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Deep structures and breakup along volcanic rifted margins: insights from integrated studies along the outer Vøring Basin (Norway)

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Abstract

Three-dimensional multichannel seismic survey and well data allows a deeper insight into rifting mechanisms and crustal structure of the Norwegian volcanic rifted margin. A surprising high-velocity lower crustal dome marked by a strong amplitude reflection (T Reflection) is described below the north Gjallar Ridge (NGR) near the volcanic plateau formed during the late Paleocene–Early Eocene breakup. Faulting along the NGR occurs during Early Campanian–Paleocene and is controlled by the crustal dome. The T Reflection was previously related to either the top of mafic underplated crust or soft lower crust updomed during the continental breakup. The influence and timing of the crustal dome on the basin structure shows clearly that the dome predates the continental breakup. Based on the structural relationship and the results of the modelling, it is therefore concluded that the T Reflection does not necessarily originate from an anomalous Tertiary magmatic event related to the breakup (underplated material), but could be also partly attributed to pre-breakup mafic material or/and inherited, high pressure granulite/eclogite rocks in the continental domain.

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1. Introduction

Volcanic rifted margins are known to differ from classical passive margins by a number of characteristics such as, (1) the huge volume of magma emplaced during early stages of accretion along the future spreading axis, typically as seaward dipping reflector sequences, (2) the lack of strong passive margin subsidence during and after breakup, and (3) the presence of a deep lower crustal body with anomalous high seismic velocities with $V_p > 7.1$ km/s (Eldholm, Gladchenko, Skogseid, & Planke, 2000; Planke, Skogseid, & Eldholm, 1991).

These diagnostic tectono-magmatic features have long been recognized in the outer Vøring Basin (Norwegian margin) and are ascribed to the emplacement of the Icelandic

mantle plume, prior to the NE Atlantic opening at 54–55 Ma (Skogseid et al., 2000; Fig. 1). The outer Vøring Basin is a complex system of faulted ridges at the base Tertiary unconformity level, located between a deep Cretaceous basin to the east and the Vøring Marginal High to the west that delimits the ocean–continent transition (Fig. 2). Large-scale geodynamic processes and rifting evolution since the post-Caledonian collapse of the Vøring Basin have been extensively described and documented in the literature (Bjørnseth et al., 1997; Brekke, 2000; Gernigon, Ringenbach, Planke, Le Gall, & Jonquet-Kolstø, 2003; Lundin & Doré, 1997; Mosar, Eide, Osmundsen, Sommaruga, & Torsvik, 2002; Osmundsen, Sommaruga, Skilbrei, & Olesen, 2002; Ren, Skogseid, & Eldholm, 1998; Walker, Berry, Bruce, Bystøl, & Snow, 1997). As part of the polyrifted system, the outer Vøring Basin was particularly affected by a Late Cretaceous–Paleocene rifting leading to the breakup and seaward dipping reflectors emplacement (Fig. 2).

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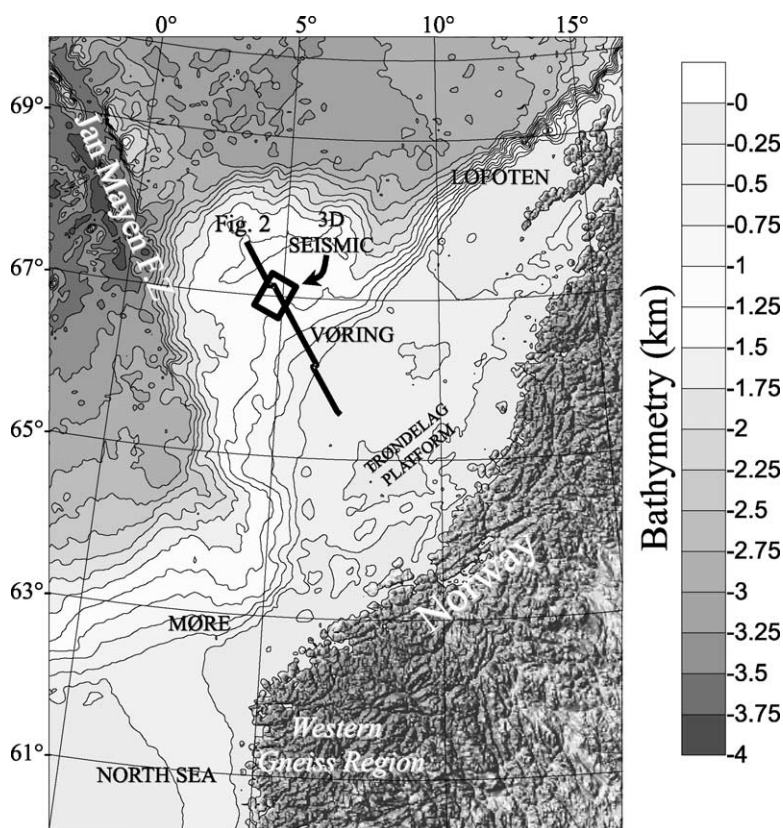


Fig. 1. Regional bathymetric map of the Norwegian margin and location of the studied area.

Two-dimensional reflection seismic and oceanic bottom seismograph (OBS) have led to new insights about the crustal-scale velocity structure of the outer Vøring Basin (Mjelde et al., 1997, 1998, 2002). One of the most interesting features concerns an atypical dome-shaped

reflection, underlying the north Gjallar Ridge (NGR) (Lundin & Doré, 1997; Ren et al., 1998), regionally mapped and named the T Reflection (Fig. 2; Gernigon et al., 2003).

