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Rifting in heterogeneous lithosphere: Inferences from numerical modeling of the northern North Sea and the Oslo Graben

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[1] Permian rifting and magmatism are widely documented across NW Europe. The different Permian basins often display contrasting structural styles and evolved in lithospheric domains with contrasting past evolution and contrasting thermotectonic ages. In particular, the Oslo Graben and the northern North Sea rift initiated in close areas of northern Europe. The Oslo Graben evolved in the cold and stable Precambrian lithosphere of Fennoscandia, whereas the northern North Sea rift took birth in freshly reworked Caledonian lithosphere. Huge volumes of magmatic rocks characterize the relatively narrow Oslo Graben. In contrast, little magmatism is documented for the wide northern North Sea rift. Differences in timing between both rifts are inferred but still debated. We present numerical thermomechanical models along a lithospheric E-W section that involves both the Oslo Graben and the northern North Sea area. Because the modeled section crosses the boundary between Caledonian and Proterozoic provinces, thermal and compositional heterogeneities are considered. As is suggested by various geophysical data sets, we also consider lithospheric thickness heterogeneities in the Precambrian lithosphere. Modeling results suggest that the northern North Sea was on top of ''weak'' lithosphere very sensitive to far-field stresses. Consequently, we suggest that rifting in the northern North Sea began as early as regional extension was effective (i.e., Late Carboniferous–Early Permian) and does not postdate the Oslo Graben as it is commonly assumed. Rifting in the ''strong'' Precambrian lithosphere is unexpected. Modeling results suggest that a pre-existing lithospheric thickness contrast within the Fennoscandian lithosphere favored rifting in the Oslo Graben. *INDEX TERMS:* 8109 Tectonophysics: Continental tectonics—extensional (0905); 8159 Tectonophysics: Evolution of the Earth: Rheology—crust and lithosphere; 8020 Structural Geology: Mechanics; 9335 Information Related to Geographic Region: Europe; 9614 Information Related to Geologic Time: Paleozoic; *KEYWORDS:* numerical modeling, rifting, rheology, lithosphere, Oslo Graben, North Sea. **Citation:** Pascal, C., and S. A. P. L. Cloetingh, Rifting in heterogeneous lithosphere: Inferences from numerical modeling of the northern North Sea and the Oslo Graben, *Tectonics*, *21*(6), 1060, doi:10.1029/2001TC901044, 2002.

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1. Introduction

[2] Since *McKenzie* [1978] our knowledge in rift dynamics has been increased significantly during the two past decades [e.g., *Ziegler*, 1994]. Various aspects concerning the mode of rifting have been explored, like the magnitude of applied strain rate [*England*, 1983; *Bassi*, 1995], the rheology and initial conditions [*Buck*, 1991; *Bassi*, 1995], the necking depth [*Kooi et al.*, 1992; *Cloetingh et al.*, 1995] or more recently the passive-active transition during rifting [*Huismans et al.*, 2001]. Most models consider that some homogeneity exists in each one of the main lithospheric layers (i.e., upper crust, lower crust, and mantle lithosphere). Homogeneity is generally assumed for the thickness, the petrological composition and the thermal properties of each lithospheric layer. Therefore, almost homogeneous integrated strength of the lithosphere is commonly assumed for modeling, except in the case of post-orogenic extension [*Braun and Beaumont*, 1989].

[3] We consider here the case of the Permian rifting in the Oslo Graben and the northern North Sea. The Permian rifting and magmatism event is a widespread event throughout western Europe [e.g., *Ziegler*, 1990]. Rift structures and magmatic rocks ranging from Late Carboniferous to Late Permian are found in various regions such as Scotland [*Francis*, 1991], northern Germany [e.g., *Breitkreuz and Kennedy*, 1999], Scandinavia [*Sundvoll et al.*, 1990; *Torsvik et al.*, 1997; *Fossen and Dunlap*, 1999] and Iberia [e.g., *Doblas et al.*, 1994]. Permo-Carboniferous rifting is also documented in Greenland [*Surlyk et al.*, 1986], in Ukraine [*Stovba and Stephenson*, 1999] and northern America [e.g., *Cameron and Muecke*, 1996]. Thus Permian rifting is seen to affect different geological provinces with contrasting thermotectonic age and contrasting lithospheric architecture. The Oslo Graben (Figure 1) evolved within the cold and stable Precambrian lithosphere of the Fennoscandian Shield [*Gaál and Gorbatschev*, 1987]. In contrast, 300 km westward from the Oslo Graben, the northern North Sea rift (Figure 1) took birth inside freshly reworked Caledonian lithosphere, hence potentially warm and weak. The two rifts display also contrasting features. The Oslo Graben is a relatively narrow rift with huge volumes of syn-rift magmatic rocks [*Neumann et al.*, 1992] whereas the northern North Sea rift is a wide rift apparently devoid of magmatism [*Christiansson et al.*, 2000]. Differences in timing between

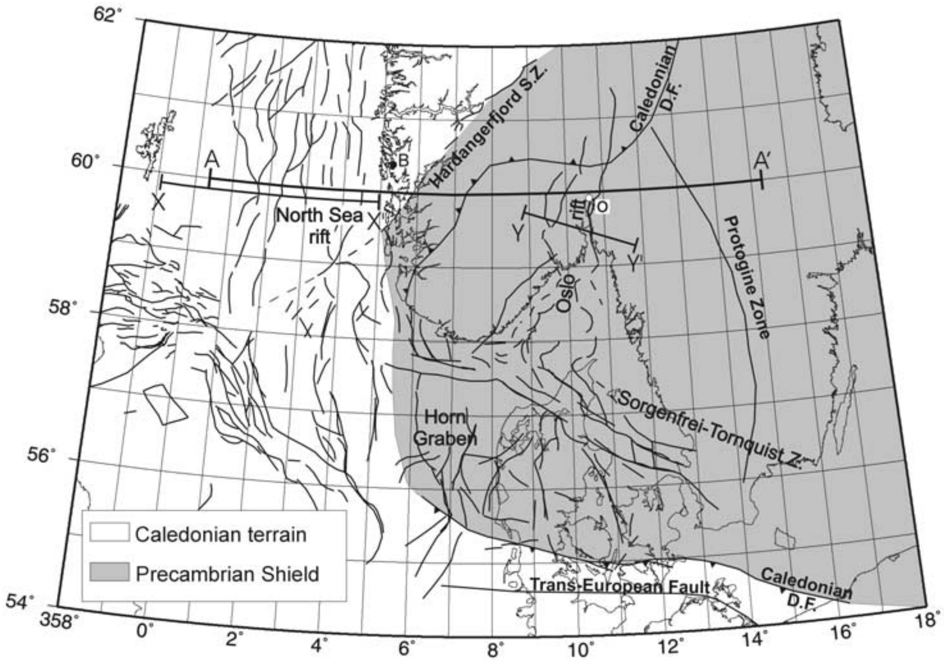


Figure 1. Simplified structural map including southern Scandinavia and northern and central North Sea. AA′ represents the modeled lithospheric section. XX′ and YY′ refer to the crustal sections shown in Figure 2. B = Bergen, O = Oslo.

the Oslo Graben (i.e., Permo-Carboniferous [*Sundvoll et al.*, 1990]) and the northern North Sea rift (i.e., Permo-Trias [*Steel and Ryseth* [1990]) are proposed. However, the age of rift onset in the northern North Sea is still debated.

[4] The present paper aims to investigate by means of thermomechanical numerical modeling the two following questions. (1) Why has the stable Fennoscandian lithosphere experienced Permo-Carboniferous rifting? (2) Were the northern North Sea rift and the Oslo Rift coeval or not? Because our modeling involves two terrains with contrasting thermotectonic ages and, because variations in crust [*Kinck et al.*, 1993] and lithosphere thickness [*Calcagnile*, 1982] are documented in southern Scandinavia, lithospheric heterogeneities are needed to be considered in the present study.

2. Tectonic Setting

2.1. Oslo Rift

[5] The Oslo Rift (Figures 1 and 2a) is a 400 km long and 60 to 120 km wide rift system, involving the Oslo Graben and its offshore continuation, the Skagerrak Graben (see a review by *Neumann et al.* [1992]). The Oslo Rift evolved inside the Sveconorwegian (1.2–0.9 Ga) province of the Baltic Shield [*Gaál and Gorbatschev*, 1987]. Early Paleozoic subsidence is revealed by up to ~2.5 km of Cambro-Silurian sediments preserved inside the Oslo Graben and up to ~5 km in the Skagerrak Graben. The Caledonian event affected weakly the northern part of the Oslo Graben [e.g., *Morley*, 1994]. The stratigraphic gap ranging from Late Silurian to Late Carboniferous [*Bjørlykke*, 1983] shows that the area of the future Oslo Graben remained above sea level after removal of the Caledonian range.

[6] Late Carboniferous pre-rift sediments in the Oslo Graben, show evidences of marine incursions in a shallow sag-like basin, arguing for a passive rift scenario [*Olaussen et al.*, 1994]. The pre-rift phase is also characterized by sill intrusions between 304 and 294 Ma. Rift paroxysm began at 290 Ma with extrusion of basalts, followed by extrusion of felsic "Rhomb-Porphyry" lavas between 290 and 276 Ma. Faulting and graben formation took mainly place during this time span and paleostress analyses carried out by *Heeremans et al.* [1996] argue for a driving normal stress regime with σ_3 striking ENE-WSW. Maximum normal throw estimates are in the order of 3 km for the Olslofjord fault [*Neumann et al.*, 1992]. The rift relaxation phase (276–240 Ma [*Sundvoll et al.*, 1990]) is characterized by caldera collapse and granitic intrusions at less than 3 km depth. These granites outcrop on the graben floor present-day. Modeling of fission track data suggests a thickness of 2 to 4 km for the missing pile of syn-rift sediments in the Oslo Graben [*Rohrmann et al.*, 1994]. In addition, fission track data indicate that these sediments were mostly eroded during uplift of southern Norway and Sweden in Mesozoic times [*Rohrmann et al.*, 1994; *Cederbom*, 2001].

