The Bjorøy Formation: a newly discovered occurrence of Jurassic sediments in the Bergen Arc System

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During the construction of a subsea road tunnel across Vatlestraumen near Bergen, a ca. 10-m-wide subvertical zone of Jurassic sediments (here named the Bjorøy Formation) was encountered. The Bjorøy Formation constitutes a basal gneiss breccia, conglomerate, sandstone, coal, and unconsolidated sand. Palynological analyses suggest an early to middle Oxfordian (early Late Jurassic) age for the sandstone, and a similar age is indicated for coal fragments in the unconsolidated sand. This makes the Bjorøy Formation time equivalent to the offshore Sognefjord Formation farther west on the Horda Platform. The Bjorøy Formation is preserved in a pre-Jurassic fault zone. Reflection seismic data indicate that Jurassic sediments also may occur in thicknesses of up to 50–60 m above the tunnel as S(SW)-dipping strata. Evidence of marine influence on rocks of the Bjorøy Formation is consistent with an Oxfordian marine transgression of the eastern margin of the (northern) North Sea, and indicates that at least parts of southwestern Norway were covered by the sea in the latest Jurassic. The deposition of Late Jurassic sediments on crystalline basement in the Bergen area indicates that little erosion of the basement has taken place since late Jurassic times, and that the so-called 'paleic surface' (pre-Neogene peneplain) and parts of the Norwegian strandflat may be an old (mostly Jurassic) exposition. The fault rocks in the Vatlestraumen fault zone show evidence of repeated fault activity during decreasing P-T conditions. At least two pre-depositional (pre-Oxfordian) episodes of faulting are recorded, of which the first shows evidence of crystallo-plastic deformation of quartz. Most fault rocks were formed prior to deposition of the Bjorøy Formation, but post-depositional (late or post-Jurassic) fault rocks are recognized as unconsolidated gouge zones. Late or post-Jurassic vertical movements may have been up to several hundreds of meters across the Hjeltefjord fault zone west of Bjorøy, where it also offsets the paleic surface.

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The bedrock geology of Norway is dominated by Precambrian and lower Paleozoic metamorphic and crystalline rocks. Devonian conglomerates and sandstones are the youngest sedimentary rocks previously described in southern and central mainland Norway, with the exception of the Permian clastics in the Oslo Rift and Jurassic sediments beneath the Beitstadfjord, Trøndelag. In northern Norway, onshore post-Silurian sediments are known only from Andøya where Jurassic–Lower Cretaceous sediments occupy an 8-km^2 large area (Dalland 1975). In general, a profound hiatus therefore exists between Precambrian or lower Paleozoic rocks and Quaternary deposits.

The situation is quite different for the areas offshore Norway. Exploration for hydrocarbons in the North Sea has provided valuable information about the post-Caledonian development in the North Sea rift system, and the available geologic database from the North Sea is significant. The geologic data acquired offshore also contain information regarding the post-Caledonian history of the mainland, and attempts to combine offshore and onshore geology are now becoming more common (Doré 1992; Riis & Fjeldskaar 1992; Stuevold et al. 1992; van der Beek 1995). In addition, erosional remnants of (possibly) Mesozoic sediments are known from the Beitstadfjord, Edøyfjord, Karmsund, Lista Basin, and Frohavet areas (Kjerulf 1870; Nordhagen, 1921; Horn 1931; Oftedahl 1975; Bøe & Bjerkli 1989; Bøe 1991, Bøe et al. 1992). Such findings are of great value and help to increase our fragmentary sedimentological, geomorphological and structural understanding of the post-Caledonian development of the Norwegian mainland.

A zone of Jurassic sediments was encountered in a technically problematic tunnel project between the Alvøen area and the island of Bjorøy near Bergen during the fall of 1994. This new discovery of Mesozoic sediments on the West Norway mainland area provides exclusive information about the post-Caledonian development of this part of the country. In this article we present and discuss the data extracted from the Bjorøy area.

Regional setting

The Bjorøy tunnel is located in the Hjeltefjord fault zone between Sotra and Bergen (Figs. 1, 2). Geologically, the area is part of the Bergen Arc System, as defined by Kolderup & Kolderup (1940). It is generally assumed that the Øygarden Complex forms the parautochthonous

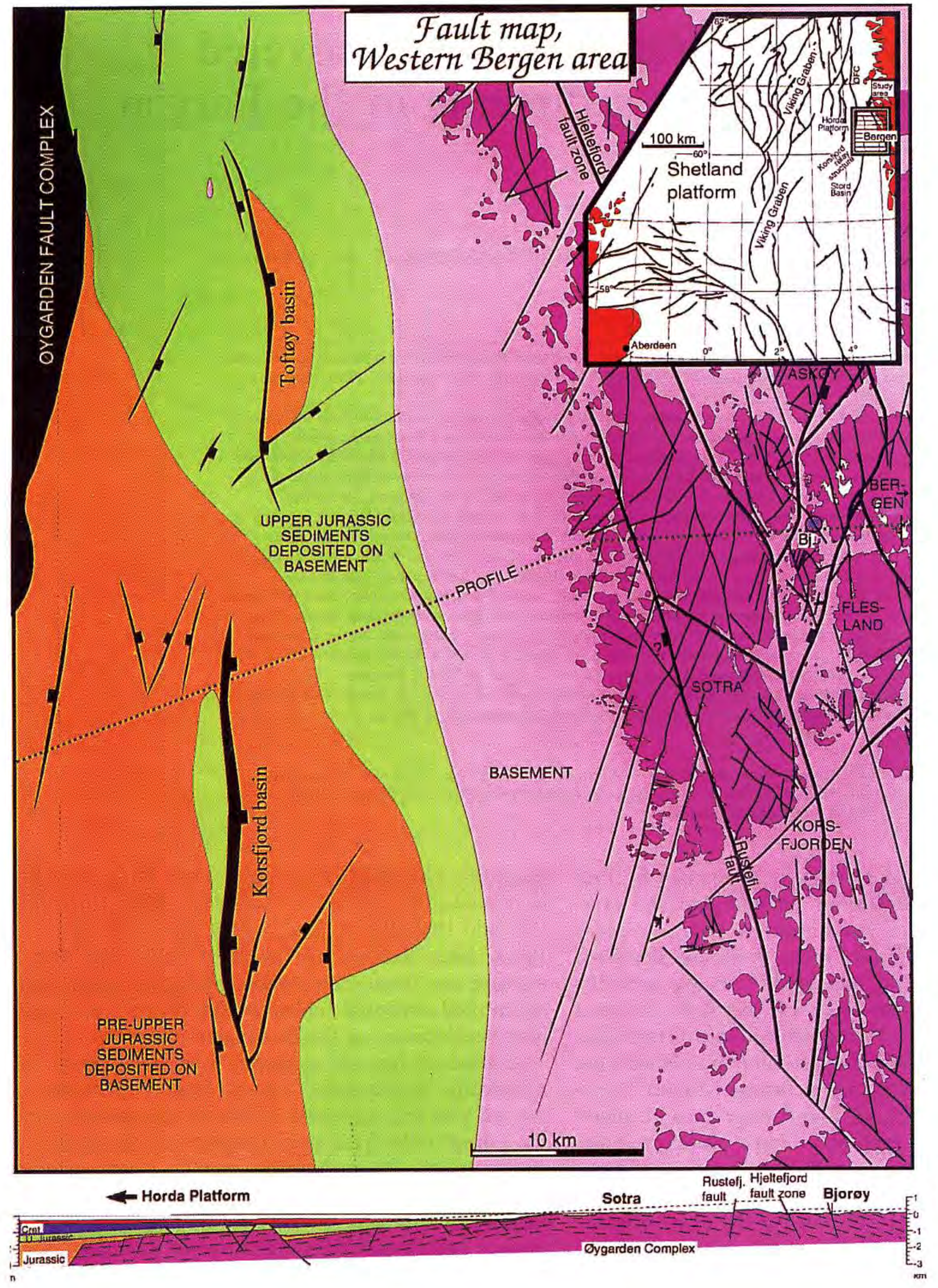

Fig. 1. Geologic map of the Bergen area, including offshore geology east of the Øygarden Fault Complex Profile line is indicated.

basement to the adjacent Caledonian nappes of the Minor Bergen Arc, Ulriken Gneiss Complex and the Lindås Nappe (Anorthosite Complex) (Sturt & Thon 1978). The Minor and Major Bergen Arcs consist of sheared Ordovician (ophiolite-related) and Proterozoic (continental-type) rocks (Dunning & Pedersen 1988; Fossen 1989; Fossen & Austrheim 1988), whereas the other units in the Bergen Arc System have mainly yielded Proterozoic radiometric ages (Sturt et al. 1975; Burton et al. 1995). All these rocks are influenced by Caledonian deformation, and pre-Caledonian structures are preserved in lenses and mega-lenses enveloped by the composite Caledonian fabric.

