Extension, crustal structure and magmatism at the outer Vøring Basin, Norwegian margin

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Abstract: Regional analysis of new 2D and 3D multichannel seismic data has improved interpretation of the crustal configuration and structural style along the Norwegian margin. Five domains with different structural styles and evolutions are defined along the outer Voring Basin: (1) the Nyk High–Nagflar Dome; (2) the north Gjallar Ridge; (3) the Gleipne saddle; (4) the south Gjallar Ridge; (5) the Rån ridge. Early Campanian–Early Paleocene and Early to mid-Cretaceous extensional events are evidenced. Timing of deformation and structural styles observed along each segment reflect a lateral variation of the rifted system, probably affected by magma-tectonic processes. Correlation with the deep structures of the outer Voring Basin shows that the shallow structure in that basin is directly controlled by a deep-seated, strong, high-amplitude reflection (the T reflection), marking the top of a high-velocity body ($v_p > 7 \text{ km s}^{-1}$). The relation between the lower-crustal architecture and the subsurface basin structures has implications for the margin evolution and for the nature of the high-velocity body.

Keywords: Norwegian margin, rifting, magmatism, underplating.

The Norwegian margin is part of the NE Atlantic rift system (Fig. 1). It is characterized by a long period of episodic rifting initiated after the Caledonian orogeny (Doré et al. 1999; Brekke 2000; Brekke et al. 2001). The overall tectonic framework of the margin between 62° and 69°N consists of a central NE-trending deep Cretaceous basin (the Voring and Møre basins), flanked by palaeo-highs, platforms and the elevated mainland (Blystad et al. 1995).

In a regional context, the Trøndelag Platform and the Halten Terrace, to the east (Fig. 3), are the best areas to illustrate the Jurassic evolution, which was strongly influenced by Triassic salt tectonics resulting in the development of both low-angle detachment and steeply dipping fault structures (Koch & Heum 1995; Pascoe et al. 1999). A major unconformity at the base of the Cretaceous marks the Late Jurassic–Early Cretaceous rifting episode, which is commonly considered as the major rifting event in the Halten Terrace (Blystad et al. 1995). Although not proven by well control, the Triassic–Jurassic sediments may be present below the thick Cretaceous series in the central Vøring Basin and in the outer Voring Basin (Blystad et al. 1995). The Cretaceous evolution of the Norwegian margin is also a subject of debate. Doré et al. (1999) proposed separate Late Jurassic and Cretaceous rift episodes in the Voring Basin, whereas Blystad et al. (1995) and Brekke (2000) argued for a continuous rift episode from Mid-Jurassic to Early Cretaceous time. According to Pascoe et al. (1999), extension in the northern part of the Halten Terrace continued until Late Aptian to Early Cenomanian time.

The previous structural works described the outer Vøring Basin mainly in the northern part (Skogseid & Eldholm 1989; Lundin & Doré 1997; Mogensen et al. 2000) or discussed the Gjallar Ridge in detail (Ren et al. 1998) but few studies were performed in the southern part. Several regional reviews and modelling studies of the Norwegian margin have been published (Eldholm et al. 1989; Skogseid 1994; Blystad et al. 1995; Koch & Heum 1995; Bjørnseth et al. 1997; Robert et al. 1997; Walker et al. 1997; Hjelstuen et al. 1999; Brekke 2000; Tsikalas et al. 2001), but few structural studies have focused on the early rifting evolution and the structure of the outer Vøring Basin, investigated in this paper (Figs 1 and 3).

The outer Vøring Basin consists of a NE-trending system of ridges generally assigned to a Maastrichtian–Paleocene episode (Lundin & Doré 1997; Ren et al. 1998) or to an Early Cenomanian–Paleocene rifting event (Bjørnseth et al. 1997) (Fig. 1). It is overlain to the west by Tertiary flood basalts (seaward-dipping reflectors) extruded before and during the continental break-up in a short period of time (63–54 Ma) (Saunders et al. 1997). Before this volcanic event, a regional uplift close to the Cretaceous–Tertiary boundary is observed along the North Atlantic rift system and is interpreted to reflect interaction of the Iceland mantle plume with the base of the lithosphere (Dam et al. 1998; Skogseid et al. 2000).