Comparisons with similarly-scaled and -shaped extensional structures related to metamorphic core complexes in

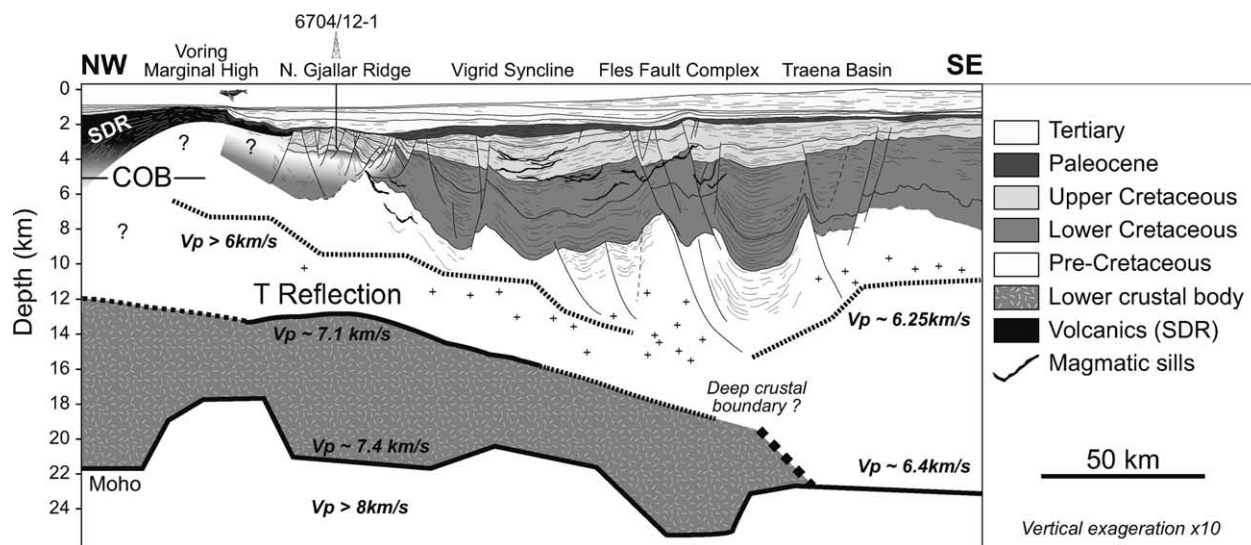


Fig. 2. Depth-converted cross-section of the Vøring Margin. The NGR is located close to the breakup volcanism illustrated by the seaward dipping reflectors (SDR) of the Vøring Marginal High. The T Reflection observed on 2D seismic match with the top of the lower crustal body ($V_p > 7$ km/s) described by Raun (2000).

either post-orogenic collapse or back-arc settings close to oceanic spreading axis (Woodlark Basin) led Lundin and Doré (1997) to suggest that the NGR domal crustal structure may be the result of a crustal softening triggered by massive injections within the lower crust at an early stage of the continental breakup.

One of the main assumptions of this previous crustal interpretation was to directly assign the crustal doming beneath the outer Vøring Margin to mantle-induced magmatism. Such a chronology and type of crustal deformation have important implications about the extensional development of the Norwegian volcanic margin and its petroleum system. Therefore, the nature of the lower crust below the NGR is questioned in the present work on the basis of recent 3D seismic data (SG9604 survey of Saga Petroleum) further calibrated by new well data (6704/12-1) and integrated with a gravity and magnetic dataset (Figs. 2–4).

The aim of this paper is to discuss (1) the 3D geometry and the geophysical properties of the crustal structure underlying the NGR, (2) the relationship between the T Reflection and the subsurface deformation, and (3) the structural and temporal evolution of the NGR with regards

to lithospheric rupture and its implication for the understanding of the tectonics of volcanic margins in general.

2. The T Reflection: geophysical observations

The T Reflection is a mid-crustal seismic marker observed in a large part of the NGR present at the base Tertiary level (Lundin & Doré, 1997; Figs. 1–3). The 3D geometry of the T Reflection is well constrained on the NGR, where it is expressed as a round-shaped feature, 20 km wide between 7 and 8 s twt, with a top at 7–7.5 s (Fig. 4a). Toward the southeast, the reflection deepens below the Vigrid Syncline and disappears at 8.5 s twt on seismic lines imaging down to 12 s twt. On the strike profile (Fig. 4b), the along-strike arch-shaped reflection is clearly imaged and the timeslice at 7.5 s shows that the T Reflection is slightly elongated in the NW–SE direction (Fig. 3c). Crustal-scale velocities still suggest that the T Reflection is shallower than the present-day Moho estimated from OBS processing at 20 km in depth (Fig. 2). V_p/V_s has been also estimated between 1.8 and 1.85 with an increase of about 3% in the NW–SE direction (Digranes et al., 1998).

