NGU REPORT 2016.028

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REPORT

Report no.: 2016.028	**ISSN: 0800-3416 (print)** **ISSN: 2387-3515 (online)**	**Grading:** ~~Confidential until 1st April 2019~~ open

Title:
Nature of boundaries between crystalline basement and sedimentary rocks in the Møre-Trøndelag coastal area - reinterpretation based on digitized sparker lines, 2D seismic and detailed bathymetry

Authors: Rise, L., Osmundsen, P.T., Bøe, R., Chand, S. and Redfield, T.F.	**Client:** Norwegian Deep Water Program (Seabed Project), Lundin Norway AS, AkerBP ASA
County: Norway	**Commune:**
Map-sheet name (M=1:250.000)	**Map-sheet no. and -name (M=1:50.000)**
Deposit name and grid-reference:	**Number of pages:** 46 **Price (NOK):** 190,- **Map enclosures:** 1

Fieldwork carried out:	**Date of report:** 30th November 2016	**Project no.:** 360000	**Person responsible:**

Summary:

This report is part of the SPARDIG project. The main aim of the project has been to transform old analogue sparker records from the Norwegian continental shelf into SEG-Y format. Off Møre and Trøndelag, these data were interpreted together with 2D seismic lines and bathymetric data to study the geology of the transition zone between crystalline basement and the overlying sedimentary rocks.

The objective of the scientific part of the project has been to utilize the new data set to make an updated geological map. We were able to classify the basement-sediment contact based on the contact relationships and to update the map accordingly. Several new faults were mapped based on detailed bathymetry and the seismic data.

Exposures of weathered basement at the seafloor and juxtaposition of basement and sediments across inherited faults were observed up to several kilometers along strike. These relationships provide important links to the deeper structure and stratigraphy of the Mid-Norwegian margin. A suite of triangular Quaternary basins observed along the basement-sediment contact in the Møre area highlights the need to investigate further the possibility of Quaternary fault reactivation.

Keywords: Marine Geology	IKU Sparker	Reginal seismic
2D seismic	Møre-Trøndelag	Faults
Weathered basement	Bathymetry	Sedimentary basin

CONTENTS

APPENDIX (MAP ENCLOSURE)

Chand, S., Bøe, R., Rise, L., Osmundsen, P.T., Redfield, T.F. Map of the crystalline basement-sediment contact and fault pattern, Mid-Norway. Appendix to NGU report 2016.028.

1. INTRODUCTION

SPARDIG (Transforming analogue sparker records from the Norwegian continental shelf into SEG-Y format and application of the data to re-interpret the basement-sediment contact in the Møre-Trøndelag area) is a two-year project initiated in 2014 by the Geological Survey of Norway (NGU). Analogue sparker data were acquired during the years 1970-1982 by the Continental Shelf Institute (IKU). IKU later reorganized and joined the Sintef Group (first as IKU Petroleum Research, later as Sintef Petroleum Research). The data make up a regional grid (Figure 1) from 60°N (northern North Sea) to c. 71°30'N (Tromsøflaket, SW Barents Sea).

The responsibility of the seismic data base was transferred from IKU Petroleum Research to NGU in 1998. This included storage of the physical data (i.e. original paper rolls and half-scale film copies), and safe storage of the corresponding digital navigation database. From around year 2000, seismic interpretation has mainly been carried out on digital data using PCs or work stations. It is time-consuming and imprecise to transfer interpretations between digital 2D seismic and analogue seismic lines, and the IKU sparker data have thus rarely been used together with digital 2D seismic data. NGU has a responsibility to secure analogue geological data for the future, and this was the background for initiating the present project.

The old IKU sparker data are unique due to the regularity of the extensive data grid, and also because the lines have much higher seismic resolution than ordinary 2D seismic lines. Integrated interpretation of SEG-Y transformed sparker data, 2D seismic data and high resolution bathymetric data has a great potential when it comes to improving geological maps. A better understanding of the Quaternary stratigraphy will also improve regional geotechnical evaluations, which are of importance for planning pipeline routes and other site investigations.

The main objective of the research part of the project has been to utilize all available data to study the boundary between sedimentary rocks and crystalline basement in the Møre-Trøndelag coastal area. Part of the boundary is constituted by the Møre-Trøndelag Fault Complex (MTFC), which is a regional system of large sub-parallel NE-SW faults with a very long movement history. In addition to the new SEG-Y versions of the sparker lines, 2D seismic data and new bathymetric data have been applied. The main focus has been on (1) mapping the contact between basement and sedimentary rocks and (2) mapping of faults within the submerged crystalline basement zone. The new interpretations have been merged with information from earlier maps (Rokoengen et al. 1988, Sommaruga and Bøe 2002), which has resulted in an updated geological map of the coastal zone between Nordøyane and Vikna (62°30'-65°N) (Appendix 1, Figure 2).

The technical part of the project - scanning of old paper rolls of reflection seismic data and transformation to SEG-Y format - has been carried out by CNRS (Centre National de la

Recherche Scientifique, Strasbourg), and is not included in the present report. Description of the technical procedures are reported in Chand et al. (2016).

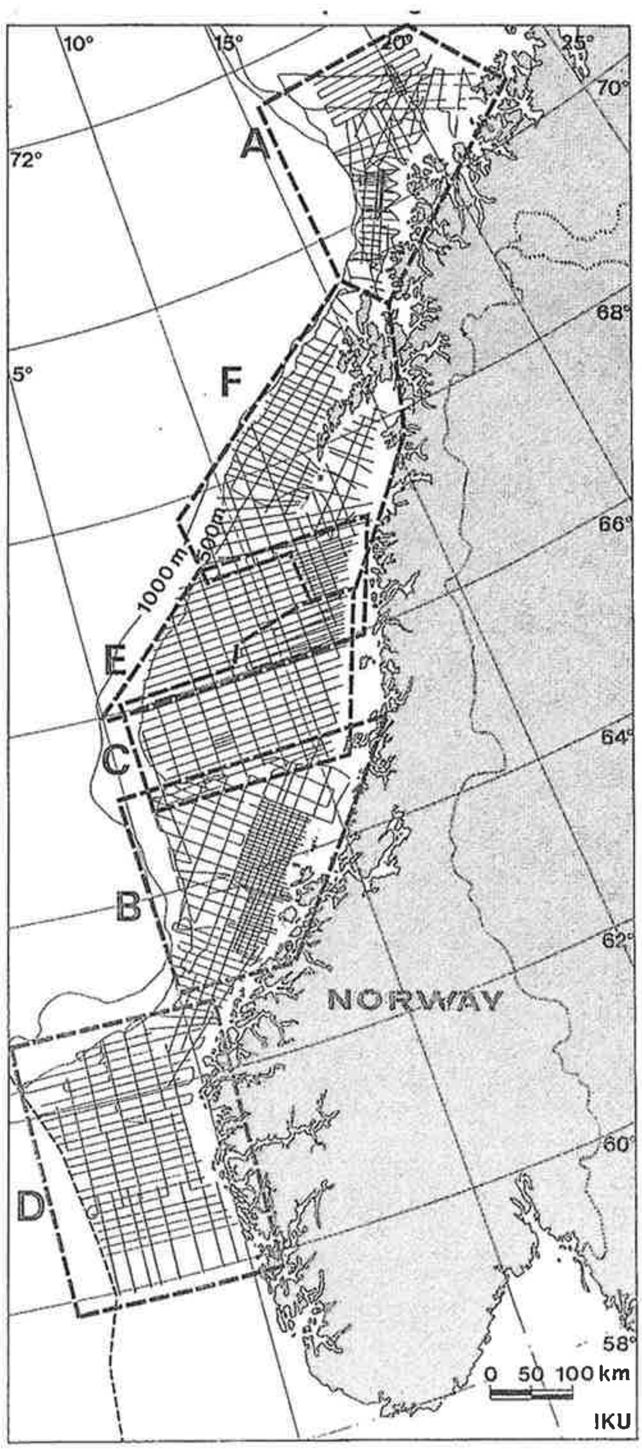


Figure 1. IKU sparker grid acquired during the years 1970-1982. IKU subdivided the lines into data packages (letters A-E) which were offered for sale. Every second line in the dense grid close to the coast in package B is boomer data (IKU 1984).

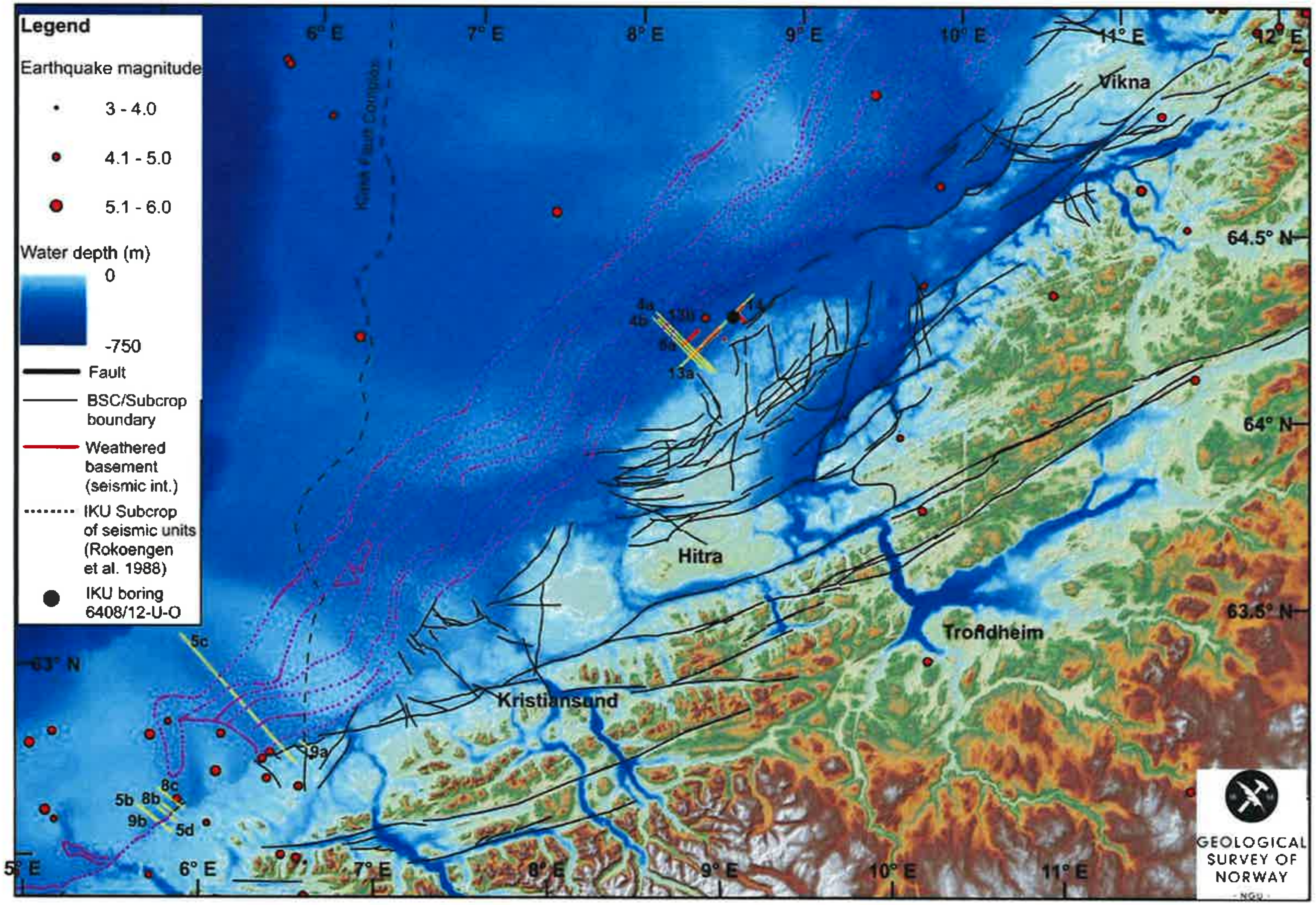


Figure 2. Bedrock map between Nordøyane and Vikna (see map enclosure for details). Note the location of seismic line segments shown in report figures. Figure numbers are indicated.

2. DATA AND METHODS

Data were collected during the years 1972-1982, totaling c. 33 000 km (IKU 1984) (Fig. 1). A 3-electrode analogue sparker (1000 Joule) was applied on nearly all survey lines. For the dense grids off Mid Norway, every second line was collected by boomer. The data were recorded on EPC graphic recorders, usually with a scale of 0.5 s. TWT (two way travel time). For some lines, a scale of 0.75 s. or 1 s. TWT was used. The survey speed was commonly between 4 and 5 knots. Penetration varies from 0.1 to 0.5 s. TWT, and the quality is generally good to acceptable, often reflecting the survey weather.

In the early eighties, the data were subdivided in 6 packages (A-E, Figure 1), which were offered for sale to oil companies as half scale (25 cm) paper copies. For positioning, an integrated system with satellite, Loran C, Decca Main Chain, log and gyro was used when collecting the data in south Helgeland package (C), parts of the Troms package (A) and parts of the North Sea package (D). For the rest of the data, positioning is based on Decca Main Chain (see also Chand et al. 2016).

The navigation files from Troms (area A) were missing, and IKU Petroleum Research kindly offered us to apply other analog sparker profiles collected in the same area. These lines were part of the database in the industry project 'Shallow Seismic and Sampling off Troms 1984' (Sættem et al. 1985). The lines are not shown in figure 1.

After processing at CNRS, the data were received as individual files in SEG-Y file format and divided into different surveys. The data were copied into separate folders and first checked for consistency in header and amplitude values using the free seismic viewer software (Seisee). A Petrel project was created representing the study area. The basic culture data include the coastline, regional bathymetry and high resolution bathymetry (Norwegian Hydrographic Service/Olex), geology and tectonic data (NGU database), earthquake locations (NORSAR) and IKU subcrop map of bedrock units (Rokoengen et al. 1988). Although slightly updated regional bedrock maps have been published (Sigmond 1992, 2002), we found it most relevant to show the bedrock boundaries interpreted by IKU as they are mainly based on the sparker data and existing bathymetry at the time of interpretation (Figure 2, Appendix 1).

The location of IKU bedrock coring 6408/12-U-01 is shown, as it will be referred to in the text. 2D regional seismic data available to NGU through the DISKOS database were downloaded and loaded into the Petrel project for cross checking and interpretation. The SPARDIG seismic data were then loaded into the Petrel project in separate folders representing individual surveys. Since the data contain mainly the positive values of the trace, a grey scale based colour ramp was used to plot the data. The data were again cross checked for inconsistencies with location and continuity. These include missing/wrong navigation, gap in the data, mismatch with the seafloor due to wrong delay correction, etc.

The interpretation includes identification of bedrock boundaries sub-cropping below Quaternary sediments. Priority was given to the contact between crystalline basement and sedimentary rocks (BSC), and faults in the submerged coastal zone which have not been mapped earlier due to poor bathymetry (Figure 2, Appendix 1). Also boundaries from previous bedrock mapping are shown (Rokoengen et al. 1988, Sommaruga and Bøe 2002). The boundaries of down faulted nearshore basins (Sommaruga and Bøe 2002) have been slightly modified in this project, mainly due to improved bathymetry.

3. GEOLOGICAL BACKGROUND AND PREVIOUS MAPPING IN THE STUDY AREA

In mainland Norway, Mesozoic sedimentary rocks (Jurassic and Cretaceous) crop out only on Andøya. These are the youngest rocks on land anywhere in Norway. Triassic dykes occur in West Norway, while Mesozoic structures and fault products are common at major and minor fault zones in various parts of coastal Norway (Bøe et al. 2010). Sedimentary rocks occur in half-grabens in many fjords, especially in Mid Norway and northern Nordland. Most of these are of Middle-Late Jurassic age, and are interpreted to represent the remains of a much more extensive Jurassic-Cretaceous sedimentary succession that covered large parts of coastal Norway. These sedimentary rocks were downfaulted during tectonic activity in Late Jurassic-Early Cretaceous times thus escaping late Tertiary-Pleistocene erosion. The largest downfaulted basins in the study area are shown in figure 3.

Erratic blocks of Mesozoic rocks were found in Norway for the first time in 1845, on the northwest shore of Beitstadfjorden (Figure 3). In 1867, T. Dahl investigated an outcrop of coal utilised by local farmers on Andøya. Subsequent mapping on Andøya and new finds of erratic blocks along the coast of Norway indicated that Mesozoic rocks could be present in several fjords and offshore the present coastline (Ørvig 1960 and references therein). Oftedahl (1975) was the first to map Mesozoic rocks in the coastal zone. This activity was intensified in the 1980s with publication of several studies (Holtedahl 1988, 1993, Bøe and Bjerkli 1989, Bøe 1991, Bøe et al. 1992, 2005, 2008, 2010, Thorsnes 1995, Fossen et al. 1997, Bøe and Skilbrei 1998, Davidsen et al. 2001a, b, Sommaruga and Bøe 2002). In addition, shallow sampling and stratigraphic drilling was performed by IKU (now Sintef Petroleum Research) in many subcropping sedimentary units along the coast (Mørk et al. 1983, Bugge et al. 1984, 1989, 1993, 2002, Sættem et al. 1985, Fjerdingstad et al. 1985, Aarhus et al. 1987, Skarbø et al. 1988, Rokoengen et al. 1988, Smelror et al. 1989, Hansen et al. 1992, Smelror et al. 1994, Løseth and Tveten 1996). The offshore Mesozoic sedimentary stratigraphy and structures are well documented in numerous contributions by academia and the petroleum industry (e.g., Evans et al. 2003, Martinsen and Dreyer 2001, Wandås et al. 2005, Ramberg et al. 2006, Smelror et al. 2009).