2.2. North Sea Rift

[7] The Permian northern North Sea rift (Figures 1 and 2b) is a 500 km long and 150 km wide rift system [*Christiansson et al.*, 2000]. The late Paleozoic evolution

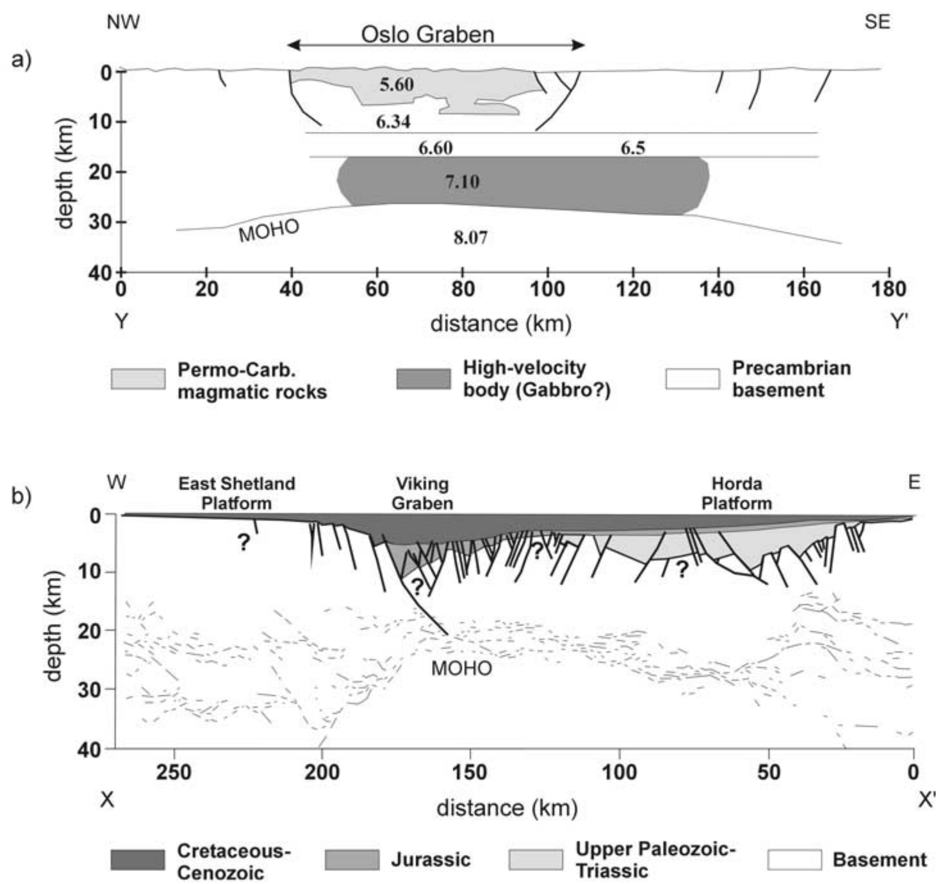


Figure 2. Crustal sections across (a) the Oslo Graben (with *P* wave velocities) and (b) the northern North Sea, modified after *Neumann et al.* [1992] and *Christiansson et al.* [2000], respectively. See Figure 1 for location.

of the North Sea was partly obscured by late Jurassic rifting and post-rift subsidence in Cretaceous and Cenozoic times [e.g., *Ziegler*, 1990]. The late Paleozoic geology is documented through geophysical methods and onshore-offshore correlations [*Nøttvedt et al.*, 2000], so that the pre- and syn-rift Permian evolution is less constrained in the northern North Sea than in the Oslo Graben.

[8] The northern North Sea area (Figures 1 and 2b) was strongly reworked and metamorphosed during the Caledonian orogeny (i.e., ~500–400 Ma [*Roberts and Gee*, 1985]). Post-orogenic extension of the Caledonian mountains in early Devonian times led to significant thinning of western Norway [*Andersen et al.*, 1991; *Fossen*, 1992]. Occurrence of Devonian continental basins along the Scottish [*Mykura*, 1991] and Norwegian [*Steel et al.*, 1985] coasts indicate that the northern North Sea hosted Devonian basins as well and, thus was also affected by the extensional event.

[9] To date Carboniferous and Permian deposits have never been drilled in the northern North Sea. Combined geophysical studies (i.e., seismic profiling, magnetics, and gravimetry) show that up to 4 km of upper Paleozoic (i.e., post-Caledonian and pre-Triassic) sediments remain on the Horda Platform, offshore Norway [*Hospers et al.*, 1986] and probably inside the Viking Graben [*Hospers and Ediriweera*, 1991; *Christiansson et al.*, 2000]. Furthermore, seismic profiles show that these sediments are trapped in half-grabens [*Faerseth et al.*, 1995; *Christiansson et al.*, 2000]. The exact age of these sediments is still unknown but the top of the syn-rift sequence was drilled and dated as early Triassic (i.e., Scythian [*Steel and Ryseth*, 1990]). However, on the Horda Platform late Paleozoic sediments are clearly imaged, by means of seismic reflection, as syn-rift packages overlain by the Upper Permian Zechstein salt [*Heeremans et al.*, 2000]. Kinematic reconstructions by *Gabrielsen et al.* [1999] suggest that Permian extension was orientated E-W in the North Sea. Tectonostratigraphic forward modeling suggests, furthermore, that Permian rifting in the northern North Sea began by late early Permian times (i.e., Kungurian [*Odinsen et al.*, 2000]). However, Permian dykes intruded along the Norwegian coast [*Faerseth et al.*, 1976; *Torsvik et al.*, 1997] appear to predate the commonly assumed Kungurian(?)-Scythian rift event. Dyke intrusions are also associated to normal faulting in the former Caledonides of western Norway [*Eide et al.*, 1997; *Andersen et al.*, 1999]. The Late Carboniferous–Early Permian uplift of the Bergen Region is attributed by *Dunlap and Fossen* [1998] to shoulders uplift in response

Table 1. Thermal and Mechanical Parameters Used in the Modeling[a]

	Heat Generation ($\mu W/m^3$), A_0		
Thermal parameters	Caledonian	Precambrian	Conductivity (W/m/K), k
Upper crust	2.5	1.5	2.5
Lower crust	1.5	0.4	2.3
Lithospheric mantle	0.01	0.01	3.7
Mechanical parameters	Young Modulus (Pa), E	Poisson's Ratio, ν	Density (kg/m^3), ρ
Upper crust	$50\ 10^9$	0.25	2700
Lower crust	$70\ 10^9$	0.25	2900
Lithospheric mantle	$70\ 10^9$	0.25	3300
Power law creep	Strain Rate Coefficient (Pa^{-n}/s), A_p	Stress Exponent, n	Activation Energy (J/mol) E_p
	Parameters Set 1		
Upper crust: wet quartzite	$1.26\ 10^{-13}$	1.9	172600
Lower crust: felsic granulite	$2.01\ 10^{-21}$	3.1	243000
Lithospheric mantle: wet dunite	$3.98\ 10^{-25}$	4.5	498000
	Parameters Set 2: "Strong Rocks"		
Upper crust: dry quartzite	$6.03\ 10^{-24}$	2.72	134000
Lower crust: mafic granulite	$8.83\ 10^{-22}$	4.2	445000
Lithospheric mantle: dry dunite	$7.94\ 10^{-18}$	3.6	535000
	Parameters Set 3: "Weak Rocks"		
Upper crust: wet granite	$7.94\ 10^{-16}$	1.9	140600
Lower crust: wet diorite	$1.26\ 10^{-16}$	2.4	212000
Lithospheric mantle: wet dunite	$3.98\ 10^{-25}$	4.5	498000

[a]Thermal parameters after *Balling* [1995], elastic parameters and densities after *Carmichael* [1989], creep parameters after *Carter and Tsenn* [1987].

to rifting in the northern North Sea. Finally, the occurrence of Early to mid-Permian syn-rift sediments and volcanics to the north, in eastern Greenland [*Surlyk et al.*, 1986], and, to the south, in the central North Sea [*Dixon et al.*, 1981; *Heeremans et al.*, 2000] suggest that the northern North Sea was also part of the same rift system in early Permian times.

3. Model Setup and Assumptions

3.1. Modeling Procedure and Rheology

[10] We used the FEM software package Ansys (Ansys Inc., Canonsburg, USA) because of its ability to handle lateral heterogeneities. Each simulation is operated on two separate but identical FEM grids. Each grid contains ~600 quadratic plane-strain structural or thermal elements. The two calculation grids exchange information in a loop-fashion procedure (i.e., one grid is updated with the results from the other one). The first grid calculates the lithospheric thermal state according to the steady state heat equation:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = -\frac{A}{k} \qquad (1)$$

where T is temperature, z is depth, A is heat generation by radioactive decay, and k is thermal conductivity.