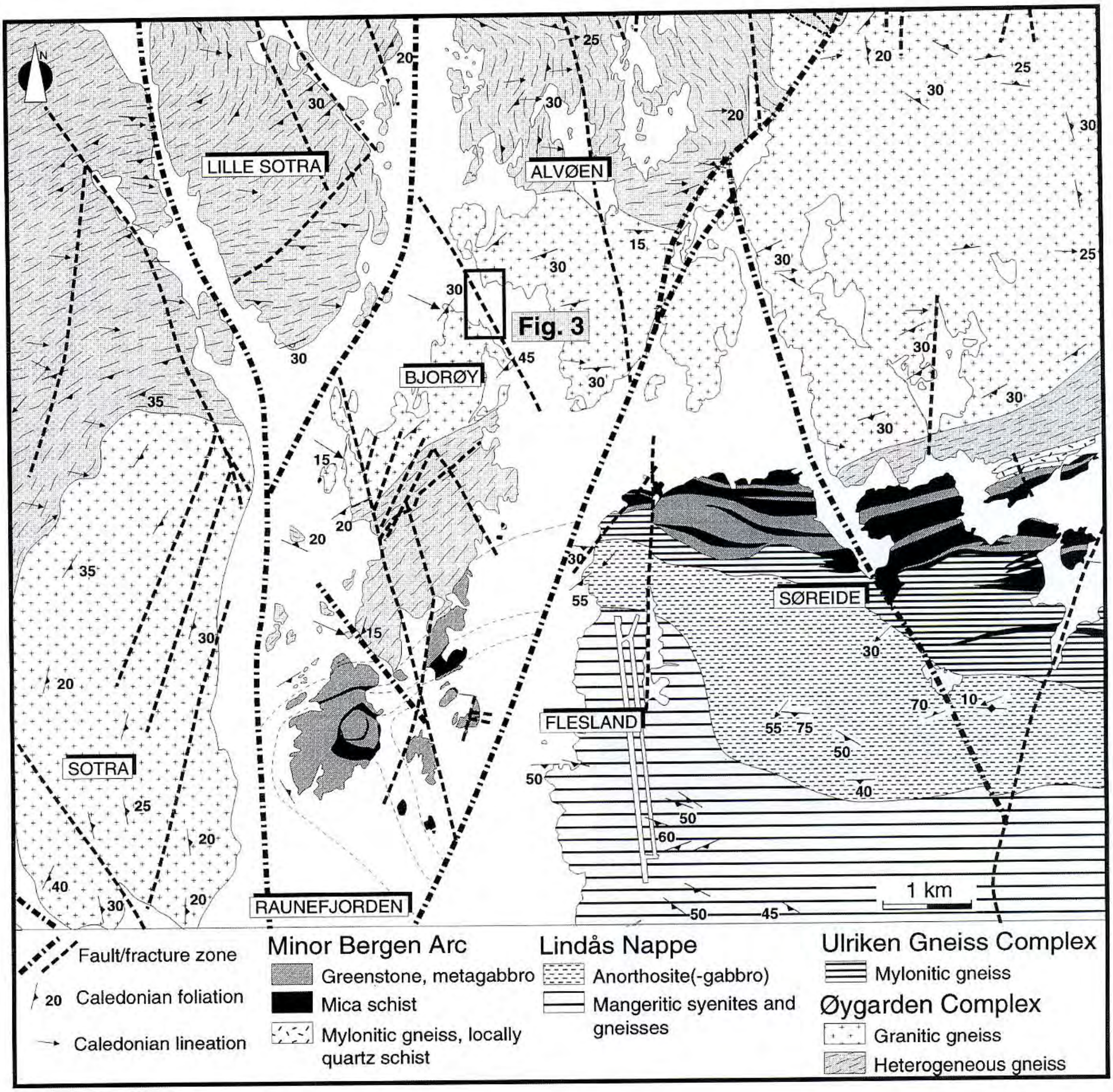

Fig. 2. Bedrock map of the Bjorøy area. Mainly after Fossen & Thon (1988).

The Caledonian fabric and structures were formed during the top-to-the-E thrusting prior to and during the continent–continent collision between Laurentia and Baltica. Regional-scale reworking of the Caledonian fabric by top-to-the-W translation of the allochthonous units occurred in Devonian time (Fossen 1992), and strong top-to-the-W fabrics are found in the western part of the Øygarden Complex (Fossen & Rykkelid 1990; Rykkelid & Fossen 1992), as well as in the eastern part of the Major Bergen Arc (Fossen 1993).

The island of Bjorøy is located in the Øygarden Complex close to the Minor Bergen Arc and the Lindås Nappe (Fig. 2). This part of the Øygarden Complex is dominated by (proto)mylonitic gneisses with top-to-the-E shear indicators, as are the rocks of the Minor Bergen Arc south and east of Bjorøy (Fossen 1993).

The Bjorøy tunnel

Construction of the Bjorøy tunnel near Bergen was settled in May 1993, and operations started in November the same year after collection of a small amount of seismic refraction data. The tunnel was planned to cross under the sea in a N–S direction at a maximum depth of 80 m below sea level (Fig. 3). Even in the early stages of the tunnel work, it became obvious that the gneiss was strongly fractured, and water leakage into the tunnel became severe as the tunnel reached below sea level. Even though extensive concrete injections were carried out, 3 m^3 of loose sand flowed out from a 12-m-long hole made during the cement injection work (on 21 September 1994). In addition, large fragments of coal (up to 10 cm) were brought out from the hole, together with considerable amounts of saline water (200 l/min). As a consequence, further tunnel work was postponed, and extensive core drilling was carried out to map the geology in front of the tunnel. During the same period, additional seismic refraction data were acquired to map low velocity zones along the tunnel route.

Careful injection of rapidly hardening micro-cement and low-viscosity acrylics made it possible to force the zone of sediments and coal. The sediment zone was penetrated during the spring of 1995, and the entire tunneling work was completed in August 1995.

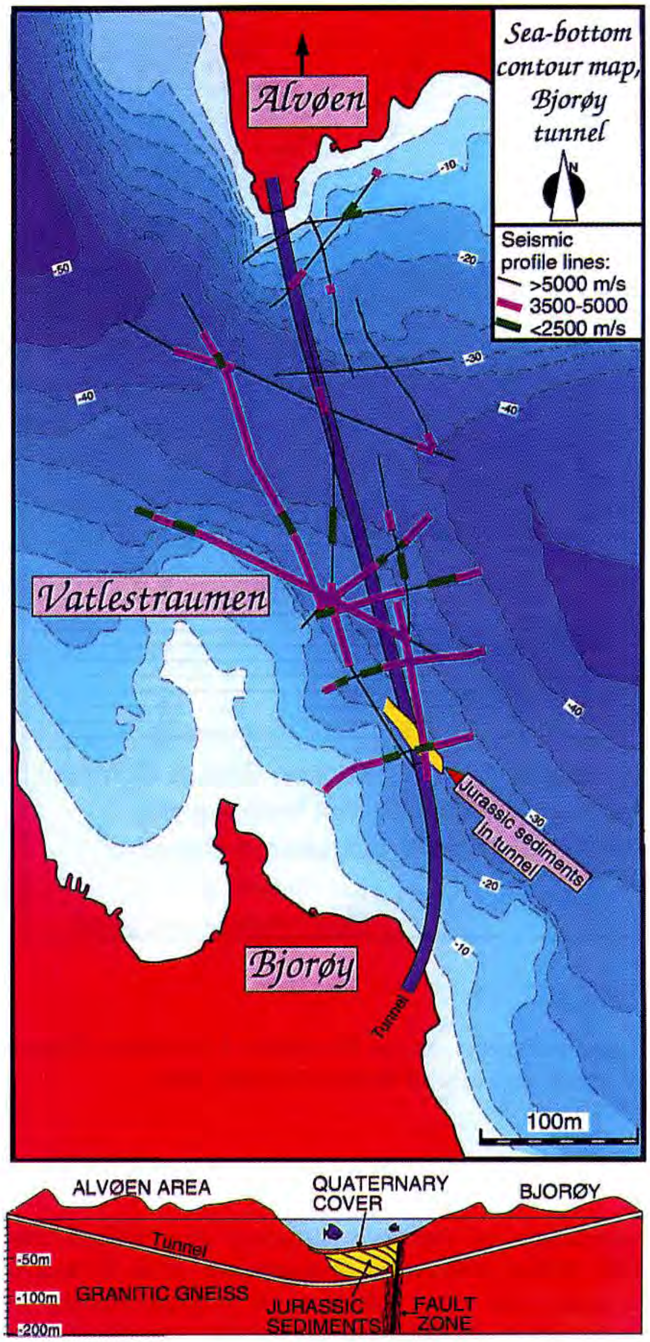

Fig. 3. The subsea part of the Bjorøy tunnel with depth curves of sea bottom in meters. The tunnel is located in the saddle point between Bjorøy and the mainland. The maximum depth of the tunnel is 80 m below sea level. Locations of refraction seismic lines and velocity intervals are indicated, as well as the location of Jurassic sediments in the tunnel.

The Bjorøy Formation and adjacent rocks

Approximately 160 m of cores from the zone of sedimentary rocks and adjacent basement rocks were studied in detail and form the main basis for the description of the Bjorøy Formation. Additional observations were made in the tunnel before the walls were plastered with concrete (usually within 2 h after each blasting operation). Five main types of rocks are distinguished (Figs. 4 and 5); gneiss, tectonic gneiss breccia, and conglomerate, well-consolidated sandstone, and unconsolidated or very poorly consolidated sand. The gneiss is part of the Øygarden Complex (Fossen & Thon 1988), whereas the sediments form a distinct and previously unknown formation in the area. We propose the name *Bjorøy Formation* for these sediments.

Gneiss

The gneiss in the tunnel area is typical for this part of the Øygarden Complex. It is a heterogeneous gneiss unit of predominantly granitic to granodioritic composition that generally exhibits a proto-mylinitic fabric. Bands of dioritic and amphibolitic character occur, as do biotite-rich gneiss layers. The gneiss has been described in more detail by Weiss (1977).

Tectonic gneiss breccia

A gradual transition is seen from weakly fractured gneiss through strongly fractured gneiss to a tectonic gneiss breccia. The gneiss breccia consists of angular fragments up to some tens of centimeters long in a light-green network or matrix (Fig. 6b). The green color is mainly caused by epidote-group minerals – a characteristic feature of many fault zones in the Bergen area.

Sedimentary breccia and conglomerate

The sedimentary breccia and conglomerate are cohesive rocks which consist of millimeter to centimeter-scale gneiss fragments that may vary in shape from angular to rounded. Angular fragments dominate, and it is not always easy to make a distinction between tectonic and sedimentary breccia. One mesoscopic criterion that has

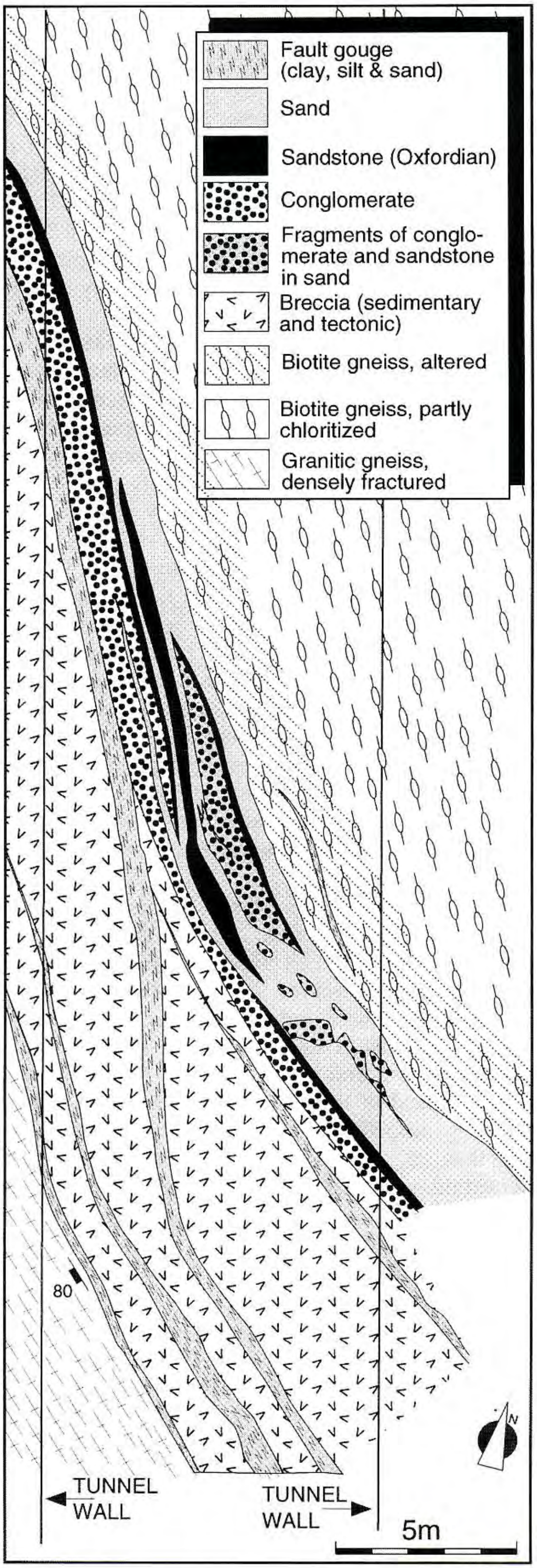

Fig. 4. Geologic map of the Bjorøy Formation, based on core data and observations in the tunnel. Modified from Fossen et al. (1995).

been found useful is the slightly darker green color of the matrix in the sedimentary breccia and conglomerate, possibly atttributable to weathering of the green minerals eroded from the fault rocks in the adjacent gneiss. Another criterion is open fractures in the tectonic breccia that never occur in the sedimentary breccia or in the other sediments of the Bjorøy Formation.

