Depth of extensional faulting on the Mid-Norway Atlantic passive margin

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Two crustal-scale cross-sections of the Mid-Norwegian Atlantic passive margin are discussed. Large W- and E-dipping normal faults relate to extension of the continental crust following the Caledonian orogeny and the subsequent opening of the Atlantic Ocean. The passive margin extends from the ocean-continent boundary west of the Vøring Marginal High to the innermost extensional normal faults 90 km west of the Caledonian thrust front. Based on earthquake data and published results of geophysical modelling and seismic interpretation, the average depth to which the normal faults extend in the offshore domain is estimated to 20±5 km. This depth corresponds to the brittle-ductile transition in the crust of the stretched Mid-Norwegian continental margin. Above this transition the crust extended by brittle faulting (tilted blocks); below this limit the crust extended in a ductile manner.

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Introduction

Knowledge of the present-day structure at crustal and lithospheric scale and of the depth to the major extensional faults helps us to understand the large-scale tectonic processes involved in the development of the Mid-Norwegian passive margin. Two crustal-scale cross-sections, one in the Lofoten area and the other along the Storlien-Trondheim-Vøring transect are discussed (Figs. 1 and 2). The depth to the detachment and/or the depth to which the extensional faults extend, has been investigated by analysis of earthquake depths (Fig. 3) in combination with interpretations of existing seismic surveys and geophysical modelling.

The Mid-Norway passive margin developed in continental crust and reaches from the innermost extensional normal faults, near Åre some 90 km west of the Caledonian thrust front close to Östersund (Sweden), to the western termination of the Vøring Marginal High and the transition to oceanic crust (Figs. 1 and 2). The structure and geology in the central part of the Mid-Norway Atlantic margin is the result of a polyphase deformation, including the development of an active margin (Caledonides), followed by multiple extensional events leading to the development of a new passive margin. The Caledonian structures comprise a succession of stacked nappes, resulting from the closure of the Iapetus Ocean and the convergence of Baltica and Laurentia during Early Palaeozoic time, forming the Caledonian (Scandian) orogen. A succession of extensional events eventually culminated with the opening of the North Atlantic Ocean (Vågnes et al. 1998, Doré et al. 1999, Gabrielsen et al. 1999, Brekke 2000). The Late Palaeozoic-Mesozoic sedimentary cover sequences were deposited in this extensional environment. Continued extension and deposition since the latest Cretaceous in this proto-NE Atlantic eventually led to the opening of the Atlantic Ocean. Such sedimentary sequences are found in the offshore realm where the structural style is dominated by graben development and locally inverted dome structures of Tertiary age. For a detailed discussion of the regional geology onshore and offshore the reader is referred to papers by Gee et al. (1985), Roberts & Gee (1985), Stephens & Gee (1985) and Stephens et al. (1985); and the structural elements maps of the Norwegian continental shelf (Blystad et al. 1995); the metamorphic, structural and isotope age map, and the bedrock map of Central Fennoscandinavia (Lundqvist et al. 1996, 1997).

The cross-sections discussed are simplified regional sections linking the onland with the offshore structures. They are based on existing and available data, combined with new interpretation at depth, and show simplified, viable, structural solutions. The emphasis is on the post-Late Permian extensional structures, and on the location and depth of the major, normal fault systems affecting the crust. A distinction is made between basement *sensu lato* (s.l.) and sedimentary cover. Included in the basement s.l. are the Caledonian nappes, the autochthonous substratum (basement *sensu stricto* (s.s.)), and the Devonian and Early Permo-Carboniferous grabens with their variably metamorphosed sedimentary rocks. The sedimentary cover comprises all post-Late Permian deposits. The detailed geology and structures of the different tectonic units are not represented on the sections for reasons of readability.

Thermo-mechanical and rheological modelling is beyond the scope of this paper, as is the detailed discussion of the possible relationship of the extensional structures and the Caledonian compressional (thrust)/extensional structures.

