Post-Caledonian structural evolution of the Lofoten and Vesterålen offshore and onshore areas

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The Lofoten/Vesterålen land area is the only exposed basement high on the continental margin around mainland Norway. The onshore and offshore areas went through a rapid crustal cooling from temperatures higher than 550°C at maximum Caledonian metamorphism, through temperatures around 300–400°C in late Devonian/mid-Carboniferous, to surface temperature in mid-Jurassic. During the early to mid-Jurassic, a smooth, peneplained basement relief developed throughout the area. In mid-Jurassic, a period of normal faulting, subsidence and sedimentation was initiated and large parts of the Lofoten/Vesterålen off- and onshore areas subsided. Faulting occurred more or less continuously throughout the mid-Jurassic to early Cretaceous, but the largest fault movements took place during the early Cretaceous, presumably in Albian to Aptian times. During the early Cretaceous, the Lofoten Ridge developed as a horst while the surrounding areas (Vesterålen/Andøya and sedimentary basins) subsided below a several km thick Lower Cretaceous succession. The final rifting phase during late Cretaceous and Palaeocene was focused west of the Utrøst Ridge and Andøya, but minor faulting also occurred throughout the Andøya/Vesterålen/Lofoten area. During a late Cenozoic compressional phase the entire Lofoten and Vesterålen margin east of the present shelf edge was uplifted and eroded. The erosion and resulting isostatic uplift continued throughout the glacial period.

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Introduction

The Lofoten and Vesterålen islands (Fig. 1) constitute parts of a basement high on the mid-Norwegian margin characterised by thinned continental crust. This is demonstrated by gravity data (Norges geologiske undersøkelse & Statens kartverk 1992) (Fig. 2) and deep crustal profiles (Mjelde et al. 1993) (Fig. 3), which demonstrate crustal thicknesses between 20 km and 27 km in this area. The Lofoten/Vesterålen area is the only exposed basement high on the continental margin around mainland Norway and the only exposures of Jurassic and Cretaceous sediments in Norway are located on Andøya in the northern part of the study area (Dalland 1981). In view of the similarity in crustal thickness (20–27 km), the onshore and offshore areas have experienced roughly similar amounts of post-Caledonian crustal extension and the structural evolution is comparable. This paper describes and compares onshore observations with those from seismic data in the surrounding offshore sediment basins in order to establish a framework for the post-Caledonian structural evolution. Of particular interest is the comparison between the mid-Jurassic to early-Cretaceous geologic evolution described from Andøya (Dalland 1981) with observations in the surrounding sedimentary basins. The detailed work reported in this paper is focused on the transition between Lofoten and Vesterålen and the northern Ribban Basin, but relevant information from the shelf from 67°30′N to 69°30′N is used to construct the geologic history.

Onshore

Geologic setting

A suite of crystalline rocks dated to 2700 through 1140 ± 135 Ma (Griffin et al. 1978) is exposed on the islands of Lofoten and Vesterålen. These rocks are metamorphozed to granulite facies in the west and to amphibolite facies in the east. Caledonian rocks, as well as Caledonian deformation of the Precambrian rocks, are almost absent, except for a few pegmatite dikes on Moskenesøy that give K-Ar ages of 317 ± 3 Ma (muscovite) and 418 ± 2 Ma (biotite) (Griffin et al. 1978). The nearest exposed Caledonian rocks are found on the eastern side of Hinnøy (Fig. 1). They are of garnet-kyanite grade (Griffin et al. 1978), indicating temperatures more than 550°C corresponding to burial of ~18 km assuming a geothermal gradient of 30°C/km. This unit is placed tectono-stratigraphically above the Precambrian rocks (Stephens et al. 1985). Caledonian thrust sheets were probably also transported above the Precambrian rocks in Lofoten and Vesterålen from an original position west of these islands. During the Caledonian orogeny the present outcropping Precambrian rocks in Lofoten and Vesterålen were located deep in the crust.

The present understanding of the post-Caledonian geological evolution from the on-shore area is mainly based on an analysis of the mid-Jurassic to lower Cretaceous sediments on Andøya (Dalland 1981) (Fig. 4). Here, a transgression initiated during Bajocian (Manum, Bose & Vigran 1991) and fluvial sands of the Hestberget Member

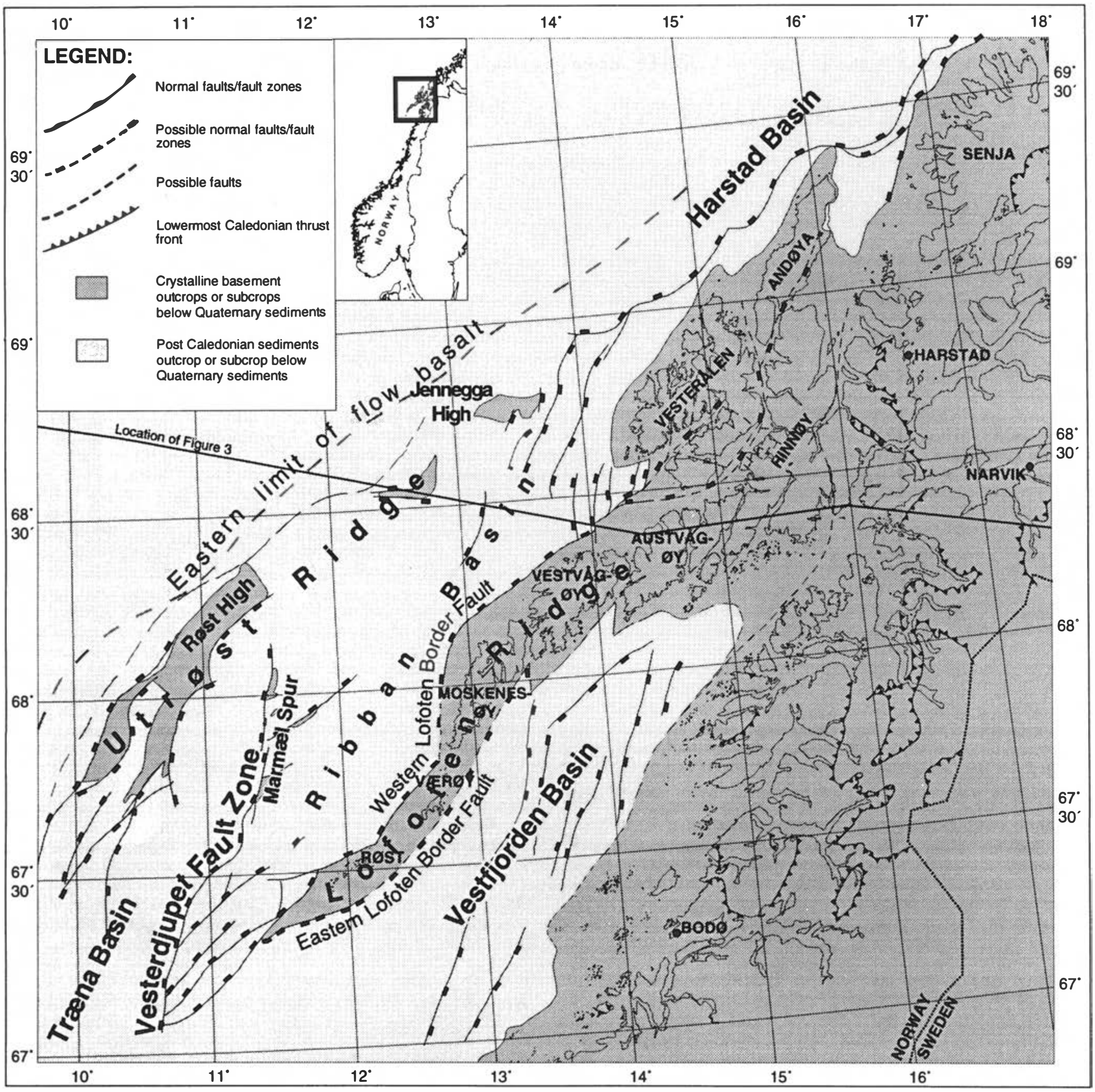

Fig. 1. Structural overview map of Lofoten, Vesterålen, surrounding sediment basins and structural highs. The structural elements are defined by Blystad et al. (1995). The location of the crustal profile in Fig. 3 is indicated.

(lower part of the Ramså Formation) covered the kaolinized weathered basement in the depressions in downfaulted blocks. The Ramså Formation grades into shallow marine sandstones (Bonteigen Member) of Oxfordian/Kimmeridgian age. More marine conditions existed during the deposition of the Dragneset Formation in Kimmeridgian and Volgian times. Uplift associated with block faulting created an unconformity that separates the upper Jurassic Dragneset Formation from the lower Cretaceous Nybrua Formation of Ryazanian and Valanginian age. The Nybrua Formation is believed to have been deposited under shallow marine conditions, partly below wave base. Between the Nybrua Formation and the overlying Skarstein Formation, which is the upper part of the Andøya stratigraphy, an unconformity or non-deposition during Hauterivian is suggested. The Skarstein Formation comprises marine silty shales (Nordelva Member) of Hauterivian and Barremian? age in the lower part, and in the upper part relatively deep marine turbidites (Hellneset Member) of Aptian age.

