A plume beneath the Oslo Graben?

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Introduction

In order to discuss the development of the Oslo Graben in terms of plate vs. plume models, it is most important to understand its spatial and temporal relationship with other areas in NW Europe. Despite its “abnormal” development, the Oslo Graben is temporally associated with nearby magmatic events in areas such as southern Sweden, north-west Germany, Scotland and the central North Sea (see, for example, *Wilson et al.* (2004) for an overview of Carboniferous-Permian magmatism and rifting in north-western Europe). The most important of these events is the emplacement of a suite of alkaline and tholeiitic basalts at ca. 300-290 Ma (the Carboniferous-Permian boundary) (*Sundvoll et al.*, 1990; *Breitkreuz & Kennedy*, 1999; *Heeremans et al.*, 2004b; *Monaghan & Pringle*, 2004; *Timmerman*, 2004). Except for this basaltic spike, all the areas show different tectonomagmatic developments.

The focus of this web page will be on the formation of the Oslo Graben. This graben has long been known as a highly-magmatic continental rift, with accommodation and transfer zones separating the different graben segments (*Olaussen et al.*, 1994). It has been studied for over a hundred years and a large amount of geological and geophysical data have been acquired. Despite this, scientists still argue about its origin. The present paper will try to shed some light on the discussion regarding whether a plume contributed to the origin of the Oslo Graben or not. Before starting the discussion, I give a short introduction to the tectonomagmatic development of the Oslo Graben.

The tectonomagmatic evolution of the Oslo Graben

The onshore Oslo Graben forms, together with the offshore Skagerrak Graben, the Oslo Rift (*Ro et al.*, 1990). The rift terminates in the Sorgenfrei-Tornquist Zone (see Figures 1 and 2).