[11] Constant thermal conductivities are assumed for each lithospheric layer. The temperature at the surface is assumed to be T = 0°C, whereas it is taken equal to T = 1333°C at the base thermal lithosphere. No lateral heat flow is allowed at model edges. The present-day surface heat flow for the Precambrian domain (i.e., 40 to 60 mW/m^2 [*Balling*, 1995; *Artemieva and Mooney*, 2001]) is assumed to have remained stable during Phanerozoic. This assumption is consistent with the assumption that the lithosphere structure of the Precambrian shield has not changed significantly. Note that heat flow reduction, by radioactive decay of the heat producing crustal isotopes, is negligible during the corresponding time span. Thermal parameters (Table 1) for the Precambrian province were taken after *Balling* [1995] and assumed to be valid at t = 305 Ma. At t = 305 Ma, the Caledonian Province was characterized by a thermotectonic age of ~130 My. Consequently, this province was still relatively young and warm. Thermal relaxation was almost completely achieved after 130 My but syn- and post-orogenic plutonism probably enriched the crust with radioactive elements. Moreover, Devonian extension [*Andersen et al.*, 1991; *Fossen*, 1992] probably reheated Caledonian lithosphere. We assigned to the Caledonian domain a surface heat flow of ~75 mW/m^2, in the range of measured values for 100–150 Ma lithosphere [*Artemieva and Mooney*, 2001]. The thermal parameters (Table 1) were selected in order to account for this surface heat flow. Results from the thermal grid (i.e., temperature at each node) are exported to the mechanical one.

[12] A viscoelastic rheology was selected for the mechanical grid. Stretching was applied to model edges in agreement with field data that argue for a passive rifting scenario [*Olaussen et al.*, 1994]. Relatively small β ratios

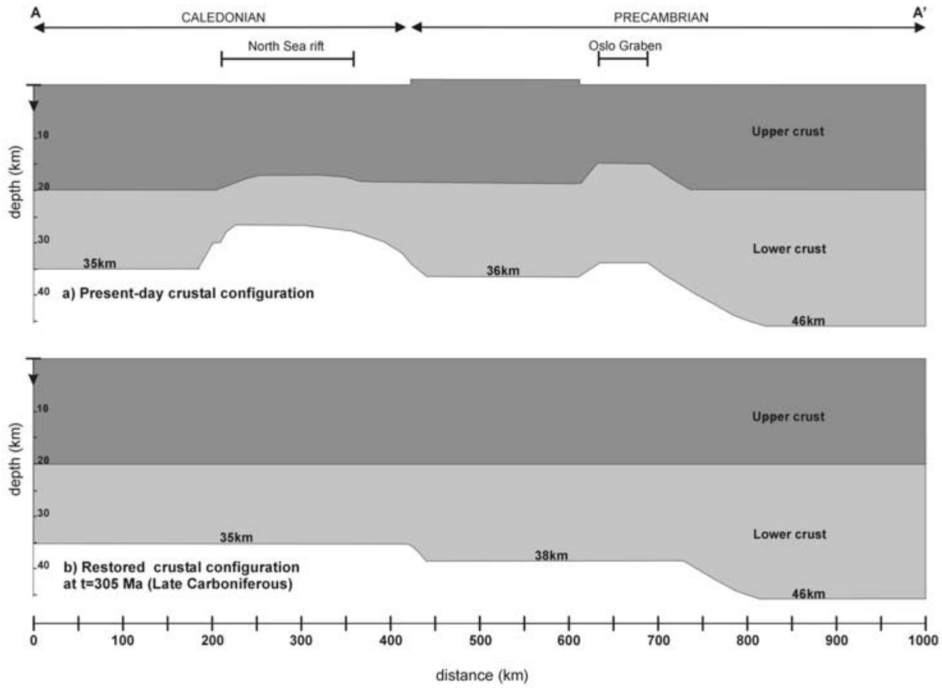


Figure 3. (a) Present-day crustal structure along section AA′. (b) Restored crustal structure at t = 305 Ma, onset of the Permo-Carboniferous rifting. See text for details.

(i.e., $\beta < 1.3$ [*Pallessen*, 1993]) and long lasting rifting (i.e., 60 My [*Sundvoll et al.*, 1990]) are associated to the Oslo Graben. Thus relatively low strain rate values (i.e., $\sim 10^{-16}\ s^{-1}$) were applied to models. We restricted the analysis to a time span equivalent to the duration of maximum rift activity (i.e., ~30 My). Buoyancy restoration forces were simulated in attaching spring elements to the main density contrast interfaces (for an explanation see *Williams and Richardson* [1991]). Spring parameters were updated after each strain increment (i.e., every 1 My) in order to minimize possible artifacts. For each one of the three main lithospheric layers (i.e., upper and lower crust and mantle lithosphere) the mode of deformation (i.e., elastic or viscous) depends on rock composition, temperature and strain rate. Viscosity is submitted to power law creep [e.g., *Ranalli*, 1995] through the constitutive equation linking strain rate, $\dot{\varepsilon}$, to differential stresses, σ:

$$\dot{\varepsilon} = A_p \sigma^n \exp\left(-E_p/RT\right) \quad (2)$$

where A_p is the creep constant, n the creep exponent, E_p the activation energy, all three parameters being material-type dependent, and R, the Gas Constant.

[13] Three sets of different petrologies were used in our models (Table 1). The thermal grid is updated every 1 My with the results (i.e., node displacements) of the mechanical one and the new thermal state of the lithosphere is calculated. In turn, the new thermal state is transferred to the mechanical grid every 1 My and a new mechanical run is performed. Note that involvement of the asthenospheric mantle in the evolution of the system is not considered here. However, recent modeling studies [*Pascal et al.*, 2002] that consider it confirm the main conclusions of the present one.

3.2. Geometry of the Model

[14] We modeled the lithospheric section AA′ (Figure 1). Section AA′ crosses from W to E Caledonian and Precambrian terrains that host the northern North Sea and the Oslo Graben respectively. Present-day crust geometry (Figure 3a) was drawn according to Moho maps from *Kinck et al.* [1993] and *Thybo* [1997], and according to various deep seismic lines [*Kanestrøm*, 1971; *Tryti and Sellevoll*, 1977; *Cassel et al.*, 1983; *Guggisberg et al.*, 1991; *Christiansson et al.*, 2000]. The present-day crust geometry was corrected in order to reconstruct the initial geometry at the onset of the Permo-Carboniferous rift and magmatic event, at t ~ 305 Ma [*Sundvoll et al.*, 1990]. In other words, we inferred the likely pre-rift crustal thickness of the northern North Sea and the Oslo Graben in taking relatively stable neighboring blocks (i.e., the Shetland Platform and southern Norway, respectively) as templates. Note that we also added 2 km of crust to southern Norway (Figure 3b) to account for post-Permian erosion of the basement in this region [*Doré*, 1992; *Rohrman et al.*, 1995].

[15] The restored section (Figure 3b) shows that shallowing of the Moho occurs from east to west [*Kinck et al.*, 1993]. One remarkable feature of this trend is the sharp drop in crustal thickness occurring close to the eastern boundary of the Oslo Graben. As pointed out by *Kinck et al.* [1993], rifting of the Oslo Graben cannot totally account for this