The outer Vøring Basin is also an interesting area for investigating the relationships and interactions between crustal magmatism and basin deformation in space and time. Large amounts of seismic refraction and reflection data have greatly improved knowledge of the crustal structure along the outer Vøring Basin and the Vøring Marginal High (Mutter et al. 1984; Plonke et al. 1991; Skogseid et al. 1992; Eldholm & Grue 1994). Commonly observed below the margin, a high P-wave velocity body ($v_p > 7 \text{ km s}^{-1}$) (lower-crustal body) is interpreted as homogeneous, underplated mafic crust associated with pervasively intruded crust (White & McKenzie 1989; Mjelde et al. 1997; Eldholm et al. 2000). Previous studies have pointed out the isostatic impact of the lower-crustal body on the subsidence of the margin (Skogseid 1994; Robert et al. 1997; Walker et al. 1997). At the mid-crustal scale, Lundin & Doré (1997) inter-
interpreted the geometry of the Late Cretaceous–Paleocene normal faulting along the Gjallar Ridge as a mid-Cretaceous to Paleocene metamorphic core complex caused by magmatism at the base of the crust.

This paper is a regional overview of the entire outer Vøring Basin with broader implications for the deformation of rifted systems and/or the development of volcanic margins. The aims of this study are: (1) to constrain and refine the structural and stratigraphic history of the outer Vøring Basin; (2) to describe the along-strike structural variation of the sub-basins and their genetic relationships with the deep crustal geometry; (3) to attempt to document the variability of the structural styles and their links with the Tertiary magmatism or/and the structural inheritance. Because the official nomenclature proposed by Blystad et al. (1995) is not sufficiently detailed to describe the structural complexity of the outer Vøring Basin, additional informal names are proposed for specific structures (Table 1).

Data, methods and interpretation confidence

This work is mainly based on the interpretation of a regional database of more than 100 000 km of 2D seismic reflection, at 2 km × 1 km spacing, tied to wells on the Trøndelag Platform and to some released information from recent wells in the More and Vøring basins. Three-dimensional seismic reflection data are also used, particularly a 3D seismic survey covering the northern part of the Gjallar Ridge (Fig. 1). Interpretation was carried out within a single Geoframe™ project covering the region between 62°N and 68°N, and was undertaken in the framework of the preparation of the 16th Norwegian concession round (2001). Compilation of proprietary ship track (Norwegian Petroleum Directorate (NPD) database and TGS-NOPEC surveys V2R96, MWT96, HT97, KFW98 and RSW98) and public gravity data (Sandwell & Smith 1997) are also used and correlated with the regional structure.

The Early and pre-Cretaceous markers are calibrated with the numerous Halten Terrace exploration wells but the pre-Turonian basin history of the outer Vøring Basin is mostly based on seismic interpretation. In addition to Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP) data (Eldholm et al. 1989; Hjelstuen et al. 1999), released data from recently drilled wells (Fig. 1) on the Nyk High (6707/10-1) (e.g. Kittilsen et al. 1999), Vema Dome (6706/11-1), north Gjallar Ridge (6704/12-1) and Helland Hansen Dome (6505/10-10) supply further calibrations. Wells 6707/10-1 and 6706/11-1 are drilled on a structural high position and do not penetrate the lower section of the synrift sequence below the Coniacian–Turonian series. The Gjallar well (6704/12-1) reached the Lower Campanian series. Around the south Gjallar and Rån ridges, the interpretations rely mostly on regional correlations of seismic facies.
Table 1. Characteristics of the outer Voring Basin

