Carboniferous–Permian rifting and magmatism in southern Scandinavia, the North Sea and northern Germany: a review

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Abstract: During the Late Carboniferous and Early Permian an extensive magmatic province developed within northern Europe, intimately associated with extensional tectonics, in an area stretching from southern Scandinavia, through the North Sea, into northern Germany. Within this area magmatism was unevenly distributed, concentrated mainly in the Oslo Graben and its offshore continuation in the Skagerrak, Scania in southern Sweden, the island of Bornholm, the North Sea and northern Germany. Available geochemical (major- and trace-element, and Sr–Nd isotope, data) and geophysical data are reviewed to provide a basis for understanding the geodynamic setting of the magmatism in these areas. Peak magmatic activity was concentrated in a narrow time-span from *c.* 300 to 280 Ma. The magmatic provinces developed within a collage of basement terranes of different ages and lithospheric characteristics (including thicknesses), brought together during the preceding Variscan orogeny. This suggests that the magmatism in this area may represent the local expression of a common tectono-magmatic event with a common causal mechanism. Available geochemical (major and trace element and Sr-Nd isotope data) and geophysical data are reviewed to provide a basis for understanding the geodynamic setting of the magmatism in these areas. The magmatism covers a wide range in rock types both on a regional and a local scale (from highly alkaline to tholeiitic basalts, to trachytes and rhyolites). The most intensive magmatism took place in the Oslo Graben (ca. 120 000 km^3) and in the NE German Basin (ca. 48 000 km^3). In both these areas a large proportion of the magmatic rocks are highly evolved (trachytes-rhyolites). The dominant mantle source componet for the mildly alkali basalts to subalkaline magmatism in the Oslo Graben and Scania (probably also Bornholm and the North Sea) is geochemically similar to the Prevalent Mantle (PREMA) component. Rifting and magmatism in the area is likely to be due to local decompression and thinning of highly asymmetric lithosphere in responses to regional stretching north of the Variscan Front, implying that the PREMA source is located in the lithospheric mantle. However, as PREMA sources are widely accepted to be plume-related, the possibility of a plume located beneath the area cannot be disregarded. Locally, there is also evidence of other sources. The oldest, highly alkaline basaltic lavas in the southernmost part of the Oslo Graben show HIMU trace element affinity, and initial Sr-Nd isotopic compositions different from that of the PREMA-type magmatism. These magmas are interpreted as the results of partial melting of enriched, metasomatised domains within the mantle lithosphere beneath the southern Olso Graben; this source enrichment can be linked to migration of

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carbonatite magmas in the earliest Paleozoic (ca. 580 Ma). Within northern Germany, mantle lithosphere modified by subduction-related fluids from Variscan subduction systems have provided an important magma source components.

During the Carboniferous and Permian, northern Europe experienced widespread magmatism and graben formation (e.g. Ziegler 1990, 1992). The earliest manifestations of this activity are in the UK and Ireland (Monaghan & Pringle 2003; Praeg 2003; Timmerman 2003; Upton *et al.* 2003; Wilson & the PCR Project Team 2003). In this paper we concentrate on Carboniferous–Permian tectono-magmatic activity in an area comprising the North Sea from about 51°N to about 61°N along the western coast of Norway, the Netherlands, northern Germany, Denmark, southernmost Sweden, the Skagerrak and the Oslo Graben (Fig. 1).

Extensional tectonics in southern Scandinavia, the North Sea and northern Germany started during Carboniferous times, and continued until opening of the Norwegian–Greenland Sea (e.g. MONA LISA Working Group 1997 and references therein). Magmatism was unevenly distributed; the main areas include the Oslo–Skagerrak Graben, Scania (southern Sweden), the Danish island of Bornholm, the North Sea and northern Germany (Fig. 1). In contrast to the long-lasting tectonic activity, the magmatism in these areas was concentrated in a restricted period, starting about 300 Ma ago, with the bulk of the activity occurring between 300 and 280 Ma (e.g. Klingspor 1976; Sundvoll *et al.* 1992; Breitkreuz & Kennedy 1999; Heeremans *et al.* 2000, 2004; M. J. Timmerman pers. comm. 2001).

The Carboniferous–Permian tectonic and magmatic activity was spread across an area of great structural and tectonic complexity (Fig. 2), which includes the Precambrian Baltic Shield to the north, and crosses the Caledonian Deformation Front into Avalonia, and the North Variscan Deformation Front into Variscan Europe (Fig. 2) (e.g. Gossler *et al.* 1999; Krawczyk *et al.* 1999). A S-dipping zone, the Tornquist Conversion Zone (Fig. 2), that separates crust with different Moho topography and different internal structures, is interpreted as the true southern boundary of the Baltic Shield (Gossler *et al.* 1999). Furthermore, the Baltic Shield is cut by the Sorgenfrei–Tornquist Zone that continues southeastwards through eastern Europe along the Tornquist–Teisseyre Zone.

Despite the wide area involved, and the great variation in intensity over this area, the coincidence in time of Carboniferous–Permian magmatism in southern Scandinavia, the North Sea and northern Germany strongly suggests that it represents local expressions of a common, tectono-magmatic event with a common causal mechanism. Although a lot of information and understanding has been obtained through studies of the individual areas, the mechanisms and processes that caused this tectono-magmatic event can only be understood through an overview of the entire area. Here we use available geochemical and geophysical data as a basis for a discussion of magma generation processes and the causal mechanisms for the Carboniferous–Permian tectono-magmatic activity.

Regional tectonic framework and crustal structure

The Oslo–Skagerrak Graben, Scania and Bornholm are located within the Precambrian Baltic Shield (Fig. 2). In general, this area of cratonic basement is characterized by thick crystalline crust (>40 km) with a lower crust of relatively high seismic velocity (6.9–7.0 $\mathrm{km s^{-1}}$; e.g. Thybo 1997 and references therein; Abramovitz *et al.* 1999; Gossler *et al.* 1999). However, the areas of Carboniferous–Permian (and younger) rifting and magmatism (Fig. 1) have a highly variable Moho topography whose shallower parts coincide with the locations of grabens and sedimentary basins (e.g. Thybo 1997). The crust along the Oslo–Skagerrak Graben is markedly thinner than that in adjacent areas. Crustal thickness decreases southwards, reaching a minimum of 24–26 km where the Skagerrak Graben meets the Sorgenfrei–Tornquist Zone in NW Denmark (e.g. Ro *et al.* 1990*a*; Ro & Faleide 1992; Thybo, 1997) (Fig. 1). A strong positive gravity anomaly along the Oslo–Skagerrak Graben reaches a maximum of >40 mgal in the Skagerrak Graben (Fig. 3), and the graben area shows higher seismic velocities in the lower crust (7.0–7.1 $\mathrm{km\,s^{-1}}$) than the areas to the east and west (e.g. Ramberg 1976; Tryti & Sellevoll 1977; Cassell *et al.* 1983; Gundem 1984; Neumann *et al.* 1992 and references therein). For the Oslo–Skagerrak Graben these features have been interpreted as the result of large volumes of dense cumulates in the deep crust, associated with the surface magmatism (e.g. Ramberg 1976;