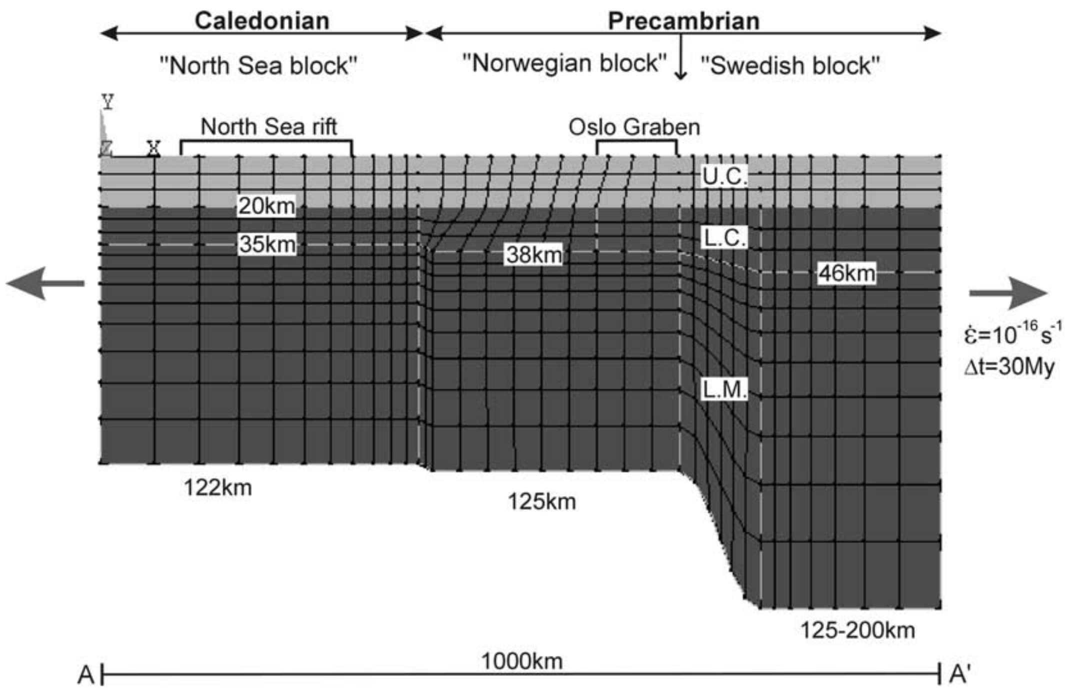
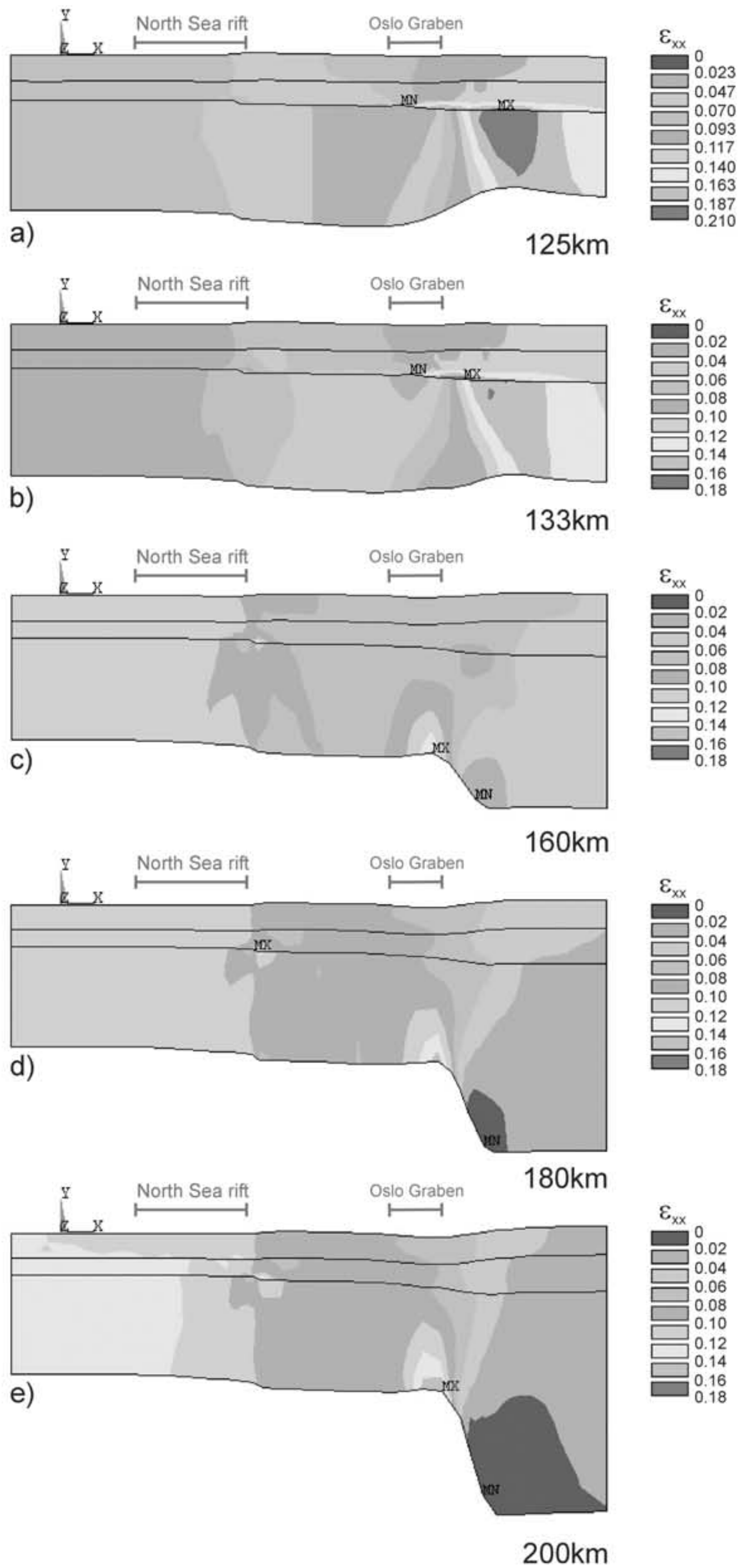


Figure 4. Lithospheric model along section AA′. The depth of the base lithosphere below the Swedish block is varied between 125 and 200 km in the modeling. All other geometrical parameters are kept constant. Different petrologies are used in the modeling (see Table 1 and text). The amount of applied strain rate, $\dot{\varepsilon}$, and the duration of rifting, Δt, are indicated. U. C. = upper crust, L. C. = lower crust, L. M. = lithospheric mantle.

sharp change in crustal thickness. The upper crust-lower crust boundary has nowadays a complex geometry but generally undulates about 20 km depth, outside the rifted zones [*Kanestrøm*, 1971; *Cassel et al.*, 1983; *Guggisberg et al.*, 1991]. For the sake of simplicity we assumed that this boundary was a straight line along section AA′ (Figure 3b). Preservation of early Paleozoic sediments inside the Oslo Graben and the middle Paleozoic regional stratigraphic break suggests that the area under scope was peneplained before Permian rifting took place. We assumed no topography at t = 305 Ma (Figure 3b). A relief was established in the Caledonian province during Carboniferous [*Eide et al.*, 1999] but may be it was insignificant [*Lidmar-Bergström*, 1996]. Major Precambrian ductile shear zones are crossed by the modeled section AA′ (Figure 1). Although Precambrian structures are known to have exerted some local control on the development of the Oslo Graben [*Swensson*, 1990; *Sundvoll and Larsen*, 1994], most of these major shear zones experienced minor brittle faulting in Late Proterozoic-Phanerozoic times [e.g., *Bingen et al.*, 1998], suggesting that they were annealed in Permo-Carboniferous times. We thus assumed that they did not affect notably the mechanical properties of the crust.

[16] Surface wave dispersion analyses [*Calcagnile*, 1982] and deep seismic lines [*Lie et al.*, 1990] argue for present-day lithosphere thickness of ~125 km in the Oslo Region and southern Norway. Subsidence analysis of the Skagerrak Graben [*Pedersen et al.*, 1991] suggests a similar pre-rift thickness. We also assumed a similar order of thickness for the northern North Sea lithosphere (Figure 4). Note that significant along-strike variations are likely [*Faerseth et al.*, 1995]. For contrasting values [*Calcagnile*, 1982; *Husebye et al.*, 1986; *Babuška et al.*, 1988; *Vecsey et al.*, 2000; *Artemieva and Mooney*, 2001] are proposed for the litho-

Figure 5. (opposite) Horizontal strain (i.e., ε_{xx}) distributions for five models with uniform petrologies for the upper crust, the lower crust and the mantle lithosphere (see set 1, Table 1). The depth of the base lithosphere below the Swedish block ranges between 125 and 200 km and is taken as degree of freedom (experiments a to e). All other parameters are indicated in Figure 4 and Table 1. Note that locations of maximum and minimum horizontal strain switch between the Swedish block and the Norwegian block when the depth of the base lithosphere increases. Furthermore, when the lithosphere thickness contrast between the two blocks becomes significant maximum horizontal strain is predicted below the Oslo Graben. The deformation pattern is magnified 30 times. See color version of this figure at the back of this issue.


North Sea rift
Oslo Graben
Y
X
MN
MX
a)
125km
εxx
0
0.023
0.047
0.070
0.093
0.117
0.140
0.163
0.187
0.210
b)
133km
εxx
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
c)
160km
d)
180km
e)
200km

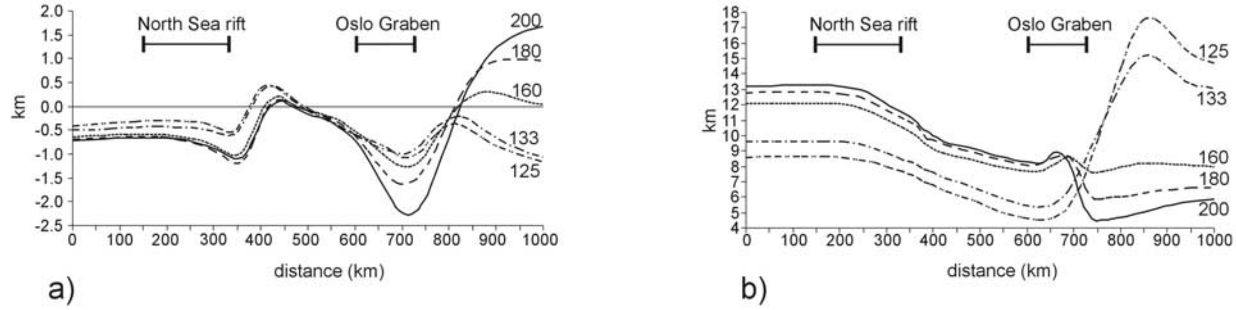


Figure 6. (a) Surface and (b) base lithosphere deflections in function of the Swedish block base lithosphere depth (in km). Positive and negative numbers indicate uplift and subsidence, respectively. The curves correspond to the five models depicted in Figure 5. Note that subsidence and base lithosphere uplift are enhanced in the Swedish block for shallow base lithosphere depths below it (i.e., no or moderate lithosphere thickness contrasts). In contrast, subsidence and base lithosphere uplift are enhanced in the Oslo Graben area for significant lithosphere thickness contrasts (i.e., curves 180 and 200 km).

sphere thickness east of the Oslo Graben (i.e., where deepening of the Moho occurs), we set it as a degree of freedom in our modeling.