3.1 Mesozoic sediments and structures on the continental shelf off Mid Norway

In the Permian and Early Triassic, rift basins continued to develop between Norway and Greenland as a result of crustal extension that had started already in Devonian and Carboniferous time. An embayment of the ocean gradually developed towards the south (Blystad et al. 1995, Brekke 2000). A warm climate persisted throughout the Triassic, and in the Late Triassic, global plate motions gradually led to a more humid climate (Müller et al. 2005). This caused strong chemical weathering and oxidation of land areas, and deposition of red-coloured sediments both on land and along the coasts. Deposition of mudstones and some evaporites predominated between Norway and Greenland in the Early Triassic. In the Middle Triassic, the area of rifting in the Norwegian Sea became less active and there was a change to deposition on fluvial plains. In the Late Triassic, there was renewed stretching of the crust (Müller et al. 2005). This resulted in marine transgressions with deposition of more than 1000 m of salt and mudstone, followed by continental sedimentation, first lake and finally fluvial deposits. The Triassic succession in the Norwegian Sea is locally several thousand metres thick (Müller et al. 2005, Nystuen et al. 2006).

In the latest Triassic, crustal movements caused uplift of mainland Norway, precipitation increased, and coarse-grained sediments were deposited along the coast and on the continental shelf (Müller et al. 2005). This deposition (Åre Formation) continued into the Early Jurassic, when extensive bogs, resulting in thick coal beds, developed on coastal plains. A shallow seaway with strong tidal currents gradually developed between the ocean in the north and Tethys. The sandstones of the Tilje Formation show evidence of this tidal environment (Martinius et al. 2001). Due to a wet climate, pronounced erosion and denudation of mainland Norway occurred. Sediments were deposited in estuaries and deltas along a strongly fluctuating coastline, with sandstone units covering large parts of the shelf (Dalland et al. 1988, Brekke et al. 2001). Several of the most important hydrocarbon reservoirs in the Norwegian Sea are of Early and Middle Jurassic age.

In the latest Middle Jurassic-Late Jurassic, NW–SE extension was renewed along the rift axis in the Norwegian Sea (Blystad et al. 1995). This caused subsidence and development of large rift structures with numerous horsts and grabens on the Mid-Norwegian shelf (Gabrielsen et al. 1999, Osmundsen et al. 2002). The eastern flank of the rift in the Norwegian Sea is represented by the Halten and Dønna Terraces and the Nordland Ridge, while the Trøndelag Platform represents the rift shoulder to the east. At the same time, there was extensive deposition of organic-rich mud in isolated fault basins, and coastal areas were transgressed due to a global sea-level high stand. The Spekk Formation, deposited in the Late Jurassic, is the major source rock for hydrocarbons on the Mid-Norwegian shelf.

In the Cretaceous, a transition from extension and rifting to seafloor spreading in the Norwegian Sea occurred. Campanian-Palaeocene rifting was followed by seafloor spreading in the Early Eocene (Brekke et al. 2001, Færseth and Lien 2002, Lien 2005). Due to crustal thinning and thermal subsidence, deep, regional basins formed along the main axis of the rift movements, e.g., the Møre, Vøring and Vestfjorden basins. The main Campanian-Palaeocene rifting and seafloor spreading took place to the west of these basins (Brekke et al. 2001). The basins were filled with 8–10 km of fine-grained sediments derived mainly from the west (Greenland) (Brekke 2000). Sandstones deposited on submarine fans were derived partly from Greenland, from local highs such as the Nordland Ridge, and in some areas from the Norwegian mainland (e.g., Lien 2005).

3.2 Mesozoic sediments and structures in the coastal zone of Mid Norway

The development of Mesozoic basins along the coast of Mid Norway is closely related to activity on the long-lived MTFC, which can be traced from the southern Møre Basin Margin to the inner parts of Trondheimsfjorden and farther northeast into the Grong district (Grønlie and Roberts 1989, Grønlie et al. 1994, Blystad et al. 1995, Gabrielsen et al. 1999). Two of the major onshore fault systems of the MTFC are the steeply NW-dipping Hitra-Snåsa and Verran Faults (Figure 3), which originally developed in Devonian time in a late-Caledonian, ductile, sinistral shear regime (Grønlie and Roberts 1989, Osmundsen et al. 2006).

Mid Norway was affected by a rift episode lasting from the Bajocian to the Volgian, but with transition from an initial rifting stage to a rifting climax in the Callovian (e.g, Brekke et al. 2001, Færseth and Lien 2002). This resulted in essentially dip-slip normal faulting along the older structural lines of weakness and development of horst and graben (half-graben) structures. Subsequently, a phase of dextral strike-slip movements downfaulted and deformed the sequences, especially in the Beitstadfjorden Basin (Bøe and Bjerkli 1989).

The Beitstadfjorden Basin (14 km long and 6 km wide) (Figure 3) is located at the northeastern extremity of Trondheimsfjorden. The basin is related to a SSE-dipping normal fault, which is a branch of the generally steeply WNW-dipping Verran Fault system. Many smaller faults within the basin are sub-parallel to the main fault of the Verran Fault system. Another set of faults, oriented NNE–SSW, crosscuts the ENE–WSW system and is therefore considered to be younger (Bøe and Bjerkli 1989). Strata dip up to 15° to the NNW, i.e., towards the deepest parts of the basin, but changes of dip occur along faults and along the strike of the basin. The thickness of the Jurassic succession is around 1000 m.

The Edøyfjorden Basin (Figure 3) is an elongated half-graben (18 km long and 3 km wide) that is downthrown in the south-southeast by the ENE–WSW-trending Hitra-Snåsa Fault (Bøe and Bjerkli 1989). A few hundred metres farther south, another fault probably represents the southwestern prolongation of the main Verran Fault. Mesozoic strata generally dip 15–25° towards the south-southeast, but swing into an E–W strike in the northeastern wedge of the basin. The vertical slip along the Hitra-Snåsa Fault is of the order of several hundred metres to 1 km, and the thickness of the Mesozoic succession is c. 1000 m.

The Frohavet Basin (almost 60 km long and up to 20 km wide) (Figure 3) is controlled by two large normal faults that downthrow to the northwest (Bøe 1991). A narrow basement ridge separates the main basin from a smaller, elongated basin close to the Froan Islands in the northwest. The Tarva Fault and the Dolmsundet Fault occur along the southeastern margin of the basin (Figure 2, Appendix 1). Many small synthetic and antithetic faults occur along the major faults. A third fault trend, NW-SE, is represented by only a few structures, but these seem to offset the NE-SW faults and are, therefore, thought to be younger. Gentle synclines within the basin are mainly oriented NE-SW, subparallel to the Tarva and Dolmsundet Faults. Seismic units thicken slightly towards the Tarva Fault, indicating syn-depositional movements. The maximum thickness of Jurassic rocks, in the central part of the basin, is c. 1200 m.

Griptarane (Figure 3) is a basement topographic high located west of Smøla (Bøe and Skilbrei 1998). Griptarane is surrounded by Jurassic strata, which are covered by thicker Cretaceous units to the west. Jurassic rocks are preserved in a synclinal flexure, oriented NE-SW to the southeast of the Griptarane high, and NW-SE to the northeast and southwest of Griptarane. Dips are 3-10°. Several large, WNW–ESE-trending normal faults with downthrows towards the northeast occur. The WNW–ESE structural trend is subparallel to the orientation of fjords and lineaments along the coast of Møre and Trøndelag, and also to fault trends within the Devonian basins. Two of these faults offset the Jurassic-basement boundary. There are also several large, NE–SW-trending faults. Most of these dip towards the northwest, and the one at the northwest margin of Griptarane continues as a major fault towards the Slørebotn Sub-Basin/Møre Basin Margin. The thickness of the Jurassic succession is c. 600 m south of Griptarane.

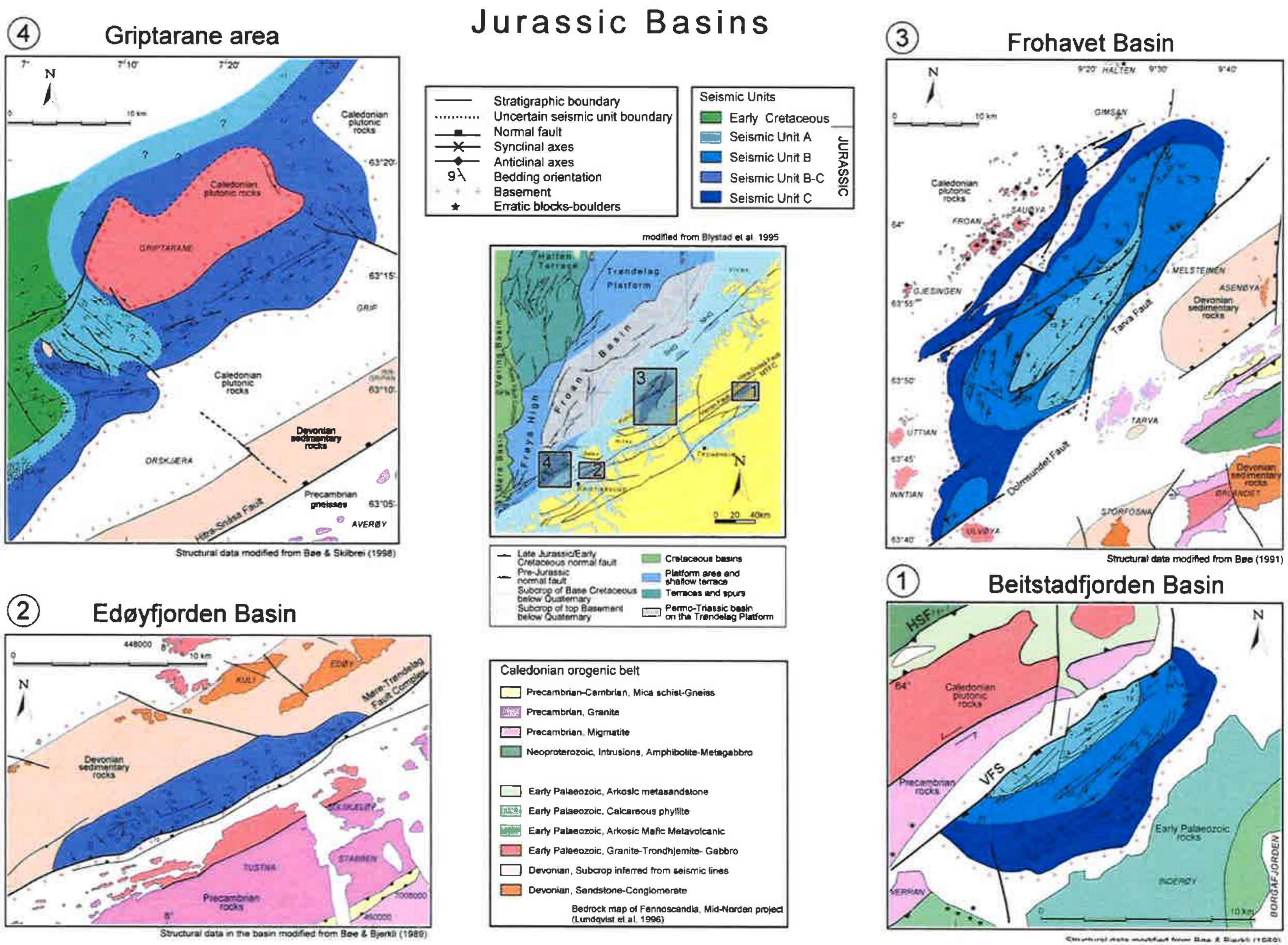


Figure 3. Overview of half-grabens with Mesozoic sedimentary successions in Mid Norway. From Sommaruga and Bøe (2002).

3.3 Seismic units and stratigraphic correlation between basins in the coastal zone

On seismic sections from the Beitstadfjorden and Frohavet Basins, seismic units A (upper), B (middle) and C (lower) have been identified (Sommaruga and Bøe 2002) (Figure 3). The Edøyfjorden seismic sections show a single seismic unit, which can possibly be attributed to Units B–C in Frohavet and Beitstadfjorden. The Griptarane area presents two seismic units; the upper unit may possibly be attributed to Unit A and the second to Units B–C. In terms of facies, Unit C was interpreted to comprise predominantly continental sandstones and conglomerates, Unit B shales or mudstones, while Unit A represents alternating sandstone, shale and carbonate (Sommaruga and Bøe 2002). The succession from Unit C to Unit A may reflect a general upward change from continental to shallow-marine deposition.

The most reliable information on the age of the three units is from nearby drillholes in the Slørebotn Sub-Basin, Møre Basin-Frøya High and Møre Basin Margin (Skarbø et al. 1988, Smelror et al. 1994, Jongepier et al. 1996) and fossiliferous erratic blocks left by glaciers on islands and skerries on the oceanward side of the basins (Kjerulf 1870, Nordhagen 1921, Carstens 1929, Horn 1931, Manum 1964, Vigran 1970, Bugge et al. 1984, Johansen et al. 1988). Erratic blocks from Beitstadfjorden and Frohavet constrain the uppermost Unit A to Callovian age (Melke Formation equivalent). The underlying Units B and C are thought to be equivalent to the offshore Fangst Group. In the Edøyfjorden Basin, a 1 m-long core comprises coarse-grained sediments possibly of Early-Middle Jurassic age, but this age assignment is uncertain.

Erratics of Cretaceous rocks have not been found along the shores of the studied basins (Bøe et al. 2010). This may either reflect a lack of Cretaceous rocks available for erosion, or be due to destruction of Cretaceous rock fragments (possibly shale) by the eroding glaciers. Permo-Triassic rocks may occur below some of the Jurassic successions, and probably also in small, isolated basins (Thorsnes 1995) northeast of the Frohavet Basin.

Blocks from Beitstadfjorden include iron-rich sand- and siltstones rich in plant fragments, interpreted to have been deposited in river channels and on flood plains (Oftedahl 1972). It is also noteworthy that reworked Middle Jurassic to Early Cretaceous dinoflagellate cysts have been found in Holocene sediments in Verdalsbukta and outside the Tautra ridge in the Trondheimsfjord (Scholze 1986), suggesting that not only Middle Jurassic, but also younger Mesozoic marine sediments were deposited farther eastwards (Bøe et al. 2010). It must be remembered however that the marine limit in these areas is 150-200 m, and that erratic blocks may have been transported and deposited by ocean currents in late glacial to Early Holocene times. Blocks from Frohavet are dominated by well-sorted sandstones with marine fossils, interpreted to represent shallow-marine deposits. It is assumed that in the Middle Jurassic there was a NW–SE transition from a continental to a shallow-marine environment in Mid Norway (Bøe 1991, Sommaruga and Bøe 2002). In the Late Jurassic much of the present coastal area was covered by a shallow sea. Farther offshore, depths were more than 2000 m (e.g., Jongepier et al. 1996, Færseth and Lien 2002).

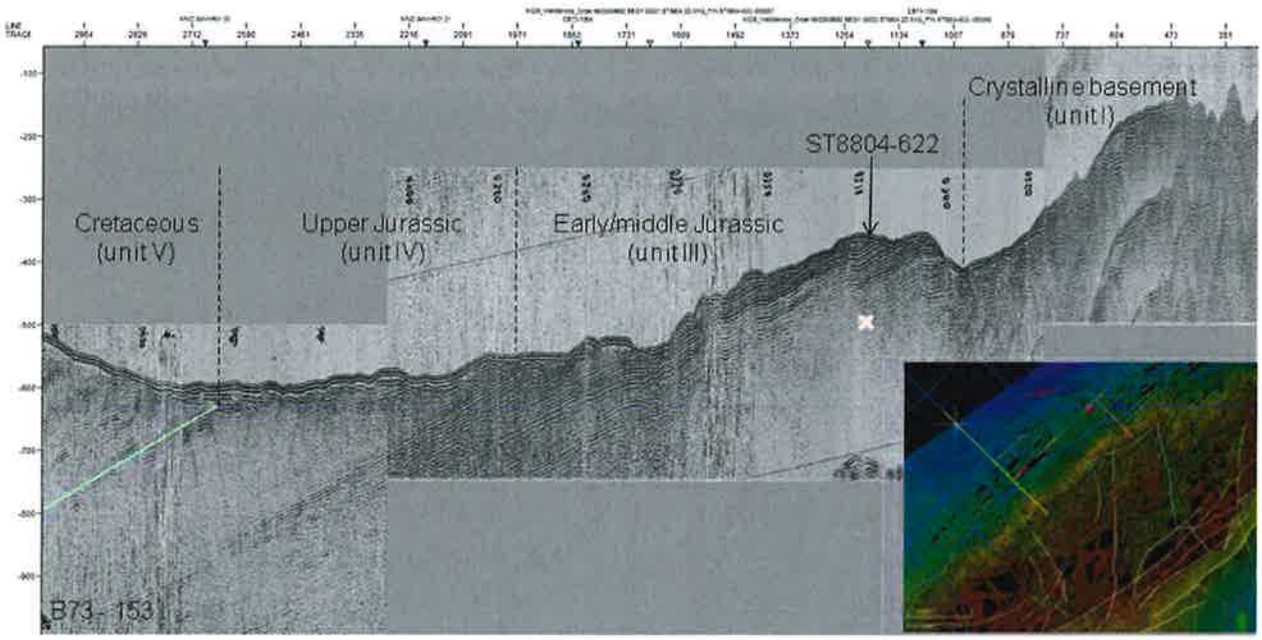
Organic matter maturation in erratic blocks from Beitstadfjorden suggests a burial depth of 1.8–2.3 km (Weisz 1992). During the Late Tertiary to Pleistocene, as much as 1000 m of Jurassic and younger sediments may have been eroded and only the Middle Jurassic and possibly older Mesozoic sediments have been preserved in the deepest half-grabens (Bøe et al. 2010).