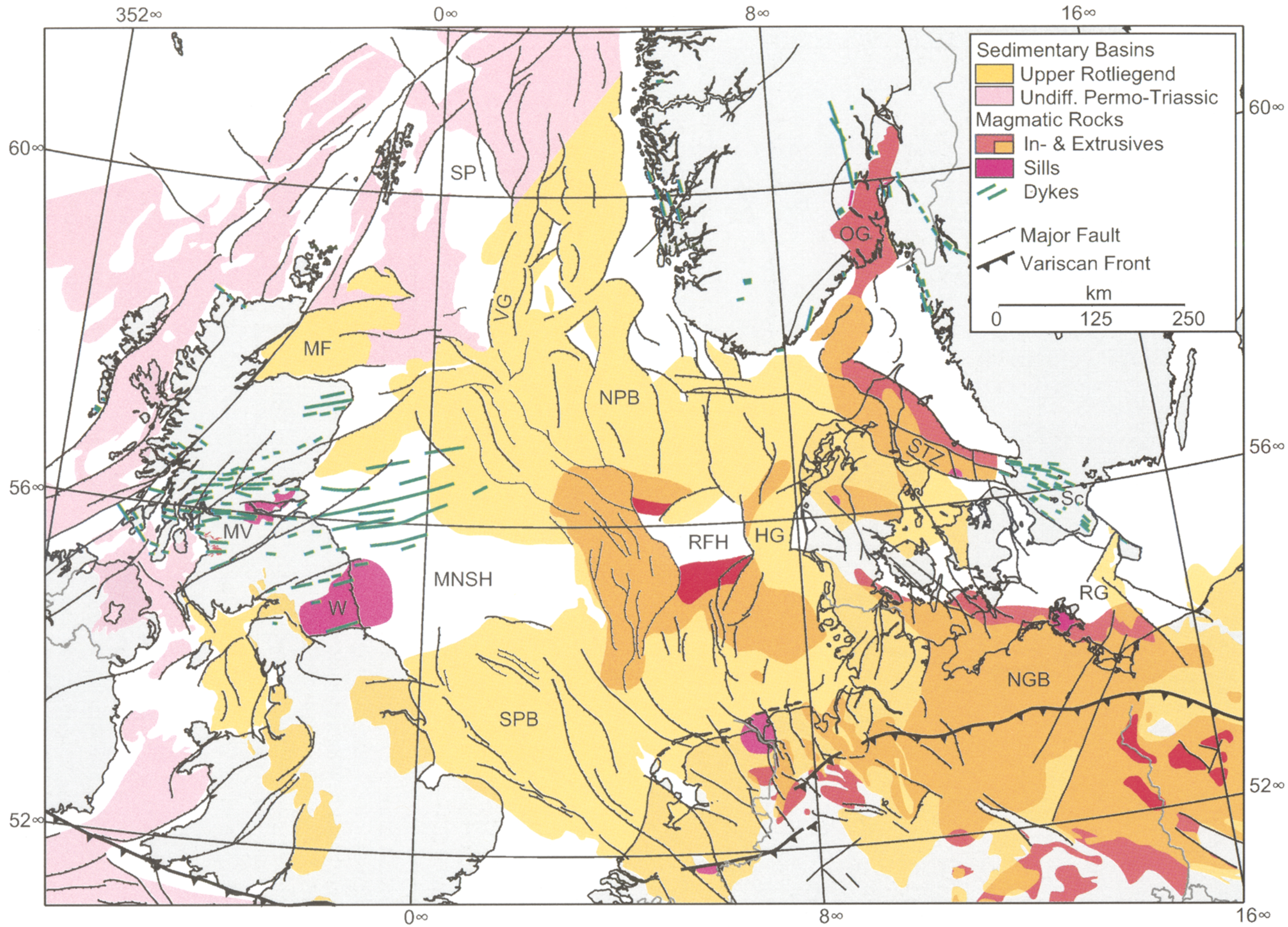

Fig. 1. Map of Permo-Carboniferous magmatism, tectonic elements and main structures in northern Europe (based on a compilation by Heeremans & Faleide; Heeremans *et al.* 2004*a*). SP, Shetland Platform; MF, Moray Firth; MV, Midland Valley; W, Whin Sill; VG, Viking Graben; NPB, Mid-North Sea High; RFH, Ringkøbing–Fyn High; HG, Horn Graben; STZ, Sorgenfrei–Tornquist Zone; RG, Rønne Graben; NGB, Northern German Basin; OG, Oslo Graben; Sc, Scania.

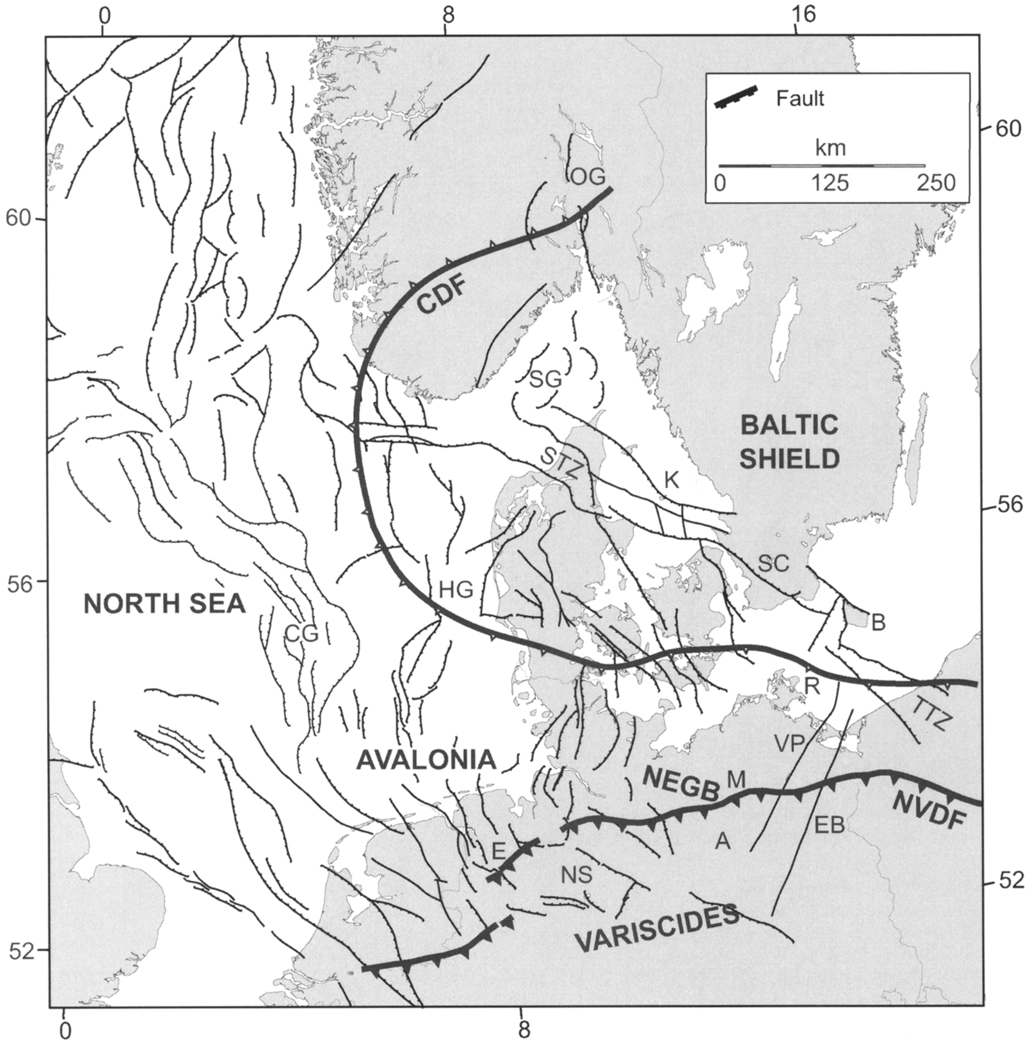

Fig. 2. Simplified map showing tectonic framework, and sample locations discussed in this paper, based on maps by Benek *et al.* (1996) and Gossler *et al.* (1999). A, Altmark; B, Bornholm; CDF, Caledonian Deformation Front; CG, Central Graben; E, Emsland: EB, East Brandenburg; HG, Horn Graben: K, Kattegat; M, Mecklenburg; NEGB: NE German Basin; NS, Niedersachsen; NVDF, North Variscan Deformation Front; OG, Oslo Graben; R, Ruegen; SC, Scania; SG, Skagerrak Graben; STZ, Sorgenfrei–Tornquist Zone; TTZ, Teisseyre–Tornquist Zone; VP, Vorpommern.

Neumann 1980, 1994; Neumann *et al.* 1986, 1988*a*).

A regional dyke swarm in Scania, southern Sweden, follows the NW–SE trend of the Sorgenfrei–Tornquist Zone. The dykes are located in an area where the crustal thickness of the Precambrian Shield decreases from 44 to 32 km over a very short distance (e.g. Thybo 1997). A zone of high positive gravity anomalies strikes SE from northern Denmark, and is coincidental with the Scania dykes and an associated swarm on the Baltic Sea island of Bornholm (Fig. 3). The largest maximum along this anomaly (>40 mgal) is located over the NW part of the Scania dyke swarm, and another, smaller, maximum over the Bornholm dyke swarm (Fig. 3). Its position and orientation imply that this gravity anomaly is closely related

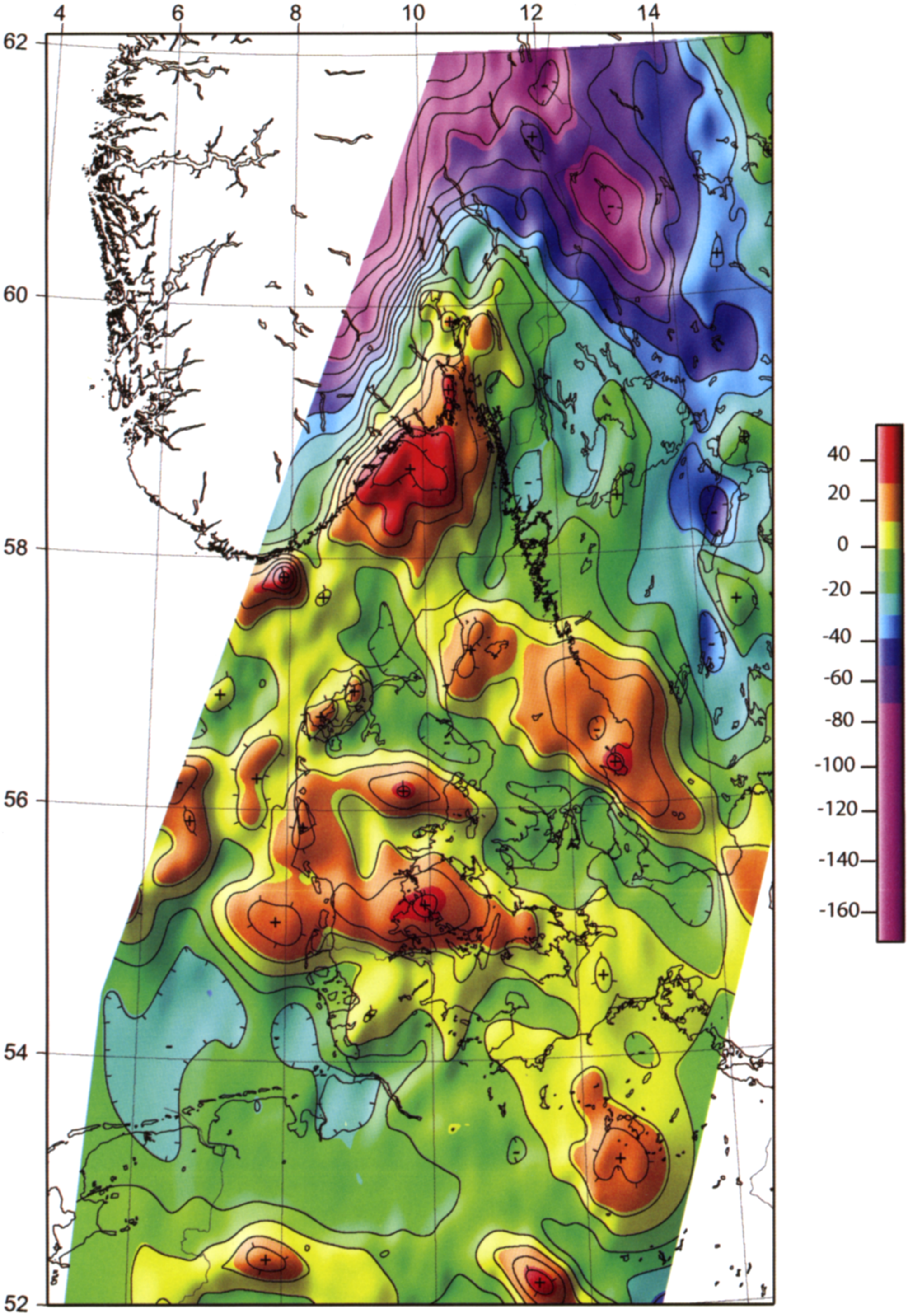

Fig. 3. Bouguer anomaly map with a 50 km low-pass filter, based on data from the European Geotraverse (Klingele *et al.* 1992).

to the Scania and Bornholm dyke complexes. The anomaly is interpreted to reflect the presence of dense rocks in the deep crust (e.g. Thybo 1997).