The gneiss fragments in the sedimentary breccia and conglomerate are of the same types as the surrounding gneiss. In addition, occasional rounded quartz fragments and clasts of micaceous ultramylonite similar to those of the Minor Bergen Arc have been observed. There is a rapid, but gradual transition from sedimentary breccia through grain-supported conglomerate and matrix-supported conglomerate to sandstone with scattered gneiss pebbles (Fig. 6c–e).

Sandstone and sand

Well-consolidated fine to medium-grained *sandstone* occurs in the cores as a dark-grey, cohesive rock. Sandstone adjacent to the conglomerate contains occasional fragments of the green, matrix-supported conglomerate described above. Softe ('ductile') deformation of conglomerate fragments in the sandstone suggests that the conglomerate was unconsolidated or only weakly consolidated at the time when the sandstone was deposited. Many quartz grain contacts in the sandstone show evidence of pressure-solution (Fig. 6d–e), and a thin layer of quartz cement is locally precipitated along grain boundaries. The quartz cement is not easily detected optically, but cathodoluminescence analyses indicate up to 5% quartz cement in most of the sandstone, and locally more (O. Walderhaug, pers. comm. 1996).

The sandstone has retained a porosity (blue color in Figs. 6d and 7b) that varies from almost none to 15% across short (cm-scale) distances. Alternating light and dark-grey laminae of different composition are seen in hand specimens, and are clearly disturbed by fault movements (Fig. 8a). The light grey sandstone (upper part of Fig. 7b) is well sorted, and consists typically of ca. 90% quartz, 8% feldspar (mainly K-spar and myrmekites typical of the adjacent granitic gneisses) and minor amounts of mica, opaques and coal fragments.

The dark-grey sandstone (lower part of Fig. 7b) is less well sorted, and contains ca. 20% matrix that fills the volume between the quartz and feldspar grains almost completely. Pressure solution or quartz cementation is not commonly seen in this part of the sandstone, possibly because the higher matrix content reduces grain-contact stresses. Overgrowth of K-spar on feldspar grains is typical for both types of sandstone (Fig. 9).

Samples of what looked like millimetre long coal fragments in the sandstone turned out to be aggregates of very fine, powdery organic debris known as 'smur' in coal mining terminology. Plentiful small fragments of vitrinite and inertinite also appear in the interstitial clay in the sandstone, which also contains abundant pyrite. The vitrinite looks bright with no indication of post-depositional oxidation. Larger fragments appear to be of reworked coal, containing more than one maceral. These phytoclasts were most probably derived from reworked peat deposits.

The *unconsolidated sand* intervals consist of very quartz-rich (>90%) sand with *coal fragments* (Fig. 7a) in addition to small amounts of biotite and opaques. The stratification in the sand is disturbed by faulting and folding. An acrylic-cemented sand specimen examined under the microscope was found to be petrographically similar to the sandstone, but with little evidence of K-spar overgrowths. No evidence of pressure-solution or cementation was found along the grain contacts. Parts of the sand are rich in coal, whereas other parts contain little or no coal fragments (Fig. 7a). The coal fragments are up to 4 cm long in the cores, and include parts of branches of trees with annual rings still preserved. Larger coal fragments (up to 25 × 20 × 10 cm) were discovered in the tunnel section during the main tunneling operations (Fig. 8b).

The studied coal fragments from the unconsolidated sand included coal and carbargillite. Using ultraviolet light, the coal samples were found to consist of traces of algae, low content of cuticle, spores and resin. The carbargillite consisted of traces of algae, rich in content of spores and low content of cuticle. The samples looked fresh with no sign of oxidation.

Spatial distribution of the Bjorøy Formation

The zone of sediments is only up to 7 m thick in the tunnel (Fig. 4), and occurs in a narrow, subvertical fracture zone in the gneiss (Fig. 5). The bedding in the tunnel was generally found to be subvertical, and the scattered occurrence of blocks of sandstone, coal and conglomerate together with unconsolidated, layered sand exhibits a melange-like appearance. These relationships are obviously caused by fault movements after deposition of all the sediments, as supported by the presence of clay-rich gouge zones within rocks of the Bjorøy Formation.

Fig. 5. Sections through the sediment zone in the tunnel, as seen from Bjorøy. Note the vertical appearance of the layers. Based on sketches provided by K. G. Holter. See Fig. 4 for legend.

A total of six high-resolution seismic reflection data profiles (mini-airgun with single channel recording, 10 cu. inch primary chamber, 30 cu. inch secondary chamber) were collected from the Vatlestraumen area in January 1995 (Fig. 10). The data reveal a zone of dipping reflections beneath the sea bed or thin Quaternary sediments (Fig. 11). The dipping reflections occur in an up to 50–60-m-thick zone and in places are exposed on the sea floor and in other places covered by a few meters of Quaternary sediments. Although the sea-bed multiple in most of the area masks the base of the dipping reflections, these are observed to downlap on the gneissic crystalline basement with an angular unconformity (Fig. 11). The zone of dipping reflections is generally observed in the central part and on the southern side of Vatlestraumen.

The dipping reflections show apparent dips to the SE on SE–NW-oriented lines, whereas E–W-oriented lines display westerly dips (Fig. 10). If we assume that the reflections define a set of relatively planar and constantly oriented surfaces throughout the area covered by the seismic data (which to some extent is justified by the fairly constant dip along the seismic lines), the dip vectors shown in Fig. 10 should reveal this plane by defining a great circle when plotted on a stereonet. As shown in Fig. 10 (lower left-hand corner), the best fit great circle indicates that the reflections dip to the south or south–southwest at about 30°.

Seismic refraction data across the tunnel frequently show sound velocities on the order of 3000–5000 m/s in much of the area (Fig. 3), which is lower than expected for the gneisses observed in the tunnel and on the surrounding mainland and islands. The low-velocity observations generally coincide with the areas of the dipping reflections, and they are not limited to short intervals typical of low-velocity fracture zones. The observed low velocities are more typical of sedimentary rocks than of crystalline basement. Furthermore, the observed dense pattern of S-dipping reflections is characteristic of layered sedimentary rocks and is commonly found in rocks of Jurassic and Triassic age along the Norwegian margin of the North Sea Rift (e.g. Bugge et al. 1984; Bøe et al. 1992).

Alternative interpretations could be that the low velocities and the stratified seismic character were caused by fracturing and tectonic structuring of crystalline basement rocks. Observations from the tunnel and the surrounding areas show that fracture zones in the gneiss are much steeper than the seismic reflections and less widespread than the low-velocity area. Furthermore, the gneiss layering dips to the SE, whereas the seismic reflections exhibit S or SSW dips. Hence, these alternative interpretations are not very likely. It cannot, however, be ruled out that the dipping reflections are some sort of

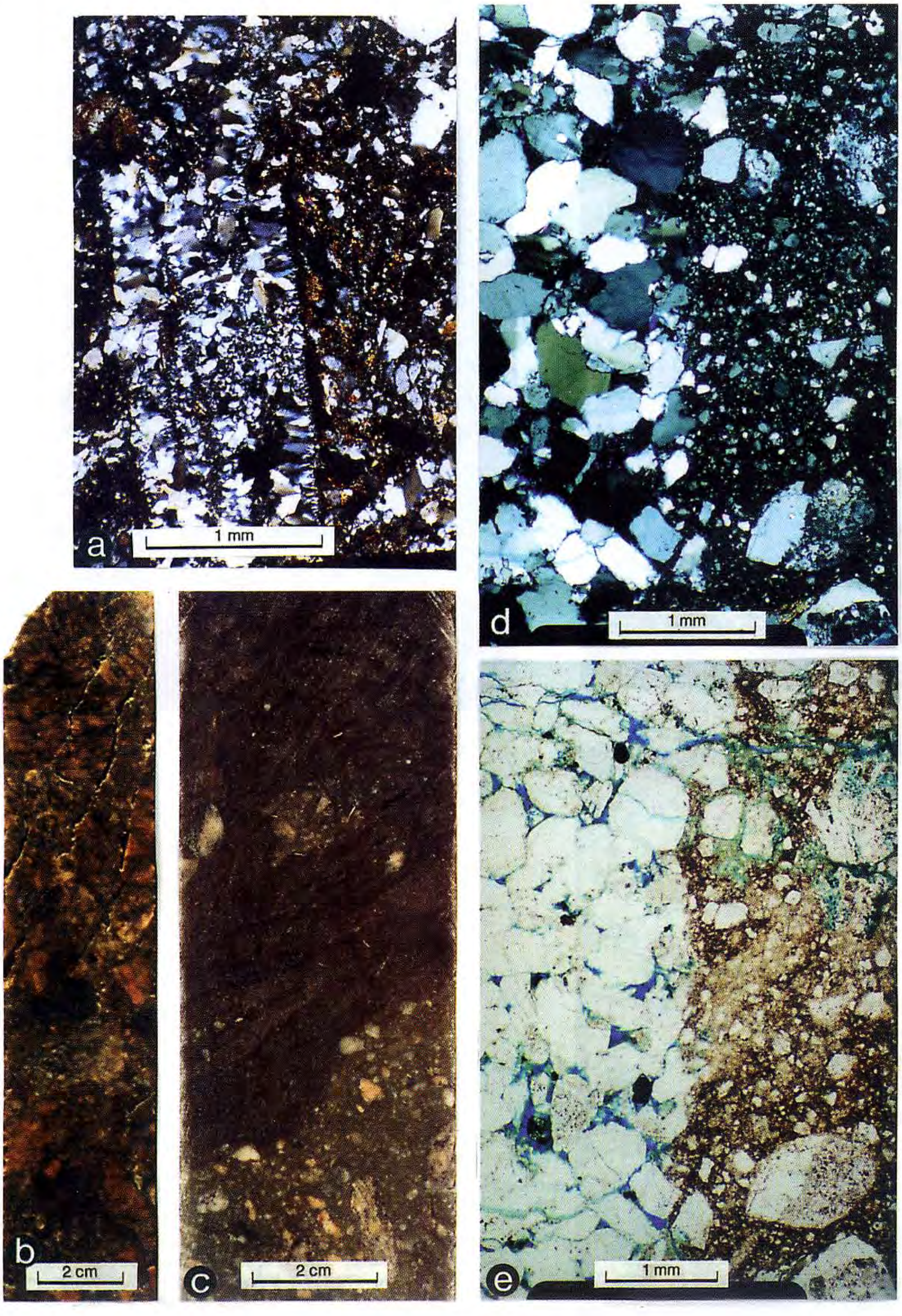

Fig. 6. Photographs of core samples from the Bjorøy tunnel. (a) Thin section view of the conglomerate, showing quartz clast where the texture of the quartz shows evidence of crystallization in an open void (fracture). (b) Tectonic breccia (note open fractures which post-date brecciation but pre-date deposition of the Bjorøy Formation). (c) Transition conglomerate–sandstone. (d) Sand vein in conglomerate. Evidence of pressure solution at grain contacts. Conglomerate to the right. (e) Same as (d) with plane-polarized light.

