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Nearshore Mesozoic basins along the central Nordland coast, Norway

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REPORT

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Title:
Nearshore Mesozoic basins along the central Nordland coast, Norway

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Summary: In 2003, a seismic data acquisition and erratic block sampling cruise was undertaken along the Nordland coast of Norway in the project "THE RECYCLING OF AN OROGEN: Provenance and routing of detritus from Norway to the Mid-Norwegian margin". Altogether, fifty single-channel seismic lines with a total length of 646 km and 52 blocks of erratic sedimentary rocks were aquired in an area between Vikna and Gildeskål. One day of seismic profiling in 1998 had documented the existence of downfaulted sedimentary rocks in Ternholmfjorden in Meløy. In 2002, seismic profiling was undertaken to further map the area (Bøe et al. 2003). A search for ice-transported Mesozoic erratics on nearby islands and skerries (along the transport direction of former ice-streams) resulted in numerous findings. Microfossil dating of the blocks, containing shells and coal fragments, gave Middle to Late Jurassic ages. Reconnaissance seismic profiling (one seismic line) by NGU in Lyngværfjorden, northeast of Træna, in 1998 showed the presence of sedimentary rocks also there. In the present project, we have performed detailed mapping of the boundaries and internal structures of the partly fault-bounded sedimentary rock basins in Ternholmfjorden/Stabbfjorden and Lyngværfjorden (hereafter called the Stabbfjorden and Lyngværfjorden basins) as well as of the southeastern boundary of the Vestfjorden Basin in Meløy and Gildeskål. The NE-SW-trending Stabbfjorden basin is 28 km long and 3-10 km wide, with a sedimentary rock succession that is up to 800 m thick. The Lyngværfjorden basin is elongated in the NNE-SSW direction. Its length is about 12 km, whereas the width is up to 3 km and the depth possibly more than 350 m. The erratic sedimentary blocks comprise conglomerates, sandstones, siltstones and mudstones. Microfossil analyses show that they range in age from Barremian to Triassic. The majority of the samples are of Middle-Late Jurassic age. The erratic sedimentary blocks have been divided into 15 lithofacies. These mostly reflect shallow marine deposition, but it is possible that the oldest samples, of Triassic age, were deposited in a continental environment. It appears that the lithofacies reflect the well-known tectonic phases and sea-level changes that have been reported for the Middle Jurassic-Early Cretaceous in this area. The maturity of organic material was determined by measuring vitrinite reflectance on representative samples. The measurements show that the organic material can be classified as immature. It should be noted, however, that shallow gas of probable thermogenic origin is observed in Quaternary deposits along the margin of Vestfjorden. This gas may originate from deeper, more mature strata in the Vestfjorden Basin.

Keywords: Dating	Mesozoic	Nordland
Shallow seismic	Erratic blocks	Stratigraphy
Sedimentology	Structural geology	Tectonics

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Appendix 2. Dating results and descriptions of erratic cobbles and boulders of sedimentary rocks found on the Froan islands (Rise et al. 1989), northwest of Frohavet, Trøndelag.

Appendix 3. Microfossil analyses (palynomorphs) of erratic blocks. F: Froan; S: Selvær; G: Grønna; R: Rorstabben; K: Kallsholmen; T: Torvvær; D: Dørvær; FU: fungal remains; TA: taeniated pollen; NA: not analysed.

1. INTRODUCTION

Over the past thirty years, areas of Mesozoic rocks and fault basins have been extensively mapped along the coast of Southern Norway and parts of Northern Norway (e.g. Oftedahl 1972, Oftedahl 1975, Dalland 1981, Holtedahl 1988, Bøe & Bjerkli 1989, Bøe 1991, Bøe et al. 1992, Thorsnes 1995, Fossen et al. 1997, Bøe & Skilbrei 1998, Davidsen et al. 2001, Bugge et al. 2002, Sommaruga & Bøe 2002). To a large degree, age estimates of the rock successions have been based on dating of ice-transported erratic blocks found on islands and skerries close to the outcrop areas of these rocks. The distribution of the rocks has been compiled on 1:250 000 and larger-scale bedrock maps, recently published by the Geological Survey of Norway (NGU).

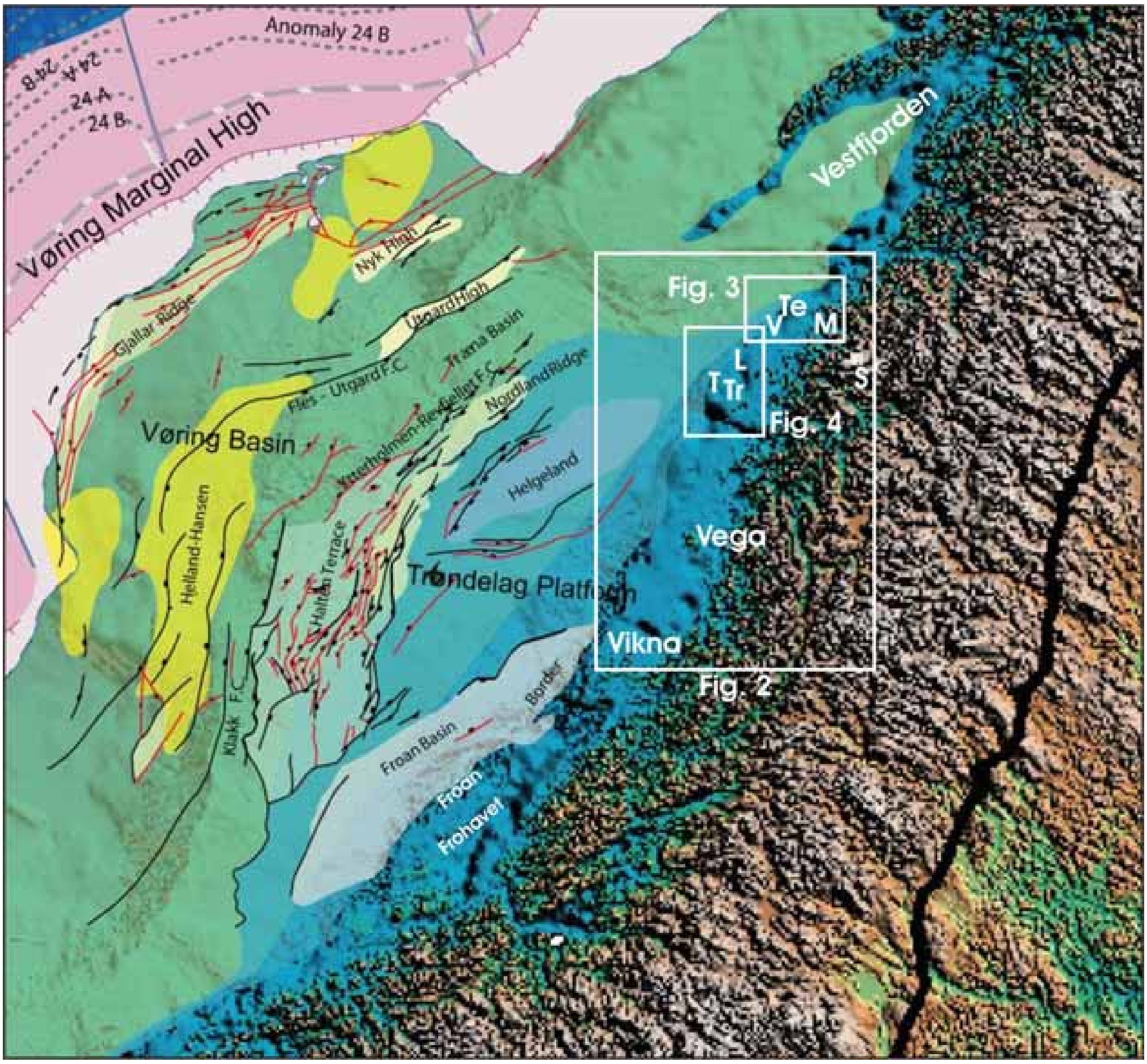


Figure 1. Overview map showing the location of the investigated area between Vikna and Vestfjorden. The locations of Figures 2, 3 and 4 are shown. T: Træna; Tr: Trænfjorden; L: Lyngværfjorden; V: Valværfjorden; Te: Ternholmfjorden; M: Meløy; S: Svartisen.

The area that has gained least attention is the Nordland coast, between Vikna and Vestfjorden (Fig. 1). Along this coastal stretch, there are open sea areas without skerries, up to 25 km wide, that have never been mapped by reflection seismic methods. The exact landward boundary of Mesozoic rocks is commonly uncertain, and it has not been known if Mesozoic basins occur between islands and skerries landward of this boundary.

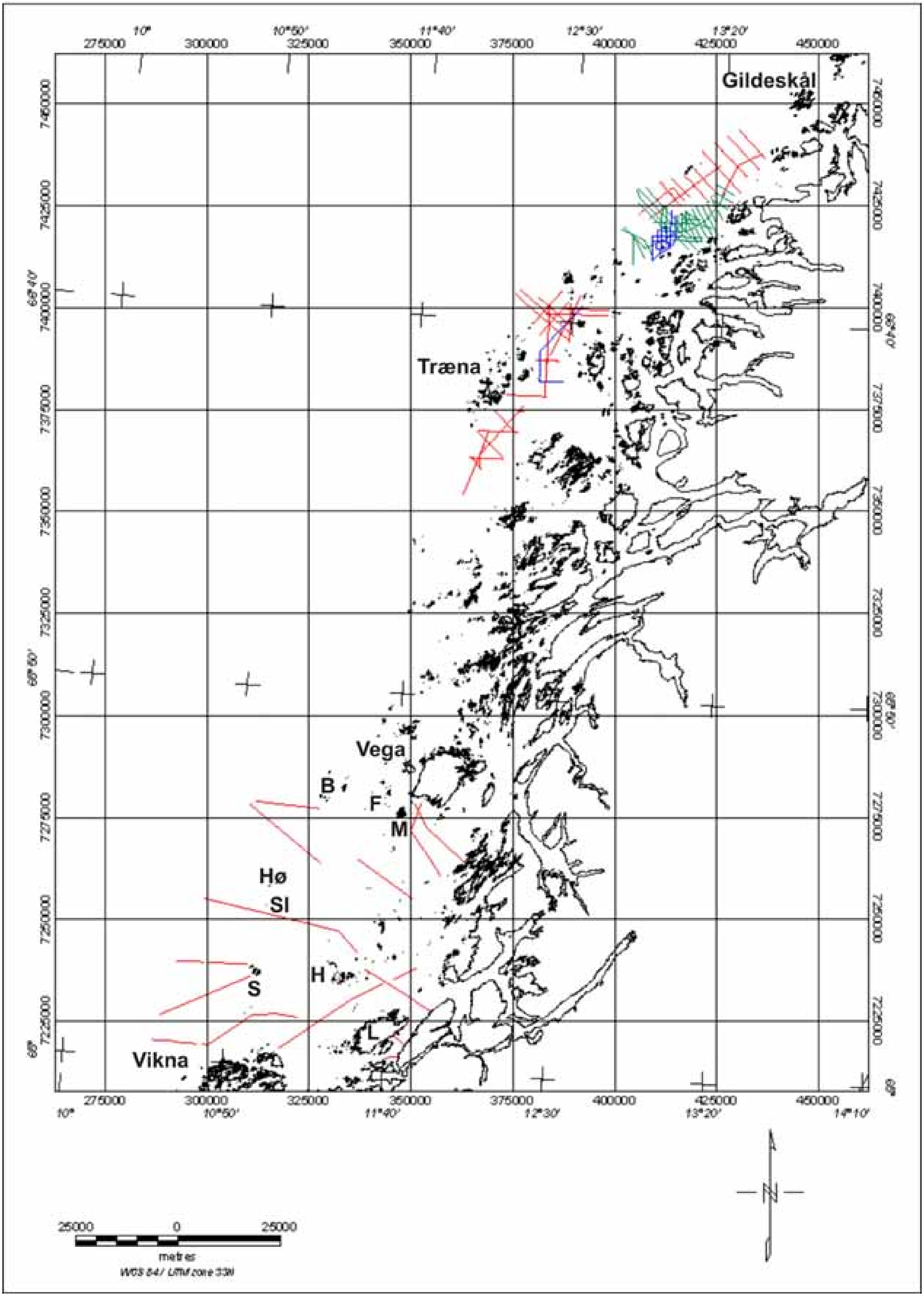
In 2002-2003, NGU carried out a project for Norsk Mineralutvikling AS in Ternholmfjorden and Valværfjorden, northwest of Svartisen in Meløy kommune (Fig. 1). One day of seismic profiling in 1998 had documented the existence of downfaulted sedimentary rocks in Ternholmfjorden. In 2002, four days of seismic profiling were undertaken to further map the area (Bøe et al. 2003). A search for ice-transported Mesozoic erratics on nearby islands and skerries (oceanward of the Mesozoic basin) resulted in numerous findings, and 35 blocks were collected. Microfossil dating of the blocks, containing shells and coal fragments, gave Middle to Late Jurassic ages.

Reconnaissance seismic profiling (one seismic line) by NGU in Lyngværfjorden (northeast of Træna) in 1998 showed the presence of sedimentary rocks also there (Fig. 1). This find has previously not been reported. Bugge et al. (2002) documented a thick Permo-Triassic succession in boreholes south of Træna. It was thus considered possible that sedimentary rocks could occur in Trænfjorden, between the two areas.

In the present report, we summarize the work that has been undertaken in 2003 and 2004 in the project "THE RECYCLING OF AN OROGEN: Provenance and routing of detritus from Norway to the Mid-Norwegian margin". The mapping of nearshore Mesozoic basins in this project has been carried out in areas not previously investigated by seismic methods.

2. DATA ACQUISITION AND METHODS

Seismic data aquisition and sampling of sedimentary erratic blocks was carried out by the NGU during a cruise with NGU's research vessel FF Seisma in the time period 6.-29. August 2003 (NGU cruise 0304). Eleven days were used for seismic profiling, and five days were used for block sampling, wheras five days were used for transport between Trondheim and the survey areas.



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2.1 Seismic data acquisition

Altogether, fifty single channel seismic lines with a total length of 646 km were acquired in an area between Vikna in the south (65ºN) and Gildeskål in the north (67º10'N) (Figs. 2-4). The majority of the seismic lines were oriented perpendicular to the assumed strike direction of sedimentary rock successions. In addition, several tie lines were acquired. The distance between individual seismic lines varies strongly, depending on the presence of sedimentary rock successions.

A 40 in^3 sleevegun fired every 3.5 seconds (7-9 m horizontal separation between each shot point at 4.5 knots) was used as an acoustic source. This was deployed together with a boomer (Geopulse), and the two signal sources were run sequentially. The reflected signals were recorded by a Benthos streamer (7.5 m activ part with 50 hydrophones). Real time seismic data were printed on an EPC 9800 termic printer with two channels. Channel A was used for printing boomer data filtered at 600-3000 Hz, while channel B was used for printing sleevegun data filtered at 100-600 Hz. A sweep of 0.5 s was used for both channels. In addition, the seismic data were stored digitally in SEGY-format.

The seismic data exhibit a maximum penetration of 0.2-0.3 s TWT (seconds two-way travel time) into the Mesozoic sedimentary successions. Assuming a seismic velocity of 3500 m/s in these rocks, this corresponds to a penetration of 350-525 m. A seismic velocity of 3500 m/s has also been used for calculation of bedding orientation (strike and dip) in the Mesozoic successions, where seismic lines cross each other. For calculation of Quaternary sediment thickness, it has been assumed that silty clay has a seismic velocity of 1650 m/s, while till has a velocity of 2000 m/s.

For the interpretations, we have also used seismic data acquired during NGU cruises 9801 in 1998 (8 lines, 57 profile km) and 0207 in 2002 (31 lines, 256.5 profile km) (Bøe et al. 2003) (Figs. 2-4), as well as relevant seismic lines acquired by IKU Petroleum Research in the 1980's.

2.2 Magnetic data

Marine magnetometer data were acquired along seismic profiles with a GSM 19 Overhauser proton magnetometer. Such data have previously proven to be useful for locating faults and geological boundaries. The data have been interpreted along with NGU's existing aeromagnetic marine magnetometer data collected during NGU cruise 0207 in 2002.