<table>
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<tr>
<th>Structural element</th>
<th>Main geological features</th>
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<tr>
<td>Nyk High(^a)</td>
<td>NE-trending structural high Cretaceous–Paleocene depocentre inverted during Tertiary. High position during the Maastrichtian</td>
<td>Not observed? High-velocity sills Poorly expressed. High-velocity sills</td>
<td>Latest Cretaceous–Paleocene Collapse during Paleocene</td>
</tr>
<tr>
<td>Hel Graben–Naglfar Dome(^a)</td>
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<tr>
<td>North Gjallar Ridge(^b)</td>
<td>Major tilted blocks affected by low-angle faulting, partly controlled by a shale décollement layer</td>
<td>The north Gjallar Ridge is influenced by the dome-shaped T reflection (top of the high-velocity body ((V_p &gt; 7.1 \text{ km s}^{-1}))</td>
<td>Inversion Early Eocene–Present Early Campanian?–Paleocene</td>
</tr>
<tr>
<td>Fenris Graben(^a)</td>
<td>Graben onlapped by the inner flows. Located in the western part of the north Gjallar Ridge and south Gjallar Ridge segments</td>
<td>T reflection observed and expected below the inner lava flows</td>
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<td>Gleipne saddle(^b)</td>
<td>Synform, saddle structure, influenced by magmatic sill injection. Minor faulting</td>
<td>Progressive plunging of the T reflection</td>
<td>Early Campanian?–Early Paleocene</td>
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<td>South Gjallar Ridge(^b)</td>
<td>Tilted panels controlled by step faults connected with Palaeozoic–Jurassic panels</td>
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<td>Rån basin(^b)</td>
<td>Cretaceous depocentre influenced by voluminous sill intrusion. Subaerial volcanism is reduced compared with the other sub-basins</td>
<td>Transition zone between the T reflection and the top basement</td>
<td>Early–mid-Cretaceous Late Jurassic–mid-Cretaceous?</td>
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<td>Rån ridge(^b)</td>
<td>Uplifted Triassic–Jurassic depocentre sealed by the base Cretaceous unconformity. Tilted panels controlled by a décollement layer</td>
<td>Top faulted basement correlated with the T reflection</td>
<td>Early Campanian–Early Paleocene Late Jurassic–mid-Cretaceous?</td>
</tr>
</tbody>
</table>

\(^a\) Nomenclature after Blystad et al. 1995.
\(^b\) Informal names used in this paper.

Fig. 2. Bouguer residual gravity anomaly map, 50 km high-pass filtered (courtesy of TGS NOPEC/VBPR). Abbreviations as in Figure 1. Numbers represent the location of the five domains.
Structure and evolution of the outer Vøring Basin: evidence for along-strike variation

Gravity data

The 50 km high-pass filtered Bouguer residual gravity anomaly map of the outer Vøring Basin shows various trends and structures (Fig. 2). Negative anomalies are found to be consistent with the sub-basins, whereas positive anomalies reflect the structural highs and lows mapped in this study (Figs 1 and 4). The complex pattern of gravity anomalies can be used together with the structural map to define five structural domains, comprising from north to south: (1) the Nyk High–Hel Graben domain, with a NE–SW positive anomaly for the Nyk High and a north–south to NE–SW negative trends for the Hel Graben; (2) the north Gjallar Ridge domain, bounded to the north by the Rym Fault Zone and showing a main positive rounded anomaly; (3) the Gleipne saddle domain, characterized by a gravity low; (4) the south Gjallar Ridge domain, marked by a broad NE–SW-trending positive anomaly, adjacent to a negative anomaly situated below the inner lava flows; (5) the Rán ridge domain, with NW–SE and east–west orientations located in the prolongation of the oceanic Jan Mayen Fracture Zone that also coincides with major NW–SE positive trends in the oceanic domain (Fig. 3).

The five domains coincide with high or low structures characterized by a gradual along-strike variation without any clear boundaries. Nevertheless, approximate limits can be proposed to better define the five zones or domains (Fig. 4), illustrated below by a summary of their tectonostratigraphic evolution (Fig. 5) and detailed geoseismic profiles (Fig. 8).

Nyk High–Hel Graben

The morphology of this segment is dominated by the Nyk High, which separates the Nágrind Syncline from the Hel Graben (Fig. 6a). The Nyk High is bounded to the west by a major normal fault complex whereas the Hel Graben has subsequently been inverted to form the Naglfar Dome (Fig. 1). The Nyk High is, together with the Gjallar Ridge and the Vema Dome, one of the few structures recently drilled in the Vøring Basin. The Nyk High is a large SE-tilted faulted block affected by an array of Early Campanian–Early Paleocene, NW-dipping normal faults. The normal faults are interpreted to detach at depth in Lower Cretaceous(?) shales and they appear to be located above faulted blocks of similar polarity at base Cretaceous level.

Well 6707/10-1 was drilled in a faulted block SE of the Nyk High and bottomed in Santonian strata. The constant thickness of the Turonian–Santonian series and their apparent continuity towards the Hel Graben suggest minor south-dipping normal faulting before the Early Campanian in the Hel Graben (Fig. 8a). In the northern prolongation of the Nágrind Syncline, the Nyk High probably remained unfaulted until Late Maastrichtian time during the deposition of the thick Nise formation sand in Santonian–Early Campanian time. As interpreted here, the uniform thickness of the Upper Cretaceous seismic package suggests also that most of the tilting and uplift of the Nyk High occurred during the Late Paleocene–Eocene (Fig. 5).