3.4 Mapping of bedrock units west of the crystalline basement

Based on the sparker lines and bathymetry, IKU mapped the subcrop of ten bedrock units (Rokoengen et al. 1988). The topography often reflects the different resistance to glacial erosion, and was a guidance to map geological boundaries, particularly in areas with an open seismic grid. The subcrop of the units are shown in the enclosed map (Appendix 1), and units from Cretaceous (unit V) and older are shown in figure 4a. Several of the units and their sequence boundaries are characteristic also in 2D data (Figure 4b). Most of the sequence boundaries mapped by Rokoengen et al. (1988) are easily recognized in 2D lines. The IKU bedrock map shows more uncertain boundaries south of Frøyabanken (Rokoengen et al. 1988), and our interpretation of 2D seismic data west of Griptarane confirm this.

Off mid Norway, the subcrops of units in the IKU map correlates well with the bedrock maps in scale 1:3 and 1:4 million published by Sigmond (1992, 2002). The newer maps provide updated information on sedimentary facies and chronology. The chronology/lithology in the IKU map was based mainly on information from grabs and 3 m long cores in areas of thin Quaternary sediment cover. The updated maps also included information tied in from wells and shallow boreholes.

Offshore information from the IKU mapping program was also used for compilation of NGU's bedrock geology maps in scale 1:250 000. The oldest subcropping sedimentary rocks in the Møre-Trøndelag area is interpreted to be of early/middle Jurassic age (IKU unit III; Rokoengen et al. 1988). Reinterpretation done during work on the Namsos map sheet (Solli et al. 1997), suggested that Triassic rocks (IKU unit II) subcrop in a small area northeast of Froøyene. This interpretation has not been confirmed by sampling, and unit II is not shown in the attached map (Appendix 1).



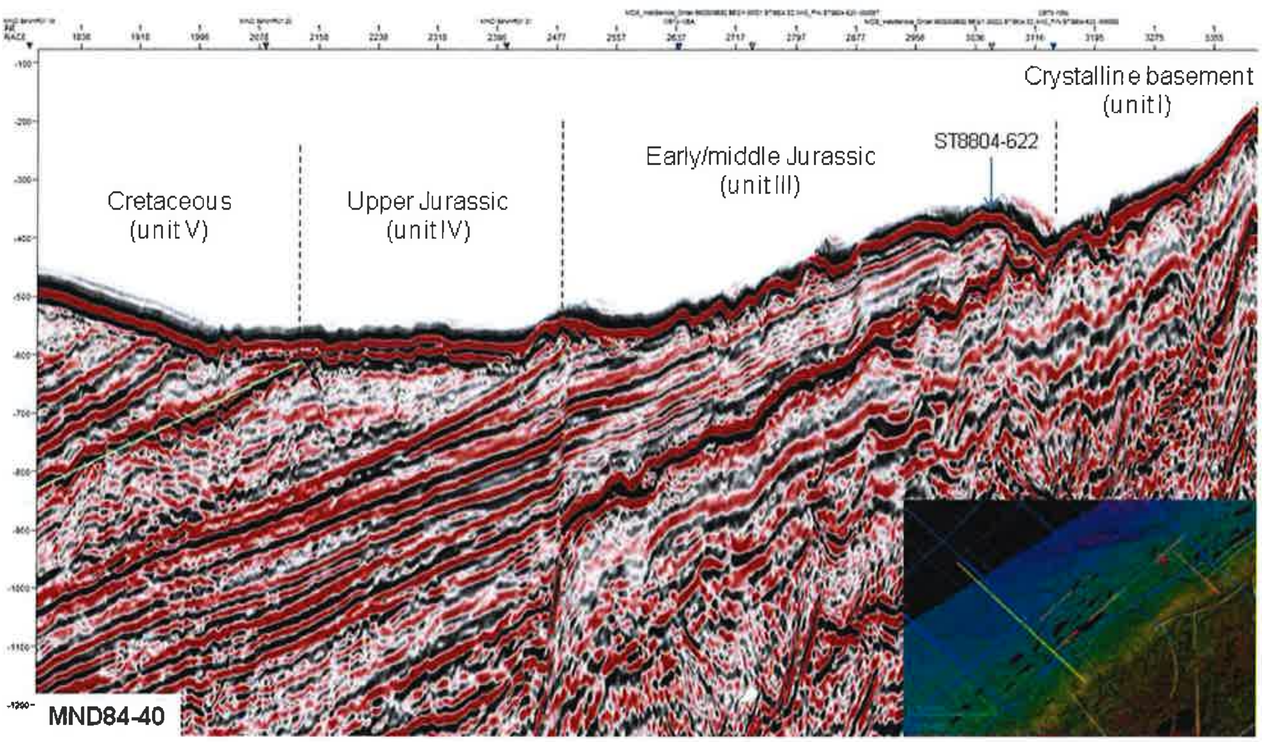
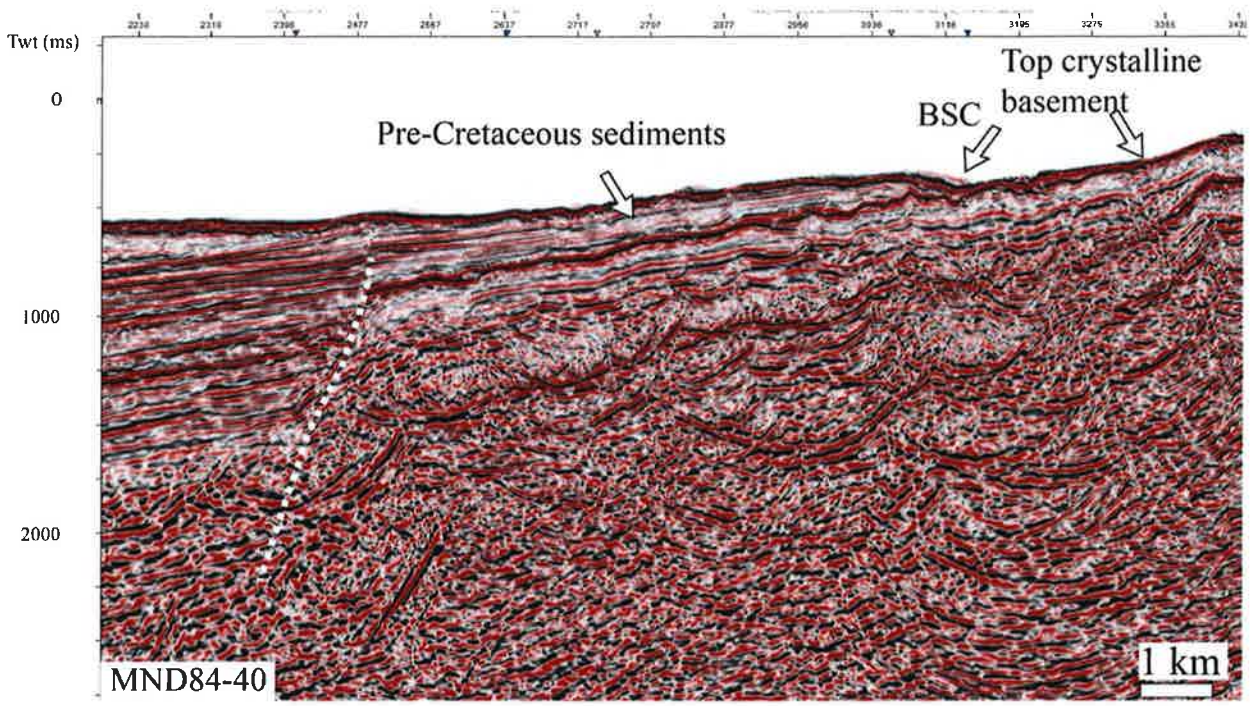


*Figure 4**a** (top). Eastern part of sparker line B73-153 showing Mesozoic sediments and the boundary to the crystalline basement. Only a thin cover of Quaternary sediments occurs above the bedrock surface. The arrow shows the intersection with line ST8804-622, and the white cross shows where weathered basement was interpreted on this line (see figure 13a). The green line on the inset map shows the location of the seismic line (NW of Froøyene). **b**) The same IKU units seen on a parallel 2D line (MND84-40), located 900 m SW of line B73-153. This line crosses ST8804-622 directly south of the location where the weathered basement zone was interpreted (see figure 13a).*

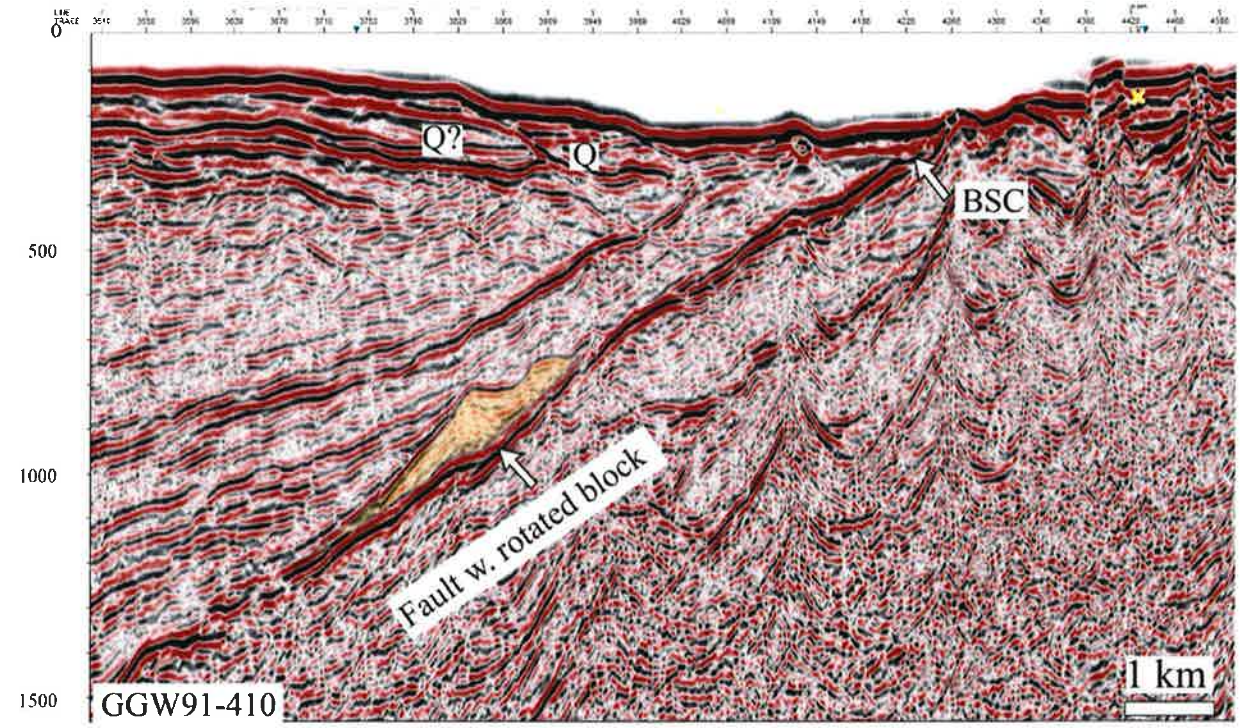
4. RE-INTERPRETATION OF THE CONTACT BETWEEN SEDIMENTS AND CRYSTALLINE BASEMENT

We have investigated and partially re-mapped the contact between crystalline basement and sedimentary rocks (BSC) in the offshore area between 62°30'N and 65°N, with the aim of providing a more detailed account of its character. On the first order, the contact can be classified as `sedimentary´ or `fault-defined´, marked as thin and thick line segments, respectively, on the map (Figure 2, Appendix 1). This reflects to some extent the larger-scale underlying rift structure, which changes considerably from areas inboard of the Vøring Basin (i.e. the Trøndelag Platform) to the area inboard of the Møre basin and Slørebotn Subbasin (e.g. Blystad et al. 1995). A landwards rising top of crystalline basement, buried under Mesozoic sediments and incised by the strandflat, is observed on a number of seismic lines that cross the Trøndelag Platform. At depth, the basement is rotated by landwards as well as seawards dipping faults of pre-Late Triassic age (e.g. Osmundsen et al. 2002).

In parts of the Møre area, the BSC is commonly represented by the SE boundary fault to the Slørebotn subbasin, normally constituted by strands of the Møre-Trøndelag Fault Complex. Responsible for major crustal thinning in the Jurassic (Jongepier et al. 1996, Gabrielsen et al. 1999, Osmundsen and Ebbing 2008), the seafloor expression of this inherited fault complex varies considerably. In more detail, the contact displays several variations over this theme, which have not been detailed on the map but that may serve as a basis for further studies. The character of the basement-sediment contact may provide useful information with respect to the potential occurrence of Mesozoic weathering surfaces as well as, possibly, areas of relatively recent faulting. In figure 5 we show examples of different types of contact relationships encountered in the study area, and in figure 6 we summarize these observations. The different contact relationships have different implications with respect to saprolite preservation as well as for possible Quaternary movements on inherited faults.

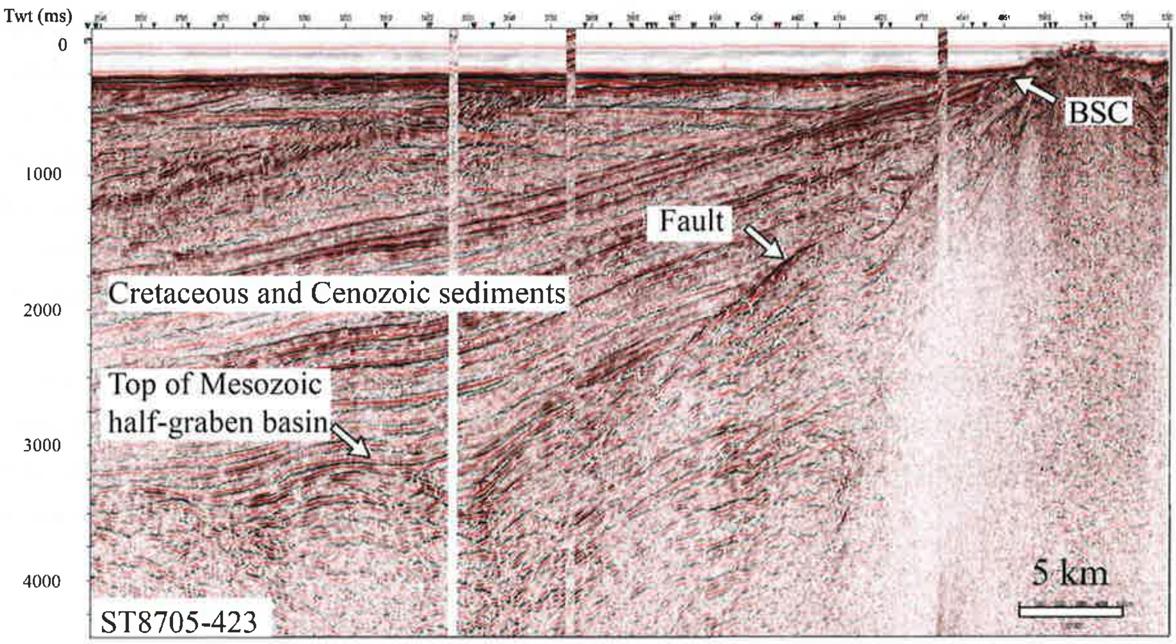


a)

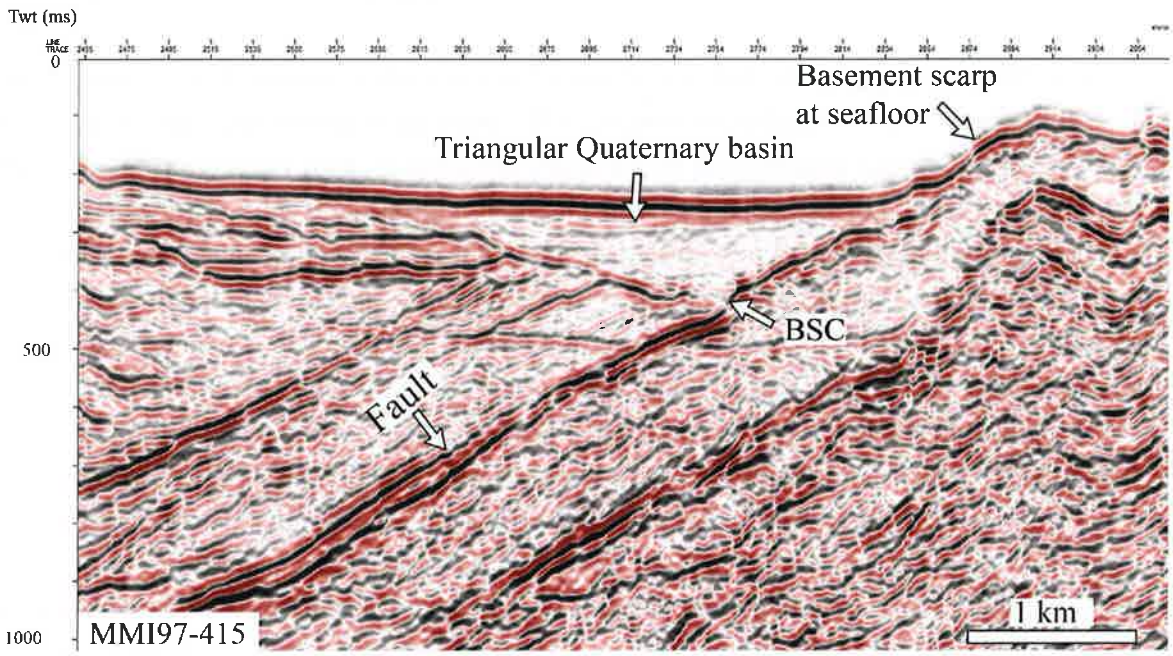


b)

Figure 5. (text see below)



c)



d)

Figure 5 (a-d). Examples of contact relationships encountered along the Basement-Sediment Contact (BSC) in the Møre-Trøndelag area (for further explanation of the examples, see text). For location, see figure 2. Q= Quaternary sediments.