Onshore/offshore cross-section

Seismic investigations, both onshore and offshore, have imaged structures at depth in different areas between the

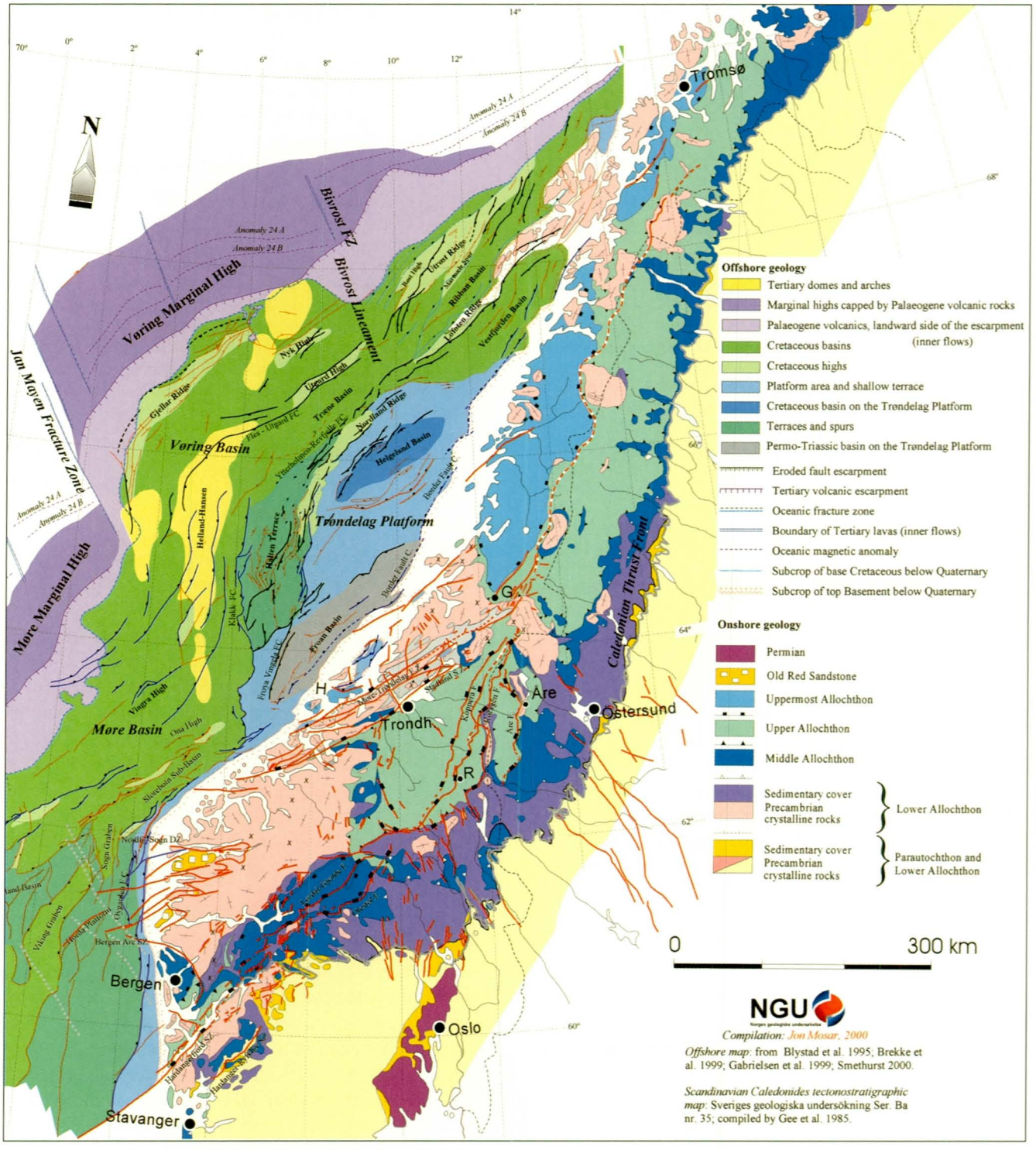

Fig. 1. Simplified tectonostratigraphic map of the Atlantic Norwegian passive margin. Bold black lines show location of crustal-scale cross-sections in Fig. 2. In red, blue and black are shown the post-Late Permian normal faults onshore, as well as faults with undetermined movement/age. H = Hitra; R = Røragen; Trondh. = Trondheim.