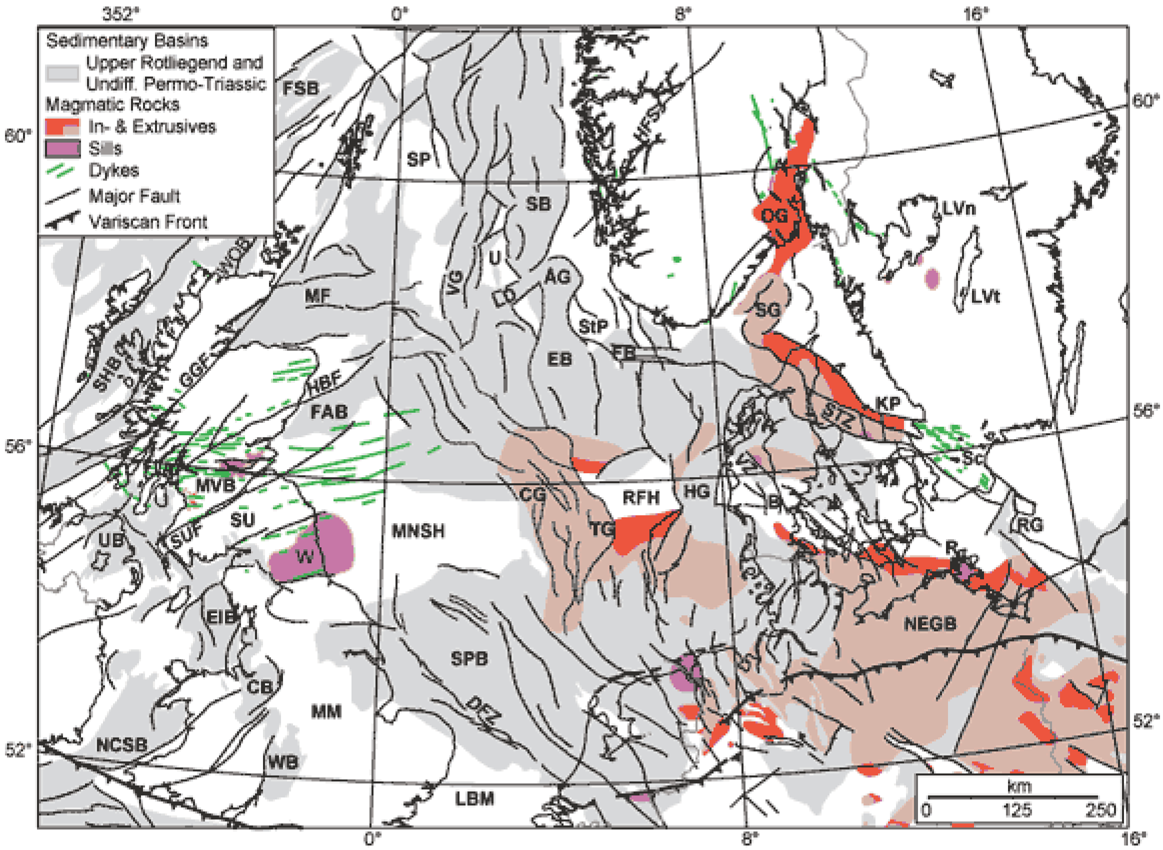


Figure 1: Overview map for the Late Carboniferous – Early Permian with structural names. Some basins are of undifferentiated Permo-Triassic age. Basins: B = Brande Graben; CB = Cheshire Basin; CG = Central Graben; DB = Dutch Bank Basin; EB = Egersund Basin; EIB = Eastern Irish Sea Basin; FAB = Forth Approaches Basin; FB = Farsund Basin; FSB = Faroes-Shetland Basin; HG = Horn Graben; LD = Ling Depression; MF = Moray Firth; MVB = Midland Valley Basin; NCSB = Northern Celtic Sea Basin; NEGB = North-East German Basin; OG = Oslo Graben; RG = Rønne Graben; SB = Stord Basin; SG = Skagerrak Graben; SHB = Sea of Hebrides Basin; SPB = Sole Pit Basin; STZ = Sorgenfrei-Tornquist Zone; TG = Tail End Graben; UB = Ulster Basin; WB = Worcester Basin; WOB = Western Orkneys Basin; ÅG = Åsta Graben. Highs: KP = Kattegat Platform; LBM = London-Brabant Massif; MM = Midland Massif; MNSH = Mid-North Sea High; RFH = Ringkøbing-Fyn High; Sc = Scania; SP = Shetland Platform; StP = Stavanger Platform; U = Utsira High. Regional structures: DFZ = Dowsing Fault Zone; GGF = Great Glen Fault; HBF = Highland Boundary Fault; HSZ = Hardangerfjorden Shear Zone; LGF = Lærdal-Gjende Fault; SUF = Southern Uplands Fault; VDF = Variscan Deformation Front; VFZ = Vinding Fracture Zone. Geographical names: LVn = Lake Vännern; LVt = Lake Vättern; R = Rügen; SU = Southern Uplands (From (Heeremans et al., 2004a).

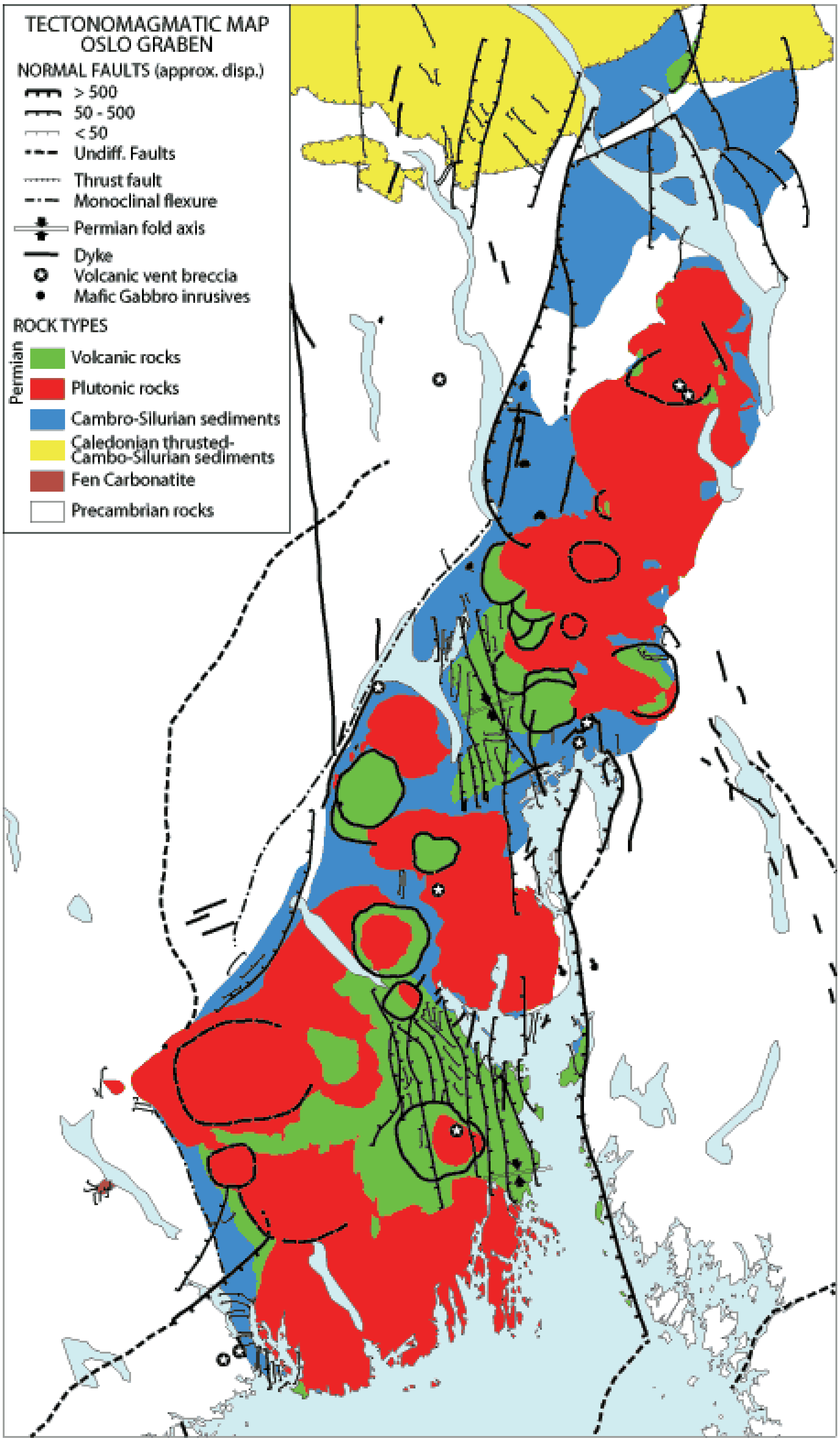


Figure 2: Tectonomagmatic map of the Oslo Graben (from Ramberg & Larsen, 1978).