The pattern of variable crustal thickness continues to the west and south into Denmark and the North Sea, across the Tornquist Conversion Zone (Fig. 2) (e.g. Erlström *et al.* 1997; MONA LISA Working Group 1997; Thybo 1997). The crust beneath the Central Graben of the North Sea is about 5 km thinner than that below the adjacent areas (MONA LISA Working Group 1997). The southern North Sea shows deep crustal reflectivity that may be related to underplating between the Central and Horn grabens (MONA LISA Working Group 1997). In the north German part of Avalonia (Fig. 2) the crust is 25–26 km thick, and the seismic velocity above the Moho is only about 6.3 km s^{-1} (Abramovitz *et al.* 1999). In the NE German Basin, the crust is uniformly 30–32 km thick (Bayer *et al.* 1999). However, the thickness of the crystalline crust decreases from 32 km at the basin margins to *c.* 22 km beneath the centre of the basin, and a thick, high-velocity (6.9–7.5 km s^{-1}), high-density layer is located beneath the centre of the basin (e.g. Rabbel *et al.* 1995; Bayer *et al.* 1999; Fleibinhaus *et al.* 1999). Rabbel *et al.* (1995) proposed that the high-velocity, high-density layer represents magmatic intrusions, whereas Bayer *et al.* (1999) considered Late Carboniferous magmatic underplating as only one of several possible interpretations of the high-density layer. Alternative possibilities are that it is a remnant of East Avalonia, or is the cumulative result of a series of magmatic events during the Palaeozoic and Mesozoic (Bayer *et al.* 1999).

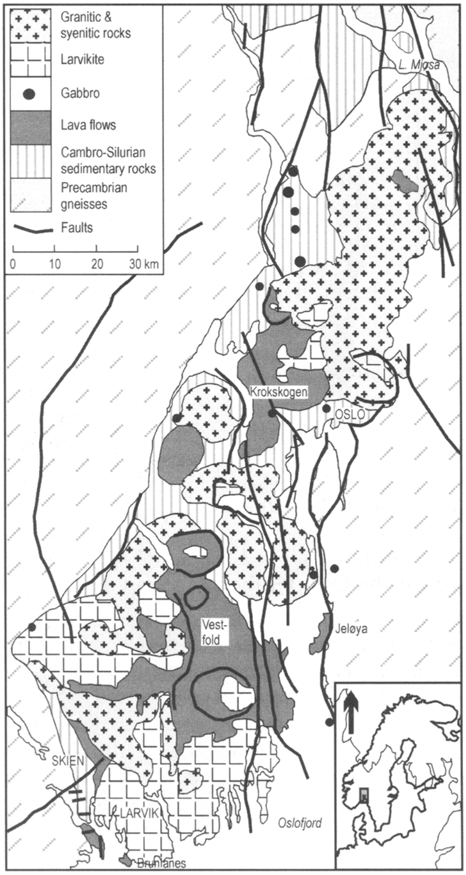

Fig. 4. Simplified map of the Oslo Graben showing different rock types (after Ramberg & Larsen 1978). Syenites and granites plot in the trachyte and rhyolite fields, respectively, in Figure 6, larvikites in the trachyandesite field and gabbros in the basalt–tephrite fields. The lavas are mainly basalts and rhomb porphyry flows (trachyandesites; Fig. 6a, b).

The Oslo–Skagerrak Graben

Tectono-magmatic evolution and age relationships

The Oslo–Skagerrak Graben is a composite graben complex that extends northwards from the Sorgenfrei–Tornquist Zone to Lake Mjøsa where it appears to die out (Figs 1 and 4). The northern part, the Oslo Graben, consists of a *c.* 200 km-long and 35–65 km-wide graben containing large volumes of rift-related extrusive and intrusive rocks, and minor amounts of contemporaneous sedimentary rocks (Fig. 4). The Oslo Region or Oslo Graben has long been recognized as a Palaeozoic magmatic province (e.g. von Buch 1810; Lyell 1835, 1837; Brøgger 1890; Goldschmidt 1911; Barth 1945). Seismic investigations have shown that the Oslo Graben continues southwards into the Skagerrak Graben (e.g. Ro *et al.* 1990*a*, *b*). Because of the degree of exposure, the geology of the Oslo Graben is very well known, in contrast to the submarine Skagerrak Graben. However, seismic data and well cores indicate considerable magmatic and tectonic activity within the Skagerrak in Late Carboniferous–Early Permian time, including a *c.* 1 km-thick sequence of lavas (Heeremans *et al.* 2004).

The tectono-magmatic history of the Oslo Graben has been divided into five main stages (e.g. Ramberg & Larsen 1978; Sundvoll & Larsen 1990, 1993; Olaussen *et al.* 1994). A brief review is given below. A large number of rocks in the Oslo Graben have been dated by the

Table 1. *Age determinations on Permo-Carboniferous magmatic rocks in different parts of northern Europe (e.g. Klingspor 1976; Sundvoll & Larsen 1990, 1993; Sundvoll* et al. *1992; Marx 1994; Dahlgren* et al. *1996; Breitkreuz & Kennedy 1999; Heeremans* et al. *2004; M. J. Timmerman unpublished data 2002).*

Area	Oslo Graben	Scania	North Sea Central Graben	North Sea Horn Graben	NE German Basin
Oldest date (Ma)	304 ± 8	294	299 ± 3	284	302 ± 3
Period of magmatism (Ma)	305–241	294–274	295–280	280–260	302–294

Rb–Sr dating method, giving a range of about 305–240 Ma for the main phases of magmatic activity (e.g. Sundvoll & Larsen 1990, 1993; Sundvoll *et al.* 1990, 1992). However, U–Pb dating of zircon and baddeleyite in the Larvik pluton (Fig. 4) strongly suggests that the Rb–Sr method may give ages which are too young (Dahlgren *et al.* 1996), implying that the total period of magmatism may have been significantly shorter than indicated by the Rb–Sr age determinations.

The timing of the different evolutionary stages of the Oslo Graben is as follows.

Pre-rift stage. The oldest lavas in the Oslo Graben were erupted unconformably on top of a sedimentary sequence called the Asker Group (e.g. Henningsmoen 1978; Olaussen *et al.* 1994). The Asker Group sediments are interpreted to represent fluvial-dominated deltas that prograded into a lacustrine or brackish water basin (Olaussen *et al.* 1994). Fossils in the upper part of this sequence indicate an upper Westphalian age (*c.* 312–300 Ma; Olaussen *et al.* 1994). This is in agreement with the youngest U–Pb age determination, 319 ± 5 Ma, obtained from detrital zircon grains from sandstones in the upper Asker group, which defines the upper limit for the onset of volcanism in the Oslo Graben (Dahlgren & Corfu 2001).

Rift stage 1: initial rifting. A series of sills and dykes of trachyandesite–rhyolitic composition intruding the Asker Group, with Rb–Sr ages of 304 ± 8 to 294 ± 7 Ma (Table 1, Fig. 5), are believed to represent the earliest magmatism in the Oslo Graben (e.g. Ramberg & Larsen 1978; Sundvoll *et al.* 1992). The main formation of the Oslo Graben started with the onset of widespread basaltic volcanism (termed B1), and vertical movement along NNW–SSE- to N–S-trending faults. The B1 basalt sequence at Brunlanes is about 800 m thick (S. Dahlgren pers. comm. 2002), whilst that at Skien in the southernmost part of the Oslo Graben is *c.* 1500 m thick (Segalstad 1979) (Fig. 4). In the Vestfold and Jeløya rift segments the B1 sequences are 170–180 and 800–1500 m thick, respectively (Schou-Jensen & Neumann 1988), whereas B1 at Krokskogen, north of Oslo, consists of only one, or a few, tholeiitic flows *c.* 15 m thick. The only B1 lava that has been dated is a tholeiitic basalt from Krokskogen (Fig. 4), which has an Rb–Sr whole-rock age of 291 ± 8 Ma (Sundvoll & Larsen 1990; Sundvoll *et al.* 1990). U–Pb dating of zircon and baddeleyite in the oldest part of a composite larvikite (monzonite) intrusion in the Larvik area, which appears to have acted as a feeder to rhomb porphyry lavas overlying the B1 basalts in Vestfold, gives an age of 298.6 ± 1.4 Ma (Dahlgren *et al.* 1996). In the Vestfold area the emplacement of Rift stage 1 B1 basalts most probably, therefore, took place between about 305 and 299 Ma. The early B1 basalts are the most primitive magmatic rocks within the Oslo Rift, and thus provide the best constraints for the nature of their mantle source region and the processes that initiated partial melting.

Rift stage 2: the main rifting period. This stage defines the main development of the Oslo Graben and was accompanied by extensive fissure eruptions of trachyandesitic rhomb porphyry (RP) lavas and minor volumes of basaltic lavas (termed B2, B3, etc.). The RP lavas give whole-rock Rb–Sr ages of 294 ± 6 to 283 ± 8 Ma for Vestfold and 290 ± 4 to 276 ± 6 Ma for Krokskogen (Sundvoll *et al.* 1990). Large, composite monzonite–nepheline syenite intrusions (larvikites and lardalites) appear to have been emplaced partly contemporaneous with, and partly after, the extrusion of the RP lavas in the southern part of the Oslo Graben. The Larvik composite pluton (Figs 4 and 5) gives Rb–Sr ages of 281 ± 4 to 276 ± 6 Ma, whereas skeletal zircons give a total U–Pb age range of 298.6 ± 1.4 to 292.1 ± 0.8 Ma (Dahlgren *et al.* 1996) (Table 1, Fig. 5). This strongly suggests that the Rb–Sr data give ages that are too young (Dahlgren *et al.* 1996), that Rift stage 2 occurred earlier and that the main period of magmatism (Rift stages 1–2) lasted for a shorter period of time than assumed previously.