oceanic crust to the west of the Vøring Marginal High, and the overthickened, extended continental crust to the east (Storlien-Östersund, Sweden). It appears that the onshore portion is affected by extensional, crustal-scale faulting and development of small basins (Fig. 2; see also Hurich et al. 1988, Sjöström & Bergman 1989, Sjöström et al. 1991, Wilks & Cuthbert 1994, Andersen 1996, Hartz & Andresen 1997, Andersen et al. 1999). These structures are similar to those described in western and southern Norway (Fossen & Rykkelid 1992, Andersen 1996, Hurich 1996, Dunlap & Fossen 1998, Fossen & Dunlap 1998, Osmundsen et al. 1998, Fossen et al. 1999, Gabrielsen et al. 1999, Christiansson et al. 2000). Normal faulting also occurred in the continental crust in the Ofoten-Lofoten area further north (Rykkelid & Andresen

1994, Coker et al. 1995, Hames & Andresen 1996, Klein et al. 1999). Similar faults are also present in the offshore substratum of the Trøndelag Platform, in the Vøring Basin, as well as beneath the Lofoten and Utrøst Ridges (Blystad et al. 1995, Doré et al. 1999, Gabrielsen et al. 1999).

Two E-W cross-sections are discussed (Figs. 1 and 2): one from east of Åre (Sweden), through Trondheim and the Fosen Peninsula, and across the Trøndelag Platform into the Vøring Basin; and a second across the Lofoten area, through the Utrøst High into oceanic crust. Interpretations of the offshore setting of both sections are based on: 1) published geoseismic profiles after seismic reflection data (Blystad et al. 1995), 2) seismic refraction data (Planke et al. 1991, Mjelde et al. 1993, 1996, 1997, 1998, Planke & Eldholm 1994), and 3) geophysical modelling (Goldschmidt-Rokita et al. 1988, Skogseid et al. 1992, Skogseid 1994, Skogseid & Eldholm 1995, Olesen et al. 1997, Digranes et al. 1998).

Interpretations of the different published data, while largely in agreement, are not necessarily identical. The cross-sections discussed herein try to satisfy the most relevant observations and attempt to highlight the most important changes in basin structure, fault geometry, and basement/Moho depth.

In the southern Vøring-Åre section, four main domains are recognised (Fig. 2): [I] the Åre-Trondheim-Fosen area, [II] the Trøndelag Platform, [III] the Vøring Basin, [IV] and the Vøring Marginal High that forms the transition to oceanic lithosphere to the west. These four domains are underlain by continental crust. Along the Vøring-Åre section, the passive margin is rather wide (500 km offshore + 220 km onshore) compared with the Lofoten margin (250 km) or many other segments of the Atlantic Ocean. However, equally wide margins exist, for example, off Newfoundland (Tankard & Welsink 1989, Welsink et al. 1989, Driscoll et al. 1995) or along the northeast margin of Greenland.

In the Åre-Trøndelag portion of the section, it is possible to utilise deep seismic reflection data (Hurich et al. 1988, 1989, Gee 1991, Palm 1991, Palm et al. 1991, Hurich 1996, Hurich & Roberts 1997 and in prep.) to constrain the structures at depth. This profile shows a 10-15 km-thick stack of Caledonian nappes (Fig. 2), which resulted from thrusting of the exotic terranes from Laurentia/Iapetus and the imbrication of the W-subducting margin of Baltica (Gee et al. 1985, Stephens et al. 1985, Stephens & Gee 1989, Rey et al. 1997). Post-dating the Caledonian structures, a series of at least four, mainly west-dipping, normal faults cut the fold-and-thrust belt (Norton 1986, 1987, Gee 1988, Sjöström & Bergman 1989, Sjöström et al. 1991, Gee et al. 1994, Wilks & Cuthbert 1994, Andersen 1996, Hurich & Roberts 1997, Andersen et al. 1999) (Figs. 1 and 2).

The innermost normal faults, including the Røragen detachment (Sjöström & Bergman 1989, Gee et al. 1994), are located west of the frontal thrust of the Caledonian orogenic wedge. The fault with the largest normal offset is located within the Meråker Nappe, and has been termed the Kopperå fault (Hurich & Roberts, in prep., D. Roberts, pers. comm. 2000). Farther east is the Røragen detachment, located close to the Norwegian-Swedish border and there overprinting a major thrust; and the innermost normal fault – here called provisionally the Åre fault – located 1 km west of Åre (Sweden) (Figs. 1 and 2).