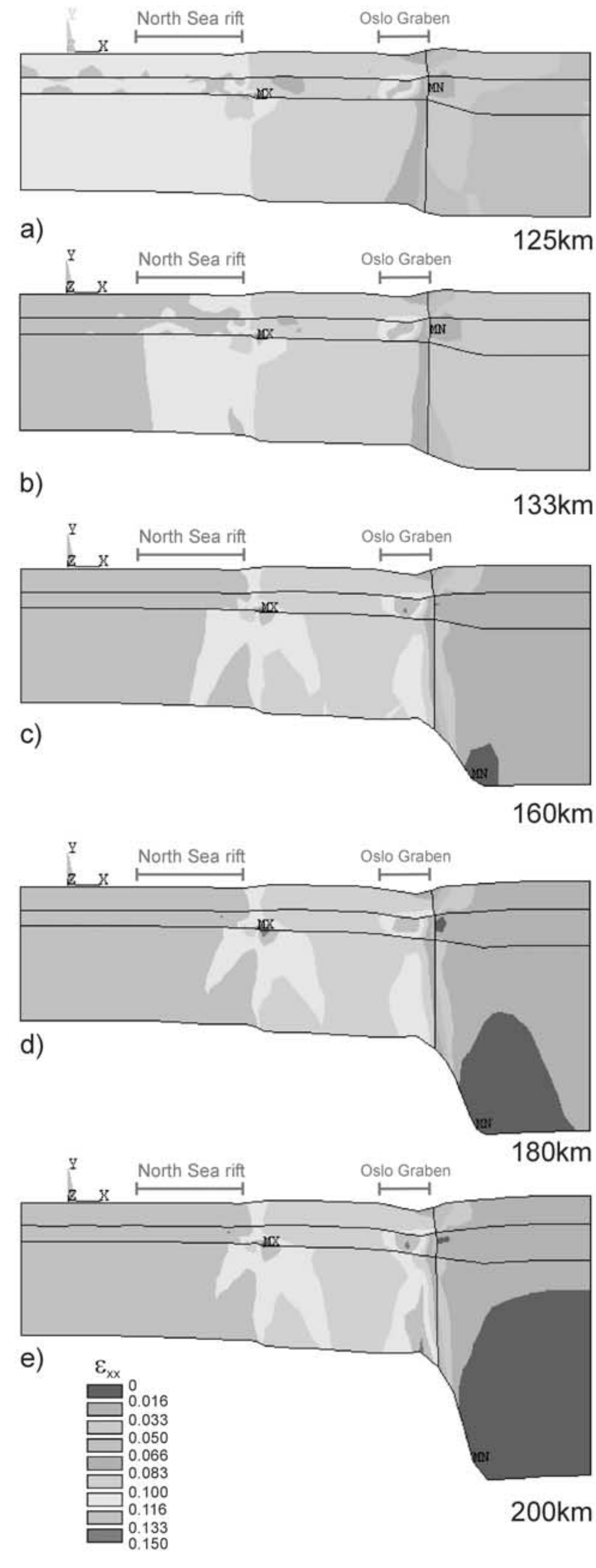
4. Modeling Results

[17] The purpose of the modeling is to explore the impact of varying lithosphere thickness (hence thermal state) and composition for the three lithospheric domains of section AA′ (Figure 4), on strain distributions and consequent uplift-subsidence patterns in the models. We chose to explore these two parameters because (1) they are first-order parameters in controlling the strength of the lithosphere [*Ranalli*, 1995] and (2) as was discussed previously, they are expected to vary along the modeled section. As was already established in previous studies [e.g., *Buck*, 1991; *Bassi*, 1995], base lithosphere deepening and a more mafic or anhydrous rock composition result in increasing lithospheric strength. We expect here that heterogeneous lithospheric strength along the section results in heterogeneous strain distribution. The modeling results are compared to actual locations and geometries of the Oslo Graben and the northern North Sea rift and discussed in the following section.

4.1. Influence of Lithosphere Thickness Contrast

[18] The first modeling attempt was carried out by varying the lithosphere thickness below the eastern part of the modeled section AA′ (Figure 4). The lithosphere thickness is varied between 125 km, corresponding to a flat-base lithosphere configuration, and 200 km, which is in the range of maximum lithosphere thickness inferred for the Fennoscandian Shield [*Calcagnile*, 1982; *Kukkonen and Peltonen*, 1999; *Artemieva and Mooney*, 2001]. All other parameters (Figure 4 and Table 1) were kept constant and the models were stretched parallel to the E-W axis (i.e., perpendicularly to the structural trend of the Oslo and North Sea rifts). We selected petrology set 1 (Table 1), which represents an average rheological behavior [*Govers and Wortel*, 1993]. Resulting horizontal strains along the modeled sections are presented in Figure 5. Surface and base lithosphere deflections along the modeled sections are presented in Figures 6a and 6b, respectively. We note that increasing the lithosphere thickness contrast results in transferring progressively maximum strains from the eastern part to the central part of the model (Figure 5). This result is accounted by the progressive lithosphere strengthening of the eastern part of the model when the base lithosphere is deepened.

[19] For the first model (Figure 5a), we assumed no lithospheric thickness contrast. When submitted to stretching, maximum horizontal strain concentrations are simulated in the mantle and the lower crust of the "Swedish block." The central part of the model behaves here as a strong block, where minimum strain is predicted (Figure 5a). A broad and shallow subsided area is predicted in the modeled Precambrian province (i.e., maximum depth ∼1 km, Figure 6a, 125 curve). Shallow subsidence is simulated for the "North Sea block" (i.e., ∼0.5 km, Figure 6a, 125 curve). In turn, moderate uplift is predicted at the eastern edge of the "Norwegian block" (i.e., Bergen Region). The base lithosphere is strongly uplifted for the Swedish block (i.e., ∼18 km, Figure 6b, 125 curve) and to some extent below the North Sea (∼8–9 km). These first model results are explained by the differences in thermal state existing between the three blocks. More heat generation was assigned to the North Sea block (i.e., the Caledonian province) resulting in its expected weakening with respect to the Precambrian province. In the Precambrian province, the ratio crust thickness on lithosphere mantle thickness increases from the Norwegian to the Swedish block. Because crustal rocks are weaker than mantle rocks and produce more heat by radioactive decay (see Table 1), the strength of the Swedish block is less relatively to the strength of the Norwegian block. Hence the Norwegian block appears to be the strongest block in the present simulation (Figure 5a).



[20] In a case where the base lithosphere of the Swedish block is deeper, modeled strain concentrations are progressively transferred to the Oslo Graben and North Sea areas (e.g., compare Figure 5b with Figure 5c), implying that the Swedish block is the stronger and more stable of the blocks. This effect is accounted for by the following points: when we deepen the thermal base lithosphere of the Swedish block, (1) the ratio of the crustal thickness relative to lithosphere mantle thickness is decreased, and (2) the integrated lithospheric strength of this block is increased by relaxation of the isotherms.

[21] We note that horizontal strains are notably reduced in the Swedish block with respect to the Norwegian block for a significant lithosphere thickness contrast between both blocks (i.e., 35 km or 160 km thick lithosphere for the Swedish block; Figure 5c). Furthermore, when the lithosphere thickness contrast becomes significant, subsidence is enhanced both in the Oslo Region and the North Sea area, whereas uplift is reduced in the present-day Norwegian coast (Figure 6a, 160 to 200 curves). In turn, we also note that uplift of the Swedish block is enhanced when the base lithosphere is progressively deepened below it. Significant uplift of the Swedish block is predicted for a lithosphere thickness contrast of minimum 55 km (Figure 6a, 180 curve). When the lithosphere thickness of the Swedish block is increased, the base lithosphere is particularly uplifted below the North Sea and the Norwegian blocks. In contrast, base lithosphere uplift in the Swedish block is reduced and becomes negligible (i.e., ~5–6 km) for the last model run (Figure 6b, 200 curve). Although the effect remains modest in the present models, we note that focusing of base lithosphere uplift below the Oslo Graben is predicted for significant lithosphere thickness contrasts (Figure 6b, 160 to 200 curves).

4.2. Contrasting Petrologies

[22] Previous results suggest that deformation inside the Precambrian craton was primarily controlled by a preexisting lithosphere thickness contrast, accounting for contrasting strengths between the Norwegian and the Swedish blocks. However, lithospheric strength is also strongly controlled by petrological composition [*Ranalli*, 1995]. For the present modeling attempt we selected petrology set 2 (i.e., relatively strong rocks, Table 1) and 3 (i.e., relatively weak rocks) for the Swedish block and for the

Figure 7. (opposite) Horizontal strain (i.e., ε_{xx}) distributions for five models where contrasting petrologies exist between the Swedish block (i.e., strong rocks for the upper crust, the lower crust and the mantle lithosphere) and the remaining blocks (i.e., weak rocks for the upper crust, the lower crust and the mantle lithosphere, see Table 1). The depth of the base lithosphere below the Swedish block ranges between 125 and 200 km and is taken as degree of freedom (experiments a to e). All other parameters are indicated in Figure 4 and Table 1. The deformation pattern is magnified 30 times. See color version of this figure at back of this issue.

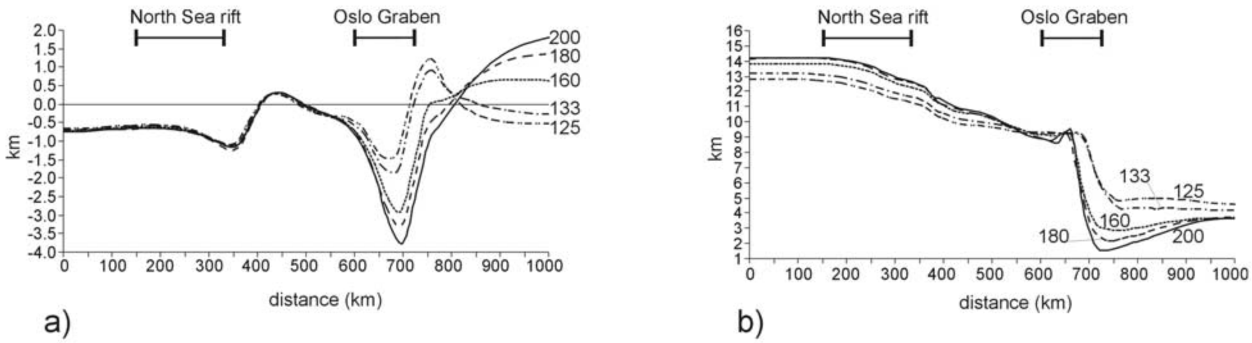


Figure 8. (a) Surface and (b) base lithosphere deflections in function of the Swedish block base lithosphere depth (in km). Positive and negative numbers indicate uplift and subsidence, respectively. The curves correspond to the five models depicted in Figure 7. Note that shallow subsidence is predicted in the Swedish block for shallow base lithosphere depths below it (i.e., no or moderate lithosphere thickness contrasts). Subsidence is always predicted in the Oslo Graben area and the northern North Sea.

remaining parts of the models, respectively. Similar conditions than previously were applied and the base lithosphere of the Swedish block was progressively deepened. As expected, the eastern part of the model concentrates minimum strains and maximum strains are transferred to the central and western parts (Figure 7).

