RESEARCH ARTICLE

Mesozoic sediments and structures onshore Norway and in the coastal zone

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In mainland Norway, Mesozoic sedimentary rocks (Jurassic and Cretaceous) outcrop 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. 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.

Introduction

The aim of this contribution is to summarise results from studies of Mesozoic sediments and structures onshore Norway and in the coastal zone over the past 150–160 years. A comprehensive summary of this kind has previously not been published, although Ørvig (1960) presented a small chapter, mainly on the Mesozoic rocks on Andøya, in *'Geology of Norway'*.

Erratic blocks of Mesozoic rocks were found in Norway for the first time in 1845, on the northwest shore of Beitstadfjorden (Figure 1). 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). Geophysical and geological mapping of the Norwegian continental margin started in the 1960s. The mapping of the shelf was intensified after discovery of the Ekofisk oil field in the North Sea in 1969. However, 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, 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. 1989, Smelror et al. 1989, 1994,

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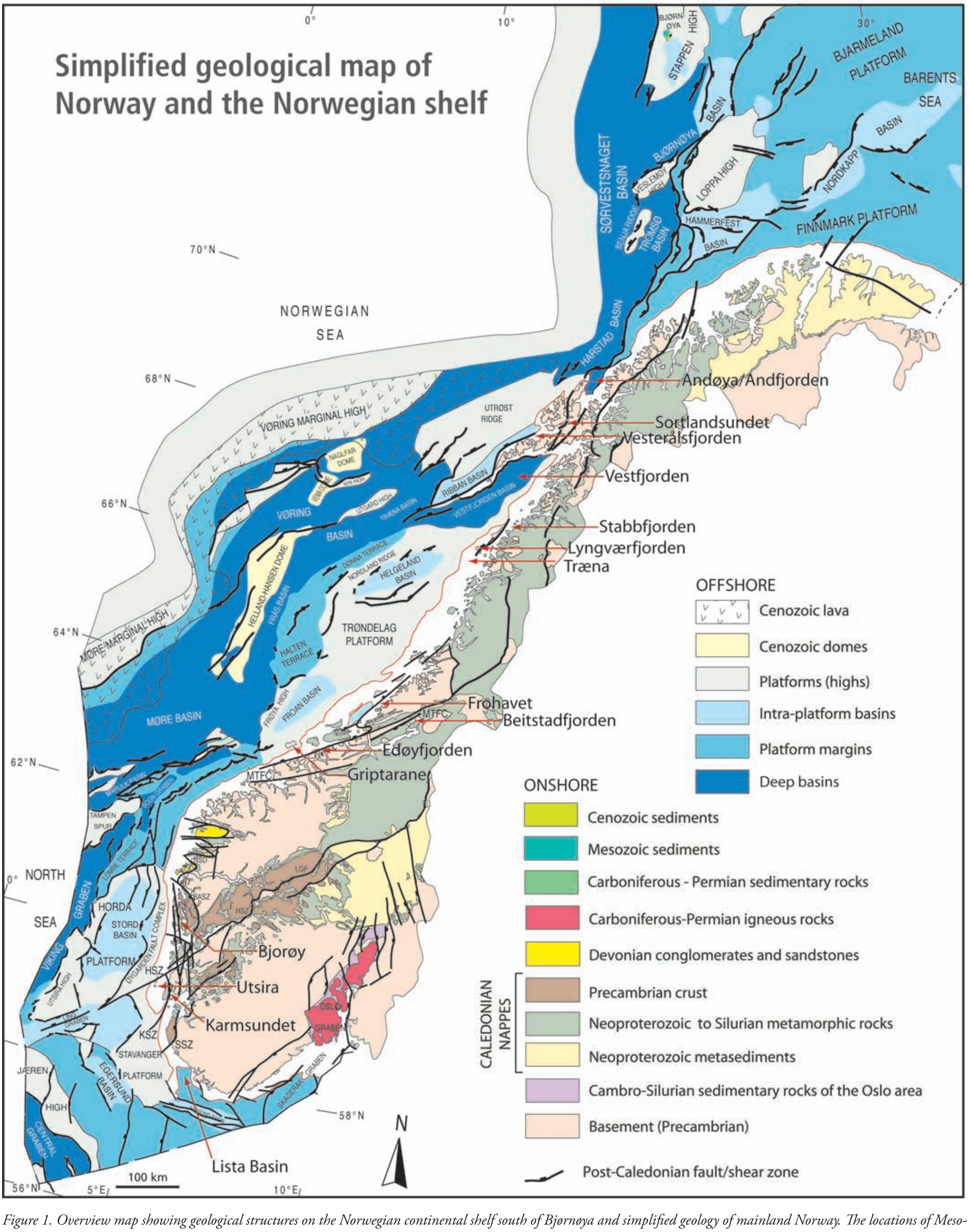

Figure 1. Overview map showing geological structures on the Norwegian continental shelf south of Bjørnøya and simplified geology of mainland Norway. The locations of Mesozoic basins, successions and structures discussed in the text are shown. The compilation is based on maps from the Norwegian Petroleum Directorate, the Geological Survey of Norway, and various published and unpublished data.

Hansen et al. 1992, 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). The focus of this chapter is thus on Mesozoic rocks and structures in the coastal zone of mainland Norway, with only a short overview of the continental shelf.

Mesozoic sediments and structures on the continental shelf

Barents Sea

The Barents Sea (Figure 1) is located in an intracratonic setting between the Norwegian-Russian mainland, the Arctic Ocean margin and the Norwegian-Greenland Sea (Figure 1). The region has been affected by several phases of tectonism since the termination of Caledonian movements in the Early Devonian. The dominant structural trends are ENE–WSW to NE–SW and NNE–SSW to NNW–SSE, with a local influence of WNW–ESE-striking elements (Gabrielsen et al. 1990). Major faults with similar trends are known from the mainland of Finnmark, Norway, and Northwest Russia, where Mesozoic ages of movement have been inferred (Lippard and Roberts 1987, Karputz et al. 1993, Roberts and Lippard 2005). The post-Devonian succession of the Barents Shelf shows a close resemblance to the Upper Palaeozoic to Tertiary successions on Svalbard, which represent an uplifted part of the northern Barents Shelf.