Along the coast, the polyphase Møre-Trøndelag Fault Complex forms a major high-strain shear zone cutting through the Central Norwegian Caledonides (Gabrielsen 1989, Grønlie & Roberts 1989, Séranne 1992, Roberts 1998). Multiple reactivation recorded along this fault complex ranges from sinistral ductile movement in the Devonian period (Grønlie & Roberts 1989) to brittle offsets in Late Cretaceous-Early Tertiary time (Grønlie et al. 1990, 1991). From the distribution of earthquakes (Fig. 3) it appears that the present-day seismic activity along this fault is very low or non-existent (NFR/NORSAR 1998). The Møre-Trøndelag Fault Complex appears to be an upper crustal feature that terminates against a major extensional fault at depth (Fig. 2), as has been interpreted from deep seismic profiling (Hurich & Roberts 1997). A similar conclusion has been reached from recent investigations on the Great Glen Fault (McBride 1995), which bears analogies with the Møre-Trøndelag Fault Complex (Coward 1993, Chauvet & Séranne 1994).

Offshore, the southern cross-section shows a strongly variable thickness of the crust. This is related to rifting, partly in Permo-Jurassic time, but mainly during the Cretaceous period (Doré et al. 1997, 1999, Swiecicki et al. 1998, Brekke et al. 1999, Brekke 2000). The Trøndelag Platform is affected by few, major, normal fault systems and the crust appears to have been only moderately stretched. Mesozoic basins and stretching were possibly superimposed on important Palaeozoic (Devono-Carboniferous?) basins. Normal faults with large throws were active mainly in the Vøring Basin (Brekke et al. 1999, Brekke 2000). In the central Vøring Basin, the crust is very thin (Fig. 2) and lithospheric mantle is present quite close to the floor of the sedimentary basin (Skogseid 1994, Skogseid & Eldholm 1995). Conversely, the sedimentary basins are very deep with up to 8-12 km of sediments.

The cross-section in the Lofoten area shows a typical, tilted block, margin geometry with major, west- and east-dipping, normal faults. The section shows four different structural highs: [I] onshore area, [II] Lofoten Ridge, [III] Marmæle Spur, and [IV] Røst High. The most important thinning of the crust is observed to the west of the Vestfjorden Basin, beneath the Lofoten Ridge (Mjelde 1992, Mokhtari & Pegrum 1992, Mjelde et al. 1993, Goldschmidt-Rokita et al. 1994, Løseth & Tveten 1996). Unlike the Åre-Trondheim-Vøring section, the Lofoten cross-section shows a width of only some 250 km for the passive margin realm. The strong thinning of the lower crust beneath the Lofoten Ridge - from 11.5 to 2 km - appears to be due mainly to ductile stretching in the lower crust.