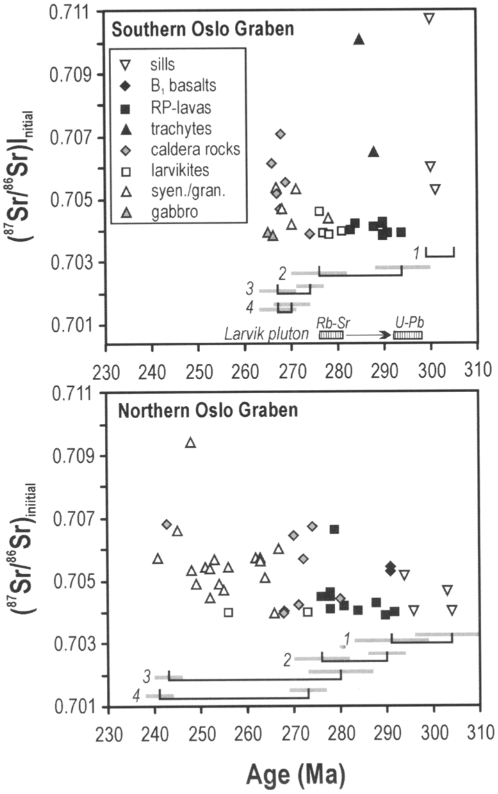

Fig. 5. Initial Sr isotope ratios plotted against ages (obtained from Rb–Sr whole-rock and mineral isochrons) for magmatic rocks in the Oslo Graben. The age ranges for the different rift stages are shown in solid lines in the lower part of each diagram, with grey boxes indicating 2σ errors. Numbers in italics indicate rift stages as given in the text. The sills intruding the Asker Group have been assigned to the pre-rift stage by e.g. Ramberg & Larsen (1978) and Sundvoll *et al.* (1992), but their ages overlap with the ranges of Rift stage 1 (initial rifting), implying that they belong to this stage. Sills: evolved sills intruding the Asker Group; trachytes: trachytic lavas interbedded with RP lavas; caldera rocks: lavas and intrusions associated with calderas; syen./gran.: large composite syenite and granite intrusions. For larvikites in the Larvik composite pluton (southern Oslo Graben) the age range obtained by the Rb–Sr method (Sundvoll & Larsen 1990) is compared to that obtained by the U–Pb method (Dahlgren *et al.* 1996). It seems likely that the Rb–Sr method, in general, gives ages that are too low for the Oslo Region.

Rift stage 3: central volcanoes and graben fill. With time, the magmatic style changed from shield volcanism and fissure eruptions to the development of central volcanoes, many of which went through stages of caldera collapse. Lavas, central intrusions and ring dykes associated with the calderas give Rb–Sr ages of 274 ± 3 to 266 ± 5 Ma for Vestfold and 280 ± 7 to 243 ± 3 Ma for Krokskogen (Sundvoll & Larsen 1990; Sundvoll *et al.* 1990) (Fig. 5).

Rift stage 4: emplacement of composite batholiths. This stage is dominated by the intrusion of large composite batholiths of trachyandesitic (larvikites, etc.) to rhyolitic compositions (syenites and granites) (Figs 4 and 6). These intrusions make up about 50% of the magmatic rocks exposed at the surface (Table 2). Rb–Sr isochrons give ages of 270 ± 4 to 267 ± 4 Ma for Vestfold and 273 ± 4 to 241 ± 3 for the northern part of the Oslo Graben (Sundvoll & Larsen 1990) (Fig. 5). As suggested above, Rb–Sr age determinations on the magmatic rocks in the Oslo Graben may be too young, and U–Pb zircon dating is required to confirm the age ranges obtained for Rift stages 3 and 4.

Dyke intrusions appear to have taken place throughout the rifting period, and comprise mafic–highly evolved magma types. The mafic dykes are dominated by alkali basaltic compositions, but include some tholeiitic (subalkaline) basalts. The magmatism also includes a series of small gabbro intrusions (Fig. 4). Rb–Sr whole-rock and mineral isochrons on two gabbros give 265 ± 11 and 266 ± 6 Ma (Sundvoll *et al.* 1990) (Fig. 5), placing them at a late stage in the rift history. However, gabbro emplacement may, like that of the dykes, have taken place over a long period.

Major- and trace-element chemistry

The geochemical characteristics and *total alkali-silica* (TAS) classification (Le Bas *et al.* 1986) of the various rock types exposed in the Oslo Graben are summarized in Figure 6a, b, based on the data of Larsen (1978), Ramberg & Larsen (1978), Segalstad (1979), Neumann (1980), Fjerdingstad (1983), Andersen (1984*a*, *b*), Schou-Jensen & Neumann (1988), Anthony *et al.* (1989), Neumann *et al.* (1990, 2002), Nilsen (1992), Trønnes & Brandon (1992), Dunworth *et al.* (2001) and Neumann & Dunworth (unpublished data). The B1 volcanism (Rift stage 1), decreases in alkalinity ([$Na_2O + K_2O$]/SiO_2) from south to north along the graben axis. The strongest degree of alkalinity is found in the B1 basalts at Brunlanes (Fig. 4) (S. Dahlgren pers. comm. 2002) and in the lower part of the B1 sequence (mainly tephrites) near Skien (Fig. 6a). In the Skien sequence the degree of alkalinity also decreases upwards (with decreasing age) from strongly to mildly alkaline basalts in the

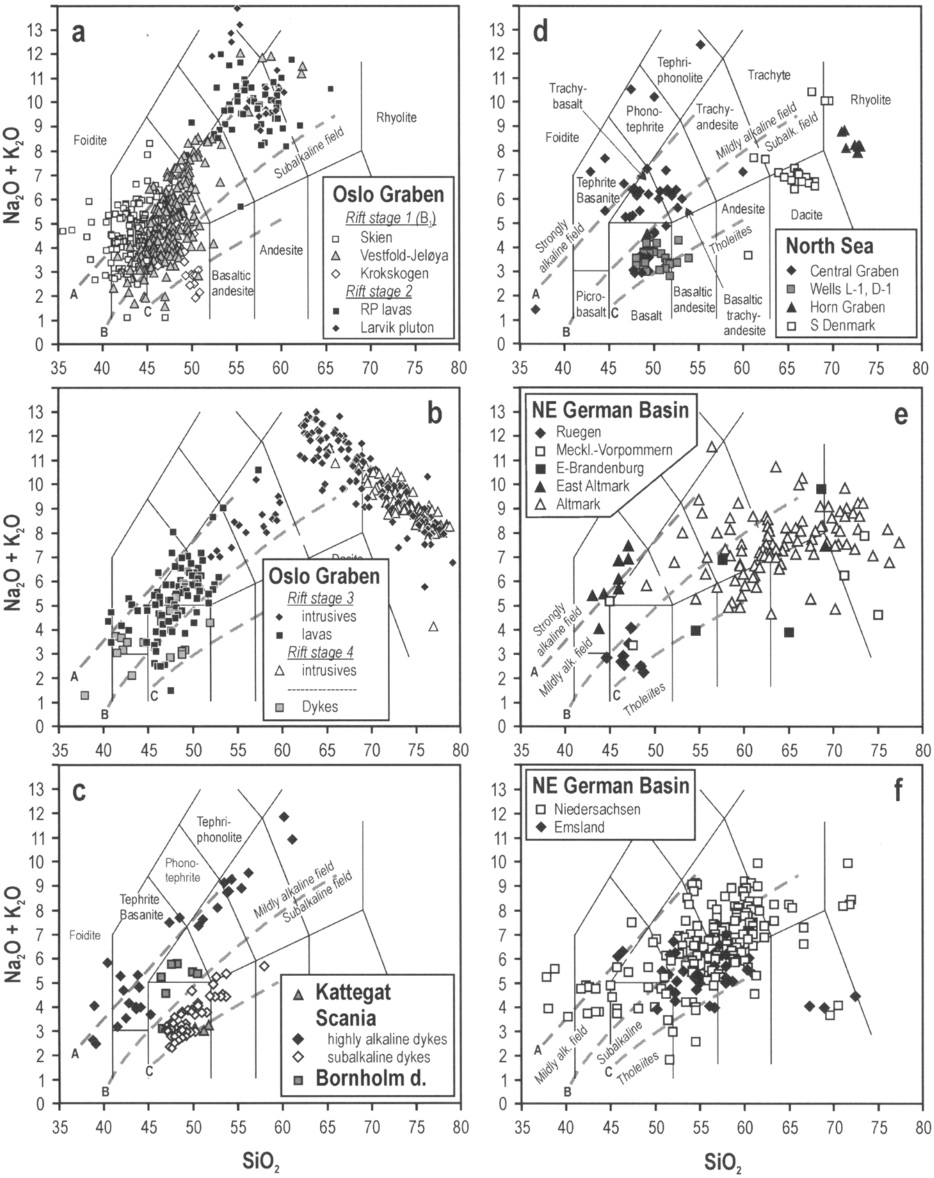

Fig. 6. Petrochemical classification diagram for Permo-Carboniferous magmatic rocks in different parts of N Europe (after Le Bas *et al.* 1986). Strongly alkaline–mildly alkaline (A), alkaline–subalkaline (B) and subalkaline–tholeiitic (C) field boundaries are from Saggerson & Williams (1964), Kuno (1968) and MacDonald (1968), respectively. Because of high volatile contents in some of the rocks, the figure is based on data recalculated to 100% dry. (**a**) Magmatic rocks in the Oslo Graben emplaced during Rift stage 1 (B1 basalts) and Rift stage 2 (rhomb porphyry lavas; larvikites and associated rocks in the Larvik pluton). (**b**) Magmatic rocks in the Oslo Graben emplaced during Rift stages 3 and 4 (data from Larsen 1978, Ramberg & Larsen 1978; Segalstad 1979; Neumann 1980; Fjerdingstad 1983; Andersen 1984*a*, *b*; Schou-Jensen & Neumann 1988; Anthony *et al.* 1989; Neumann *et al.* 1990, 2002 unpublished data; Nilsen 1992; Trønnes & Brandon 1992; Dunworth *et al.* 2001). See text for further explanation. (**c**) Dykes in Scania and Bornholm (data from Obst 1999, 2000; Obst *et al.* 2004), and magmatic rocks retrieved from wells in the Kattegat (Fig. 1) along the NW continuation of the Scania dyke swarm (data from Aghabawa 1993; Timmerman unpublished data). (**d**) Magmatic rocks retrieved from different parts of the North Sea (Fig. 1; data from Aghabawa 1993). (**e, f**) Lavas from drill cores in the NE German Basin (Fig. 1; data from Marx 1994 and Benek *et al.* 1996).