In figure 5a, the top of basement rises towards the coast, exposing a surface located directly south of where weathered basement is likely to occur at the seafloor (see also figures 4b and 13a). Figure 5b shows a strand of the MTFC, overlain by a small, rotated fault-block. The fault is truncated by an erosional scour defining the BSC, with no significant topographic expression at the seafloor. In figure 5c, the Hitra-Snåsa Fault of the MTFC is associated with a seafloor scarp which forms the SE boundary of a broad, symmetric seafloor depression partly filled with Quaternary sediments. The BSC is located at the foot of the scarp. Seawards-dipping Mesozoic sediments and rotated fault-blocks are banked against the fault at depth, but there is no indication of the age of the latest fault movement. There are no constraints on the formation of the seafloor scarp; it could be produced by differential erosion across the BSC or by late fault movements.

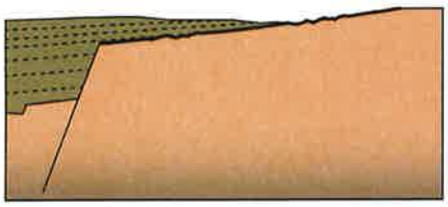
The section in figure 5d shows a seafloor scarp at the continuation of the basement surface in the form of a fault and a triangular Quaternary basin juxtaposed against the fault. A possible interpretation of this geometry is that of a Quaternary half-graben. More examples of similar configurations are given in figures 8 and 9.

4.1 Types of contact relationships in the study area

4.1.1 Exhumed and/or incised, pre-Cretaceous top-basement surface

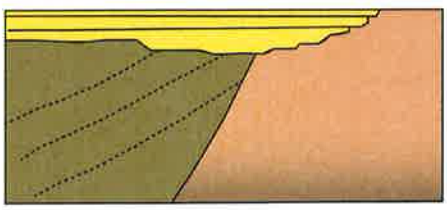
Figure 6a shows the basement surface as conformably overlain or onlapped at a very low angle by pre-Cretaceous sedimentary rocks. The mapped boundary between crystalline basement and sedimentary rocks is set at the point where the glacially scoured, present-day seafloor truncates the seawards-dipping basement-cover contact. The exhumed basement-cover contact continues landwards for 4-5 km as a smooth, gently seawards dipping top of basement. The detailed character of this basement is unknown, but its smooth character may indicate it represents a weathered pre-Cretaceous erosion surface, or, alternatively, bedding in relatively resistant Paleozoic sediments. In the study area, the best preserved example of this type of contact is north of Frøya, where the exhumed, smooth top of basement stands out in the bathymetric data (Figure 7). Inboard of this area, the exhumed pre-Cretaceous basement-cover contact is incised at a low angle by the subhorizontal strandflat. The detailed topography of the strandflat appears as considerably rougher than the areas where the basement-cover contact is preserved, notably because of the pattern of criss-crossing fracture lineaments (Figure 7).

Figure 5a illustrates how in this configuration, the preservation potential for a Mesozoic or older weathered basement surfaces inboard of the BSC will depend on the angle between the inherited basement weathering surface and the strandflat. In areas with down faulting of Mesozoic basin remnants, additional areas of sub-Mesozoic weathering products may be preserved (e.g. Sommaruga and Bøe 2002). Such products may also be preserved in faults and fractures that penetrated the basement below the syndepositional surface.



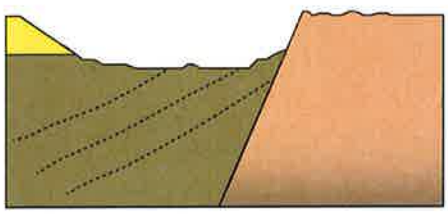
a)

Exhumed/incised, pre-Cretaceous top basement surface. Compare to figure 5a.



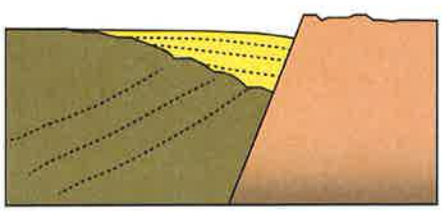
b)

Eroded and overstepped fault scarp. Compare with figure 5b.



c)

Fault scarp at the seafloor without draping sediments. Compare to example in figure 5c.



d)

Fault scarp with Quaternary basin and/or warped seafloor morphology. Compare to example in figures 8 and 9.

Figure 6. Conceptual line-drawings illustrating different types of contact relationships encountered along the BSC. Yellow: Quaternary sediments. Green: Mainly Mesozoic sediments. Brown: Continental crystalline crust. See text for additional discussion.

4.1.2 <u>Eroded and overstepped fault scarp</u>

In areas where large, seawards-facing Mesozoic faults occur close to the present-day coast, such as in the Møre area, erosion into old fault scarps can locally be observed close to the basement-cover contact. The sediments overlying the eroded fault scarp represent Mesozoic deposits, such as in figure 6a, or in other cases draping Quaternary sediments have been deposited in an incising glacially scoured depression (Figure 6b). Alternatively, the scour geometry is not filled with sediment, but nevertheless crosses the sediment-basement contact without significant relief.

4.1.3 Fault scarp at the seafloor without draping sediments

In figure 6c, the BSC is constituted by a fault scarp, representing the SE side of a wide scour-like depression in the seafloor. The sediments juxtaposed with the fault scarp are Mesozoic in age, bearing witness of kilometers of Mesozoic fault displacement during formation of the Slørebotn Subbasin (see Jongepier et al. 1996). In the absence of preserved Cenozoic strata banked against the scarp, the scarp morphology may result from differential (glacial) erosion of crystalline bedrock vs. sediments, or, alternatively from relatively young faulting events.

4.1.4 Fault scarp with Quaternary basin and/or warped seafloor morphology

Figure 8 shows variations along the BSC along a 5 km long segment of the contact NW of island Aukra. In two seismic sections, a basement scarp occur just east of the Quaternary basin, interpreted to represent the top of the fault complex that provides the SE boundary to the Slørebotn Subbasin (i.e. the MTFC, Jongepier et al. 1996). The hanging wall adjacent to the fault scarp preserves an asymmetric, wedge-shaped Quaternary basin, with a geometry that varies somewhat along strike. The age of this basin appears to be late- to post-glacial, and it unconformably overlies more steeply dipping Mesozoic strata. Inside the Quaternary basin, bedding onlaps this low-relief, landwards dipping unconformity. In line sections from survey MMI97 (Figure 8), resolution is limited in terms of identifying the internal bedding structure. In sparker lines B75-110 and B75-115, however, the resolution is somewhat better (Figure 9). Here a wedge shape can be identified inside the Quaternary basin, with slightly steeper dips in the lower parts of the succession close to the fault scarp. Unconformable surfaces can tentatively be interpreted inside the basin fill.

In all examples in figures 8 and 9, the seafloor dips gently in the direction of the fault scarp. This type of seafloor morphology is also observed in a number of sections where wedge-shaped Quaternary basins have not been identified. In these areas, the seafloor is quite smooth and gives the impression of a gently warped planar surface. Laterally, this geometry is transitional into one apparently more affected by glacial scour.

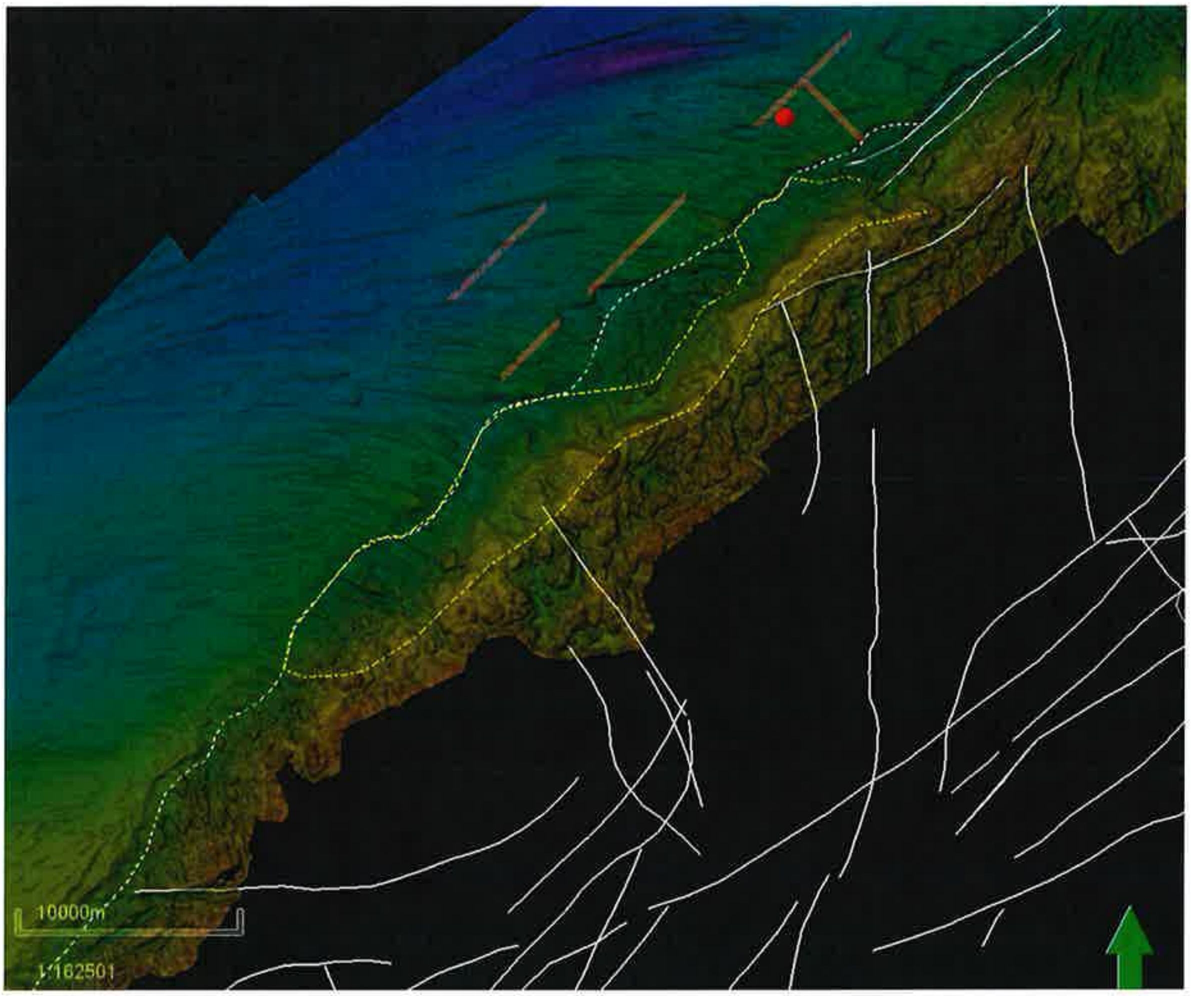


Figure 7. Shaded relief bathymetric image (50 m grid) north of Frøya (MAREANO multibeam data set). The white stippled line shows the Basement-Sediment Contact (BSC). The relatively smooth basement area inboard of the stippled yellow line may indicate that weathered basement occurs. Note the rough seafloor east of the yellow line. The continuous white lines mark large faults interpreted from another data set. The colored straight segments west of the white stippled line mark weathered basement below Mesozoic sediments (interpreted on seismic lines). The red dot is the location of IKU borehole 6408/12-U-01, where weathered granite was cored.

4.2 Discussion of contact relationships along the basement-sediment boundary

The preservation potential for weathered basement inboard of the BSC depends on 1) the dip direction and age of major faults that deformed and rotated the crystalline basement in the pre-Jurassic rift phases and 2) the angle of incision into the crystalline bedrock by the strandflat. Where the sub-Mesozoic basement surface rises gently landwards, either as the rotated hanging wall of landwards facing faults or, alternatively, as the eroded footwalls of buried, seawards facing faults, the preservation potential for weathered basement inboard of the BSC would depend on the angle of incision of the strandflat into the crystalline bedrock. Deviations from this pattern does, however, occur where Mesozoic basin remnants are downfaulted into the strandflat (see above).

Where seawards-dipping, Jurassic-Cretaceous faults provide the BSC, the amount of footwall erosion is rarely clear. As several kilometers of Jurassic and later faulting must have led to significant footwall uplift, the top of basement in the footwalls of, for instance, offshore strands of the MTFC does not necessarily represent the pre-rift top of basement. Rather, in cases such as those illustrated in figures 8a-c it appears that the top of basement is largely constituted by the strandflat. In these cases, the angle of incision into the pre-rift erosional template is unknown, as is the degree of preservation of the sub-Mesozoic erosional surface. The density of fractures and faults revealed by bathymetry as well as local onshore observations of weathering along faults and fractures indicate that zones of weathered basement may exist.

In restricted areas along the offshore continuation of the MTFC, 5-10 km along strike, wedge-shaped Quaternary basins occur with a morphology different from those commonly associated with glacial scours. Albeit a glacial scour origin cannot be totally excluded, some of our observations, such as those illustrated in figure 8, indicate that the basins represent Quaternary half-graben. As they are juxtaposed with portions of the MTFC, the implication would be that parts of the MTFC underwent post-glacial reactivation, in an area which lies directly inboard of the Storegga Slide. As IKU sparker lines show much better resolution in the Quaternary than the 2D lines, we propose that a future shallow seismic survey should be conducted to validate or negate a hypothesis involving Quaternary faulting. If this hypothesis is validated, several explanations have to be explored, such as tectonic reactivation related to post-glacial uplift or compaction in the sediments. In the light of the present-day seismicity, it cannot be excluded that these portions of the MTFC represent a geohazard.

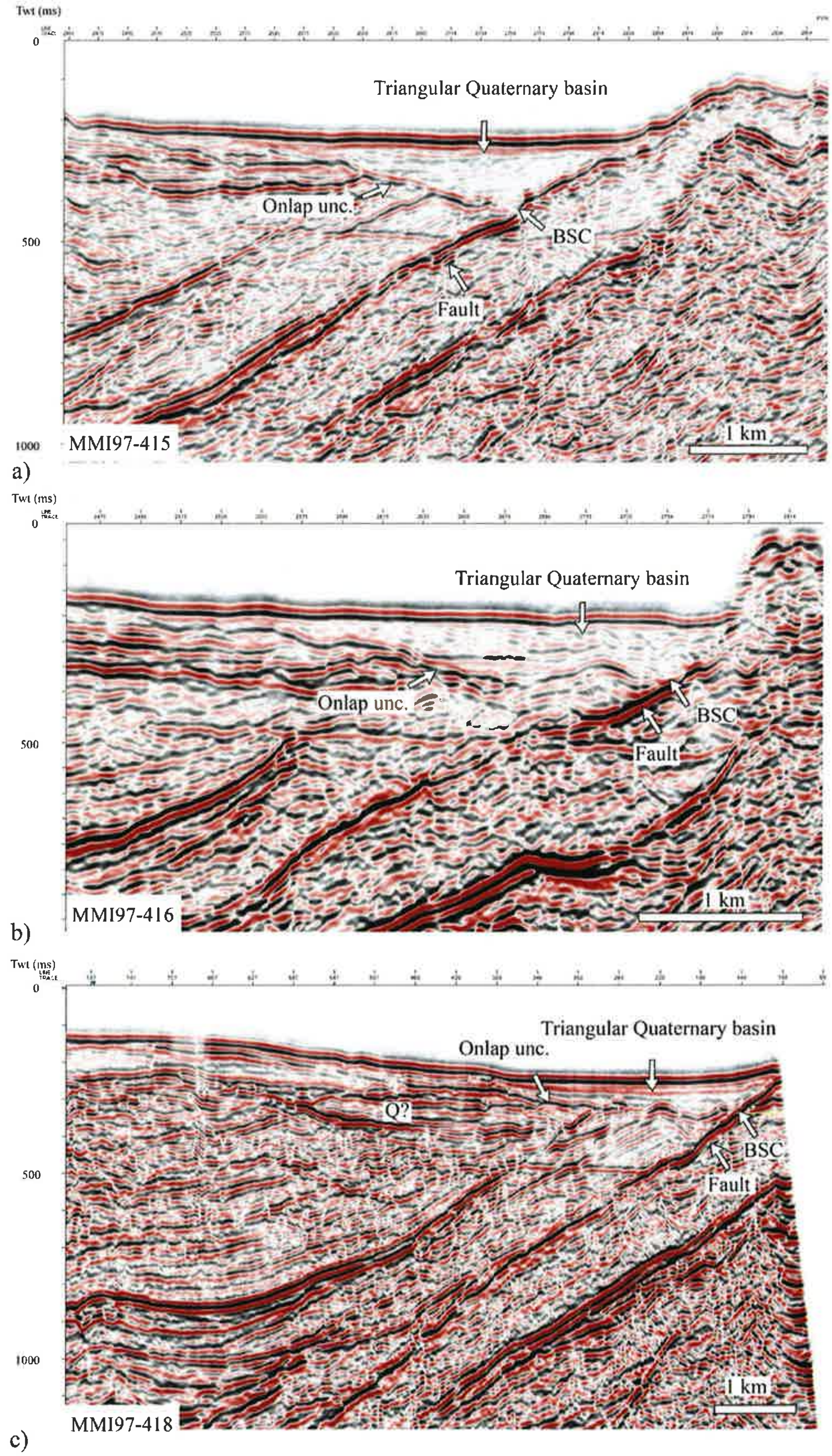


Figure 8a-c. Examples of wedge-shaped Quaternary basins resembling fault-controlled half-graben, juxtaposed with (reactivated?) portions of the MTFC. The sections are characterized by a well-imaged, seawards dipping, low-angle fault plane and a landwards dipping onlap unconformity below the Quaternary basin. Q=Quaternary sediments.