Underplated magmatic material occurs in both sections

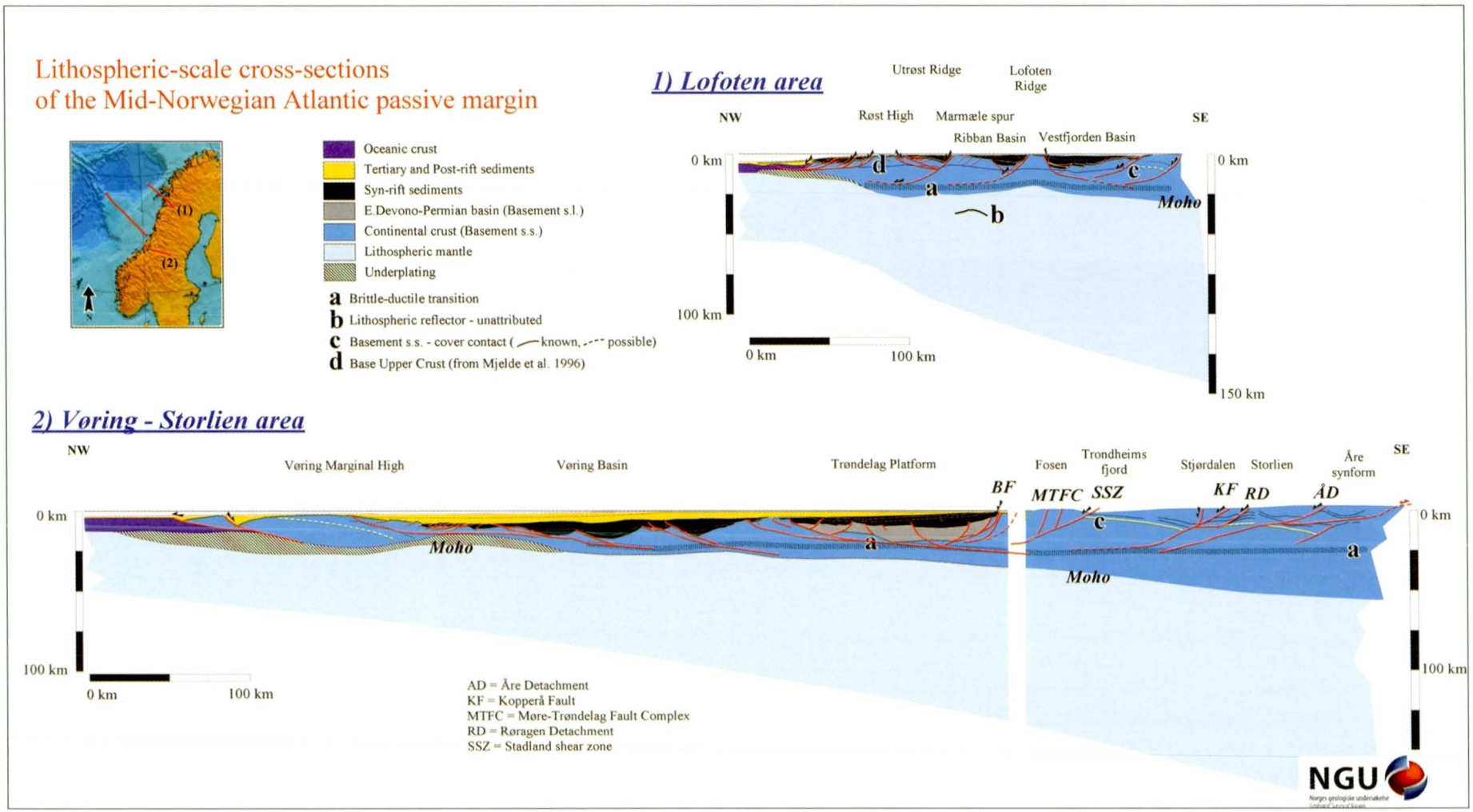

Fig. 2. Crustal-scale cross-sections of the Mid-Norwegian Atlantic passive margin. Cross-sections are compiled and simplified from existing data (see references in text). Faults in the offshore domain have been extended to depth into the zone of the brittle-ductile transition. Caledonian basement-cover structures in the offshore area are inferred, by analogy with information from the onshore structures. Onshore structures in the Fosen-Storlien area are from deep seismic profiling (Hurich & Roberts 1997). The Swedish portion of the section is from Palm et al. (1991).