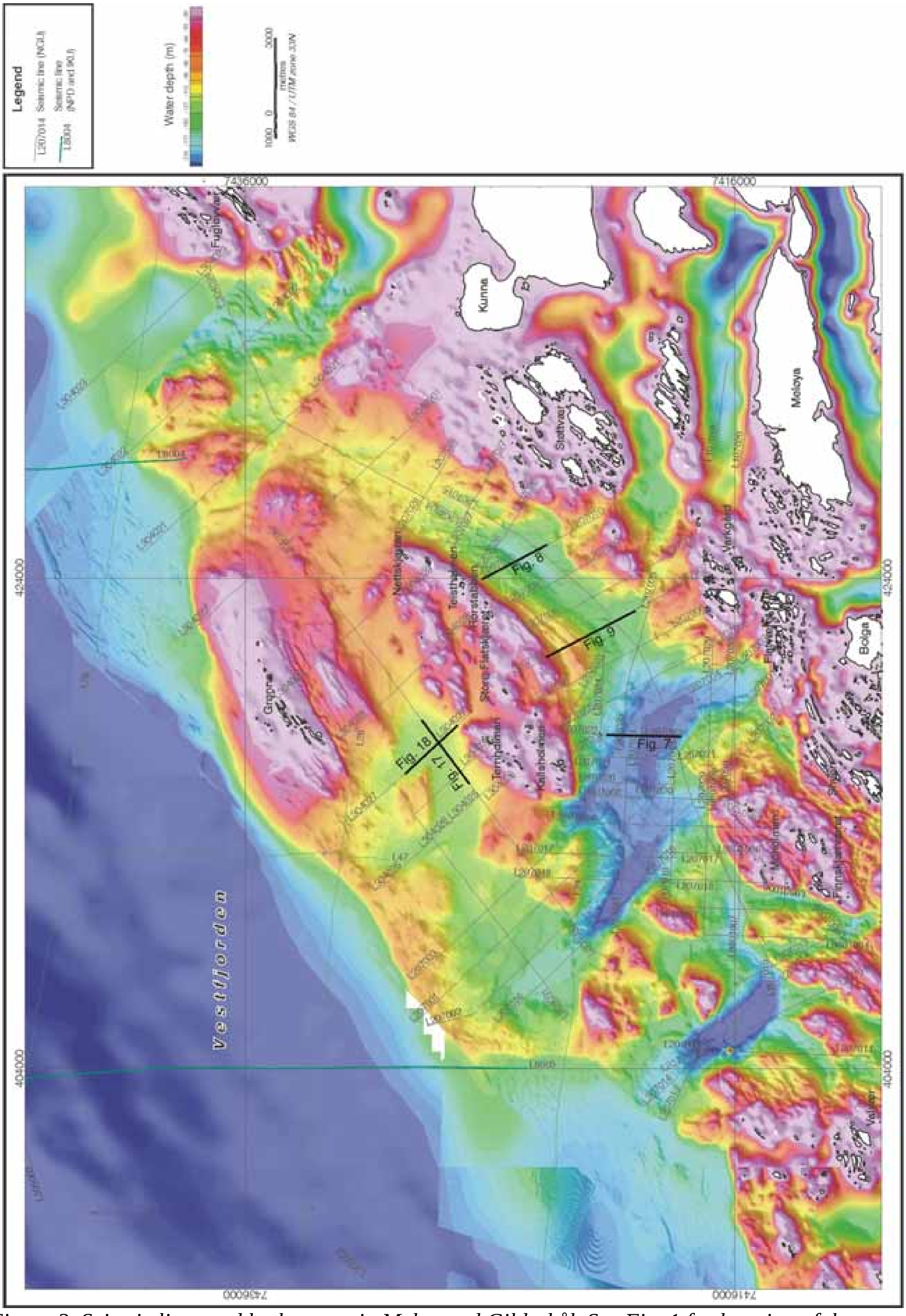

Figure 3. Seismic lines and bathymetry in Meløy and Gildeskål. See Fig. 1 for location of the survey area.

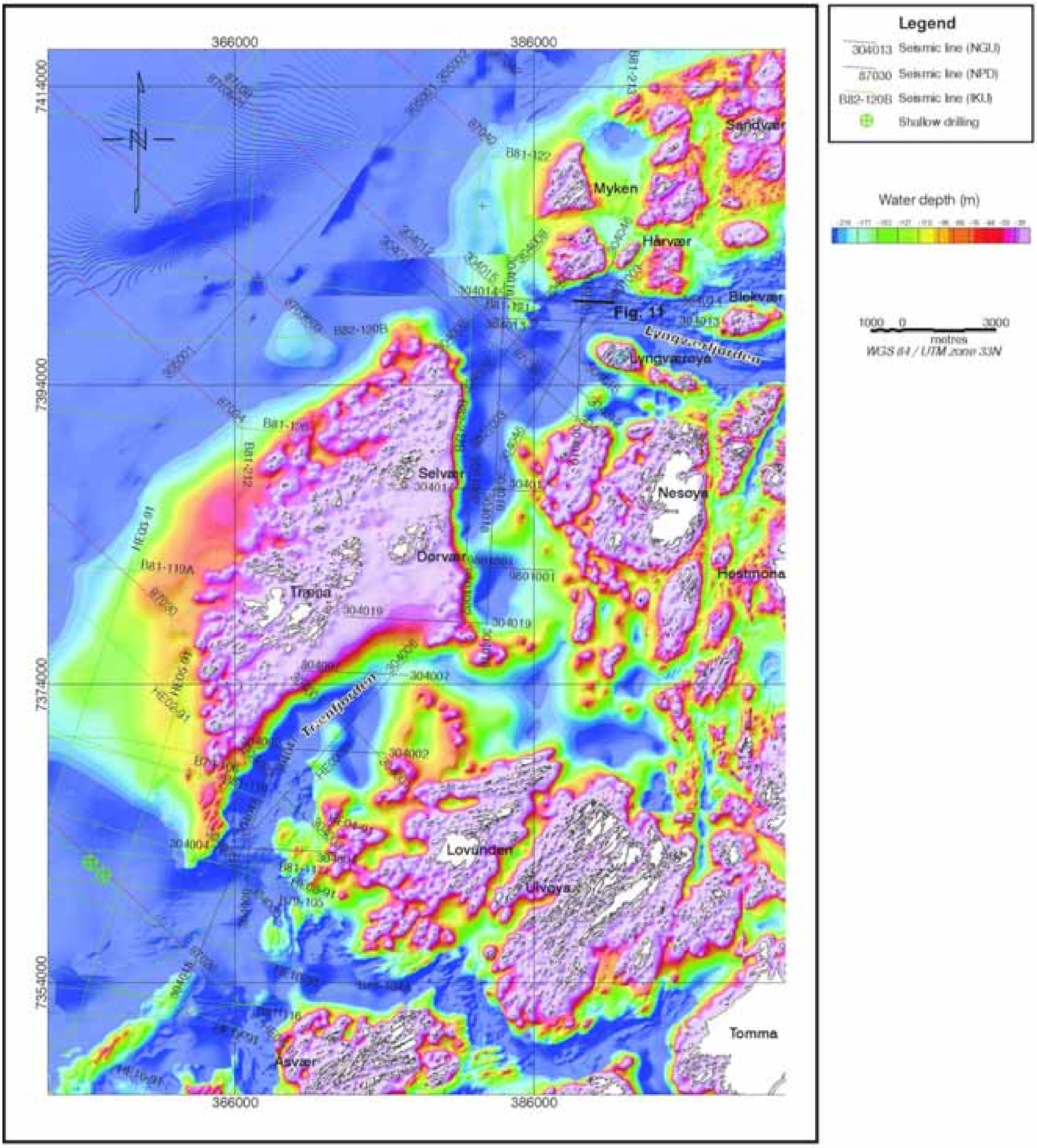

Figure 4. Seismic lines, shallow boreholes and bathymetry in Træna, Lurøy and Rødøy. See Fig. 1 for location of the survey area.

2.3 Bathymetry

Water depths were recorded along all seismic lines and stored digitally. Swath bathymetry was acquired from Statens kartverk Sjøkartverket in order to study ice transport directions and source areas for erratic sedimentary blocks transported by glaciers during the final stages of the last glaciation. Areas southeast and northeast of Træna (985 km^2), were chosen for this study due to the presence of a Mesozoic sedimentary basin in Lyngværfjorden (see below).

We have also used swath bathymetry covering an area of ca. 800 km^2 northwest of Meløya. These data were bought from Sjøkartverket in connection with the project in 2002-2003 (Bøe et al. 2003), and were used for interpretation of ice transport directions in that area. Nearshore Mesozoic basins were not found between Vikna and Vega, and swath bathymetry has thus not been studied in that area.

Detailed grids of the swath bathymetry data have been used for interpreting ice flow directions. In addition, 50 m grids of the swath bathymetry data were combined with a 50 m grid (bought from Statens kartverk) covering all of Norway, onshore and offshore. The combined bathymetry is shown for the investigated areas between Træna and Gildeskål (Figs. 3 and 4).

2.4 Sampling of erratic sedimentary boulders

A Mesozoic sedimentary basin has previously been found in Ternholmfjorden-Stabbfjorden (Bøe et al. 2003). Thirty-five samples were collected on islands and skerries northwest of this basin in 2002, of which 10 were dated, giving Middle to Late Jurassic ages. A search for samples was conducted on the islands Kallsholmen, Store Flatskjeret, Rorstabben, Teistholmen, Båsan and Nettskjeran. Finds were made on Kallsholmen, Rorstabben and Teistholmen (Fig. 5). In the present project, sampling was conducted on the Grønna islands, at the very boundary to Vestfjorden (Fig. 3). Numerous erratic blocks were found in a beach bar deposit (reworked moraine).

The seismic profiling confirmed an assumption from 1998 that a Mesozoic sedimentary basin occurs in Lyngværfjorden, northeast of Træna. A search for sedimentary erratic blocks was therefore carried out on the islands of Træna (Austholmen, Torvvær, Dørvær, Selvær, Arvær, Båsan, Froholmane, Klubsskjæra og Skarvholmen), and on islands east and north of Træna (western coast of Nesø, Lyngvær and Myken) (Fig. 5). Samples of Mesozoic age were found on Selvær, and on Torvvær (uncertain age).

No samples were found on the islands and skerries in the Vikna-Vega area (Sklinna, Hortavær, Sliflesin, Høgbraken, Bremsteinen, Fugleværet, Muddværet) (Fig. 2).

A total of 52 blocks were collected in 2003. An inventory of all blocks collected during the cruises in 2002 and 2003 is given in Appendix 1.

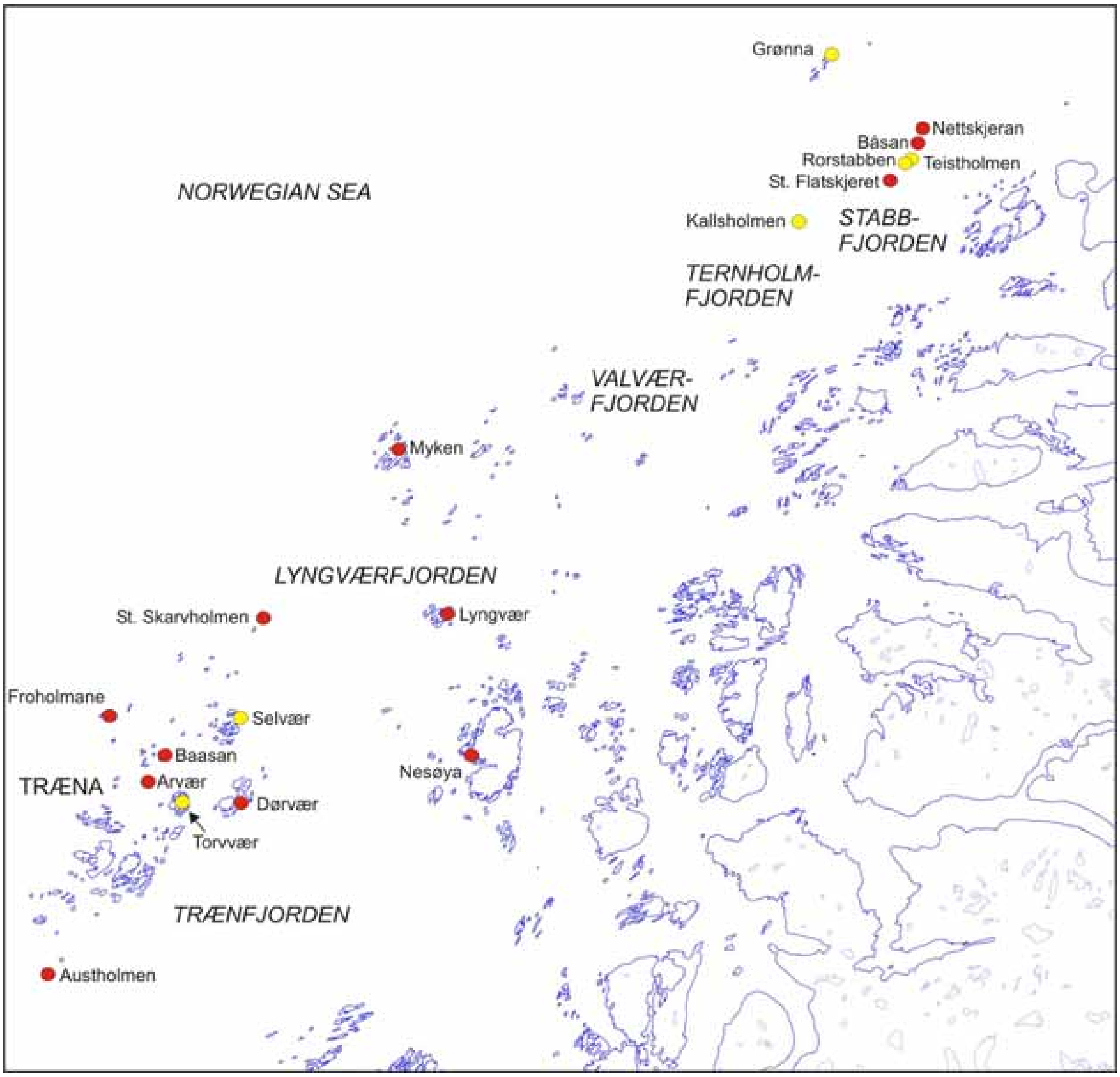

Figure 5. Sampling localities in the Træna-Meløy area. Yellow circles: Localities with finds of erratic sedimentary blocks of Mesozoic age. Red circles: localities without finds of erratic sedimentary blocks of Mesozoic age.

3. TERNHOLMFJORDEN-STABBFJORDEN AREA

3.1 Distribution of sedimentary rocks

A previously unknown, downfaulted area (hereafter informally named the Stabbfjorden basin) of layered, sedimentary rocks in Ternholmfjorden and Stabbfjorden was reported by Bøe et al. (2003). In the present project, it was decided to conduct more detailed mapping in an attempt to delimit the area of sedimentary rocks, and to map seismic stratigraphy and structural geology. It was also decided to perform a detailed mapping of the boundary between the sedimentary rocks in Vestfjorden and the older rocks landward of this.

In Ternholmfjorden and Stabbfjorden, sedimentary rocks occur over a 28 km long stretch, from northwest of Moholmen, in the southwest, to the northwest of Støttvær, in the northeast

(Fig. 6). An area of basement rocks, 3-10 km wide, separates the sedimentary rocks of the Stabbfjorden basin from the sedimentary rocks in Vestfjorden. The Stabbfjorden basin reaches a maximum width of ca. 6 km between Flatværet/Varkgård and Kallsholmen (this island, with a lighthouse, is located on the southernmost of the Ternholman islands) (Fig. 6). In the southwest, the Stabbfjorden basin terminates in two wedge shaped structures, one northwest of Moholmen and one southwest of Ternholman (Fig. 6). A small area of sedimentary rocks occurs between the wedges, and a similar occurrence is found north-northeast of Kallsholmen.

In addition to a detailed mapping of the Stabbfjorden basin, the nature and position of the southeastern boundary of the Vestfjorden sedimentary basin has been revised as a result of these investigations (Fig. 6). The remapping has shown that north of Valvær (at the outlet of Valværfjorden) and southwest of Grønna there are depositional contacts with slightly undulating trends. It is possible that sedimentary rocks extend eastwards between Ternholman and the Grønna Islands. It is also possible that such rocks may occur west of Kallsholmen, in the area between the Stabbfjorden Basin and the Vestfjorden Basin, but the seismic data do not allow certain identification.

3.2 Seismic stratigraphy in the Stabbfjorden basin

The thickness of Quaternary deposits varies from zero to more than 100 m. The greatest thicknesses occur along the margins of Vestfjorden (Fig. 6), and locally in the deeper parts of Ternholmfjorden (Fig. 7), Stabbfjorden and Valværfjorden.

In Stabbfjorden, the character of the seismic signals allows subdivision of the sedimentary rock succession into several units. The lowermost unit, which occurs with a primary, depositional unconformity on top of the bedrock (Fig. 8), is well stratified with strong, low amplitude reflectors that are laterally relatively persistent. In the uppermost part of this interval, there is a prograding wedge with reflectors showing downlap towards the northwest (Fig. 9).

The next unit is relatively homogeneous, with weak, high-amplitude, laterally persistent reflectors. In its lower part, reflectors onlap the underlying wedge in a southeasterly direction. The uppermost unit again has strong, low amplitude reflectors but in this unit, they are less laterally persistent and parallel than in the lowermost unit.

The sedimentary succession in Stabbfjorden can be traced into Ternholmfjorden. There, the succession is cut by several faults (see below), which makes it hard to follow the boundaries between the various units.

The sedimentary rock succession in the Stabbfjorden basin reaches a thickness of several hundred metres. Because of difficulties to see details below the first seabed multiple (Figs. 7-9) it is difficult to give exact numbers, but the thickness is more than 400 m both in Ternhomfjorden and Stabbfjorden. In Stabbfjorden the thickness may reach as much as 800 m.