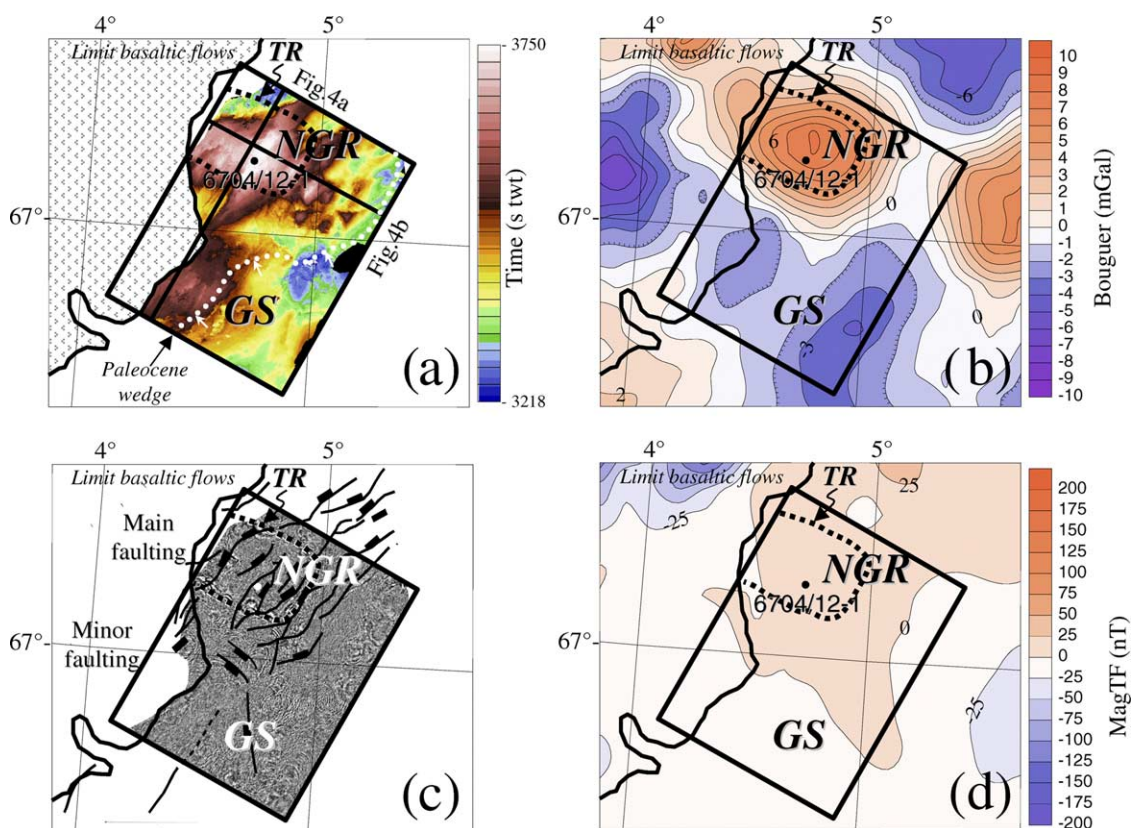


Fig. 3. Results of 3D seismic survey between NGR and the Gleipne saddle (GS) to the South. The location of well 6704/12-1 is shown. (a) Base Tertiary unconformity time-map. (b) 50 km filter Bouguer anomaly (2×2 min gridded), from Sandwell and Smith (1997). (c) Geometry of the T Reflection (TR) on a timeslice at 7.5 ms draped with the Campanian–Paleocene fault pattern. (d) Magnetic total field signature of the NRG (5×5 km² gridded) from Verhoef et al. (1996). The crustal dome, located beneath the closure of the base Tertiary level, coincides with the main positive gravity anomaly, but it does not suggest a strong magnetic change.