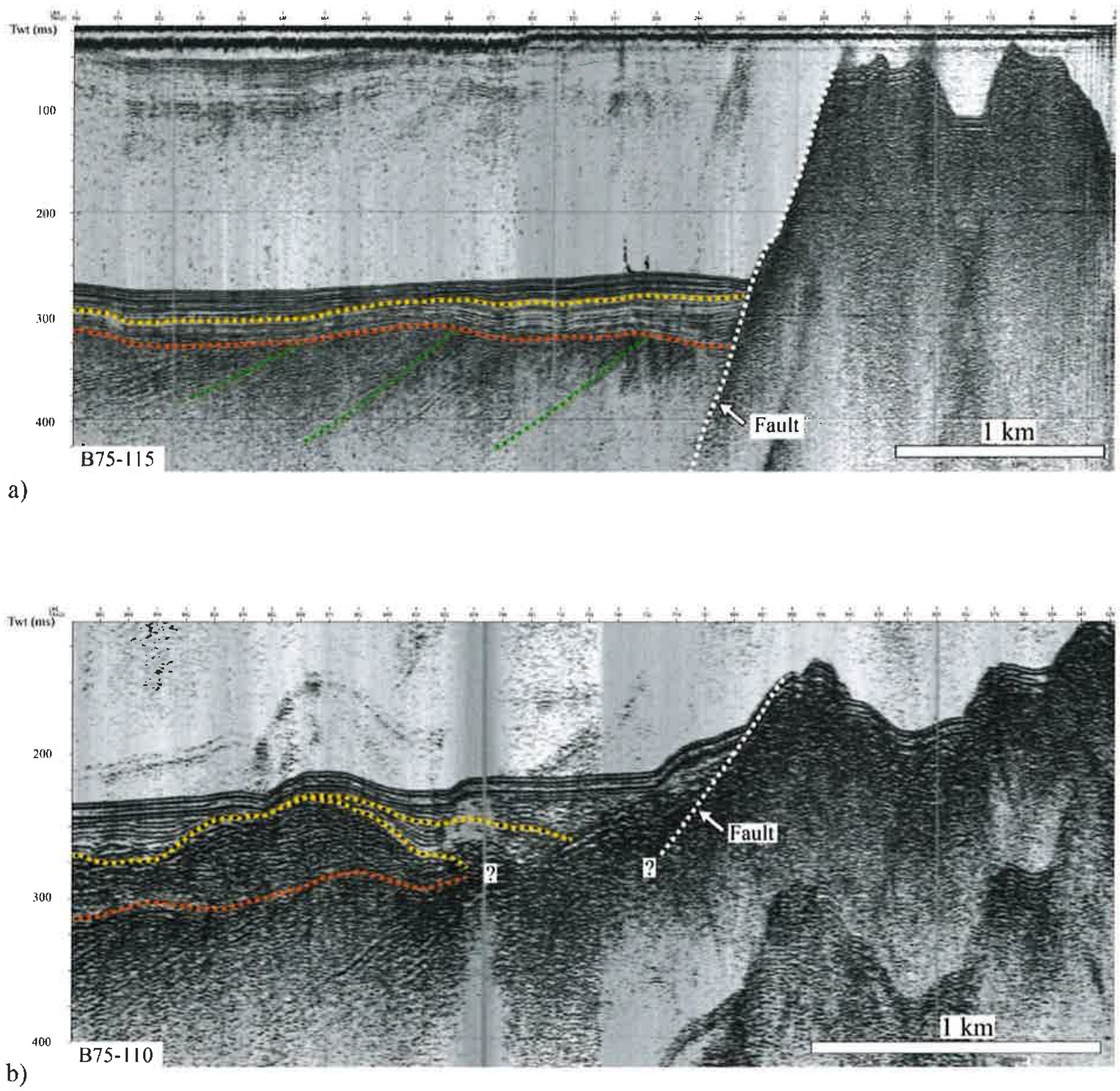


Figure 9a-b. SPARDIG lines showing triangular Quaternary basins similar to, but smaller than the ones illustrated in figure 8. Note high resolution in the Quaternary sedimentary wedges. Stippled red lines = contact with underlying, rotated Mesozoic strata (bedding shown by stippled green line), yellow stippled lines: unconformities identified internally in the Quaternary basin fill, indicating at least 2 phases of erosion and sedimentation. The relationships between the wedge-shaped basin with its internal unconformities and the seawards dipping fault are consistent with a sedimentary wedge created by normal faulting along the MTFC. The dip of the master fault is steeper than in the area of figure 8.

5. FAULTS AND BASINS IN THE NEARSHORE ZONE

5.1 The Møre-Trøndelag Fault Complex(MTFC)

The Møre-Trøndelag Fault Complex (MTFC) is a long-lived fault complex exposed onshore in the Trondheim region and continuing offshore into the area of the Slørebotn Subbasin of the eastern Møre Basin (Figure 2, Appendix 1). Early phases of activity along the MTFC were closely linked to Devonian extensional tectonics; later movements accompanied Mesozoic rifting (Jongepier et al. 1996, Sommaruga and Bøe 2002). Normally-reactivated fault strands of the MTFC also controlled Late Cretaceous-Cenozoic `post-rift´ uplift of the Norwegian mainland (Redfield et al. 2005). Thus, on the regional scale, the MTFC displays a wide range of fault geometries, kinematics and deformation products.

The MTFC originated as a set of ENE-WSW-trending sinistral shear zones and faults that developed along the flanks of regional, doubly plunging upright folds in the outer Trondheim area (Séranne 1992, Robinson 1995, Osmundsen et al. 2006). The MTFC has been interpreted as a regional transfer zone that connected the Devonian Nordfjord-Sogn Detachment Zone of southwest Norway with the Høybakken Detachment of the Fosen Peninsula and the Kollstraumen Detachment north and east of Vikna (Seranne 1992, Braaten et al. 2002).

Inferred Palaeozoic, sinistral phases of movement are typically characterized by chlorite-and epidote-bearing deformation products including suites of dark grey to grey-green, welded cataclasites, breccias and occasionally pseudotachylite, that decorate fault planes with kinematic indicators showing strike-parallel transport (Figure 10). In places, flower structures occur in terms of thrusts that splay off strands of the MTFC, producing complex local geometries.

Figure 10. Strike-parallel transport lineations on fault plane of the main MTFC at Tjeldbergodden.

A number of strands of the MTFC were reactivated in the Triassic, Jurassic and the Late Cretaceous or Cenozoic, as evidenced by associated Triassic offshore deposits (Mørk and Johnsen 2005), Jurassic half-graben basins (e.g. Bøe and Bjerklie 1989, Sommaruga and Bøe 2002, Bøe et al. 2010) and by jumps in apparent apatite fission-track ages indicating movements in the Late Cretaceous or later (Redfield et al. 2005). The MTFC continues offshore to provide the SE border of the Triassic-Cretaceous Slørebotn Subbasin SW of the Klakk Fault Complex. The Slørebotn Subbasin experienced a major phase of faulting and block rotation in the Latest Jurassic (Jongepier et al. 1996), and the border fault towards the crystalline basement was associated with several kilometers of displacement, as part of a linked extensional system in the Gossa High area (e.g. Osmundsen and Ebbing 2008). Displacements increase towards the SW, where the border fault becomes the main border to the deep Møre Basin. At the level of the seafloor, this border fault partly coincides with the contact between crystalline basement and sedimentary rocks in areas SW of Smøla (see above).

5.1.1 Architecture of reactivated MTFC strands onshore in the Møre area

In the Møre region, reactivation of the pre-existing Paleozoic structural grain gave rise to complex fault zones with zeolite mineralizations (mainly laumonite) and up to 3 or 4 generations of breccias and cataclasites that partly post-date zeolite growth (Bauck 2010). Other common fault products are gouge and unconsolidated breccias (e.g. Osmundsen et al. 2010). Along the reactivated fault strands, transport lineations in the form of grooves and mineral fibres, combined with asymmetric kinematic indicators show mainly downdip, hangingwall-to-the NNW transport (Redfield et al. 2005, Osmundsen et al. 2010). Thus, displacements along the southwestern parts of the MTFC were dominated by normal-sense displacements at the time when the zeolite mineralizations and zeolite-bearing breccias and cataclasites formed. Meters-thick fault cores with a phletora of deformation products crop out in the Møre region (Bauck 2010). Larger strands of the MTFC are demonstrably hidden in NE-SW-trending fjords in the Møre area, as indicated by refraction studies and drillcores obtained by the Norwegian road authorities. In some cases these have been studied in detail (Bøe et al. 2005). Locally, the host rocks adjacent to a fault strand show alteration in the form of clay minerals replacing minerals in the metamorphic host rock without any visible brittle deformation of the host-rock structure. This is interpreted to represent deep weathering, or alternatively fluid-assisted host-rock alteration. Because such products weather easily at the surface, they are easily removed by erosion. They may therefore be more widespread than hitherto recognized.

Evidence for fairly recent normal fault activity in certain parts of Norway has been extracted from the topographic (Redfield et al. 2005, Osmundsen and Redfield 2011, Redfield and Osmundsen 2013) and geomorphic (Osmundsen et al. 2010) signatures of the mountains (Figure 11). One such area in particular is the MTFC. Present-day drainage patterns of the seaward facing steep topographic escarpment and the gentler inland backslope closely mimic those imposed atop fault blocks in actively-uplifting fault blocks (e.g., Leeder and Gawthorp 1987; see discussion in Redfield and Osmundsen 2013). The mean azimuth peak from trunk drainages of the backslope match both the general breakup azimuth and the mean azimuth to slickenlines measured from brittle fault planes in the MTFC region itself (Redfield and Osmundsen 2013).

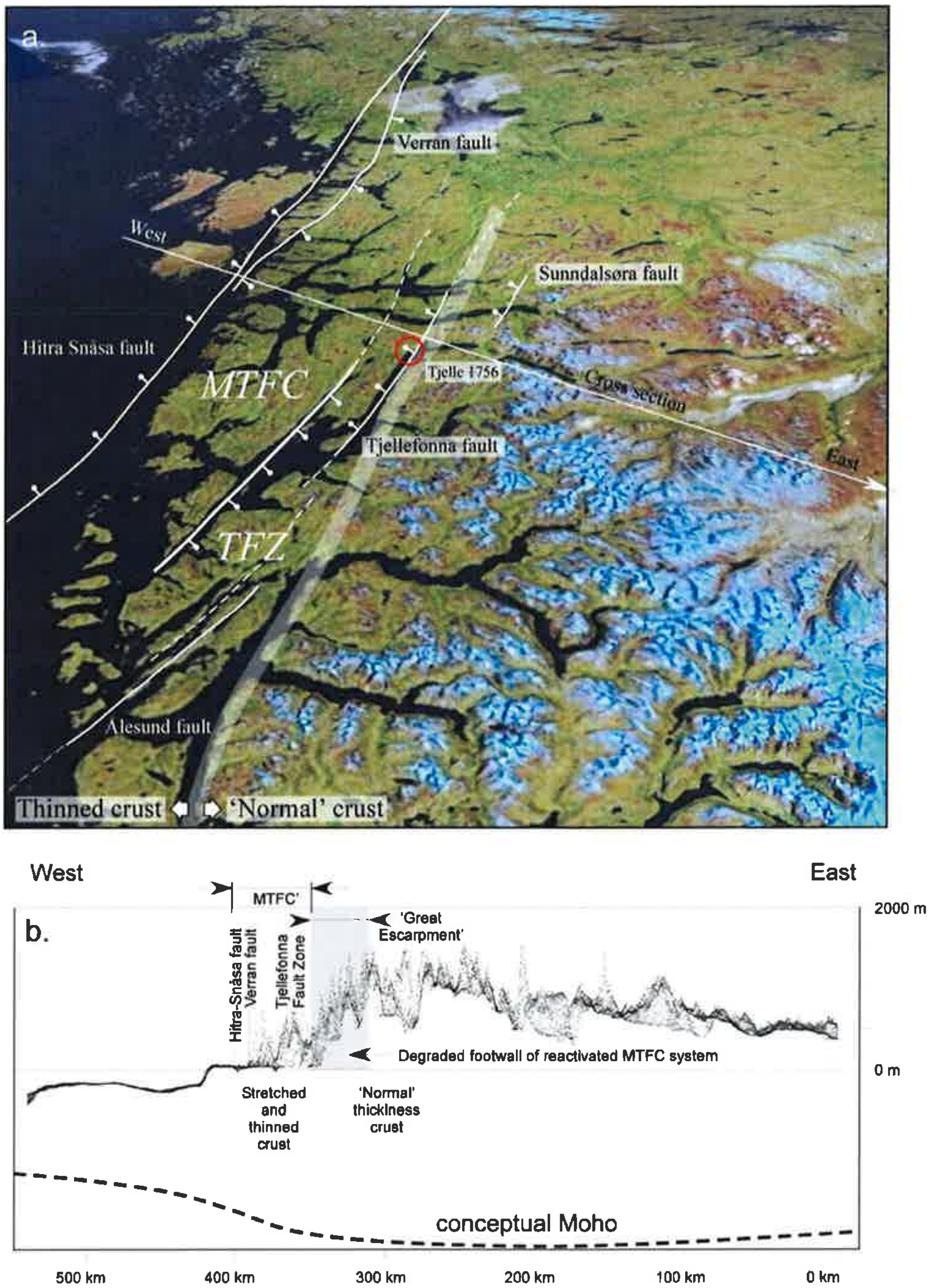


Figure 11. Overview image and cross-section showing the inner and outer strands of the MTFC and their effect on today's topography. ***a)*** *shows the Hitra Snåsa /Verran fault strands to the west, and the Ålesund / Tjellefonna strands to the east. These last two make up the Tjellefonna Fault Zone (TFZ). Heavy white line approximates the transition from crystalline crust of 'normal' to 'stretched' thickness (e.g., 39 km; see Redfield and Osmundsen 2013, 2015 for discussion). Red circle shows the location of the 1756 Tjelle rockslide (see Redfield and Osmundsen 2009).* ***b)*** *shows a topographic cross section across the MTFC. Note the topographic asymmetry and the spatial coincidence of the TFZ fault strands with the base of the 'Great Escarpment.'*

5.2 Mapping of faults from high resolution bathymetry

The Olex bathymetric database has revealed a number of fault lines in the drowned crystalline basement zone (Figure 2, Appendix 1). Most of these were unknown from previous mapping, particularly in areas without seismic data. We have interpreted the most evident ones, but from the database a more detailed interpretation is possible. Several of the lineaments line up with faults mapped on land, but only a few of the fault segments related to the MTFC have marked on the attached map (Figure 2, Appendix 1).

5.3 Down faulted basins

Most of the information about down faulted basins are based on dense grids of mini airgun lines acquired by NGU. These data are not included in the present project, and are not available in SEG-Y format. A few IKU lines cross the down faulted basins, and confirm the interpretations. Minor changes of the outline of the basins have been done due to the improved bathymetry available during recent years. The detailed bathymetry gives a better view of the major faults, including those which mark the basin boundaries. The updated interpretations are presented in the attached geological map (Appendix 1). The new map also shows the location of two small basins off northern Fosen, north and southwest of Buholman. Based on the improved bathymetry, one of these has been reduced in size compared to the interpretation of Thorsnes (1995).

6. SEISMICITY AND POTENTIAL RELATION TO NEOTECTONIC MOVEMENTS

Earthquakes suggest that some faults are currently active. Although the earthquakes are generally classified as 'intra-cratonic,' many appear related to the structural templates that characterize the Norwegian extended margin. This is reasonably established in the scientific literature generally as well as locally. Sykes (1978) suggested the occurrence of intraplate earthquakes in general is related to preconditioning factors that created zones of crustal weakness, and Norwegian onshore and offshore seismicity robustly reflects this (Redfield and Osmundsen 2015).

Earthquakes of $M_w >= 5.0$ are not uncommon within Fennoscandia, and historical events of these magnitudes have occurred along Norway's coast (Husebye and Kebeasy 2004, Husebye 2005, Bungum and Olesen 2005a, b). However, no $M_w >= 6.0$ has occurred in Norway during the time period covered by instrumentation. The repeat interval for $M_w >= 6.0$ events is not currently well-constrained. Bungum et al. (2005) suggested that application of the 'ergodicity principle' (replacing time for space) implies an 'earthquake deficit' in Norway.

Although the MTFC is a pronounced zone of inherited structural weakness, for much of its onshore length its historical seismicity has been minimal. It is possible that a significant earthquake caused a catastrophic rockslide/tsunami event at Tjellefonna in 1756 (Figure 11; see Morsing 1757, Redfield and Osmundsen 2009). A general rule of thumb is that ground shaking associated with Mw >= 6.0 is required to trigger even already destabilized hill slopes (Keefer 1984a, b). This relationship might be taken to imply Norway's most recent Mw >= 6.0 event occurred at this time. However, the triggering mechanism at Tjellefonna remains uncertain (Sandøy 2012). Were it not an earthquake, the most recent candidate for an Mw >= 6.0 event would be pushed farther back in time. The 'ergodicity principle' earthquake deficit prediction of Bungum et al. (2005) should therefore be considered seriously.

The wedge-shaped Quaternary basins identified in this study strongly resemble rotated half-graben basins. They are located directly inboard of the 8,2 Kyr Storegga Slide and are juxtaposed with strands of the MTFC. As a summary of comprehensive investigations related to the development of the Ormen Lange gas field (located below the slide scar), Bryn et al. (2005) pointed to several destabilization factors of importance, but found it most likely that a strong earthquake had been the main trigger of the huge slide. The age of the Quaternary triangular basins is unknown, but they may represent evidence for postglacial seismic activity.