Several high-angle normal faults, often with relatively brittle fault rocks, are observed to cut through the Precambrian rocks (Tveten 1978; Dalland 1981; Bartley 1982). On Andøya, a set of nearly vertical NNE–SSW

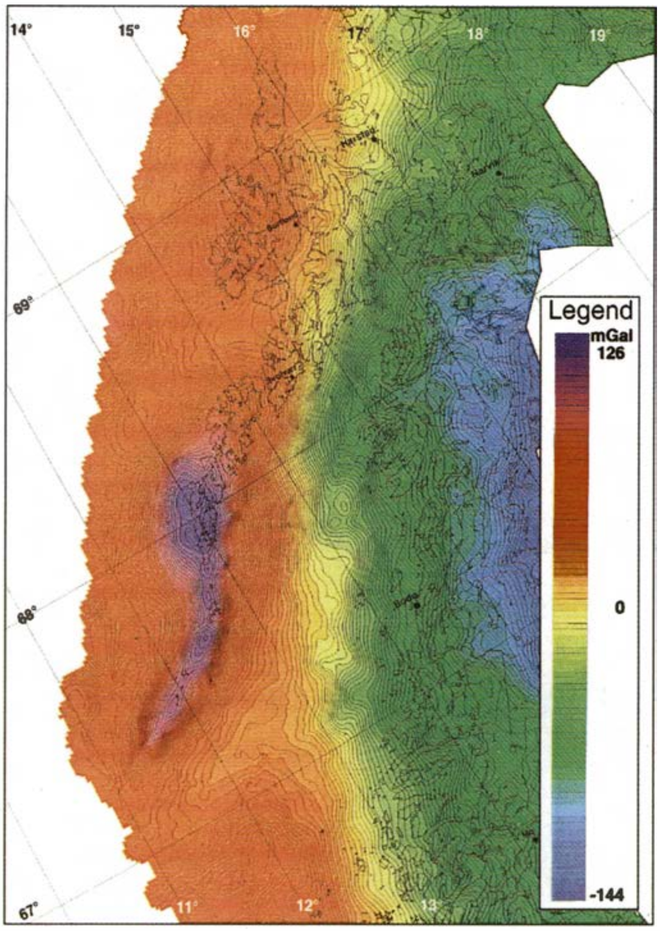

Fig. 2. Bouguer gravity map (*Norges geologiske undersøkelse & Statens Kartverk* 1992). The boundary between the approximately 40 km thick continental crust below mainland Norway and the continental margin is defined by the steep gravity gradient east of Vestfjorden Basin (yellow zone). The higher densities below the Lofoten/Vesterålen area are mainly due to a thinner continental crust than on mainland Norway and demonstrates that Lofoten/Vesterålen constitutes part of the margin. The highest gravity on Moskenesøy is probably due to a combination of doming of Moho to around 20 km (Mjelde et al. 1993) and high-density rocks in the area.

striking faults with small displacements are observed to be younger than the lower Cretaceous sediments (Dalland 1975) indicating a relative late tectonic episode here. Indications of the post-Caledonian history are also found in the radiometric (K-Ar) ages from a weathering profile in the basement below the Mesozoic sediments on Andøya (Sturt, Dalland & Mitchell 1979).

Onshore faults

Several faults have been observed in the field. Some can be followed over some distance, but most of the faults are only observed in local outcrops. Both sub-horizontal and sub-vertical faults are observed. It is a general observation that the fault rocks in the sub-horizontal faults were formed at higher temperatures than the sub-vertical faults, which often indicate brittle deformation. In the following, some of the observed faults and fault zones are described, starting with those indicating highest temperatures during deformation. Widely distributed mesoscopic pseudotachylytes are also presented and can be related to the post-Caledonian regional structural development.

Sub-horizontal fault zones. – A few metres thick ultramylonitic and micro-brecciated zone that strikes NE–SW and dips around 30° to the NW was described by Heier (1960) on SE Langøya (Figs 5, 6). The zone separates unaltered anorthosites above from underlying mangerites. Simple shear observations indicate upper block movements towards the NW. Medium- to low-grade mineral paragenesis is observed in the mylonitic fault zone, but post-tectonic overgrown amphibole is also seen. The zone has not yet been dated by isotope methods. The foliation in the mangeritic gneiss beneath the

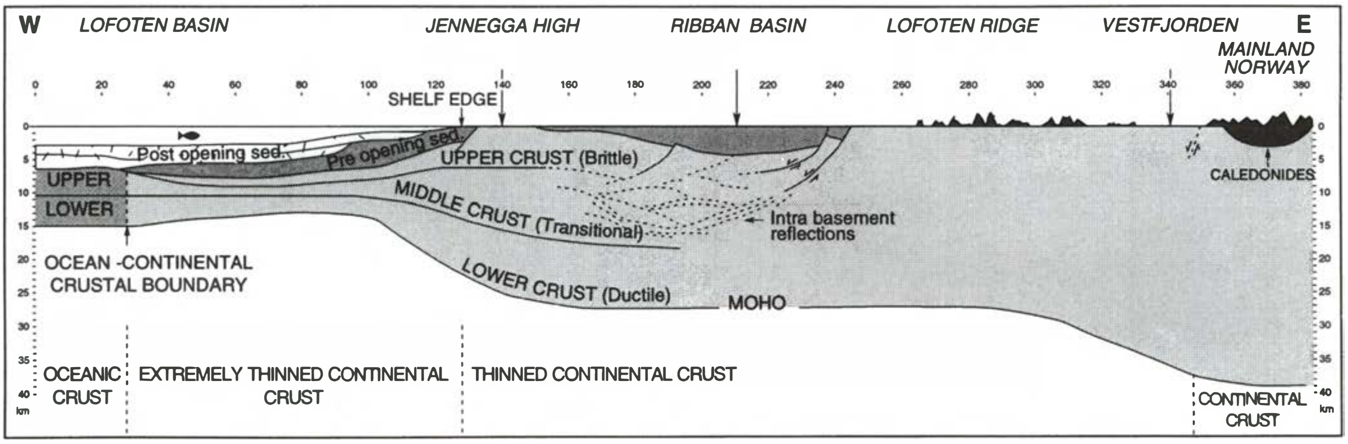

Fig. 3. Simplified E–W crustal profile from mainland Norway to the continental–oceanic transition. The profile demonstrates the decrease in crustal thickness from approximately 40 km below mainland Norway to less than 30 km below the Lofoten/Vesterålen islands. Lofoten and Vesterålen are therefore a currently exposed basement high on the extended and thinned continental margin. Westward, a further reduction to crustal thickness around 15 km is seen at the shelf edge. The western part of the profile is modified after Mjelde (1991). The depth to Moho below the northern Lofoten islands is extended from Sellevoll (1983) based on gravimetry data (Fig. 2). The crustal thickness below the Norwegian mainland is extrapolated northwards from the Blue-Norma profile (Goldsmith-Rokita et al. 1988) with basis in gravimetry data. The approximate location of the profile is given in Fig. 1.

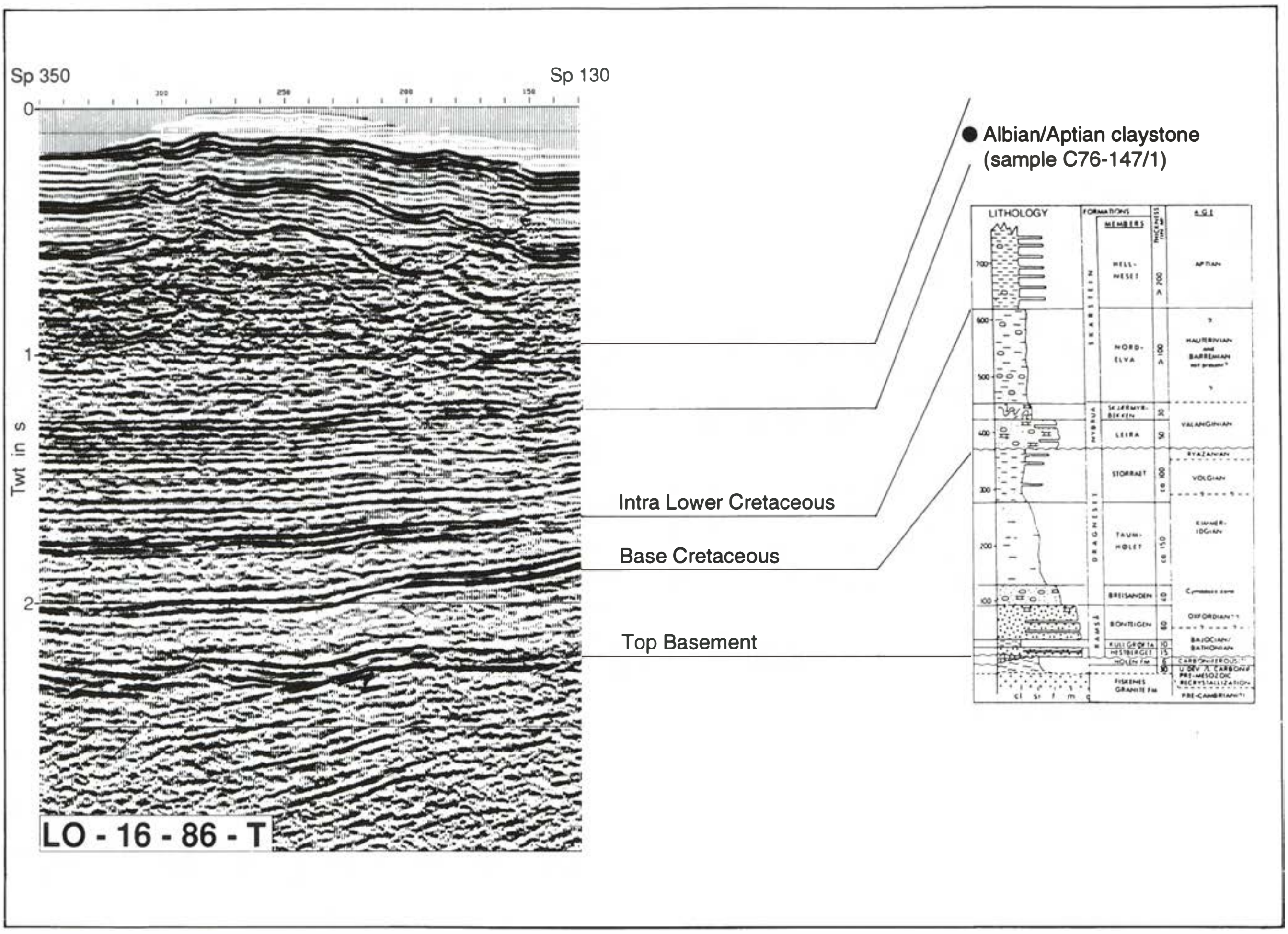

Fig. 4. Suggested correlation of the seismic reflectors top basement, base Cretaceous and intra lower Cretaceous in the Ribban Basin to the Jurassic and Cretaceous succession on Andøya (Dalland 1981).

ultramylonite fault zone decreases gradually to approximately 200 m below the zone, where the foliation almost disappears. This fault zone is cut by sub-vertical NE–SW trending and NW–SE trending faults (Fig. 6).