In the latest Permian and Early Triassic, the western Barents Shelf experienced uplift and erosion, followed by a tectonically relatively quiet period in the Triassic to Early Jurassic. During the Mesozoic, the shelf experienced repeated cycles of coastal and deltaic progradations into the wide shelf basin from the north and northwest. The Triassic and Early Jurassic succession consists of a series of thick, upward-coarsening sequences assigned to the Sassendalen and Kapp Toscana groups. The coastal sediments of the Sassendalen Group grade eastwards and southwards into shelf mudstones, and in the southwestern Barents Shelf, shallow to deep shelf sediments were deposited. The overlying Kapp Toscana Group contains a number of upward-coarsening sequences, with an increasing content of sandstones towards the top. On Svalbard, the uppermost part is condensed. The group consists of nearshore, deltaic deposits.

A period of crustal stretching and associated block faulting started in the Middle Jurassic and increased during the Late Jurassic, terminating with the formation of the major basins and highs on the Barents Shelf (Gabrielsen et al. 1990). During this period of crustal extension, some areas experienced rapid and extreme subsidence (Tromsø Basin, western Bjørnøya Basin), while other areas show signs of local inversion (i.e., along the Ringvassøya-Loppa Fault Complex). The Middle Jurassic to Lower Cretaceous succession is dominated by dark, commonly organic-rich mudstones, but includes also deltaic and shelf sandstones (Nøttvedt et al. 1993, Dallmann et al. 1999, Smelror et al. 2001). Condensed units of shelf carbonates were developed on local highs during the Valanginian-Barremian (Smelror et al. 1998). In the Aptian-Albian, a thick series of stacked, transgressive shelf sandstones, siltstones and shales accumulated over larger parts of the Barents Shelf.

The opening of the Arctic Basin in Late Cretaceous time resulted in uplift of the northern Barents Sea region. On Svalbard, Upper Cretaceous and lowermost Tertiary strata are missing. On the shelf, reverse faulting and folding occurred in several areas, even though extension may have continued on the regional scale (Gabrielsen et al. 1990).

Norwegian Sea

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 (Figure 1) 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).

North Sea

The North Sea basin (Figure 1) (Evans et al. 2003) probably initiated in the Permian at approximately the same time as the Oslo and Skagerrak Grabens to the southeast and related graben systems to the north (Færseth 1996). Basin subsidence accelerated into the Triassic, and continental, clastic red-beds, up to several kilometres thick, are found in many of the deep North Sea wells. The stratigraphic thickness of Triassic strata is largely controlled by Permian salt structures in the southern North Sea. In the northern North Sea, where Permian salt is thin or absent, the Triassic stratigraphy is controlled by the evolution of half-grabens (Steel and Ryseth 1990, Færseth 1996).

The Øygarden Fault Complex (Figure 1) comprises coast-parallel fault segments with up to 5 km vertical throw, and defines the eastern margin of the Permo-Triassic North Sea rift. As shown by Steel and Ryseth (1990), it includes a wedge-shaped, syntectonic, Lower Triassic succession overlain by Middle Triassic to Middle Jurassic post-rift sediments. The Permo-Triassic rift axis is interpreted to be located beneath the Horda Platform east of the Late Jurassic Viking Graben (Færseth et al. 1996, Odinsen et al. 2000).

The Permo-Triassic rift phase terminated at the end of the Early Triassic, and clastic post-rift deposits then filled into the passively subsiding rift basin until the onset of a new rift phase in the late Middle Jurassic. A general change in post-rift sedimentation, from continental Triassic to deltaic conditions in Early to Middle Jurassic time, occurred. The Jurassic sandstones, notably the Brent Group, form major reservoirs in the North Sea (Husmo et al. 2002).

A framework of faults was established throughout the North Sea during the Permo-Triassic rifting phase (Færseth 1996). Some of these were reactivated during the late Middle Jurassic to latest Jurassic rifting. Large faults defining first-order fault blocks show evidence of kilometre-scale, pre-Jurassic offsets (e.g., Færseth 1996, Gabrielsen et al. 1999, Fossen 2000, Odinsen et al. 2000). The Late Jurassic rift axis, defined by the right-stepping Viking Graben, was located west of the Horda Platform. The Øygarden Fault Complex and many other faults on the Horda Platform thus experienced only modest post-Triassic reactivation.

In the Late Jurassic, the Viking Graben and deep parts of rotated fault blocks developed into deep marine basins in which organic-rich shales of the Viking Group (Draupne Formation) were deposited. These form the main source of hydrocarbons in the North Sea. Jurassic rifting ended for the most part in Mid Volgian time although extension locally continued into the Cretaceous (Færseth et al. 1995, Færseth and Lien 2002).

In the Cretaceous, the North Sea experienced infill of deep basins created during the Late Jurassic rifting climax. Periods of significant tectonic activity occurred, and during Hauterian-Barremian times, local structural highs were uplifted and deeply eroded. The Barremian landscape was largely filled in by the end of the Early Cretaceous, and all structural highs and most of the eastern basin margin were flooded in the Santonian (Bugge et al. 2001). The Cretaceous stratigraphic column is dominated by shales and, in the southern North Sea, chalks formed by accumulation of *coccoliths* from a planktonic calc algae. Sandstones can be linked to periods of tectonic activity and/or change in relative sea level (Bugge et al. 2001).

Mesozoic sediments and structures onshore and in the coastal zone

The paragraphs beneath summarise work on Mesozoic sediments and structures onshore Norway and in the coastal zone. The summary is mainly based on published work, but several new figures are presented.

Northern Norway

Andøya and Andfjorden

Andøya (Figure 1) contains the only succession of Mesozoic sediments in mainland Norway. The field was first detected by T. Dahl in 1867 (Ørvig 1960), and a minor coal bed at the southern margin of the field led explorationists to drill for coal in the last part of the 19th century. During the 1970s, hydrocarbon drilling was undertaken by a local-based company, and detailed sedimentological investigations were carried out by Dalland (1981 and references therein).

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 (Figure 2) (Zwaan et al. 1998). 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 age of the weathering zone is poorly constrained and debated. 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).

The outcrop area on Andøya is located at the western margin of a narrow N–S-trending graben. The graben continues below Andfjorden to the east, where the thickness is 2–3 km, and farther northwards into the deep Harstad Basin (Figure 1). The succession consists of two major upward-fining sequences, one of Bajocian-Bathonian to Volgian age, and the other of Ryazanian/Valanginian to Aptian age (Birkelund et al. 1978, Dalland 1981, Zakharov et al. 1981, Aarhus et al. 1986) (Figure 3).

The lowermost Ramså Formation comprises braided river sands at the base (Hestberget Member), overlain by lake or lagoonal deposits with local coals (Kullgrøfta Member), and fluvial to beach and shallow-marine sands in the upper part (Bonteigen Member) (Figure 3). The overlying Dragneset Formation grades from calcareous sandstone (Breisanden Member) in the lower part to siltstone and shale in the upper part (Taumhølet and Ratjønna members). Remains of Ichtyosaurians and many other fossils have been found in this member (Ørvig 1960 and references therein).