7. WEATHERED BASEMENT

7.1 Previous studies of weathered basement rocks in Norway

Andøya contains the only succession of Mesozoic sediments on land Norway. A weathering zone, and thin remnants of a formerly very thick Palaeozoic sediment cover underlie sediments of Middle Jurassic age (Dalland 1981, Manum et al. 1991). The Jurassic-Cretaceous succession on Andøya is approximately 900 m thick, and occurs in a small, partly fault-bounded area at the eastern coast of the island. The age of the weathering zone is poorly constrained and debated (Bøe et al. 2010). Sturt et al. (1979) reported a K-Ar age of Late Devonian/Middle Carboniferous for the weathering profile, while Løseth and Tveten (1996) and Smelror et al. (2001) suggested that the extensive weathering of the basement took place in the Middle Jurassic. This latter interpretation is based on correlation to the offshore record where similar weathering profiles have been recorded (Smelror et al. 2001, Mørk et al. 2003).

Several areas of assumed Mesozoic weathering have been found on land in Mid Norway (Olesen et al. 2012, 2013). Many of these are related to fault and fracture zones. Areas of possible Mesozoic deep weathering in Frohavet have previously been described by Bøe (1991), Sommaruga and Bøe (2002) and Bøe et al. (2005, 2010), and locations are marked on the attached map (Figure 2, Appendix 1). One of these occurs in the southwestern part of Frohavet where the Jurassic succession is down faulted along the Dolmsundet Fault north of Ulvøya. The Dolmsundet Fault continues towards the southwest between Hitra and Dolmøya (Bøe 1991) (Figure 3). Farther north, the 5.3 km-long Frøya Tunnel between Dolmsundet and Frøya passes through a major zone of faulting and brecciation which parallels the MTFC (Bøe et al. 2005). Faults and fractures are concentrated in deformation zones that developed during Devonian to Tertiary crustal movements (Bøe et al. 2005). Drillcores from these zones include segments comprising possible Upper Palaeozoic and Mesozoic sediments. These were probably deposited on a fractured peneplain, and subsequently incorporated into faults during their reactivation in Mid Jurassic and later times. Extensive weathering of the fault rocks mainly post-dates brittle deformation and brecciation. Part of the weathering may have occurred in Late Triassic-Early Jurassic time, prior to the Middle Jurassic transgression and deposition of the sedimentary succession in Frohavet (Bøe et al. 2005). Also Olesen et al. (2007, 2013) have suggested the presence of Mesozoic deep-weathered fracture zones in south Norway.

A similar situation where the present seabed may be close to a an old peneplain occurs in the western extension of Frohavet northeast of Frøya. Here the Jurassic strata become almost sub horizontal towards the west before they disappear (Bøe 1991). It is difficult to locate the exact western boundary of the Jurassic strata from shallow seismic data, and this may reflect the presence of a weathering zone with a gradual transition from weathered basement to stratified Jurassic deposits. It is also possible that weathered basement occurs at the seafloor, below a Quaternary sediment cover, west of the Mesozoic Frohavet Basin (see attached map). Also the eastern boundary of the Frohavet Basin, north of the Tarva Fault (Figure 3) is hard to locate exactly. Weathered basement may therefore occur in this area, and possibly also farther northeast towards the shallow fault basins mapped by Thorsnes (1995).

7.2 Indication of weathered basement from seismic interpretation

Diamond coring of the subcropping bedrock was performed at seven locations off Møre-Trøndelag in 1988 (Skarbø et al. 1988). At one of the locations (IKU 6408/12-U-01) the target was to drill through a thin bedded section of Mesozoic sediments, and check if the transparent acoustic unit below also comprised sedimentary rocks (Figure 12). The coring showed that a Late Toarcian sequence of mudstone interbedded with sandstone beds is resting unconformably on a kaoline weathered granite. The granite was encountered at 32 m below the seafloor, and the coring continued for 9 m. The upper 3-4 m were strongly weathered, but the degree of alteration decreased downwards.

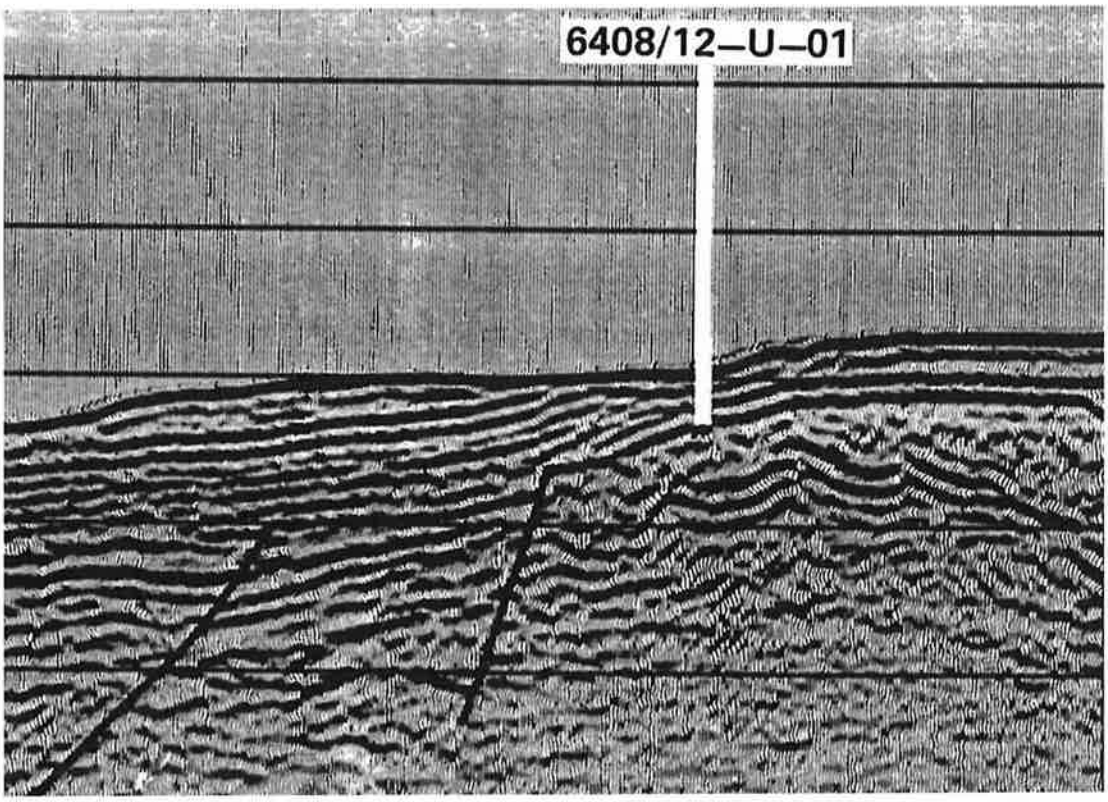
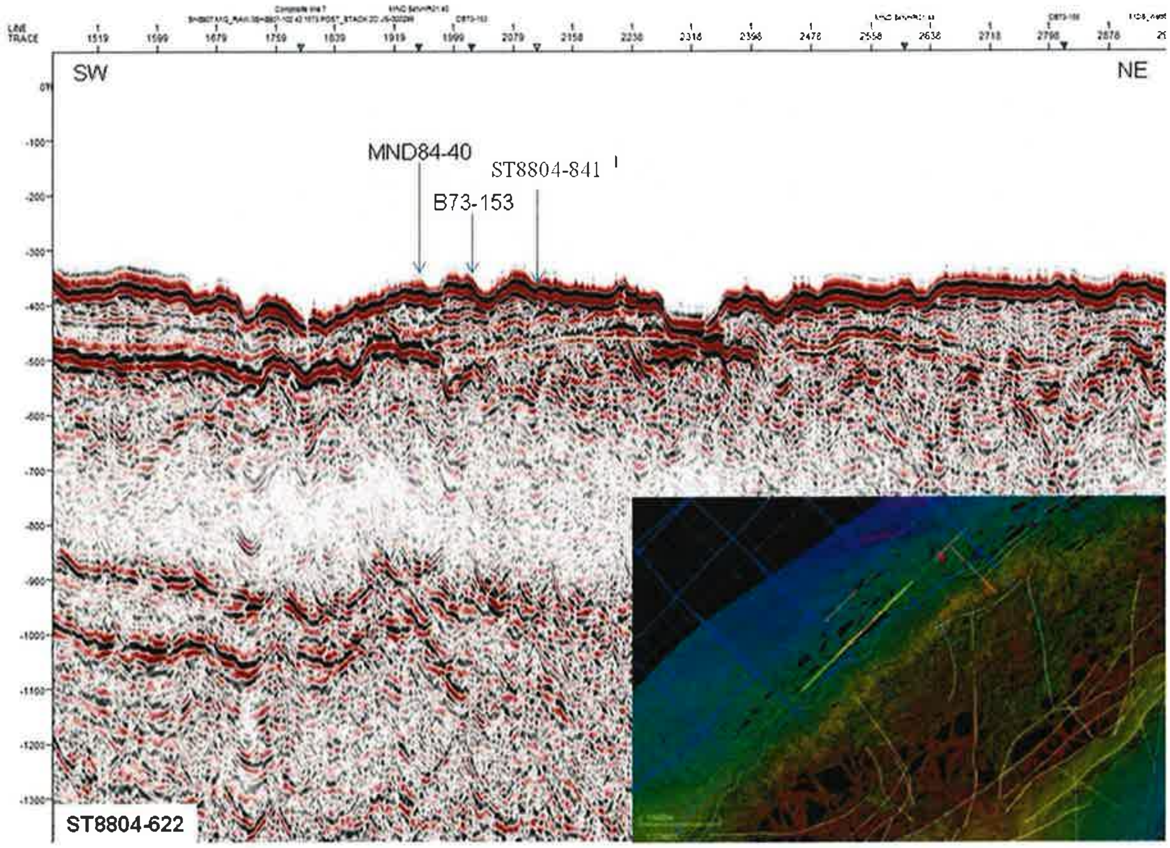


Figure 12. IKU boring 6408/12-U-01 shown on the multichannel seismic line IKU-111-87 (from Skarbø et al. 1988). Below the 8 m thick Quaternary sediments, >20 m of Middle Jurassic sandstones were cored (93% core recovery). Strongly weathered granite was encountered at 32.2 m below the seafloor. The boring was terminated at 41.3 m, and the degree of weathering decreased downwards. Note that the sediment-basement contact is smooth, and that the weathered zone has an acoustic transparent character. The line was run SE-NW and it is 100 ms twt between scale lines.

The seismic lines acquired in order to plan the IKU drilling program, are recorded to 2.5 s. and have higher resolution than conventional 2D lines. The acoustic transparent character seen on line IKU-111-87 representing weathered rocks (Figure 12), cannot be seen on line MND84-48 which was run along exactly the same track.. However, on several other lines close to boring IKU 6408/12-U-01, the crystalline bedrock reflection varies in amplitude (Figures 13 and 14). A very strong seabed reflection indicates most likely a large impedance contrast between unweathered crystalline basement and sedimentary rocks. We therefore assume that seismic lines showing low or variable amplitudes, or no reflections at all, indicate areas of weathered bedrock (marked with stars on the map in Appendix 1).



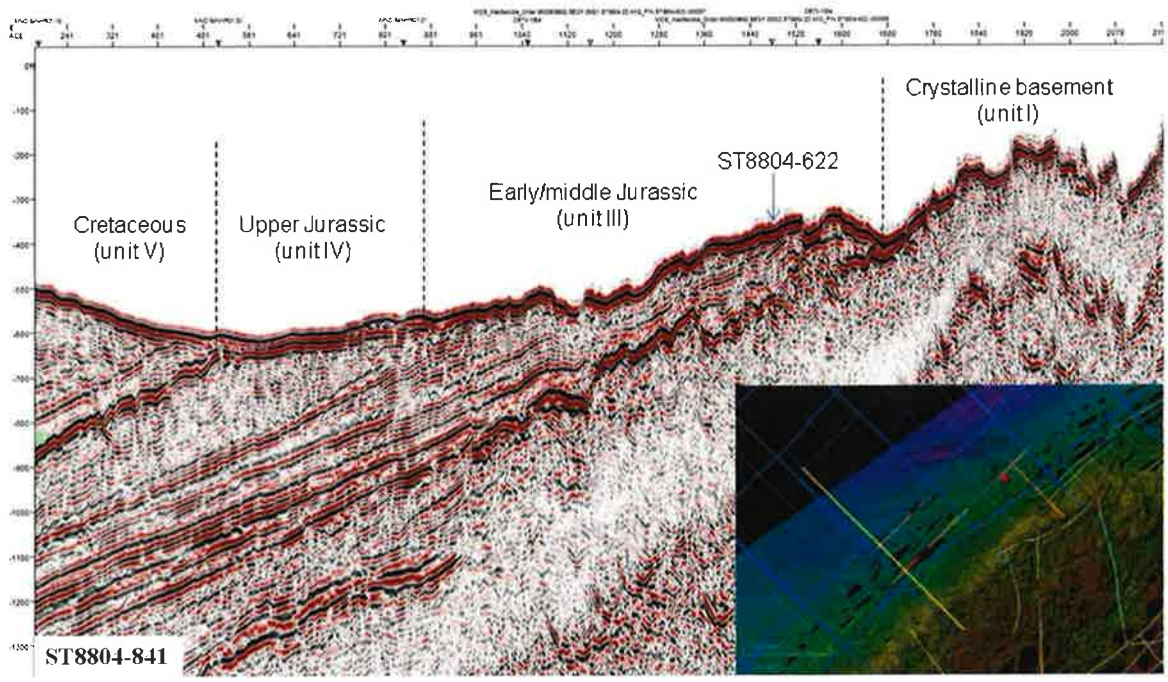


*Figure 13**a**, top). Segment of line ST8804-622 (yellow on inset map) located SW of boring 6408/12-U-01(red circle). Note that strong reflections as well as very week ones occur at the boundary between sediments and the crystalline basement. Weak/variable reflections probably indicate areas of weathered basement. **b**) Line ST8804-841 shows variable and weak basement reflections where it intersect ST8804-622. For comparison, see the parallel line MND84-40 located 2 kilometers to the south, which displays high amplitude reflections at the basement contact (Figure 4b).*

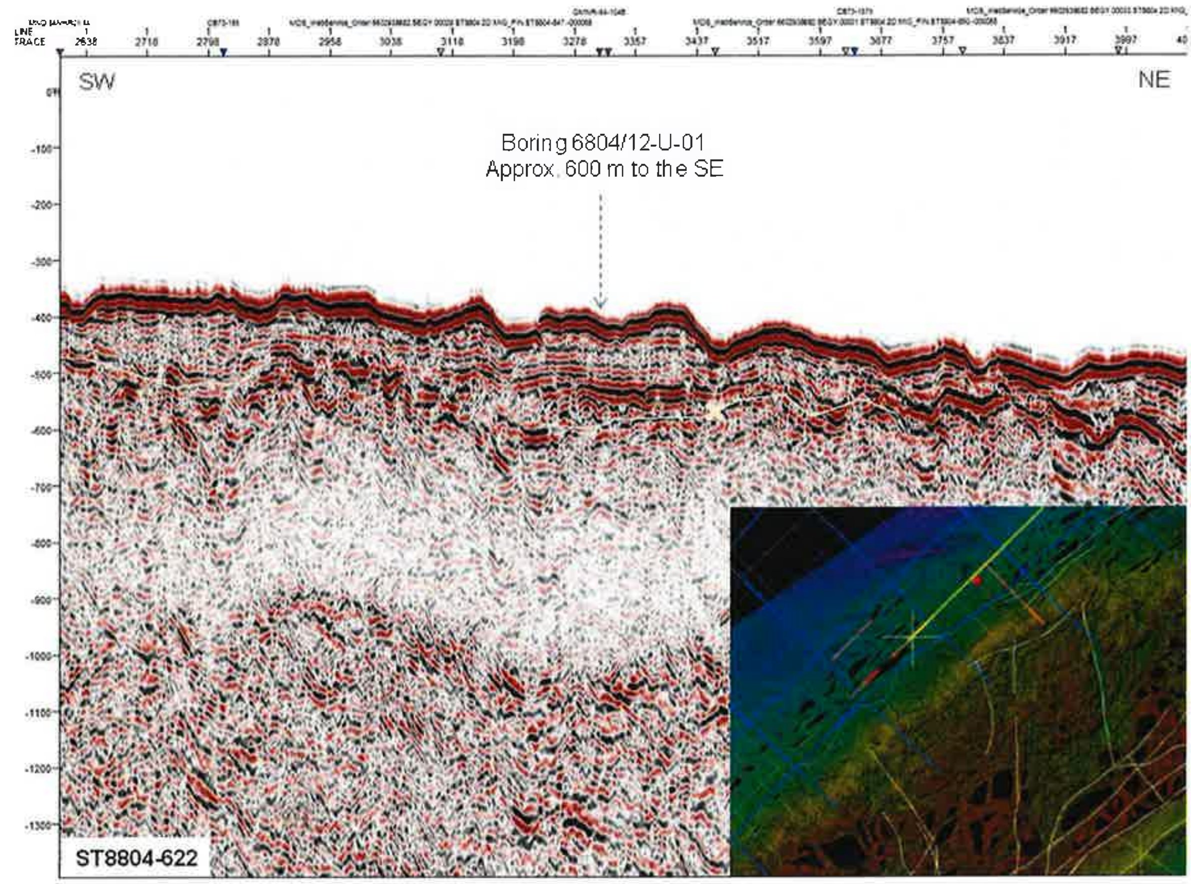


Figure 14. Segment of line ST8804-622, here passing close to the IKU borehole 6408/12-U-01 where weathered basement was cored. Note variable and locally weak reflection character at the inferred basement boundary, which may indicate that the degree of weathering varies in the area. The yellow line on the inset map shows location of the line and the red dot the position borehole.