The development of the Oslo Graben has been divided into 5 main stages (*Ramberg & Larsen*, 1978; *Sundvoll et al.*, 1990; *Sundvoll & Larsen*, 1993; *Olaussen et al.*, 1994). These are:

1. Stage 1: Pre-rift: Representative of this stage is the deposition of the Asker Group sediments (*Henningsmoen*, 1978; *Olaussen*, 1981; *Olaussen et al.*, 1994) on top of a deformed Cambro-

Silurian sedimentary succession. These Asker Group sediments are interpreted as representing fluvial-dominated deltas, prograding into lacustrine or brackish water basins. A marine incursion is found in the upper part of the succession as indicated by fossils of Westphalian age (*Olaussen*, 1981). This age is confirmed by U-Pb ages to be 319 ± 5 Ma, derived from detrital zircon grains from sandstones in the upper Asker Group (*Dahlgren & Corfu*, 2001).

Stage 2: Initial rifting: The earliest magmatic products (Rb-Sr ages 304 ± 8 and 294 ± 7 Ma) related to rifting in the Oslo Graben are represented by trachyandesitic-rhyolitic sills and dykes, some of them termed "mænaites" (*Ramberg & Larsen*, 1978; *Sundvoll et al.*, 1992). The sills typically intrude the base of Cambrian Alum-shales, on top of PreCambrian basement. The main onset of rifting started with the emplacement of widespread basaltic volcanism termed B1. Whereas the southern part of the Oslo Graben is dominated by alkaline magmatism, the northern part experienced tholeiitic magmatism. Thicknesses vary from 800-1500 m in the south to ca. 15 m in the north (see *Neumann et al.*, 2004 and references therein). Initial faulting took place prior to basalt extrusion as evidenced by faulted Asker Group sediments underlying undisturbed lavas in the Krokskogen area. Rb-Sr dating of a tholeiitic lava flow gave an age of 291 ± 7 Ma, but U-Pb ages of a larvikite intrusion, which is younger than the B1-basalts, are 298.6 ± 1.4 Ma, suggesting that basalt volcanism probably started earlier (*Dahlgren et al.*, 1996). The B1 basalts are the most primitive basalts in the Oslo Graben.

Stage 3: The main rifting period: The main rifting period is characterized by extensive vertical movements along the main master faults and extensive fissure eruptions of trachyandesitic rhomb porphyry lavas. In addition, minor basaltic lavas were extruded (*Ramberg & Larsen*, 1978). The rhomb porphyry lavas are inferred to be associated with the intrusion of large bodies of monzonite and nepheline syenites (larvikites and lardalites). U-Pb age determinations of these larvikite plutons provide ages ranging from 292.1 ± 0.8 to 298.6 ± 1.4 Ma (*Dahlgren et al.*, 1996). Rb-Sr age determinations performed on the rhomb porphyry lavas and the larvikites gave ages ranging from 276 ± 6 to 294 ± 6 Ma (*Sundvoll et al.*, 1990). These are now assumed to underestimate the true ages.

Stage 4: Central volcanoes, caldera collapse and graben fill: The next step in graben evolution involved a change from shield volcanism to the development of central volcanoes and caldera collapse. Associated with these phenomena are lavas, dykes, central intrusions and ring dykes. Erosion of the rift flanks caused deposition of fan-shaped debris flows.

Stage 5: Batholith emplacement: The final stage of graben development involved the emplacement of intermediate to silicic intrusions (larvikites, syenites, granites). Parts of these intrusions were derived from partial melting of the crust.

Dyke intrusions are common in the Oslo Graben and occurred over the entire time-span of graben evolution. They vary widely in size and composition, from mafic to silicic. The compositions of the mafic dykes resemble those of the basaltic lavas, *i.e.* mostly alkaline, but some tholeiitic dykes exist as well.

Discussion

Whether or not a plume contributed to the origin of the Oslo Graben has long been a debate among scientists. So far, most studies point towards a plate-model solution (*Olaussen et al.*, 1994; *Pedersen & van der Beek*, 1994; *Heeremans et al., 1996*; *Heeremans & Faleide*, 2004; *Pascal et al.*, 2004), but active contributions from the asthenospheric mantle have not been ruled out (*Heeremans et al., 1996*; *Neumann et al.*, 2004). The following sections address some important issues related to the plume-plate discussion, some of which are criteria used by *Courtillot et al.* (2003) and *Anderson* (2005):

Age progressive tracks: There is no evidence at all that the Carboniferous-Permian magmatism in NW Europe, including the Oslo Graben, is related to an age progressive "hot-spot" track as might be expected to be associated with a plume. Paleomagnetic studies indicate that at ca. 300 Ma, the area of interest was located approximately 10° north of the equator and ca. 10° east of its current position (*e.g., Wilson et al.*, 2004). During the Carboniferous, the Laurussia and Gondwana plates underwent rapid northward motion (*e.g., Torsvik & Cocks*, 2004), suggesting that if a plume was present a clear "hot-spot" track should be present. In addition, the combination of rapid plate motion and long-lived, fixed magmatic activity does not support a plume model.