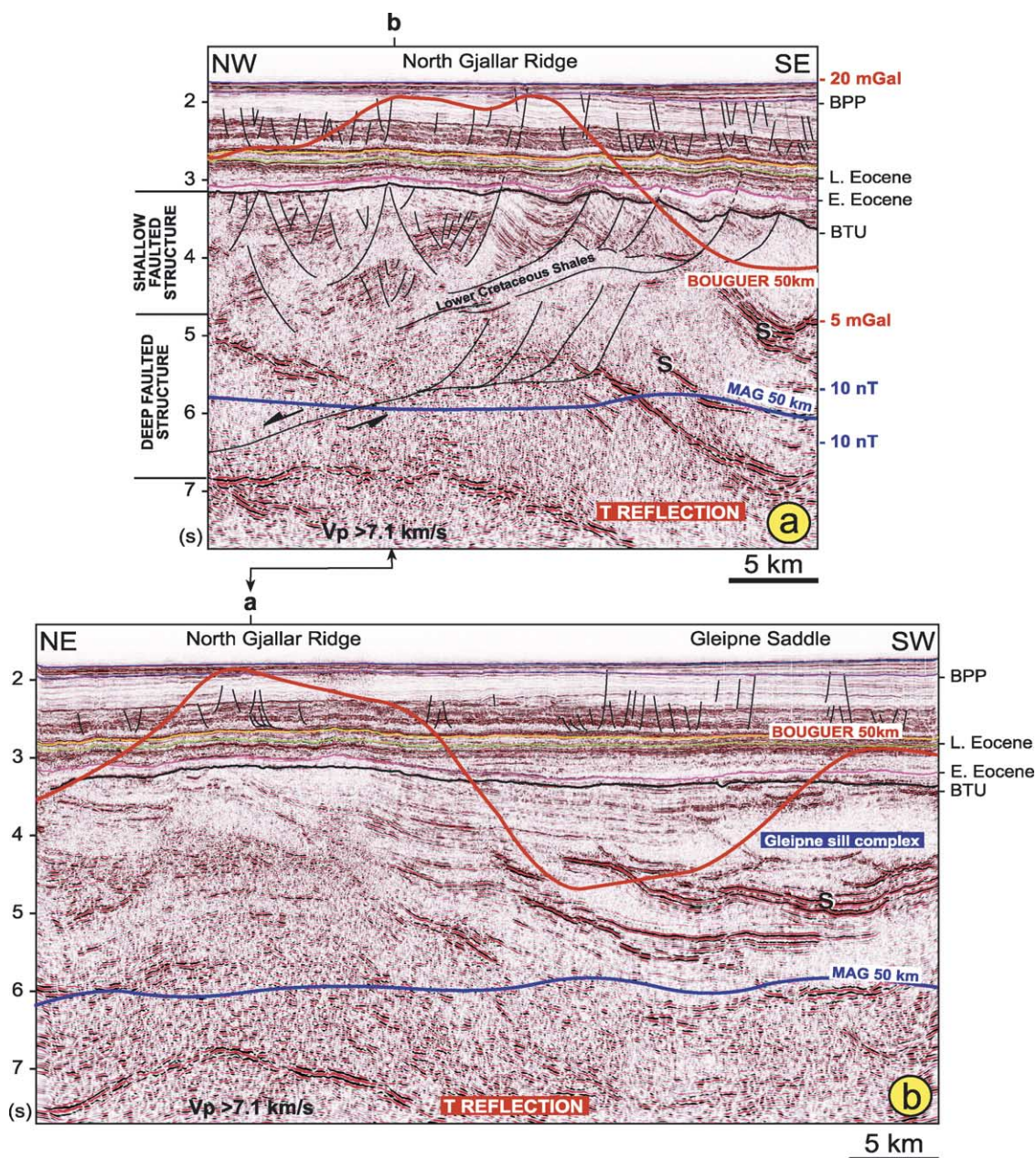


Fig. 4. Reflection seismic lines showing the uppermost crustal structure of the NGR (see location on Fig. 3a). (a) Cross-line illustrating the rollover geometry of the NGR which is sealed by the base Tertiary unconformity (BTU) and controlled in depth by a decollement level. During the Early Campanian–Early Paleocene, the extension at shallow level is characterised by a rollover geometry accommodated in depth by a detachment fault zone connected with the T Reflection. (b) Strike-line between the NGR and the Gleipne saddle showing the NE–SW corrugation of the T Reflection. The T Reflection delimits a high-velocity, dense and low-magnetic crustal dome.

Using the well velocities and a compilation of regional interval velocities, the top of this dome-shaped T Reflection is estimated at around 12–13 km on top of the dome (Fig. 2) with lateral variation to the north and the south, where the T Reflection appears approximately at 14–16 km. Uncertainties were included in the depth modelling because there are no direct velocity measurements of the pre-Campanian sediment in this area. There are estimated to 1–2 km depth for the pre-Campanian levels. The velocity derived from the 2D seismic stack velocity also appears to us 10% higher on

average to those derived from the OBS models published in Mjelde et al. (1997, 1998, 2002). Hence, the top of the T Reflection, repositioned in the OBS depth model, may be located at $13\text{--}14 \pm 2$ km. Ren et al. (1998) and Skogseid et al. (2000) also suggest that the top of the T Reflection lies between 10 and 15 km, matching with the top of the high velocity lower crustal body. At this level, Mjelde et al. (1997) suggest that the T Reflection marks the top of the interval with $V_p > 7.1$ km/s, further interpreted as top of mafic/ultramafic underplated material (Fig. 2).

The dome has an obvious positive signature on the 50 km filtered Bouguer anomaly, whereas no significant magnetic anomaly is associated with the crustal dome (Fig. 4). In the conjugate Greenland margin, Schlindwein and Jokat (1999) show that a high velocity lower crustal body, also interpreted as Tertiary underplating, coincides with a prominent magnetic anomaly that cannot be explained by the exposed Tertiary volcanics or shallow sills alone. Surprisingly, on the Norwegian side, the lower crustal body observed in the outer Vøring Basin is not associated with such a significant magnetic signature (Fichler et al., 1999).

Two hypotheses may explain the lack of a significant magnetic signature of the lower crustal body observed along the NGR. It may be linked (1) to the lack of mafic mineral assemblages within the crustal dome, or (2) to mafic material located above the Curie temperature (540–570 °C). Extrapolating at depth the high thermal gradient superficially measured in the well 6704/12-1 (53 °/km), and considering that rock conductivities increase in depth as a porosity function (Brigaud, Chapmans, & Le Douaran, 1990), the temperature for a vertical heat flow, at 13–15 km, should remain above the Curie temperature isotherms. Furthermore, elevated heat flow induced by thick instantaneous underplating, emplaced during Paleocene, is unlikely to have a thermal effect now after 55 Ma of cooling (Fjeldskaar, Johansen, Dodd, & Thompson, 2003). Recent thermomechanical modelling (Gernigon, 2002) also shows that the present temperatures range between 250 and 270 °C near the T Reflection. Therefore, if the dome is of magmatic and mafic origin, it is difficult to reconcile with its low magnetic character. The geophysical background instead suggests that the T Reflection represents a high impedance boundary associated with a high-density body (high-velocity contrast) and no magnetic susceptibility.