Table 2. *An overview over estimated volumes of Permo-Carboniferous magmatic rocks in different parts of NE Europe. See text for further information and explanations.*

	Total volume (km^3)	Basaltic rocks	Intermediate rocks	Syenitic–granitic rocks
Oslo Graben				
Rift stage 1	≈500	100%		
Rift stage 2 RP lava	≈2000		100%	
Larvik larvikite	≈10 000		100%	
Rift stage 3	≈500	≈20%	≈40%	≈40%
Rift stage 4 syenites–granites	≈14 000			100%
Observed	≈28 000^1	≈6%	≈44%	≈50%
Eroded	25 000–30 000??			
Deep-seated	>65 000	100%		
Skagerrak Graben				
Basaltic lavas	≈4000??	100%	??	??
Shallow intrusives	??			
Deep-seated	>>65 000??			
Scania				
Observed	≈4000^2	90–95%^{3}	5–10%^{3}	
Deep-seated	??			
Bornholm				
Observed		<<4000	90–95%^{3}	5–10%^{3}
Deep-seated	??			
North Sea				
Observed	??			
Deep-seated	??			
NE German Basin				
Observed	≈48 000^4	≈4%^{4}	≈26%^{4}	≈70%^{4}
Deep-seated	??			

References: [1]Ramberg (1976); [2]Henkel & Sundin (1979); [3]Obst (unpublished data 2002); [4]Benek *et al.* (1996).

upper part of the lava sequence. The Vestfold and Jeløya B1 sequences consist of mildly alkaline–subalkaline basalts (Fig. 6a). B1 at Krokskogen is tholeiitic (Fig. 6a). The B1 sequence in Jeløya includes rare rhyolites and ignimbrites. The rhomb porphyry lavas extruded during Rift stage 2 are trachyandesites, and the associated basaltic lavas are mildly alkaline–subalkaline. The larvikites and associated rocks plot mainly in the trachyandesite field. Rift stage 3 comprises a wide range of rock types from basaltic to rhyolitic, whereas magmatism during Rift stage 4 is restricted to highly silicic rocks (Fig. 6b).

The trace-element characteristics of the magmatic rocks provide important constraints on the nature of the mantle sources involved in the petrogenesis of the parental magmas, and also on the nature of crustal contamination and magmatic differentiation processes. Information about the chemical characteristics of the mantle source(s) is best preserved in the most mafic rocks, which are least affected by fractional crystallization. Discussion of the trace-element geochemistry of the Oslo Rift magmatism is therefore restricted to rocks with >5 wt% MgO. In PM-normalized trace-element variation diagrams (PM = primordial mantle as defined by McDonough & Sun 1995; e.g. Fig. 7) the trace elements are ordered according to their relative degree of incompatibility in mantle minerals with respect to mafic silicate melts. The element Rb has the strongest tendency to be partitioned preferentially into the melt phase and is, therefore, plotted furthest to the left; the relative degree of incompatibility decreases from left to right. Different PM-normalized trace-element patterns for mafic igneous rocks (often expressed as characteristic ratios between, and different concentrations of, the incompatible trace elements plotted) are diagnostic of the mantle source composition and mineralogy, the degree of partial melting, and the extent of magmatic differentiation and crustal contamination. In these kinds of trace-element variation diagrams we compare enrichment factors, not absolute concentrations of the elements. An enrichment factor, indicated by the subscript N, is the ratio between the concentration of a given element in the sample and the concentration in PM (e.g. $La_N = La_{sample}/La_{PM}$). In Figures 8 and 9 trace-element ratios are used to highlight mantle

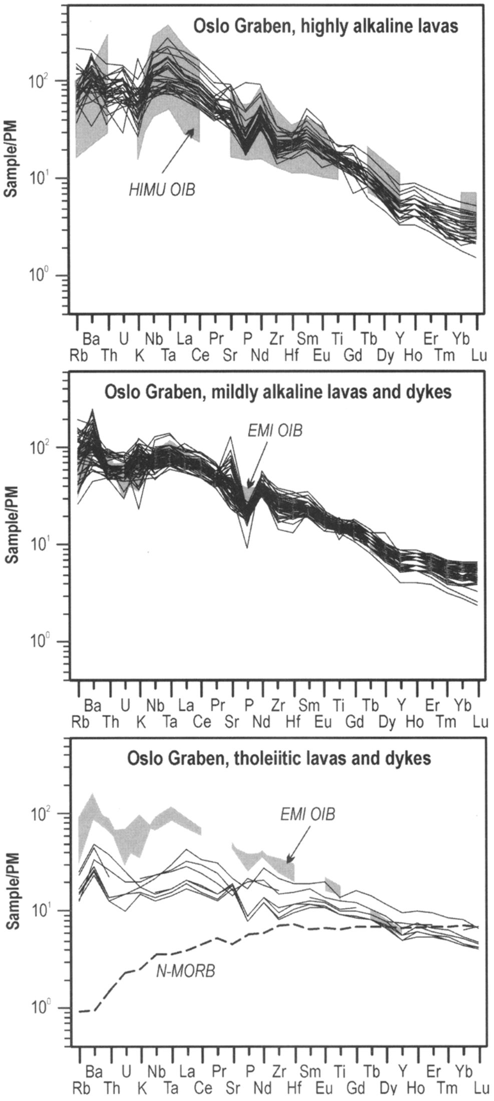

Fig. 7. Trace-element concentrations in mafic lavas, dykes and sills in the Oslo Graben, normalized to the primordial mantle (PM) as defined by McDonough & Sun (1995). 'Highly alkaline lavas' represent B1 lavas in the Skien area, southern Oslo Graben; 'tholeiitic lavas and dykes' include the B1 lava at Krokskogen north of Oslo; 'mildly alkaline lavas' comprise all other analyses of mafic lavas, including B1 lavas from Vestfold and Jeløya in the central Oslo Graben. Data from Anthony *et al.* (1989), Neumann *et al.* (1990, 2002), Dunworth *et al.* (2001), B. Sundvoll (unpublished data) and M. J. Timmerman (unpublished data). The fields HIMU OIB (data on basalts with MgO> 5 wt% from Raivavae, Rurutu, Saint Helena and Tubuaii from Weaver *et al.* 1987; Dupuy *et al.* 1988; data for St. Helena have been used to interpolate the fields through Ta and Dy), EMI OIB (data for basalts with MgO> 5 wt% from Gough and Trista da Cunha islands from Weaver *et al.* 1987) and N-MORB (average depleted mid-ocean ridge basalts; data from Sun & McDonough 1989) are shown for comparison. The highly alkaline mafic lavas in the Oslo Graben show clear affinity to HIMU OIB lavas, whereas the mildly alkaline ones resemble EMI OIB lavas. The tholeiitic lavas and dykes differ from EMI OIB by lower enrichment in the most strongly incompatible elements, and lower enrichment factors for Nb–Ta than for LREE.

source characteristics and the trace-element signature of crustal contamination processes. Different positions or domains in these diagrams imply derivation from, or influence by, chemically distinct mantle or crustal sources. The field of mantle sources involved in oceanic intraplate