On the mountain tops of Hinnøy another sub-horizontal fault zone has been mapped (Fig. 6). It is a ductile shear zone that has an almost horizontal attitude. The zone separates augen gneiss and a small anorthosite lens above from mangerites below. Chlorite, recrystallized red K-feldspar and epidote indicate retrogradation during formation. The fault zone occurs at different horizontal levels because it has been faulted by later sub-vertical

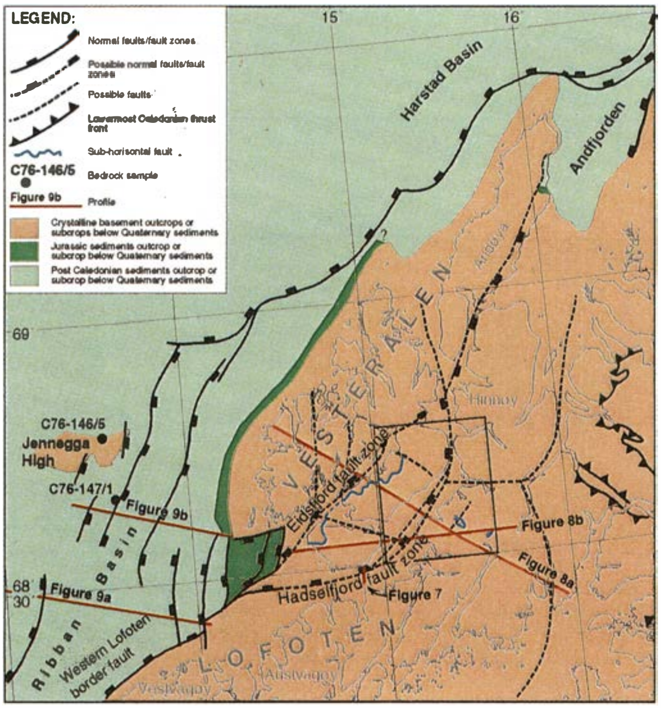

Fig. 5. Map indicating the possible extension of some of the regionally important fault zones. The Western Lofoten Border Fault branches into the Eidsfjord and Hadselfjord fault zones at approximately 68°30′N. Note that the offshore fault pattern at 68°30′N appears to continue onshore. The Jurassic sediments which sub-crop west of Vesterålen are assumed to sub-crop both east of Andøya and in the Andfjorden but cannot be followed further north due to lack of seismic data in the near coast zone. A detailed fault map (Fig. 6) is located in the frame. The location of the topographic profiles (Fig. 8), geological profiles (Fig. 9) and the two bedrock samples are also indicated.

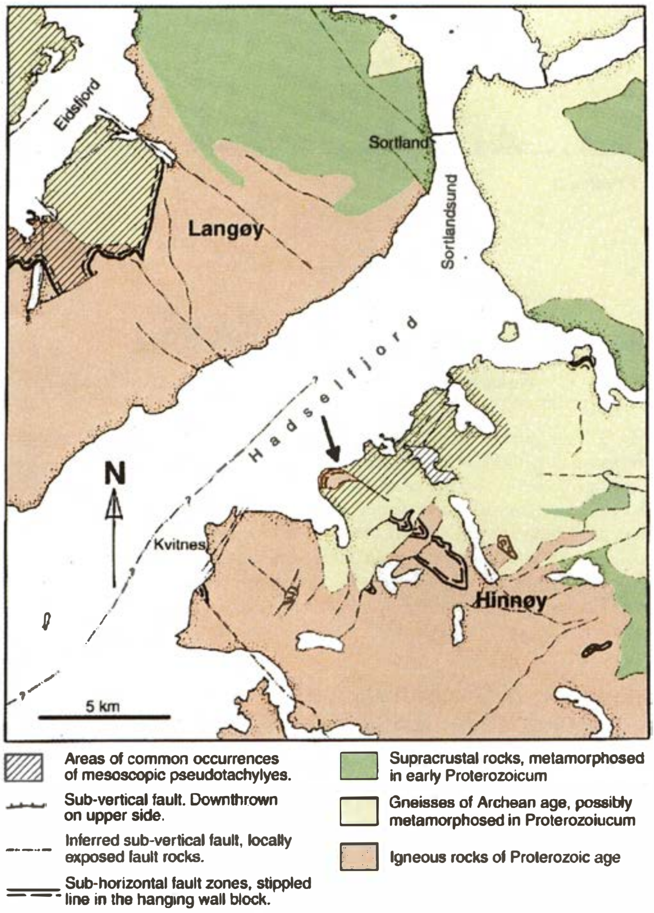

Fig. 6. Detailed geological map from map sheet Sortland (simplified after Tveten 1990). Note that the sub-vertical faults cut the sub-horizontal faults and that a sub-vertical NW–SE-striking fault cuts the sub-vertical NE–SW-striking fault (arrow). Location shown in Fig. 5.

faults. Most of them strike NE–SW but some also strike NW–SE (Fig. 6).

Pseudotachylytes. – Pseudotachylytes are observed in the granulite facies rocks throughout Vesterålen, NW of the Hadselfjord (Fig. 6). They are all mesoscopic structures which cannot be traced individually for more than 100 m and are normally less than 5 mm thick. Their orientation is sub-horizontal or dipping gently to the N or NW (Olesen et al. in press).

In one locality, the pseudotachylytes are observed to cut the foliation in the ultramylonitic fault zone on Langøya, and the formation of the pseudotachylytes therefore postdates this fault zone. On the other hand, the sub-vertical faults cut the pseudotachylytes. The pseudotachylytes are therefore intermediate in age between the sub-horizontal mylonite fault zone on Langøya and the sub-vertical faults. Even if they might have significance for the post-Caledonian structural development, they are not yet dated or observed to be directly related to regional faults onshore or offshore.

It is generally accepted that pseudotachylytes represent the fossil remnants of palaeoseismic events (Sibson 1975; Allen 1979). In general, they either form at relatively shallow depths (2–10 km) or mid-crustal levels (10–20 km) (Magloughlin & Spray 1992). Swanson (1992) indicates that they form at crustal temperatures between 50° and 400°C. One hypothesis is that the mid-crustal pseudotachylytes form within the crystalline-plastic regime via the propagation of faults, initiated at shallow levels, downward into the ductile middle to lower crust (Sibson 1977). The occurrence of microlites in the analysed pseudotachylytes in Lofoten and Vesterålen indicates that they were formed at depths greater than 6 km (Swanson 1992).

Sub-vertical faults. – Sub-vertical normal faults are common in the Lofoten/Vesterålen area. Several types of fault rocks are observed within these fault zones. The most common are: (1) phyllonites; (2) sheared veins filled with zeolites and calcite; (3) cemented breccias, usually encompassed by densely jointed and somewhat altered host rock; and (4) gouge. The absolute age of these faults has not been determined, and even relative ages are difficult to verify in the field. In some fault zones, evidence for reactivation has been found. However, in a few places, field evidences indicate that thin zeolite fault zones and gouge rocks are relatively late structures. In map view (Fig. 6), we can observe that the sub-vertical faults represent at least two separate fault events. The oldest faults generally strike NE–SW. These are cut by a later set of faults that strike NW–SE.

Table 1. Radiometric ages from the Lofoten and Vesterålen area.

Age Ma	Locality	Radiometric method	References	Blocking temperatures
328 ± 4	Andøya	K-Ar Muscovite	Sturt et al. 1979	350 ± 50°C^{1}
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317 ± 3	Moskenes	K-Ar Muscovite	Griffin et al. 1978	350 ± 50°C^{1}
418 ± 2	Moskenes	K-Ar Biotite	Griffin et al. 1978	300 ± 50°C^{1}
390 ± 6	NW Hinnøy	K-Ar Biotite	Griffin et al. 1978	300 ± 50°C^{1}
460 ± 12	Leknes	40 Ar/39 Ar Hornblende	Tull et al. 1985	685 ± 53°C^{2}
349 ± 6	Leknes	40 Ar/39 Ar Biotite	Griffin et al. 1978	373 ± 21°C^{2}
364 ± 6	Leknes	40 Ar/39 Ar Biotite	Griffin et al. 1978	373 ± 21°C^{2}

(1) Jager & Hunziker 1979; (2) Berger & York 1981.