At 10–20 km west of the Nyk High, the Cretaceous basin was mainly eroded during Maastrichtian to Early–(mid?)–Paleocene. During this period, the uplifted and eroded area represented the

Fig. 3. Regional cross-section of the Voring margin from the Voring Marginal High to the Trøndelag Platform. IF, inner flows; LF, landward flows; SDR, seaward-dipping reflectors. Location is shown in Figure 1.
highest position of the segment. Partly concomitant with the uplift of the Nyk High, the structure of the Hel Graben and the presence of Paleocene sediments above the base Tertiary unconformity argue for a sudden collapse of the basin during the mid–Late Paleocene–Eocene, in agreement with Lundin & Dore (2002). The mid–Late Paleocene deformation is coeval with emplacement of high-velocity sills in the Hel Graben, which is thus interpreted as a probable igneous centre during this period (Berndt et al. 2000). The break-up magmatism is expected to be involved in the sudden uplift of the Nyk High structure. By analogy with structures deduced from sand–silicone models (Bonini et al. 2001), a lateral flow and a boudinage of the melted lower crust, triggered by underplated magma, may explain both the Nyk High uplift and the Hel Graben collapse (Fig. 6). A slightly different magma-tectonic model has been also proposed by Lundin et al. (2002), who interpreted the Hel Graben as a major cauldron that collapsed during Paleocene time.

North Gjallar Ridge

The north Gjallar Ridge domain represents the ridge itself and part of the Fenris Graben (Figs 1 and 8b). The ridge is well expressed at the base Tertiary level (Fig. 6) and it is mostly dissected by arrays of NW-dipping faults (Figs 8b and 9). Strongly truncated by the base Tertiary unconformity, above the circular-shaped gravity high (Fig. 4), each block is characterized by well-layered reflections that are interpreted as synrift deposits (Fig. 9). Swieciki et al. (1998) proposed a Triassic–Jurassic age for these deposits, but recent drilling and in-house dating show it to be of Campanian–Maastrichtian age so that the Base Tertiary unconformity is assumed to represent a hiatus between Lower Maastrichtian and Upper Paleocene (or/and Lower Eocene) series. Contrary to the models established by Walker et al. (1997) and Ren et al. (1998), continuous detachment crosscutting the entire upper crust is not observed and an intricate system of detachment faults, controlling block rotation during the Atlantic rifting, is mainly limited to the upper part of the basin (Fig. 9). In the eastern limb of the ridge, strongly rotated small blocks are observed above a chaotic transparent seismic facies, believed to represent (middle?) Cretaceous mobile shales (Fig. 9). The shales, interpreted to have acted as a décollement for the overlying rollover feature, seem to die out laterally to the north, where faults are steeper. The rollover structure predicts a westward thickening of the synrift sequences and is at least partly concomitant with onlap and pinch-out of Turonian–Paleocene formations within the Vigrid Syncline on the eastern flank (Fig. 8b). In the western part of the ridge, a sigmoidal fault pattern at the base Tertiary unconformity level (Fig. 9) also suggests dextral strike-slip deformation along NE-trending faults.

The Paleocene interval largely onlaps the north Gjallar Ridge and thus was only slightly faulted in Early Paleocene to Early Eocene time. Faulting along the ridge probably took place a few million years before the break-up in the latest Paleocene; this suggests a progressive focus of crustal deformation to the west (e.g. Lundin & Doré 1997). The westward shift may be explained by a weakening of the crust induced by the starting magmatism, as has been proposed for the west Greenland margin, where the pre-break-up deformation was progressively focused toward the igneous centres (Geoffroy et al. 2001).
Gleipne saddle

The Gleipne saddle forms a transition zone between the north and south Gjallar ridges (Figs 1 and 8c). At Cretaceous level, it is characterized by an embayment NW of the Vigrid Syncline (Fig. 1). As observed in Figure 4, the transition zone coincides with both a marked gravity low and an offset of the Vøring Escarpment (Fig. 1).

Faulting in the Gleipne saddle is not significant in comparison with the north Gjallar Ridge and no major significant block rotation is observed (Fig. 8c). However, seismic interpretation within the saddle is rendered difficult by the presence of numerous magmatic intrusions in the Cretaceous section. Nevertheless, the Cretaceous series appear to thicken from the north Gjallar Ridge into the Gleipne saddle (Fig. 4).