Fig. 7. (a) Sand and conglomerate in the Bjorøy tunnel. Two types of sand are seen, one with abundant coal fragments and one without coal (light). Evidence of tectonic disturbance of the sand is seen by offset of laminae (arrow) and brecciation of the sand. Width of photograph is about 60 cm. (b) The contact between a layer of light-colored, matrix-poor sandstone and a dark, matrix-rich sandstone. The oval fragments are coal, and a section through a thin twig is seen in the lower right section of the picture. Thin section, plane-polarized light. (c) Two generations of fractures in thin section from the tectonic breccia. A diagonal fracture is marked by mica and quartz, and the quartz is recrystallized. A later shear fracture with no sign of recrystallization runs N–S across the picture, and offsets the diagonally oriented fracture.

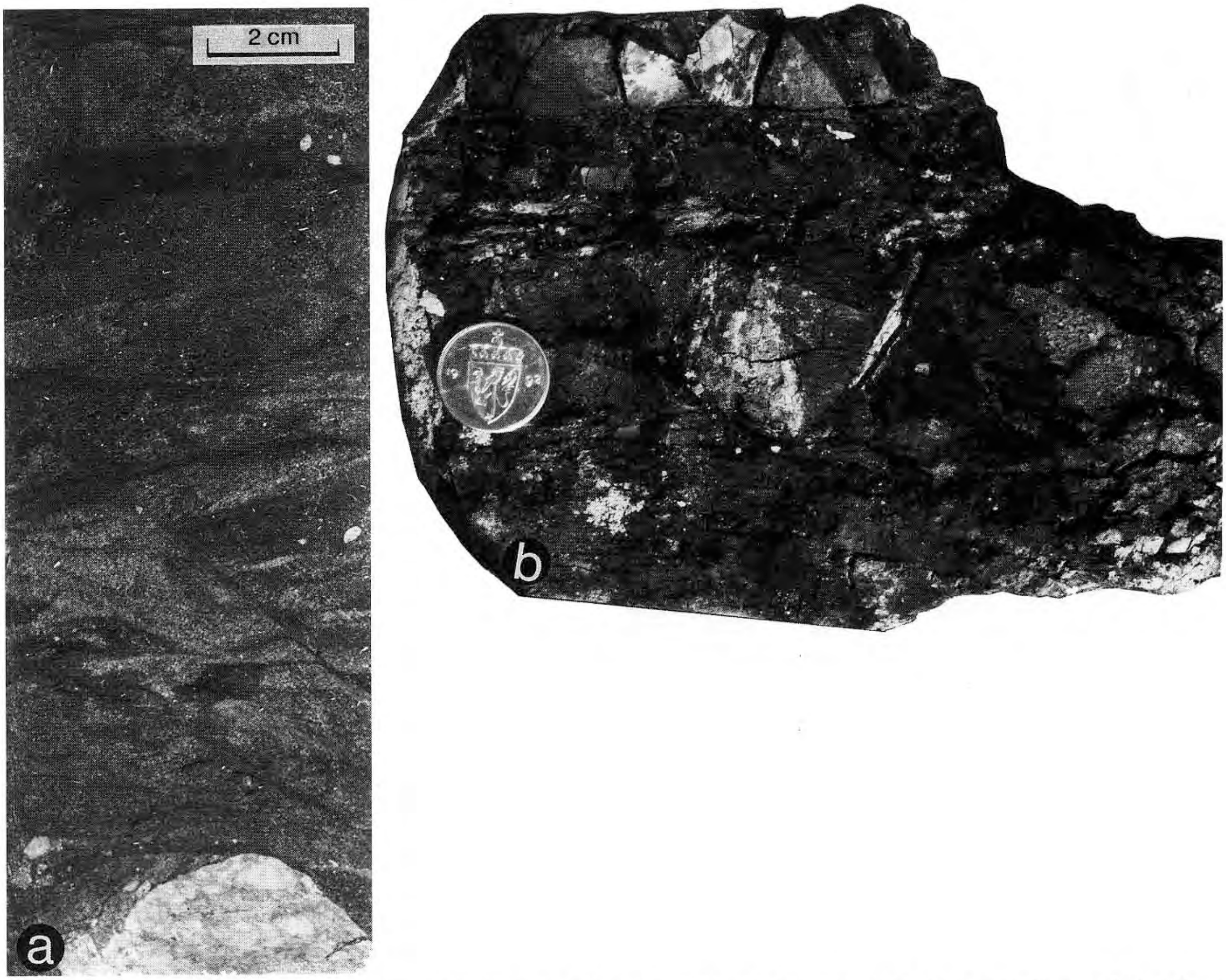

Fig. 8. (a) Sandstone with lamination cut by faults that pre-date lithification. (b) Coal fragment from the Bjorøy Formation, Bjorøy tunnel. Diameter of coin is 21 mm.

unexplained technical artefact or side reflections, but the coincidence between the low velocities and the dipping reflections, combined with the findings of Jurassic sediments in the tunnel, lead us to conclude that the zone of dipping reflections represents an erosional remnant of Jurassic sediments similar to the sand, sandstone and coal found in the fracture zone in the tunnel. These sediments thus probably acted as the source for the sediments encountered in the fault zone in the tunnel.

The seismic data thus indicate that Jurassic sediments were deposited discordantly on top of the crystalline basement, and that they are preserved in a much wider area than just the thin zone encountered in the tunnel. On seismic data the zone of dipping reflections seem to extend to Hjeltefjorden in the northwest, and it strikes close to the island of Bjorøy in the southwest. However, the southeastward extent of the dipping reflections cannot be determined from the available data.

The rock unit with the dipping reflections forms local highs on the sea floor close to Bjorøy at depths as shallow as 10–12 m. These locations would form potential targets for future drilling or sampling to test the true origin of the reflections. Until the proposed Jurassic sediments above the tunnel have been sampled, we restrict the definition of the Bjorøy Formation to the sediments found in the fault zone in the tunnel.

Age of the Bjorøy Formation

The age of the unconsolidated sand is only constrained by the occurrence of pollen and spores in the coal fragments, indicating a general Jurassic age. The possibility that the coal in the sand is older than the sand itself cannot therefore be excluded, implying that the coal was redeposited in the sand at a post-Jurassic stage. However, the very fragile nature of the coal fragments makes this a less likely possibility, since they would rapidly be deteriorated or destroyed during physical reworking.

The pollen and spore assemblages in the unconsolidated sand are compositionally similar to those found in the mid-Jurassic Ness Formation in the North Sea. The assemblages include abundant *Deltoidosporo* spp., *Cerebropollenites* spp., and bisaccate pollen. Common

Fig. 9. Overgrowth of K-feldspar on feldspar grain in the sandstone of the Bjorøy Formation.

Perinopollenites elatoides and *Baculatisporites* spp. occur, together with a few *Lycopodiacidites* spp., *Lycopodiumsporites* spp., *Corollina* spp., *Calliallasporites* spp., *Densoisporites velatus*, *Neoraistrickia* spp., *Chasmatosporites* spp., *Retitriletes* spp., and *Manumia* spp.

As opposed to the unconsolidated sand, the sandstone also contains dinocysts, indicating an early to middle Oxfordian age (Fig. 12). The dinocyst assemblage includes *Rigaudella aemula* and *Gonyaulacysta jurassica* var. *longicornis*, both having their latest occurrence at the end of the middle Oxfordian. Absence of *Mendicodinium groenlandicum* is taken as negative evidence for an age older than uppermost Callovian. Other dinocysts include *Sentusodinium psilosum*, *Gonyaulacysta eisenackii*, and *Rhynchodiniopsis cladophora*. *Botrycoccus*, *Micrhystridium*, *Cymatiosphaerae* spp., *Nummus* spp., and *Tasmanites* spp. were also recorded.

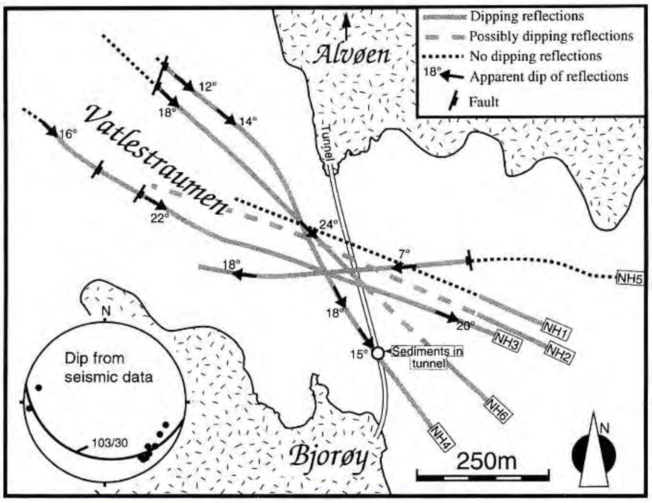

Fig. 10. Location of reflection seismic lines from Vatlestaumen. Identification of dipping reflections is indicated together with their apparent dips and possible fault locations. Stereplot of apparent dip directions fits a great circle indicating 30° dip to the S or SSW.

The age of the sedimentary breccia and the conglomerate of the Bjorøy Formation is not known, but because the conglomerate was still unconsolidated or weakly consolidated during deposition of the sandstone, they are likely to be of similar age (Jurassic). Sands in the northeastern Viking Graben of this age include the Fensfjord and Sognefjord Formations, providing reservoirs in the Troll Field some 80 km west–northwest of Bergen and Bjorøy.

Deposition and burial history

The exclusive presence of clasts of local (Bergen Arc) origin suggests short transport for at least parts of the Bjorøy Formation. The presence of dinocysts in the sandstone indicates deposition or subsequent reworking in a marine environment. Overgrowth of K-spar on primary feldspar grains (Fig. 9) supports this interpretation (Bjørlykke et al. 1995), whereas the presence of coal fragments indicates a close association with a terrigenous environment. It thus appears that the sand was deposited close to the shoreline during a period of transgression (Fig. 13).

