Possible Mesozoic sediments in fault and brecciation zones in Frøyfjorden, Mid Norway

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The 5.3 km-long Frøya Tunnel beneath Frøyfjorden, Central Norway, links the islands of Hitra and Frøya and passes through a major zone of faulting and brecciation which parallels the Møre-Trøndelag Fault Complex. Faults and fractures within the Frøyfjorden fault zone are concentrated in deformation zones that developed during Devonian to Tertiary crustal movements. Drillcores from these zones include segments comprising possible Upper Palaeozoic and Mesozoic sediments. These were probably deposited on a fractured peneplain, and subsequently incorporated into faults during their reactivation in Mid Jurassic and later times. Extensive weathering of the fault rocks and the Early Palaeozoic igneous rocks within the fault zones mainly post-dates brittle deformation and brecciation. Part of the weathering may have occurred in the Late Triassic-Early Jurassic, prior to the Middle Jurassic transgression and deposition of the sedimentary succession in Frohavet. The youngest deformation event is represented by cross-cutting, montmorillonite-filled fractures which we tentatively relate to the Tertiary thermal activity documented in nearby areas.

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Introduction

The Frøya Tunnel beneath Frøyfjorden (Figs. 1 and 2), in coastal Mid Norway, links the islands of Hitra and Frøya. Construction of the 5.3 km-long sub-sea tunnel, which reaches a maximum depth of 160 m below sea level, was carried out during the years 1997-2001, while geological and geotechnical investigations started already in 1982. Prior to the start of construction, it was realised that the tunnel had to pass through a major fault/brecciation zone which parallels the nearby Møre-Trøndelag Fault Complex (MTFC), and that rocks of possible Mesozoic age could occur on or below the seabed of the fjord in the extension of the Frohavet Basin to the northeast (Oftedahl 1975, Bøe 1991). Extensive investigations were therefore conducted, including mapping of lineaments on land and in the fjord, refraction and reflection seismic surveys, drilling of coreholes on land, from a drilling ship and in the tunnel during its construction (altogether 1700 m of drillcore), and geotechnical studies (NGI 2002). In this contribution we examine fault zone complexity from a study of lithology, deformation and weathering in drillcores from Frøyfjorden. We also report the results of palynological investigations aiming at a dating of the intercalated sediments.

Regional setting

In Norway, Mesozoic sedimentary rocks are exposed only on Andøya in Nordland (Birkelund et al. 1978, Dalland 1979, Sturt et al. 1979). Basins with Mesozoic sedimentary rocks also occur in the fjords and coastal zone in northern and western Norway (e.g. Fossen et al. 1997, Davidsen et al. 2001, Sigmond 2002). In Trøndelag, the Beitstadfjord Basin in the inner part of the Trondheimsfjord (Manum 1964, Vigran 1970, Oftedahl 1972, 1975, Bøe & Bjerkli 1989, Sommaruga & Bøe 2002) and the Frohavet Basin northeast of Frøya (Nordhagen 1921, Oftedahl 1975, Bøe 1991, Sommaruga & Bøe 2002) are examples of Jurassic basins (Fig. 1). Mesozoic basins also occur south and west of the island of Smøla (Bøe & Skilbrei 1998, Sommaruga & Bøe 2002).

Mesozoic rocks offshore Møre and Trøndelag are described from exploration wells in the Slørebotn Sub-basin/Gossa High area (Jongepier et al. 1996) and from shallow coring outboard of the island of Ona (Smelror et al. 1994, Mørk & Stiberg 2003, Mørk & Johnsen, this volume), in the Froan Basin area (Mørk et al. 2003, Smelror et al. in prep.), and farther north off Vikna and Helgeland (Bugge et al. 1984, Bugge et al. 2002).

Hitra and Frøya are dominated by granitoid plutonic rocks of Mid Ordovician to earliest Silurian age, part of the Smøla-Hitra Batholith (Gautneb & Roberts 1989, Nordgulen et al. 1995). These rocks intrude a Palaeoproterozoic, medium- to high-grade, supracrustal succession (Kollung 1963, Askvik & Rokoengen 1985). The overall picture shows many similarities to that in the Helgeland Nappe Complex of Nord-Trøndelag and Nordland (Nordgulen et al. 1993). A sedimentary succession of latest Silurian to Early Devonian age lies unconformably upon Ordovician diorite on Hitra (Siedlecka & Siedlecki 1972, Bøe et al. 1989). Lower to Middle Devonian sedimentary rocks also occur southeast of Frohavet, on the Fosen Peninsula, (Siedlecka 1975, Bergfjord