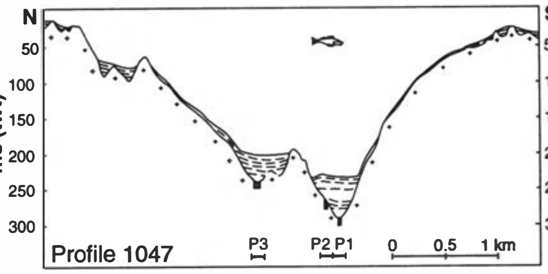

Fig. 7. Seismic refraction profiles (P1, P2 and P3) across part of the Hadselfjord showing low-velocity zones (black) (~ 3400–3800 m/s relative to the general 5100 m/s) below the lowest topographic parts of the fjord. The profile illustrates the gully in Hadselfjord. The low-velocity zones are interpreted to represent the Hadselfjord Fault Zone as fault zones.

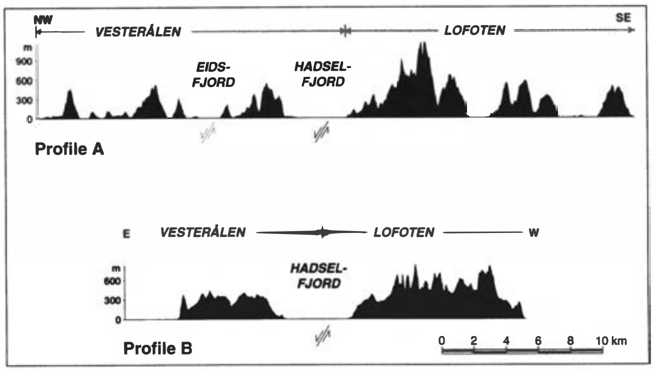

Fig. 8. Two profiles A and B demonstrate topographic and geomorphologic changes across the Hadselfjord fault zone. The Eidsfjord and Hadselfjord fault zones are indicated on the profiles. Vesterålen has the lower topography with most of the mountain peaks around 600 m or lower. In Lofoten many of the mountain peaks are around 900–1000 m. The highest peak Møysalen (1266 m) is more than 500 m higher than the highest mountains in Vesterålen. Profile B indicates that the geomorphology in Lofoten is high amplitude, more alpine, than in Vesterålen. Location in Fig. 5. Four times vertical exaggeration.

Regional sub-vertical faults/fault zones. – By correlating onshore mapped mesoscopic faults with lineaments observed on satellite images, topographic and bathymetric maps, geophysical lineaments, and occasionally contrasting lithologies and/or structures across the fault zones, it has been possible to trace several fault zones (Fig. 5). Some of the faults that can be traced over some distance are described below:

Hadselfjord Fault Zone. – A NE–SW striking fault zone is postulated to exist in the Hadselfjord. Seismic refraction profiles across part of the fjord show low-velocity zones (~ 3400–3800 m/s relative to the general 5100 m/s) below the lowest topographic parts of the fjord (Fig. 7). Bathymetric data define a marked trench trending NE in the sound. On the northwest side of Sortlandssundet, the mangeritic host rock is locally shattered and jointed in a more than 500 m wide zone along the shore. The deformation terminates against a NW trending fault on the northern side. On the SE side of Hadselfjord, at Kvitnes (Fig. 6), a NE trending fault separates two different mangerite types. It follows a topographic lineament, but the fault rock is not exposed. Several sub-parallel NE–SW striking faults are mapped in this area (Fig. 6). The sub-horizontal shear zone on Hinnøy is found only SW of the Hadselfjord Fault Zone. The above described observations, together with anomaly patterns on gravimetric maps (Olesen et al. in press), and numerous small-scale faults and joints of similar orientation, indicate that a fault zone exists in the Hadselfjord. The fault has been traced NE-ward to Sortlandssundet. At this locality the movement is either pivoted or shifted to a N–S-trending fault following the strait of Sortlandssundet northwards, west of Andøya (Fig. 5).

Topographic and geomorphologic contrasts can be seen across the Hadselfjord (Fig. 8). In Vesterålen (Langøy and Hadseløy) most of the mountain peaks are around 600 m with the highest peaks around 750 m. The relief within the mountain areas is of lower amplitude than in Lofoten. To the SE of Hadselfjord (Austvågøy and Hinnøy) there is an alpine type topography with high amplitude relief. Most of the mountain peaks are around 800 to 1000 m and the highest, Møysalen (1266 m), is 506 m higher than in the highest peak in Vesterålen. There is thus an obvious topographic and geomorphologic shift from Vesterålen across the Hadselfjord to Lofoten.

Eidsfjord fault zone. – A NE–SW striking fault zone is interpreted to exist in the Eidsfjord (Fig. 5). On the SE side of the fjord, a minimum 10 m wide fault zone is exposed. It strikes parallel to Eidsfjord. The fault zone comprises strongly sheared and retrograded rock fragments. Similar faults are observed along the NW shore of Eidsfjord. These are interpreted as parts of a large NE–SW striking fault zone. Along the extension of Eidsfjord to the NE, a 1 km wide low topography zone runs across Langøya. Different fault-rock types are found here (cemented breccias, crushed breccias, black chlorite phyllonites) indicating repeated fault movements. It is likely that the fault zone, which runs parallel to the Eidsfjord, continues NE-ward over Langøya and further into the fjord. In the low topography zone onshore, the offset cannot be very large because the same supracrustal rock units are found in an adjacent position on both sides. There is a marked magnetic lineament parallel to the Eidsfjord (Olesen et al.). No significant topographic changes are observed across the Eidsfjord (Fig. 8).

The Eidsfjord fault zone probably branches into several N–S-striking faults northward on Langøya (Fig. 5). The N–S-striking faults are located in the low topography landscape.

Eastern Andøya fault zone. – A NNE–SSW striking fault that downthrows to the east runs to the west of the Jurassic and Cretaceous sediments on eastern Andøya (Fig. 5). Changes in lithology together with a topographic signature, indicate a southward continuation of the fault zone to approximately 15 km south of the sediment outcrops. A further southward extension is possibly indicated by a sub-sea gully in the fjord south of Andøya.

Age of faulting. – Limited information exists on the exact age of movement on the onshore faults. The exceptions are several phases of faulting interpreted to have occurred on Andøya during the mid-Jurassic, Ryazanian, and early Cretaceous, probably Aptian (Dalland 1981). A set of post-Aptian NNE–SSW striking faults is also found on Andøya (Dalland 1975). These faults may be dated by Coniacian (87 ± 1 to 86 ± 1 Ma) and early Eocene (53 ± 6 Ma) K-Ar ages on mylonitic fault zones in the weathering profile under the sediments on Andøya (Sturt, Dalland & Mitchell 1979).

Offshore

Geologic setting

The Lofoten/Vesterålen margin can be subdivided into an eastern and a western part at the shelf edge where the crustal thickness decreases from ~25 km to 15 km (Fig. 3). The western border of the Utrøst Ridge (Fig. 1) is located at the transition. Velocity data (Mjelde 1991) show that the continental crust has a constant thickness of approximately 15 km further westward to the continental-oceanic crustal transition. Flow basalts of assumed late Palaeocene/early Eocene age have their eastern terminations just west of the shelf edge (Fig. 1). Below the flow basalt, which is an acoustic barrier, gravimetric data indicate a local sediment basin approximately 3.5 km thick (Sellevoll et al. 1988). Above the flow basalt, the sediment thickness is up ~1.5 km.

The eastern part of the margin, which is the focus of the present paper, has crustal thickness varying between 20 and 27 km (Åm 1975; Sellevoll & Thanvarachorn 1977; Eldholm, Sundvor & Myhre 1979; Sellevoll 1983; Goldsmith-Rokita et al. 1988; Sellevoll et al. 1988; Sellevoll & Mokthari 1988; Mjelde 1991; Mjelde et al. 1993; Mjelde & Sellevoll 1993). The eastern border of the extended margin is defined where the thickness of the crust increases to approximately 40 km (Fig. 3). Interpretations based on the gravity anomaly map of Norway (Fig. 2) suggest that this border can be extended northwards at the coast from the Blue Norma Profile (located south of Fig. 1) (Goldsmith-Rokita et al. 1988) to the east of Vestfjorden.