[23] In detail, the first model (Figure 7a) presents an initial flat base lithosphere at 125 km depth below the Precambrian province, that is to say no lithosphere thickness contrast. We note that minimum horizontal strain is predicted in the Swedish block. Maximum strain concentrations are mainly predicted in the North Sea block and in the lower crust of the Norwegian block below the Oslo Graben. Subsidence in the order of 1 to 1.5 km is predicted in the North Sea area and the Oslo Graben (Figure 8a, 125 curve). Moderate uplift (i.e., <0.5 km) in the Bergen Region but pronounced uplift (i.e., >1 km) just east of the Oslo Graben are predicted. By contrast, away from this latter uplifted zone shallow subsidence (i.e., ~0.5 km, Figure 8a, 125 curve) occurs in the Swedish block.

[24] When the lithosphere thickness contrast is increased between the Norwegian and the Swedish blocks, we note that horizontal strains are reduced in the Swedish block (e.g., compare Figure 7a with Figure 7e). Horizontal strains remain almost stable for the North Sea block in all experiments. In contrast, strain is particularly enhanced in the lower crust and the mantle lithosphere below the Oslo Graben when the Swedish block base lithosphere is deepened.

[25] The subsidence pattern of the Oslo Graben is deepened and broadened in function of the lithosphere thickness contrast (Figure 8a). Subsidence for the Oslo Graben reaches up to 4 km in our modeling (Figure 8a, 200 curve). The uplift pattern in the Swedish block is progressively enhanced, broadened, and shifted toward the eastern edge of the models (Figure 8a). In particular, subsidence in this latter block fades away when the lithosphere thickness contrast is superior to 35 km. Surface deflection patterns of the western part of the Norwegian block and of the North Sea block remain stable in the present modeling. This last remark applies also for the base lithosphere of the two areas. We note that the increase of base lithosphere uplift below them, in function of the lithosphere thickness contrast, remains modest (i.e., <1.3 km, Figure 8b). The amount of uplift of the base lithosphere of the Swedish block is decreased up to 3 km in function of the lithosphere thickness contrast.

4.3. Contrasting Heat Generations and Petrologies

[26] For this last modeling attempt we propose to explore the consequences of affecting "strong" (i.e., Table 1, petrology set 2) and "weak" (i.e., Table 1, petrology set 3) rocks to the North Sea block and the Precambrian province, respectively. It is expected that low strain affects the North Sea block during the experiment. We aim by this attempt to investigate whether onset of rifting could have been delayed in the northern North Sea as compared with the Oslo Graben. In order to keep stable the Swedish block, we modeled for it a lithospheric thickness contrast of 35 km with the Norwegian block (i.e., the base lithosphere was set to 160 km depth below Sweden).

[27] Pronounced concentrations of horizontal strain are now predicted exclusively inside the Norwegian block (Figure 9). In particular, strain is focused in the mantle lithosphere below the Oslo Graben. The whole Norwegian block is affected by subsidence. In particular, significant subsidence (i.e., up to 2 km, Figure 10a) is predicted in the Oslo Graben area and in the Bergen Region. A shallow basin (i.e., up to 0.5 km, Figure 10a) inside the North Sea block is also predicted. Pronounced (i.e., >14 km, Figure 10b) base lithosphere uplift is simulated for the Norwegian block.

5. Discussion

[28] Our modeling results show that, in context of passive rifting, localization of rifting in the Oslo Graben and uplift

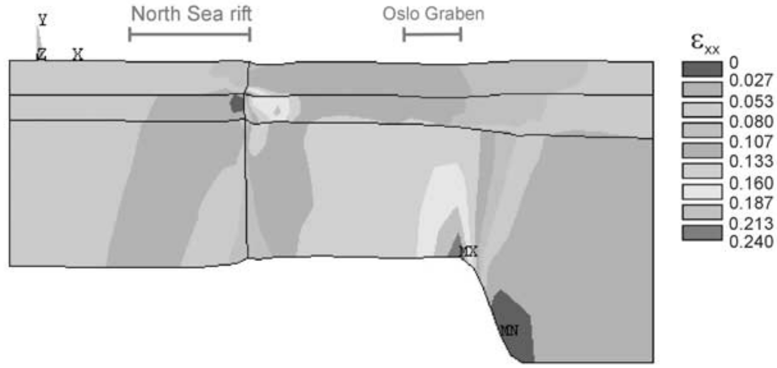


Figure 9. Horizontal strain (i.e., ε_{xx}) distributions for a model where contrasting petrologies exist between the North Sea block (i.e., strong rocks for the upper crust, the lower crust and the mantle lithosphere) and the remaining blocks (i.e., weak rocks for the upper crust, the lower crust and the mantle lithosphere, see Table 1). The depth of the base lithosphere below the Swedish block was set to 160 km. All other parameters are indicated in Figure 4 and Table 1. Note that horizontal strain is focused in the Norwegian block. The deformation pattern is magnified 30 times. See color version of this figure at the back of this issue.

of the Swedish block can be explained by significant deepening of the base lithosphere east of the graben (Figures 6a and 8a). Modeling results also suggest that, because Caledonian lithosphere was in a warmer state than Precambrian lithosphere, rifting in the northern North Sea is likely to have been coeval to rifting in the Oslo Graben.

[29] Our modeling suggests that deepening of the base lithosphere follows deepening of the Moho [*Kinck et al.*, 1993] immediately to the east of the Oslo Graben. This inference agrees remarkably well with the results from *P* wave residuals analyses made by *Babuška et al.* [1988] and *Plomerová et al.* [2001] along a teleseismic line parallel to our modeled section AA′. In addition, comparison between early Paleozoic mantle xenoliths data, from various places of the Fennoscandian Shield, with present-day lithosphere rigidity [*Poudjom Djomani et al.*, 1999] and thermal state [*Kukkonen and Peltonen*, 1999] suggests that the lithosphere outside the Caledonian Province and the Permian rift zones has not been significantly modified for more than 500 My. Hence, in agreement with recent geochemical studies claiming that continental roots under cratons are preserved over long periods [*Pearson*, 1999], the lithosphere thickness contrast observed present day seems to have remained stable for hundreds of millions of years.

[30] Furthermore, thermal modeling from *Cederbom et al.* [2000] suggests a denudation rate of 6–28 m/My in westernmost southern Sweden during the Permo-Carboniferous event (see Figures 5b, 5d, and 5e of the corresponding paper). Uplift rates calculated from the modeled surface deflections (Figures 6a and 8a) are in agreement with previous values for lithosphere thickness contrasts between 35 and 55km, and range from 10 to 30 m/My. Following *Calcagnile* [1982], *Lie et al.* [1990] and *Pedersen et al.* [1991] we selected for the Norwegian block lithosphere a thickness of 125 km. Thus the previous thickness contrast values correspond to lithosphere thickness between 160 and

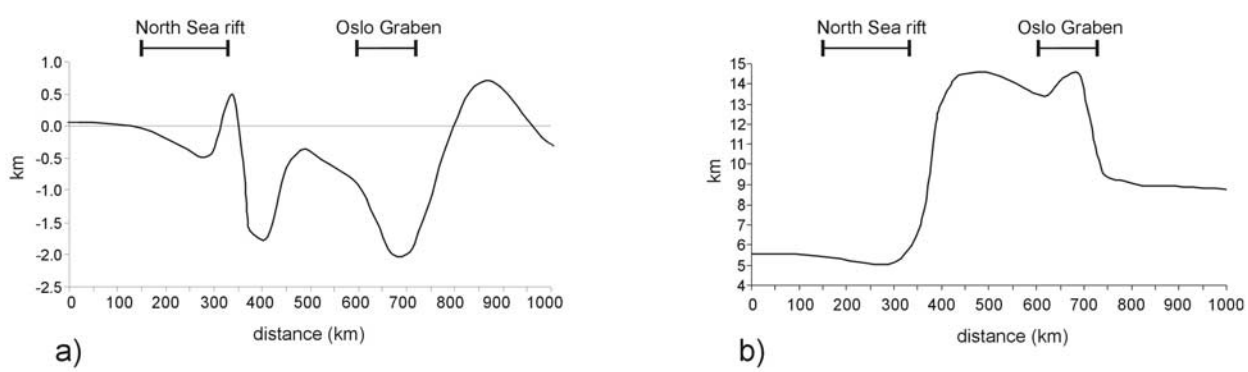


Figure 10. (a) Surface and (b) base lithosphere deflections. Positive and negative numbers indicate uplift and subsidence, respectively. The curves correspond to the model depicted in Figure 9. Note that significant subsidence and strong base lithosphere uplift is predicted in the whole Norwegian block.

180 km in Sweden. Such depths for the base Mlithosphere below Sweden remain in agreement with estimates made by *Babuška et al.* [1988] and *Vecsey et al.* [2000]. In summary, our assumption of contrasting thickness for the Sveconorwegian lithosphere seems to be in agreement with present-day observations and paleothickness estimates. Model results account for by rift localization in the Oslo Graben and the Permian uplift pattern in Sweden. Previous models of the Oslo Rift considered the influence of a thermal anomaly [*Ro and Faleide*, 1992] or differential stretching and a "wet" mantle lithosphere [*Pedersen and van der Beek*, 1994]. The present model is unable to account for by melting. Nevertheless, modeling results show that significant strain concentrations in the mantle lithosphere, and potentially decompression melting, can also be expected in standard mantle temperatures and a dry peridotite composition, if lithosphere thickness heterogeneity is considered.