During Early Paleocene–Mid-Eocene time, a sedimentary wedge infilled westwards from the Vigrid Syncline into a large part of the subsiding Gleipne saddle (Figs 4 and 8c). Moreover, inner volcanic flows, emplaced during the break-up, flowed around the north Gjallar Ridge and preferentially infilled the southern part of the Fenris Graben (Fig. 1), hence suggesting its low structural position with regard to the north Gjallar Ridge (e.g. Lundin & Doré 1997).

South Gjallar Ridge

The south Gjallar Ridge lies between the Gleipne saddle and the Rån basin (Figs 1 and 8d) and is bounded to the east by the Fenris Graben. The structural history is not constrained by proximate well control and is based only on regional seismic facies correlation.

The south Gjallar Ridge is a prominent elongated high (75 km × 50 km) at base Tertiary unconformity level. The south Gjallar Ridge is expressed by steep NW-dipping normal faults bounding elongated rotated blocks (Fig. 8d). The faulting activity is assumed to be of Early Campanian–Early Paleocene age as similarly stated for the north Gjallar Ridge. The structural style suggests domino deformation rather than the listric faulting evident in the north Gjallar Ridge. The layered seismic facies of the synrift sediments are less well developed than in the north Gjallar Ridge, whereas the faults show less displacement (Fig. 8). The Vigrid Syncline to the east is marked by Early Cretaceous faulting, sealed near the base Cenomanian level (Fig. 8d).

The gravity low, observed in the western part of the segment, is inferred to correspond to the progressive down-faulting of the Cretaceous basin in the Fenris Graben. However, this area is poorly imaged because of the emplacement of the inner lava flows (Fig. 8d).

Rån ridge

The Rån ridge is the southwesternmost domain of the outer Voring Basin and appears to be different from the other ridges (Figs 1 and 8e). The domain is composed of the Rån ridge and is
bounded by the Rån basin to the west and lies to the SE of the Jan Mayen Fracture Zone (Fig. 1). A significant part of the Rån ridge lies beneath the inner flows to the west and numerous intrusions affect the Cretaceous and older series (Fig. 8e).

The axis of the Rån ridge is shifted eastwards relative to the Gjallar ridges (Fig. 1). On its eastern flank, the Rån ridge is defined by a clear unconformity, not yet drilled but interpreted to be the base Cretaceous unconformity. The feature is a broad high limited by major NNE-trending listric faults facing the WNW and cut in the south by the Jan Mayen Fracture Zone (Fig. 1). To the east, low-angle normal faults are detached between the base Cretaceous unconformity and a strong seismic marker, which is structured into tilted blocks and is interpreted as the top basement (Fig. 8e).

Furthermore, Early to mid-Cretaceous (Aptian–Cenomanian?) normal faulting is observed, concomitant with onlaps, wedging and erosion features on the eastern flank of the Rån ridge (Fig. 8e). To the west, thinning of the series lying between the base Cretaceous unconformity and the top basement interval suggests that the Rån ridge was a depocentre during pre-Cretaceous time. Its current morphology may result from uplift and inversion of the pre-Cretaceous depocentre during Early to mid-Cretaceous time.

During the Late Cretaceous, some faults in the Rån ridge were reactivated (Fig. 8e). Normal faults associated with the late phase of rifting are mainly located to the west and do not overprint the faults belonging to the Rån ridge system. The fault array of the south Gjallar Ridge cannot be confidently traced into the Rån basin because of a loose seismic grid and (magmatic) sill intrusions.

To the NW of the Rån ridge, the Rån basin is a narrow NE-oriented Cretaceous depocentre severely intruded by sills (Figs 1 and 8e). Several NW-trending transfer zones deduced from unpublished gravity data affect the Rån basin because of a loose seismic grid and (magmatic) sill intrusions.

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Jurassic to mid-Cretaceous rift events in the outer Voring Basin

The rifting in the outer Voring Basin has been assigned previously to a Late Cretaceous–Paleocene episode (Lundin & Dore 1997; Walker et al. 1997), likely to be Maastrichtian–Paleocene in age (Ren et al. 1998). In this study, an Early Campanian age is inferred for the initiation of the late rifting event. It coincides with a sudden decrease of the sand influx in the Nyk High and the Vema Dome area, as well with faulting and uplift in the north Gjallar Ridge, and it is finally linked to a sudden and major kinematic change in the North Atlantic at 80 Ma, as suggested by Torsvik et al. (2001).