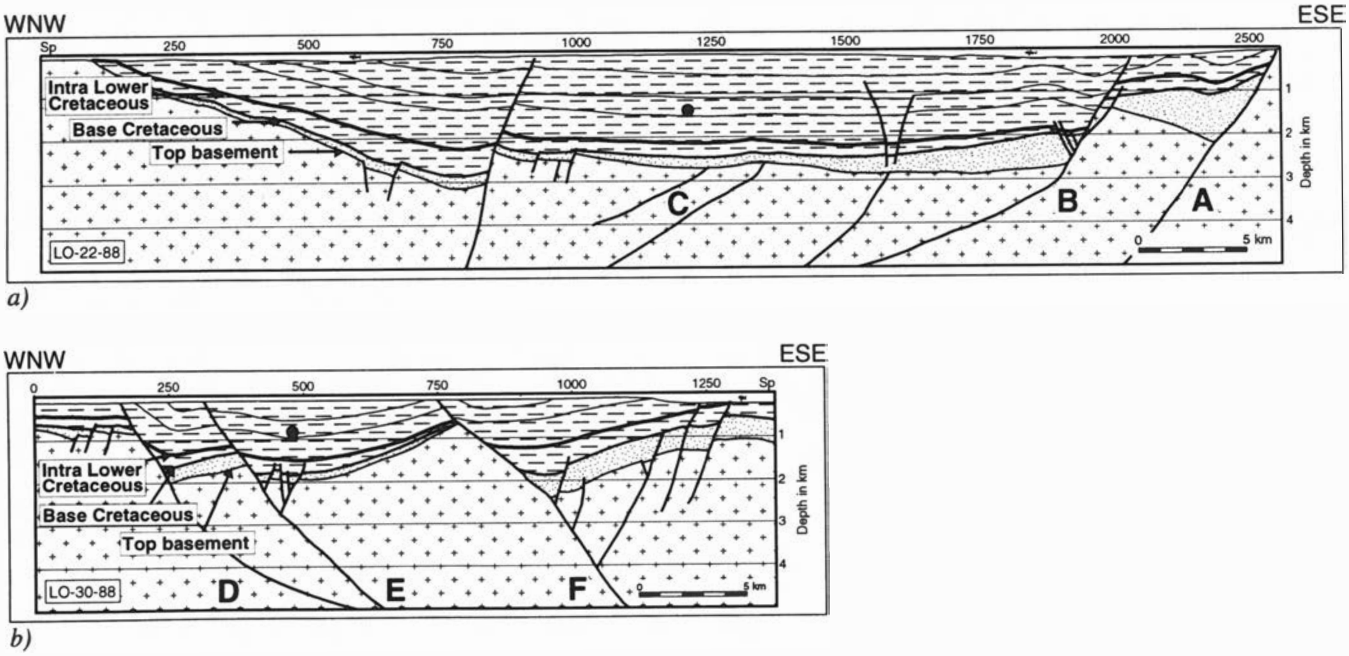

Fig. 9. Two WNW–ESE-striking depth converted geoseismic profiles in the northern Ribban Basin describing the structural style shift north and south of 68°30′N. Location in Fig. 5. Two times vertical exaggeration. The dot ● indicates the approximate stratigraphic position of the Aptian-Middle Albian bedrock sample (C76-147/1). (a) LO-22-88 (sp. 1-2307) shows the structural style south of 68°30′N. Western Lofoten Border Fault, which is a major listric normal fault (A) separates the Precambrian basement rocks on the Vestvågøy from sedimentary rocks in the northern Ribban Basin. The fault plane is described by variable medium to low amplitude discontinuous reflections, which indicate that the fault soles out in basement at approximately 4 s (twt) (below the profile). It has a displacement greater than ~3 km. The fault strikes NE–SW. Six km further west, a second listric normal fault (B), which also detaches in basement, continues the down-stepping into the deeper part of the northern Ribban Basin. The throw at fault B is approximately 1.5 km. These two faults limit a fault block rotated ~10° to the SE. The top basement surface, which has been used as reference to calculate amounts of extension on the seismic section, is not preserved in Lofoten to the SE. The lack of a reference point here only allows us to calculate minimum values for the fault movement. The two faults (A) and (B) have minimum 4 km throw and 4 km heave. Note that the faults at (C) terminate upward at the top basement reflector, indicating fault activity prior to mid-Jurassic peneplaination. (b) LO-30-88 (sp. 1-1358) is characteristic of the structural style north of 68°30′N. The listric faults downthrow to the east and the fault blocks are rotated up to approximately 15° to the west. The faults D, E and F, which can be followed as low amplitude and discontinuous intra-basement reflections, curve and sole out at a depth of approximately 2.5–3 s (twt) (below the profile). The total heave along this profile is 6 km, while the throw is approximately 2 km on the largest fault. The wedge-shaped sediment layers, varying gradually from thin on the crests to thick in the basins, and thickness variations across faults, demonstrate the syntectonic sedimentation. Faulting occurred during the time represented by sediments between the top basement and base Cretaceous reflectors, but most of the fault displacement occurred during early Cretaceous time.

Structurally, the margin comprises several basement highs and basins (Mokthari 1991; Blystad et al. 1995) where the Utrøst Ridge, Ribban Basin, Lofoten Ridge, Vesterålen basement high and Vestfjorden Basin are the largest structures (Fig. 1). The Utrøst Ridge comprises both basement highs (Røst High and Jennegga High) and areas with limited sediment cover (Brekke et al. 1992; Sigmond 1992). The eastern limit of the Utrøst Ridge is fault-bounded to the northern Træna Basin in the south, while it has a more gradual transition to the Ribban Basin in the north. The northern Træna Basin is a half graben, downfaulted to the west from the Vesterdjupet Fault Zone. Several small basement highs sub-crop at the Marmæle Spur.

The Ribban Basin can be characterized as a half graben downfaulted to the west along the Western Lofoten Border Fault in the south (Fig. 9a). At approximately 68°30′N the structural style changes to intra-basinal rotated fault blocks (Fig. 9b). The shift in structural style occurs along the eastward continuation of the Jennegga lineament defined by Mokthari & Pegrum (1992). South of the shift, the Lofoten Ridge is a fault-bounded horst (Jørgensen & Navrestad 1981). North of the shift in structural style, the sediments are gradually truncated and no faults bound the Vesterålen and Andøya islands (Fig. 5). These islands, which constitute a basement high, can be described as a basement core of a large NNE–SSW-striking anticline that plunges slightly to the north. The Andfjord basin has limited sediment cover and can be described as a syncline east of the Vesterålen-Andøya anticline. It also plunges slightly to the north.

Northern Ribban Basin. – Two depth-converted geoseismic profiles (Fig. 9) have been chosen to illustrate the geology and structural styles in the northern Ribban Basin. These profiles are located north and south of the change in structural style and west of where most of the onshore mapping has been done (Fig. 5).

A continuous and high amplitude reflection (Figs. 4, 10), which has been interpreted as the top basement, occurs on both profiles (Fig. 9). The smooth surface demonstrates that the basement must have been peneplained throughout much of the Lofoten and Vesterålen shelf before the area was flooded and sedimentation initiated. Another high amplitude and continuous reflection, that defines an angular unconformity, occurs above the top basement reflector (Fig. 4). It is termed 'base Cretaceous' (see discussion below). Several minor faults terminate at approximately this level (Fig. 9). The thickness of the seismic unit between the top basement and base Cretaceous reflectors varies from 0 to 0.3s (twt) (~0–450 m). Regionally, the thickness decreases southwards in the northern Ribban Basin until the base Cretaceous reflector onlaps basement west of Vestvågøy. Above the base Cretaceous reflector, a 0.1–0.3s (twt) (~150–450 m) thick transparent interval is limited by another high-amplitude continuous reflection, termed 'intra lower Cretaceous' (Fig. 4). The overlying interval, which continues up to the base Quaternary unconformity, is a uniform, sub-parallel, continuous and medium amplitude interval.

South of 68°30′N, the Western Lofoten Border Fault, which is normally one single fault, separates the Precambrian rocks onshore from the sediments in the Ribban Basin. The fault zone is characterized by a large throw, locally up to more than 6 km, and downfaults to the west (Fig. 9a). Reflections from the Western Lofoten Border Fault, which can be followed as low-amplitude reflections downwards into the basement, demonstrate that the fault is listric and soles out in the middle part of the crust (Fig. 3). The Western Lofoten Border Fault can be traced along the western flank of Lofoten from south of Røst to west of Austvågøy (Fig. 1). The location of the fault is not well-defined west of Moskenesøy.

The crust below the Lofoten shelf has been sub-divided into an upper, a middle and a lower zone because of the stepwise increases in velocities (Mjelde et al. 1991). A similar three layer sub-division was suggested on the basis of intra-basement reflections in the Ribban Basin (Løseth 1990) (Fig. 10). In the upper part of the crust frequent intra-basement reflections occur. Some of the reflections can be traced as continuations of faults in the overlying sediment package, while others terminate upward at the top basement reflector. If the reflections that terminate at the top basement also represent fault planes, they define faulting before the lowermost assumed mid-Jurassic sediments were deposited. All the reflections from these fault planes seem to detach around 4–5 s (twt). The reflections are interpreted to represent fault planes or fault zones comprising retrograded rocks, probably similar to those found onshore. The middle 'transition' zone appears around 4–5 s (twt). It is characterized by relative chaotic intra-basement reflections and by the detachment of faults. The reflection pattern sometimes resembles mega augen or mega lenses (Figs. 3, 10). The lower zone has few intra-basement reflections and continues down to Moho, inferred at approximately 8 s (twt). This reflection pattern resembles that described by Hamilton (1987) in the Basin and Range province. The three zones are interpreted as the upper brittle, middle transitional, and lower ductile deformation zones. The observations favour a pure shear crustal deformation model in this area.

North of 68°30′N, the structural style changes to several rotated fault blocks downfaulted to the east (Fig. 9b). The major differences from the southern area are a shift in the direction of downfaulting, smaller throws, significant rotation of the fault blocks, faults detaching at shallower levels and an increase in the number of faults. Intra-basement reflections occur less frequently north of 68°30′N.