Up to several kilometers of Cretaceous and Tertiary sediments overlie the Jurassic strata in the deepest parts of the North Sea basin, thinning across the crests of rotated fault blocks and towards the basin margins. Towards the Norwegian mainland, these strata obtain a westerly dip and become truncated by the base Quaternary unconformity. The Cretaceous and Tertiary (pre-Neogene) strata show total (uneroded) thickness on the order of 1.5 km in the western Horda Platform area. Closer to the coastline, the Tertiary and Cretaceous strata are removed by erosion (the *entire* Tertiary–Cretaceous package is removed by erosion some 50 km west of Bjorøy). A decrease in primary thicknesses of these strata is expected across the present coastline (e.g. Riis 1996), and the 1.5 km thickness therefore represents a *maximum* estimate of Cretaceous and Tertiary overburden in the Bjorøy area.

These considerations are in accordance with results of vitrinite analysis performed on coal fragments from the *unconsolidated sand*. Vitrinite reflectance values of 0.28–0.29 R_0 indicate temperatures less than 50°C. From these data, rocks of the Bjorøy Formation cannot have experienced more than one kilometer of overburden. The preservation of wood-fiber structures in the coal fragments supports this conclusion. The present data suggest that the uplift estimate of 1500 m in the coastal areas of southern Norway suggested by Doré & Jensen (1996)

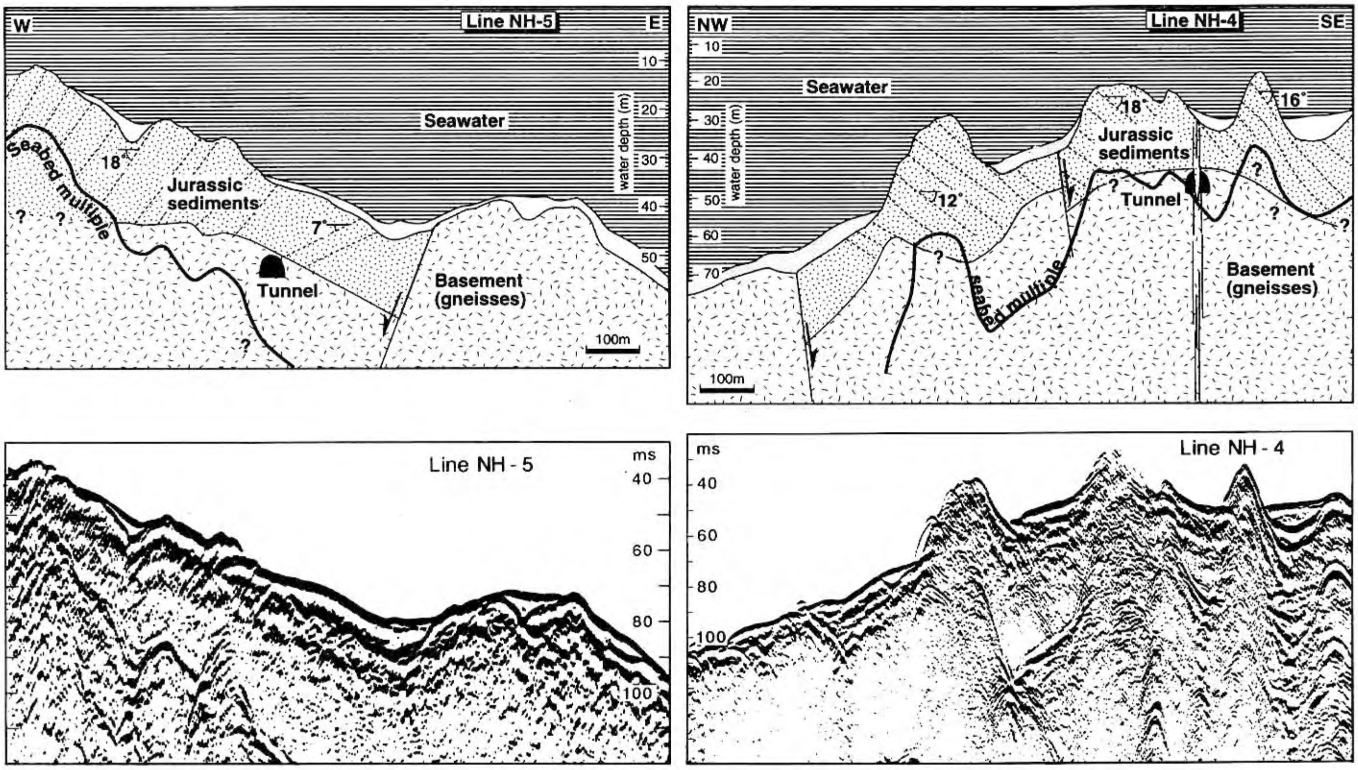

Fig. 11. High-resolution reflection seismic lines (mini air-gun, single channel recording) from the Vatlestraumen area, with interpretations. Although the data quality does not allow for any detailed interpretation, it indicates that layered sedimentary rocks may be preserved as an erosional remnant above the crystalline basement in Vatlestraumen. Note that the line drawings are not depth converted, and the depth scale indicates the depth to the sea bottom.

may be too large, at least for the Bjorøy area, and estimates in the range of 500–1000 m, as suggested by Riis (1996), seem more likely.

The *sandstone* also contains fragments of organic material, and with rather variable vitrinite reflectance values averaging at 0.32 R_0, i.e. similar to coal samples from the unconsolidated sand. The scatter could reflect pre-redepositional oxidation, or possibly the effect of hot fluids flushing through the sandstone during later faulting.

Meso- and microstructural observations in the fault zone

Microscopic studies and cross-cutting relations of the fractured gneiss from the tunnel indicate the following sequence of structural events: (1) development of pervasive (proto)mylonitic fabric; (2) faulting with formation of ultramylonitic fault rocks; (3) tensile fracturing and mineralization (vein infill); (4) faulting with the formation of greenish micro-breccia; (5) tensile fracturing and opening of fissures; and (6) faulting with formation of gouge zones.

(Proto)mylonitic gneiss fabric

The granitic gneiss is a well foliated and slightly porphyroblastic rock where K-feldspars (longest diameter 0.5 to 10 mm) and, less frequently, plagioclase grains occur in a fine-grained matrix of quartz and feldspar. Some of the most heavily deformed parts of the gneiss can be classified as mylonite or ultramylonite (Fig. 14a). The mylonitic gneiss foliation may contain elements of Precambrian deformation, although the main fabric is clearly attributed to the Caledonian orogeny.

Fractures with ultramylonitic fault rocks

Up to 3-mm-wide shear fractures are common in several of the investigated samples. These fractures cross-cut the pervasive Caledonian foliation, commonly at high angles. Using a hand-lens, minor rock fragments can be identified within some of these fractures, which also exhibit a pronouned flow foliation. These factures are filled by very fine-grained quartz, and on the micro-scale, the flow foliation is defined by monomineralic (quartz) zones with slightly increasing grain size towards the fracture walls (Fig. 14b). The foliation within the bands is in places emphasized by internal fractures coated with mica and Fe(OH)-minerals. The general texture suggests that the rock has locally recrystallized during a late stage of the semi-ductile/semi-brittle deformation. Some fault-rock samples show a gradation from mylonite, where porphyroclasts may constitute up to 30% of the rock volume, to ultramylonite.

Veins

Some mineral-filled veins with widths on the order of 0.1 mm or less occur. The mineral fill is very fine-grained

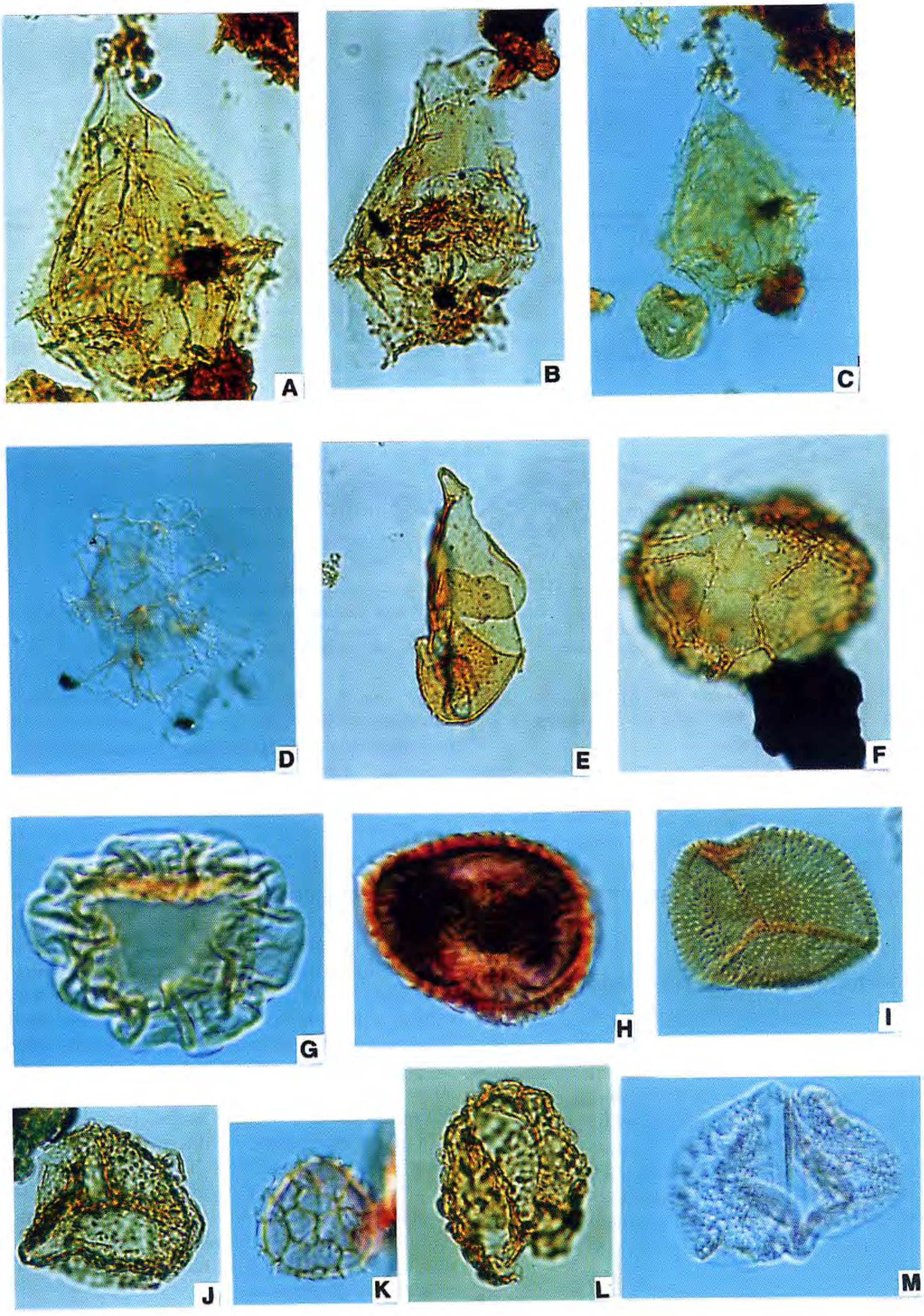

Fig. 12. Selected palynomorphs recorded from the sandstone of the Bjorøy Formation, Bjorøy tunnel (magnification 500× unless otherwise stated. A (700×): *Gonyaulacysta jurassica* var. *longicornis*. B: *Gonyaulacysta eisenackii*. C: *Gonyaulacysta jurassica* var. *longicornis*. D: *Rigaudella aemulum*. E: *Sentusodinium* sp. F: *Rhynchodiniopsis cladophora*. G (700×): *Calliallasporites* sp. H: *Lycopodiacidites* sp. I: *Sestrosporites pseudoalve latus*. J: (?) *Baculatisporites* sp. K: *Lycopodiumsporites* sp. L: *Cerebropollenites* sp. M: Bisaccate pollen.

quartz, chlorite, and limonite. The quartz in these veins is typically recrystallized. In some cases it can be demonstrated that veins are offset by zones of unrecrystallized micro-breccia, and that the veins accordingly are older (Fig. 7c).