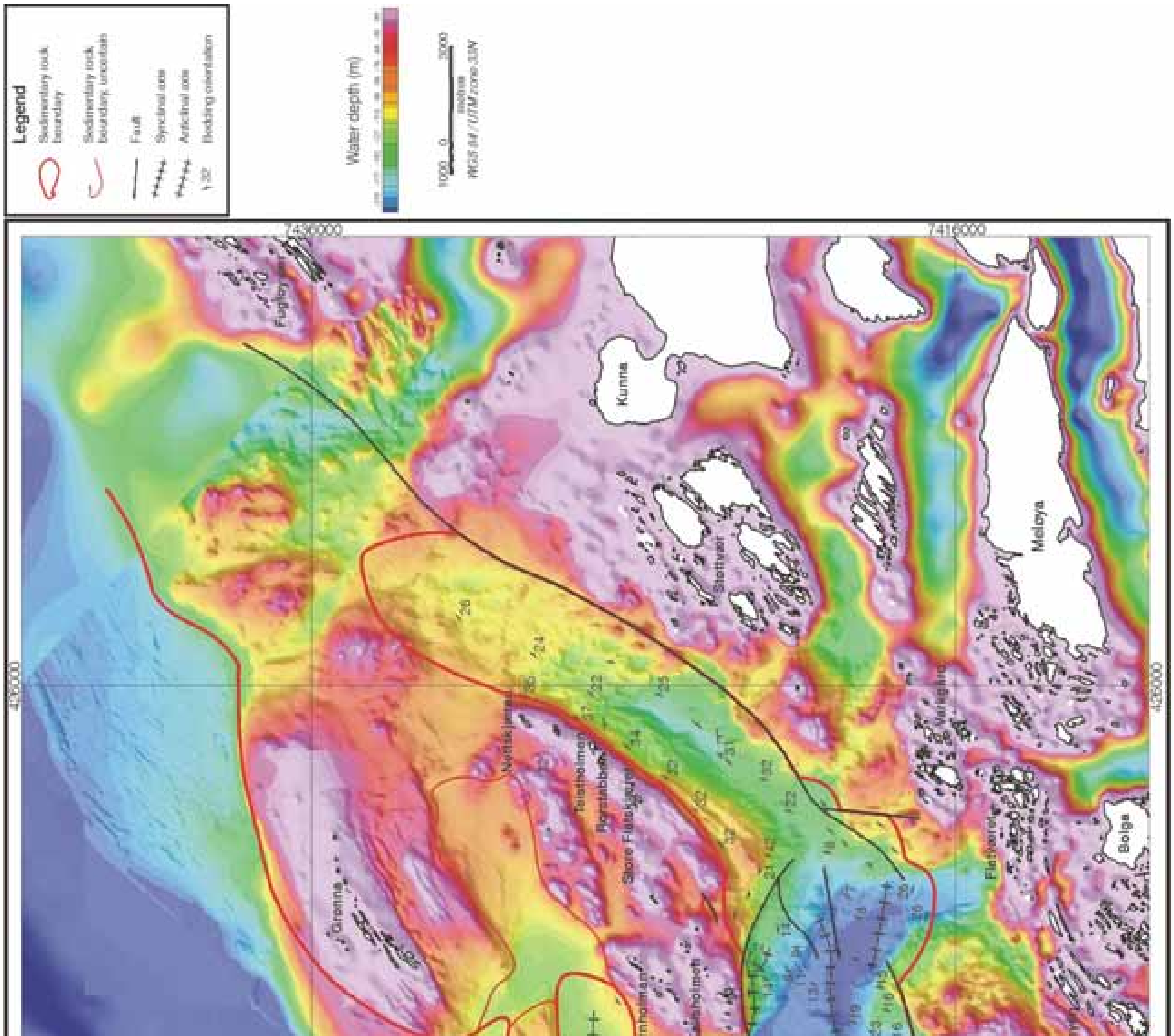

Figure 6. Geological map of the Stabbfjorden basin and the southeastern margin of the Vestfjorden basin in Meløy and Gildeskål. The geological interpretations are superimposed on the 50 m-grid bathymetry map. Note the NE-SW ice-marginal delta outside Grønna.

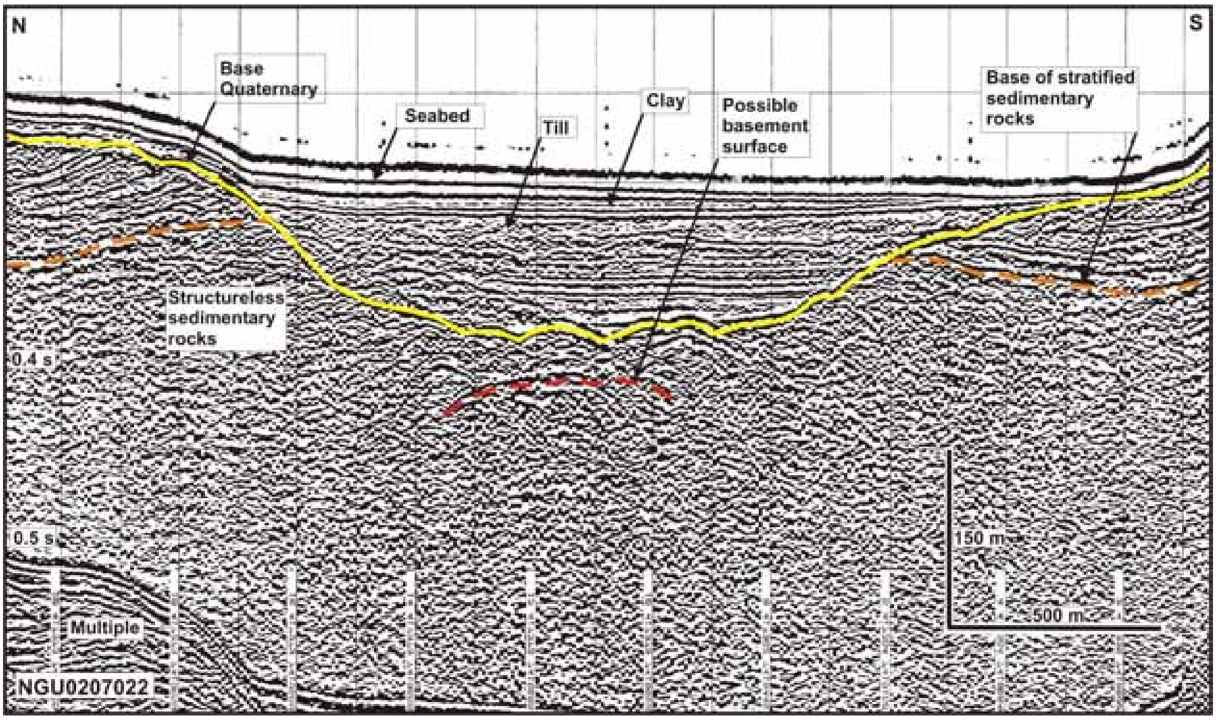

Figure 7. Part of seismic line NGU0207022 from Ternholmfjorden. Note the deep Quaternary erosion and the thick superficial deposits in the central part of the fjord. See Fig. 3 for location of the seismic section.

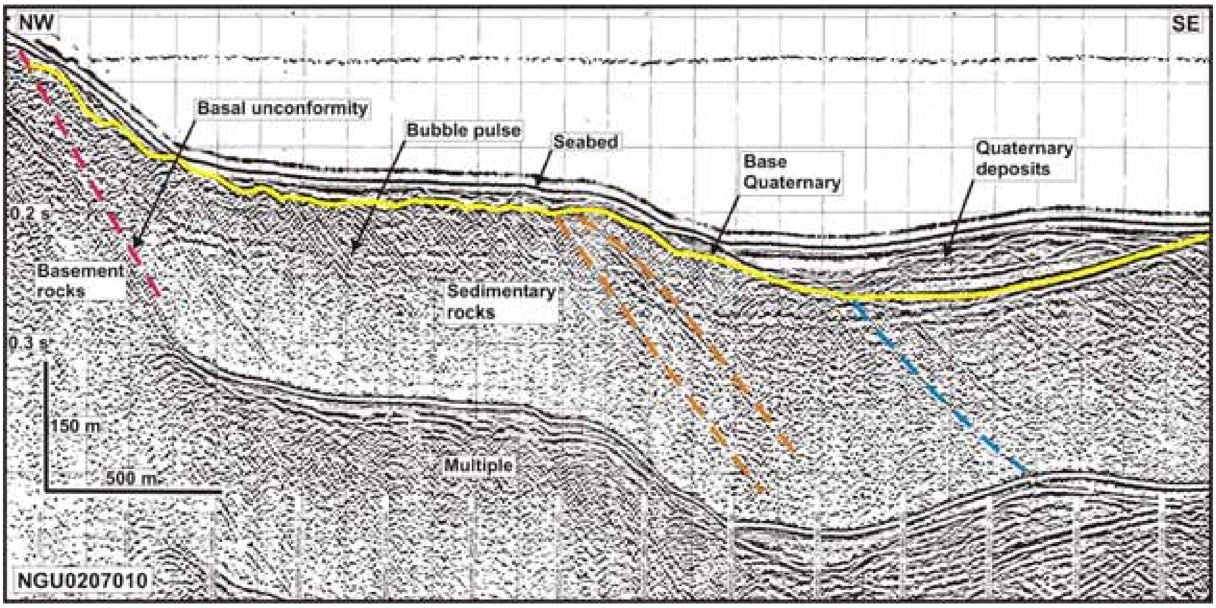

Figure 8. Part of seismic line NGU0207010 from Stabbfjorden. Note the sediment wedge between the orange reflectors, indicating sediment transport towards the northwest. The sediments were probably deposited in a shallow-marine environment during coastal progradation. Also note the homogeneous interval, without clear reflectors, between the uppermost orange and the blue reflector. The sediments in this interval were probably deposited during/after a transgression towards the southeast. See Fig. 3 for location of the seismic section.

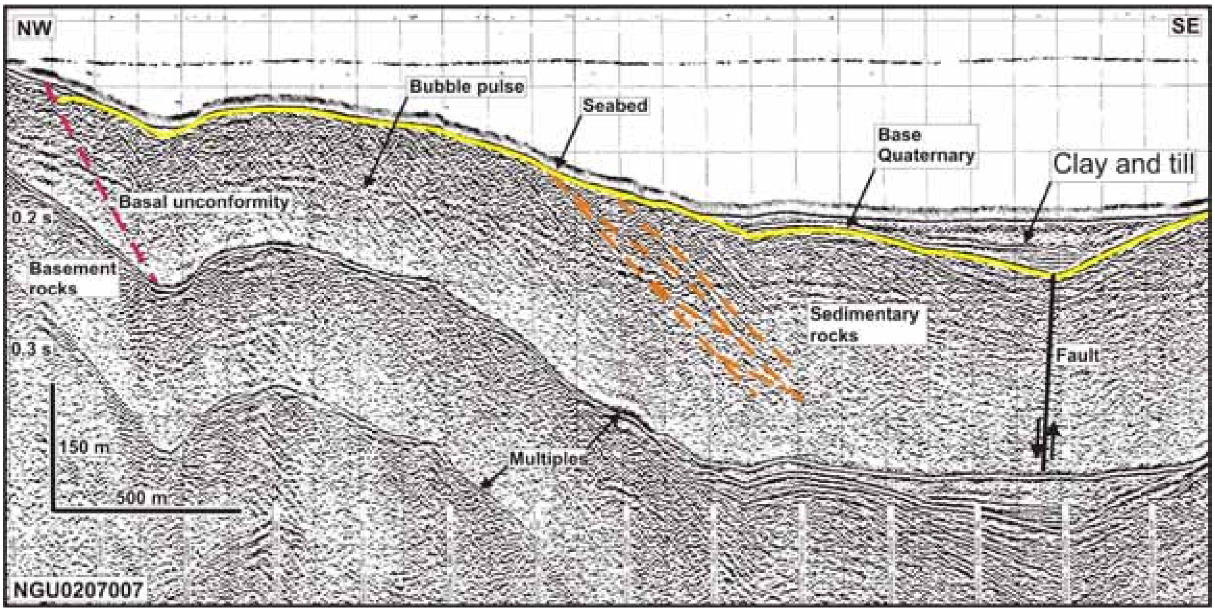

Figure 9. Part of seismic line NGU0207007 from Ternholmfjorden/Stabbfjorden. Note the sediment wedges between the orange reflectors. These probably reflect progradation of a coastline or a delta, while the sediments above the orange reflectors were deposited during/after a transgression. See Fig. 3 for location of the seismic section.

3.3 Structural geology

The sedimentary rocks in Stabbfjorden and Ternholmfjorden occur in a downfalted basin. The boundaries of the basin are partly defined by normal faults and partly by primary depositional contacts (Fig. 6). The southwestern part of the Stabbfjorden basin is cut by several faults, and has a relatively complicated structural pattern. The northeastern part is a simple half-graben.

Two major faults occur along the southeastern boundary of the Stabbfjorden basin. The southwesternmost of these is ca. 8 km long, and passes Moholmen at a distance of 600 m. Northwest of Varkgard there is a right-lateral offset of ca. 1 km before another fault continues towards the northeast for more than 20 km (Fig. 6). The layering of the sedimentary succession dips into the fault planes (towards the southeast) at angles up to 21º. At the offset between the two faults, there is a depositional contact. Close to the contact, the layering of the succession dips up to 26º in northerly and nortwesterly directions.

South of Ternholman, the northwestern boundary of the basin is defined by a ca. 9 km long, curved fault with downthrow towards the south. This fault occurs only 100-200 m south of Kallsholmen. The layering in the sedimentary succession is almost horizontal along the fault, but a weakly developed syncline can be traced for 2-3 km in an E-W-direction south of the lighthouse. It is also possible that a syncline occurs in the westernmost part of the fault-bounded wedge southwest of Ternholman.

The western boundary of the basin, in the area between the fault-bounded wedges north of Moholmen and southwest of Ternholman, is a primary unconformity. From here eastwards the basement is relatively shallow, and an ENE-WSW-trending anticline has been defined. Normal faults occur along the limbs of this anticline, in the east.

East of Ternholman, the northwestern boundary of the Stabbfjorden basin is a primary unconformity. The contact between sedimentary rocks and basement rocks is well expressed in the seismic data; at Rorstabben the sedimentary rocks occur at a distance of only 200 m from the skerries. Along the contact, the sedimentary strata dip steeply towards the southeast, a dip angle of up to 37º has been calculated.

West of Ternholman, the southeastern boundary of the Vestfjorden sedimentary basin is offset by several normal faults, and synclines and anticlines occur in the sedimentary succession (Fig. 6). Only 2.5 km of basement rocks separate the Stabbfjorden basin from the Vestfjorden Basin west of Ternholman. Between Grønna and Ternholman, sedimentary rocks are present in an east-west-trending syncline. A possible continuation of the sedimentary rock succession is indicated towards the northeast from this (Fig. 6).

4. TRÆNA AREA

4.1 Lyngværfjorden

An occurrence of sedimentary rocks (hereafter informally named the Lyngværfjorden basin) west of the Lyngvær islands in Lyngværfjorden (Fig. 10) is here reported for the first time. One reconnaissance seismic line run in 1998 showed the presence of sedimentary rocks below the fjord bottom. In the present project, it was decided to perform detailed mapping of the area.

The Lyngværfjorden basin is elongated in NNE-SSW-direction (Fig. 10). Its length is about 12 km, while the width is up to 3 km. The southernmost termination of the basin is poorly defined by the seismic data. The sedimentary rock succession reaches a thickness of at least 350 m in the northern part of the basin. In the south, the maximum thickness of this succession is less than 200 m. However, in one seismic line, there are indications of inclined strata also at deeper levels, below an angular unconformity. If this interpretation is correct, several hundred meters of older sedimentary rocks may occur below the uppermost succession.

The character of the seismic signals does not allow a subdivision of the upper sedimentary rock succession in the Lyngværfjorden basin. This can partly be related to a generally steep dip of the layering and a complex structural geology (see below), but may also reflect a locally homogeneous, coarse-grained and poorly layered succession giving rise to relatively discontinuous reflectors. A well-layered succession is, however, displayed in some seismic sections (Fig. 11).

The structural pattern of the Lyngværfjorden basin is complex, with rapid changes of strike and dip over short distances, and probably many small faults displacing the layering. The southeastern and northeastern boundaries of the basin are primary depositional contacts, where the bedding generally dips into and the basin at angles up to 15º. One or possibly two major faults define the northwestern/western boundary of the basin. Within the basin, several small faults and fold axes (synclines) strike NE-SW.