Earlier deformation (mid-Cretaceous and Late Jurassic–earliest Cretaceous?) is also involved in the development of the outer Voring Basin. Mid-Cretaceous faulting is observed along the Rån ridge (Fig. 8e), whereas the axis of the Paleocene rifted zone is shifted slightly further to the west in the Voring margin.
Fig. 8. Seismic line drawing through various segments of the outer Voring Basin, defined in Table 1. TR, T reflection. Location is shown in Figure 1.
The deep structure of the Rån ridge exhibits low-angle faults with pre-Cretaceous displacement that could be related to a Jurassic–earliest Cretaceous rifting controlled by Triassic salt as documented on the Halten Terrace. Mid-Cretaceous deformation (mid-Aptian to Cenomanian?) is recorded in the Rån ridge area. It is considered as a significant rifting phase in the southern segment and may be correlated with a mid-Cretaceous phase evidenced in the northern Halten Terrace by Pascoe et al. (1999).

A progressive thinning of the interval between the top basement and the base Cretaceous unconformity to the east in the Rån ridge suggests that it was a depocentre during pre-Cretaceous time (Fig. 8e). Even if the nature of the pre-Cretaceous series is not well determined, the Rån ridge domains interpreted as a depocentre during Permian–Late Jurassic (?) was later uplifted during mid-Cretaceous time synchronously with the progressive downflexure of the south Vøring Basin. This agrees with the palaeogeographical interpretations of Brekke et al. (2001) and Martinius et al. (2001) suggesting an emerged Early–Mid-Jurassic hinterland located to the east in the current central Vøring Basin.

**Relation between deep and shallow structures**

The crustal architecture along the outer Vøring Basin suggests a direct relationship between the shallow deformation of the basin and the high-amplitude reflection observed at mid-crustal depth (Lundin & Doré 1997; Ren et al. 1998). The strike section along the outer Vøring Basin (Fig. 4) illustrates its mid-crustal structure, which is mainly characterized by the strong, high-amplitude T reflection (Gernigon et al. 2001). The T reflection is clearly mapped from the north Gjallar Ridge to the Rån ridge whereas it is not observed in the Nyk High on the conventional seismic data available in this study (Fig. 8).

Mapping of the T reflection reveals three broad high zones, lying respectively below the north Gjallar Ridge, the south Gjallar Ridge and the Rån ridge segments (Fig. 10). These mid-crustal highs strictly correlate with positive gravity anomalies (Fig. 10). The T reflection exhibits a dome shape with a flat top at 7.5 s two-way travel time (TWT) beneath the northwestern part of the north Gjallar Ridge and the Fenris Graben and deeps below the Vigrud Syncline (Fig. 8). To the south, the T reflection deepens below the Gleipne saddle, but shallows below the south Gjallar Ridge (Figs 4, 8 and 10). In this area, the reflection forms mostly a NW-trending elongated high with two peaks at 7.6 s TWT, separated by a trough interpreted as a transfer zone that also affects the shape of the T reflection below the Vigrud Syncline (Fig. 10). Below the Rån ridge, the underlying T reflection can be mapped continuously and coincides with the top basement previously described at 7–8 s TWT (Fig. 10). However, it shows a morphology characterized by faulted blocks that differ from the smooth shape observed below the south and north Gjallar ridges. The faulted blocks occur as NE-oriented highs, 20–25 km wide, and limited to the south by the Jan Mayen Fracture Zone and to the north by a NW-trending transfer zone. The most prominent high corresponds to both the main Bouguer positive anomaly (Fig. 10) and the highest position of the Rån ridge at base Cretaceous level.

The geometry of the T reflection is believed to have controlled the structural evolution of a large part of the outer Vøring Basin. Cretaceous–Paleocene depocentres preferentially developed
where the T reflection is deep, whereas most of the erosional features at the base Tertiary level occur on the north and south Gjallar ridge, where the T reflection is shallower (Figs 4 and 8). Despite uncertainties concerning the Mesozoic picking and calibration, it is believed that the entire Cretaceous series may be thinner above the north and south Gjallar ridges compared with the Gleipne saddle. The domal shape of the T reflection appears genetically associated with the faulting in the outer Vøring Basin (Fig. 8) and its structural influence may have started as early as Campanian–Maastrichtian time. Furthermore, a correlation between the intensity of intrusions and the geometry of the T reflection is also inferred from the preferred distribution of sills in the synform structures overlying the T reflection (Fig. 4).