Figure 2. Map showing the locations of Mesozoic successions on Andøya and in Andfjorden, Gavlfjorden, Vesterålsfjorden and Sortlandssundet. The map is partly based on unpublished seismic data supplied by B. Davidsen. Dark green: previously unpublished areas of Mesozoic rocks.

The overlying Nybrua Formation, separated from the Jurassic succession by an unconformity, forms a regionally extensive unit of shallow-marine marl and sandstone in the lower part of the Cretaceous (Leira and Skjærmyrbekken members). Overlying this unit are intermediate- to deep-marine mudstones and shales of the Skarstein Formation (Nordelva and Hellneset members). Parts of the Andøya succession are lithologically similar to time-equivalent sections in East Greenland, the northern North Sea, the Norwegian Sea and the Barents Sea (Dalland 1981, Smelror et al. 2001) (Figure 4).

A period of major uplift and erosion took place during the Late Triassic. Faulting occurred in Middle Jurassic and probably also during Hauterivan/Barremian and Aptian time. The northern boundary fault of the Mesozoic succession is clearly syndepositional in nature. There may also have been tectonic activity in Late Berriasian/Early Valanginian and Turonian times.

Vesterålen

The Sortlandsundet basin (Figures 1 and 2) is a half-graben (5 x 3.5 km) defined by a normal fault in the southeast and unconformable boundaries to the northeast, northwest and southwest (Davidsen et al. 2001a, b). Mesozoic sedimentary strata within the basin are more than 440 m thick and display seismic reflectors dipping a few degrees to the southeast. Glacier-transported erratic blocks, assumed to derive from the Sortlandsundet basin, are found along the shorelines 3–10 km north of the basin. These blocks, which comprise quartz-rich sediments varying in grain size from conglomerates to fine sandstones, contain numerous fossils, e.g., bivalves, belemnites, ammonites and plant remains. Dinoflagellates from the samples show that a majority of the samples are probably of Bathonian-Callovian age, while age determination based on bivalves gives a Portlandian age for some of the samples (Fürsich and Thomsen 2005). The contrasting age determination has not been explained.

Mesozoic strata also occur in Vesterålsfjorden and Gavlfjorden (Figure 2) (Davidsen et al. 2001b). In Gavlfjorden, seismic data indicate fault boundaries along the eastern and western margins of the fjord, while the southern boundary is an unconformity. The Mesozoic succession is here up to 300 m thick.

Vestfjorden

The Vestfjorden Basin (Figure 1) is essentially a Cretaceous half-graben with its main boundary fault to the northwest, along the Lofoten Ridge (Blystad et al. 1995). Important normal faults also occur to the southeast, along the mainland, where Triassic and Jurassic rocks may locally subcrop at the seabed. The basin contains 8–10 km of Cretaceous sediments, interpreted to reflect mainly passive infill of the Jurassic rift topography (e.g., Færseth and Lien 2002). However, the area has not been opened up for oil and gas exploration, and the sedimentary succession

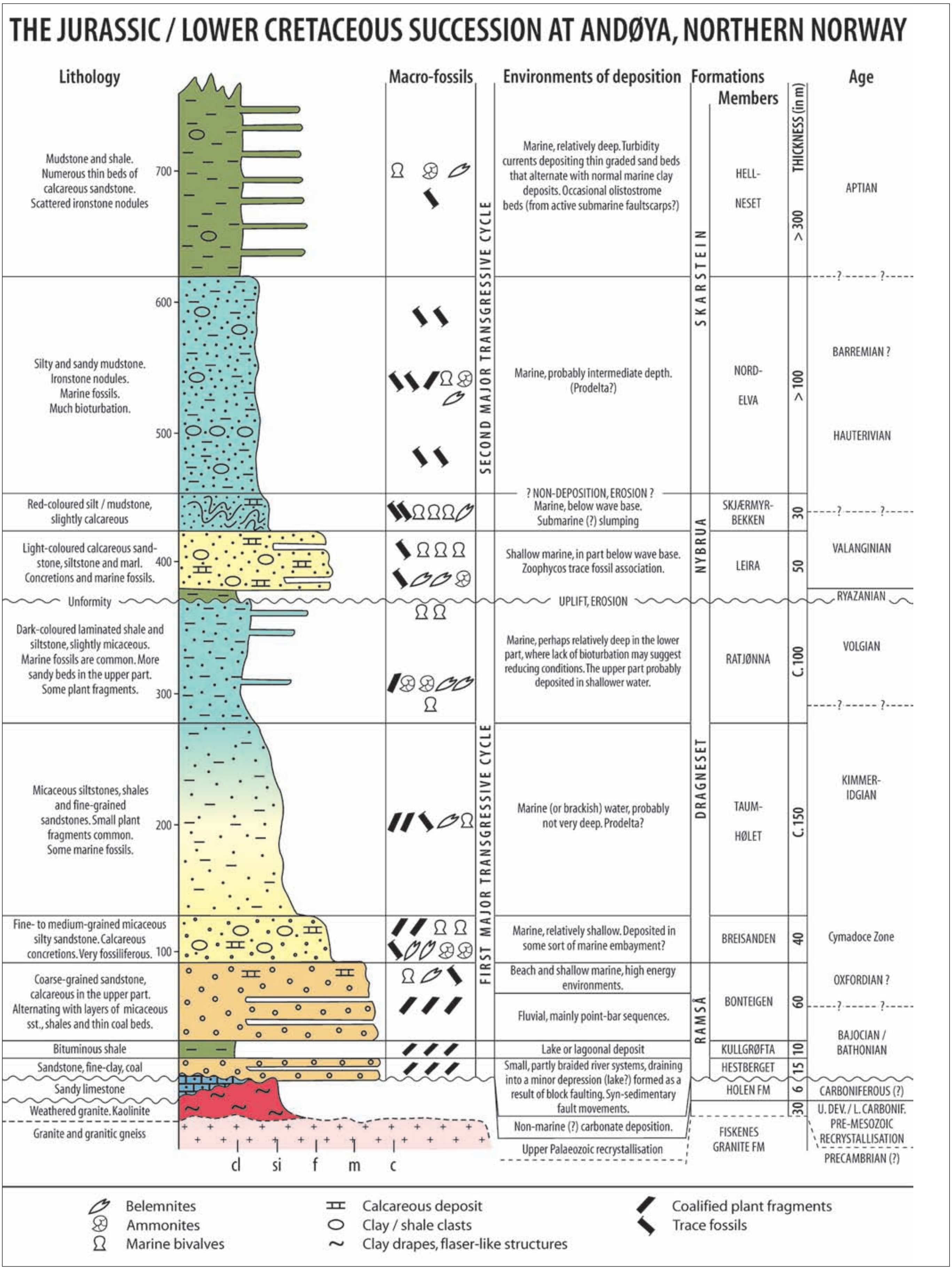

Figure 3. The Mesozoic sedimentary succession on Andøya. Only the lower part of the Lower Cretaceous Hellneset Member is shown. Redrawn from Dalland (1981).

is thus poorly known. It is assumed that there was a connection between the Andfjorden and Vestfjorden basins before the Late Tertiary-Quaternary uplift and erosion.