3. Basin deformation and relation with the crustal dome

3.1. Structure

The NGR, at the base Tertiary unconformity level, is a 50 × 50 km² structure (Fig. 3a). The base Tertiary unconformity on top of the ridge marks a hiatus between the latest Maastrichtian formations and a thin layer of Late Paleocene sediments drilled by the well 6704/12-1. To the East of the ridge, onlaps and pinch-outs of Upper Cretaceous–Paleocene formations on the western part of the Vigrid Syncline are observed and show that the NGR was a relative high during this period (Fig. 2). Between the base Tertiary unconformity and the T Reflection, the NGR displays a complex crustal structure involving two main structural levels (Figs. 4 and 5).

The uppermost level represents shallow NE–SW-trending normal fault system, mainly localized above the crustal dome, highlighted by the positive Bouguer anomaly. Faults

and well-layered reflections are seismically imaged on the NGR and tilted structures are located on top of the crustal dome (Fig. 3c). The shallow faulted structures were recently drilled (6704/12-1) and proved to be Early Campanian–Maastrichtian synrift formations. The fault pattern involves both antithetic and synthetic faults, as well as low-angle faults that feature a rollover controlled in depth by a detachment, with an apparent shallow inclination to the west. On the eastern limb of the ridge, a transparent seismic facies reflecting small diapirs suggests that the detachment may lie in mobile shales acting as a decollement level. Stretching factors measured geometrically along this structural level have β_{cret} factors lower than 1.1.

A deeper structural level is observed below the Cretaceous shales and in turn overlies deeper reflections that mimic syn-rift wedges which are part of a distinct tilted block system, still apparently dipping to the west. On the eastern limb of the ridge, sill intrusions prevent any accurate seismic interpretation. The deeper fault-block system remains poorly dated due to the lack of regional control. At mid-crustal scale, the deep tilted blocks root above a low-angle shear zone connected to the strong T Reflection. Deeper, and close to the T Reflection, concordant reflections mimic the top geometry of the dome and further suggest a ductile deformation of the deep basin.

3.2. Structural evolution of the NGR

The different structural levels record the crustal stretching in different manners during the NGR evolution (Fig. 5).

The upper level represents syntectonic wedges and tilted blocks probably faulted during an Early Campanian–Paleocene rifting and accommodated at depth by a decollement layer within Lower Cretaceous (Albian–Cenomanian?) shales. The shape of the dome controls the fault pattern.

The second level is interpreted as being older than Early Cretaceous and represents block structures cut by a large low-angle ductile shear zone at depth, which splays upwards into normal faults. A normal displacement along this low-angle shear zone is expected during the pre-breakup rifting in order to accommodate the extension of the overlying tilted blocks in depth.

The deepest level corresponding to the T Reflection was probably updomed during the rifting and may have accentuated block rotation and low-angle faulting, in a similar way as the isostatic denudation and rolling-hinge process described by Axen and Bartley (1997) and Koyi and Skelton (2001). Extension on low-angle faulting is known to accommodate high-magnitudes of crustal stretching in rifted basins. Therefore, the interpretation of low-angle shear zones inferred in the deeper part of the NGR is not surprising considering that extension on the shallow part of the Cretaceous basin (low β_{cret}) is unable to accommodate the large magnitude of crustal thinning expected to have occurred just prior to the lithospheric rupture (Fig. 5).

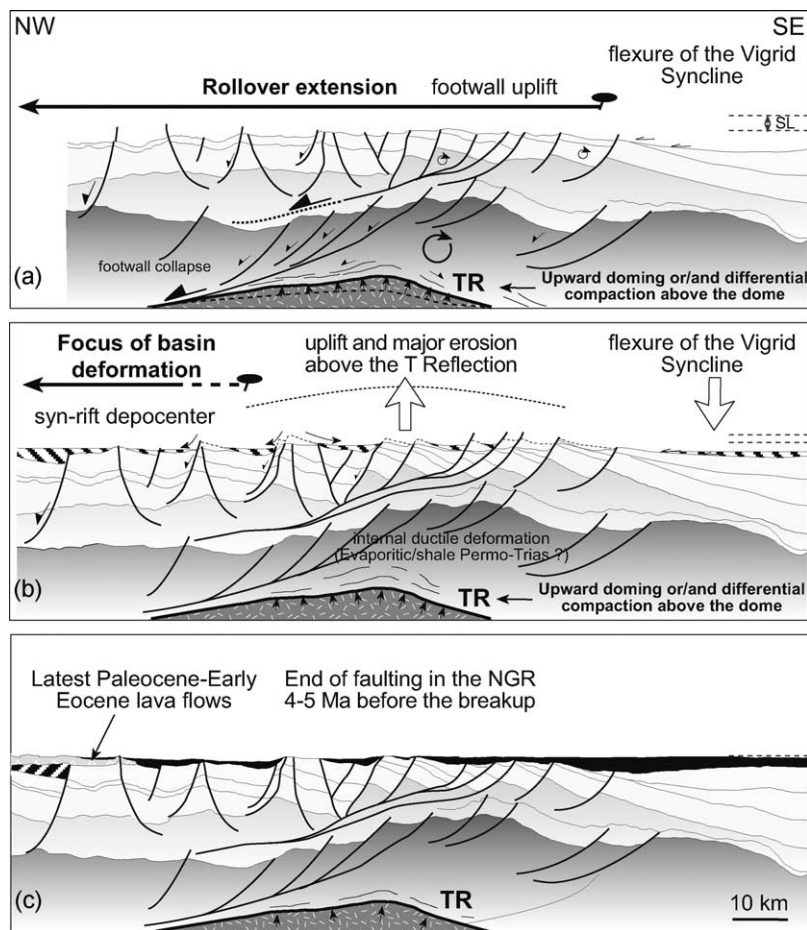


Fig. 5. Three-stage kinematic model for the stretching and geometric evolution of the NGR from the Early Campanian (a), to the latest Maastrichtian–Early Paleocene main uplift (b), and up to the final break-up in the latest Paleocene–Earliest Eocene (c).