Implications for the nature of the lower-crustal body in a volcanic margin context

At 7–8 s TWT (10–15 km) below the north and south Gjallar ridges, the T reflection coincides with the lower-crustal reflection described by Skogseid & Eldholm (1987), whereas it is shallower than the Moho estimated by Mjelde et al. (1997) at 20 km depth below the north Gjallar Ridge. The T reflection coincides with the top of the lower-crustal body \( V_p > 7.1 \text{ km s}^{-1} \) determined by ocean bottom seismometers (OBS) (Mjelde et al. 1997). Below the Rån ridge, recent OBS data recording shows also that \( V_p \) velocities measured below the T reflection are relatively high, approximating 6.5–8 km s\(^{-1}\) (T. Raum, personal communication).

Lundin & Doré (1997) suggested that the dome-shaped T reflection may represent the top of a lower-crustal diapir, triggered by mafic underplating, and inducing a fall of viscosity and a rising of the lower continental crust. This magma-tectonic process is similar to the model suggested above for the formation of the Nyk High (Fig. 6). Such a model fits the timing of both the main magmatic event (commonly dated between 63 and 54 Ma) and the Nyk High uplift (Fig. 5).

In the north Gjallar Ridge, fault patterns above the dome suggest activity before Paleocene time (Fig. 5). Assuming that the dome is a magmatic-induced feature (Lundin & Doré 1997) implies that instantaneous emplacement of thick underplated bodies had started already during Campanian–Early Maastrichtian time in the north Gjallar Ridge domain. However, we are not aware of any evidence supporting such a young and huge magmatic activity during this period (e.g. Saunders et al. 1997). Because the dome strongly influences the structure of the pre-break-up rifted system in the outer Vøring Basin, the T reflection is interpreted as probably being a structure emplaced before the main magmatic event, considered to be Late Paleocene to Early Eocene in age in the North Atlantic domain (Saunders et al. 1997). From the overall characteristics mentioned above, we suggest that the crustal dome bounded by the T reflection may be partly characterized by high-pressure granulite or eclogitic material that also displays high \( V_p \) (7.2–8.5 km s\(^{-1}\)) (Fountain et al. 1994) as documented in the Caledonides of Western Norway (Austrheim 1990) or below the Mesozoic rifted basins in the North Sea (Christiansson et al. 2000). This interpretation has
important implications for thermal history, the mantle temperature and the magmatic production along the Voring volcanic margin because it challenges and minimizes the size of the Tertiary underplated lower crust, which is generally correlated with the whole lower-crustal body.

Conclusion

Description of the various segments along the outer Voring Basin shows that the Norwegian margin architecture varies along-strike. Five NE-trending domains, marked by contrasted structural styles and evolutions, correspond to ridges and sub-basins, named, from north to south: (1) the Nyk High–Hel Graben; (2) the south Gjallar Ridge; (3) the Gyplements saddle; (4) the south Gjallar Ridge; (5) the Rå ridge.

The Rå ridge differs from the other domains as it is a pre-Cretaceous structure that was subsequently uplifted and affected by west-verging listric faults during Jurassic—Early Cretaceous time. This domain evolved independently with regard to the Gjallar ridges and Nyk–Hel Graben systems, which were mostly affected by the Early Campanian–Paleocene rifting leading to the break-up in Early Eocene time. A strong high-amplitude reflection at mid-crustal depth is mapped between the north Gjallar Ridge and the Rå ridge. The so-called T reflection coincides both with the positive gravity anomalies and the top of the high-\(V_p\) lower-crustal body, previously interpreted as mafic underplating below the north Gjallar Ridge. A strong correlation between the shape of the T reflection and the upper-crustal deformation sealed by Upper Paleocene series suggests that the lower-crustal body influenced the sedimentary basin before the break-up and probably started as early as the onset of the latest rifting in Early Campanian time.

The T reflection is interpreted as the top of a lower-crustal crystalline body, inferred to be partly Caledonian (?) in age and displaying an eclogitic nature that may also account for its high \(V_p\) values.

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