Uplift: An angular unconformity exists between the Asker Group sediments and the underlying Cambro-Silurian successions, which represent a time-span of ca. 100 m.y. During this time erosion took place, but it did not remove the entire Cambro-Silurian succession, since this succession is preserved within the Oslo Graben proper. The deposition of the Asker Group sediments indicates pre-rift subsidence. Only after the termination of tectonomagmatic activity in the Oslo Graben, erosion removed ca. 3-5 km of Palaeozoic rocks (*Zeck et al.*, 1988; *Rohrman et al.*, 1994). All this indicates that no pre-rift uplift occurred prior to the development of the Oslo Graben, suggesting the absence of a plume.

$^3He/^4He$: No studies on $^3He/^4He$ have been done directly on samples from the Oslo Graben, due to the lack of mantle xenoliths. However, olivines extracted from mantle xenoliths found in Carboniferous-Permian dykes from Scotland, contemporaneous with the B1 basalts of the Oslo Graben, have been analysed for $^3He/^4He$ (*Kirstein et al.*, 2004). These studies show that $^3He/^4He \pm 1\sigma$ ratios vary from 0.97 ± 0.05 Ra to 6.33 ± 0.21 Ra. (Ra is the atmospheric ratio.) $^3He/^4He$ values higher than ~10 Ra are postulated to be associated with mantle plume activity (*Courtillot et al.*, 2003). These results thus argue for a non-plume source for the Scottish magmatic rocks. Assuming a genetic relationship between the Scottish basalts and those in the Oslo Graben, suggests that a similar conclusion can be drawn for the formation of the most primitive basalts in the Oslo Graben. [Ed: See also Helium fundamentals page]

Large Igneous Province: Large Igneous Provinces are generally believed to represent the start of plume activity and are often found at the beginning of “hot-spot” tracks (*Courtillot et al.*, 2003; *Anderson*, 2005). Although the volumes of magmas produced during the Carboniferous-Permian period in north-western Europe are relatively large (estimates are: Oslo Graben, 120,000 km^3 total volume of magmatic rocks; NW Germany, 48,000 km^3 of volcanic rocks, *Benek et al.*, 1996; *Neumann et al.*, 2004), they are small compared to Large Igneous Provinces. In addition, the time span of magmatic activity extends for more then 60 m.y. in the Oslo Graben. Although the magmatic activity occurred in pulses, the overall magma production rate was fairly low (ca. 0.01 km^3a^{-1}).

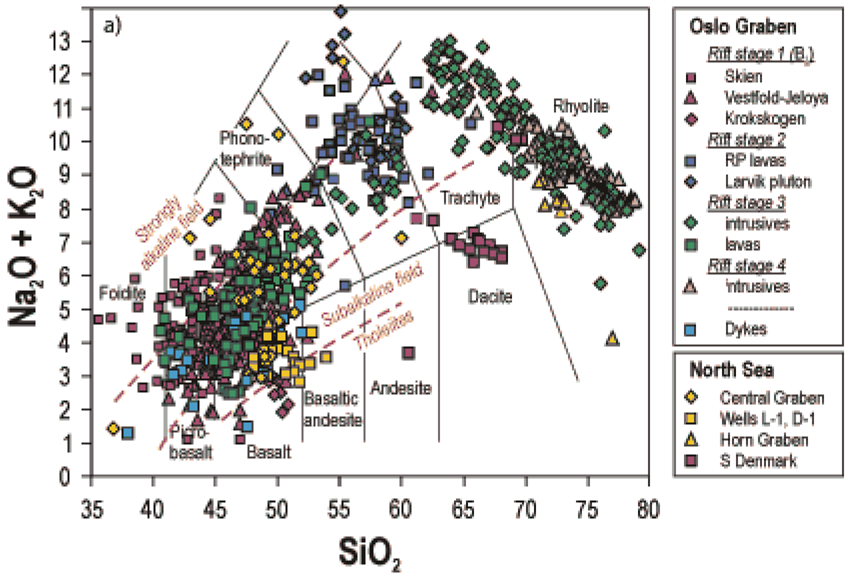
Mantle temperatures: *Neumann* (1994) estimated the extrusion temperatures of the basaltic lavas to be approximately 1270-1340°C. This indicates normal or slightly elevated mantle temperatures and suggests that the extensive Oslo Graben magmatism was not associated with a major temperature anomaly. Other alternative hypotheses proposed by *Neumann* (1994) are:

1. a “wet-spot”,
2. decompression melting due to lithospheric stretching, and
3. a combination of causal mechanisms.

Numerical studies focusing on the formation of the southern and northern Permian Basins (*van Wees et al.*, 2000; *Frederiksen et al.*, 2001), which formed as a result of late Carboniferous-early Permian rifting, indicate that a thermal event occurred prior to the formation of these basins. However, these authors do not discuss possible temperature anomalies.

Other related topics

Geochemical studies: The geochemical signature of the basaltic lavas in the Oslo Graben indicate that they are derived from mantle sources of the types tapped at ocean islands (HIMU, PREMA) (*Neumann et al.*, 2004) (Figure 3). However, melts derived from refractory mantle beneath the continental lithosphere may acquire such signatures through interaction with metasomatized lithospheric mantle. The lithospheric mantle melts beneath the Oslo Graben were probably metasomatically enriched by carbonatite fluids in early Palaeozoic times in association with the formation of the Fen intrusion (see for location Figure 2). Rocks from related areas (Scotland, Scania, the central North Sea and NW Germany) show similar geochemical signatures (*Neumann et al.*, 2004; *Upton et al.*, 2004). In the NW German Basin, 70% of the volcanic succession consists of rhyolites. Their chemical signature points to derivation from, or interaction with, a lithospheric mantle source with a subduction-related component (*Benek et al.*, 1996).