The relative uplift may be also explained by ‘boudinage’ and differential compaction of the sedimentary section, controlled and accommodated in depth by the pre-existing dome-shaped basement structure (Fig. 6e). In this case, ductile flow and diapirism within the lower crustal dome (Fig. 6c; Lundin & Doré, 1997) are not necessary. Nevertheless, semi-ductile shear deformations are interpreted on top of the T Reflection, but these are likely to represent the ductile behaviour of the deep sedimentary rocks (Figs. 5 and 6).

Faulting in the NGR is sealed at the erosive base Tertiary unconformity, draped by Upper Paleocene–Early Eocene sediments. This deformational event coincides with the Icelandic plume–lithosphere impingement during the late Maastrichtian–Early Paleocene (Skogseid et al., 2000). The faulting in the NGR ended before the breakup (Early–mid Paleocene) and reflects a progressive focus of the deformation toward the future breakup zone (Fig. 5b and c). This focus may be interpreted as a result of a punctual weakening of the lithosphere as suggested by numerical (Govers & Wortel, 1993) or analogue models showing that a melted zone within the lithosphere may strongly control the localization of stretching (Callot, Geoffroy, & Brun, 2002).

During the Early Campanian–Paleocene rift event, the NGR was also in a structurally high position above the crustal dome. It was mainly eroded in comparison to the Gleipne saddle, which formed a depressed zone, where the crustal dome and major tilted structures are not observed (Fig. 3c; Gernigon et al., 2001). The relative uplift of the NGR is suggested by (1) erosional surfaces well observed in the NGR but not in the Gleipne saddle and (2) a more important Paleocene–Early Eocene wedge and late Paleocene inner lava flow wedges, which preferentially filled the Gleipne saddle and by-passed the NGR (Fig. 3a).

4. Discussion: the origin of the lower crustal dome: a breakup magmatic-related feature?

4.1. The ‘Mafic/ultramafic’ model

So-called lower crustal bodies are commonly observed near the continent–ocean boundary of several volcanic margins (Eldholm et al., 2000) where they show a range of V_p velocities between 7.1 and 7.7 km/s. According to White and McKenzie (1989) and Eldholm et al. (2000), lower