The area northwest of Froøyene, where several seismic lines indicate weathered basement below Mesozoic rocks, shows a fairly smooth morphologic character east of the BSC (Figures 7 and 15). There are strong indications of weathered basement rocks (saprolites) below Mesozoic sediments to the NW of the BSC, and this apparently smoother zone could have formed due to fairly 'recent' exposure of glacial erosion. We postuate that weathered basement did occur below the sedimentary rocks, and is reflected in the smooth morphological character. The preservation potential of weathered basement east of the BSC contact is depending of several factors (see above).

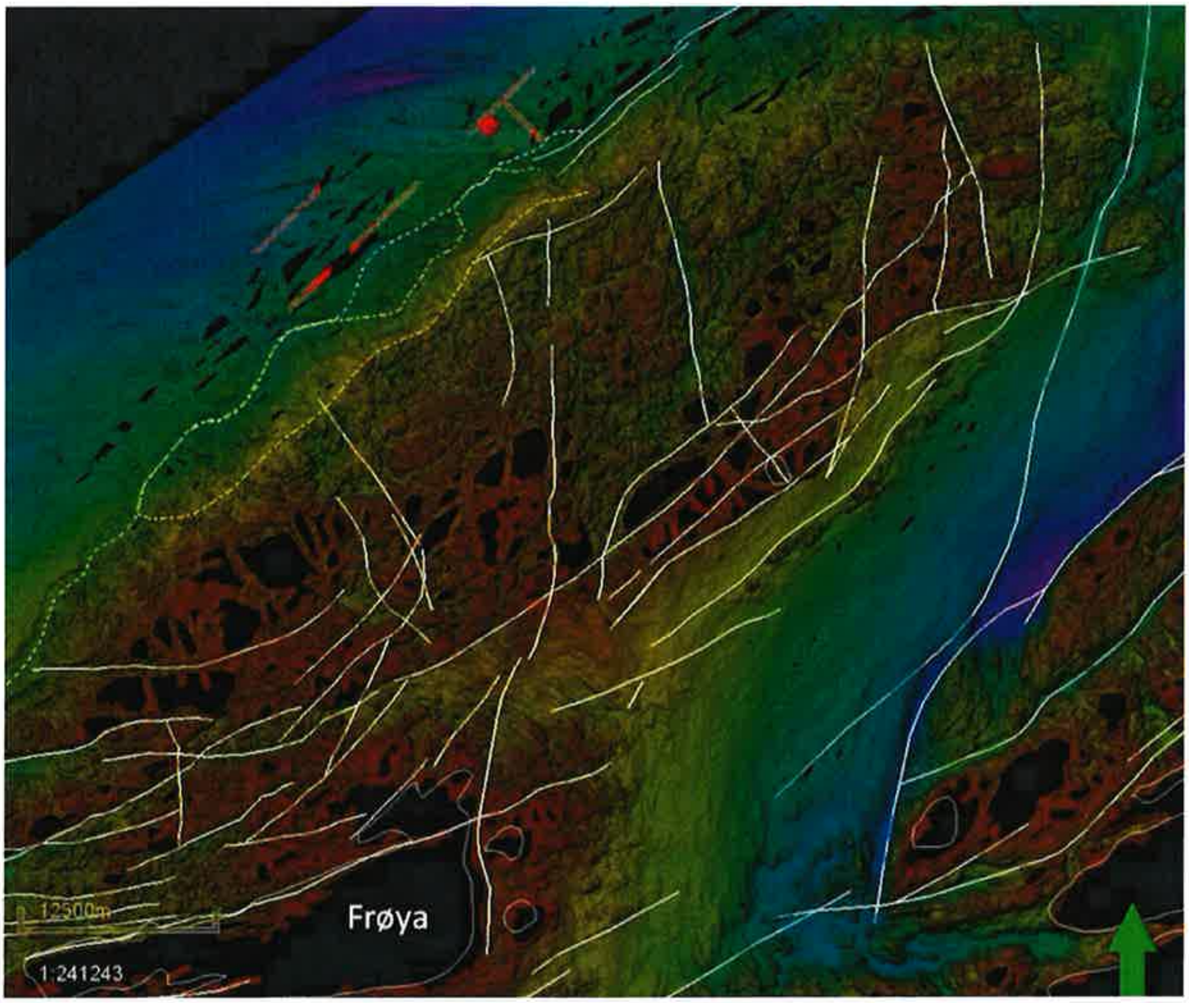


Figure 15. Bathymetry (OLEX database) showing the seafloor north of Frøya. Note the fairly smooth area inboard the stippled yellow line. We suggest that the morphology reflects that weathered basement rocks are preserved in this zone. The basement sediment contact (BSC) is marked with a stippled white line, and a continuous white line where it is faulted in the north. Interpretation of the main faults have for the first time been possible due to the improved bathymetry in the submerged basement zone. The colored straight segments west of the white stippled line mark weathered basement below Mesozoic sediments (interpreted on seismic lines). The red dot is the location of IKU borehole 6408/12-U-01, where weathered granite was cored. An image of higher resolution is shown in figure 7.

8. SUMMARY

This study of the Møre-Trøndelag coastal area is part of the SPARDIG project, where the main aim has been to transform old analogue sparker records from the Norwegian continental shelf into SEG-Y format. The objective of the scientific part of the project has been to utilize the new data set together with 2D seismic and bathymetric data to study the geology of the transition zone between crystalline basement and overlying sedimentary rocks to make an updated geological map.

- The SEG-Y versions of the sparker data and conventional 2D seismic data interpreted together appear to improve the geological interpretations.
- The data sets are supplementary to each other as the sparker data have higher resolution, while the 2D data have better penetration.
- The contact between sedimentary rocks and the crystalline basement has been studied in detail, and classified as 'sedimentary' or 'fault-defined'. In most areas the boundary deviates only slightly from previous mapping.
- Major faults have been interpreted from bathymetric data of good quality, and presented on the geological map.
- The improved bathymetry has caused slight reinterpretation of down-faulted sedimentary basins in the crystalline basement zone.
- Smooth morphology directly landward of the crystalline basement - sediment contact (BSC) northwest of Froøyane (north of Frøya) indicates presence of weathered rocks.
- Seismic data strongly indicate weathered basement locally below Mesozoic sediments. Weathered granitic rocks have previously been cored below Mesozoic sediments.
- Quaternary triangular basins east of the Slørebotn Subbasin, at the faulted contact between sediments and crystalline basement possibly record postglacial seismic activity.

9. REFERENCES

Bauck, M.S. (2010) Fault rock assemblages and fault architecture in the Møre-Trøndelag Fault Complex. M.S. thesis, Norwegian University of Science and Technology, Trondheim, 97 pp.

Blystad, P., Brekke, H., Færseth, R.B., Larsen, B.T., Skogseid, J. and Tørudbakken, B. (1995) Structural elements of the Norwegian continental shelf. Part II: the Norwegian Sea Region. Norwegian Petroleum Directorate Bulletin, 8, 1–45.

Brekke, H. (2000) The tectonic evolution of the Norwegian Sea continental margin with emphasis on the Vøring and Møre Basins. In Nøttvedt, A. (ed.) Dynamics of the Norwegian margin, Geological Society of London Special Publication, 167, 327–378.

Brekke, H., Sjulstad, H.I., Magnus, C. and Williams, R.W. (2001) Sedimentary environments offshore Norway—an overview. In Martinsen, O.J. and Dreyer, T. (eds.) Sedimentary Environments Offshore Norway—Palaeozoic to Recent, Norwegian Petroleum Society Special Publication, 10, pp. 7–37.

Braaten, A., Osmundsen, P.T., Nordgulen, Ø., Roberts, D. and Meyer, G. (2002) Orogen-parallel extension of the Caledonides in northern Central Norway: an overview. Norwegian Journal of Geology, 82, 225-241.

Bryn, P., Berg, K., Forsberg, C.F., Solheim, A. Kvalstad, T.J. (2005) Explaining the Storegga Slide. Marine and Petroleum Geology 22, 11-19.

Bugge, T., Knarud, R. and Mørk, A. (1984) Bedrock geology on the mid-Norwegian continental shelf. In Norwegian Petroleum Society (ed.) Petroleum Geology of the North European Margin, Graham and Trotman, London, pp. 271–283.

Bugge, T., Elvebakk, G., Bakke, S., Fanavoll, S., Lippard, S.J., Leith, L., Mangerud, G., Möller, N., Nilsson, I., Rømuld, A., Schou, L., Vigran, J.O., Weiss, H.M. and Aarhus, N. (1989) Shallow drilling Barents Sea 1988. Main report. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 21.3444.00/03/89, 348 pp.

Bugge, T., Leith, D.A., Mangerud, G., Ringås, J.E., Weiss, H.M., Leith, L., Ritter, U. and Vigran, J.O. (1993) Shallow drilling Helgeland 1992. Main report. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 23.1684.00/02/93, 263 pp.

Bugge, T., Ringås, J.E., Leith, D.A., Mangerud, G., Weiss, H.M. and Leith, T.L. (2002) Upper Permian as a new play model on the Mid-Norwegian continental shelf; investigated by shallow stratigraphic drilling. American Association of Petroleum Geologists Bulletin, 2002, 107–127.

Bungum, H., Lindholm, C. and Faleide, J.I. (2005) Postglacial seismicity offshore mid-Norway with emphasis on spatio-temporalmagnitudal variations. Marine and Petroleum Geology, 22, 137–148.

Bungum, H. and Olesen, O. (2005a) The 31st of August 1819 Lurøy earthquake revisited. Norwegian Journal of Geology, 85, 245-252.

Bungum, H. and Olesen, O. (2005b) Reply to Comments on the Lurøy 1819 earthquake controversy by E.S. Husebye. Norwegian Journal of Geology, 85, 257-258.

Bøe, R. (1991) Structure and seismic stratigraphy of the innermost mid-Norwegian continental shelf: an example from the Frohavet area. Marine and Petroleum Geology, 8, 140–151.

Bøe, R. and Bjerkli, K. (1989) Mesozoic sedimentary rocks in Edøyfjorden and Beitstadfjorden, Central Norway: Implications for the structural history of the Møre-Trøndelag fault zone. Marine Geology, 87, 287–299.

Bøe, R. and Skilbrei, J.R. (1998) Structure and seismic stratigraphy of the Griptarane area, Møre Basin margin, mid-Norway continental shelf. Marine Geology, 147, 85–107.

Bøe, R., Sørensen, S. and Hovland, M. (1992) The Karmsundet Basin, SW Norway: stratigraphy, structure and neotectonic activity. Norsk Geologisk Tidsskrift, 72, 281–283.

Bøe, R., Mørk, M.B.E., Roberts, D. and Vigran, J.O. (2005) Possible Mesozoic sediments in fault and brecciation zones in Frøyfjorden, Mid Norway. Norges geologiske undersøkelse Bulletin, 443, 29–35.

Bøe, R., Smelror, M., Davidsen, B. and Walderhaug, O. (2008) Nearshore Mesozoic basins off Nordland, Norway: Structure, age and sedimentary environment. Marine and Petroleum Geology, 25, 235–253.

Bøe, R., Fossen, H. and Smelror, M. (2010) Mesozoic sediments and structures onshore Norway and in the coastal zone. NGU Bulletin, 450, 15-32.

Carstens, C.W. (1929) Brunkullfund på Tun, Verran. Det Kongelige Norske Videnskabers Selskabs Skrifter, 2, 32–33.

Chand, S., Schaming, M., Raharimalala, M. R., Rise, L. and Olsen, H.A. (2016) Transformation of analogue sparker profiles from the Norwegian continental shelf to seg-y format. Spardig Technical report. NGU report 2016.038, 45 pp.

Dalland, A. (1981) Mesozoic sedimentary succession at Andøy, northern Norway and relation to structural development of the North Atlantic Area. Canadian Society of Petroleum Geologists Memoir, 7, 563–584.

Davidsen, B., Smelror, M. and Ottesen, D. (2001a) Et nyoppdaget mesozoisk basseng i Sortlandsundet, Vesterålen. Geonytt 2001, Geological Society of Norway Annual Meeting, Oslo, 8.–10. January 2001, pp. 42–43.

Davidsen, B., Sommaruga, A. and Bøe, R. (2001b) Final report: sedimentation, tectonics and uplift in Vesterålen. Phase I—localizing near-shore faults and Mesozoic sediment basins. NGU Report 2001.011, 16 pp.

Evans, D., Graham, C., Armour, A. and Bathurst, P. (2003) The millennium atlas: petroleum geology of the Central and Northern North Sea, Geological Society of London, 990 pp.

Fjerdingstad, V., Mørk, A., Vigran, J.O., Bugge, T., Fanavoll, S. and Leith, L. (1985) Shallow drilling Barents Sea 1984. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 01.0217.00/01/85, 142 pp.

Fossen, H., Mangerud, G., Hesthammer, J., Bugge, T. and Gabrielsen, R.H. (1997) The Bjorøy Formation: a newly discovered occurrence of Jurassic sediments in the Bergen Arc System. Norsk Geologisk Tidsskrift, 77, 269–287.

Færseth, R.B. and Lien, T. (2002) Cretaceous evolution in the Norwegian Sea—a period of tectonic quiescence. Marine and Petroleum Geology, 19, 1005–1027.

Gabrielsen, R.H., Odinsen, T. and Grunnaleite, I. (1999) Structuring of the northern Viking Graben and the Møre Basin; the influence of basement structural grain, and the particular role of the Møre-Trøndelag Fault Complex. Marine and Petroleum Geology, 16, 443–465.

Grønlie, A. and Roberts, D. (1989) Resurgent strike-slip duplex development along the Hitra-Snåsa and Verran Faults, Møre-Trøndelag Fault Zone, Central Norway. Journal of Structural Geology, 11, 295–305.

Grønlie, A., Naeser, C.W., Naeser, N.D., Mitchell, J.G., Sturt, B.A. and Ineson, P.R. (1994) Fission track and K-Ar dating of tectonic activity in a transect across the Møre-Trøndelag Fault Zone, central Norway. Norsk Geologisk Tidsskrift, 74, 24–34.

Hansen, J.W., Bakke, S., Løseth, H., Mørk, A., Mørk, M.B.E., Rise, L., Smelror, M., Verdenius, J.G., Vigran, J.O. and Weiss, H.M. (1992) Shallow drilling Nordland VI and VII 1991. Main report. Continental Shelf and Petroleum Technology Research Institute (IKU). Report 23.1594.00/02/92, 390 pp.

Holtedahl, H. (1988) Bedrock geology and Quaternary sediments in the Lista basin, S. Norway. Norsk Geologisk Tidsskrift, 68, 1–20.

Holtedahl, H. (1993) Marine geology of the Norwegian continental margin, Norges geologiske undersøkelse Special Publication, 6, 150 pp.

Horn, G. (1931) Über kohlen-gerölle in Norwegen. Norsk Geologisk Tidsskrift, 12, 341–361.
Huseby, E.S. (2005) Comments on the Lurøy 1819 earthquake controversy. Norwegian Journal of Geology, 85 253-256. ISSN 029-196X.

Husebye, E.S., Kebeasy, T.R.M. (2004) A re-assessment of the 31st of August 1819 Lurøy earthquake - not the largest in NW Europe. Norwegian Journal of Geology. 84, 57-66.
IKU (1984) Shallow seismic data from the Norwegian Continental Shelf. Description of IKU's data packages. 9 pp. February 1984.

Johansen, M., Poulsen, H., Skjæran, H., Straume, T. and Thorsplass, J.O. (1988) Froanbassengets Dannelse og Jurassiske Sedimenter. Report, Norwegian Institute of Technology (NTH), 103 pp.

Jongepier, K., Rui, J.C. and Grue, K. (1996) Triassic to Early Cretaceous stratigraphic and structural development of the northeastern Møre Basin, off Mid-Norway. Norsk Geologisk Tidsskrift, 76, 199–214.

Keefer, D.K. (1984a) Landslides caused by earthquakes. Geological Society of America Bulletin, 95, 4, 406-421.

Keefer, D.K. (1984b) Rock avalanches caused by earthquakes: source characteristics. Science, 223, 4642, 1288-1290.

Kjerulf, T. (1870) Undersøgelse av Nogle Kulslags og Torv. Videnskabselskabet i Christiania Forhandlingar, pp. 404–413.

Leeder, M. R. and Gawthorpe, R. L. (1987) Sedimentary models for extensional tilt-block/half-graben basins. Geological Society, London, Special Publications, 28(1), 139-152.

Løseth, H. and Tveten, E. (1996) Post-Caledonian structural evolution of the Lofoten and Vesterålen offshore and onshore areas. Norsk Geologisk Tidsskrift, 76, 215–230.

Lien, T. (2005) From rifting to drifting: effects on the development of deep-water hydrocarbon reservoirs in a passive margin setting, Norwegian Sea. Norwegian Journal of Geology 85, 319-332.

Manum, S.B. (1964) Nytt om Verran-kullene. Fossil-Nytt, 3, 1–2.

Manum, S.B., Bose, M.N. and Vigran, J.O. (1991) The Jurassic flora of Andøya, northern Norway. Review of Palaeobotany and Palynology, 68, 233–256.

Martinsen, O. and Dreyer, T. (eds.) (2001) Sedimentary environments offshore Norway—Palaeozoic to Recent, Norwegian Petroleum Society Special Publication, 10, 490 pp.