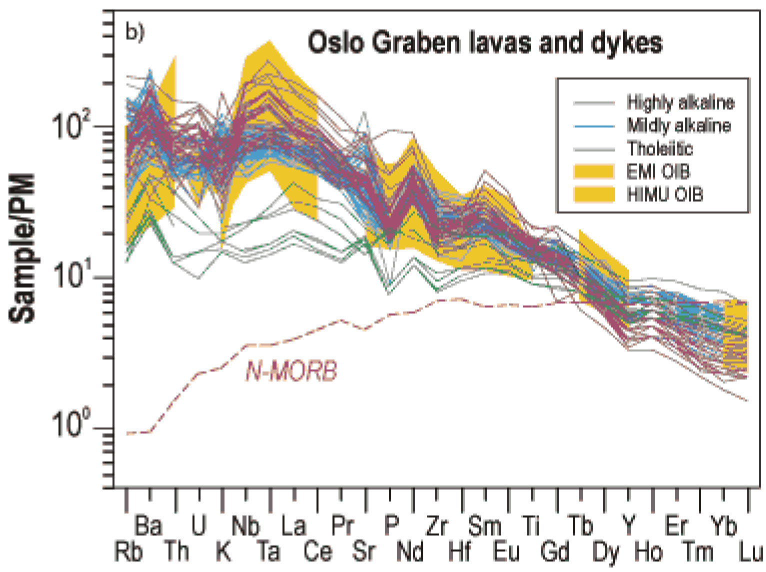


Figure 3: a) Petrochemical classification diagram for Permo-Carboniferous magmatic rocks in the Oslo Graben (after Le Bas et al. 1986), based on Figure 6 in Neumann et al. (2004). b) Trace element concentrations in mafic lavas, dykes and sills in the Oslo Graben, normalised to the primordial mantle (PM) as defined by (Mcdonough and Sun, 1995) based on Figure 7 in Neumann et al. (2004).

Numerical modelling studies: Numerical modelling studies have shown that the Oslo Graben could have formed in passive plate models (*Pedersen & van der Beek*, 1994; *Pascal et al.*, 2004). *Pedersen & van der Beek* (1994) presented a 1-dimensional model that includes conduction and differential thinning of the lithosphere and concluded that the Oslo Graben was not affected by a mantle plume. However, their model assumed a constant melt production over 60 m.y., indicating the very low magma production rate of ca. 0.005 km^3a^{-1}. The model presented by *Pascal et al.* (2004) shows the development of the Oslo Graben as a genetic response to pre-existing lithospheric structure. Their model shows significant lithospheric thinning in a narrow zone below the Oslo Graben, suggesting the possibility of small-scale convection within the asthenospheric mantle (Figure 4). Unfortunately, due to limitations in the modelling software, their model terminates when magma generation starts.

Although these models have their limitations, they indicate that tectonic forces and pre-existing lithospheric structure played an important role in the formation of the Oslo Graben.