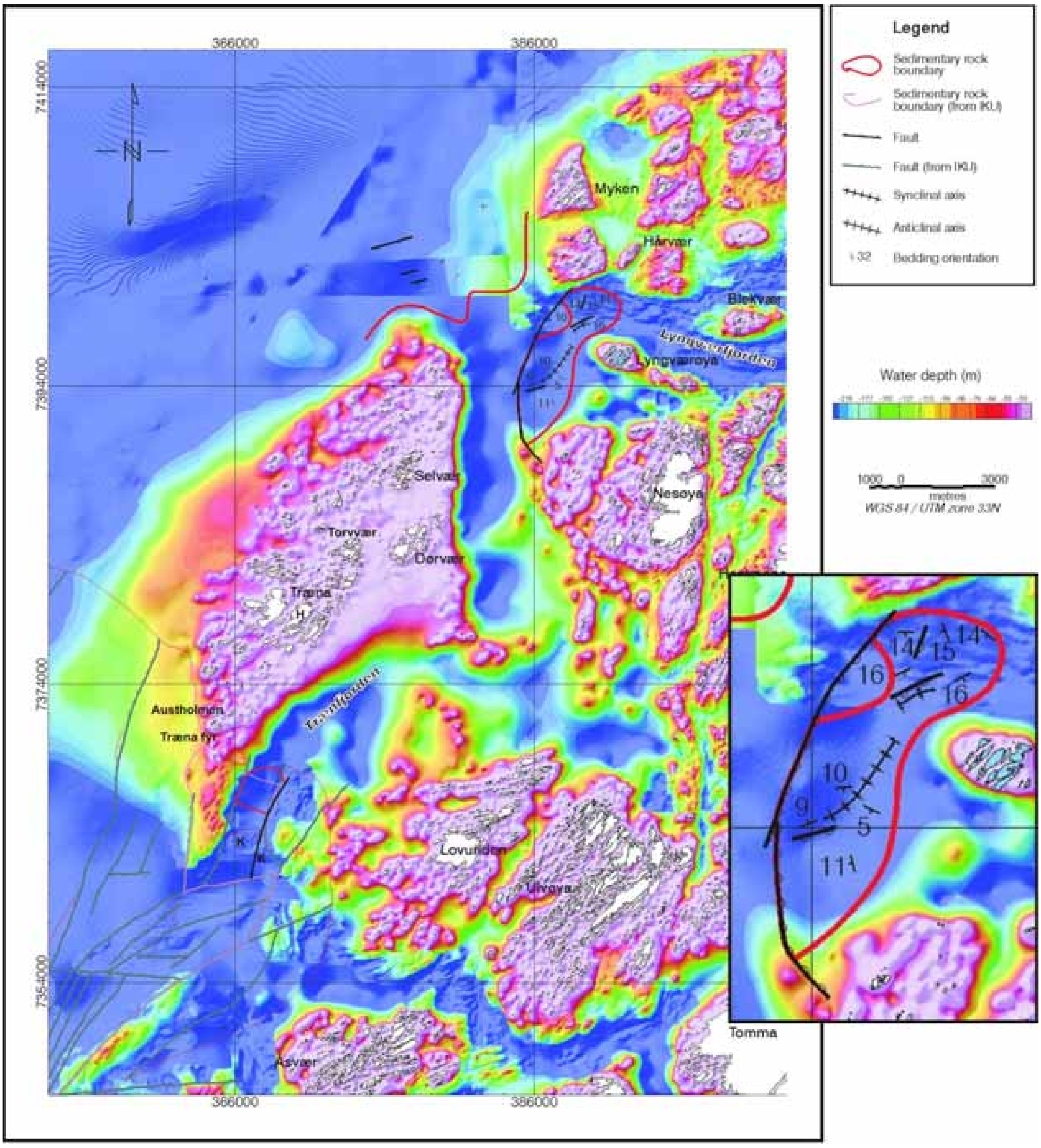

Figure 10. Geological map of the Lyngværfjorden basin and the Træna area. The geological interpretations are superimposed on the 50 m-grid bathymetry map. Note the blow-up of the Lyngværfjorden basin. H: Husøy; K: possible coral reefs in southern Trænfjorden.

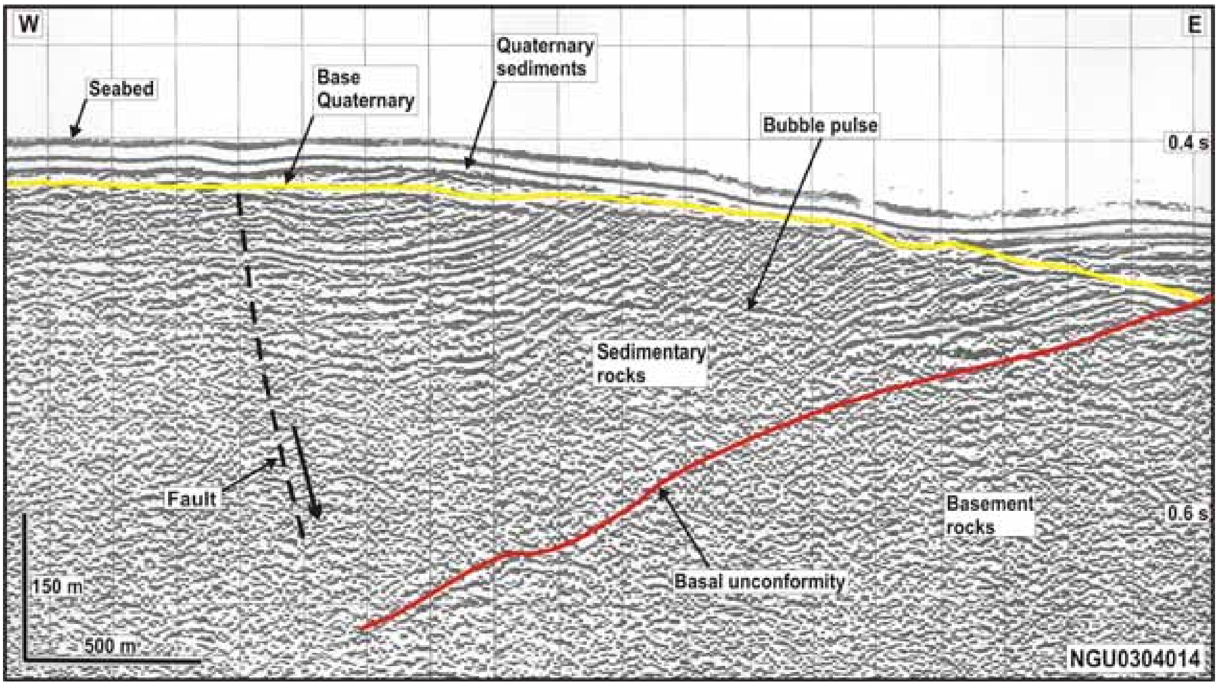

Figure 11. Part of seismic line NGU0304014 from Lyngværfjorden. Note the dipping reflectors showing the presence of sedimentary rocks below the sea bed. See Fig. 4 for location of the seismic section.

The offshore area northwest of Lyngværfjorden/north of Træna was mapped by IKU (Sintef Petroleumsforskning AS) in the early eighties (Rokoengen et al. 1988). Seismic data and seabed samples showed that Triassic rocks occur in an up to 6 km-wide zone along the coast. Lower-Middle Jurassic rocks occur northwest of this, but Triassic rocks locally penetrate the succession due to heavy faulting along NE-SW trends. A predominant NE-SW fault direction in the offshore Triassic succession is also indicated by our seismic data (Fig. 10). It is possible that the Triassic succession can be traced into Lyngværfjorden northeast of Træna, but this interpretation is uncertain. The uncertainty is partly due to poor seismic resolution below an up to 100 m-thick Quaternary succession that occurs offshore and in the southwestern parts of Lyngværfjorden, northeast of Træna.

4.2 Trænfjorden

Southern Trænfjorden and the area southwest of Træna were mapped by IKU during their project "Shallow Drilling Helgeland 1992" (IKU 1995, Bugge et al. 2002). A 750 m-thick, Upper Permian-Lower Triassic fully marine succession of sandstones, coarse-grained turbidites, shales and reworked sabkha sediments was cored 12 km southwest of the southernmost island of the Træna archipelago (Træna fyr/Austholmen). IKU's seismic interpretation also shows an area of Triassic sedimentary rocks in southern Trænfjorden.

In the present project, it was decided to map the remaining part of Trænfjorden in a search for Mesozoic sedimentary rocks also east of the Træna islands. The mapping has confirmed the presence of a sedimentary rock basin trending north-northeastwards in southern Trænfjorden (Fig. 10). The basin is fault-bounded on both sides, but its termination towards the north-northeast, ca. 3 km southeast of Træna fyr, is probably a depositional contact.

We have not observed sedimentary rocks farther northeast in Trænfjorden, but based on the presently available data set it is difficult to be conclusive. Although the seismic data are of good quality, the seismic energy may have been too low to penetrate old, low-porosity sedimentary rocks. Also, if sedimentary rocks with sub-horizontal layering occur in the fjord east and southeast of Husøy, they may have been overseen due to shallow water depths and numerous seabed multiples. Dipping reflectors indicating inclined strata were, however, neither observed in this part of Trænfjorden, nor in Trænfjorden east of Dørvær and Selvær.

5. VIKNA-VEGA

Reconnaissance seismic profiling was performed in the ocean areas between Vikna and Vega, including the fjords Lekafjorden, Hortafjorden, Melsteinfjorden and Gimsefjorden (Figs. 1 and 2). The Vikna-Vega area has previously not been mapped by seismic methods. Our investigations did not, however, reveal new occurrences of stratified, sedimentary rocks. The seismic data confirm the position of the landward boundary of stratified Mesozoic rocks, as interpreted by Gustavsson & Bugge (1995) based on old IKU seismic data and commercial seismic data.

Although layered sedimentary rocks were not observed in the seismic data, a search for erratic sedimentary blocks was conducted on several islands and small archipelagos between Vikna and Vega. Sklinna, Hortavær, Sliflesin, Høgbraken, Bremsteinen, Fugleværet and Muddværet (Fig. 2) were visited, but no erratic sedimentary rocks were found.

The negative results from the seismic investigations and the block search indicate that extensive occurrences of sedimentary rocks of Mesozoic and Cenozoic age are absent in the ocean area between Vikna and Vega. Small occurrences may still be present, but were not spotted. Poorly stratified or well-cemented sedimentary rocks of Late Palaeozoic age may be present, but such occurrences were not observed in the seismic data, obtained with a 40 in^3 sleevegun.

6. ERRATIC SEDIMENTARY BLOCKS

6.1 Depositional age

In addition to the ten samples dated by Bøe et al. (2003), thirty new samples from Nordland were prepared for microfossil analyses at NGU Lab and dated. Of these thirty samples, nine were from the 2002 collection, while 21 were sampled in 2003.

It was also decided to perform microfossil analyses on six samples collected by Rise et al. (1989) from Froan (Fig. 1). Previously, these samples were dated by means of macrofossils, and a Bathonian-Callovian age was obtained. It was considered important to use a similar dating method on the two collections.

Dating of erratic blocks was done using acid-resistent microfossils (palynomorphs), i.e. pollen, spores and dinoflagellate cysts. Cores from the continental shelf are commonly dated by this method because: 1) acid-resistent microfossils are usually numerous, even in small samples, 2) they are degradation-resistent, and 3) their stratigraphic distribution is well documented. Pollen and spores have a relatively wide stratigraphic distribution and can thus rarely be used for exact age determination. Dinoflagellate cysts, on the other hand, occur over narrower time intervals, and are thus better suited for biostratigraphic age determination. The drawback using dinoflagellate cysts is that they are marine (with a few exceptions) and therefore may occur in low numbers in beach and delta deposits.

Summaries of the dating results/interpreted ages are presented in Appendix 1 (Nordland) and Appendix 2 (Froan), while the results of all the microfossil analyses are presented in Appendix 3. The dated samples range in age from Barremian to Triassic. The majority of the samples are of Middle-Late Jurassic age. Three samples from Froan gave a Bajocian-Callovian age, which is in agreement with previous dating results giving Bathonian-Callovian ages.

6.2 Lithofacies

The erratic sedimentary blocks comprise conglomerates, sandstones, siltstones and mudstones (Appendix 1). Various sandstones and mudstones predominate. The samples are generally rich in carbonate, and many contain coal fragments and shells/shell fragments. Based on colour, texture, structure and age, the erratic blocks have been divided into 15 lithofacies (Table 1, Fig. 12). Lithofacies 1-3 are of Early Cretaceous age, lithofacies 4 is of Late Jurassic age, lithofacies 5 and 8 are of both Middle and Late Jurassic age, whereas lithofacies 6, 7, 9, and 10 are of undefined Middle to Late Jurassic age. Lithofacies 11 and possibly also 12-13 are of Triassic age. Lithofacies 14 (limestone) and 15 (dark reddish sandstone and conglomerate) are probably pre-Mesozoic in age.

Table 1. Lithofacies of sedimentary erratic boulders from the Nordland coast.

Facies	Description	Age
1	Grey, stratified, poorly sorted, conglomerate with shells and coal fragments	Early Cretaceous
2	Dark grey, massive to vaguely bedded, well-sorted medium sandstone.	Early Cretaceous
3	Light grey, massive, well-sorted mudstone	Early Cretaceous
4	Grey-very dark grey, massive, well-sorted mudstone and siltstone with shells and coal fragments	Late Jurassic
5	Dark grey, massive, well-sorted very fine to fine sandstone with shells and coal fragments	Middle and Late Jurassic
6	Light (brownish) grey, massive and (cross-) laminated, well-sorted siltstone with shells	Undefined Middle-Late Jurassic
7	Dark grey, poorly sorted, massive and bedded/cross-bedded, pebbly, medium to very coarse sandstone with shells and coal fragments	Undefined Middle-Late Jurassic
8	Light (yellowish) grey to grey, massive to weakly stratified, moderately to well-sorted, medium to very coarse sandstone with shells and coal fragments	Middle and Late Jurassic
9	Light grey, stratified, bioclastic medium-grained sandstone	Undefined Middle-Late Jurassic
10	Light grey-grey, massive and (cross-) laminated very fine-fine sandstone with shells and coal fragments	Middle Jurassic
11	Yellowish grey, moderately sorted, bioclastic medium-grained sandstone with intraformational silt clasts and shells	Triassic
12	Yellow, poorly sorted, bioturbated (roots), medium-coarse sandstone with shells, coal fragments, terrestrial palynomorphs and fungal remains	Not determined
13	Light yellowish brown, massive, well-sorted, fine-medium sandstone	Not determined

14	Light grey, massive, recrystallized?, well-sorted fine-grained limestone	Not determined
15	Dark reddish, massive to bedded (cross-bedded), moderately to well-sorted medium-coarse sandstone and conglomerate	Pre-Mesozoic ? Not determined

Figure 12. a) Example of lithofacies 1; grey, stratified, poorly sorted conglomerate with shells and coal fragments of Early Cretaceous age.

Figure 12. b) Example of lithofacies 2; dark grey, massive, well-sorted sandstone of Early Cretaceous age.

Figure 12. c) Example of lithofacies 3; light grey, massive, well-sorted mudstone of Early Cretaceous age.

Figure 12. d) Example of lithofacies 4; grey-very dark grey, massive, well-sorted mudstone and siltstone with shells and coal fragments of Late Jurassic age.

Figure 12. e) Example of lithofacies 5; dark grey, massive, well-sorted, very fine-fine sandstone with shells and coal fragments of Middle-Late Jurassic age.

Figure 12. f) Example of lithofacies 6; light (brownish) grey, massive and (cross-) laminated, well-sorted siltstone with shells of Middle-Late Jurassic age.

Figure 12. g) Example of lithofacies 7; dark grey, poorly sorted, massive and bedded/cross-bedded, pebbly, medium- to very coarse-grained sandstone with shells and coal fragments of Middle-Late Jurassic age.

Figure 12. h) Example of lithofacies 8; light (yellowish) grey to grey, massive to weakly stratified, moderately to well-sorted, medium- to very coarse-grained sandstone with shells and coal fragments of Middle-Late Jurassic age.

Figure 12. i) Example of lithofacies 9; light grey, stratified, medium-grained, bioclastic sandstone of Middle-Late Jurassic age.

Figure 12. j) Example of lithofacies 10; light grey-grey, massive and (cross-) laminated, very fine to fine-grained sandstone with shells and coal fragments of Middle Jurassic age.

Figure 12. k) Example of lithofacies 11; yellowish grey, moderately sorted, bioclastic medium-grained sandstone with intraformational silt clasts and shells of Triassic age.

Figure 12. l) Example of lithofacies 12; yellow, poorly sorted, bioturbated (roots), medium- to coarse-grained sandstone with shells, coal fragments, terrestrial palynomorphs and fungal remains of assumed Triassic age.

Figure 12. m) Example of lithofacies 13; light yellowish brown, massive, well-sorted fine- to medium-grained sandstone of assumed Triassic age.

Figure 12. n) Example of lithofacies 14; light grey, massive, recrystallized, well-sorted, fine-grained limestone of unknown age.

Figure 12. o) Example of lithofacies 15; dark reddish, massive to bedded/cross-bedded, moderately to well-sorted medium- to coarse-grained sandstone and conglomerate of pre-Mesozoic age.

6.3 Source areas and glacial transport directions

The Norwegian continental margin has been affected by several cycles of growth and decay of the Fennoscandian Ice Sheet. Evidence for this former ice sheet activity is found in the seismic stratigraphy of the shelf and slope, and in the morphology of sea-floor sediments. The regional bathymetry of the Mid-Norwegian shelf comprises a series of cross-shelf troughs, separated by shallower banks. Trænadjupet and Sklinnadjupet off Nordland, and also Vestfjorden, exhibit mega-scale lineations along trough long-axes, showing that the ice stream/sediment transport direction was towards the southwest outside the outermost skerries (Ottesen et al. 2002). Further out, the ice stream direction turns towards the northwest (Fig. 13).