Micro-breccia

In hand specimens, the gneissic foliation and the ultramylonite bands are seen to be off-set by large numbers of millimeter-wide fractures with a white or grey-brownish fracture fill. Such fractures are generally more abundant than the ultramylonite bands, and are the main agents in brecciation of the country rock, frequently defining angular to subangular centimeter-size fragments. These fractures are distinguished from the ultramylonitic fractures by their more angular fragments, purely cataclastic deformation characteristics (no recrystallization), and no prominent foliation.

In the microscope these fractures are identified as 0.1–10-mm-wide deformation bands filled with micro-breccia. A vague flow foliation may occasionally be identified along the fracture margins, whereas no flow foliation is observed in the central parts.

Single grains and rock fragments up to 3 mm in size are trapped in a very fine-grained matrix of brown mica, quartz and feldspar. The volume percentage of fragments within the fractures varies from 20% in the wider, to locally 70% in the thinner fractures. Rock fragments are identified as fragments of the local country rock.

A weak, cataclastic foliation defined by very fine quartz grains occurs toward the margins of the micro-breccia. This may suggest that the brittle deformation was formed by reactivation of more ductile deformation structures, or that deformation took place continuously during decreasing temperatures.

Fissures

Open fissures are common in several of the samples investigated. These may or may not have thin (1 mm or less) mineral drapings of chalcedony, quartz, calcite and very fine-grained unidentified minerals. The open fissures clearly cross-cut the micro-breccia described above, as can be seen both in hand samples and under the microscope.

Gouge zones

Several gouge zones of a few centimeters of some tens of centimeters of width were observed in the fractured gneiss and also in the sediments of the Bjorøy Formation in the tunnel. The gouge is a somewhat greasy, clay-rich

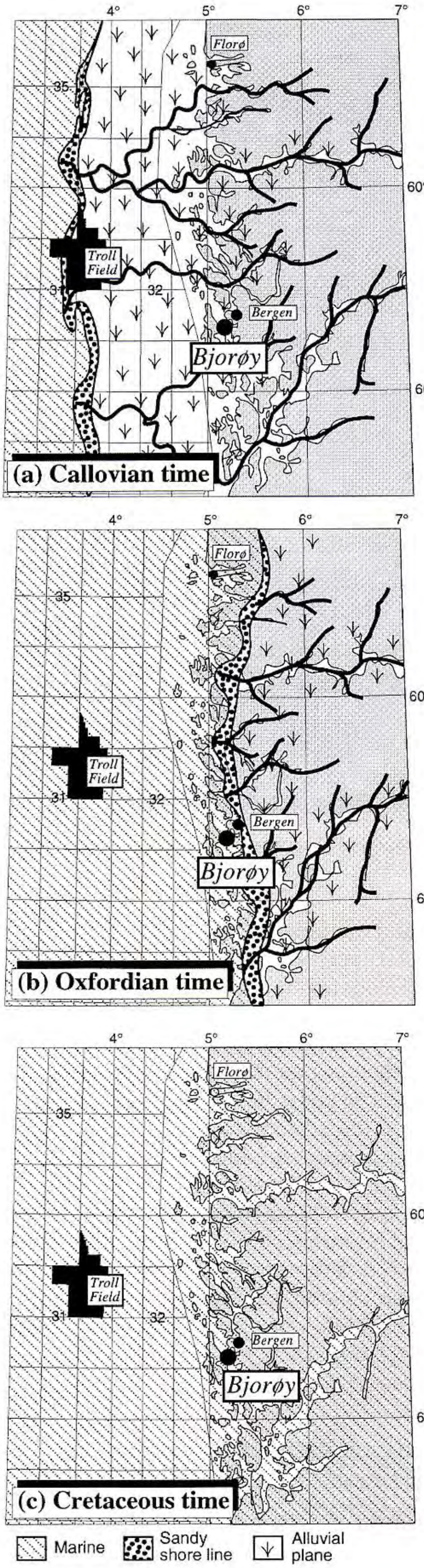

Fig. 13. The position of the shore-line, offshore West Norway during the Middle to Late Jurassic and the Cretaceous. A general transgression in the late Jurassic may have been the culmination of significant flooding of southern Norway in the Cretaceous.

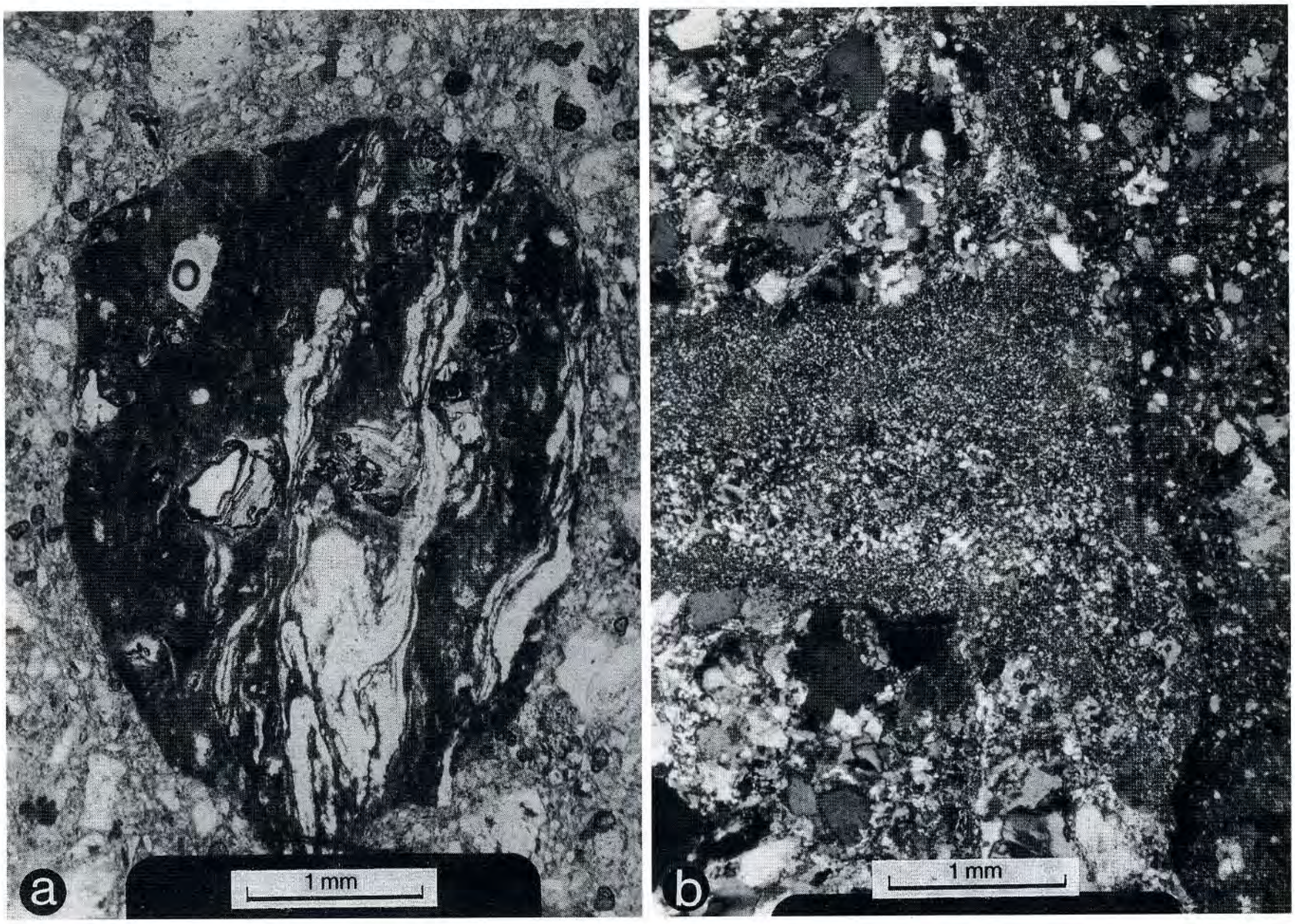

Fig. 14. (a) Clast of ultramylonite in the conglomerate of the Bjorøy Formation. (b) Quartz-filled fracture in gneiss clast in the conglomerate, where the quartz shows evidence of recrystallization. Note banding in the quartz caused by variations in grain size.

rock which occurs in continuous zones that appear to mark the latest faulting in the area.

Meso- and microstructural observations of the Bjorøy Formation

The sandstone of the Bjorøy Formation contains a considerable number of microfaults or shear bands (deformation bands) that offset the bedding by up to a few centimeters (Fig. 8a). There is no evidence of grain fracturing processes associated with these microfaults. Hence, the deformation must have occurred while the sandstone was still unconsolidated. Similarly, brittle deformation structures are not very common in the conglomerate, which implies that also the conglomerate experienced little internal deformation after consolidation. Nevertheless, joints do occur in the sandstone. A thin coating of pyrite has been found on one such joint, which must have been a fracture formed after lithification of the sandstone.

A number of small-scale faults were observed in the unconsolidated sand in the tunnel (Fig. 7a). Together with the rather chaotic appearance of sedimentary stratification in the sand (rapidly changing orientation of bedding and remarkable variations in thickness), this suggests that much of the post-depositional deformation was accommodated by movements within the unconsolidated sand.

Fault gouge zones occur in the sand, where the mica content is much higher than that in the sandstone outside of the zone. The gouge is soft and smooth, and similar to the gouge in the adjacent gneiss.

The spatial occurrence of the Bjorøy Formation in the tunnel provides additional evidence of fault-related deformation. Scattered fragments of coal in the sand could be a result of sedimentary processes during deposition, but the overall subvertical bedding observed in the tunnel and the chaotic mixtures of sand, sandstone and conglomerate can only be explained by fault movement(s) after deposition of the Bjorøy Formation.