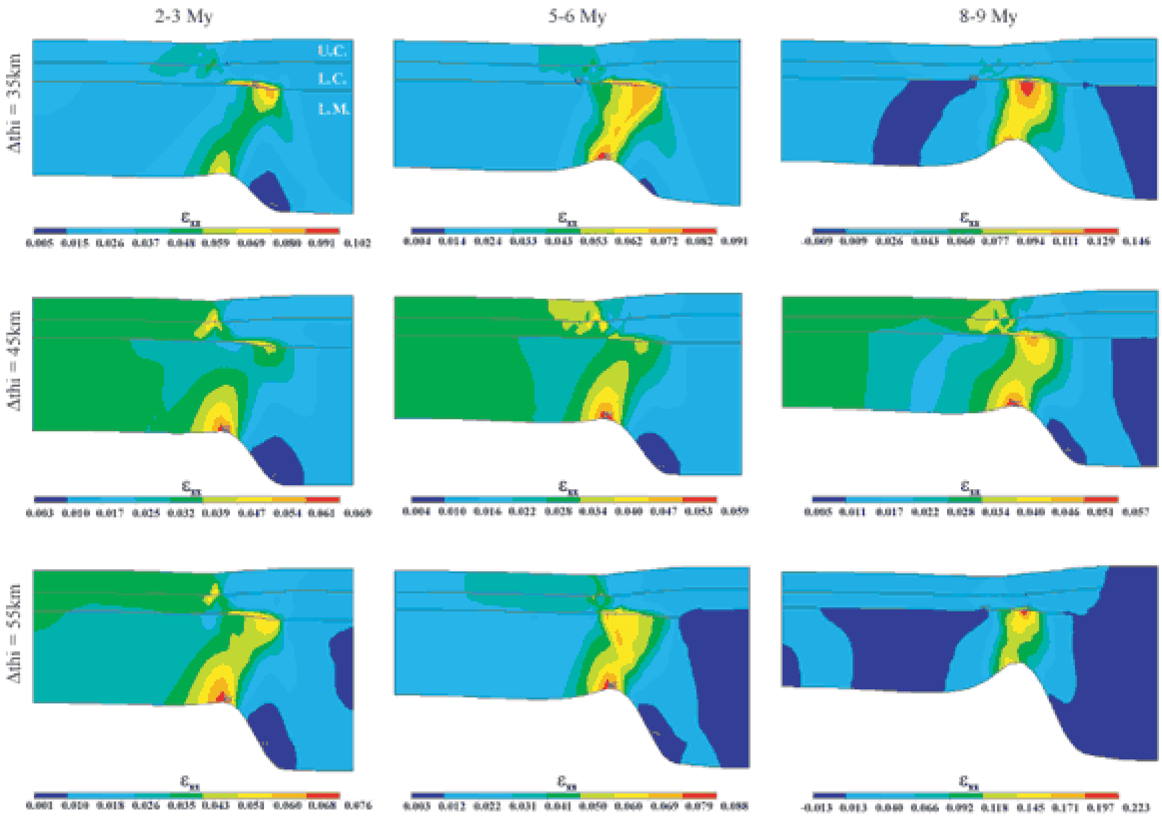


Figure 4: Horizontal strain (e_{xx}) distributions computed for different lithosphere thickness contrasts (Δthi) across an east-west section over the Oslo Graben at different times of the model run. Positive strain values indicate stretching. The models were stretched for 10 m.y. with a velocity of 1.6 cm/a. Note the different scales for strain in each figure. U.C., L.C. and L.M. are respectively Upper Crust, Lower Crust and Lithospheric Mantle (from Pascal et al., 2004).

Plate configuration

A major factor that must be taken into account when discussing the tectonomagmatic evolution of the Oslo Graben and related areas is the plate configuration at the time of magmatic activity. The entire area has undergone major lithospheric compression over the last 100-150 m.y., resulting in heterogeneous crustal and lithospheric thicknesses (*e.g., Kinck et al.*, 1993). Two major collisions, the Laurentia-Greenland – Baltica collision (the Caledonian orogeny) and the Laurussia – Gondwana collision (the Variscan orogeny) had a major impact on the later development of the area (*Ziegler*, 1990; *Olaussen et al.*, 1994; *Veevers et al.*, 1994). The area of interest is located exactly at the intersection of the Caledonian and Variscan orogenies. During the Variscan orogeny and its aftermath, the foreland was strongly affected by strike-slip tectonics with dextral transtensional and transpressional movements along deep-seated pre-existing faults (*Ziegler*, 1990; *Coward*, 1993; *Mogensen*, 1994; *Olaussen et al.*, 1994; *Veevers et al.*, 1994; *Heeremans et al., 1996*; *Verdier*, 1996). Extensional continental basins developed, creating space for the deposition of continental clastic material (*Ziegler*, 1990; *Heeremans & Faleide*, 2004; *Heeremans et al.*, 2004a). These basins are interpreted as large extensional sag basins caused by extensional tectonics and thermal cooling after a large thermal event (*van Wees et al.*, 2000; *Frederiksen et al.*, 2001).

Distribution of magmatic products

Carboniferous-Permian magmatic activity in NW Europe was not evenly distributed over space or time. The distribution of alkaline and tholeiitic dykes with an age of ca. 300-290 Ma in Scotland, Oslo and Scania, caused *Ernst & Buchan* (1997) to suggest a plume head below Jutland (Denmark). However, the Scottish dyke swarm seems to terminate abruptly in the central North Sea (Figure 1). No evidence of other dyke activity has so far been discovered on the east side of the Central Graben. Figure 1 shows that the distribution of the magmatic successions seems to be controlled by fault-related structures closely associated with the development of the northern and southern Permian Basins (*e.g., Heeremans et al.*, 2004a). This indicates tectonic control on magma migration and possibly also on magma generation.

Conclusion

Most studies of the Oslo Graben and related areas, do not show unambiguous evidence for the contribution of a mantle plume in the tectonomagmatic development. However, studies do show possible contributions from asthenospheric melt sources. Numerical modelling studies have shown that prior to the development of the northern and southern Permian basins, a strong thermal event occurred (*van Wees et al.*, 2000; *Frederiksen et al.*, 2001). Strong evidence against plume activity includes:

1. The lack of an age-progressive volcanic track,
2. pre-magmatic subsidence instead of uplift,
3. low to moderate $^3He/^4He$ values,
4. the absence of a large igneous province, and
5. normal or only slightly elevated mantle temperature.

However, the widespread basaltic spike at ca. 300-290 Ma suggests a sudden, hot anomaly below the area at the time of dyke and lava emplacement. This anomaly has a considerable lateral extent, of the order of 10^3 km.

Numerical modelling and careful examination of the plate configuration and paleogeography suggests that extensional tectonic activity was the main driving force for basin development. However, extension of a heterogeneous lithosphere may result in asthenospheric mantle rising adiabatically and a more active role for asthenospheric mantle melts. This might also explain the uneven distribution of magmatic rocks in the area.

Whether or not a plume was active beneath NW Europe at the time of formation of the Oslo Graben, is still an unresolved question. Most studies favour a model in which plate tectonic forces were responsible for rifting and consequent magma generation resulted from lithospheric thinning. However, an active role of a hot mantle cannot be ruled out and a combination of different models might explain the formation of the Oslo Graben better.