Stabbfjorden/Lyngværfjorden/Træna

The Stabbfjorden and Lyngværfjorden basins (Figure 1) were discovered during reconnaissance mapping in 1998 (Bøe et al. 2008). The NE–SW-trending Stabbfjorden basin, northwest of Meløya, is 28 km long and 3–10 km wide, with a sedimentary rock succession that is up to 800 m thick. The Lyngværfjorden basin, northeast of Træna, has a length of about 12 km, whereas the width is up to 3 km and the depth possibly more than 350 m. Ice-transported, erratic blocks of sedimentary rocks found on skerries near the two basins comprise conglomerates, sandstones, siltstones and mudstones (Figure 5). Palynomorphs show that they range in age from Barremian to Triassic (Bøe et al. 2008). The majority of the samples are of Middle-Late Jurassic age and reflect shallow marine deposition. The Triassic sediments were possibly deposited in a continental environment. The lithofacies reflect the well-known tectonic phases

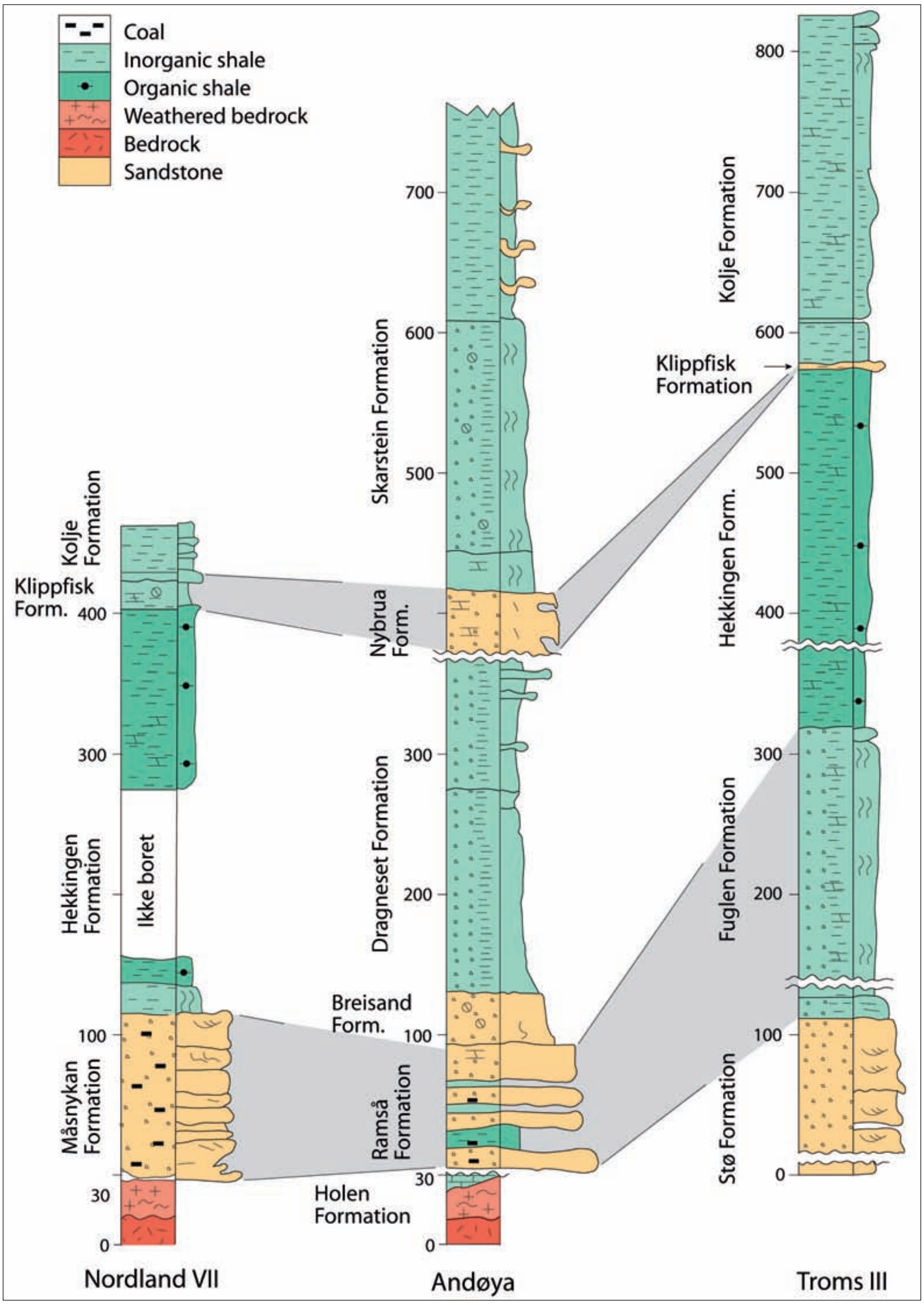

Figure 4. Lithostratigraphic and sequence stratigraphic correlation between cored successions at Andøya, Troms III and Nordland IV. Modified from Smelror et al. (2001) and Henningsen (2006).