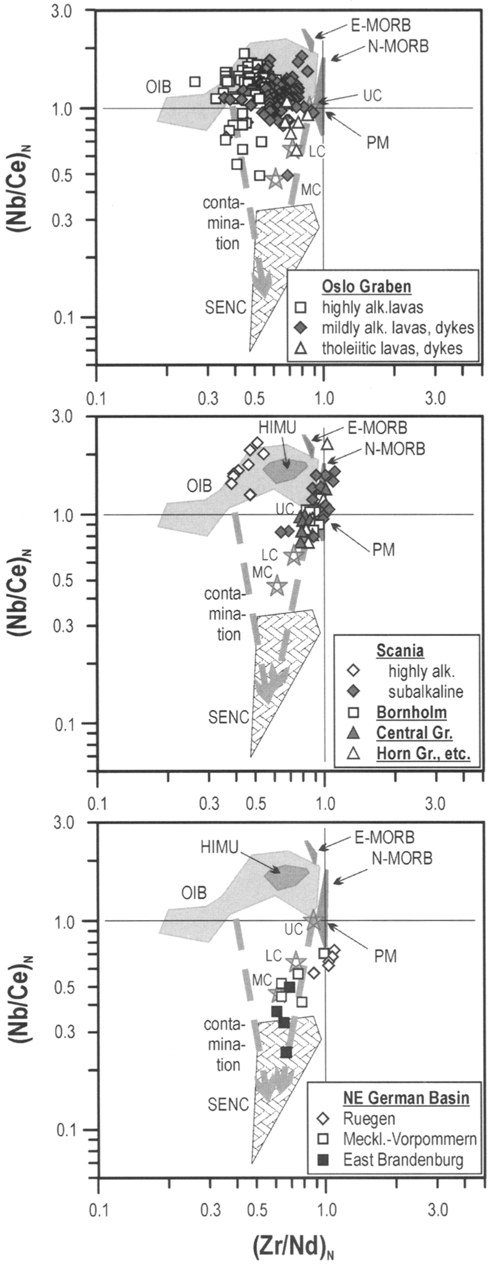

Fig. 8. $(Nb/Ce)_N$ plotted against $(Zr/Nd)_N$ for Carboniferous–Permian basaltic lavas and dykes in the Oslo Graben (data from Anthony *et al.* 1989; Neumann *et al.* 1990, 2002; Dunworth *et al.* 2001; B. Sundvoll unpublished data; M. J. Timmerman unpublished data), Scania (data from Obst 1999; Obst *et al.* 2004; M. J. Timmerman, unpublished data), Bornholm (Obst 2000), the North Sea (M. J. Timmerman, unpublished data) and the NE German Basin (data from Benek *et al.* 1996; M. J. Timmerman unpublished data). The OIB field is based on ocean island basalts with >5 wt% MgO (data for Hawaii: Clague & Frey 1982; Ascension, St. Helena, Tristan da Cunha and Gough: Weaver *et al.* 1987; the Austral Islands: Dupuy *et al.* 1988; Gran Canaria: Hoernle & Schmincke 1993; Tenerife: Neumann *et al.* 1999; the Azores: Almeida 2002); the HIMU field is based on data for St. Helena, Tubuaii, Rurutu and Raivavae. SENC: Precambrian SE Norwegian crust (data from Knudsen *et al.* 1997; Knudsen & Andersen 1999). UC, MC and LC: upper, middle and lower continental crust, respectively, as defined by Rudnick & Fountain (1995). The arrows indicate increasing influence by crustal contamination or subduction-related processes.

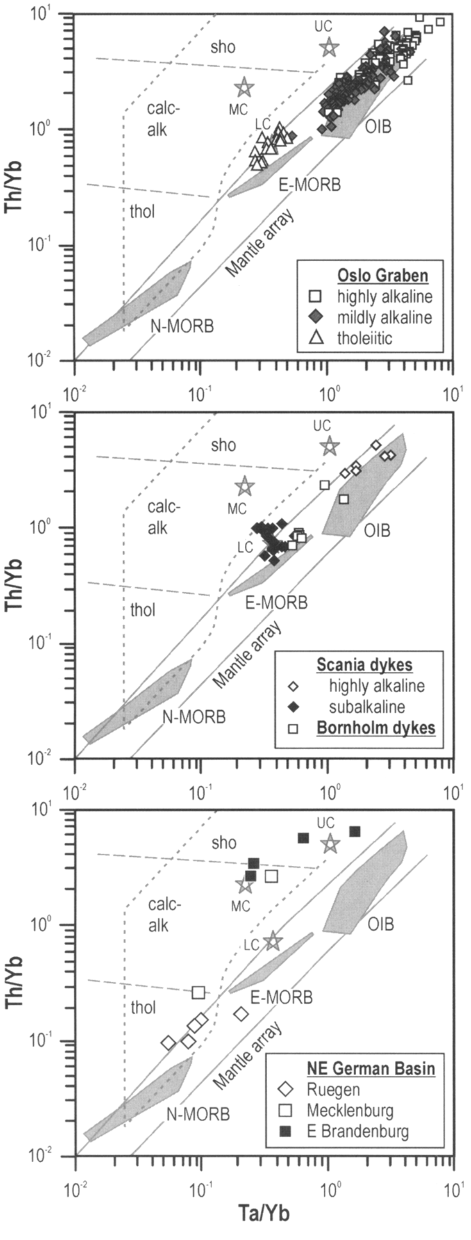

Fig. 9. Th/Yb plotted against Ta/Yb for Carboniferous–Permian basaltic lavas and dykes in the Oslo Graben, Scania, the North Sea and the NE German Basin (data sources as in Fig. 8). OIB: ocean island basalts with >5 wt% MgO (data sources as in Fig. 8). UC, MC and LC: upper, middle and lower continental crust, respectively, as defined by Rudnick & Fountain (1995). The mantle array and field of mafic lavas associated with destructive plate margins (field enclosed by the dashed line) are taken from Pearce (1982). Thol: tholeiitic; calc-alk: calc-alkaline: sho: shoshonitic lavas.

magmatism is marked ‘OIB’, and is defined on the basis of recent ocean island basalts (OIB e.g. EM = enriched mantle). As these basalts have extruded on oceanic lithosphere, no contamination by continental crustal rocks is possible. In order to detect the effects of crustal contamination we show average crustal compositions (as given by Rudnick & Fountain 1995), a field representative of the composition of the SE Norwegian crust (SENC; Knudsen *et al.* 1997; Knudsen & Andersen 1999) (Fig. 8) and a field of mafic lavas from destructive plate margins (Fig. 9), as defined by Pearce (1982).

The mafic rocks (>5% MgO) in the Oslo Graben (OG) are divided into three main groups based on their compositional characteristics and geographic location. The ‘highly alkaline OG group’ comprises all B1 lavas in the Skien area. The ‘mildly alkaline OG group’ consists of all B1 lavas in Vestfold and Jeløya, all younger basaltic lavas from different parts of the Oslo Graben and all diabase dykes that do not have a tholeiitic character. The ‘tholeiitic OG group’ consists of the B1 flows at Krokskogen together with a series of subalkaline, tholeiitic dykes from different parts of the Oslo Graben.

The ‘highly alkaline OG group’ is characterized by strong enrichment in highly incompatible elements relative to mildly incompatible elements (e.g. $\mathrm{La_N} = 63$–205; $\mathrm{Lu_N} = 1.5$–5.2), positive anomalies in Ta and Nb, and negative anomalies in P, Zr and Hf (Fig. 7). The degree of enrichment in strongly incompatible elements and the sizes of the Ta–Nb and Zr–Hf anomalies show a general decrease upwards in the Skien B1 lava sequence (Anthony *et al.* 1989). The trace-element patterns of the ‘mildly alkaline OG group’ partly overlap with the ‘highly alkaline OG group’, but the former are, on average, somewhat less enriched in strongly incompatible elements (e.g. $\mathrm{La_N} = 45$–173; $\mathrm{Lu_N} = 2.4$–7.4) and show less marked positive Nb–Ta and negative Zr–Hf anomalies than the ‘highly alkaline group’. In Figures 8 and 9 most of the alkaline lavas and dykes fall within the OIB field. Their different trace-element patterns are reflected in somewhat different positions within the OIB field. In the $\mathrm{(Nb/Ce)_N} - \mathrm{(Zr/Nd)_N}$ diagram (Fig. 8) the ‘highly alkaline group’ falls in the central part of the OIB field ($\mathrm{[Zr/Nd]_N} = 0.28$–0.63, average = 0.47), and the ‘mildly alkaline OG group’ in the right-hand part of the OIB field ($\mathrm{[Zr/Nd]_N} = 0.38$–0.89, average = 0.64). In Figure 9, the ‘highly alkaline group’ falls in the high, and the ‘mildly alkaline group’ in the low, Ta/Yb–Th/Yb part of the OIB field. Rocks plotting between the OIB and SENC fields in Figure 8 have suffered crustal contamination.

The least incompatible element-enriched Oslo Region B1 rocks belong to the 'tholeiitic group' (e.g. $La_N = 17$–42, $Lu_N = 4.0$–6.7; Fig. 7). This group differs from the highly and mildly alkaline types by being mildly depleted in Nb and Ta relative to light rare earth elements (LREE), and by showing no significant depletion in Zr and Hf relative to REE (rare earth elements) ($[Zr/Nd]_N$ range is 0.68–0.86 with 0.75 as the average; Fig. 8). In Figure 8 the 'tholeiitic group' plots outside the OIB field and shows a clear fingerprint of crustal contamination. In Figure 9 these lavas plot partly inside the mantle array close to the enriched mid-ocean ridge basalt (E-MORB) field, but overlap with the average composition of the lower crust (LC; Rudnick & Fountain 1995).

Radiogenic isotopes

In general, some of the strongest constraints about the nature of the mantle source(s) of the parental magmas and the extent of crustal contamination are provided by the Sr–Nd isotope compositions of the magmatic rocks (e.g. Sun 1980; Zindler & Hart 1986; Stein & Hofmann 1994; Hofmann 1997), as these are not affected by partial melting or subsequent fractional crystallization processes.