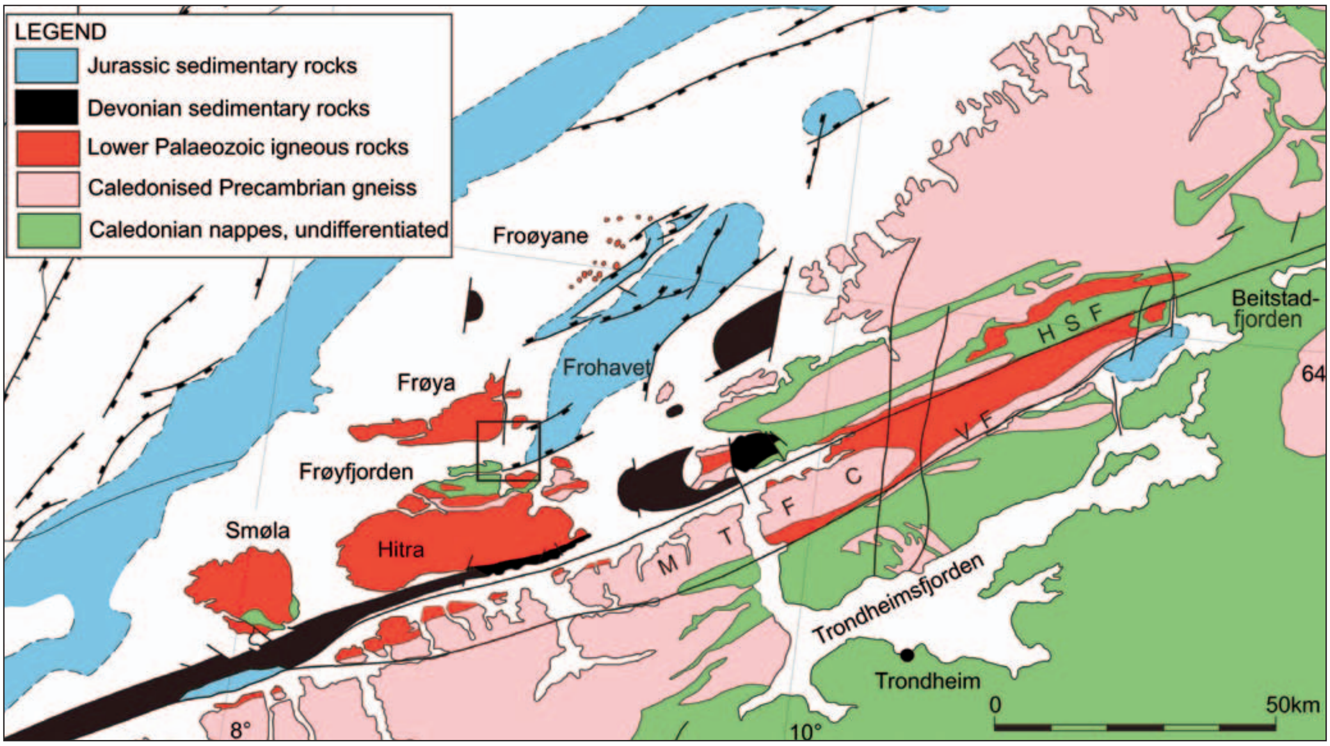

Fig. 1. Geological overview map. Subcropping Jurassic rocks are shown in blue colour. Devonian rocks on land and below the sea are shown in black. MTFC – Møre-Trøndelag Fault Complex; HSF – Hitra-Snåsa Fault; VF – Verran Fault.

1989), and at Vingleia, north of Frøya (Nordgulen et al. 1990, Bøe et al. 1992). Plant fossils and spores of Early and Mid Devonian age have been described from several of the localities (Høeg 1945, Allen 1976).

Hitra is situated northwest of the ENE-WSW-trending Hitra-Snåsa Fault, one of the two most prominent structures that define the MTFC. This major fault complex is known to have been active at various times from the Devonian to the Tertiary (Grønlie & Roberts 1989, Grønlie et al. 1994). Other, similarly trending faults in this part of Mid Norway, such as the Tarva and Dolmsundet faults along the southern margin of the Frohavet Basin (Bøe 1991, Sommaruga & Bøe 2002), may be associated with the MTFC. The Dolmsundet fault can be traced from the northeast into the narrow sound Dolmsundet between Hitra and Dolmøya (Fig. 2). Structural studies along the MTFC on Fosen have concluded that there was an early phase of ductile, sinistral strike-slip movement of Devonian age. This has now been confirmed by isotopic dating (Sherlock et al. 2004). The studies have also provided evidence of more brittle, sinistral or dextral shear movements in Late Palaeozoic, Mesozoic and even Tertiary time (Grønlie & Roberts 1989, Grønlie & Torsvik 1989, Grønlie et al. 1990, 1991, 1994, Sættem & Mørk 1996, Watts 2001). Numerical modelling of far-field stress patterns from the Mid-Norwegian shelf does, in fact, predict a minor component of dextral strike-slip along the MTFC in Tertiary time (Pascal et al. 1999, Pascal & Gabrielsen 2001).

Fault rocks and weathering products

On Hitra and Frøya, major lineaments, representing faults and megafractures, show three principal trends: ENE-WSW, NE-SW and NW-SE (Bering et al. 1986, Braathen 1996, Sættem & Mørk 1996). A N-S trend is also evident on Frøya. In Frøyfjorden, four very pronounced ENE-WSW trending lineaments have been reported: 1) along the southern coast of Frøya between Grønholman and Løkskjæra; 2) centrally in Frøyfjorden south of Løkskjæra; 3) along the northern coast of Dolmøya north of Seibalskjæra, and 4) in Dolmsundet between Dolmøya and Hitra (Fig. 2, Sættem & Mørk 1996). These lineaments are evident as deep trenches up to several tens of metres wide, and are believed to represent zones of faulting and brecciation. Major lineaments (faults or fractures) also trend N-S and NE-SW, while many, but shorter and less pronounced lineaments occur along NW-SE and WNW-ESE trends (Braathen 1996, Sættem & Mørk 1996).