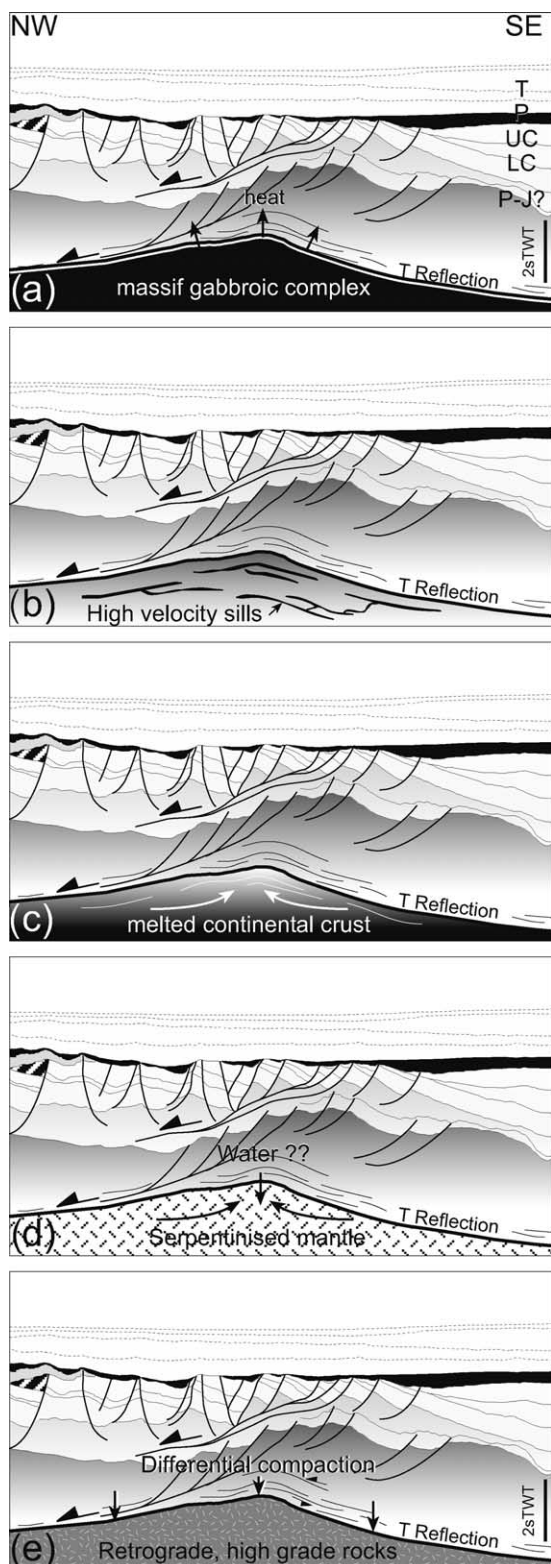


Fig. 6. Five hypotheses for the nature of the high-velocity crustal dome observed beneath the NGR: (a) Massif gabbroic complex emplaced during the Late Paleocene continental break-up (Mjelde et al., 1997, 1998). (b) Lower continental rocks injected by scattered sills intrusions. (c) Melted continental crust induced by deeper magma chamber and leading to a lower crustal diapirism (Lundin and Doré, 1997). (d) Serpentinised mantle rocks inducing a fall of viscosity and a progressive updoming of the lower crust

crustal bodies are likely to correspond to gabbroic to olivine cumulates derived from picritic melts that underplated the lower crust mainly during the breakup volcanic event (Fig. 6a). Berndt, Skogly, Planke, and Eldholm (2000) note that the geophysical expression of the high-velocity mafic lower crust is complex and may be alternatively interpreted as either a massif magmatic structure or a preexisting crust injected by scattered high-velocity sills (Fig. 6b). Then, Fjeldskaar, Johansen, Dodd, and Thompson (2003) show that underplating may induce significant isostatic and heatflow effects, which could be important for maturity and hydrocarbon generation. Therefore, timing of emplacement with regard to the breakup and the real nature of the lower crustal bodies (particularly in the continental domain) are critical and significant factors to better analyse and model the petroleum system along volcanic margins.

Regional considerations show that the magmatic activity in the North Atlantic domain occurred throughout the entire Paleocene period between 63 and 54 Ma with a peak at 50–55 Ma (Saunders, Fitton, Kerr, Norry, & Kent, 1997). According to the high-velocity character of the lower crust and its position close to the seaward dipping reflectors, a mafic/ultramafic interpretation has been proposed by Mjelde et al. (1997, 1998) to explain the high V_p values observed below along the breakup axis and below the NGR.

An integrated seismic-gravity-magnetic interpretation shows that the T Reflection originates from a boundary separating a high-density, low-susceptibility, and high-velocity middle crustal unit from the overburden. It is thus not a reflection from a thin layer, such as a sill intrusion or a fault zone. The T Reflection is also unlikely to have first originated from the top of the 'Tertiary' magmatic underplated unit since it clearly existed prior to the Paleocene and because the underlying high-velocity body is likely to be non-magnetic.

Mjelde et al. (2002) still note that the lower crustal high velocity in the Vøring Basin is decoupled from the breakup itself, and could be restricted to a process occurring during the latest phase of rifting prior to breakup. According to one of the reviewers, it could mean that lower crustal intrusions might have been formed during Late Cretaceous. In this case, our evolution model of the NGR could be carefully used as an argument to favor evidence of Campanian?–Maastrichtian underplating below the Vøring Basin. According to White and McKenzie (1989) large amount of high Mg-content melt, expected to have high velocity lower crust should be a consequence of the Icelandic mantle plume. However, impingement of the Icelandic plume with

(Ren et al., 1998). (e) Pre-existing high-grade rocks (granulites/eclogites) related to an inherited post-Caledonian metamorphic core complex. A differential crustal compaction process above retrograde high-grade rocks may explain both the structure of the NGR and the high V_p velocities observed below the T Reflection. LC: Lower Cretaceous; P: Paleocene; P–J: Paleozoic–Jurassic? undifferentiated; T: Tertiary; UC: Upper Cretaceous.

the North Atlantic lithosphere is recorded at ~ 65 – 60 Ma beneath Greenland (Lawver & Muller, 1994) and this makes it difficult to explain its direct thermal involvement along the Late Cretaceous rift system located 500–1000 km away from its axis if the melt is emanated from a localized source beneath Greenland. Furthermore, Ren et al. (1998) show that the mantle plume does not necessarily influence the subsidence history of the NGR before Paleocene time. Alternative geodynamic models may however explain moderate pre-breakup magmatism without involving hot mantle plume effect. For example, moderate temperature (~ 1330 °C), mantle heterogeneities, small-scale convection in connection with the pre-breakup rifting may also explain both the earliest important melt production along the NE Atlantic and high V_p velocities associated with lower crustal bodies (Anderson, 2000; Boutillier & Keen, 1999; Korenaga et al., 2000).

4.2. The ‘serpentinisation’ model

Another possible explanation that could account for both the non-magnetic and high-velocity characteristics of the NGR lower crust is for this interval to consist of pre-breakup crystalline rocks. The non-magmatic lower continental crust below the outer Vøring Margin is generally attributed to a granodioritic crust with V_p wave velocities ranging between 6.5 and 7 km/s (Raum, 2000). However, it has been observed from geophysics that the lower crust has locally higher velocities. From that point of view, a serpentinized mantle, for example, displays a large range of V_p waves, ranging between 5 and 7.5 km/s and high V_p/V_s values > 1.8 (O’Reilly, Hauser, Jacob, & Shannon, 1996), quite similar to the values observed below the T Reflection (Fig. 6c). Serpentinised mantle below the T Reflection has already been suggested by Ren et al. (1998) and that suggestion implies a pre-magmatic emplacement of the dome below the NGR. However, such rocks are only expected to occur within highly stretched extensional crustal domain in highly saturated water conditions (Boillot, Mougnot, Girardeau, & Winterer, 1989). Such environments are difficult to explain at depths of 8–9 km (depths without post-rift sediments during the last stage of rifting) below the NGR, where the high hydrostatic pressures do not favour a downward migration of sea water fluids. The same conclusion is drawn in Mjelde et al. (2002) based on V_p/V_s results and a discussion on the large scale crustal stretching of the Vøring Margin.