References

- Anderson, D.L., 2005. Scoring hotspots: the plume & plate paradigms, in: G.R. Foulger, J.H. Natland, D.C. Presnall and D.L. Anderson (Editors), *Plates, Plumes and Paradigms*, Geological Society of America Special paper 388, in press.
- Benek, R., Kramer, W., McCann, T., Scheck, M., Negendank, J.F.W., Korich, D., Huebscher, H.D. and Bayer, U., 1996. Permo-Carboniferous magmatism of the Northeast German Basin, *Tectonophysics*, **266**, 379-404.
- Breitkreuz, C. and Kennedy, A., 1999. Magmatic flare-up at the Carboniferous/Permian boundary in the NE German basin revealed by SHRIMP zircon ages, *Tectonophysics*, **302**, 307-326.
- Courtillot, V., Davaille, A., Besse, J. and Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle, *Earth and Planetary Science Letters*, **205**, 295-308.
- Coward, M.P., 1993. The effect of late Caledonian and Variscan continental escape tectonics on basement structure, Paleozoic basin kinematics and subsequent Mesozoic basin development in NW Europe, in: J.R. Parker (Editor), *Petroleum Geology of Northwest Europe*; Proceedings of the 4th conference, Geological Society of London, London, United Kingdom, pp. 1095-1108.
- Dahlgren, S., Corfu, F. and Heaman, L.M., 1996. U-Pb isotopic time constraints, and Hf

and Pb source characteristics of the Larvik plutonic complex, Oslo Paleorift. Geodynamical and geochemical implications for the rift evolution, *V.M. Goldschmidt Conference*, Ruprecht-Karls Universität, Heidelberg, Germany, pp. 120.

- Dahlgren, S. and Corfu, F., 2001. Northward sediment transport from the late Carboniferous Variscan Mountains: zircon evidence from the Oslo Rift, Norway, *Journal of the Geological Society*, **158**, 29-36.

- Ernst, R.E. and Buchan, K.L., 1997. Giant radiating dyke swarms; their use in identifying pre-Mesozoic large igneous provinces and mantle plumes, in: J.J. Mahoney and M.F. Coffin (Editors), *Large igneous provinces; continental, oceanic, and planetary flood volcanism*, Geophysical Monograph, 100, American Geophysical Union, Washington, DC, United States, pp. 297-333.

- Frederiksen, S., Nielsen, S.B. and Balling, N., 2001. A numerical dynamic model for the Norwegian-Danish Basin, *Tectonophysics*, **343**, 165-183.

- Heeremans, M., Larsen, B.T. and Stel, H., 1996. Paleostress reconstruction from kinematic indicators in the Oslo Graben, southern Norway. New constraints on the mode of rifting, *Tectonophysics*, **266**, 55-79.

- Heeremans, M. and Faleide, J.I., 2004. Late Carboniferous-Permian tectonics and magmatic activity in the Skagerrak, Kattegat and the North Sea, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223, The Geological Society, London, pp. 157-176.

- Heeremans, M., Faleide, J.I. and Larsen, B.T., 2004a. Late Carboniferous - Permian of NW Europe: an introduction to a new regional map, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*. Geological Society Special Publication, The Geological Society, London, pp. 75-88.

- Heeremans, M., Timmerman, M.J., Kirstein, L.A. and Faleide, J.I., 2004b. New constraints on the timing of late Carboniferous - early Permian volcanism in the central North Sea, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223, The Geological Society, London, pp. 177-194.

- Henningsmoen, G., 1978. Sedimentary rocks associated with the Oslo region lavas. In: J.A. Dons and B.T. Larsen (Editors), *The Oslo Paleorift; a review and guide to excursion*, Bulletin - Norges Geologiske Undersøkelse, 337. Universitetsforlaget, pp. 17-24.

- Kinck, J.J., Husebye, E.S. and Larsson, F.R., 1993. The Moho Depth Distribution in Fennoscandia and the Regional Tectonic Evolution from Archean to Permian Times, *Precambrian Research*, **64**, 23-51.

- Kirstein, L.A., Dunai, T.J., Davies, G.R., Upton, B.G.J. and Nikogosian, I.K., 2004. Helium isotope signature of lithospheric mantle xenoliths from the Permo-Carboniferous magmatic province in Scotland - no evidence for a lower-mantle plume, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223, The Geological Society, London, pp. 243-258.

- Mcdonough, W.F. and Sun, S.S., 1995. The Composition of the Earth, *Chemical Geology*, **120**, 223-253.

- Mogensen, T.E., 1994. Paleozoic Structural Development along the Tornquist Zone, Kattegat Area, Denmark, *Tectonophysics*, **240**, 191-214.

- Monaghan, A.A. and Pringle, M.S., 2004. $^{40}Ar/^{39}Ar$ geochronology of Carboniferous-Permian volcanism in the Midland Valley, Scotland, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous*

Magmatism and Rifting in Europe, Geological Society Special Publication, 223, The Geological Society, London, pp. 219-241.

- Neumann, E.R., 1994. The Oslo Rift - P-T Relations and Lithospheric Structure, *Tectonophysics*, **240**, 159-172.

- Neumann, E.R., Wilson, M., Heeremans, M., Spencer, E.A., Obst, K., Timmerman, M.J. and Kirstein, L., 2004. Carboniferous-Permian rifting and magmatism in southern Scandinavia, the North Sea and northern Germany: a review, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223, The Geological Society, London, pp. 11-40.