Fault rocks, such as breccia, cataclasite and gouge, are common in many of the weakness zones penetrated by the Frøya Tunnel beneath Frøyfjorden (Sættem & Mørk1996, NGI 2002). Both consolidated and poorly consolidated fault rocks can be recognised, and a variety of vein minerals is also present. Investigation of the drillcores has shown that the deformation zones and low-velocity zones contain strongly weathered gneisses, granites, mafic rocks and breccias, and in some intervals the rocks are partially or completely altered to various clays. Weathering is most extensive in the strongly deformed and brecciated rocks, but there are also examples of pervasive weathering in apparently coherent plutonic rocks (Sættem & Mørk 1996). Common weathering products from the mafic and feldspathic rocks are swelling mixed-layer clay and mica/illite, with a variable presence of dolomite, kaolinite, goethite, hematite and talc. Soft and pale-coloured 'weathering breccias' may represent strongly weathered cataclasites.

The fault complex in Frøyfjorden was initially studied in vertical boreholes close to Frøya (BH-1A, 44 m water depth) and Dolmøya (BH-2, 58 m water depth) that penetrated bedrock below a thin Quaternary overburden (Figs. 2 and 3). Cores from sub-horizontal boreholes drilled through weakness zones during the tunnel construction display a lithology similar to that in the vertical boreholes. The cores are very heterogeneous with respect to lithology, deformation intensity and weathering. The cored rock types comprise foliated gneiss, mafic to intermediate plutonic rocks, deformed and brecciated granite pegmatite (autobreccia), migmatite gneiss, augen gneiss, mylonite, diverse cataclasites, fault breccias, matrix-rich breccias of possible sedimentary origin (see below), and various weathering products and fracture fills (Fig. 3).

Strongly weathered plutonic rocks, such as diorite and quartz diorite, alternate with fault breccias composed of granite-pegmatite clasts on a 0.5-3 m scale in the bore-hole close to Frøya (BH-1A) (31 and 62 m depth). Fine-grained cataclastic rocks and gouge occur in thin shear bands in the plutonic rocks at 54-56 m depth. The strongly weathered igneous rocks show contacts against foliated and weathered gneisses in the upper part of the core. The plutonic rocks are considered to correspond to the tonalitic rocks on Frøya.

Borehole BH-2 close to Dolmøya penetrated deformed gneisses and fault breccias (Fig. 3). An interval of fine-grained, matrix-rich breccia that includes sedimentary debris occurs within deformed gneisses at 52-58 m depth (Fig. 4, see below). Fractures in the breccia carry red coatings and slickensides. Fault breccias and gneiss in the upper part of the core are pervaded by a network of calcite-cemented microfractures, and rocks with extensive calcite replacement occur in the upper part of the core. Similar gneisses in northern Dolmøya include marbles (Kollung 1963), and we believe that this marble-bearing unit could have acted as a source for the calcite cementation and replacement of fault rocks in the upper part of the core. Chlorite and mica/illite occur along fractures in the gneiss below the fault zone in BH-2.

Fracture density is high throughout the cores, and fractures have variable dips. Some fracture surfaces display lineations and slickensides. Lineations are commonly at a low angle to the horizontal plane, suggesting that strike-slip or oblique slip movements have occurred. Sættem & Mørk (1996) concluded that these slickenside lineations represent strike-slip movements younger than the Jurassic, possibly including a Miocene dextral phase. Fractures with slickensides are commonly associated with red-brown coatings that include swelling mixed-layer clay and iron

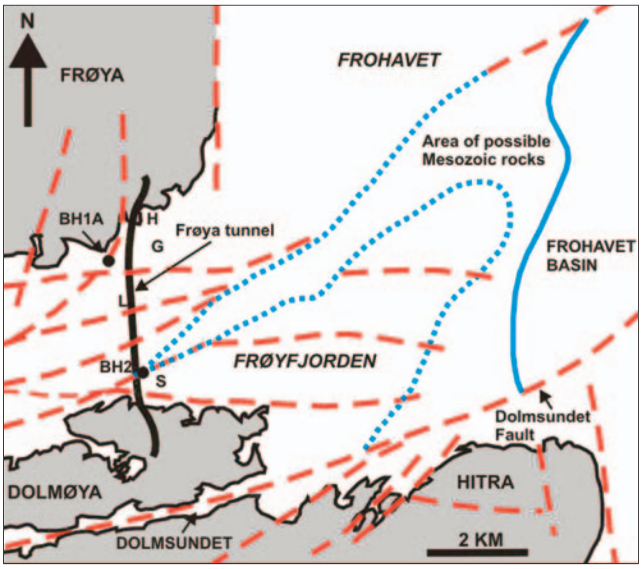

Fig. 2. Tectonic lineaments interpreted from bathymetry and aerial photographs in the Frøyfjorden area (modified from Sættem & Mørk 1996). The location of the Frøya tunnel, boreholes BH1A and BH2 and major fault and fracture zones (dashed lines) are shown. H: Hammarvik; G: Grønholman; L: Løkskjæra; S: Seibalskjæra. See Fig. 1 for location. The western border of the Frohavet Basin is indicated by the continuous blue line.