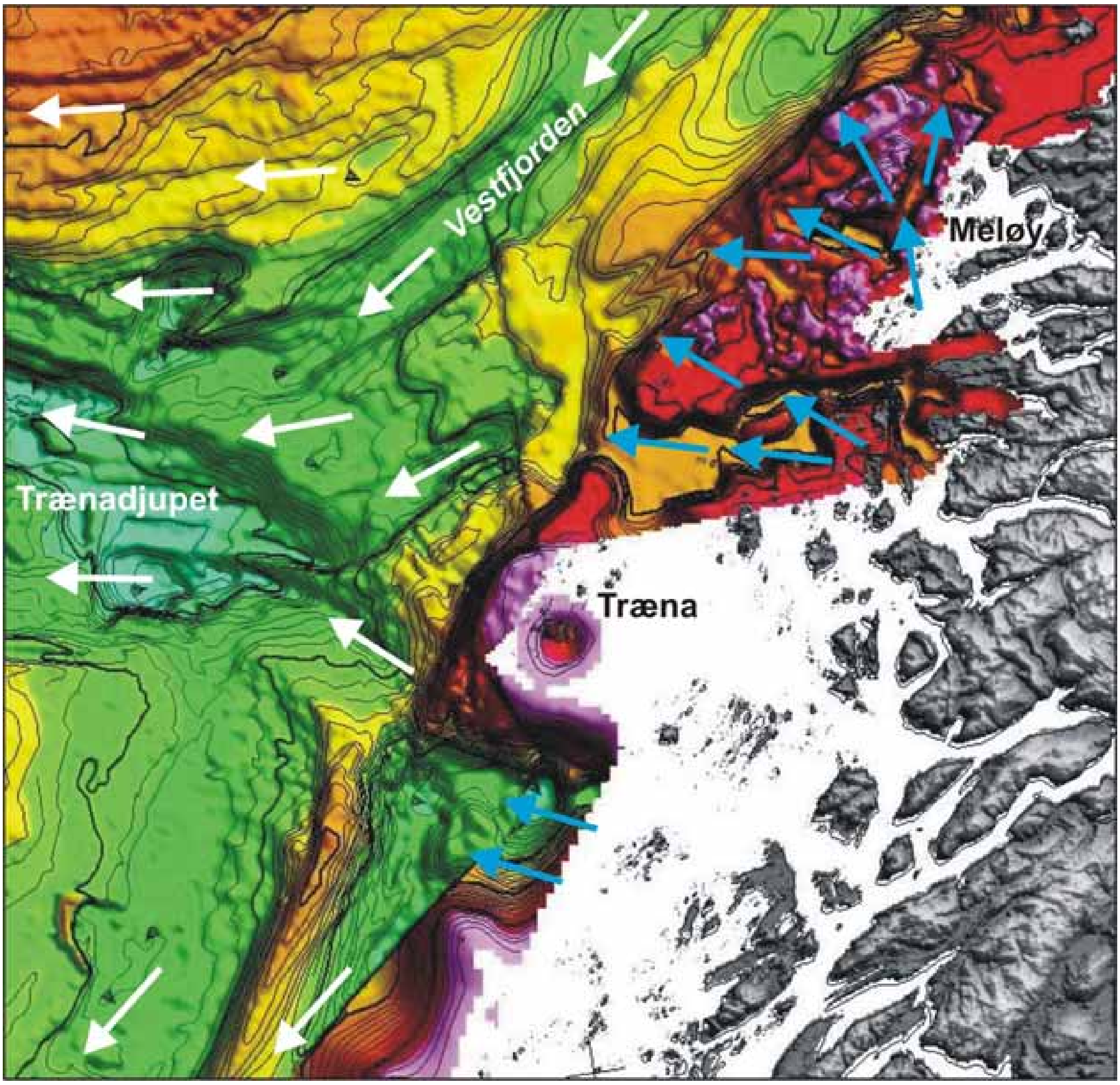

Figure 13. Ice transport directions superimposed on regional bathymetry (bathymetry compiled by Dag Ottesen) in the Træna-Meløy area. Blue arrows: directions derived from swath bathymetry; white arrows: directions derived from regional bathymetry.

Southeast of the outermost skerries, local ice transport directions have not previously been studied in great detail, although work has been done on land (Olsen 2002). It was thus decided to use swath bathymetry to elucidate ice transport directions and source areas for erratic sedimentary blocks. Swath bathymetric data were obtained from the sedimentary rock basins as well as from the areas to the east of these, where such data were available.

In the Stabbfjorden basin area, the top of the Quaternary succession is locally fluted by moving glaciers, and a general glacier transport direction from the southeast towards the northwest is evident. This trend is especially clear north of Varkgård in Stabbfjorden, and west of Kallsholmen in Ternholmfjorden (Figs. 6 and 13). Southeast of Rorstabben, the lineations indicate a more northerly movement. The glacial lineations show that the erratic sedimentary blocks on Kallsholmen derive from the Stabbfjorden basin in Ternholmfjorden, and that the erratic blocks on Rorstabben stem from the Stabbfjorden basin southeast of Rorstabben.

Swath bathymetry shows that the beach ridge at Grønna is made of morainal material derived from the southeast, and that a major glacial debris lobe has been constructed at the margin of Vestfjorden (Fig. 3). This lobe, which the swath bathymetry indicates post-dates the ice stream in Vestfjorden, can probably be related to an ice dome in the Svartisen area.

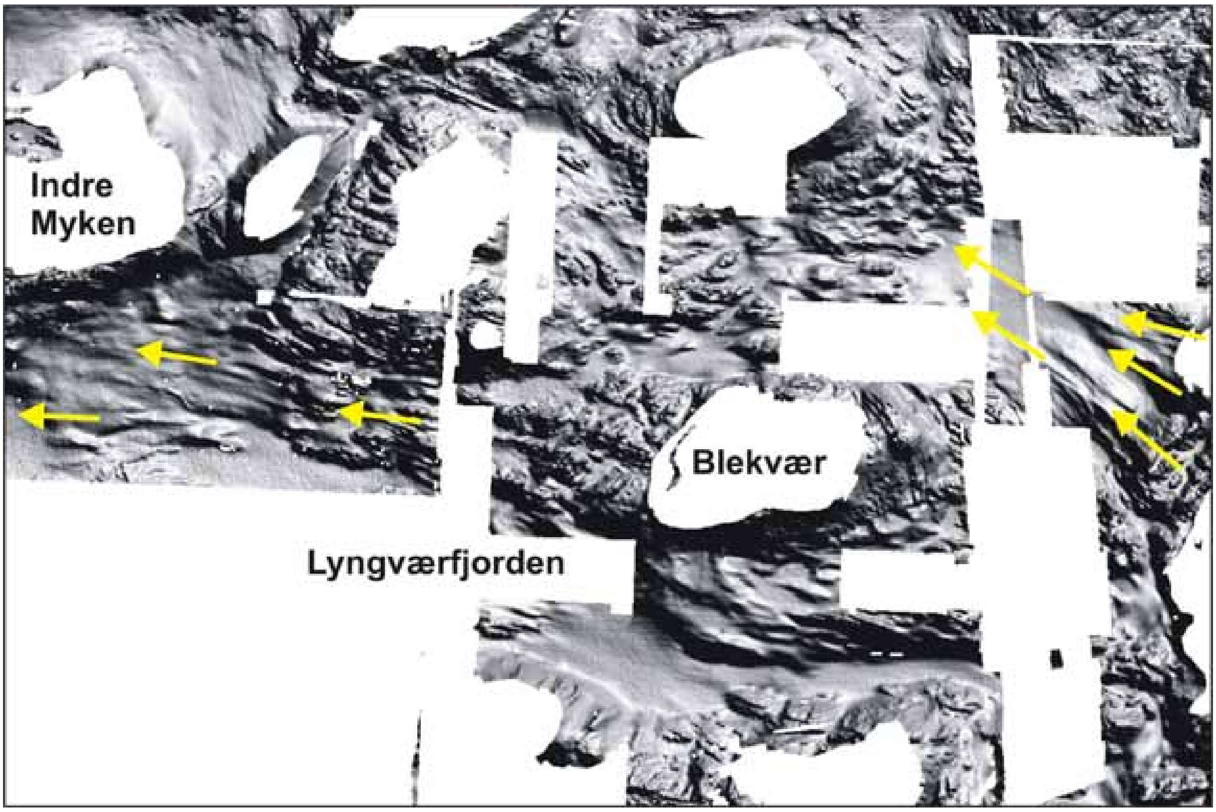

Figure 14. Glacial lineations (arrows) in the Lyngværfjorden area. Note that the ice transport direction is towards the northwest and west-northwest. Shaded relief image (illuminated from the northeast) derived from swath bathymetry.

In the Lyngværfjorden area, glacial lineations and flutes point to a glacier movement direction towards the west-northwest (Fig. 14). Erratic sedimentary blocks were not found on the small skerries north-northwest of the Lyngværfjorden basin. However, on Selvær and Torvvær, in the central part of the Træna archipelago, blocks of Middle-Late Jurassic and Triassic age occur. Sedimentary rocks have not been identified in the fjord southeast of these islands. This may be due to shallow water depths and a flat and even seabed, which cause numerous seabed multiples in the seismic data and which makes interpretation difficult. It is thus possible that sedimentary rocks may be present below the fjord bottom. Another possibility is that local ice-flows, not expressed in the swath bathymetry, may have caused transport of erratics from the Lyngværfjorden basin southwestwards towards Selvær and Torvvær.

Sedimentary rocks of Permian and Triasic age have previously been mapped southwest of Træna and in the fjord between Lovund and Træna, southeast of Træna (IKU 1995). The succession was drilled in the area southwest of Træna (Bugge 2002). From swath bathymetric data, a glacier movement direction towards the northwest is evident also southeast of Træna, but erratic sedimentary blocks were not found during our search on the southernmost islands of the Træna archipelago.

7. DEPOSITIONAL ENVIRONMENT AND STRATIGRAPHIC CORRELATION

7.1 Stabbfjorden basin

Based on the seismic data and the erratic sedimentary blocks, an interpretation of the sedimentary environment during deposition of the succession in the Stabbfjorden basin can be put forward.

The lowermost, stratified unit in the Stabbfjorden basin probably represents marine sediments deposited on a shallow shelf in the Middle Jurassic. This interpretation is supported by the presence of numerous marine micro- and macrofossils in many of the samples from this time interval (lithofacies 5-10). The shelf sedimentation may have been interrupted by pulses of coastal and/or continental deposition. Proximity to a coastal or deltaic depositional environment is suggested by the high number of coal fragments in many of the shallow marine sediment samples. The coal has to be derived from a continental setting, e.g. coastal swamps or river planes. The northwestward prograding sequence in the upper part of the unit probably reflects build-out of a coastline or a delta system from the southeast during a relative sea-level fall. The sediments in the prograding sequence are thus most likely dominated by sandstones.

The prograding sequence is transgressed by unit 2, which we interpret to be deposited in a marine environment following a relative sea-level rise. We interpret this homogeneous unit, with weak, continuous, high-amplitude reflectors to represent mainly fine-grained sediments (lithofacies 4-9) deposited in late Middle Jurassic-early Late Jurassic times.

The uppermost unit in the Stabbfjorden basin was probably deposited in a shallow-marine, near-coast environment in the Late Jurassic-Early Createaceous, following a second relative sea-level fall. This unit is probably represented by sandstones of Volgian-Ryazanian (lithofacies 8) and Early Cretaceous age (lithofacies 2), and conglomerates of Barremian age (lithofacies 1). A mudstone sample of Valanginian-Hauterivan age from Grønna (lithofacies 3) is probably also derived from the Stabbfjorden basin (uppermost part of the succession). The conglomerates of lithofacies 1 possibly reflect faulting and rejuvenation of the hinterland. The conglomerate boulders contain clasts of sandstone - possibly older Mesozoic rocks.

In 1960, beleminites of Jurassic-Cretaceous age were found on land at Svartisen, southeast of the Stabbfjorden basin (Grønlie 1973). These were found in moraine deposits in front of Østerdalsisen, but it has been claimed that they were also found in rock outcrops. The exact locality of the finds was never reported. Grønlie (1973) concluded that if Østerdalsisen has eroded the fossils, there is a possibility that rocks of Jurassic-Cretaceous age may occur beneath larger parts of the Svartisen plateau. In addition, Grønlie (1973) referred to the late bergmester K.L. Bøckman in Nordland, who claimed that Mesozoic belemnites and ammonites were found during construction works in Glomfjord, east of the Stabbfjorden basin, in 1909. If these reports are correct, it implies that Jurassic and possibly Cretaceous sediments were deposited far eastwards in Nordland and possibly into Sweden.

A similar interpretation was presented by Brekke (2001), who also suggested that in the Middle Jurassic there was a connection between the Norwegian Sea and the Barents Sea via an open seaway eastwards and northwards through Sweden and Finland (Fig. 15). His palaeogeographical maps for the Middle Jurassic show the Stabbfjorden/Ternholmfjorden area located close to the boundary between coastal/shallow-marine conditions with deposition of predominantly sandstones in the north, and shallow-marine conditions, with deposition of more fine-grained sediments in the Helgeland Basin in the south (Fig. 15). Brekke et al. (2001) interpreted the source areas for the sediments to be uplifted domes located in southern Norway, in the present Møre and Vøring Basins, and between northern Norway (Troms/Finnmark) and Greenland. The domes were an early expression of the volcanic activity and rifting to come later in the Jurassic, Cretaceous and Tertiary.

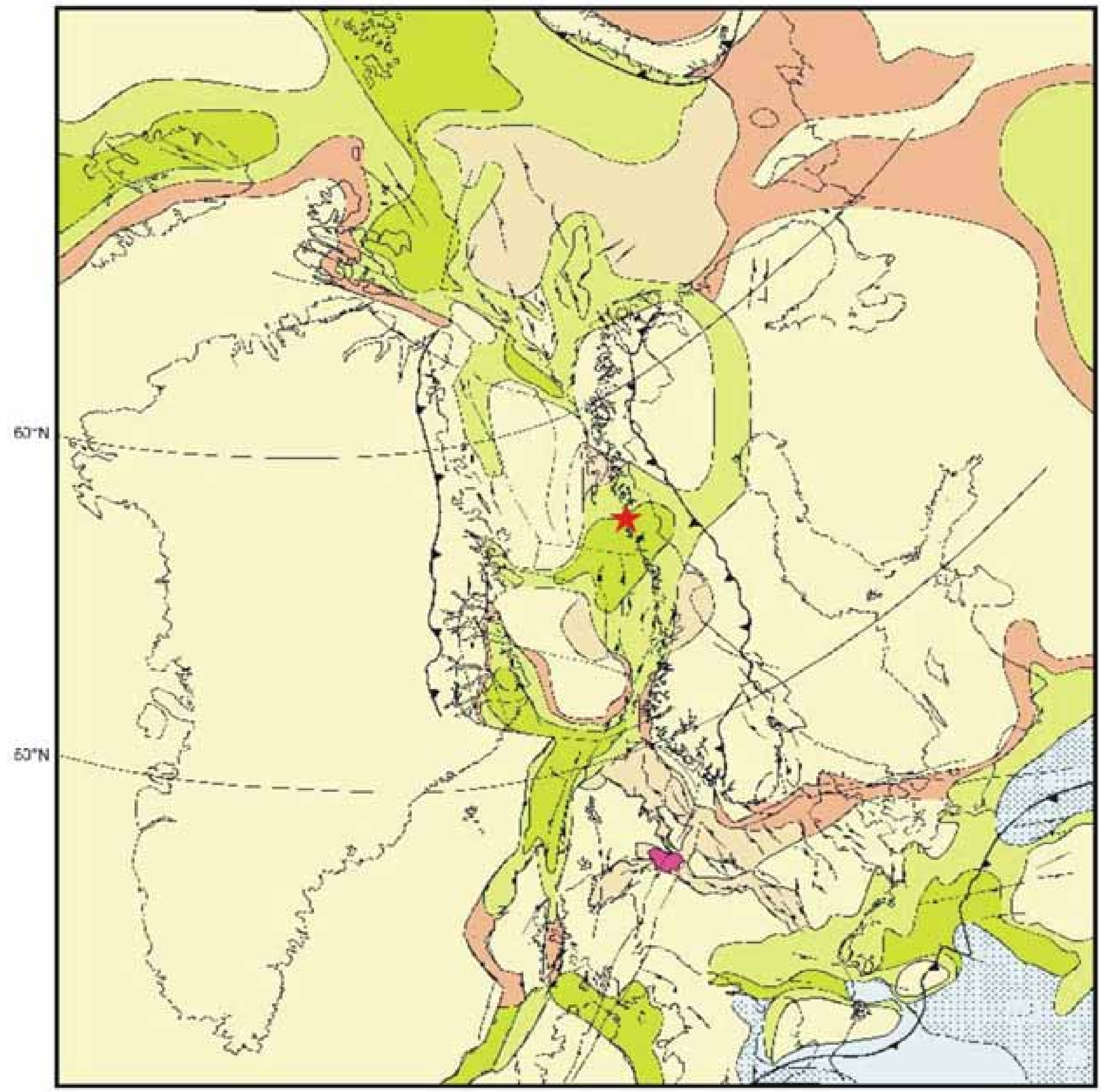

Figure 15. Palaeogeographic reconstruction for the Middle Jurassic (Bajocian). The Stabbfjorden basin (red star) is located between an area of coastal/shallow-marine deposition (sandy sediments) in the north (light green colour) and shallow-marine deposition (finer grained sediments) in the south (darker green colour). According to this map, the Træna area was located in a more basinal position than Stabbfjorden, in the Middle Jurassic. Modified from Brekke et al. (2001).