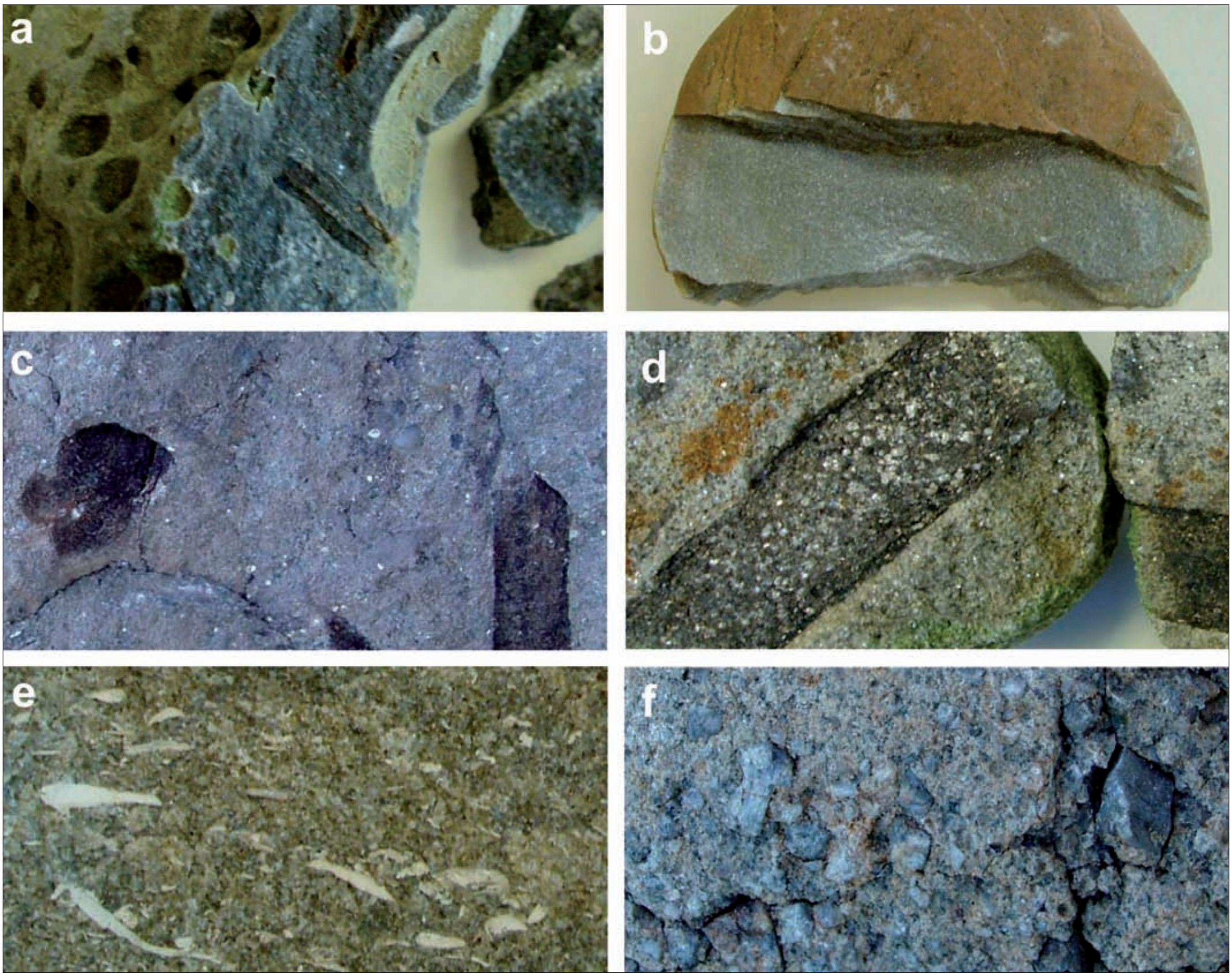

Figure 5. Photographs of erratic blocks from the Stabbfjorden basin. (a) Middle-Upper Jurassic sandstone with shells and coal fragments, (b) Middle-Upper Jurassic siltstone with shells, (c) Upper Jurassic sandstone with shells and coal fragments, (d) Middle-Upper Jurassic sandstone with shells and coal fragments, (e) Middle-Upper Jurassic bioclastic sandstone, (f) Lower Cretaceous conglomerate. The pictures are approximately 4 x 8 cm. Modified from Bøe et al. (2008).

and sea-level changes that have been reported for the Middle Jurassic-Early Cretaceous in this area. A succession of assumed Triassic age also occurs in Trænfjorden, southeast of Træna (Bøe et al. 2008). This can probably be correlated with an Upper Permian-Lower Triassic, fully marine succession of sandstones, coarse-grained turbidites, shales and reworked sabkha sediments cored 12 km southwest of the Træna islands (Bugge et al. 2002).

Mid Norway

The development of Mesozoic basins along the coast of Mid Norway is closely related to activity on the long-lived Møre-Trøndelag Fault Complex (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, 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 down-faulted and deformed the sequences, especially in the Beitstadfjorden Basin (Bøe and Bjerkli 1989).

Beitstadfjorden Basin

The Beitstadfjorden Basin (14 km long and 6 km wide) (Figures 6 and 7) 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