oxides/hydroxides. Other fractures are calcite cemented. Fractures coated by yellow-green montmorillonite represent a younger generation of fracturing and mineralisation, postdating brecciation. Torske (1983) described montmorillonite as cavity fill within a granite breccia close to a major N-S fault along the east coast of Frøya, interpreted as a fluidization breccia related to Tertiary mantle pluming. The late veining in the present area could likewise be related to Early Tertiary geothermal activity documented by nephelinitic volcanism in nearby areas (Bugge et al. 1980, Prestvik et al. 1999).

Sedimentary rocks and palynological dating

In the core material from the deformation zones, there is evidence of incorporation of sedimentary rocks in breccia. Palynological dating (see below) suggests a wide range in age for this material, from Devonian to Late Cretaceous and younger (Table 1). The sedimentary rocks occur within consolidated, matrix-rich breccias (Fig. 4). Deformation is shown by common slickensides as well as by partly crushed and comminuted rock fragments.

Rock fragments within the breccias are composed mainly of gneiss. However, fragments of re-deposited sedimentary breccia and dolomite-veined, matrix-rich, sedimentary rock also occur (Fig. 4). The red matrix is composed of quartz, feldspar, kaolinite, mixed-layer clay minerals and hematite. Chlorite and dolomite may also be present (Sættem & Mørk 1996).