Martinius, A.W., Kaas, I., Næss, A., Helgesen, G., Kjærefjord, J.M. and Leith, D.A. (2001) Sedimentology of the heterolithic and tide-dominated Tilje formation (Early Jurassic, Halten Terrace, offshore mid-Norway). In Martinsen, O.J. and Dreyer, T. (eds.) Sedimentary environments offshore Norway—Palaeozoic to Recent,Norwegian Petroleum Society Special Publication, 10, pp. 103–144.

Morsing, C. (1757) En kortileg beskrivelse over Jordskiælvet, og Fieldets Nedfald, Som skede udj Nesset-Præstegiæld i Romsdahls Provstie, og Throndheims Stift udj Norge, nestafvigte Aar, Natten til dend 23 Februarij 1756. Kiøbenhafn, 13 December, 1757. Norsk Historisk Kjeldskrift Institutt, Boks 23, Kringsjå, Oslo 8, Norge.

Müller, R., Nystuen, J.P., Eide, F. and Lie, H. (2005) Late Permian to Triassic basin infill history and palaeogeography of the Mid-Norwegian shelf—East Greenland region. In Wandås, B.T.G., Nystuen, J.P., Eide, E. and Gradstein, F.M.. (eds.) Onshore-offshore relationships on the North Atlantic Margin., Norwegian Petroleum Society Special Publication, 12, 155–189.

Mørk, M.B.E. and Johnsen, S.O. (2005) Jurassic sandstone provenance and basement erosion in the Møre margin – Froan Basin area. Norges geologiske undersøkelse Bulletin 443, 5–18.

Mørk, A., Aarhus, N., Bugge, T. and Mills, N. (1983) Shallow drilling of Mesozoic rocks off Helgeland 1982. Continental Shelf and Petroleum Technology Research Institute (IKU) Report P–248/1/83, 332 pp.

Mørk, M.B.E., Vigran, J.O., Smelror, M., Fjredingstad, V. and Bøe, R. (2003) Mesozoic mudstone compositions and the role of kaolinite weathering—a view from shallow cores in the Norwegian Sea (Møre to Troms). Norwegian Journal of Geology, 83, 61–78.

Nordhagen, R. (1921) Fossilførende blokker fra Juratiden på Froøyene utenfor Trondheimsfjorden. Naturen, 45, 110–115.

Nystuen, J.P., Müller, R., Mørk, A. and Nøttvedt, A. (2006) Fra ørken til elveslette—fra land til hav. In Ramberg, I.B., Bryhni, I. and Nøttvedt, A. (eds.) Landet blir til—Norges geologi, Norsk Geologisk Forening, Trondheim, pp. 328–353.

Oftedahl, C. (1972) A sideritic ironstone of Jurassic age in Beitstadfjorden, Trøndelag. Norsk Geologisk Tidsskrift, 52, 123–134.

Oftedahl, C. (1975) Middle Jurassic graben tectonics in Mid-Norway. In Norwegian Petroleum Society (ed.) Jurassic Northern North Sea, pp. 1–13.

Olesen, O., Dehls, J.F., Ebbing, J., Henriksen, H., Kihle, O. and Lundin, E. (2007) Aeromagnetic mapping of deep-weathered fracture zones in the Oslo Region—a new tool for improved planning of tunnels. Norwegian Journal of Geology, 87, 253–267.

Olesen, O., Bering, D., Brönner, M., Dalsegg, E., Fabian, K., Fredin,O., Gellein, J., Husteli, B., Magnus, C., Rønning, J.S., Solbakk,T., Tønnesen J.F. and Øverland, J.A. (2012) Tropical Weathering In Norway, TWIN Final Report. NGU Report 2012.005, 188 pp.

Olesen, O., Kierulf, H.P., Brönner, M., Dalsegg, E., Fredin, O. and Solbakk, T. (2013) Deep weathering, neotectonics and strandflat formation in Nordland, northern Norway. Norwegian Journal of Geology, 93, 189-213.

Osmundsen, P.T. and Ebbing, J. (2008) Styles of extension offshore Mid Norway and implications for mechanisms of crustal thinning at passive margins. Tectonics 27, TC6016, 1-25.

Osmundsen, P.T., Sommaruga, S., Skilbrei, J.S. and Olesen, O. (2002) Deep structure of the Mid Norway rifted margin. Norwegian Journal of Geology, 82, 205–224.

Osmundsen, P.T., Eide, E.A., Haabesland, N.E., Roberts, D., Andersen, T.B., Kendrick, M., Bingen, B., Braathen, A. and Redfield, T.F. (2006) Kinematics of the Høybakken detachment zone and the Møre-Trøndelag Fault Complex, central Norway. Journal of the Geological Society of London, 163, 303–318.

Osmundsen, P.T., Redfield, T.F., Hendriks, B.H.W., Bergh, S., Hansen, J-A., Henderson, I.H.C., Dehls, J., Lauknes, T.R. Larsen, Y., Anda, E. and Davidsen, B. (2010) Fault-controlled alpine topography in Norway. Journal of the Geological Society of London, 167, 83-98.

Osmundsen, P.T. and Redfield, T.F. (2011) Crustal taper and topography at passive continental margins. Terra Nova, 23, 349-361.

Ramberg, I.B., Bryhni, I. and Nøttvedt, A. (eds.) (2006) Landet blir til—Norges geologi, Norsk Geologisk Forening, Trondheim, 608 pp.

Redfield, T.F., Osmundsen, P.T. and Hendriks, B.W.H. (2005) The role of fault reactivation and growth in the uplift of western Fennoscandia. Journal of the Geological Society of London 162, 1013-1030.

Redfield, T. F. and Osmundsen, P.T. (2009) The Tjellefonna fault system of Western Norway: Linking late-Caledonian extension, post-Caledonian normal faulting, and Tertiary rock column uplift with the landslide-generated tsunami event of 1756. Tectonophysics 474, 106–123.

Redfield, T.F. and Osmundsen, P.T. (2013) The long-term topographic response of a continent adjacent to a hyperextended margin: A case study from Scandinavia. Geological Society of America Bulletin 125, 184-200.

Redfield, T.F. and Osmundsen, P.T. (2015) Some remarks on the earthquakes of Fennoscandia: A conceptual seismological model drawn from the perspectives of hyperextension. Norwegian Journal of Geology 94, 233–262.

Robinson, P. (1995) Extension of Trollheimen tectono-stratigraphic sequence in deep synclines near Molde and Brattvåg, Western Gneiss Region, southern Norway. Norsk Geologisk Tidsskrift 75, 181-198.

Rokoengen, K., Rise, L., Bugge, T. and Sættem, J. (1988) Berggrunnsgeologi på midtnorsk kontinentalsokkel - Bedrock geology on the Mid Norwegian continental shelf. M 1:1 000 000. IKU Publication no. 118, 1988.

Sandøy, G. (2012) Back-analysis of the 1756 Tjellefonna rockslide, Langfjorden. M.Sc. Thesis, Norwegian University of Science and Technology, Trondheim.

Seranne, M. (1992) Late Paleozoic kinematics of the MøreTrøndelag Fault Zone and adjacent areas, central Norway. Norsk Geologisk Tidskrift. 72, 141-158.

Sigmond, E.M.O. (1992) Bedrock map of Norway and adjacent ocean areas. Scale 1:3 million. Geological Survey of Norway.

Sigmond, E.M.O. (2002) Geological map. Land and Sea areas of Northern Europe. Scale 1:4 million. Geological Survey of Norway.

Skarbø, O., Bakke, S., Jacobsen, T., Krokstad, W., Lundschien, B., Myhr, M.B., Rise, L., Schou, L., Smelror, M., Verdenius, J., Vigran, J.O. and Århus, N. (1988) Shallow drilling off

Møre-Trøndelag 1988. Main report. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 21.3434/00/03/88, 289 pp.

Scholze, A. (1986) En palynologisk og maringeologisk undersøkelse av Holocene sedimenter fra Trondheimsfjorden. Cand.scient-thesis, University of Oslo, 117 pp.

Skarbø, O., Bakke, S., Jacobsen, T., Krogstad, W., Lundschien, B., Myhr, M.B., Rise, L., Schou, L., Smelror, M., Verdenius, J.G., Vigran, J.O. and Århus, N. (1988) Shallow drilling off Møre Trøndelag 1988. Main report. IKU Report 21.3434.00/03/88, 289 p., 9 apps.

Smelror, M., Jacobsen, T., Rokoengen, K., Bakke, S., Bøe, R., Goll, R.M., Lippard, S.J., Mørk, A., Rise, L., Vigran, J.O., Weiss, H.M. and Aarhus, N. (1989) Shallow drilling Farsund Subbasin 1989. Main report. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 21.3460.00/04/89, 242 pp.

Smelror, M., Jacobsen, T., Rise, L., Skarbø, O., Verdenius, J.G. and Vigran, J.O. (1994) Jurassic to Cretaceous stratigraphy of shallow cores on the Møre Basin Margin, Mid-Norway. Norsk Geologisk Tidsskrift, 74, 89–107.

Smelror, M., Mørk, A., Mørk, M.B.E., Weiss, H.M. and Løseth, H. (2001) Middle Jurassic-Lower Cretaceous transgressive-regressive sequences and facies distribution off northern Nordland and Troms, Norway. In Martinsen, O.J. and Dreyer, T. (eds.) Sedimentary environments offshore Norway—Palaeozoic to Recent, Norwegian Petroleum Society Special Publication, 10, 211–232.

Smelror, M., Petrov, O.V., Larsen, G.B. and Werner, S. (eds.) (2009) Atlas—Geological History of the Barents Sea, Geological Survey of Norway, Trondheim, 135 pp.

Solli, A. Bugge, T. og Thorsnes, T. 1997 Geologisk kart over Norge, berggrunnskart Namsos, M 1:250 000, Norges geologiske undersøkelse.

Sommeruga, A. and Bøe, R. (2002) Geometry and subcrop maps of shallow Jurassic basins along the Mid-Norway coast. Marine and Petroleum Geology, 19, 1029–1042.

Sturt, B.A., Dalland, A. and Mitchell, J.L. (1979) The age of the sub Mid-Jurassic tropical weathering profile of Andøya, Northern Norway, and the implications for the Late Palaeozoic palaeogeography in the North Atlantic region. Geologische Rundshau, 68, 523–542.

Sykes, L. (1978) Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism and other tectonism postdating continental fragmentation. Reviews of Geophysics 16, 4, 621–688.

Sættem, J., Aarhus, N., Elvebakk, G., Leith, L. and Vigran, J.O. (1985) Shallow seismic and sampling off Troms 1984. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 04.1224.00/01/85, 63 pp.

Thorsnes, T. (1995) Structural setting of two Mesozoic half-grabens of the coast of Trøndelag, Mid-Norwegian shelf. Norges geologiske undersøkelse Bulletin, 427, 68–71.

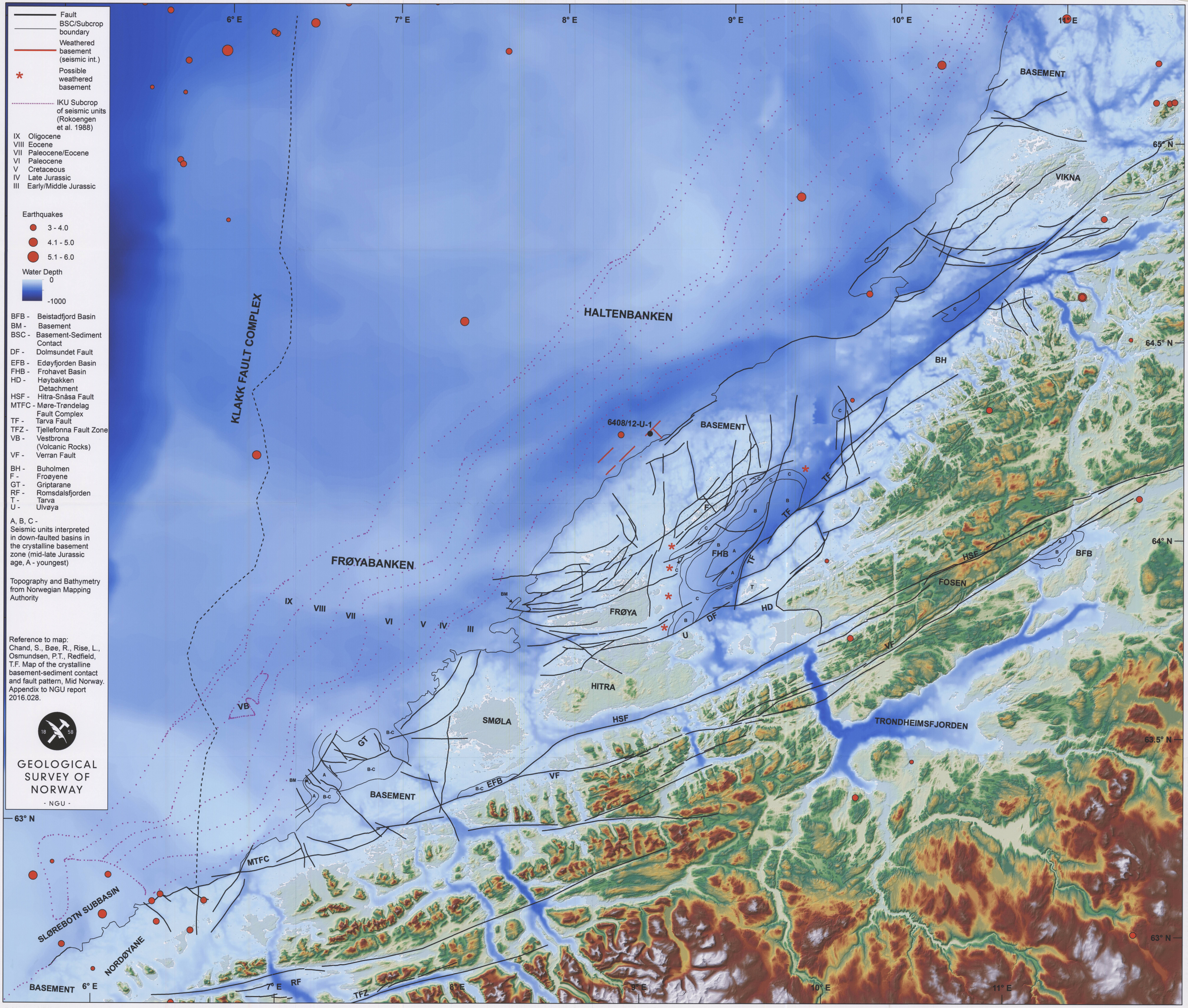
Vigran, J.O. (1970) Fragments of a Middle Jurassic flora from northern Trøndelag, Norway. Norsk Geologisk Tidsskrift, 50, 193–214.

Wandås, B.T.G., Nystuen, J.P., Eide, E.A. and Gradstein, F. (eds.) (2005) Onshore-offshore relationships on the North Atlantic Margin., Norwegian Petroleum Society Special Publication, 12, 305 pp.

Weisz, G. (1992) An investigation of Jurassic coals from Haltenbanken and Beistadfjorden. A comparison of composition and maturity. Diploma thesis, Norwegian Institute of Technology (NTH), Norway, 79 pp.

Ørvig, T. (1960) The Jurassic and Cretaceous on Andøya in northern Norway. In Holtedahl, O. (ed.) Geology of Norway, Norges geologiske undersøkelse, 208, pp. 344–350.

Aarhus, N., Bugge, T., Elvebakk, G., Fjerdingstad, V., Leith, T.L., Mørk, A., Rendall, H., Skarbø, O. and Weiss, H.M. (1987) Shallow Drilling Elf Aquitaine/Norsk Hydro/Statoil Barents Sea 1987. Main Data Report. Continental Shelf and Petroleum Technology Research Institute (IKU) Report 21.3435.00/02/87, 199 pp.


Fault
BSC/Subcrop boundary
Weathered basement (seismic int.)
Possible weathered basement
IKU Subcrop of seismic units (Rokoengen et al. 1988)
IX Oligocene
VIII Eocene
VII Paleocene/Eocene
VI Paleocene
V Cretaceous
IV Late Jurassic
III Early/Middle Jurassic
Earthquakes
3 - 4.0
4.1 - 5.0
5.1 - 6.0
Water Depth
0
-1000
BFB - Beistadfjord Basin
BM - Basement
BSC - Basement-Sediment Contact
DF - Dolmsundet Fault
EFB - Edøyfjorden Basin
FHB - Frohavet Basin
HD - Høybakken Detachment
HSF - Hitra-Snåsa Fault
MTFC - Møre-Trøndelag Fault Complex
TF - Tarva Fault
TFZ - Tjellefonna Fault Zone
VB - Vestbrona (Volcanic Rocks)
VF - Verran Fault
BH - Buholmen
F - Froøyene
GT - Griptarane
RF - Romsdalsfjorden
T - Tarva
U - Ulvøya
A, B, C - Seismic units interpreted in down-faulted basins in the crystalline basement zone (mid-late Jurassic age, A - youngest)
Topography and Bathymetry from Norwegian Mapping Authority
Reference to map: Chand, S., Bøe, R., Rise, L., Osmundsen, P.T., Redfield, T.F. Map of the crystalline basement-sediment contact and fault pattern, Mid Norway. Appendix to NGU report 2016.028.
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- NGU -
6° E
7° E
8° E
9° E
10° E
11° E
65° N
64.5° N
64° N
63.5° N
63° N
KLAKK FAULT COMPLEX
HALTENBANKEN
FRØYABANKEN
BASEMENT
VIKNA
BH
6408/12-U-1
FHB
FRØYA
HITRA
SMØLA
FOSEN
BFB
HSF
VF
TRONDHEIMSFJORDEN
HD
DF
U
TF
GT
EFB
MTFC
VB
SLØREBOTN SUBBASIN
NORDØYANE
RF
TFZ
IX
VIII
VII
VI
V
IV
III

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