The magmatic rocks of the Oslo Graben, including both strongly and mildly alkaline basalts, tholeiites, rhomb porphyry lavas, larvikites, syenites and granitic rocks, exhibit a wide range of Sr–Nd isotope compositions (Figs 5 and 10). The most isotopically depleted samples ($^{143}Nd/^{144}Nd = 0.51245$–$0.51255$, $^{87}Sr/^{86}Sr =$ 0.703–0.704 at 300 Ma; Neumann *et al.* 1988*a*, *b*, 1990, 2002; Sundvoll & Larsen 1993) plot close to the isotopic composition of the PREMA (PREvalent MAntle) mantle end-member 300 Ma ago (Stein & Hofmann 1994). This source appears to have dominated the petrogenesis of a large proportion of the Oslo Graben magmatism (Neumann *et al.* 2002). There appear to be two trends in the Nd–Sr isotope data arrays towards lower initial $^{143}Nd/^{144}Nd$ ratios and higher $^{87}Sr/^{86}Sr$ ratios (Fig. 10). One trend, typical of the most evolved rock types (trachytic–rhyolitic), shows strongly increasing Sr with moderately decreasing Nd isotope ratios. This trend is believed to reflect upper crustal contamination. The other trend, showing moderately increasing initial $^{87}Sr/^{86}Sr$ with decreasing initial $^{143}Nd/^{144}Nd$, is defined mainly by mafic to moderately evolved rocks (basalts, RP lavas and larvikites) and may reflect contamination of the ascending mantle-derived magmas by continental crustal rocks with moderately high $^{87}Sr/^{86}Sr$, possibly in the lower crust (e.g. Neumann *et al.* 1988*a*, *b*, 1990, 2002; Sundvoll & Larsen 1993; Dunworth *et al.* 2001), but may also be due to

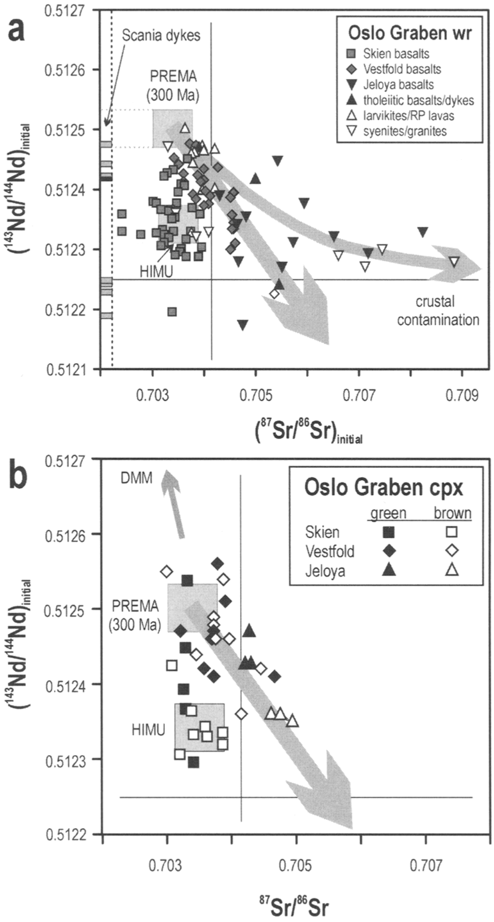

Fig. 10. **(a)** Initial Nd-Sr isotopic ratios for magmatic rocks in the Oslo Region. Data from Anthony *et al.* (1989), Neumann *et al.* (1988*b*, 2002), Dunworth *et al.* (2001) and Dunworth (unpublished data 2002). PREMA: the prevalent mantle source of Stein & Hofmann (1994) recalculated to 300 Ma ago. Initial Nd isotope ratios for Scania dykes (data from Obst *et al.* 2004) are shown along the left-hand side of the diagram; black symbol: highly alkaline dyke; *grey symbols*: subalkaline dykes. **(b)** Initial Nd–Sr isotopic ratios for leached clinopyroxene separates from B_1 basalts in the Oslo Graben. Green and brown clinopyroxenes represent Mg-rich diopside cores (commonly resorbed) and relatively Mg-poor Ti-augite overgrowths, respectively, in zoned clinopyroxene phenocrysts (Dunworth *et al.* 2001; Dunworth & Neumann unpublished data). The solid lines represent the Bulk Earth composition.

contribution from an enriched lithospheric mantle source. The dispersion of many of the Jeløya samples to more radiogenic $^{87}Sr/^{86}Sr$ ratios than 0.705 in Figure 10a may also be a consequence of partial alteration, as these data were obtained on unleached whole-rock samples (Neumann *et al.* 2002). This is confirmed by the much more homogeneous array of isotopic compositions measured for leached clinopyroxene mineral separates from the B1 basalts in the Skien, Vestfold and Jeløya areas (Fig. 10b) (Dunworth *et al.* 2001; Neumann *et al.* 2002). The isotopic compositions of the most highly alkaline lavas in the Oslo Graben, from the lower part of the Skien B1 sequence, are distinctive, with low $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotope ratios, indicating the involvement of a mantle source component that does not appear to be involved in the petrogenesis of any of the other magmatic rocks in the province (Anthony *et al.* 1989; Dunworth *et al.* 2001) (Fig. 10). The Skien mantle source component has some affinity to the HIMU mantle end-member observed in oceanic island basalts (HIMU = 'High μ', where $\mu = {}^{238}U/{}^{204}Pb$) (Hofmann 1997; Dunworth *et al.* 2001). This component could be a distinct sub-lithospheric mantle source, or it might be associated with metasomatic enrichment in the lithospheric mantle, for example associated with the emplacement of the nearby Fen carbonatite complex at *c.* 580 Ma (Andersen 1987 and references therein). The location of the PREMA mantle source will be considered further below.

Volume estimates

The data presented in Figure 6 may superficially suggest that basaltic rocks are the most abundant magmatic rock type in the Oslo Graben. This is not, however, true. The largest volumes are made up by shallow intrusions of trachyandesitic–rhyolitic compositions (larvikites, syenites and granites; Fig. 6) emplaced during Rift stages 2 and 4 (Table 2). On the basis of surface exposures and gravity data, Ramberg (1976) estimated the total volume of extrusive and intrusive magmatic rocks in the Oslo Graben to be *c.* 28 000 km^3 (Fig. 4, Table 2), of which basaltic rocks make up about 6%, rocks of intermediate composition (trachyandesites in Fig. 6) 44%, and syenitic–granitic rocks (trachytes and rhyolites in Fig. 6) about 50%.

However, in the Oslo Graben, the original volumes of surface and subsurface magmatism were clearly considerably larger than that seen today. Fission track studies indicate that post-Permian erosion amounts to some 3–4 km (Rohrman *et al.* 1994). The lavas presently exposed in fault blocks along the graben floor are thus only remnants of a much larger lava cover. Carboniferous–Permian dykes in the Precambrian shield east and west of the Oslo–Skagerrak Graben (Fig. 4) indicate that magmatism involved a much wider area than the main graben system where magmatic rocks are still preserved. Breccias and conglomerates in some islands along the eastern part of the Oslo fjord show transport directions from the Precambrian terrain to the east. Based on such considerations, Ramberg (1976) suggested that the original lava volume might have been 25 000–30 000 km^3, or about 100 times the presently exposed volume of about 300 km^3. This means that the total volume of magmas extruded at the surface and emplaced into magma chambers in the shallow crust in the Oslo Graben may have been at least twice that remaining today, or in the order of 60 000 km^3 (Table 2).

Significant volumes of magma are also likely to have been intruded in the deep crust beneath the graben. The high proportion of rocks of intermediate–highly evolved composition (Table 2) highlights the role of intra-crustal magmatic differentiation of the primitive, mantle-derived parental magmas accompanied by variable amounts of crustal contamination. On the basis of the available Sr–Nd isotope data (Fig. 10), the amount of crustal involvement in the petrogenesis of the magma seems to have been relatively minor. Starting with a mantle-derived basaltic parent magma, about 50–90% fractional crystallization is required to produce melts of intermediate–rhyolitic composition, implying that 50–90% of the initial melt is left somewhere in the crust as dense, high-seismic-velocity cumulates dominated by olivine and clinopyroxene. The large gravity anomaly and relatively high seismic velocities in the lower crust along the Oslo–Skagerrak Graben (Fig. 3) have been interpreted in terms of large masses of dense, high-velocity cumulates deposited in deep magma chambers during the Carboniferous–Permian magmatic event (e.g. Ramberg 1976; Neumann *et al.* 1988*a*, 1992 and references therein). The presence of cumulates in the deep crust is also supported by the presence of olivine–clinopyroxenite xenoliths with cumulate textures in an alkaline basalt at Krokskogen. Microthermometry analyses of CO_2 inclusions in clinopyroxene in these xenoliths indicate pressures of origin of 0.55–0.60 GPa, or a depth of >16–17 km, implying formation in deep-crustal magma chambers (Neumann *et al.*

1988*a*). Neumann (1994) estimated the total volume of cumulates formed through the crystallization processes that gave rise to the intermediate–evolved magmatic rocks exposed at the surface of the Oslo Graben to be about 65 000 km^3 (Table 2). In addition, there may be unknown volumes of deep-seated gabbroic intrusions in the crust beneath the Oslo–Skagerrak Graben. The total volume of magma involved in the Oslo Region may thus have been 120 000 km^3 or more (Table 2).

The volume of magmatic rocks in the offshore Skagerrak Graben is unknown. The main graben covers an area of about 40 × 100 km^2. The presence of a *c.* 1 km-thick layer of basaltic lava flows, proposed by Heeremans *et al.* (2004) on the basis of seismic reflection profiles across the graben, gives a total lava volume of 4 000 km^3 (Table 2). This is small compared to the known volumes of magmatic rocks in the Oslo Graben. However, the positive gravity anomaly along the Oslo–Skagerrak Graben system is stronger within the Skagerrak Graben than along the Oslo Graben (Fig. 3). This suggests that there may be much larger volumes of dense cumulates in the deep crust beneath the Skagerrak Graben than beneath the Oslo Graben.

The Scania and Bornholm dyke swarms

Tectono-magmatic evolution and age relationships

Scania, in the southernmost part of Sweden (Figs 1 and 2), is cut by a NW–SE- to WNW–ESE-trending regional dyke swarm dominated by tholeiitic dolerite dykes, following the Sorgenfrei–Tornquist Zone (e.g. Obst 1999; Obst *et al.* 2004). Ar–Ar age determinations range between 284.7 ± 2.2 and 273.6 ± 1.5 Ma (M. J. Timmerman unpublished data 2001) (Table 1). These samples are, however, partially altered and therefore the Ar–Ar ages may be too young. Basaltic rocks retrieved from wells (Terne-1, Hans-1) in the Kattegat, which sample the offshore NW continuation of the Scania dyke swarm (Fig. 2), have yielded K–Ar ages of 227 and 300 Ma (Aghabawa 1993). Obst *et al.* (2004) consider that the dyke swarm was emplaced between 290 and 300 Ma.

A series of Carboniferous–Permian dykes is also exposed along the northern and western coast of the island of Bornholm, SE of Scania (Fig. 2). Most of the dykes trend NNE–SSW to NNW–SSE, with N–S as the dominant strike (Obst 2000; Obst *et al.* 2004). Bornholm is located where the Sorgenfrei–Tornquist Zone is offset to the south by the Rönne Graben, and continues southwards as the Tornquist–Teisseyre Zone (Figs. 1 and 2). The dykes in Bornholm are believed to be genetically related to the offset area (Obst 2000).