In the Ribban Basin, a major angular unconformity can be observed on all seismic sections below a thin Quaternary unit. This clearly demonstrates one or several phases of major uplift and erosion. The regional subcrop map from the Norwegian shelf (Sigmond 1992)

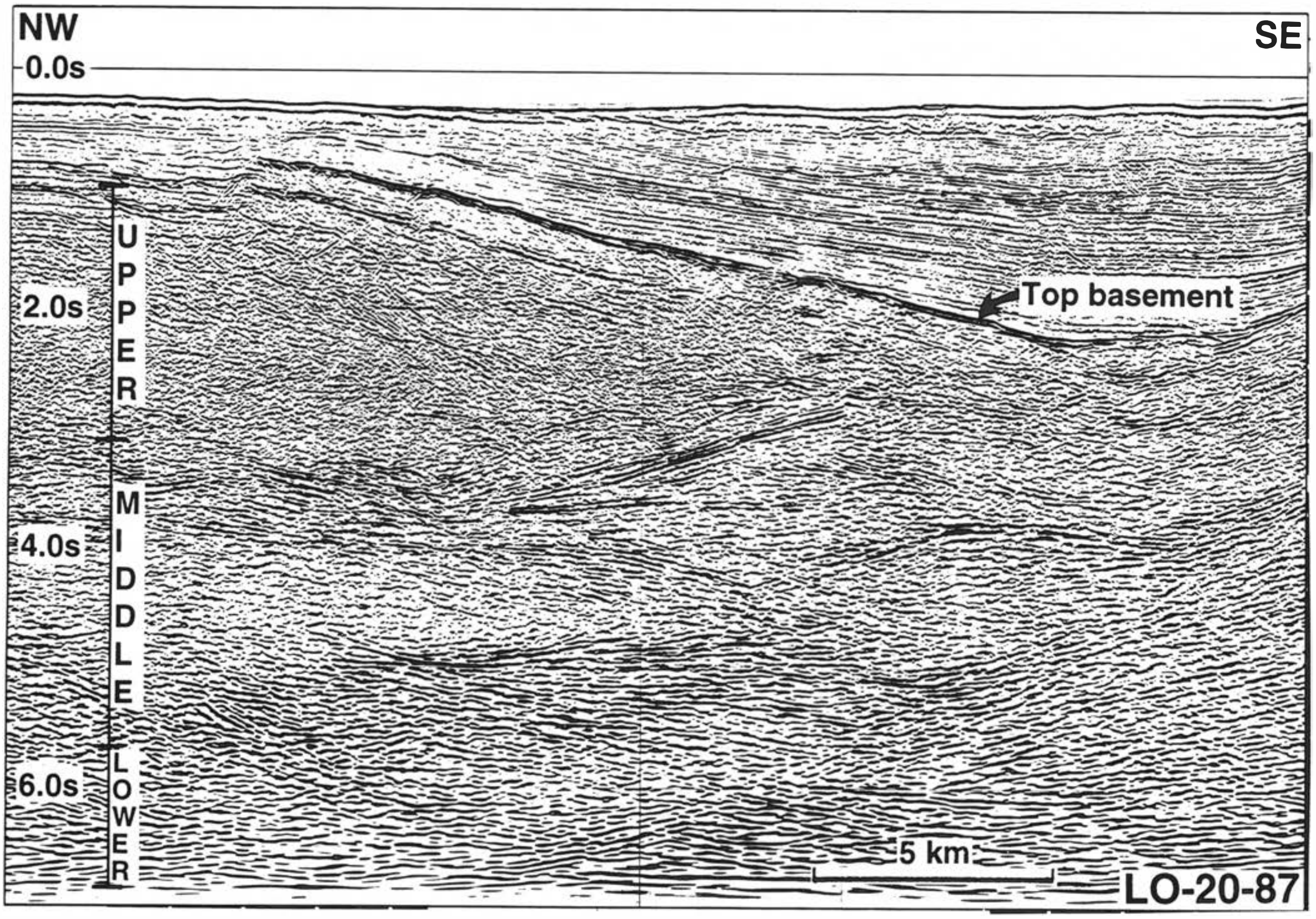

Fig. 10. Part of a NW–SE trending seismic line (LO-20–87) located west of Moskenesøy. The crust has been sub-divided into an upper, a middle and a lower zone. In the upper zone, frequent intra-basement reflections occur. Some of the reflections can be traced as continuations of faults in the overlying sediment package, while others terminate upward at the top basement reflector. The reflections are interpreted to represent fault planes or fault zones comprising retrograded rocks, probably similar to those found onshore. The middle 'transition' zone appears around 3.5–5.5 s (twt). It is characterized by relatively chaotic intra-basement reflections and by detachment of faults. The reflection pattern resembles mega augen or mega lenses. The lower zone has few intra-basement reflections and continues down to Moho, inferred at approximately 8 s (twt). The three zones are interpreted as the upper brittle, middle transitional and lower ductile deformation zones.

demonstrates that the whole shelf west of the Lofoten and Vesterålen area has been uplifted and eroded. The latest part of the erosion must have occurred after the Eocene, because sediments of this age are truncated west of Lofoten (Sigmond 1992).

Ages assigned to the seismic reflectors. – A foliated feldspathic gneiss (C76-146/5) was collected on Jennegga High (Fig. 5) in a position just below the top basement reflector (Rokoengen et al. 1977). This shows that the basement in this area constitutes Precambrian rocks, and that the top basement reflector is most likely to be correctly interpreted.

A bedrock sample (C76-147/1) comprising grey claystone was collected approximately 2.5 km north of the geoseismic section in Fig. 9b (Fig. 5). It is believed to represent the local bedrock and has been palynologically dated to Aptian to middle Albian (IKU in-house data). The approximate stratigraphic position of the bedrock sample is indicated in Fig. 9. At present this is the only age from sediments in the Ribban Basin available for publication. It is of approximately the same age as, or younger than, the Aptian mudstones and shales in the Hellneset Member (upper part of the Skarstein Formation), which are the youngest sediments preserved on Andøya (Dalland 1981). The bedrock sample is located within a seismically uniform interval.

The stratigraphy from Andøya has been correlated to the interpreted seismic reflections in the Ribban Basin (Fig. 4). The basis for the correlation is that a similar structural evolution is interpreted from seismic data in the Ribban Basin to that described from Andøya (Dalland 1981). The Aptian to middle Albian bedrock sample from the Ribban Basin is probably just slightly younger than the youngest sediments found on Andøya. Therefore, the mid-Jurassic to lower Cretaceous sediments on Andøya must be correlated somewhere below the stratigraphic position of the Aptian to middle Albian bedrock sample and above the top basement reflector. We correlate the unconformity at the top of the Dragneset Formation to the base Cretaceous reflector because both define angular unconformities. The base of the Hellneset Member has been correlated to the intra lower Cretaceous reflector, which defines the base of the seismically uniform interval, possibly turbiditic as found in the Hellneset Member (Fig. 4).

Discussion

Onshore to offshore faults correlation

The Lofoten Ridge is a horst bounded by the western and eastern border faults to the Ribban and Vestfjorden basins, respectively. The Lofoten islands constitute the currently exposed part of the ridge and all the observed onshore sub-vertical faults can be regarded as internal deformation structures in the horst. The eastern border fault is poorly defined, because of limited seismic data. Magnetic and gravity anomaly interpretations (Olesen et al.) suggest that the Eastern Lofoten Border Fault terminates northward at 68°00′N and that the main fault is located on the eastern side of the Vestfjorden Basin from 67°30′N to 68°15′N. The Western Lofoten Border Fault, which is well-defined by seismic data, is normally one major fault that defines the border to the Ribban Basin.

Just south of 68°30′N, the NE–SW-striking Western Lofoten Border Fault splays into several N–S striking faults (Fig. 1). Downfaulting to the west is observed on all these faults. Seismic data clearly demonstrate that the Western Lofoten Border Fault does not continue further north in the Ribban Basin. The NE–SW striking branch of the fault can be traced to 15°20′E based on seismic data. East of this, seismic data do not exist and the fault must be extrapolated based on other criteria. Based on onshore mapping, there are two obvious continuations of the fault, towards the Hadselfjord and the Eidsfjord fault zones. Both fault zones are interpreted to strike parallel to the fjords.

The Eidsfjord fault zone lies in the direct NE-ward continuation of the Western Lofoten Border Fault. Exposures of the onshore extension of the Eidsfjord fault zone demonstrate repeated fault activity. No significant topographic changes are observed across this fault zone (Fig. 8) but the fault zone itself defines a clear depression in the terrain. The Eidsfjord fault zone is interpreted to splay into several N–S-striking faults northward on Langøya (Fig. 5). Thus a similar fault pattern appears as that mapped just to the south in the Ribban Basin. We suggest that the NE–SW-striking Western Lofoten Border Fault continues NE-ward into the Eidsfjord fault zone and that the fault pattern mapped offshore also continues to the onshore area. A further likely implication of the correlation is that the downfaulting to the west, as observed on the Western Lofoten Border Fault, also occurred at the Eidsfjord fault zone.

The other likely continuation of the Western Lofoten Border Fault is along the Hadselfjord fault zone. The reduced basement velocity zones in the gully in the fjord (Fig. 7), which are interpreted as being caused by the presence of fault rocks, strongly suggest that there is a fault zone in Hadselfjord. Today, we can observe a topographic and morphologic shift across the Hadselfjord (Fig. 8). A relatively recent geological process is probably required to explain such a well-expressed topographic shift. Two possibilities seem reasonable:

- there has been a relatively recent significant fault activity along the fault; or
- a relatively recent erosional process has exhumed a top basement palaeo-relief.

We believe that the latter explanation is the most likely because there are no indications of a major, late Cenozoic faulting episode. The onshore landforms also demonstrate significant glacial erosion. Offshore, the sediments are eroded by glacial processes as far west as the shelf edge (Rokoengen et al. 1977). By extrapolating the westward-dipping sediments west of Vesterålen, which are truncated below a thin layer of Quaternary sediments, it appears likely that the whole Vesterålen/Andøya area was covered with sediments. Because the Lofoten Ridge is fault bounded, similar extrapolations cannot be done here. Thus, the Vesterålen/Andøya area had a lower basement relief when the late Cenozoic erosion was initiated. Since sediments are less resistant to erosion than basement rocks, such a scenario can explain why the Lofoten basement rocks produce higher mountains than Vesterålen. It is also interesting to note that deeply weathered rocks are observed on the highest mountain tops of Hadseløy. Up to 25 m thick weathering zones have also been identified on the northern Andøya (Fjalstad pers. comm.). These could represent remnants of a regional weathering profile, similar to that found below the Jurassic rocks on Andøya. The observed topographic shift over Hadselfjord therefore supports the existence of a fault zone in the Hadselfjord. We suggest that the Western Lofoten Border Fault branches into both the Hadselfjord and Eidsfjord fault zones at 68°30′N.