Five samples of red-brown, matrix-rich breccia were col-

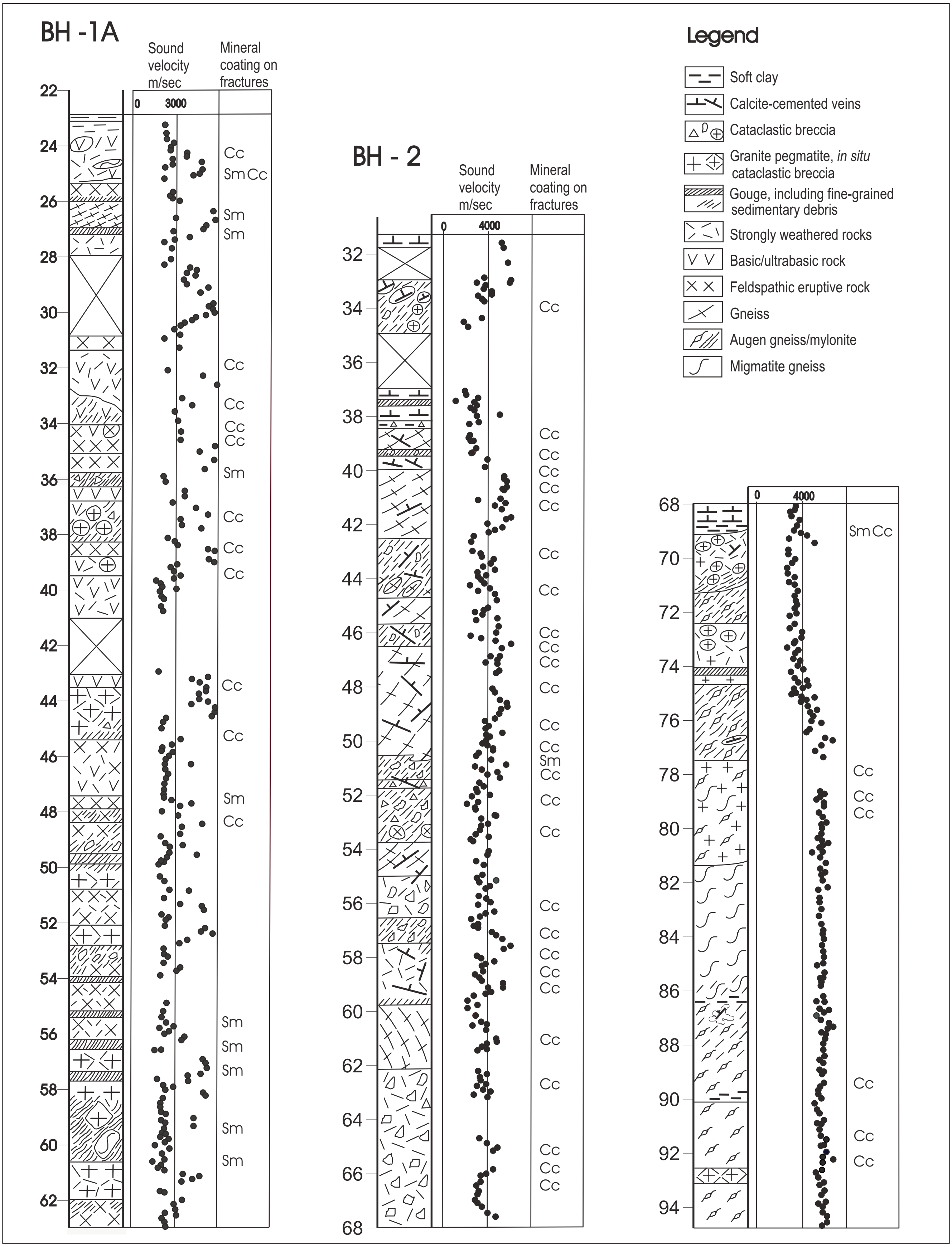

Fig. 3. Fault zone geology and sound velocity variation with depth (m below sea floor) in boreholes BH-1A and BH-2 (see Fig. 2 for location). The presence of smectite (Sm) and calcite (Cc) coatings on fracture surfaces are shown. Note the decrease in sound velocity from the massive crystalline gneisses in the lower part of BH-2 to faulted, brecciated and weathered rocks higher up in the core (above 78 m).

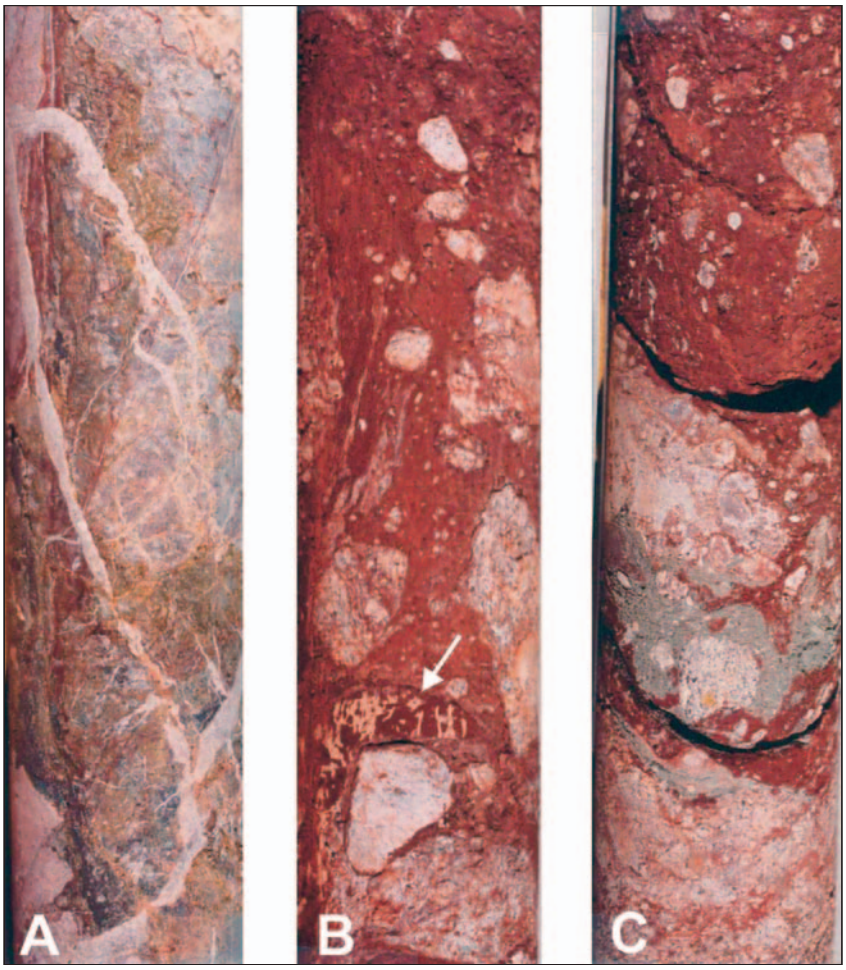

Fig. 4. Details of breccias in core BH2 (see Fig. 2 for location) from (A) c. 46.3 m, (B) 52.5 m and (C) 75 m depths. Core width is c. 7 cm. (A) Calcite-cemented and calcite-veined gneiss/fault breccia. (B) and (C) Matrix-rich, sediment- and gneiss-bearing fault breccias. Note the dolomite-veined fragment in the lower part of B (arrow).

lected from a weakness zone near Dolmøya for palynological investigation. Two of the samples are from the vertical borehole BH-2; the three others are from borehole BH-4407 that was drilled sub-horizontally through the weakness zone during the tunnel construction (Fig. 2, Table 1). Each sample was treated following standard palynological techniques, using warm hydrofluoric acid and dilute hydrochloric acid to extract organic remains from the silica. Schulze's reagent was used to brighten the plant remains before the residue was sieved to remove the smallest particles. Slides for microscopy were prepared from the sieved residue and from the oxidised residue, after separation of the remaining minerals.

Coal fragments and wood particles (tracheids) were recorded in all 5 samples and provide evidence of a sedimentary origin for some of the rocks in the fault zone. The dark brown tracheids in some cases have pores and represent remains of Devonian or younger plants. Samples from BH-2 also include rare, very dark palynomorphs that are poorly preserved and have low potential for identification and relative dating of the material. There are indeterminate spores of Devonian to Carboniferous age as well as indeterminate bisaccate pollen of Mesozoic age. More brightly coloured triporate pollen (Table 1, 52-53 m depth) represent Late Cretaceous to Tertiary plants. The fossils support the idea that the fault zone was exposed to deposition of sediments during Mesozoic to Tertiary time.