According to Brekke (2001), the connection between the ocean areas in the Norwegian Sea and the ocean areas farther north was closed due to the doming, in the Middle Jurassic. This has also been suggested by other authors, e.g. Dalland (1981), Larsen (1987), Doré (1992), Brekke et al. (1999) and Brekke (2000). The interpretation is supported by data from Andøya, which show that in the Bajocian-Bathonian, a delta in that area was supplied with sediments from the west, north and east (Dalland 1979, 1981). Further southwest in Vesterålen, shallow marine deposits from the Bathonian-Callovian occur in the Sortlandsundet basin (Davidsen et al. 2001). These can be correlated both in age and depositional environment with the deposits in the Stabbfjorden basin. Shallow-marine deposition probably also prevailed in the area of Vestfjorden between Sortlandsundet and Stabbfjorden.

The Mid-Jurassic deposits in the Stabbfjorden basin can be correlated in age and depositional environment with similar shallow marine and coastal deposits farther south along the coast of Nordland and Trøndelag (Bugge et al. 1984, Gustavson & Bugge 1995, Sommaruga & Bøe 2002), in Beitstadfjorden (Bøe & Bjerkli 1989), in Frohavet (Bøe 1991) and outside the coast of Møre og Romsdal (Smelror et al. 1994, Bøe & Skilbrei 1998). Erratic blocks and drill cores show that the sediments comprise alternating shallow-marine, coastal and continental deposits, and that they are generally coarse grained. Several of the authors mentioned above have correlated the Mid-Jurassic deposits along the coast with the Garn Formation (Bajocian-Bathonian) in the Haltenbanken area. This formation was deposited on prograding, braided delta lobes, and delta-front and delta-top facies with active fluvial and wave-influenced processes are recognized (Dalland et al. 1988).

It is possible that the prograding interval in the upper part of unit 1 in the Stabbfjorden basin (and possibly also the underlying succession) can be correlated with the Garn Formation, whereas the sediments in the lower part of unit 2 can be correlated with the fine-grained Melke Formation (Bajocian-Oxfordian) in the Norwegian Sea. It should be noted, however, that the Garn Formation is absent in the Trænabanken area (Dalland et al. 1988), and that it may be discontinously developed along the palaeo-coastline.

In the Late Jurassic, the accumulation areas in the Norwegian Sea subsided. At the same time there was a sea-level rise. This caused deposition of steadily more fine-grained sediments in shallow-marine and deep-marine environments farther offshore. Organic-rich clays (Spekk Formation, Oxfordian-Ryazanian) were deposited over large parts of the Norwegian Sea, but have not been found in time-equivalent samples by us.

According to Brekke et al. (2001) Ternholmfjorden/Stabbfjorden was a deposition area for shallow marine, fine-grained, clay-rich and carbonaceous sediments in the Late Jurassic (Fig. 16). This fits with our finds of dark to very dark grey siltstones and mudstones of Early Oxfordian to Early Volgian age (lithofacies 4) on Kallsholmen, Grønna, and possibly on Rorstabben (Appendix 1, Table 1). However, we also find coarse clastics of Volgian to Early Ryazanian age (lithofacies 8) on Rorstabben and possibly on Kallsholmen, Grønna and Selvær (Table 1). A sea-level fall occurred in the Volgian (Dalland et al. 1988). This, along with crustal movements, caused coarse-grained sediments to be deposited on submarine fans along fault blocks, and coastal progradation with deposition of coarse-grained material in shallow-marine and deltaic settings.

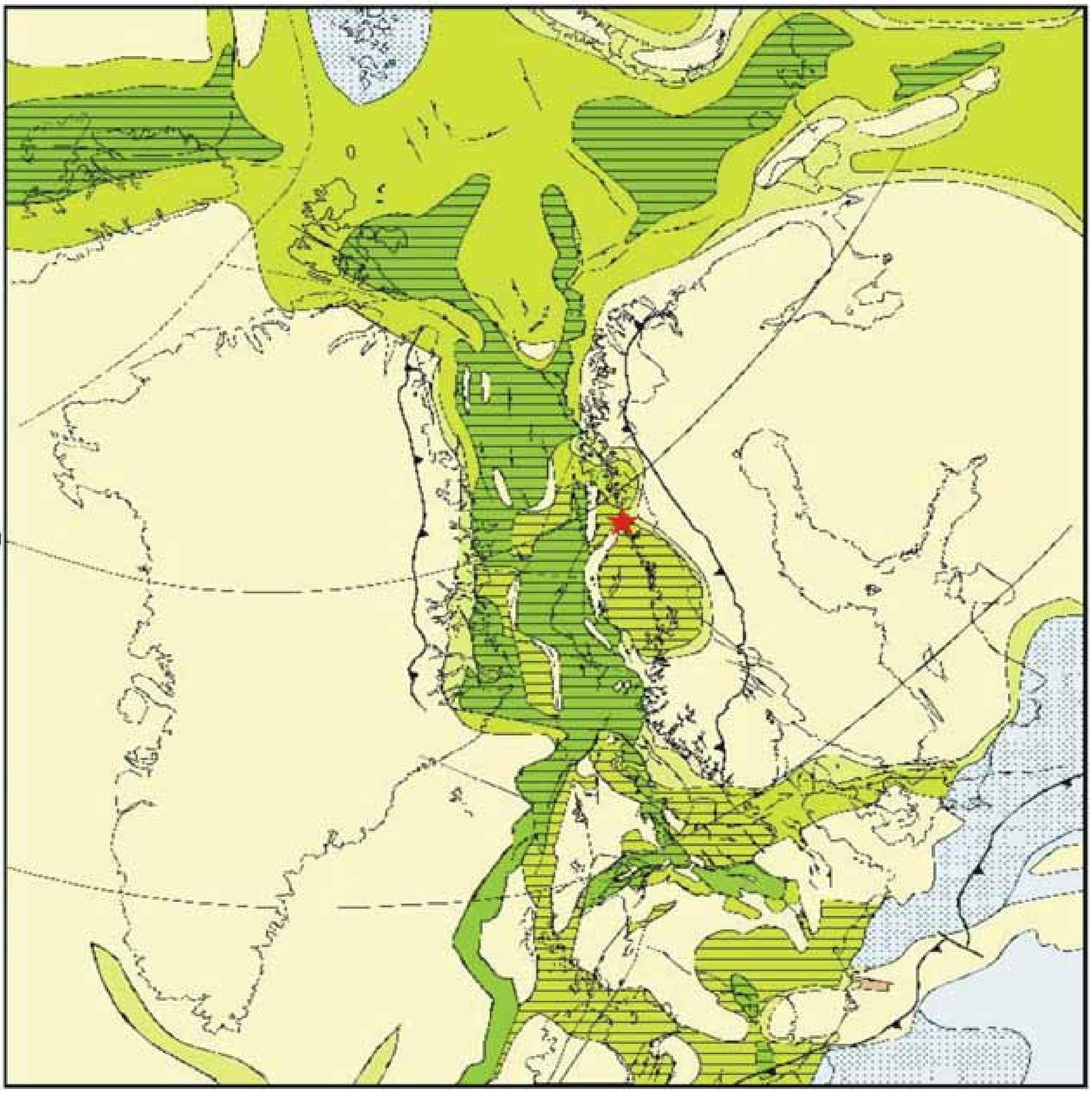

Figure 16. Palaeogeographic reconstruction for the Late Jurassic (Oxfordian-Kimmeridgian). Stabbfjorden (red star) is located in an area of shallow-marine, fine-grained deposition, but close to areas of coastal/shallow-marine deposition (more sandy sediments) in the east. According to this map, the Træna area was located slightly farther offshore than Stabbfjorden in the Late Jurassic. Horizontal ornament: carbonaceous shale. Modified from Brekke et al. (2001).

The Ternholmfjorden/Stabbfjorden area may have experienced rapid shifts in depositional environment over short distances in the Late Jurassic. Brekke et al. (2001) indicated a zone of coastal/shallow-marine deposition east of the Stabbfjorden basin, along the border of Fennoscandia (Fig. 16). To the southwest, the northeastern part of the Nordland Ridge experienced subaerial erosion, and crustal movements probably caused large variations in depositional environment along the ridge. One example is the shallow marine sand-dominated Rogn Formation, which has a restricted distribution both in space and time (Oxfordian-Kimmeridgian).

The Ryazanian low-stand was followed by a renewed sea-level rise to an intermediate maximum in the Barremian (Brekke et al. 2001). The Early Neocomian was still dominated by emergent structural highs and platform areas, and the Ryazanian erosional unconformity on top of the carbonaceous marine shales is widespread (Vollset & Doré 1984, Dalland et al. 1988, Surlyk 1990, Smelror et al. 1998). In Ryazanian through Hauterivan times, deep basinal areas continued to develop by subsidence along the rift axis, e.g. the Vøring Basin. Shallow basins such as the Nordland Basin, within the platform areas, accumulated lime-rich open marine mudstones and shales (Brekke et al. 2001). A carbonaceous mudstone sample of Valanginian-Hauterivan age from Grønna (Appendix 1, Table 1, Fig. 12c) represents the sediments deposited during this time interval. We are not able to identify seismic units of Cretaceous age in the present data set. This would probably require drilling of the succession in the Stabbfjorden basin.

The increasing sea level that led to widespread shale and marl deposition in platform areas and in starved distal deeps was halted by a sudden sea-level drop at the peak of the Barremian high-stand (Brekke et al. 2001). This gave time to renewed delta progradation from the transgressed land areas, e.g. the Wealdon paralics in southern England (Doré 1991), the Nordelva Member on Andøya (Dalland 1981) and the Helvetiafjellet Formation on Svalbard (Nemec et al. 1988). Two conglomerate samples of Barremian age from Grønna and Rorstabben (Table 1, Appendix 1, Fig. 12a) are interpreted to reflect this event.

7.2 Lyngværfjorden and Træna area

We have no rock samples that with certainty derive from the Lyngværfjorden basin, and glacial lineations show a transport direction towards the open sea west of that area. However, local glacier tongues may have been directed towards the southwest, and many of the erratics found on the Træna islands may thus have been eroded from the Lyngværfjorden basin. Samples collected here range in age from Triassic to Early Oxfordian. The Jurassic ones are thought to be derived from the Lyngværfjorden basin. The sedimentary facies of the Middle-Late Jurassic samples from Træna suggest a depositional environment similar to that in the Stabbfjorden basin. An unusual sample of this age from Selvær comprises light grey, stratified, bimodal, medium-grained, bioclastic sandstone (lithofacies 9, Table 1). We interpret this as a marginal-marine/shallow-marine sediment.

A major Middle Permian tectonic event led to the establishment of a seaway from the Barents Sea area southward and to the separation of Greenland and Norway (Doré 1991). Following this event, there was a change from continental to marine deposition off Mid-Norway. A 750 m-thick succession of Upper Permian-Lower Triassic (Ufimian-Griesbachian) marine clastic sediments has been drilled south of Træna (Bugge et al. 2002). Another marine transgression from the north occurred in the Lladinia-Carnian (Jacobsen & van Veen 1984). An erratic sample of Triassic bioclastic sandstone from Selvær (Table 1, lithofacies 11) was probably deposited during one of these transgressions. The sample must have been eroded from the seabed of Trænfjorden or Lyngværfjorden. Two other samples from Selvær are probably Triassic as well, but their age could not be determined from microfossils. One sample did not contain identifiable palynomorphs, whereas the other contained abundant fungal remains of terrestrial origin (Table 1, lithofacies 12 and 13). Provided these two samples are of Triassic age, it indicates that the eastern part of Trænfjorden/southern Lyngværfjorden was located in a continental setting during their deposition. The source of the Permian-Triassic sediments in the Træna area was probably Upper Devonian-Lower Permian sandstones eroded from an area immediately to the east of this (Bugge et al. 2002).

8. TECTONIC DEVELOPMENT

In the Stabbfjorden basin, the sedimentary succession occurs in a half-graben with a boundary fault along its southeastern margin (Fig. 6). In Ternholmfjorden, also the northern margin of the basin is defined by a major fault. Syn-sedimentary fault activity has not been identified in connection with deposition of the Middle Jurassic succession. Neither have we detected syn-sedimentary fault activity during deposition of the Upper Jurassic part of the succession, but here the interpretations are more uncertain because of a complicated stratigraphy.

A phase of extension was initiated in the late Middle Jurassic (Blystad et al. 1995, Færseth 1996, Brekke et al. 2001). The main phase of extension lasted from the Late Oxfordian-Early Kimmeridgian until Ryazanian-Valanginian times. Tectonic movements during this time interval caused a marked rejuvenation of the topography, and a complicated pattern of tectonic highs and lows at various scales developed. One of the highs is the Nordland Ridge, which reaches southwestwards from the Ternholman/Grønna area, immediately north of Ternholmfjorden/Stabbfjorden (Figs. 1 and 16). It is probable that the boundary faults of the Stabbfjorden basin, the large faults northwest of Ternholman, and the newly discovered Grønna Fault north of Grønna (Olesen et al. 2002), which are all sub-parallel to the Nordland Ridge, originated during this tectonic phase.

Træna is located south of the northeastward continuation of the Nordland Ridge (Figs. 1 and 16). Some of the faults mapped by IKU in southern Trænfjorden appear to have a trend that is sub-parallel to the northeastward continuation of the Ylvingen Fault Zone on the Trøndelag Platform. This fault zone is of Late Jurassic to Early Cretacous age (Blystad et al. 1995). In their seismic profiles, Bugge et al. (2002) show that several of the NE-trending faults south of Træna were active during deposition of the Upper Permian-Lower Triassic succession there.

9. HYDROCARBON POTENTIAL

9.1 Maturity and depth of burial

The maturity of organic material was determined by measuring vitrinite reflectance on representative samples from Rorstabben, Grønna, Selvær and Kallsholmen (Tables 2 and 3, Ferriday 2004). Table 2 shows that the average maturity of the samples with highest confidence level is ca. 0.35% Ro. Thus, the organic material is classified as immature.

Table 2. Vitrinite reflectance of representative samples. Ro: % vitrinite reflectance (maturity); No: number of measurements; Co: confidence level, ranging from A (very high) to F (very low). Form, content and colour were examined in ultra-violet light to better determine fluorescent material in the samples.

Sample	Age	Ro	No	Co	Form	Content	Colour	Comments
Rorstabben-2	Bajocian-Callovian	0.36	20	C	Spores	Trace	Yellow	Silty sst., micaceous, iron oxides
Rorstabben-3	Bajocian-Callovian	0.34	20	B	Spores	Trace	Yellow	Siltstone, iron oxide traces
Rorstabben-5	Volgian	0.48	4	E	-	-	-	Sandstone, iron

								oxides, pyrite decomposed, vitrinite possibly oxidised
Grønna-1	Barremian	0.65	20	E	-	-	-	Silty limest., variable Ro, probably reworked
Selvær-7	Early Oxfordian	0.36	20	C	Spores	Trace	Yellow	Calc. siltst., variable Ro possibly due to H/C impregnation and reworking
Kallsholmen-1	Volgian	0.35	20	C	Carbonate Spores	Moderate Trace	Yellow Yellow	Marly limest., variable Ro possibly due to H/C impregnation
Kallsholmen-5	Callovian-Kimmeridgian	0.34	20	C	Spores	Trace	Yellow-Yellow/ Orange	Calcareous siltstone

Maturity is dependent on time and temperature, whereas temperature is dependent on depth and temperature gradient. Maturity is not reversible, and thus expresses maximum maturity reached by the rock sample during its temperature and depth history. Without a maturity profile of the stratigraphic section from where the samples originate and knowledge of the temperature gradient in the area, the burial history of the samples remains unknown. However, if we compare with near-by areas on the Mid-Norwegian shelf, a similar maturity (0.35% Ro) is reached at a maximum depth of ca. 2000 m. Organic matter maturation in erratic blocks from Beitstadfjorden suggests a burial depth from 1.8-2.3 km (Weisz 1992). Similar burial depths are also inferred from Jurassic basins in Vesterålen (Davidsen et al. 2001) and in Frohavet (Gran 1990).

Table 3. Organic petrography of representative samples. A: Algae; S: Spores; C: Cuticle; R: Resin.

Sample	Amorph-inite	Bitumen	Phytoclasts							Comments
			Content	Compsition (%)						
				Liptinite				Vitrinite	Inert./ Reworked	
				A	S	C	R			
Rorstabben-2	Low	-	Trace	-	Trace	-	-	Trace	Trace	
Rorstabben-3	Moderate	-	Low	-	Trace	-	-	100	Trace	
Rorstabben-5	-	-	Vrt. barren	-	-	-	-	Trace	Trace	
Grønna-1	-	Trace	Trace	-	-	-	-	30	70	Suspect high % of re-working, bitumen as interstitial wisps
Selvær-7	Mod-Rich	-	Low-Mod	-	Trace	-	-	80	20	Some reworked material, some H/H impregnation
Kallsholmen-1	Moderate	-	Low-Mod	-	Trace	-	-	80	20	H/C impregnation?
Kallsholmen-5	Low-Mod	-	Trace	-	Trace	-	-	100	Trace	

The average age of the samples with the most confident measurements is ca. 160 million years (ranging from 150-170 million years). From their maximum burial depth, the sedimentary rocks at the present seabed must have been through a several million-year long period of uplift and erosion. It probably also took several million years for the rocks to reach their maximum burial depth. This implies that the effective time the rocks have been near maximum burial depth has to be much shorter than 160 million years. A diagram published by Stach et al. (1982) shows that a maximum temperature of 50ºC (2 km burial depth with a temperature gradient of 25ºC/km) over an effective time period of 6 million years is enough to reach a maturity of 0.35% Ro. At a maximum temperature of 40ºC, this maturity will be reached within 10-12 million years. It should be noted that at such low values for Ro as 0.35, there are many uncertainties in the calculations.