The consequence of the correlation is that the western Lofoten border fault and its continuation in the Hadselfjord Fault Zone define the northern border of the Lofoten Ridge. Even though the ridge is intersected by several sub-vertical faults, the Lofoten Ridge can be regarded as one structural element. The Vesterålen/Andøya area is more complex and probably comprises several fault blocks. Further onshore mapping is necessary to understand the fault pattern and sub-division into individual fault blocks.

Timing of events

Age information of the post-Caledonian evolution is limited to the dated sediments from Andøya (Dalland 1981; Manum, Bose & Vigran 1991), one bedrock sample from the Ribban Basin and post-Caledonian radiometric ages from Lofoten and Vesterålen (Table 1) (Griffin et al. 1978; Sturt, Dalland & Mitchell 1979; Bartley 1981; Tull et al. 1985). In addition, regional correlations to the mid-Norwegian shelf (Brekke & Riis 1987; Dalland et al. 1988), to the Hammerfest Basin (Worsley, Johansen &

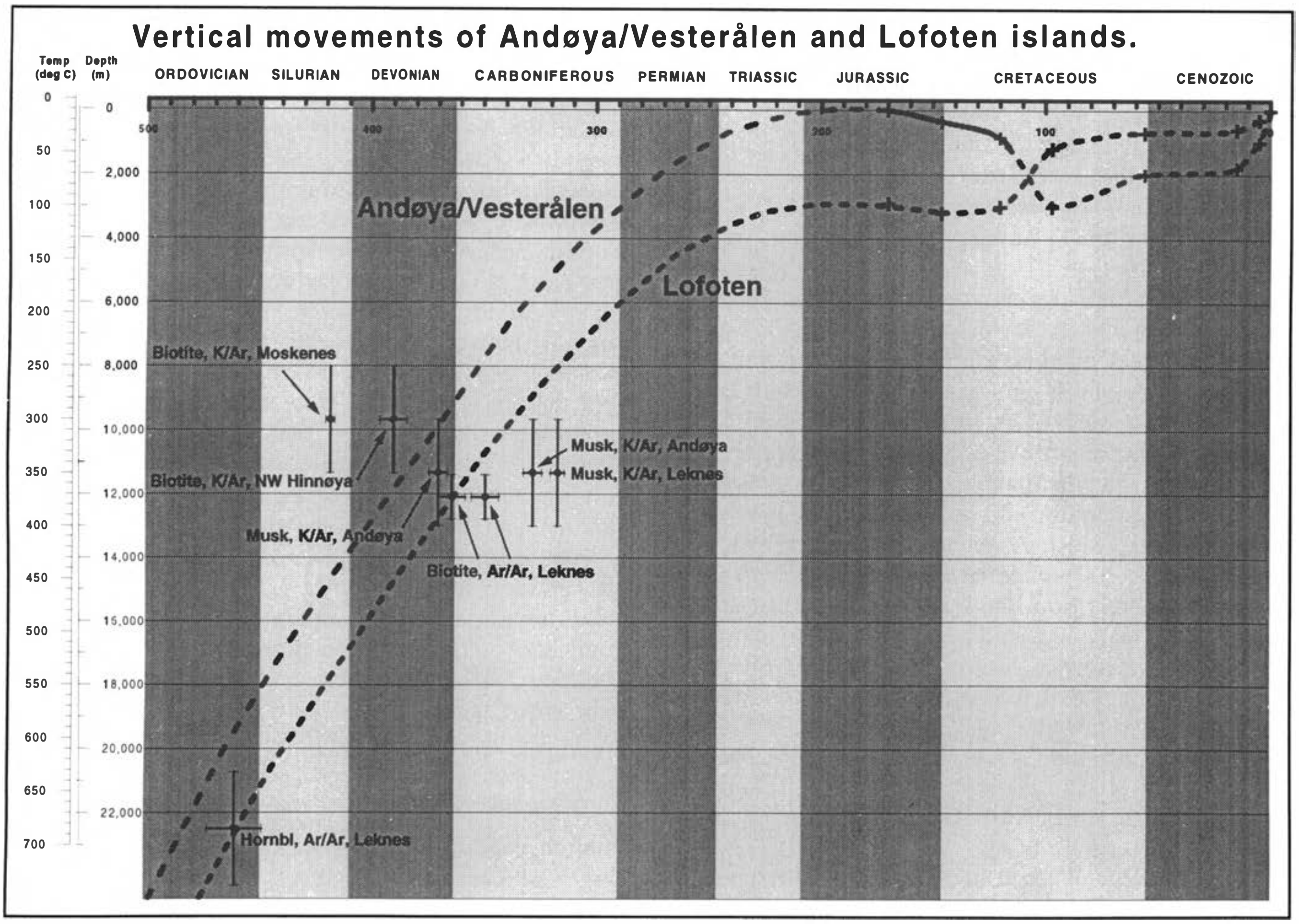

Fig. 11. Two suggested uplift and subsidence curves, one for Andøya/Vesterålen and the other for Lofoten. The full line on the Andøya curve indicates subsidence based on sediment thicknesses from Andøya (Dalland 1981). Note that Lofoten was uplifted and eroded while Andøya subsided during the latest part of the early Cretaceous. The radiometric ages and closing temperatures plotted on the figure are given in Table 1.

Kristensen 1988) and to the Vøring Basin (Talwani & Eldholm 1977; Eldholm, Thiede & Taylor 1989) can be discussed. Below, we have sub-divided the discussion of the post-Caledonian evolution into four parts: pre-mid-Jurassic; mid- and late-Jurassic; early Cretaceous; and post-early Cretaceous. The first and last of these periods are the least well understood.

Pre-mid-Jurassic tectonic events

The Caledonian allochthonous metasediments immediately overlying the Precambrian rocks on the Eastern Hinnøy are of garnet-kyanite grade. They indicate P-T conditions at maximum Caledonian metamorphism in excess of 550°C, i.e. depths around 18 km, assuming a thermal gradient of 30°C/km. The Caledonian nappes were most likely once placed tectonostratigraphically above the Precambrian rocks in the Lofoten/Vesterålen area. On Andøya the Caledonian rocks were eroded before the mid-Jurassic when subsidence started and sediments were deposited on the weathered Precambrian basement (Dalland 1981). This demonstrates significant post-Caledonian uplift and erosion on Andøya before the mid-Jurassic.

Radiometric ages give further information of the uplift history of the Lofoten and Vesterålen areas (Table 1). Two likely cooling curves, one for the Lofoten and one for the Vesterålen/Andøya area, have been given (Fig. 11). The palaeogeothermal gradient is not known and it is therefore kept constant at 30°C/km. A rapid cooling from temperatures higher than 550°C at maximum Caledonian metamorphism, through 400–300°C during late Devonian/mid Carboniferous, to surface temperature at mid-Jurassic, is shown for Andøya. The Lofoten/Vesterålen area probably acted as a major clastic source area during this period when significant amount of rocks must have been eroded.

A different pre-mid-Jurassic uplift and subsidence history was interpreted for Andøya by Sturt, Dalland & Mitchell (1979) based on 12 K-Ar whole rock analyses from the weathered basement immediately underlying the mid-Jurassic sediments. They suggested that the weathering profile was of Carboniferous age and that the random spread in K-Ar ages (earliest Carboniferous (342 ± 4 Ma) to early Jurassic (198 ± 3 Ma)) could be explained by a model with quick uplift and erosion in the late Devonian and early Carboniferous age followed by new subsidence during Carboniferous and Permian, and new uplift and erosion during the Triassic and earliest Jurassic. Based on this interpretation, Dalland (1981) assumed a Palaeozoic age for the non-fossiliferous Holen Formation.

The K-Ar data can be reinterpreted to give a different uplift and subsidence history. The analyses are from whole rock samples in the weathering profile. It is therefore likely that the K-Ar ages contain remnants from the initial blocking system. It is also clear that at least part of the system must have been reset during the weathering process. Hamilton, Kelley & Fallick (1989) state that any form of partial open-system behaviour will result in a calculated age that is geologically meaningless. Depending on the amount of Ar diffusion from the different samples, the mixing of ages between blocking temperatures (late Devonian/mid Carboniferous), which are found in the unweathered basement, and the termination of weathering, which is defined by the overlying mid-Jurassic sediments, should be the result. This is also what the 12 K-Ar ages from the weathered basement samples show (Sturt, Dalland & Mitchell 1979). The reinterpreted uplift and subsidence history suggested in this paper (Fig. 11) implies that the Andøya area continued to be uplifted and eroded after the Carboniferous. Minor periods with sedimentation can have occurred during the Permian and Triassic ages. An implication of the reinterpretation is that the Holen Formation must be of Permian to mid-Jurassic age.

The sediments in the Ribban Basin are interpreted to have been deposited on the Precambrian basement, as on Andøya. A Precambrian foliated feldspathic gneiss, which was collected from the Jennegga High (Fig. 5), shows that the Caledonian nappes do not extend this far west. Thus we suggest that not only Andøya, but much of the Vesterålen and Lofoten islands and shelf, went through the same major uplift and erosion history during post-Caledonian to pre-mid-Jurassic times.