Discussion

Based on the drillcore data, the geology of Hitra and Frøya (Kollung 1963, Nordgulen et al. 1995), and the geology in Frohavet (Bøe 1991, Sommaruga & Bøe 2002), we think that a major, NE-SW to ENE-WSW-trending fault zone, with several splays, is located in Frøyfjorden, and that these faults have been active at several times since the Devonian. A similar suggestion was made by Oftedahl (1975) and Braathen (1996). This structural feature is here referred to informally as the Frøyfjorden fault zone.

The drillcores show evidence of many episodes of deformation, fracturing and brecciation. The oldest phase is represented by intrusive dykes of the igneous complex in BH-1A. Mylonites of possible late-Caledonian origin record shear deformation in the gneisses in borehole BH-2. These older structures are cut by hydrothermal veins, which may be as young as Late Permian or Jurassic if they are comparable to the hydrothermal activity interpreted elsewhere along the MTFC (e.g., Grønlie & Torsvik 1989, Grønlie et al. 1994). Younger deformation events with cataclasis resulted in the formation of fault breccias, microbreccias and gouge..

Bøe (1989) described weathering breccias and regolith development below the Downtonian-Devonian sediments on Hitra. However, the Devonian and older Palaeozoic sedimentary rocks in the area have been subjected to low-grade metamorphism (Bøe et al. 1989). From the relationships between deformation and weathering in the present study, we thus interpret the main phases of weathering in Frøyfjorden to be younger than the Devonian. From a study of sediments deposited in the offshore area, Mørk et al. (2003) have described a major phase of weathering in the Late Triassic-Early Jurassic.

Extensive weathering is observed only in rocks from the Frøyfjorden fault zone, and not onshore on Hitra and Frøya. Granite pegmatite occurring in the fault zone shows evidence of both brittle deformation and weathering. In contrast, the relatively coherent fabric of the weathered plu-

Table 1. Results of palynological investigations of borehole samples from the Frøya Tunnel.

Borehole and depth	Material	Analytical results
BH-2, 52.00-52.07 m	Red, matrix-supported gneiss breccia/gouge/cataclasite + possibly sheared sedimentary rocks	One spore of Devonian-Carboniferous affinity (Si 26.6-106.5 exp. 10). Triporate pollen (light coloured) represent Late Cretaceous or younger material. Tracheid remains represent material of Devonian or younger age.
BH-2, 52.77-52.85 m	Red matrix-supported gneiss breccia/gouge/cataclasite + possibly sheared sedimentary rocks	One bisaccate pollen grain of indeterminate Mesozoic age (Si 34.1-97.9 exp. 11). Brownish tracheid remains represent material of Devonian or younger age.
BH-4407, 39.85-40.00 m	Reddish-brown breccia	Yellow bisaccate pollen, tricolpate pollen of Late Cretaceous or younger age. Brownish tracheid remains represent material of Devonian or younger age.
BH-4407, 82.20-82.40 m	Red sandstone or possibly breccia	Brown to black tissue of undifferentiated cells (Ox 25.8-95.6) and brownish tracheid remains represent material of Devonian or younger age. Black minerals dominate the residue.
BH4407, 83.60-83.80 m	Red conglomerate or possibly breccia	Opaque minerals with ragged surfaces. Brownish tracheid remains represent material of Devonian or younger age.

tonic rocks in parts of BH-1A suggests that deformation was localised in the intervening shear zones, and this, in turn, indicates that the weathering detected in this part of the fault zone took place after the main deformation events.

Seismic data from the southwestern part of Frohavet show that Jurassic sediments were deposited on a more or less horizontal surface, probably representing an old peneplain (Bøe 1991). The present sea-bed surface in Frøyfjorden occurs at approximately the same elevation as the peneplain. Weathering processes and erosion must have acted on the surface repeatedly, possibly since the Permian, forming sediments and removing them again. Only in topographic lows, in fractures and deep clefts, possibly created by faults, have sediments been partially preserved. During Mid Jurassic time and in later tectonic events, the faults were reactivated, and the sediments which had been deposited on the peneplain were incorporated into the fault zones.

Conclusions

The investigations in Frøyfjorden, made in connection with construction of the Frøya Tunnel, have shown the existence of a complex fault zone with rocks varying from massive migmatitic gneisses to completely hydrothermally altered rock masses with a consistency like medium-soft clay. Low-velocity weakness zones several tens of metres wide are present. Faults and fractures within these zones, and in the Frøyfjorden fault zone as a whole, developed during Devonian to Tertiary movements, as is also the case along the MTFC. Drillcores from the weakness zones include plutonic rocks from the Smøla-Hitra Batholith as well as migmatitic gneisses, metasedimentary rocks and fossiliferous rocks reflecting Late Palaeozoic, Late Mesozoic and Tertiary ages of deposition. The Mesozoic sediments were probably deposited on a fractured peneplain, and subsequently incorporated in and along the faults during their reactivation in Mid Jurassic and later times. Extensive weathering of fault rocks and igneous rocks within the weakness zones mainly post-dates the brittle deformation and brecciation. Some of the weathering may have occurred in the Late Triassic-Early Jurassic, prior to the Mid Jurassic transgression and deposition of the sedimentary succession in Frohavet. The youngest deformation event is represented by cross-cutting, montmorillonite-filled fractures which we tentatively relate to the Tertiary thermal activity documented in nearby areas.