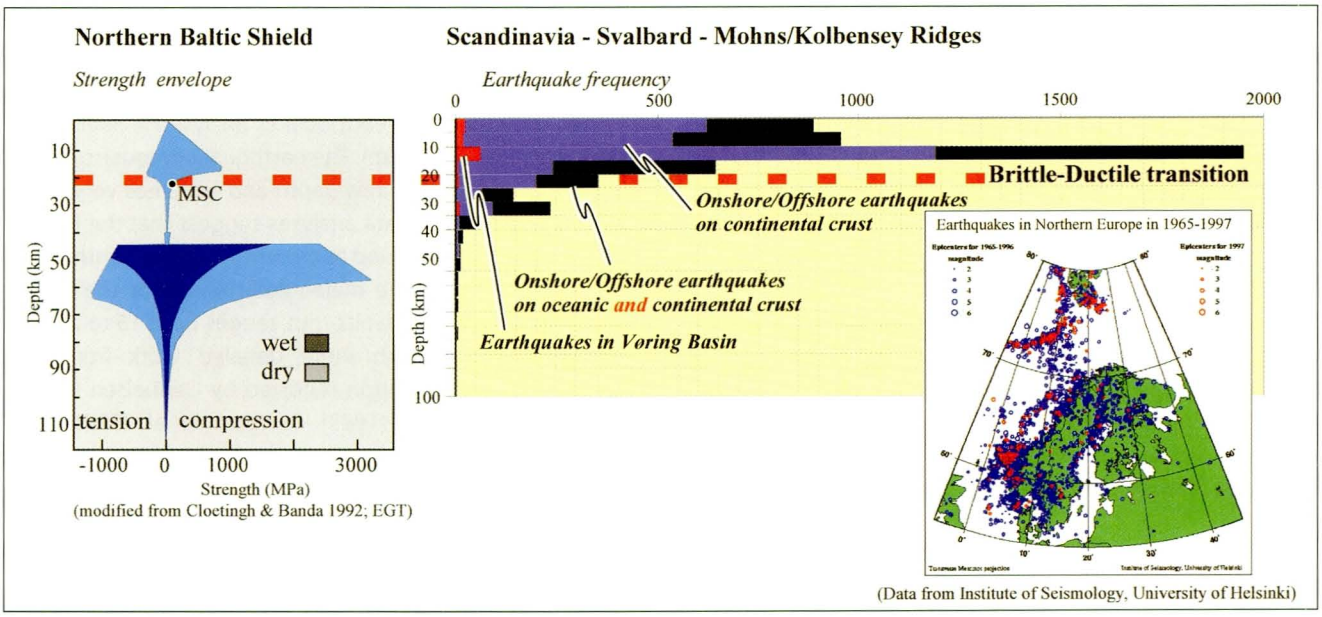

Fig. 3. Depth of earthquakes from Norway and the Norwegian Sea and the strength envelope for the Northern Baltic Shield. Analyses of earthquake depths show that most of the seismicity occurs in the middle-upper crust above 25 km depth. The strength-depth relationship of the lithosphere is expressed by rheological profiles or strength envelopes. The base of maximum occurrences of earthquakes corresponds well with the base of the mechanically strong crust (MSC) deduced from the strength profile and coincides with the brittle-ductile transition (rheologies are for quartzite, diabase and olivine/dunite layering; Cloetingh & Banda 1992).

along the ocean-continent (passive margin) boundary, at the crust-mantle transition (Skogseid et al. 1992, Mjelde et al. 1997, 1998). This underplated material has been interpreted from high-velocity bodies below the crust, and is thought to have resulted from adiabatic decompressional melting of the mantle, followed by preferential melt migration along the crust-mantle boundary (Skogseid et al. 1992). There appears to be a smaller volume of underplated material along the Lofoten section than along the Vøring-Åre profile. In general, the amount of underplated material (high-velocity intrusions in the lower crust) decreases landwards. Some magma underplating may be of Cretaceous age, in view of the stronger extension that affected the Vøring Basin during this period. Similar magmatic underplating has been recorded along many profiles along the European Atlantic margin (Faeroe, Rockall, Greenland, North Sea, Møre).

Polyphase extensional faulting and tilted block margin

Both orogenic and post-orogenic (post-Late Permian), polyphase, extensional deformation dissected the Caledonides. Extensional faulting was active at different periods and at different depths, and has been documented from isotope ages, mineral assemblages and sedimentation history (Boundy et al. 1996, Torsvik et al. 1997, Andersen 1998, Klein et al. 1999).

Extension is known to have started in Early Devonian (c. 405 Ma) at depths of c. 10 km, following the Scandian collisional climax. Simultaneously and continuing into the Middle Devonian, sediments were deposited in actively extending half-grabens in the hangingwalls to the Caledonian nappes (Steel 1976, Bøe et al. 1989, Osmundsen & Andersen 1994, Osmundsen et al. 1998, Andersen et al. 1999). These sediments were folded and metamorphosed at sub-greenschist to lower greenschist facies (Bøe et al. 1989) and subsequently brought to the surface, most likely due to normal faulting and extension (Fossen 1992, 2000).