[31] The modeling suggests that geological observations (i.e., rift localization in the Oslo Graben and uplift in Sweden) can also be accounted by lower lithosphere thickness contrast values if a marked petrological contrast between the Norwegian block and the Swedish block is introduced (Figure 8a). The existence of a marked petrological contrast between the Norwegian block and the Swedish block is questionable. The major terrain boundary that is present in this region of the Fennoscandian Shield (i.e., the Protogine Zone that superposes the Sveconorwegian to the 1.9–1.75 Ga Svecofenian terrain [*Gaál and Gorbatschev*, 1987]) is located in the middle of our Swedish block, ~120 km east of the place where the base lithosphere starts to deepen [*Plomerová et al.*, 2001]. Hence the potential major petrological contrast boundary of the region (i.e., a terrain boundary) does not correspond to the limit between the stable Swedish block and the Norwegian block that hosts the Oslo Rift. Unless rock composition varies at depth laterally, our first modeling assumption of uniform or near uniform petrologies for each lithospheric layer appears to be in better agreement with geological observations.

[32] Models with pronounced lithospheric thickness contrasts (i.e., more than 35 km) and uniform petrologies predict subsidence ranging from 1.2 to 2.2 km (Figure 6a, 160 to 200 curves). These values are less than syn-rift subsidence estimates of the Oslo Graben that are in the order of ~3 km [*Oftedahl*, 1952; *Ramberg*, 1976; *Neumann et al.*, 1992; *Rohrmann et al.*, 1994]. Indeed, our models do not incorporate the effects of sedimentary loads that enhance subsidence [e.g., *Burov and Cloetingh*, 1997], consequently the predicted subsidence values are here underestimated. Two other matters of discussion about the Oslo Graben are the location of the predicted maximum subsidence and the modeled width of the basin. Our models (Figure 8a) predict maximum subsidence slightly east of the actual Oslo Graben (Figure 8a). Precisely, maximum subsidence is predicted above the place where the base lithosphere starts to deepen in our models. The mismatch is explained by the uncertainty existing on the location of the "lithospheric kink." A minimum estimate for the location of the lithospheric kink of ±50 km away from the Oslo Graben rift axis can be derived from Figure 4 of *Plomerová et al.* [2001]. The present estimation argues for a closer distance than anticipated in our study, between the axis of the Oslo Graben and the westernmost point of the lithospheric kink, strengthening our hypothesis of a genetic link between the two structures.

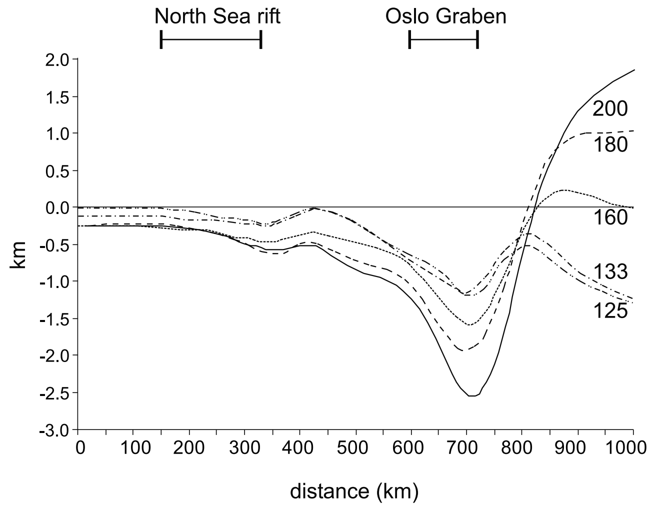


Figure 11. Surface deflections in function of the Swedish block base lithosphere depth (in km). Positive and negative numbers indicate uplift and subsidence, respectively. The same boundary conditions and material properties as in Figures 5 and 6 are adopted, heat generation values are laterally uniform ("Precambrian" heat generation set, Table 1). Note that broad subsidence patterns involving southern Norway and the northern North Sea are predicted in general.

[33] One of the limitations of our models consists in the viscoelastic rheology that was selected. Such a rheology is unable to produce strain localizations that would be predicted if plasticity (e.g., Mohr-Coulomb criterion) would have been added to describe the brittle parts of the lithosphere. Strain localization due to rupture and faulting and narrowing of the rifted zone are not incorporated in the present models [*Frederiksen and Braun*, 2001]. Subsidence is simulated in our models by flexing of the elastic part of the upper crust. From the present study we propose that the structure of the lithosphere is the first-order factor controlling rift localization. The second-order controlling factor is certainly the inherited structure of the crust. In the case of the Oslo Graben, pre-existing Precambrian fault zones were reactivated during rifting [*Swensson*, 1990; *Sundvoll and Larsen*, 1994]. Because the pre-existing structure, brittle deformation and strain weakening and localization are not included in our models, strain and subsidence is not precisely localized. This leads to predictions for subsiding areas up to a factor 4 wider.

[34] In all models including uniform petrologies between the North Sea block and the Norwegian block, significant strain concentrations occur in the North Sea lithosphere (Figures 5 and 7) and subsidence and uplift are predicted in the North Sea and the Bergen Region, respectively (Figures 6 and 8). Our prediction of uplift in the Bergen Region in

Late Carboniferous–Early Permian is in agreement with results obtained from thermal modeling of K-feldspar $^{40}Ar/^{39}Ar$ data [*Dunlap and Fossen*, 1998]. The results of *Dunlap and Fossen* [1998] suggest a denudation rate of 45–100 m/My. Maximum uplift rates ~10 m/My can be derived from our modeling results. This mismatch is partly explained by the absence of thermal expansion and its isostatic response in our models, whereas the occurrence of Permian intrusions in the Bergen Region [*Faerseth et al.*, 1976; *Torsvik et al.*, 1997; *Fossen and Dunlap*, 1999] indicates that the thermal field was seriously disturbed at that time.

[35] Up to 1 km of subsidence is predicted for the northern North Sea Basin, westward of the Norwegian coast (i.e., the Horda Platform). Even if the subsidence is underestimated, the uniform petrologies models point toward rifting in the northern North Sea as early as stretching is applied (i.e., Late Carboniferous–Early Permian). For the last modeling attempt (Figures 9 and 10), we assumed strong and weak rocks for the North Sea block and the remaining parts of the model, respectively. This assumption appears realistic as far as a terrain boundary separates the two regions of the model [*Pharaoh*, 1999]. Shallow subsidence is still predicted in the North Sea (Figure 10a), but this effect might be accounted by overestimation of heat generation in its upper crust, that in absence of constraints we took equal to 2.5 $\mu W/m^3$. The implication of the present assumption is that high strain concentrations and subsidence are now predicted for the whole Norwegian block. According to the model adopting contrasting petrologies between Caledonian and Precambrian domains, a broad Permian basin would have covered all southern Norway. Moreover, the model predicts up to 15 km of asthenosphere uplift below southern Norway (Figure 10a), which could have implied huge amounts of igneous rocks spread over the surface. The results from this model are clearly in disagreement with geological and geophysical data. Hence uniform petrologies models (see Figures 5 and 6) appear again more realistic and they support onset of rifting in the northern North Sea as early as in Late Carboniferous–Early Permian. If confirmed, the present modeling conclusion invalidates previous modeling studies on the thermal evolution of the North Sea Basin [*Odinsen et al.*, 2000].

[36] Finally, in order to test our assumption of higher crustal heat generation in the North Sea block than in the remaining parts of the model, we did the same experiments as in Figure 5 (i.e., uniform petrologies models with power law creep parameters set 1, Table 1) but in introducing laterally uniform heat generations for each lithospheric layer (i.e., "Precambrian" heat generation set, Table 1). As a result, we obtained broad subsidence patterns from the Oslo Region to the northern North Sea, when uplift of the Swedish Block is predicted (Figure 11). Because such a result appears to be unrealistic, it suggests that higher crustal heat generation and implicitly warmer lithosphere in the North Sea block is a valid assumption. However, in absence of additional constraints, it cannot be ruled out that the North Sea block lithosphere could have been thinner than assumed in this study, resulting also in a warmer thermal state.

6. Conclusions

[37] The following points summarize our conclusions.

1. Deepening of the base lithosphere at the eastern edge of the Oslo Graben is a valid explanation for development of rifting inside the cold and stable Fennoscandian lithosphere and for focusing it in the Oslo Graben.
2. Although the present models are unable to account for thermal expansion and asthenosphere diapirism, they suggest that base lithosphere uplift be enhanced below the Oslo Graben with respect to other regions of the model. Such localization may represent a key to understand the occurrence of large amounts of syn-rift magmatism in the Oslo Graben.
3. The models suggest that significant deepening ($\geq$35 km) of the base lithosphere occurred east of the Oslo Graben before the onset of rifting. Surprisingly, *P* wave residuals analyses from *Babuška et al.* [1988] and *Plomerová et al.* [2001] argue that this is also the case today. However, mantle xenolith data [*Kukkonen and Peltonen*, 1999; *Poudjom Djomani et al.*, 1999] support the hypothesis that this lithosphere step has remained during Phanerozoic.
4. The modeling study suggests that rifting may have taken place in the northern North Sea coeval to rifting in the Oslo Graben (i.e., as early as Late Carboniferous–Early Permian). If this conclusion is confirmed, a revision of current thermal models for the development of the North Sea Basin will be required.