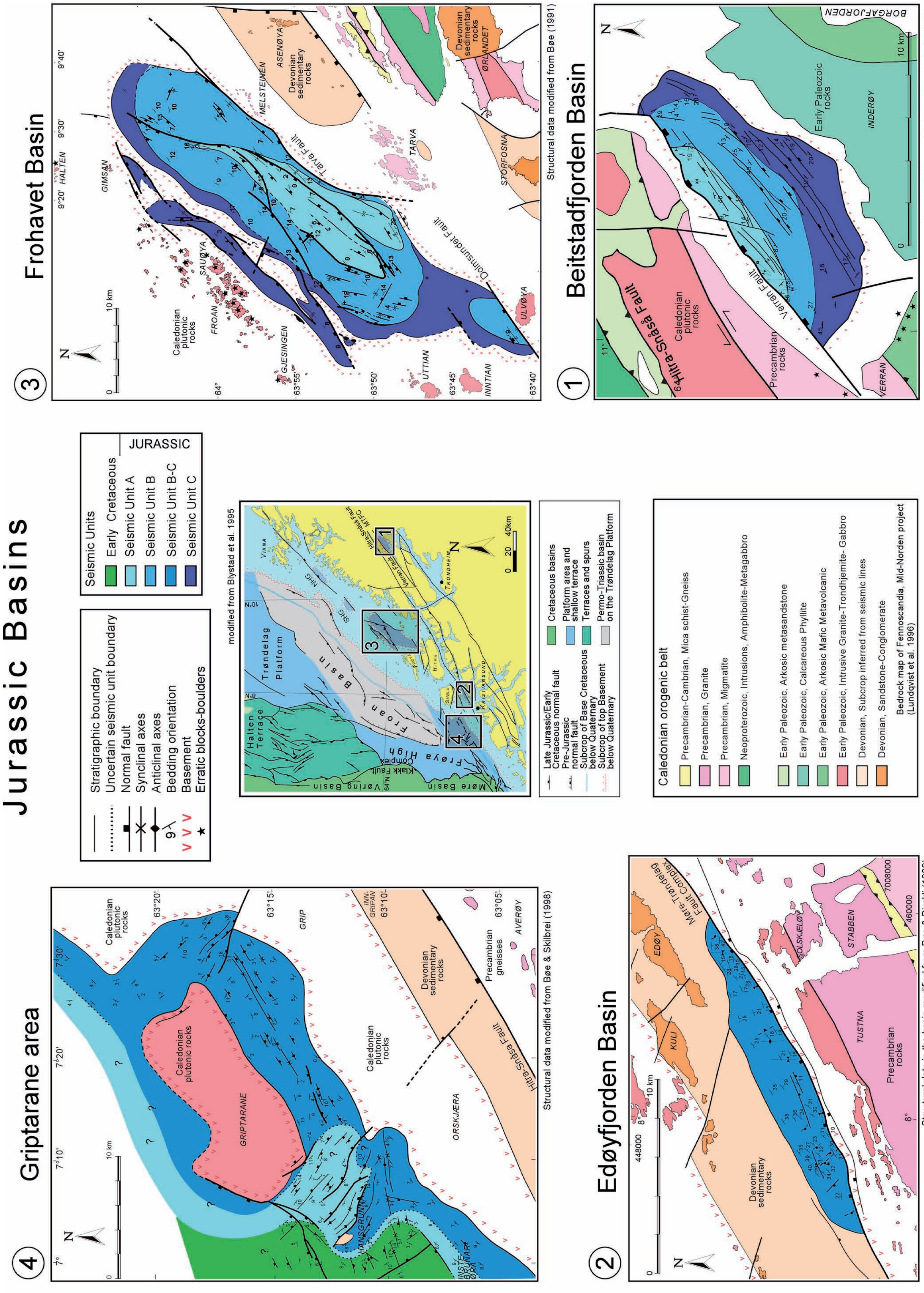

Figure 6. Subcrop maps of Jurassic basins, Mid Norway. Modified from Sommaruga and Bøe (2002).

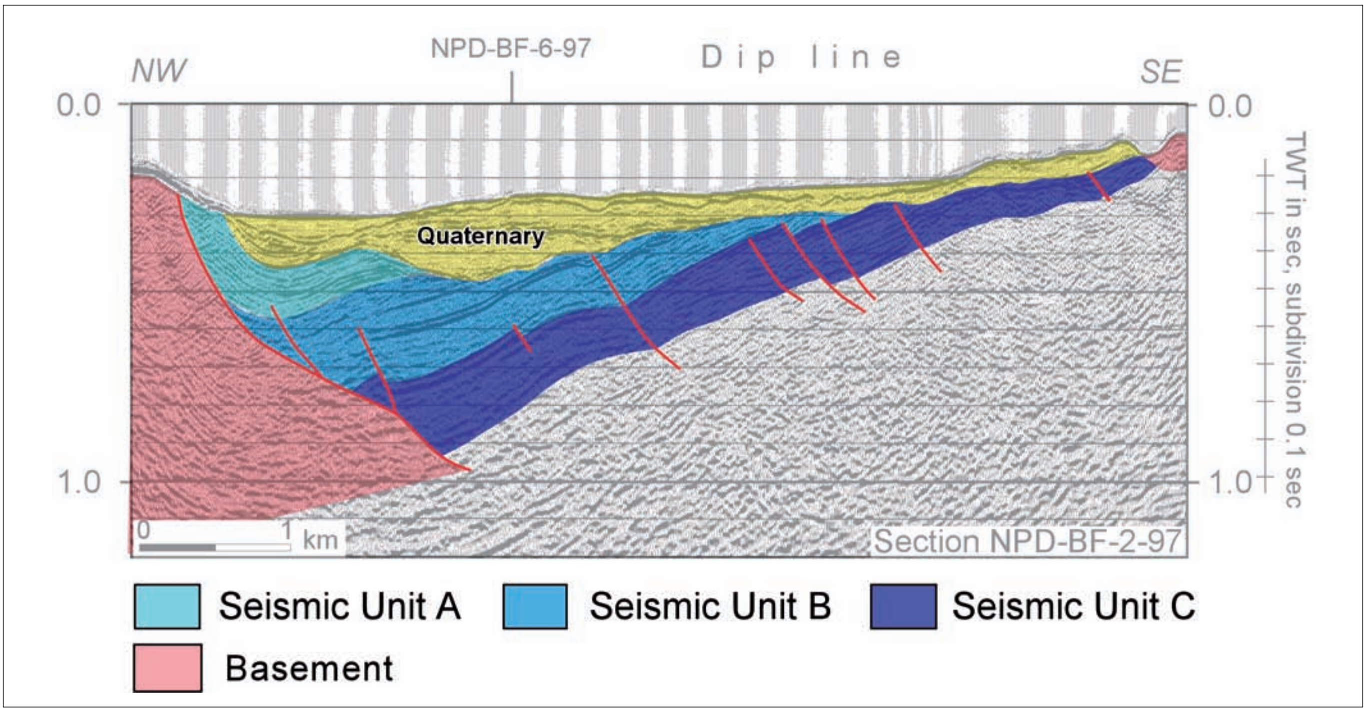

Figure 7. Seismic line, Beitstadfjord Basin. Modified from Sommaruga and Bøe (2002).

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 15º 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 (see discussion on age below) is around 1000 m.

Edøyfjorden Basin

The Edøyfjorden Basin (Figure 6) 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 15–25º 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 ca. 1000 m.

Frohavet Basin and Frøyfjorden

The Frohavet Basin (almost 60 km long and up to 20 km wide) (Figure 6) 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 (oriented NE–SW and turning to a NNE–SSW-trend in the southwest) and the Dolmsundet Fault (oriented NE–SW) occur along the southeastern margin of the basin. 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 ca. 1200 m.

The 5.3 km-long Frøya Tunnel beneath Frøyfjorden 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 (Figure 8). 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), from aeromagnetic data, has suggested the presence of Mesozoic deep-weathered fracture zones in south Norway.