Important detachment and high-angle faults affected both the present-day onshore section and the concealed offshore parts of the Caledonides. These extensional faults are linked to rifting associated with the breakup of Pangea which started in Permo-Triassic time and continued into the Mesozoic (Eide et al. 1997, 1999, Torsvik et al. 1997, Andersen et al. 1999, Braathen 1999). Thus, by way of example, during Jurassic-Cretaceous time, a small spoon-shaped sedimentary half-graben developed in Beitstadfjorden, in the innermost Trondheimsfjord, along the Verran Fault branch of the Møre-Trøndelag Fault Complex (Bøe & Bjerkli 1989). Further inland to the east, the Røragen detachment appears to be genetically linked with the Lærdal-Gjende Fault farther south. Recent investigations have shown that movement on this latter fault system occurred in the Permian and the Jurassic (Eide et al. 1997, Andersen et al. 1999). By analogy it is suggested that movements on the Åre-Røragen detachment system were also occurring during Permo-Jurassic time.

During Permo-Triassic times, basin development was most likely concentrated in the Trøndelag Platform region (but also along the present-day Greenland coast), while during the Mesozoic, the major deeper basins developed farther west (Brekke et al. 1999, Brekke 2000, Reemst & Cloetingh 2000, Skogseid et al. 2000). Associated with the

general extension of the passive margin, smaller basins also developed farther east and west (west of the Nordland Ridge). Basin development continued throughout the Cretaceous, particularly in the Vøring Basin, and finally culminated in the opening of the North Atlantic Ocean - east of the Vøring Marginal High - and the separation of Greenland and Norway (Blystad et al. 1995, Doré et al. 1997, Lundin & Doré 1997). The Norwegian Atlantic margin developed from there on as a passive margin.

NW-SE directed compressional (thrusting) and extensional (normal) faulting and strike-slip faulting is still active at the present-day as seen from earthquake data (Bungum et al. 1991 for location and detailed discussion). The most active regions lie along the western and eastern borders of the Trøndelag Platform, as well as in the Lofoten area.

Depth of the faults/detachment – rheology/earthquake data

Geological, geophysical and laboratory experiments suggest that the mechanical lithosphere is rheologically stratified. This layering reflects changes in the mechanical behaviour and flow processes of lithospheric rocks, as determined by depth-dependent physical (P, T) and chemical (mineral composition, %water) environments.

From seismic profiles onshore, as well as offshore, it can be seen that the faults which limit the major half-grabens extend into the upper crust (Fig. 2). Depending on their age of formation (from Devonian through to Cretaceous) and location, onshore vs. offshore, these grabens have been filled with sediments. Their depth in the brittle portion of the crust can be estimated from geophysical methods and by considering the strength profile of the continental crust and the depth of the present-day earthquakes. The present-day strength profile in the Central Baltic Shield (Cloetingh & Banda 1992) indicates that the mechanically strong crust extends down to a depth of 21 km (Fig. 3 – MSC = base of the mechanically strong crust). The brittle-ductile transition zone forms the lower boundary to the seismic activity. Therefore, the earthquake depth is controlled by the thickness of the brittle part of the crust. In extensional domains, as well as in compressional orogens, faults frequently root in this zone.

The depth distribution of earthquakes in Norway, the Norwegian shelf (including Svalbard) and the oceanic domain east of the mid-oceanic ridge has been analysed to determine the depth to the base of the present-day brittle crust (Fig. 3). These data include documented NW-SE extensional faulting and local NW-SE compressive events (Bungum et al. 1991, Atakan et al. 1994, NFR/NORSAR 1998).

In this oceanic-continental domain, the majority of the earthquakes are located between 0 and 25 km depth (Fig. 3). A mean depth of 14.2 km was calculated for the whole data set (ocean and continent; number of earthquakes = 5308, standard deviation = 11 km). The depth distribution of the earthquakes shows a strongly skewed distribution with a majority of earthquakes above the mean value and a rapidly diminishing number of earthquakes below the mean value. Domains underlain exclusively by continental crust (Vøring Basin, Trøndelag Platform and onshore) show a mean depth of 12.9 km (number of earthquakes analysed = 3006; standard deviation = 10.4 km). The earthquake frequency diminishes markedly below this depth and becomes very weak below 25-30 km. The data analyses suggest that the brittle-ductile transition is located at around 15-25 km depth. Thus, the depth to a possible major detachment, or the depth where the extensional faults root, ranges from 15 to 25 km. This is consistent with more detailed work from the Norwegian Atlantic margin reported by Gabrielsen (1989), Gregersen & Basham (1989), Bungum et al. (1991) and NFR/NORSAR (1998).