4.3. The ‘retrograde, high-grade rocks’ model

As previously discussed, there is a spatial relationship between the high velocity lower crustal body and the late episode of rifting (Mjelde et al., 2002). The lower crustal body is bounded to the east by the Fles Fault complex, well known to be a major weakness zone active during the long tectonic history of the Vøring Margin (Doré, Lundin,

Fischler, & Olsen, 1997). It is not excluded that the Fles Fault Complex may reflected a deep suture zone limiting different crustal terranes that can also explain the velocities contrasts of the deep lower crust on the Vøring Basin.

From the overall characteristics mentioned above, it is here suggested that the crustal dome bounded by the T Reflection may be also partly explained by high pressure granulite/eclogitic material which is known to display both high V_p waves (7.2–8.5 km/s) and high density (2.8–3.6 g cm³; Fountain, Boundy, Austrheim, & Rey, 1994; Fig. 6e). These rocks are well documented in the eastern part of the Norwegian Western Gneiss Region (Fig. 1), outcropping in the footwall of the Hornelen post-orogenic basin (Dewey, Ryan, & Andersen, 1993). Its offshore prolongation to the west has been recently interpreted in the northern North Sea below the Triassic–Jurassic rift system (Christiansson, Faleide, & Berge, 2000) or in the eastern part of the Møre Basin (Olafsson, Sundvor, Eldholm, & Kjersti, 1992). Eclogite present in these areas exhibits significant V_p values, close to 8 km/s similar to the values of the lower high velocity lower crust observed in the NGR. A large range of V_p values is not excluded for the lower crust if lower metamorphic facies rocks are considered for the lower crust (Fountain et al., 1994). Unpublished expanded spread profiles shot during the Elf Refranorge project (1983–1986) also demonstrate that the geophysical nature of the lower crust in the eastern part of the Vøring Margin is characterised by high V_p velocity values > 7 km/s at less than 20 km from the Trøndelag Platform (e.g. Planke et al., 1991). These intermediate values are also difficult to interpret either as magmatic underplated or serpentinised mantle, because both features are generally focused close to the breakup axis (Boillot et al., 1989; Eldholm et al., 2000).

The geophysical properties of the Caledonian nappes also display low magnetic attributes at normal shelf-type thermal gradients (Olesen et al., 1997) which may explain the low magnetic signature of the crustal dome below the NGR.

All these observations provide a consistent model for interpreting the T Reflection as a top of an initial old crystalline, high V_p basement crust. In the southern Trøndelag Platform, large magnitude extension along a Palaeozoic detachment has been recently documented by Osmundsen et al. (2002). It resulted in the formation and denudation of an antiformal mid-crustal feature, likely initiated during the post-Caledonian orogeny and later reactivated during the Mesozoic. This ‘reactivated core complex’ observed beneath Jurassic rotated half-grabens is very similar in size and shape to the dome feature observed below the NGR. On the other hand, the T Reflection may be ascribed to a mylonitic front as postulated by Osmundsen et al. (2002) forming the arched acoustic impedance contrast between a metamorphic lower plate with granulite/eclogitic material, and an upper plate involving crystalline rocks and/or metasediments (Fig. 6e). The dome shape is not necessarily the consequence of an intra-lower crustal ductile

flow at the level of the T Reflection. It is here suggested that rocks of the upper plate may be differently compacted or/and faulted by boudinage on both sides of a pre-existing dome during the stretching of the NGR (Figs. 5 and 6e).

5. Conclusions

1. Three-dimensional seismics and a new well calibration document an Early Campanian–Paleocene rift event along the NGR in the outer part of the Norwegian volcanic margin. At depth, the NGR fits with a circular Bouguer positive signature above a lower crustal dome delimited on top by the regional strong amplitude T Reflection. The T Reflection represents the top of a high velocity lower crustal body characterised by $V_p > 7.1$ km/s.
2. Geometric and timing relationships between the T Reflection and the upper crustal deformation (sealed by Upper Paleocene sediments) suggest that the crustal dome influenced the structural development of the sedimentary basin at least 4–10 Ma later, e.g. prior the breakup.
3. The smooth seismic character of the T Reflection below the NGR is interpreted to represent a high V_p wave velocity crystalline basement of retrograde high- and ultra high-pressure rocks similar to granulite/eclogite material involved onshore in Caledonian thrust nappes. However, the underplating hypothesis is not fully excluded during Late Cretaceous. In fact, deep lower crustal miagmatic terranes later injected by mafic material may represent a balanced view for the high velocity lower crust observed in the outer Vøring Basin. Unfortunately, proportions of each material are still difficult to unravel based on the current geophysical and geological data.
4. This interpretation has major implications for the thermal history, petroleum system, mantle temperature, and magmatic production along the Vøring Margin because the amount of Tertiary mafic material involved in the lower crustal body could be less than is thought. This may also apply to other volcanic margins in general.

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