Griptarane area

Griptarane (Figure 6) is a basement topographic high located northwest of Kristiansund, between the Frøya High and the is-

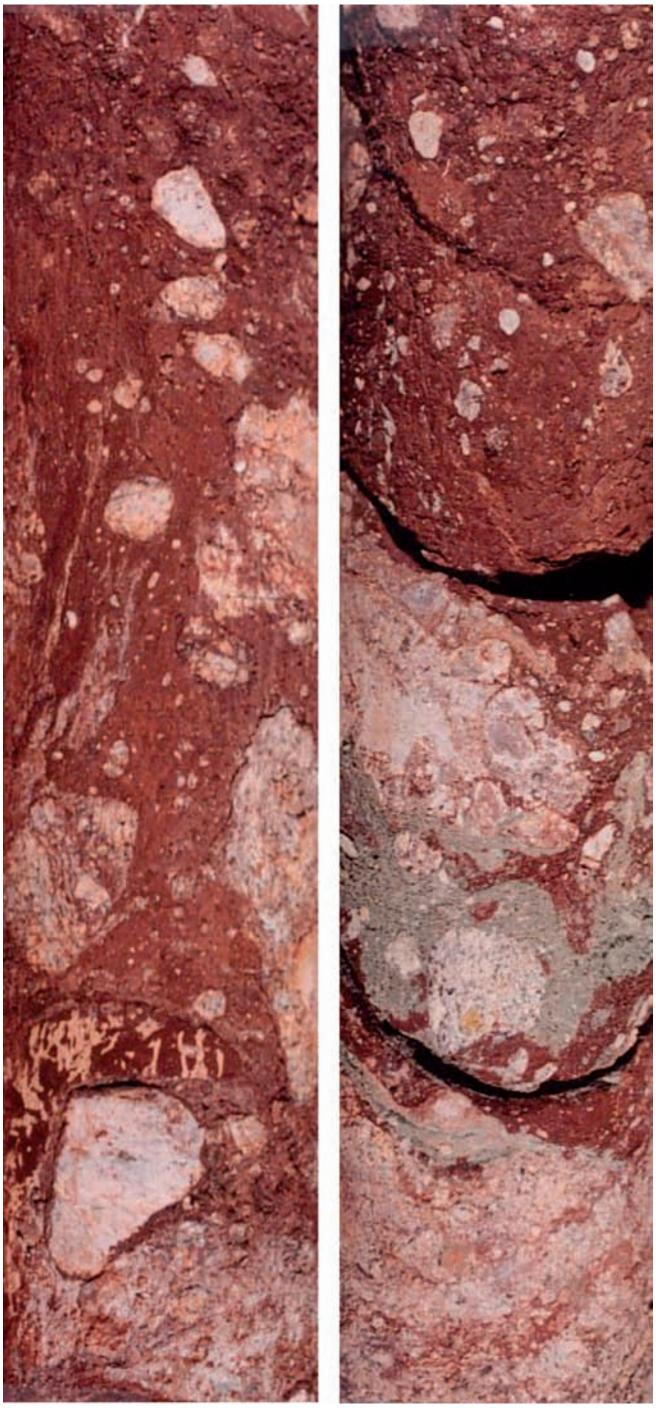

Figure 8. Matrix-rich, sediment- and gneiss-bearing fault breccias in cores from the Frøyfjorden fault zone. Core width is 7 cm. From Bøe et al. (2005).

land 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 rather shallow, 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 ca. 600 m south of Griptarane.

Seismic units, depositional environment and stratigraphic correlation

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 7). 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. 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 northeast of the Frohavet Basin (Thorsnes 1995).

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. 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. Further 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.

Western and Southern Norway

Permo-Triassic and Mid-Late Jurassic faulting in the North Sea occurred along approximately N–S-trending and at a later stage along NE–SW-trending faults (Færseth et al. 1997). Many onshore lineaments in West Norway have similar, coast-parallel trends. Some of these are fracture zones, while others have developed into faults with significant offsets.

The N–S to NNW–SSE-trending faults and fracture zones transect NE–SW-trending extensional faults that are related to Devonian extension of the thickened Caledonian crust (Fossen 2000). However, some of the NE–SW-trending faults also appear to have been reactivated in the Mesozoic, for instance the Lærdal-Gjende Fault (Andersen et al. 1999) and faults in the Sunnfjord region (Eide et al. 1997). In the coastal area, some of the fractures have been intruded by basaltic magma. Dykes (Figure 9) are up to two metres thick (Færseth et al. 1976) and gently altered by hydrothermal activity. K–Ar dating of some of the dykes gives two groups of ages; Permian and Triassic, in addition to a single Jurassic age (Færseth et al. 1976). More precise Ar–Ar dating of amphiboles in some of the dykes has given consistent Triassic ages of around 220 Ma, also for the dyke yielding a Jurassic K–Ar age (Fossen and Dunlap 1999). These ages agree with the general assumption that the first rifting phase in the adjacent North Sea basin initiated in the Permian and lasted into the Triassic. Furthermore, kinematic analysis indicates E–W to ENE–WSW extension during dyke intrusion (Fossen 1998, Valle et al. 2002), which is consistent with the North Sea Permo-Triassic rifting. The coast-parallel dykes transect older, mostly NE–SW-trending faults. The latter are typically affected by epidote mineralisation and conform to NW–SE Devonian extension in West Norway.

Figure 9. Triassic dyke crosscutting gneiss. Tofterøy, West Norway.

Along the coast, west-dipping Jurassic and Cretaceous strata overlay a peneplaned basement surface. These sediments extended eastward onto the Norwegian mainland, but were eroded during the Tertiary and Quaternary.

Bjorøy tunnel

In 1994, Jurassic sediments were encountered in a fault zone during construction of the subsea Bjorøy tunnel between Bjorøy (Figure 1) and the mainland southwest of Bergen (Fossen et al. 1997). The sediments, named the Bjorøy Formation, are strongly affected by fault movements, as seen by the broken and dismembered occurrence of the layers and their steep dips. Although the primary stratigraphic relations have been obscured by the fault movements, cores cut during the tunnelling operations show a gradual transition from granitic basement gneiss to feldspathic and polymict conglomerate, grit and sandstone. The mostly angular clasts in these sediments stem from the basement gneisses, and the sedimentary facies is thought to represent gravel and sand deposited on weathered basement rocks. Furthermore, quartz-rich sandstone (Figure 10) and sand with small fragments of coal and occasional gneiss pebbles occur in depositional contact with conglomerate. Remnants of one or more coal layers, around 10 cm thick, are also found.