9.2 Shallow gas

Shallow gas occurs in the Quaternary sediments along the margins of Vestfjorden. This is especially well expressed just northwest of Ternholman, where fine-grained, stratified deposits cover the bedrock surface. Common features are blanking of the shallow seismic boomer data due to a high content of escaping gas in the sediments, gas chimneys, and enhanced/bright reflectors due to trapping of gas between sand, silt and clay layers (Figs. 17 and 18).

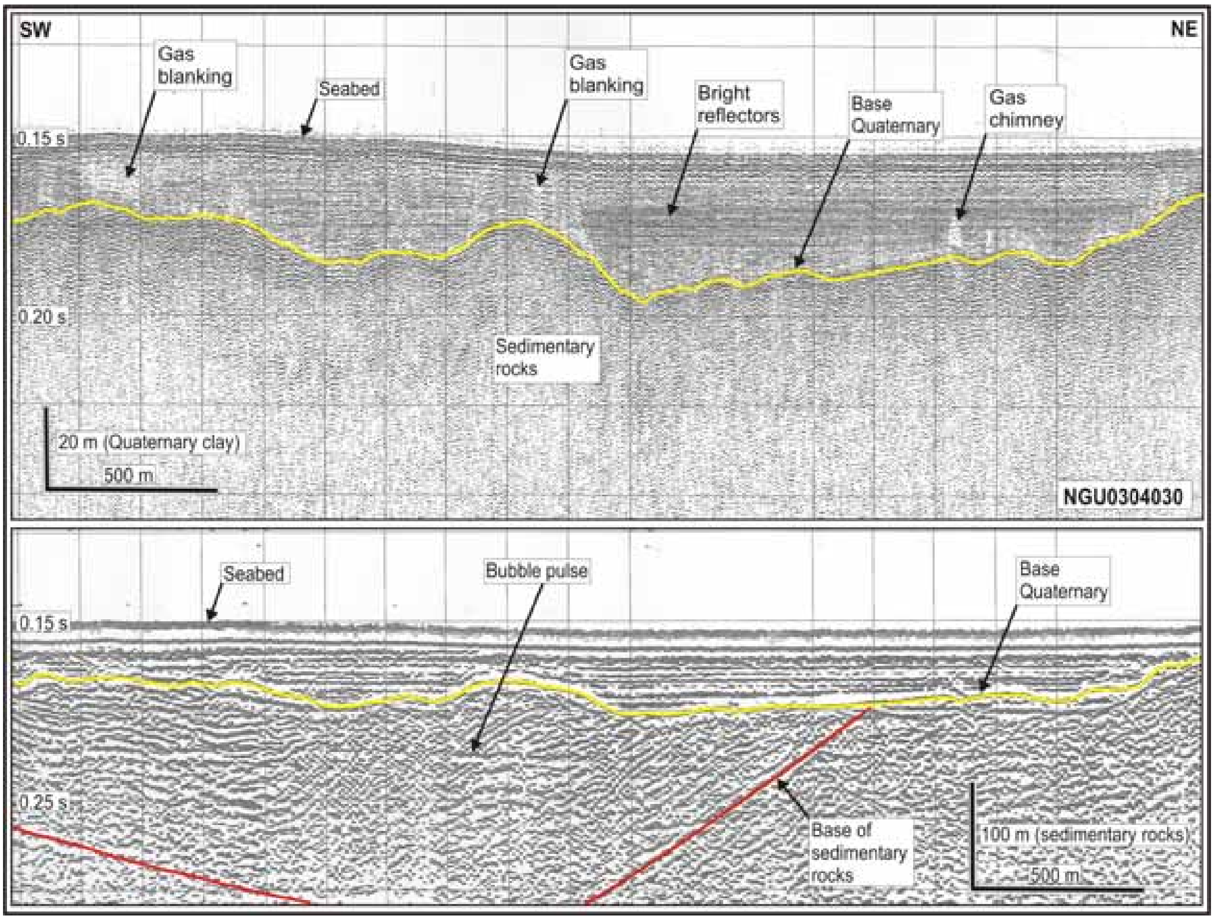

Figure 17. Seismic profile NGU0304020 southwest of Grønna exhibiting shallow gas in the Quaternary succession. Upper panel: Boomer record, filtered at 600-3000 Hz, with clear indications of shallow gas in the Quaternary succession. Lower panel: Sleevegun record, filtered at 100-600 Hz, showing the presence of layered, sedimentary bedrock below the shallow gas features. See Fig. 3 for location of the seismic line.

Shallow gas is most abundant in the lowermost part of the Quaternary succession, immediately above the bedrock surface. It appears that the gas in most cases occurs above sedimentary bedrock. These observations suggest that the gas is of thermogenic origin, and that it originates from the deeper sedimentary strata along the margins of Vestfjorden.

Thermogenic gas may indicate leaking hydrocarbon accumulations in the subsurface. Where gas occurs in Quaternary sediments above basement rocks, it might have migrated laterally along the bedrock-sediment interface before rising into the Quaternary succession.

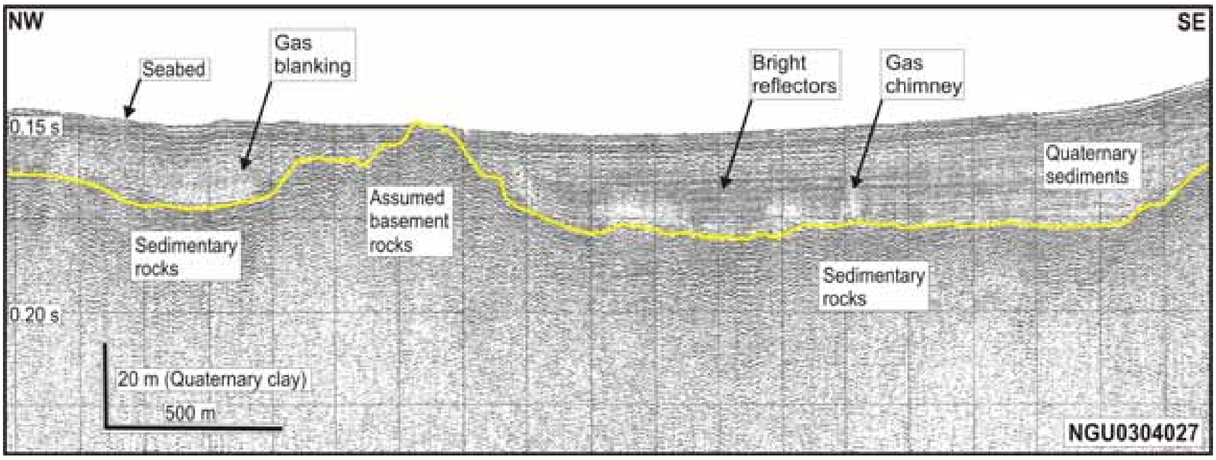

Figure 18. Seismic profile NGU0304027 southwest of Grønna exhibiting shallow gas in the Quaternary succession. Boomer record, filtered at 600-3000 Hz. See Fig. 3 for location of the seismic line.

Pockmarks are not very common, but occur in the deep Quaternary clay basin in Ternholmfjorden, south of Ternholman, and in the area of sediments with shallow gas northwest of Ternholman. Both of these areas are underlain by sedimentary rocks of probable Jurassic age.

The multibeam bathymetry indicate that coral reef mounds occur in southern Trænfjorden (Fig. 10). It has been postulated that one preferred site for coral reefs to grow may be where methane gas seeps from the subsurface (e.g. Hovland & Thomsen 1997, Hovland et al. 1998). A large part of the possible coral reef area is underlain by sedimentary rocks of assumed Triassic age, that might have generated methane gas.

10. CONCLUSIONS

In 2003, a seismic data acquisition and erratic block sampling cruise was undertaken along the Nordland coast of North-Norway in the project "THE RECYCLING OF AN OROGEN: Provenance and routing of detritus from Norway to the Mid-Norwegian margin". Altogether, fifty single channel seismic lines with a total length of 646 km and 52 blocks of erratic sedimentary rocks were acquired in an area between Vikna and Gildeskål. The aim of the cruise was to map coastal areas previously not investigated by seismic methods in a search for Mesozoic outliers and fault basins.

One day of seismic profiling in 1998 documented the existence of downfaulted sedimentary rocks in Ternholmfjorden in Meløy. In 2002, seismic profiling was undertaken to further map the area (Bøe et al. 2003). A search for ice-transported Mesozoic erratics on nearby islands and skerries (along the transport direction of former ice-streams) resulted in numerous findings. Microfossil dating of the blocks, containing shells and coal fragments, gave Middle to Late Jurassic ages. Reconnaissance seismic profiling (one seismic line) by NGU in Lyngværfjorden, northeast of Træna, in 1998 showed the presence of sedimentary rocks also there (Fig. 1).

In the present project, we have been able to perform detailed mapping of the boundaries and internal structures of the sedimentary rock basins in Ternholmfjorden/Stabbfjorden and Lyngværfjorden (hereafter called the Stabbfjorden and Lyngværfjorden basins) as well as of the southeastern boundary of the Vestfjorden Basin in Meløy and Gildeskål.

The NE-SW-trending Stabbfjorden basin is a 28 km long and 3-10 km-wide half-graben. Two major faults, separated by a right-lateral offset, occur along the southeastern boundary of the half-graben. The layering of the sedimentary succession dips into the fault planes at angles up to 21º. South of Ternholman, the northwestern boundary of the basin is defined by a 9 km-long fault 100-200 m south of Kallsholmen. Further east, the northwestern boundary of the Stabbfjorden basin is a primary unconformity, and at Rorstabben the sedimentary rocks occur only 200 m south of the skerries. Along the contact, the sedimentary strata dip at up to 37º towards the southeast. The sedimentary rock succession in the Stabbfjorden basin is up to 800 m thick.

The Lyngværfjorden basin is elongated in NNE-SSW direction. Its length is about 12 km, whereas the width is up to 3 km and the depth possibly more than 350 m. The structural pattern of the basin is complex, with rapid changes of strike and dip over short distances, and probably many small faults displacing the layering. The southeastern and northeastern boundaries of the basin are primary depositional contacts, where the bedding generally dips into and the basin at angles of up to 15º. One or possibly two major faults define the northwestern/western boundary of the basin.

The erratic sedimentary blocks found on islands and skerries comprise conglomerates, sandstones, siltstones and mudstones. Microfossil analyses show that they range in age from Barremian to Triassic. The majority of the samples are of Middle-Late Jurassic age. Based on colour, texture, structure and fossil content, the erratic blocks have been divided into 15 lithofacies. Most of the facies represent shallow-marine deposits, but it is possible that the oldest samples, of Triassic age, were deposited in a continental environment. It appears that the lithofacies reflect the well-known tectonic phases and sea-level changes that have been reported for the Middle Jurassic-Early Cretaceous in this area.

The maturity of organic material was determined by measuring vitrinite reflectance on representative samples. The measurements show that the organic material can be classified as immature. It should be noted, however, that shallow gas of probable thermogenic origin is observed in Quaternary deposits along the margin of Vestfjorden. This gas may originate from deeper, more mature strata in the Vestfjorden Basin.

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Appendix 1. Dating results and descriptions of erratic cobbles and boulders of sedimentary rocks found on skerries along the coast of Træna, Rødøy and Meløy in Nordland. The table is sorted according to age/age groups.

	Sample number	Biostratigraphic age	Age sorting	Lithology	Colour	Weathering colour	Burr. surf.	Sedimentary structures	Sorting	Fossils	Coal fragments	Facies
36	Grønna-1	Barremian	1	conglomerate	grey	grey		<3 cm thick sand lenses	poor	some, <1 cm	some, <1 cm	1
9	Rorstabben-9	No identifiable palynomorphs	1	conglomerate, clasts <1 cm	grey	grey		massive	moderate	some, <2 mm		1
32	Kallsholmen-12	Early Cretaceous	2	medium sandstone	dark grey	dark grey		vaguely bedded?	well-sorted			2
69	Grønna-34	Valanginian-Hauterivan	3	mudstone	light grey	very light grey		massive	well-sorted			3
10	Rorstabben-10	Volgian (or Early Ryazanian)	4	very coarse sandstone	grey	grey		bedded	moderate			8
5	Rorstabben-5	Volgian	4	coarse-very coarse sst.	light grey	yellowish grey		massive	moderate	molluscs <1 cm	some, < 2 cm	8
66	Grønna-31	Kimmeridgian-Early Volgian	5	siltstone	grey	light grey		massive, dish structures?	well-sorted	various, <1 cm	some, <2 mm	4
67	Grønna-32		5	siltstone	dark grey	light grey		massive, dish structures?	well-sorted			4
68	Grønna-33	Volgian	5	mudstone	very dark grey	light grey		massive	well-sorted			4
21	Kallsholmen-1	Volgian	5	siltstone	dark grey	yellowish grey		massive	well-sorted	molluscs <1 cm	some, <1 cm	4
30	Kallsholmen-10	Early Oxfordian (or Callovian?)	6	siltstone/mudstone	very dark grey	light yell. grey		massive	well-sorted			4
29	Kallsholmen-9		6	siltstone/mudstone	very dark grey	light yell. grey		massive	well-sorted			4
75	Selvær-6		6	fine sandstone	dark grey	brownish		massive	well-sorted			5
76	Selvær-7	Early Oxfordian	6	very fine sandstone	dark grey	grey	x	massive	well-sorted	many, <1 cm	many, <2 cm	5
25	Kallsholmen-5	Callovian-Kimmeridgian	6	coarse sandstone	light grey	grey		massive, dish structures?	moderate		many, <5 cm	8
4	Rorstabben-4	Middle-Late Jurassic	7	siltstone	dark grey	grey		massive, dish structures?	well-sorted	molluscs <1 mm	some, <1 cm	4
52	Grønna-17	Middle-Late Jurassic	7	fine sandstone	dark grey	yellowish grey		massive	moderate		many, <10 cm	5
61	Grønna-26	Middle-Late Jurassic	7	very fine sandstone	dark grey	grey	x	massive	well-sorted	molluscs <2 cm	many, <1 cm	5
62	Grønna-27		7	very fine sandstone	dark grey	grey	x	massive	well-sorted	molluscs <2 cm	many, <1 cm	5
63	Grønna-28		7	very fine sandstone	dark grey	grey		massive	well-sorted			5
64	Grønna-29		7	very fine sandstone	dark grey	grey	x	massive	well-sorted		some, < 1 mm	5
65	Grønna-30		7	very fine sandstone	dark grey	light grey		massive	well-sorted		some, < 1 mm	5
19	Rorstabben-19		7	very fine sandstone	dark grey	grey		massive	well-sorted	gastropod <3 cm		5
20	Rorstabben-20		7	fine sandstone	dark grey	yellowish grey	x	massive	well-sorted	molluscs <2 cm	some, <10cm	5
79	Selvær-10	Middle-Late Jurassic	7	siltstone	light brownish grey	yellowish	x	massive	well-sorted			6
77	Selvær-8	No identifiable palynomorphs	7	siltstone	light grey	rusty		laminated/cross-lam.	well-sorted			6
78	Selvær-9		7	siltstone	light grey	rusty		vaguely laminated	well-sorted			6
27	Kallsholmen-7		7	medium sandstone	dark grey	grey		vaguely bedded?	poor			7
24	Kallsholmen-4	Bathonian-Early Kimmeridgian	7	medium-very coarse sst	dark grey	grey		bedded/cross-bedded	poor		many, <15 cm	7
14	Rorstabben-14	Jurassic-Early Cretaceous	7	medium-coarse sandstone	light grey	yellowish		massive	well-sorted			8
54	Grønna-19		7	fine-medium sandstone	grey	grey		massive	well-sorted		some, <1 mm	8
31	Kallsholmen-11		7	medium sandstone	light grey	grey		massive	well-sorted		some, <1 mm	8
33	Kallsholmen-13		7	medium sandstone	light grey	grey		bedded	moderate	molluscs <1 cm		8
26	Kallsholmen-6		7	medium sandstone	light grey	grey		massive	well-sorted			8
28	Kallsholmen-8	Middle-Late Jurassic	7	medium sandstone	light grey	grey		massive	well-sorted		some, <3 mm	8
16	Rorstabben-16		7	medium sandstone	light grey	yellowish	x	massive	well-sorted		some, <3 mm	8
17	Rorstabben-17		7	medium sandstone	light yell. grey	light yell. grey		vaguely bedded	well-sorted			8
71	Selvær-2		7	medium sandstone	light grey	yellowish		vaguely bedded	well-sorted			8
45	Grønna-10	Middle-Late Jurassic	7	medium-coarse sandstone	light grey	yellowish grey		massive	well-sorted		some, <1 mm	8
46	Grønna-11		7	medium-coarse sandstone	light grey	light grey		massive	well-sorted		some, <1 mm	8
47	Grønna-12		7	medium-coarse sandstone	light grey	light grey		massive	well-sorted		some, <1 mm	8
48	Grønna-13		7	medium-coarse sandstone	light grey	light grey		massive	well-sorted		some, <1 mm	8
49	Grønna-14		7	medium-coarse sandstone	light grey	yellowish		massive	well-sorted		some, <1 mm	8
50	Grønna-15		7	medium-coarse sandstone	light grey	grey		massive	well-sorted		some, <1 mm	8
51	Grønna-16		7	medium-coarse sandstone	light grey	yellowish grey		massive	well-sorted		some, <1 mm	8
37	Grønna-2	Middle-Late Jurassic	7	medium-coarse sandstone	grey	grey		massive	moderate		many, <8 cm	8
55	Grønna-20		7	pebbly medium-coarse sst	grey	yellowish grey		massive	moderate	some, <15 mm	some, <1 mm	8
38	Grønna-3		7	medium-coarse sandstone	grey	grey		massive	moderate		many, <3 cm	8
39	Grønna-4		7	coarse-very coarse sst.	grey	grey		massive	moderate		many, <2 cm	8

Appendix 1. Dating results and descriptions of erratic cobbles and boulders of sedimentary rocks found on skerries along the coast of Træna, Rødøy and Meløy in Nordland. The table is sorted according to age/age groups.