Age relations between deformation structures in the gneiss and the Bjorøy Formation

There is a marked difference between the abundance and nature of deformation structures in the sandstone and the adjacent, fractured gneiss. The ultramylonitic fractures, micro-breccia and veins found in the gneiss are not found in rocks of the Bjorøy Formation. However, within clasts of the sedimentary breccia and the conglomerate, the fractures with associated ultramylonitic fault rock (Fig. 14a), the recrystallized veins (Fig. 14b) and the microbreccia observed in the nearby gneiss are found. Fractures terminate abruptly at the margins of the clasts, and none have been seen to continue into the matrix of the sedimentary breccia/conglomerate. Not even the latest, open fractures that are so common in the tectonic breccia (Fig. 6b) are found to affect rocks of the Bjorøy Formation. Rather, fragments of quartz with textures indicating growth in open fractures are found as *clasts* in the conglomerate of the Bjorøy Formation (Fig. 6a), indicating the existence of pre-Bjorøy Formation (pre-late Jurassic) open fractures. The only indication of open fractures in the Bjorøy Formation is a fracture face of a sandstone sample that was coated with pyrite. Hence, it appears that most brittle and semi-brittle deformation structures in the adjacent gneiss pre-dates the deposition of the Bjorøy Formation. Non-cohesive gouge zones are the only fault structures that occur in both the Bjorøy Formation and the adjacent gneiss and therefore post-date deposition of the Bjorøy Formation. Late gouge zones are also seen elsewhere along the Hjeltefjord fault zone, although they are commonly covered in debris or by the sea. From the observations made along the Hjeltefjord fault zone in general, and from the Bjorøy tunnel in particular, an important distinction can be made between non-cohesive gouge zones, which are the products of late Jurassic or younger fault activity, and more cohesive fault rocks, which represent older structures.

Fig. 15. N–S running fracture system near the tunnel entrance (the road leads to the tunnel just off the lower right corner of the picture), looking SSW.

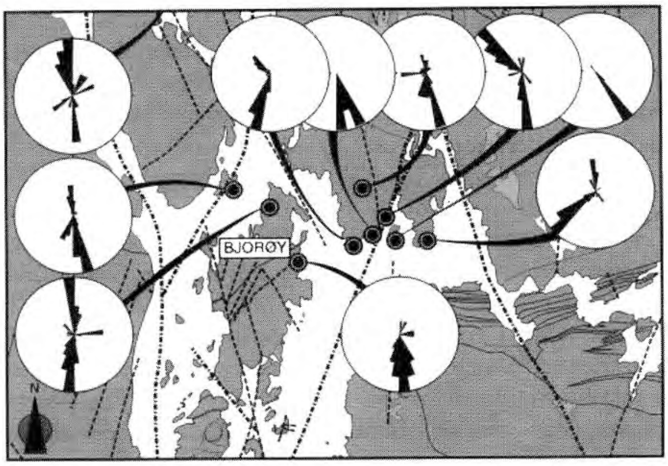

Fig. 16. Rose diagrams showing fracture orientation around the Bjorøy tunnel.

Fracture orientations around the Bjorøy tunnel

Zones of microbreccia and fractures are also identified on the island of Bjorøy near the entrance to the tunnel, and they can be seen to be steep with approximately N–S strike (Figs. 15, 16). A less pronounced E–W striking set is also developed. A subhorizontal to S-plunging lineation on fault surfaces indicates a significant (dextral) strike-slip component along the N–S system. Measurements from other localities in the vicinity of the tunnel also reflect the N–S system, whereas (N)NW–(S)SE- and (N)NE–(S)SW-oriented sets are locally more important. Typically, only one or two sets are predominant at each locality. This is because the fractures occur in zones, and the dominance of a particular fracture orientation would depend on the closeness to a zone of fractures with that specific orientation.

The (N)NW–(S)SE, (N)NE–(S)SW, and N–S fracture trends are also represented in a map of the fracture orientations in the Bjorøy area (Fig. 2). Similar trends are found from lineament analysis of aerial photographs from the Vatlestraumen area (Fig. 17). The late Jurassic Bjorøy Formation occurs along a NW–SE to NNW–SSE zone in the tunnel, which is one of the pronounced fracture zone orientations of the Hjeltefjord fault zone.

Discussion

Uplift, burial and lithification

Early fractures and microbreccias in the gneiss adjacent to the Bjorøy Formation (fractures with ultramylonitic fault rocks) show evidence of recrystallization, i.e. a process indicative of depths in excess of ca. 5 km (e.g. Sibson 1977). The later fractures only show signs of *cataclastic* deformation processes (grain-size reduction by mechanical fracturing and grinding), and the youngest fractures are open or mineral-filled fissures. This sequence of deformation is indicative of a gradual reduction in pressure and temperature during deformation, *prior* to deposition of the Bjorøy Formation. Combined with the results of the vitrinite reflectance analyses of coal or related organic matter in both the sandstone and the unconsolidated sand (above), it is possible to indicate a depth-time path for the area, as shown in Fig. 18. It thus appears that deformation occurred repeatedly along this path.

Many sand-grain contacts in the sandstone of the Bjorøy Formation show evidence of pressure solution (Fig. 6d–e) and quartz cementation. In the North Sea, quartz cementation and pressure solution generally occur at depths in excess of 3000 m, and rarely shallower than 2000 m (Bjørlykke et al. 1992). However, the vitrinite reflectance analyses of coal in the Bjorøy Formation indicate very low temperatures (less than 50°C), and a maximum burial depth of 1000 m for *both* the sandstone and the unconsolidated sand of the Bjorøy Formation is suggested. Hence, the possibility that the sandstone with pressure solution structures was deposited, buried and lithified before deposition of the unconsolidated sand can be excluded as an explanation for the differences in lithification, unless one disregards the results of the vitrinite analyses.

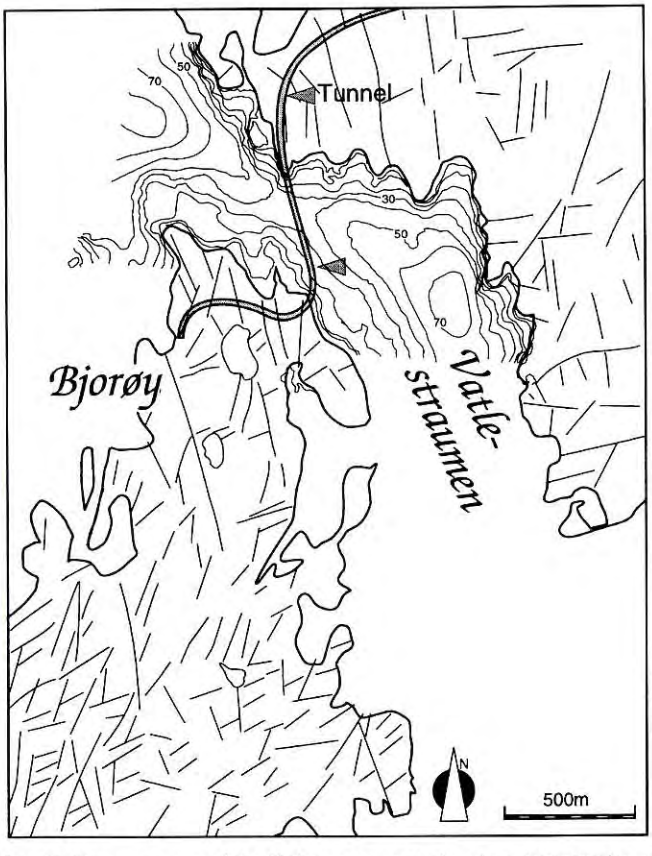

Fig. 17. Lineament map of the Vatlestraumen area, based on interpretation of aerial photographs. (N)NW–(S)SE and (N)NE–(S)SW trends dominate in addition to ENE–WSW lineaments which are related to the Caledonian foliation.

The dissolution and mobility of quartz are not only influenced by depth of burial, but also by flux of fluids. The latter is of particular importance in fault zones, which commonly act as conduits for fluids. Depending on the temperature and chemical composition of the through-passing fluids, quartz can be dissolved or precipitated. This is the obvious explanation why many faults in various tectonic and sedimentological settings show local cementation or mineralization. Abundant mineralization (quartz, fluorite, calcite and sulphites) associated with N–S striking faults and fractures along the Hjeltefjord fault zone is well known among local rock hunters, and represents evidence of hydrothermal activity. Although much of this mineralization appears to have taken place prior to deposition of the Bjorøy Formation, pryrite-covered joint surfaces on one of the sandstone samples from the tunnel indicate at least some post-depositional hydrothermal activity. Such activity may have slightly altered the vitrinite reflectance of the coal fragments in the sandstone, which shows a larger scatter than that of coal fragments from the unconsolidated sand. An additional factor that may enhance pressure solution and quartz cementation at shallow depths is the building up of high stresses at grain contacts along the fault zone. We are at present unable to determine the effect of increased stress at grain boundaries during faulting, but in either case fluids were needed to transport the dissolved silica. Hence, we suggest that the lithification of the sandstone is attributed to fluid flow along the fault zone.

Geomorphic aspects

Previous authors have suggested that southern Norway was flooded by middle (Doré 1992) or late (Riis 1996) Cretaceous time, which is recognized as a period of transgression and deposition of fine-grained clastics (mudstones) and carbonates from the offshore record. Riis (1996) points out that the marine transgression of weathered basement probably started in the present offshore area in the late Jurassic. From the information given in the present article, we know that at least the lower part of the present southwest Norwegian mainland was flooded in late Jurassic time. Vitrinite analysis of coal from the Bjorøy Formation keeps open the possibility that several hundred meters of Cretaceous sediments were deposited and later removed.