Indications of pre-mid-Jurassic extensional faulting offshore are not obvious. Several intra-basement reflectors that terminate upward at the top basement reflector in the Ribban Basin are interpreted as fault planes (Fig. 9). This implies extensional faulting prior to the deposition of the mid-Jurassic sediments. Onshore, evidences for pre mid-Jurassic faulting are not obvious, but both the sub-horizontal faults and the pseudotachylytes can represent remnants of early faulting. We suggest that the sub-horizontal fault zones developed in the deeper, ductile part of the crust. When the rocks had passed upwards through the ductile-brittle transition to a shallower level, more brittle deformation prevailed, represented by the sub-vertical faults. A similar structural development is described from some metamorphic core complexes (Davis 1987). The occurrence of microlites in the analysed pseudotachylytes in Vesterålen indicate that they were formed at more than 6 km depth (Swanson 1992). Assuming that the uplift curve (Fig. 11)is roughly correct, this implies that the pseudotachylytes were formed before the Permian.

Mid- and late-Jurassic

During the mid-Jurassic, normal faulting occurred simultaneously with the initiation of a regional transgression period. On Andøya this resulted in subsidence and sedimentation (Dalland 1981). Sedimentation and extensional faulting continued during most of the mid- and late-Jurassic period. Based on the correlation of the Andøya stratigraphy to the seismic reflectors in the Ribban Basin (Fig. 4), a similar evolution is interpreted to have occurred on the Lofoten/Vesterålen shelf. The low relief at the top basement reflector demonstrates that a peneplain existed throughout this area in early- to mid-Jurassic time. Therefore, the transgression which occurred on Andøya could easily have drowned larger parts of the present Lofoten/Vesterålen islands and shelf. Jurassic sediments have been mapped on the shelf west of Lofoten and Vesterålen. The thickness of the Jurassic unit decreases regionally towards the south, indicating a transgression from the north. Local thickness variations are observed on the different fault blocks and on Andøya gradually younger strata onlap the basement northwards (Dalland 1981). The Jurassic fault throws are seldom more than 200 m.

Early Cretaceous

Faulting continued throughout the mid-late Jurassic, and early Cretaceous in the Ribban Basin (Fig. 9), but the largest fault movements occurred during the early Cretaceous, presumably during the Albian and Aptian. This is based on a tie from the Aptian to Middle Albian bedrock sample (C76-147/1) (Fig. 4) to the seismically uniform unit and the correlation of this unit to the Hellneset Member on Andøya. The first evidence of movements on the Western Lofoten Border Fault is found during this period when the Ribban Basin developed as a major early Cretaceous basin and the Lofoten Ridge developed as a horst. Up to minimum 6 km, early Cretaceous fault throws can be seen west of Vestvågøy. Dalland (1981) argued for faulting during Aptian in the neighbouring areas to Andøya. This was based of the occurrence of large basement blocks in the turbidites of the Hellneset Member. It is likely that the suggested Aptian faulting is due to the same tectonic event as the Albian/Aptian faulting on the Lofoten border fault. It is also likely that the rather uniform seismic unit interpreted as Albian/Aptian sediments could be equivalent to the stacked thin turbidite beds of the Hellneset Member of the Skarstein Formation on Andøya.

The suggested prolongation of the Western Lofoten Border Fault to the Hadselfjord Fault Zone defines the border between the Lofoten and Vesterålen areas. Lofoten developed as a horst that acted as a clastic source area and experienced uplift, while the Ribban Basin and Vesterålen, including Andøya, subsided under significant thicknesses of lower Cretaceous sediments. Consequently, Lofoten is more deeply eroded and represents a deeper crustal level than Vesterålen (Fig. 11). Most of the sub-vertical faults, which are found on the Lofoten islands, probably developed during this period.

In Vesterålen and Andøya, the Jurassic and lower Cretaceous sediments, which sub-crop around these islands (Fig. 5) and outcrop onshore on Andøya, can be extrapolated onshore above basement. This suggests that the present land areas also subsided during most of the mid- to late-Jurassic and early Cretaceous. The subsidence was accompanied by active faulting. It is likely that rotated fault blocks similar to those observed offshore (Fig. 9b) also developed onshore. The only difference is that the sediments and upper part of the basement were later eroded onshore Vesterålen and Andøya, and only the basement parts of the faults are preserved. Some of the onshore fault zones in Andøya and Vesterålen could therefore represent the basement parts of Mesozoic faults.

Post-early Cretaceous

There is little information available from the post-early Cretaceous period in the studied area. In the northern Ribban Basin, the presumed lower Cretaceous sediments terminate upward at the base Quaternary unconformity. This angular unconformity demonstrates that significant erosion has taken place after the early Cretaceous. The Norwegian sub-crop map (Sigmond 1992) shows that this is the case for the whole Lofoten and Vesterålen shelf.

In the southern Ribban Basin, Mokthari & Pegrum (1992) showed that the Lofoten border fault was active during late Cretaceous. The Eastern Lofoten Border Fault was active during late Cretaceous and possibly Palaeocene (Hagevang & Rønnevik 1986). On Andøya, mylonite facies in fault zones in the weathering profile have yielded Coniacian (87 ± 1, 86 ± 1 Ma) and early Eocene (53 ± 6 Ma) K-Ar ages (Sturt, Dalland & Mitchell 1979). Since this faulting post-dates the weathering profile and since these samples are taken from the fault rocks, we might expect that the K-Ar system was opened during the faulting and that these ages could represent the last phase of fault movement. Therefore, faulting most likely occurred during the late-Cretaceous to Palaeocene rifting episode. Most of the tectonic activity probably took place in a zone close to the forthcoming spreading ridge. The extreme thinning of the continental crust west of the Utrøst Ridge and Andøya (Fig. 3) probably represents the focus of the late Cretaceous to Palaeocene tectonic activity. The short distance between the thinned crustal zone and Andøya, in addition to the Coniacian and early Eocene K-Ar ages from the fault zones, suggest that faulting linked to this rift phase also occurred on Andøya. The last generation of faults that strike E–W to NW–SE (Fig. 6) and NNE–SSW on Andøya might be linked to this tectonic event.

Significant erosion must also have taken place after the Eocene. Truncation of Palaeocene and Eocene sediments in the southern Ribban Basin (Sigmond 1992) demonstrates this. Some of the erosion is without doubt glacial. This is shown by the onshore land forms and by offshore observations (Rokoengen et al. 1977). The Lofoten/Vesterålen onshore and offshore areas were most likely uplifted and exposed before the glaciation started. This is demonstrated by a late-Cenozoic prograding seismic sequence immediately below the base of the Pliocene-Pleistocene glaciomarine sequence that is located south and west of the Utrøst Ridge. The late uplift of the Lofoten shelf must have initiated during the late Cenozoic.

Conclusions

The Lofoten Ridge defines a horst structure bounded by the eastern and western boundary faults of the Vestfjorden and Ribban basins, respectively. The Western Lofoten Border Fault and the correlated continuation along the Hadselfjord Fault Zone define the western and northern border of the Lofoten Ridge. Regionally, the Vesterålen/Andøya area appears as a basement core of a large NNE–SSW striking anticline that plunges slightly to the north. Internally, the Vesterålen/Andøya area is structurally complex and comprises several fault blocks. Further onshore mapping is required to define the fault pattern and individual fault blocks.

A shift in structural style appears at approximately 68°30′N where the Western Lofoten Border Fault branches into several faults. The largest are the Hadselfjord and Eidsfjord fault zones. South of the shift (Fig. 9a), the Lofoten Ridge is bounded to the Ribban Basin by one single fault with a vertical throw that locally exceeds 6 km. North of the shift, the Ribban Basin constitutes several rotated fault blocks which are downfaulted to the east (Fig. 9b). Towards the Vesterålen/Andøya islands, the sediments are gradually truncated. Based on extrapolations of the sediments, it is likely that the whole Vesterålen/Andøya area has been covered with mid-Jurassic to lower Cretaceous sediments.

Based on a reinterpretation of the K-Ar data from the weathering profile below the Jurassic sediments on Andøya (Sturt, Dalland & Mitchell 1979), a correlation of the stratigraphy from Andøya to the interpreted seismic reflections in the Ribban Basin (Fig. 4) and new observations, a new uplift and subsidence curve has been outlined (Fig. 11).

The post-Caledonian structural evolution was initiated by a rapid crustal cooling from temperatures higher than 550°C at maximum Caledonian metamorphism, through temperatures around 300–400°C in late Devonian/mid-Carboniferous, to surface temperature in mid-Jurassic. During the early to mid-Jurassic, a smooth, peneplained basement relief had developed throughout the area. In mid-Jurassic normal faulting, subsidence and sedimentation started. The preserved sediments in the northern Ribban Basin demonstrate that the transgression flooded large parts of the Lofoten/Vesterålen offshore and onshore areas and that the regional transgression came from the north. The largest fault movements took place during the early Cretaceous, presumably in Albian to Aptian times. During this faulting, the Lofoten Ridge developed as a horst that was uplifted and eroded. The surrounding areas (Vesterålen/Andøya and sedimentary basins) subsided below a several km thick lower Cretaceous succession (Fig. 11). The final rifting phase during late-Cretaceous to Palaeocene, which terminated by the onset of the ocean floor spreading in earliest Eocene, was focused west of the Utrøst Ridge and Andøya. The rifting led to the extreme thinning of the crust west of the shelf edge (Fig. 3). Minor faulting linked to this rift phase is observed onshore and offshore east of the shelf edge. During a late Cenozoic uplift phase, the entire Lofoten and Vesterålen margin east of the present shelf edge was uplifted and eroded. Erosion and resulting isostatic uplift continued throughout the glacial period.

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