	Sample number	Biostratigraphic age	Age sorting	Lithology	Colour	Weathering colour	Burr. surf.	Sedimentary structures	Sorting	Fossils	Coal fragments	Facies
40	Grønna-5	Middle-Late Jurassic	7	medium-coarse sandstone	grey	grey		massive	moderate		many, <5 cm	8
41	Grønna-6		7	medium-coarse sandstone	grey	light grey		massive	moderate		some, <1 cm	8
42	Grønna-7		7	medium sandstone	grey	grey		massive	moderate		some, <1 mm	8
43	Grønna-8		7	medium sandstone	grey	grey		massive	moderate		some, <1 mm	8
44	Grønna-9	Middle-Upper Late Jurassic	7	medium-coarse sandstone	light grey	yellowish grey		massive	well-sorted		some, <1 mm	8
34	Kallsholmen-14		7	medium-coarse sandstone	light grey	light grey		massive	well-sorted			8
11	Rorstabben-11		7	coarse-very coarse sst.	light grey	yellowish grey		cross-bedded	well-sorted	molluscs <1 cm		8
15	Rorstabben-15		7	very coarse sandstone	grey	grey		massive	well-sorted	molluscs <1 cm		8
6	Rorstabben-6		7	coarse sandstone	light grey	light grey		massive	well-sorted			8
7	Rorstabben-7		7	medium-coarse sandstone	light grey	light grey		vaguely bedded	well-sorted		some, <3 mm	8
8	Rorstabben-8		7	coarse sandstone	light grey	grey		vaguely bedded	well-sorted			8
70	Selvær-1	Middle-Late Jurassic	7	bioclastic medium sst.	light grey	light grey	x	bedded	bimodal	many, <1 cm		9
56	Grønna-21		7	very fine-fine sandstone	grey	grey	x	massive	well-sorted		some, <7 mm	10
57	Grønna-22		7	very fine-fine sandstone	grey	light grey		massive	moderate	molluscs <1 cm	some, <1 cm	10
58	Grønna-23		7	very fine-fine sandstone	grey	light grey		laminated	well-sorted			10
59	Grønna-24		7	very fine-fine sandstone	grey	grey		massive	well-sorted			10
60	Grønna-25		7	fine sandstone	grey	grey		massive	well-sorted			10
84	Torvvær-2	No identifiable palynomorphs	7	very fine sandstone	light grey	grey		cross-laminated	well-sorted			10
1	Rorstabben-1	Bathonian-?Callovian	8	fine sandstone	dark grey	yellowish grey	x	massive	well-sorted	molluscs <2 cm	some, <10 cm	5
53	Grønna-18	(Late?) Bathonian	8	pebbly coarse sandstone	dark grey	grey		massive	poor	many, <1 cm	many, <8 cm	7
22	Kallsholmen-2	Bathonian-?Callovian	8	fine-medium sandstone	grey	yellowish grey		massive-weakly stratified	well-sorted		some, <1 mm	8
12	Rorstabben-12	Bathonian-Callovian	8	medium sandstone	light yell. grey	rusty		bedded	well-sorted	molluscs <1 cm		8
3	Rorstabben-3	?Bajocian-?Callovian	8	medium sandstone	grey	rusty		massive	moderate	molluscs <5 cm	some, <3 cm	8
13	Rorstabben-13		8	medium-coarse sandstone	light grey	rusty		massive	moderate			8
18	Rorstabben-18	Middle Jurassic	8	medium-coarse sandstone	light grey	light grey	x	cross-bedded	well-sorted	molluscs <5 mm	some, <7 cm	8
23	Kallsholmen-3	?Bajocian-?Callovian	8	very fine sandstone	grey	light grey		massive	well-sorted	molluscs <3 cm		10
35	Kallsholmen-15	Bathonian-Callovian?	8	very fine sandstone	grey	grey		massive	well-sorted		some, <1 cm	10
2	Rorstabben-2	?Bajocian-?Callovian	8	fine sandstone	light grey	reddish		massive	well-sorted		many, <1 cm	10
74	Selvær-5	Triassic	9	bioclastic medium sst.	yellowish grey	light grey		intraform. silt clasts	poor	various, <1 cm		11
73	Selvær-4	Terr. palynom., fungal remains	9	medium-coarse sandstone	yellow	yellow		?bioturb./?roots/?plants	poor	various	many cm's	12
72	Selvær-3	No identifiable palynomorphs	9	fine-medium sandstone	light yell. brown	grey		massive	well-sorted			13
80	Selvær-11	Age not determined	10	fine-grained limestone	light grey	light grey	x	massive/?recrystallised	well-sorted			14
81	Selvær-12		10	fine-grained limestone	light greenish yell.	light grey	x	massive/?recrystallised	well-sorted			14
82	Dørvær-1	Not determ. Pre-Mesozoic ?	11	medium-coarse sandstone	dark reddish	dark reddish		vaguely bedded	moderate			15
85	Jutøy-Myken-1	Pre-Mesozoic ?	11	medium sandstone	dark reddish	dark reddish		massive	moderate			15
86	Kjøsøy-Nesøy-1	Pre-Mesozoic ?	11	medium sandstone	dark reddish	dark reddish		vaguely cross-bedded	well-sorted			15
87	Lyngvær-1	Pre-Mesozoic ?	11	medium sandstone	dark reddish	dark reddish		vaguely cross-bedded	well-sorted			15
83	Torvvær-1	Pre-Mesozoic ?	11	conglomerate, clasts <3 cm	dark reddish	dark reddish		well-bedded	moderate			15

Appendix 2. Dating results and descriptions of erratic cobbles and boulders of sedimentary rocks found on the Froan islands (Rise et al. 1989), northwest of Frohavet, Trøndelag.

	Sample number	Biostratigraphic age	Lithology	Colour	Weathering colour	Burr. surf.	Sedimentary structures	Sorting	Fossils	Coal fragments	Facies
1	Jamtøya-14/87	Jurassic	fine-grained sandstone	light grey	grey		laminated/cross-laminated	well-sorted	fossils, <5 mm	some, <1 mm	10
2	Indre Sandværøy-52/87	Bajocian-?Callovian	medium sandstone	light grey	yellowish		laminated/bedded	well-sorted			8
3	Store Lyngøy-57/87	Bajocian-?Callovian	medium sandstone	grey	reddish grey		bedded	moderate		many, <5 mm	8
4	Indre Sandværøy-65/87	Bajocian-?Callovian	medium sandstone	grey	grey		laminated/cross-laminated	well-sorted		many, >1 cm	8
5	Sandøya-101/87	?	pebbly medium sandstone	very light grey	very light grey		massive	moderate			8
6	Nordbuan-126/87	Jurassic	coarse sandstone	grey	yellowish		bedded	moderate	many, <1 mm	some, <1 cm	8

Appendix 3. Microfossil analyses (palynomorphs) of erratic blocks. F: Froan; S: Selvær; G: Grønna; R: Rorstabben; K: Kallsholmen; T: Torvvær; D: Dørvær; FU: fungal remains; TA: taeniated pollen; NA: not analysed.

	F14/87	F52/87	F57/87	F65/87	F101/87	F126/87	S-1	S-3	S-4	S-5	S-7	S-8	S-10	S-11	G-1	G-2	G-5	G-9	G-10	G-17	G-18	G-26	G-31	G-33	G-34	R-1	R-2	R-3	R-4	R-5	R-9	R-10	R-12	R-14	R-18	K-1	K-2	K-3	K-4	K-5	K-8	K-10	K-12	K-15	T-2	D-1
Pollen and spores					FU				FU	TA					NA										NA																		NA			
Anapiculatisporites telephorus							x																																							
Apiculatisporites ovalis																																												x		
Araucariacites australis			x			x					x		x					x		x	x					x		x	x	x					x		x	x		x						
Baculitisporites comaumensis		x		x																																										
Baculitisporites spp.			x			x	x				x		x			x	x	x		x	x		x	x		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x		x		
Bisaccat pollen																										x	x	x	x	x						x	x	x	x	x						
Callialasporites dampieri																					x	x																								
Callialasporites segmentatus		x																																												
Callialasporites spp.			x	x																				x																						
Callialasporites trilobatus											x		x																x							x	x		x	x						
Cerebropollenites macroverrucosus	x		x	x			x				x		x			x	x	x	x	x	x	x	x	x		x	x		x	x		x	x		x	x	x	x	x	x	x	x		x		
Cerebropollenites thiergartii													x								x														x									x		
Cingutriletes infrapunctus																					x																									
Clavatipollenites hughesii																																							x							
Clavatisporites sp.																							x	x																						
Concavissimisporites sp.							x																																							
Corollina spp.																														x							x		x	x						
Corollina torosus																x	x			x	x														x						x					
Contignisporites cooksonii																																								x						
Contignisporites problematicus																																			x											
Deltoidospora crassexina																												x																		
Deltoidospora minor																										x			x	x						x	x	x	x	x						
Deltoidospora spp.			x	x		x	x									x	x	x		x	x	x	x	x								x									x	x				
Deltoidospora toralis																																	x		x									x		
Exesipollenites sp.														x																																
Exesipollenites tumulus													x																																	
Krauselisporites sp.																										x																				
Laevigatosporites spp.																																			x									x		
Leptolepidites major													x					x		x	x		x	x								x														
Lycopodiumsporites spp.			x				x				x		x			x	x	x	x	x	x	x				x	x	x					x	x	x	x	x	x		x	x	x		x		
Lycopodiumsporites austroclavatidites																										x	x	x		x								x		x						
Lycopodiumsporites semimuris																																					x	x	x							
Manumia sp.							x														x																									
Marattisporites scabrosus																																					x									
Matonisporites crassiangulatus																										x																				
Neoraistrica truncata																										x																				
Perinopollenites elatoides	x			x			x				x		x			x	x	x	x	x	x	x	x	x		x	x	x	x	x		x	x	x	x						x	x		x		x
Polypodiisporites polymicroforatus																										x																				
Retusotriletes cf. mesozoicus																											x	x																		
Sestrosporites pseudoalveolatus																														x										x				x		
Stereisporites seebergensis																						x					x	x									x	x								
Stereisporites sp.																	x																													
Spheriopollenites psilatus							x				x		x			x		x	x				x	x								x												x		
Staplinisporites spp.																								x																						
Staplinisporites telatus																																			x											
Striatella jurassica																				x						x																				
Trachysporites asper																											x																			
Trachysporites fuscus																					x																									
Marine phytoplankton														FL																																
Atopodinium harmoense																						x																								
Caddasphaera halosa			x	x																						x																				
Circulodinium spp.																									x							x														
Clamydosporella nyei															x										x																					
Chlamydophorella sp.			x																											x		x														
Cleistosphaeridium sp.															x										x																					
Cribroperidinium edwardsii															x																															
Cribroperidinium globatum																							x	x								x														
Ctenidodinium ornatum																					x																									
Cyclopsiella spp.		x	x	x																	x	x					x						x				x	x			x					
Dissiliodinium spp.																					x					x											x							x		
Egmontodinium polyplacophorum																								x																						
Ellipsiodictyum cinctum																							x									x														

Appendix 3. Microfossil analyses (palynomorphs) of erratic blocks. F: Froan; S: Selvær; G: Grønna; R: Rorstabben; K: Kallsholmen; T: Torvvær; D: Dørvær; FU: fungal remains; TA: taeniated pollen; NA: not analysed.

	F14/87	F52/87	F57/87	F65/87	F101/87	F126/87	S-1	S-3	S-4	S-5	S-7	S-8	S-10	S-11	G-1	G-2	G-5	G-9	G-10	G-17	G-18	G-26	G-31	G-33	G-34
Esharisphaeridia laevigata																		x		x	x				
Escharisphaerdia pocockii	x			x												x			x					x	
Escharisphaeridia spp.																									
Evansia evittii																									
Gochteodinia mutabilis																									
Gonyaulacysta helicoidea																									x
Gonyaulacysta jurassica											x														
Gonyaulacysta pectinigera																									
Hystrichosphaeridinium arborispinum															x										
Hystrichosphaeridinium schindewolfii															x										
Impagidinium sp.															x										
Jansonia sp.																									
Kallosphaeridium spp.																x				x	x				
Korystocysta gochtii																					x				
Lacrymodinium warrenii																					x				
Leiosphaeridia spp.																									
Leptodinium sp.																									x
Liesbergia scarburghensis											x														
Lithodinia cf. stoveri															x										
Micrhystridium sp.	x									x					x					x	x			x	
Nannoceratopsis gracilis																					x				
Nannoceratopsis pellucida																									
Odeontochitina operculata															x										
Oligosphaeridium asterigerum															x										
Oligosphaeridium diliculum																									x
Orobodinium sp.																					x				
Palaeoperidinium cretaceum															x										
Pareodinia barentsensis																					x				
Pareodinia ceratophora				x																			x	x	
Pareodinia evittii			x																						
Pareodinia sp.																							x		
Perisseisphaeridium pannosum																							x		
Pluriarvalium osmingtonense																									
Pterospermopsis sp.																								x	
Phoberocysta neocomica																									x
Protoellipsoidinium spinosum																									x
Rhynchodiniopsis cladophora																									
Rhynchodiniopsis sp.																									x
Rigaudella aemula											x														
Sentusidinium rioultii				x							x												x		
Sentusidinium sp.																								x	
? Senoniasphaera sp. A																									
? Sentusidinium spp.																							x		
Sirmiodinium grossii																							x	x	x
Spiniferites ramosus															x										x
Systematophora daveyi																							x	x	
Systematophora palmula																									x
Systematophora spp.																								x	
Tasmanites spp.																							x	x	
Tehamadinium daveyi															x										x
Tehamadinium evittii																									
Tenua hystrix																									
Tubotuberella apatela															x										
Valensiella ovula			x																						
Valvaeodinium thereseae																									
Fresh-water algae																									
Botrycoccus sp.		x		x		x							x								x				

	R-1	R-2	R-3	R-4	R-5	R-9	R-10	R-12	R-14	R-18	K-1	K-2	K-3	K-4	K-5	K-8	K-10	K-12	K-15	T-2	D-1
Esharisphaeridia laevigata																					
Escharisphaerdia pocockii					x							x	x						x		
Escharisphaeridia spp.	x	x	x										x	x							
Evansia evittii	x													x							
Gochteodinia mutabilis					x																
Gonyaulacysta helicoidea																					
Gonyaulacysta jurassica															x						
Gonyaulacysta pectinigera																			x		
Hystrichosphaeridinium arborispinum																					
Hystrichosphaeridinium schindewolfii																					
Impagidinium sp.																					
Jansonia sp.	x																				
Kallosphaeridium spp.																					
Korystocysta gochtii																					
Lacrymodinium warrenii																					
Leiosphaeridia spp.	x																				
Leptodinium sp.																					
Liesbergia scarburghensis																					
Lithodinia cf. stoveri																					
Micrhystridium sp.												x									
Nannoceratopsis gracilis																					
Nannoceratopsis pellucida														x							
Odeontochitina operculata																					
Oligosphaeridium asterigerum																					
Oligosphaeridium diliculum																					
Orobodinium sp.																					
Palaeoperidinium cretaceum																					
Pareodinia barentsensis																					
Pareodinia ceratophora																					
Pareodinia evittii																					
Pareodinia sp.																					
Perisseisphaeridium pannosum																					
Pluriarvalium osmingtonense															x						
Pterospermopsis sp.																					
Phoberocysta neocomica																					
Protoellipsoidinium spinosum																					
Rhynchodiniopsis cladophora															x						
Rhynchodiniopsis sp.																					
Rigaudella aemula																	x				
Sentusidinium rioultii																					
Sentusidinium sp.																					
? Senoniasphaera sp. A												x									
? Sentusidinium spp.		x																			
Sirmiodinium grossii							x				x										
Spiniferites ramosus																					
Systematophora daveyi																					
Systematophora palmula																					
Systematophora spp.							x														
Tasmanites spp.												x		x	x						
Tehamadinium daveyi																					
Tehamadinium evittii											x										
Tenua hystrix																		x			
Tubotuberella apatela																					
Valensiella ovula												x			x						
Valvaeodinium thereseae								x													
Fresh-water algae																					
Botrycoccus sp.																			x		