The overthickened crust of the Baltic Shield is further stretched beneath the base level of these faults, mainly in the Vøring Basin (where interpretation of refraction data suggests that the lower crust almost completely disappears) and the Lofoten Ridge areas. This extension occurs below the ductile-brittle transition zone in the lower crust, where the crust deforms in a ductile fashion and may sustain substantial stretching, while the upper crust is extended largely by brittle normal faulting. Permo-Triassic, Jurassic and Cretaceous (Eide et al. 1997, Andersen et al. 1999) to Tertiary extension acted upon the continental lithosphere created after the Caledonian orogeny (following the orogenic collapse, the subducting slab-breakoff/removal of the gravitationally unstable crustal root; Andersen & Jamtveit 1990, Koyi et al. 1999). This is in accordance with the results of analogue modelling, where the upper and lower crust decouple and develop strong boudinage (necking) in the lower ductile crust, eventually juxtaposing upper crust with asthenospheric mantle (Brun & Beslier 1996, Gartrell 1997). This ductile extension is considered to be related to the stretching of the lithosphere associated with the progressive development of the North Atlantic oceanic realm.

Though its thermo-mechanical structure may have changed throughout the evolution of the margin, it has been shown that the brittle-ductile structure of the crust is a permanent feature. The position of the brittle-ductile transition, together with the zones of weakness created by the development of successive normal faults, have determined the evolution of the deformation in the crust. It has, however, been shown that for successive rift episodes the necking level remains at a rather constant depth with a best-fit solution at around 20 km for the Vøring Basin (Reemst & Cloetingh 2000). The necking level represents a zone of concentrated brittle deformation associated with a detachment zone, which gives way to a more distributed deformation in the lower crust. This level largely controls the kinematics of extension in passive margins (Kooi & Cloetingh 1992, Kooi et al. 1992, van der Beek et al. 1994, Reemst & Cloetingh 2000). In a simplified first-order approach it is suggested here that it is therefore realistic to admit that since the Early Mesozoic, the position of the ductile-brittle transition has remained

within the same depth range, even though the geometry of the crust has changed substantially in localised zones.

Conclusions

Crustal-scale cross-sections of the Mid-Norwegian Atlantic passive margin illustrate the overall geometry of the margin and the main structural features. The Mid-Norway passive margin reaches from the innermost normal faults near Åre (Sweden), some 90 km west of the Caledonian thrust front near Östersund (Sweden), to the western termination of the Vøring Marginal High and the transition to oceanic crust.

Polyphase extensional events between the Late Permian and the Palaeocene led to break-up and development of the North Atlantic Ocean in the Early Eocene (magnetic anomaly 24). Caledonian structures and nappes were cut by Late Palaeozoic to Mesozoic normal faults, and the continental crust was stretched repeatedly, leading to the development of deep sedimentary basins. The possible reactivation, as normal faults, of Caledonian thrusts or Palaeozoic extensional faults in the Trøndelag Platform-Vøring Basin area cannot be excluded, but is difficult to demonstrate with the data available to date. The same structures observed onland are expected to occur offshore, beneath the Mesozoic and Cenozoic sedimentary successions. The normal faults define a series of tilted blocks forming important half-grabens with associated structures such as roll-overs, hangingwall grabens and antithetic faults (mainly observed in the sedimentary cover sequences). The normal faults bounding the different tilted blocks do not necessarily merge into one single décollement horizon.

During the successive extensional events, the upper-middle crust behaved in a brittle manner and is characterised by normal faults. The roots of these faults are interpreted to coincide with the brittle-ductile transition zone. From earthquake depths this transition zone has been determined to lie at around 15-25 km depth.

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