The late Jurassic–Cretaceous transgression of the Norwegian mainland occurred after a prolonged (250 My) period of dry, subaerial weathering. The Norwegian mainland must at this time have been rather flat and peneplanized. This peneplain is commonly referred to as Tertiary, but is unlikely to have changed much from latest Jurassic to Tertiary times (Riis 1996). Support for

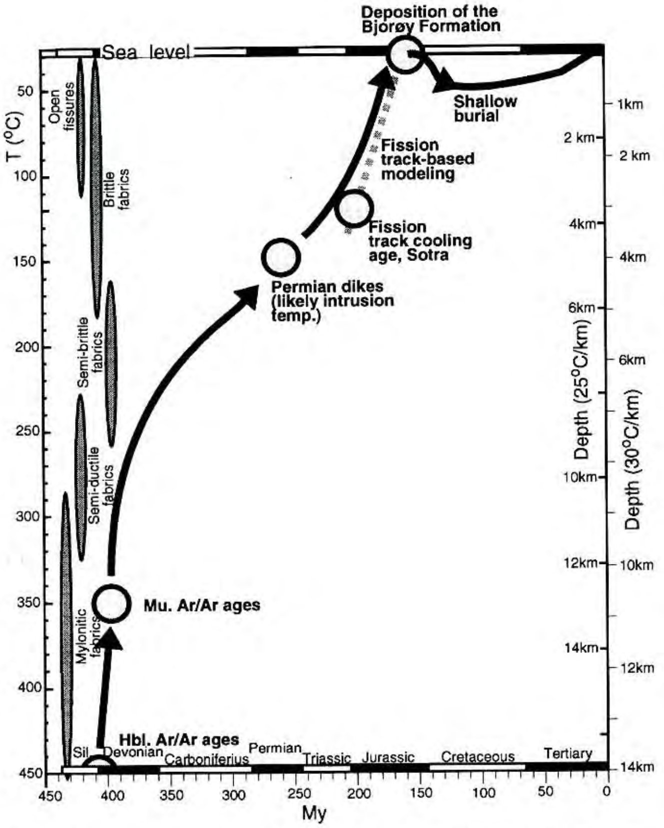

Fig. 18. Time-depth curve for the Øygarden Complex (Bjorøy–Sotra–Øygarden basement), indicating the cooling path from the Devonian to the present. The data from the Bjorøy tunnel help in constraining the Mesozoic part of the curve. Fission track data from van der Beek (1995) and Ar/Ar data from Fossen & Dunlap (unpublished) help to constrain the curve.

this interpretation is provided by fission-track modeling (van der Beek 1995), which indicates that exhumation rates dropped by an order of magnitude from the Jurassic to the Cretaceous. Furthermore, the offshore Cretaceous sedimentary record indicates little transport from the Norwegian mainland, with the exception of the Cretaceous Agat sandstones encountered further north (in wells 35/3 and 36/1; Guldbrandsen 1987). This is confirmed by fission-track analysis from the generally fine-grained Cretaceous sediments from offshore wells, indicating that Fennoscandia was not an important source area during Cetaceous sedimentation (Rohrman et al. 1996). Finally, the basement surface buried beneath Jurassic sediments near the Norwegian mainland has a very smooth and peneplain-like appearance on seismic profiles, for example in the Horda Platform area (Fig. 1). Hence, the paleic surface now represented by the many flat and equally elevated top plateaux of summits in southwestern Norway probably reflect a pre-Cretaceous peneplain (Fig. 19a) which was only reshaped during the late Cenozoic uplift of the Norwegian mainland. If the mainland was covered by Cretaceous sediments, as suggested above, this cover would effectively have preserved the paleic surface from erosion in the Cretaceous and early Tertiary, whereas late Tertiary uplift exposed the peneplain to erosion, and geomorphic features such as the Norwegian strandflat were completed (see Holtedahl 1997).

Evidence of rapid Neogene uplift of the peneplain is found from offshore seismic and well data, and several authors interpret the uplift to have occurred from the late Oligocene into the Pliocene (e.g. Jensen & Schmidt 1993; Riis & Fjeldskaar 1992; Stuevold et al. 1992). This uplift of the mainland relative to the North Sea basis caused the present westward dip (2–3°) of the Jurassic and Cretaceous layers west of Sotra and Øygarden (Fig. 1, profile). It is possible to reconstruct the pre-Tertiary geometry of the coastal area by assuming a vertical shear mechanism during the Tertiary differential uplift. The result of such a reconstruction is shown in Fig. 19b. Removal of the Tertiary flexure illustrates the Mesozoic peneplain in the Cretaceous, and displays how southern Norway could have been flooded and covered by sediments during the late Jurassic–Cretaceous transgression.

Figure 19 also shows that the westerly dip of the Mesozoic strata west of Sotra requires a post-Middle Jurassic down-to-the-E throw component on the Hjeltefjorden fault zone for strata of this age to reappear in the Bjorøy area. The normal throw component, which affects the Mesozoic peneplain, may be up to a few hundred meters.

Simultaneously with the Neogene uplift, sedimentary wedges built westward into the North Sea (Jordt et al. 1995). Although the source areas for these wedges were the uplifted Norwegian mainland, the Jurassic sediments in the Bjorøy tunnel were preserved from erosion. Whether or not the Jurassic and, possibly, Cretaceous sediments that must have covered the Bergen area were removed during this period or by later, glacial erosion is unclear. The Bjorøy Formation was preserved because of its occurrence along a fault zone, because of its location away from the areas of maximum glacial erosion (deep fjords and valleys), and possibly also because it was overlain by Cretaceous sediments until the Neogene. Assumed Mesozoic sediments in the Karmsund area (Bøe et al. 1992) occupy a similar geomorphic position, and additional remnants of Mesozoic rocks may well occur in the coastal parts of southwest Norway away from areas of strong glacial erosion.

The occurrence of the Late Jurassic Bjorøy Formation in a topographically low position in the relatively flat, coastal area west of Bergen is interesting also with respect to the development of the strandflat. The strandflat (Reusch 1894) is the uneven and partly submerged platform extending seaward from the coastal mountains, and is found along much of the coast of Norway. Although it is thought to be a mostly late Pliocene–Pleistocene feature (Holtedahl 1997), the position of the Bjorøy Formation indicates that the strandflat almost coincides with the late Jurassic surface, and thus contains Mesozoic elements.

Conclusions

Conglomerate, sand, sandstone and coal fragments (the Bjorøy Formation) were encountered in a fault zone in the

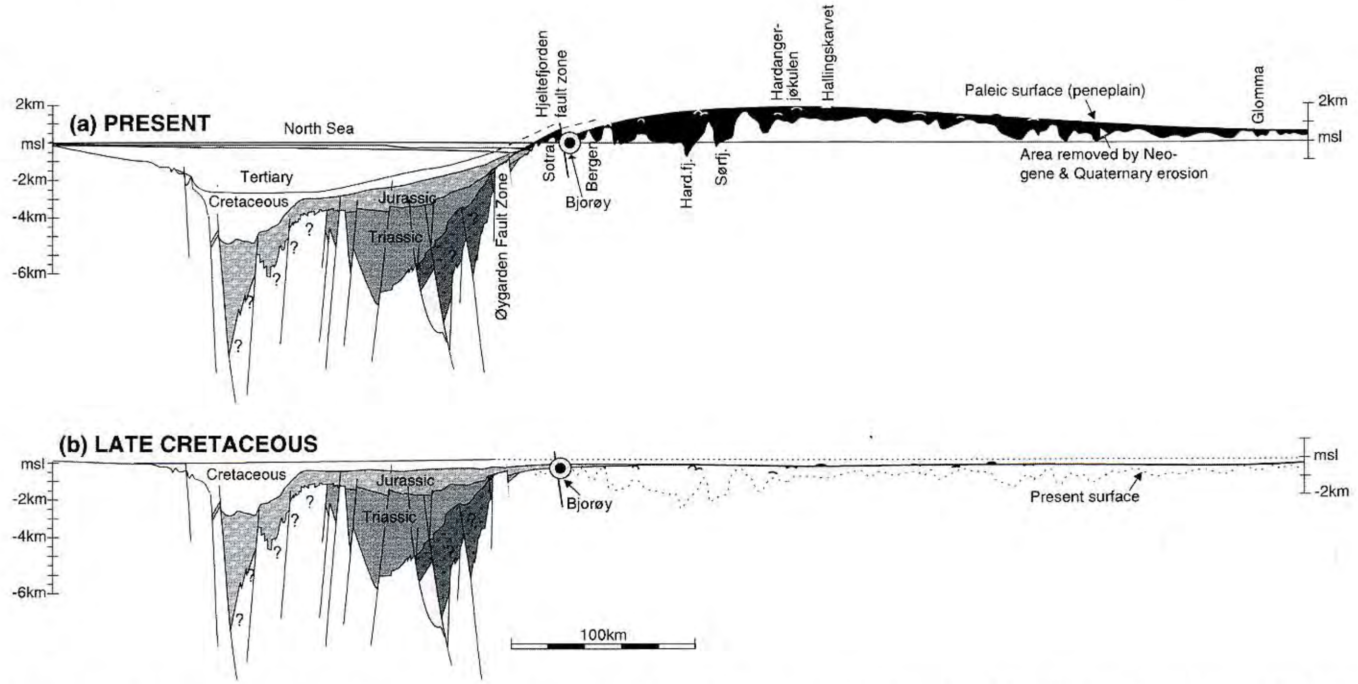

Fig. 19. (a) Profile from the Norwegian–Swedish border through Bjorøy to the North Sea. The onshore profile is adopted from Torske (1972) and connected with an interpretation of the deep-seismic profile NVGT84-02 (modified from Odinsen et al. in press). (b) Restoration of the profile to remove the effect of the Tertiary uplift of the Norwegian mainland by vertical movements. This is done by making top Cretaceous (North Sea) and the peneplain (onshore) approximately horizontal. Compaction effects of the sedimentary sequence are not considered here. See text for discussion.

Bjorøy tunnel near Bergen. The sandstone and coal of this formation are shown to be of (Late) Jurassic age. Seismic data indicate that S(SW)-dipping Jurassic strata may occur in a much wider area in Vatlestraumen, and their base appears to be located immediately above the tunnel roof. A combination of micro-paleontological, geophysical, sedimentological and structural analyses of the data extracted from the Bjorøy tunnel region has been performed, and the following Phanerozoic history is accordingly suggested for the area (Fig. 18):

1. Caledonian (Ordovician–Silurian) ductile deformation; mylonitization of the gneisses during top-to-the-east shearing.
2. Fragmentation of granitic gneiss in the semi-ductile regime: development of (ultra)mylonitic fault rocks, possibly during top-to-the-WNW extension (late Devonian?).
3. Emplacement of minor extensional veins, possibly associated with thermal relaxation, may have followed the mylonitization.
4. Continued deformation during uplift, possibly continued thermal relaxation, and ?active extension causing development of micro-breccias.
5. Culmination of the thermal relaxation stage with extensional fracturing and fibrous mineral growth on fissure walls at shallow crustal levels.
6. Sedimentary breccias and conglomerates were deposited on the faulted basement, and were then overlain by sands in the late Jurassic. Abundant coal fragments indicate a close proximity to the shoreline. Deposition of the sands was followed by or associated with a marine transgression at this time (Oxfordian).
7. Post-middle Oxfordian reactivation of the Hjeltefjord fault zone resulted in squeezing of the sediments between the gneiss walls in the fault zone so that the bedding became vertical. Faults with associated non-cohesive fault gouge formed at this stage. Local pressure solution/quartz cementation of sand, possibly due to hydrothermal activity along the fault zone.
8. The Bjorøy Formation was subsequently buried by Cretaceous and Tertiary sediments to a maximum depth of 1 km. Uplift to its present position (i.e. back to sea level) occurred mostly during the late Tertiary doming of Scandinavia.

The data presented here show that the sea level rose to cover the Sotra–Bergen area in Oxfordian time, and that the entire southwestern Norway is likely to have been covered by the sea during the continued transgression. This indicates that parts of the Norwegian mainland were flooded as early as late Jurassic time, and that what is known as the paleic surface was probably already well developed in the late Jurassic, particularly in the coastal areas.

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