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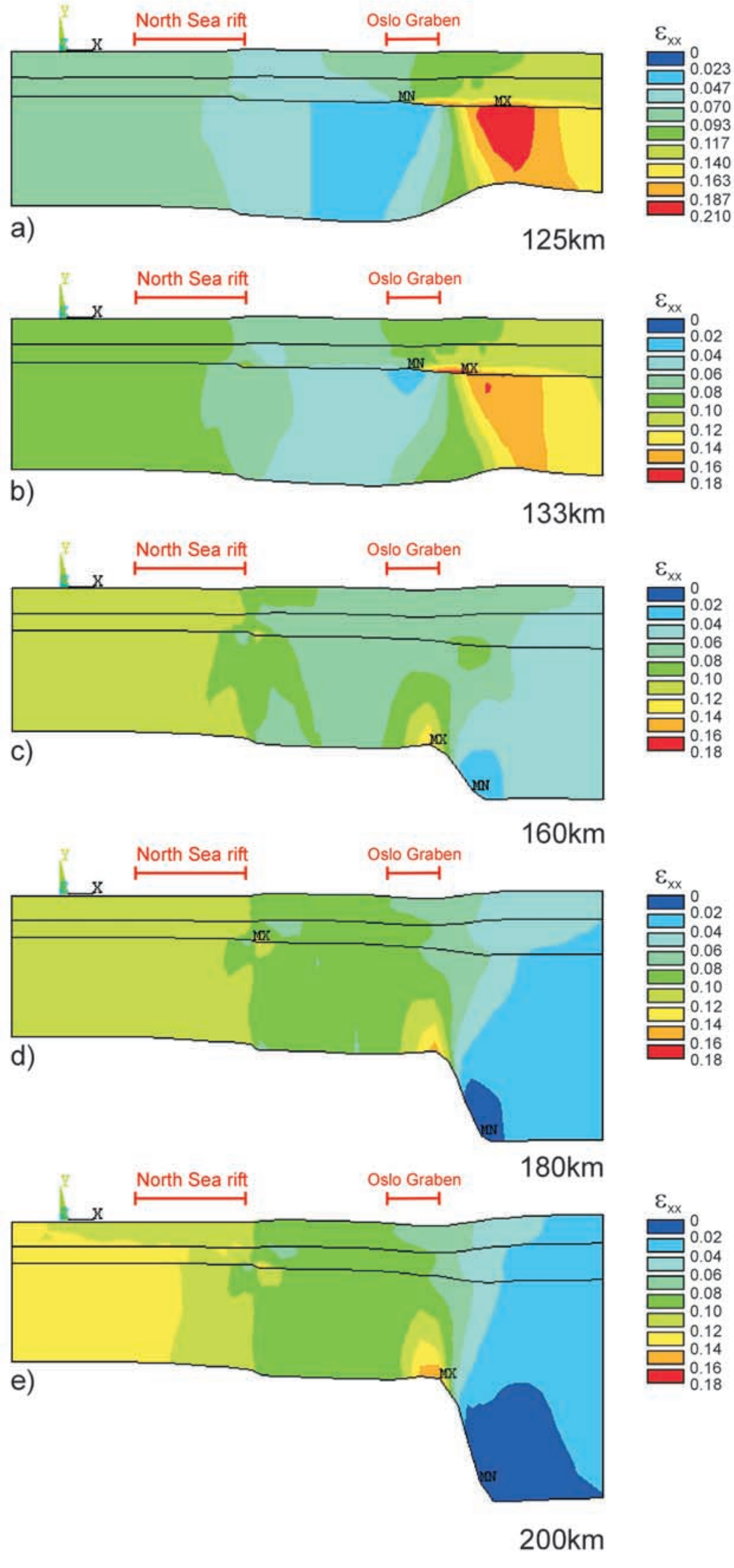
Figure 5. (opposite) Horizontal strain (i.e., ε_{xx}) distributions for five models with uniform petrologies for the upper crust, the lower crust and the mantle lithosphere (see set 1, Table 1). The depth of the base lithosphere below the Swedish block ranges between 125 and 200 km and is taken as degree of freedom (experiments a to e). All other parameters are indicated in Figure 4 and Table 1. Note that locations of maximum and minimum horizontal strain switch between the Swedish block and the Norwegian block when the depth of the base lithosphere increases. Furthermore, when the lithosphere thickness contrast between the two blocks becomes significant maximum horizontal strain is predicted below the Oslo Graben. The deformation pattern is magnified 30 times.


North Sea rift
Oslo Graben
εxx
0
0.023
0.047
0.070
0.093
0.117
0.140
0.163
0.187
0.210
MN
MX
a)
125km
North Sea rift
Oslo Graben
εxx
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
MN
MX
b)
133km
North Sea rift
Oslo Graben
εxx
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
MX
MN
c)
160km
North Sea rift
Oslo Graben
εxx
0
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
MX
MN
d)
180km
North Sea rift
Oslo Graben
εxx
0
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MX
MN
e)
200km

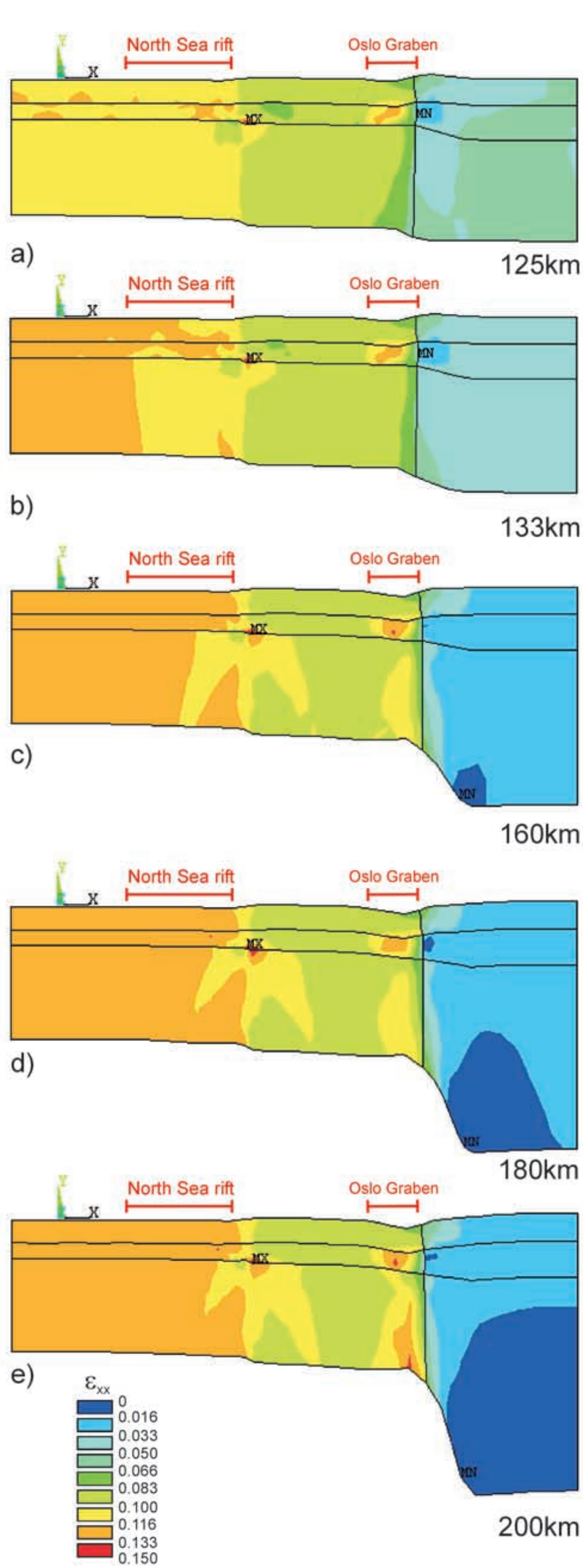

Figure 7. (opposite) Horizontal strain (i.e., ε_{xx}) distributions for five models where contrasting petrologies exist between the Swedish block (i.e., strong rocks for the upper crust, the lower crust and the mantle lithosphere) and the remaining blocks (i.e., weak rocks for the upper crust, the lower crust and the mantle lithosphere, see Table 1). The depth of the base lithosphere below the Swedish block ranges between 125 and 200 km and is taken as degree of freedom (experiments a to e). All other parameters are indicated in Figure 4 and Table 1. The deformation pattern is magnified 30 times.

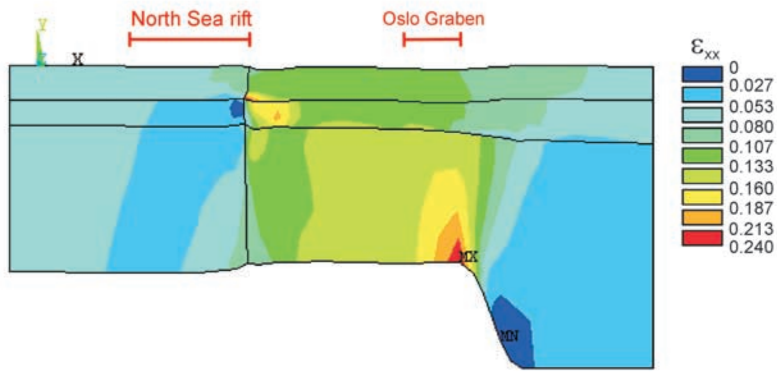

Figure 9. Horizontal strain (i.e., ε_{xx}) distributions for a model where contrasting petrologies exist between the North Sea block (i.e., strong rocks for the upper crust, the lower crust and the mantle lithosphere) and the remaining blocks (i.e., weak rocks for the upper crust, the lower crust and the mantle lithosphere, see Table 1). The depth of the base lithosphere below the Swedish block was set to 160 km. All other parameters are indicated in Figure 4 and Table 1. Note that horizontal strain is focused in the Norwegian block. The deformation pattern is magnified 30 times.