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References

Allen, K. C. 1976: Devonian spores from outer Trøndelag, Norway. *Norsk Geologisk Tidsskrift 56*, 437-448.

Askvik, H. & Rokoengen, K. 1985: Bergrunnskart Kristiansund, M 1:250 000. *Norges geologiske undersøkelse.*

Bergfjord, E. 1989: *Den strukturelle utvikling i den devonske Fosen-gruppen og dens underlag, Ørlandet, Sør-Trøndelag*. Unpublished Cand. Scient. thesis, Universitetet i Bergen, 180 pp.

Bering, D., Boyd, R., Grønlie, A., Solli, S., Atakan, K., Bryhni, I., Gautneb, H., Krill, A., Lynum, R., Olesen, O. & Rindstad, B.I. 1986: Berggrunnsgeologisk rekognosering av fire områder på kysten av Møre og Trøndelag. *Norges geologiske undersøkelse Rapport 86.027*, 96 pp.

Birkelund, T., Thusu, B. & Vigran, J. 1978: Jurassic-Cretaceous biostratigraphy of Norway, with comments on the British Rasenia cymodoce zone. *Palaeontology 21*, 31-63.

Braathen, A. 1996: Bruddsoner på Frøya og Nord-Hitra. *Norges geologiske undersøkelse Rapport 96.023*, 15 pp.

Bugge, T., Prestvik, T. & Rokoengen, K., 1980: Lower Tertiary volcanic rocks off Kristiansund – Mid Norway. *Marine Geology 35*, 277-286.

Bugge, T., Knarud, R. & Mørk, A. 1984: Bedrock geology on the mid-Norwegian continental shelf. *In*: Spencer, A.M. et al. (eds.) *Petroleum Geology of the North European Margin. Norwegian Petroleum Society, Graham & Trotman, London*, 271-283.

Bugge, T., Ringås, J.E., Leith, D.A., Mangerud, G, Weiss, H.M. & Leith, T.A. 2002: Upper Permian as a new play model on the mid-Norwegian continental shelf: investigated by shallow stratigraphic drilling. *American Association of Petroleum Geologists Bulletin 86*, 107-127.

Bøe, R. 1989: A pre-Devonian pediment in the lowermost Old Red Sandstone Hitra Group, Western Norway. *Norsk Geologisk Tidsskrift 69*, 21-28.

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

Bøe, R., Atakan, K. & Sturt, B.A. 1989: The style of deformation in the Devonian rocks on Hitra and Smøla. *Norges geologiske undersøkelse Bulletin 414*, 1-20.

Bøe, R. & Bjerkli, K. 1989: Mesozoic sedimentary rocks in Edøyfjorden and Beitstadfjorden, central Norway: implications for the structural history of the Møre-Trøndelag Fault Zone. *Marine Geology 87*, 287-299.

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

Bøe, R., Nordgulen, Ø. & Solli, A. 1992: Nord-Frøya, berggrunnskart 1422 I, M 1:50 000. *Norges geologiske undersøkelse.*

Dalland, A. 1979: The sedimentary sequence of Andøy, Northern Norway – Depositional and Structural History. *Proceedings, Norwegian Sea Symposium, Tromsø 1979. Norwegian Petroleum Society NNS/26*, 1-31.

Davidsen, B., Smelror, M. & Ottesen, D. 2001: Et nyoppdaget mesozoisk basseng i Sortlandsundet, Vesterålen. Abstract. *Norsk Geologisk Forenings XVII Vinterkonferanse,* Abstract Volume, 42-43.

Fossen, H., Mangerud, G., Hesthammer, J., Bugge, T. & Gabrielsen, R.H. 1997: The Bjorøy Formation: A newly discovered occurrence of Jurassic sediments in the Bergen Arc System. *Norsk Geologisk Tidsskrift 77,* 269-287.

Gautneb, H. & Roberts, D. 1989: Geology and petrochemistry of the Smøla-Hitra Batholith, Central Norway. *Norges geologiske undersøkelse Bulletin 416*, 1-24.

Grønlie, A., Harder, V. & Roberts, D. 1990: Preliminary fission-track ages of fluorite mineralization along fracture zones, inner Trondheimsfjord, Central Norway. *Norsk Geologisk Tidsskrift 70*, 173-178.

Grønlie, A., Nilsen, B. & Roberts, D., 1991: Brittle deformation history of fault rocks on the Fosen Peninsula, Trøndelag, Central Norway. *Norges geologiske undersøkelse Bulletin 421*, 39-57.