- Olaussen, S., 1981. Marine Incursion in Upper Paleozoic Sedimentary-Rocks of the Oslo Region, Southern-Norway, *Geological Magazine*, **118**, 281-288.

- Olaussen, S., Larsen, B.T. and Steel, R., 1994. The Upper Carboniferous-Permian Oslo Rift; basin fill in relation to tectonic development, in: A.F. Embry, B. Beauchamp and D.J. Glass (Editors), *Pangea; global environments and resources*, Memoir - Canadian Society of Petroleum Geologists, 17. Canadian Society of Petroleum Geologists, Calgary, AB, Canada, pp. 175-197.

- Pascal, C., Cloetingh, S. and Davies, G.R., 2004. Asymmetric lithosphere as the cause of rifting and magmatism in the Permo-Carboniferous Oslo Graben, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223, The Geological Society, London, pp. 139-156.

- Pedersen, T. and van der Beek, P., 1994. Extension and magmatism in the Oslo rift, southeast Norway: no sign of a mantle plume, *Earth and Planetary Science Letters*, **123**, 317-29.

- Ramberg, I.B. and Larsen, B.T., 1978. Tectonomagmatic evolution, in: J.A. Dons and B.T. Larsen (Editors), *The Oslo Paleorift: a review and guide to excursions*, Bulletin - Norges Geologiske Undersokelse, 337, Universitetsforlaget, Trondheim, pp. 55-73.

- Ro, H.E., Larsson, F.R., Kinck, J.J. and Husebye, E.S., 1990. The Oslo Rift - Its Evolution on the Basis of Geological and Geophysical Observations, *Tectonophysics*, **178**, 11-28.

- Rohrman, M., van der Beek, P. and Andriessen, P., 1994. Syn-rift thermal structure and post-rift evolution of the Oslo Rift (southeast Norway): new constraints from fission track thermochronology, *Earth and Planetary Science Letters*, **127**, 39-54.

- Sundvoll, B., Neumann, E.R., Larsen, B.T. and Tuen, E., 1990. Age Relations among Oslo Rift Magmatic Rocks - Implications for Tectonic and Magmatic Modeling, *Tectonophysics*, **178**, 67-87.

- Sundvoll, B., Larsen, B.T. and Wandaas, B., 1992. Early magmatic phase in the Oslo Rift and its related stress regime, *Tectonophysics*, **208**, 37-54.

- Sundvoll, B. and Larsen, B.T., 1993. Rb-Sr and Sm-Nd relationship in dyke and sill intrusions in the Oslo Rift and related areas, *Bulletin - Norges geologiske undersøkelse*, **425**, 23-40.

- Timmerman, M.J., 2004. Timing, geodynamic setting and character of Permo-Carboniferous magmatism in the foreland of the Variscan Orogeny, NW Europe, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223. The Geological Society, London, pp. 41-74.

- Torsvik, T.H. and Cocks, L.R.M., 2004. Earth geography from 400 to 250 Ma; a palaeomagnetic, faunal and facies review, *Journal of the Geological Society of London*, **161**, 555-572.

- Upton, B.G.J., Stephenson, D., Smedley, P.M., Wallis, S.M. and Fitton, J.G., 2004. Carboniferous and Permian magmatism in Scotland, in: M. Wilson, E.R. Neumann, G.R. Davies, M.J. Timmerman, M. Heeremans and B.T. Larsen (Editors), *Permo-Carboniferous Magmatism and Rifitng in Europe*, Geological Society Special Publication, 223, The Geological Society, London, pp. 195-218.

- van Wees, J.D., Stephenson, R.A., Ziegler, P.A., Bayer, U., McCann, T., Dadlez, R., Gaupp, R., Narkiewicz, M., Bitzer, F. and Scheck, M., 2000. On the origin of the Southern Permian Basin, Central Europe, *Marine and Petroleum Geology*, **17**, 43-59.

- Veevers, J.J., Clare, A. and Wopfner, H., 1994. Neocratonic magmatic-sedimentary basins of post-Variscan Europe and post-Kanimblan eastern Australia generated by right lateral transtension of Permo-Carboniferous Pangea, *Basin Research*, **6**, 141-157.

- Verdier, J.P., 1996. The Rotliegend sedimentation history of the southern North Sea and adjacent countries, in: H.E. Rondeel, D.A.J. Batjes and W.H. Nieuwenhuijs (Editors), *Geology of Gas and Oil under the Netherlands*, Kluwer Academic Publisheres, Dordecht, pp. 45-56.

- Wilson, M., Neumann, E.R., Davies, G.R., Timmerman, M.J., Heeremans, M. and Larsen, B.T., 2004. *Permo-Carboniferous Magmatism and Rifting in Europe*, Geological Society Special Publication, 223, The Geological Society, London, 498 pp.

- Zeck, H.P., Andriessen, P.A.M., Hansen, K., Jensen, P.K. and Rasmussen, B.L., 1988. Paleozoic paleo-cover of the southern part of the Fennoscandian Shield-fission track constraints, *Tectonophysics*, **149**, 61-6.

- Ziegler, P.A., 1990. *Geological Atlas of Western and Central Europe*, Shell Internationale Petroleum Maatschappij, The Hague.

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