding remarks

From the northeastern margin of the northern North Sea we know that a history of repeated onshore uplift and basin subsidence has controlled the sediments fed into the basin. The difference in topographic relief onshore through time is caused by both tectonic and isostatic processes.
The main conclusions that can be drawn from this study include:

- Canyons connecting a source area in the east to the sink in the west have been active and developing throughout the Late Jurassic and Early Cretaceous. These were carved into and across the basement fault-block crests on the Måløy Slope.

- The locations of the present fjords and their submarine extensions correlate with some of these major canyons, suggesting that their positions were established in the Late Jurassic or even earlier. The best-defined submarine fjord extensions within the study area are seen in Frøysjøen and Bremangerpollen, which coincide with the most prominent ancient canyons.

- The canyons seen offshore were established in or prior to the Late Jurassic and deepened in the Early Cretaceous into basement by sediment transport across the slope.

- In the Early Cretaceous, the Måløy Slope was influenced by tectonic activity on the Møre margin and sediment transport was toward the northwest.

- The repeated sediment transport and erosion observed in this study can be explained by long-wavelength (flexural) response to unloading which is resulting in unroofing/erosion onshore and thinning/deposition offshore. Consequently, the whole system is responding as a feedback system.

- In addition, reactivation of some faults resulted in a short-wavelength and more local response intra slope.

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