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

Grønlie, A. & Torsvik, T.H. 1989: On the origin and age of hydrothermal thorium-enriched carbonate veins and breccias in the Møre-Trøndelag Fault Zone, central Norway. *Norsk Geologisk Tidsskrift 69*, 1-19.

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

Høeg, O. A. 1945: Contributions to the Devonian flora of Western Norway III. *Norsk Geologisk Tidsskrift 25*, 183-192.

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

Kollung, S. 1963: Metamorfe og eruptive bergarter på Hitra. *Norges geologiske undersøkelse 223*, 161-222.

Manum, S. 1964: Nytt om Verran-kullene. *Fossil-nytt 3*, 1-2.

Mørk, M.B.E. & Stiberg, J.-P. 2003: Basement erosion and Mesozoic sandstone provenance in the Møre margin area. *In:* Norwegian Petroleum Society (ed.) *Petroleum Exploration and Production in Environmentally Sensitive Areas*, 41-44.

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

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

NGI 2002: Miljø- og samfunnstjenlige tunneler. Frøyatunnelen – Vurdering av injeksjon i forhold til Q-parametre. *Norges Geotekniske Institutt Rapport 20001042-1*, 18 pp.

Nordgulen, Ø., Solli, A., Bøe, R. & Sundvoll, B. 1990: Geologisk undersøkingar på Frøya og Froøyane. *Norges geologiske undersøkelse Rapport 90.073*, 49 pp.

Nordgulen, Ø., Bickeford, M.E., Nissen, A.L. & Wortman, G.L. 1993: U-Pb zircon ages from the Bindal Batholith, and the tectonic history of the Helgeland Nappe Complex, Scandinavian Caledonides. *Journal of the Geological Society of London 150*, 771-783.

Nordgulen, Ø., Solli, A. & Sundvoll, B. 1995: Caledonian granitoids in the Frøya-Froan area, Central Norway. *Norges geologiske undersøkelse Bulletin 427*, 48-51.

Nordhagen, R. 1921: Fossilførende blokker fra Juratiden på Froøyene utenfor Trondheimsfjorden. *Naturen 45*, 110-115.

Oftedahl, C. 1972: A sideritic ironstone of Jurassic age in Beitstadfjorden, Trøndelag. *Norsk Geologisk Tidsskrift 52*, 123-134.

Oftedahl, C. 1975: Middle Jurassic graben tectonics in mid-Norway. *In*: Norwegian Petroleum Society (ed.) Jurassic northern North Sea Symposium. *Proceedings Norwegian Petroleum Society,* 1-13.

Pascal, C., Gabrielsen, R.H., Zweigel, P., Sættem, J. & Angelier, J. 1999: Prediction of Late Cenozoic fault reactivation in the northern North Sea and the Mid-Norwegian margin from numerical simulations of far-field stress effects. Abstract. *Geonytt NGFs Vintermøte 1999*, 80-81.

Pascal, C. & Gabrielsen, R.H. 2001: Numerical modeling of Cenozoic stress patterns in the mid-Norwegian margin and the northern North Sea. *Tectonics 20*, 585-599.

Prestvik, T., Torske, T., Sundvoll, B. & Karlsson, H. 1999: Petrology of early Tertiary nephelinites off mid-Norway. Additional evidence for an enriched endmember of the ancestral Iceland plume. *Lithos 46,* 317-330.

Sherlock, S.C., Watts, L.M., Holdsworth, R.E. & Roberts, D. 2004: Dating fault-reactivation by Ar/Ar laserprobe: an alternative view of apparently cogenetic mylonite-pseudotachylite assemblages. *Journal of the Geological Society, London 161*, 335-338.

Siedlecka, A. & Siedlecki, S. 1972: A contribution to the geology of the Downtonian sedimentary rocks of Hitra. *Norges geologiske undersøkelse 275*, 1-28.

Siedlecka, A. 1975: Old Red Sandstone lithostratigraphy and sedimentation of the outer Fosen area, Trondheim Region. *Norges geologiske undersøkelse 321*, 1-35.

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

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

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

Sturt, B.A., Dalland, A. & Mitchell, J.L. 1979: The age of the sub Mid Jurassic tropical weathering profile on Andøya, Northern Norway, and the implications for the Late Palaeozoic palaeography in the North Atlantic region. *Geologische Rundschau 68*, 523-542.

Sættem, J. & Mørk, M.B.E. 1996: Frøyatunnelen: Studie basert på vertikalboringer og regional lineament-informasjon. *IKU Petroleumsforskning a.s Rapport 96.018*, 35 pp.

Torske, T. 1983: A fluidization breccia in granite at Skaget, Svellingen, Frøya. *Norges geologiske undersøkelse 380,* 107-123.

Vigran, J.O. 1970: Fragments of a Middle Jurassic flora from northern Trøndelag, *Norway. Norsk Geologisk Tidsskrift 50*, 193-214.

Watts, L.M. 2001: *The Walls Boundary Fault Zone and the Møre-Trøndelag Fault Complex: a case study of two reactivated fault zones*. Unpublished Ph.D. thesis, University of Durham, 550 pp.