The age of the sedimentary rocks has been constrained by analyses of pollen and spores from coal fragments in both the sandstone and the unconsolidated sand, and the results consistently indicate an early to middle Oxfordian age. This makes the sediments time equivalent to the North Sea Fensfjord and Sognefjord Formations, which form reservoir sandstones in the Troll field some 80 km NW of the Bjorøy locality. Thus, the sediments were deposited during the Late Jurassic-Cretaceous

Figure 10. Three core samples of the Mesozoic Bjorøy Formation. Left: Breccia, interpreted as sedimentary, with sand vein (top). Middle: transition from grit to quartz-rich sandstone with a few small coal fragments. Right: sandstone with gneiss fragments. These and other samples from the Bjorøy tunnel in West Norway are part of the Natural History Collections at Bergen Museum, University of Bergen.

transgression, which culminated with the Cretaceous flooding of much of the Norwegian mainland (Riis 1996). Today, the sedimentary rocks of the Bjorøy Formation occur in a ~10 m thick zone within the Proterozoic basement, some 70 m below sea level in an area without any trace of post-Palaeozoic sedimentary rocks. It is a challenge to understand the exact mechanisms that brought these sediments to their present position, but the fault zone they occur in must have opened and trapped the lower part of the Mesozoic deposits that were deposited on the Proterozoic basement. As the fault moved, probably at the end of the Late Jurassic rifting phase but possibly also later, the sediments were deformed and dismembered. Selective cementation of the sandstone by means of quartz dissolution, a feature generally restricted to the deeper (>3 km) North Sea reservoirs, may be related to local hydrothermal heating along the Bjorøy fault zone.

Karmsundet basin

The Karmsundet basin (Figure1) has an areal extent of ca. 28 x 5 km, and contains a sedimentary succession with a thickness of up to 600 m (Bøe et al. 1992). The rocks are preserved in a half-graben with reflectors dipping 5–25° ESE (Figure 11). The Kvitsøy fault separates the sedimentary rocks of the half-graben from Precambrian and Cambro-Silurian metamorphic rocks to the east. The western boundary of the basin is an unconformity. The age of the rocks in the Karmsundet basin has not been determined, but a Jurassic age is probable as Jurassic rocks subcrop close to the coast west of Karmøy (Rokoengen and Sørensen 1990). In the southernmost part of the Karmsundet basin, a possible unconformity separates rocks of probable Jurassic age from rocks of assumed Late Palaeozoic age (Bøe et al. 1992).

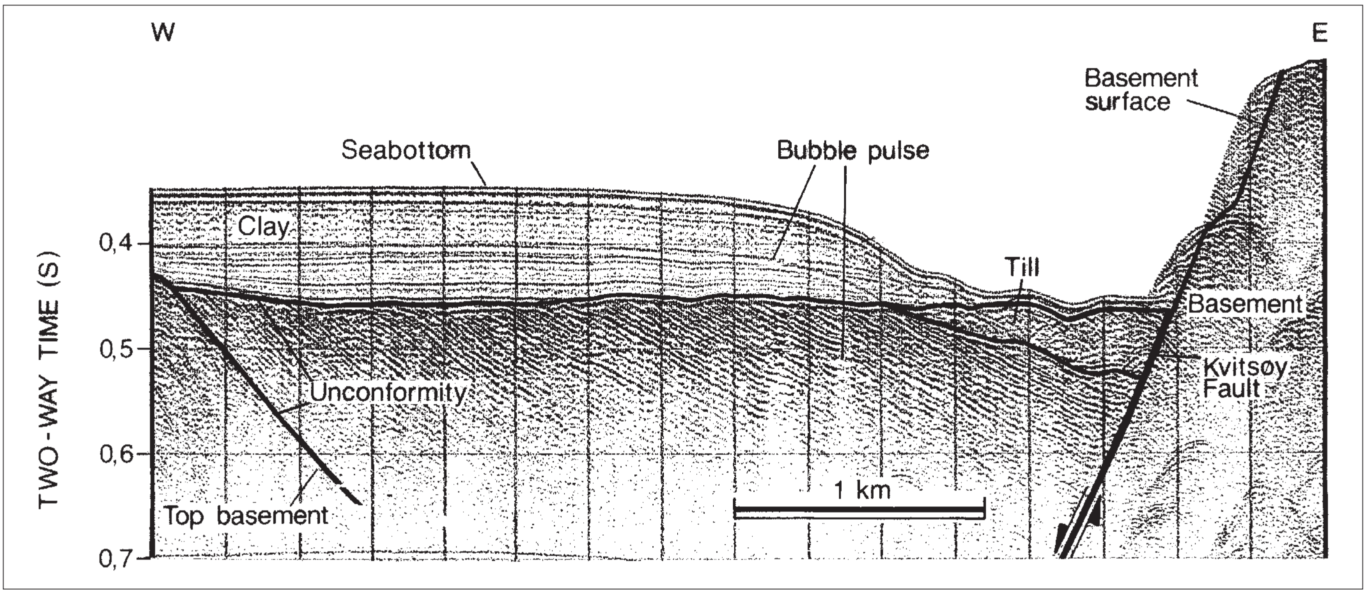

Figure 11. Seismic profile across the Karmsundet Basin. From Bøe et al. (1992).

Utsira

Upper Jurassic sedimentary rocks have been drilled north of Utsira (Figure 1) (Rokoengen et al. 1989, Rokoengen and Sørensen 1990). The succession is in lateral continuity with similar deposits on the shelf farther west. It is not preserved due to downfaulting, but rather on account of its position north of Utsira island that protected it from glacial erosion by the northward-moving Norwegian Channel Ice Stream in the Quaternary Period.

Lista basin

Sedimentary rocks of assumed Mesozoic age occur in the Lista basin (Holtedahl 1988) (Figure 1). The boundary between layered strata and older rocks, to the northeast, is marked by a major, NW–SE-trending normal fault outside the island of Hidra. Dredge samples and cores of Quaternary sediments contain flint, chalk, coal, sandstone, siltstone and limestone fragments with pollen and spores of Early Jurassic age. A Late Triassic-Early Jurassic age for the succession was suggested by Holtedahl (1988). He proposed that the sediments originally covered the Precambrian areas to the north of the Lista basin, and that the present surface is the result of exhumation of a sub-Triassic/Jurassic weathered surface. It has later been proposed that Mesozoic sediments occur beneath Quaternary sediments in the lowland areas of Lista (e.g., Bøe et al. 2000), but this has so far not been confirmed.

Summary

Smelror et al. (2001) published a detailed lithostratigraphic and sequence stratigraphic correlation of the Mesozoic succession on Andøya with age equivalent successions off Nordland and Troms (Figure 4). Such detailed correlations remain to be published for other nearshore/inshore Mesozoic basins. Although most of the coastal area has now been investigated in search for Mesozoic basins, at least at a reconnaissance scale, none of the basins, except for the one at Andøya, have been drilled and properly documented. This is a future major task that would lead to a much more thorough understanding of the Mesozoic and Cenozoic geological development of the Norwegian coastal zone.

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