Major-and trace-element chemistry

The dyke swarm in Scania comprises three chemical types or series (Fig. 6c): basanites–foidites (highly alkaline dykes), subalkaline (tholeiitic) dolerites and tephrites–trachyandesites (locally termed kullaites; Obst 1999; Obst *et al.* 2004). The tephrites and trachyandesites fall on a common trend with the highly alkaline basaltic dykes, suggesting a genetic relationship between these two groups, controlled by crystal–liquid differentiation processes. Subalkaline (tholeiitic) dolerite dykes are by far most common. The magmatic rocks sampled in the Kattegat wells also belong to the tholeiitic group (Fig. 6c) (Aghabawa 1993).

Like the 'highly alkaline OG lavas', the 'highly alkaline Scania dykes' show marked enrichment in strongly incompatible elements relative to moderately incompatible elements (e.g. $La_N = 96–184$; $Lu_N = 5.2–7.6$), and marked positive Nb–Ta and negative Zr–Hf anomalies (Fig. 11). However, in contrast to the 'highly alkaline OG group', they also show depletion in Ti relative to the adjacent REE. As the 'highly alkaline Scania dykes' are relatively MgO-rich (7.0–10.3 wt%), it seems likely that, like the negative Zr–Hf anomaly, the negative Ti anomaly is a primary melt feature rather than the result of crystallization of Fe–Ti oxides. The 'subalkaline Scania dykes' show weakly to moderately enriched trace-element patterns (e.g. $La_N = 20–70$; $Lu_N = 4.6–10.5$) with weak positive Nb–Ta anomalies, but no Zr–Hf anomalies. In Figures 8 and 9 the 'highly alkaline Scania dykes' overlap with the 'highly alkaline OG group', whereas the 'subalkaline Scania dykes' form trends from the high $(Zr/Nd)_N$ end of the OIB field towards the SENC field (Fig. 8), and from the E-MORB field within the mantle array towards the field of destructive plate boundaries (Fig. 9), strongly suggesting the involvement of a depleted mantle component and a crustal component in their petrogenesis.

Sm–Nd isotope data are available for seven subalkaline basalts and one alkaline dyke (Obst *et al.* 2004). The tholeiitic dykes show a range in initial $^{143}Nd/^{144}Nd$ ratios from 0.51248 to 0.51219 (Fig. 10). The most depleted Nd isotope compositions (highest $^{143}Nd/^{144}Nd$) are similar

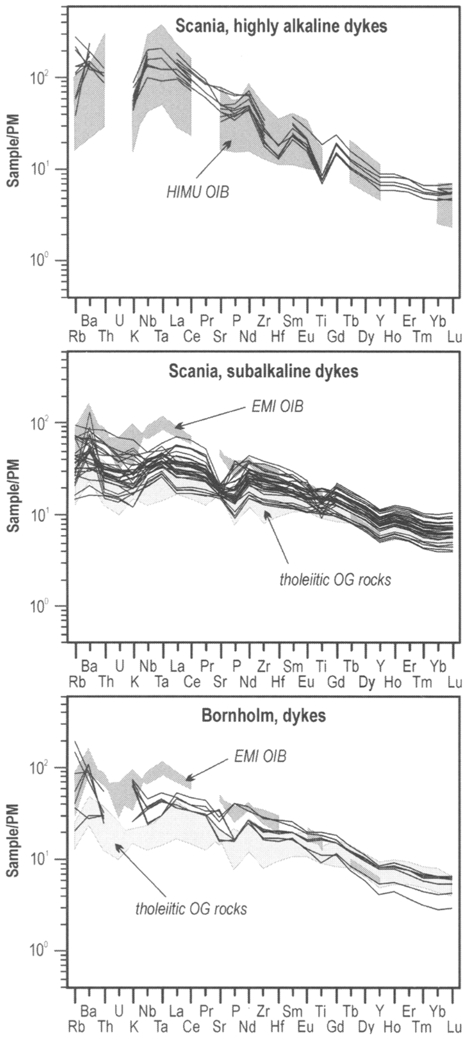

Fig. 11. Trace-element concentrations in mafic dykes in Scania and Bornholm (data from Obst 1999, 2000; Obst *et al.* 2004; M. J. Timmerman unpublished data), normalized to the primordial mantle (PM) as defined by McDonough & Sun (1995). The fields of 'highly alkaline lavas' and 'tholeiitic lavas and dykes' in the Oslo Graben (Fig. 8), HIMU and EMI OIB are shown for comparison. References to HIMU OIB, EMI OIB and N-MORB are given in the text of Figure 7. Like highly alkaline OG lavas, the highly alkaline Scania dykes show a clear affinity to HIMU OIB lavas. The subalkaline Scania dykes cover a range in incompatible trace-element concentrations, with moderate LREE/HREE ratios. Depletion in Ti relative to MREE among the most REE-rich dykes is clearly the result of fractional crystallization. Strong enrichment in Ba relative to Th and Rb in many dykes may be due to alteration or crustal contamination. The trace-element patterns of the Bornholm dykes are similar to those of the subalkaline Scania dykes.

to those found among the magmatic rocks in the Oslo Region (≈ 0.5125; Fig. 10). Samples with high initial Nd isotope ratios fall in, or close to, the mantle fields (MORB-OIB) in Figures 8 and 9, whereas those with low initial Nd isotope ratios mainly fall towards the crustal fields. The Nd isotope data thus support the trace-element indications of a crustal component.

The Bornholm dykes are mildly alkaline basalts and trachybasalts (Fig. 6c), but the suite also includes rare trachytic types (Obst 2000). The basaltic *sensu lato* dykes are markedly enriched in the most highly incompatible elements relative to the moderately incompatible elements (e.g. $La_N = 35–51$; $Y_N = 2.8–6.2$; Fig. 11). They show a tendency for depletion in Nb–Ta relative to LREE, and have no Zr–Hf anomalies. In Figure 8 they form a trend that suggests crustal contamination.

Volume estimates

The Scania dyke swarm occupies a *c.* 70 km-wide belt within the Sorgenfrei–Tornquist Zone. Single dykes range from a few metres to 100 m thick, and may be followed for up to 50 km along strike (e.g. Obst 1999). During Carboniferous–Permian times the Sorgenfrei–Tornquist Zone responded to NE–SW extension, and it is believed that the emplacement of the Scania and Bornholm dykes primarily were controlled by subparallel fractures along the Sorgenfrei–Tornquist Zone (e.g. Erlström *et al.* 1997). The total volume of the dykes is estimated to be about 4000 km^3 on the basis of available aeromagnetic data (Henkel & Sundin 1979) (Table 2). As indicated above, the dyke complex is dominated by subalkaline basaltic rock types; Obst (unpublished data) estimates that these account for 90–95% of the total volume, with some 5–10% being equally divided between highly alkaline basaltic and trachytic dykes (Table 2). The cumulate width of the Scania dykes indicates an extension in the crust increasing from about 0.6% in the SE part, to about 2.5% in the NW part of the dyke swarm. Together with the gravity high beneath the NW part, this suggests a possible centre of magma emplacement off the NW coast of Scania (Obst 1999; Obst *et al.* 2004).

The position of the positive gravity maximum above the postulated centre of magma emplacement in Scania supports a close relationship between the two, as proposed by Thybo (1997). It thus seems highly likely that the Scania dyke swarm is associated with significant magmatic underplating and/or deep crustal intrusions.

The total volume of dykes on Bornholm has not been estimated, but it is clearly considerably smaller than that of the Scania dykes. The distribution of rock types appears to be similar to that in Scania (Obst unpublished data). The local high over Bornholm on the gravity map of the Kattegat–Scania area (Fig. 3) suggests that this dyke swarm is also associated with magmatic underplating or intrusions in the deep crust.

The North Sea

Tectono-magmatic evolution and age relationships

Carboniferous–Permian lavas have also been recovered in drill cores collected from different parts of the North Sea (Figs 1 and 2). Lavas in the Central Graben give Ar–Ar ages of 299 ± 3 and 296 ± 10 Ma, whereas those in the Horn Graben give ages of 260–280 Ma, thus appearing to be somewhat younger (Heeremans *et al.* 2004*b* and references therein) (Table 1). Rifting in the North Sea seems to have started almost simultaneously with the extrusion of the first basalts; the tectono-magmatic setting is discussed in more detail in Heeremans *et al.* (2004*b*).

Major- and trace-element chemistry

The North Sea lavas show a wide compositional range and a close relationship between different compositional types and geographical location (Aghabawa 1993; Heeremans *et al.* 2004*b*) (Fig. 6d). In the Central Graben, the lava are dominated by mildly alkaline trachybasalts–tephrites/basanites, but also include highly alkaline tephrites–tephriphonolites, as well as a few subalkaline basalts. Lavas recovered in wells L-1 and D-1 east of the Central Graben (Figs 1 and 2) cover a restricted range of subalkaline–tholeiitic basalts. Lavas in the Horn Graben are mainly rhyolitic, but a few subalkaline basalts are also present; wells in the southern Danish sector of the North Sea have primarily penetrated dacitic lavas.

The limited trace-element data available (Aghabawa 1993; Heeremans *et al.* 2004*b*) indicate a range in compositions from depleted to moderately enriched in strongly incompatible elements relative to moderately incompatible elements (e.g. $\mathrm{La_N} = 6$–187; $\mathrm{Y_N} = 3.4$–10), and strong enrichment in Ba relative to Rb and Th (Fig. 12). There does not appear to be any general difference in trace-element chemistry between magmatic rocks in the Central and Horn grabens. Sufficient trace-element data to construct relatively complete trace-element patterns are only available for tholeiitic lavas from the Central Graben (Heeremans *et al.* 2004*b*)

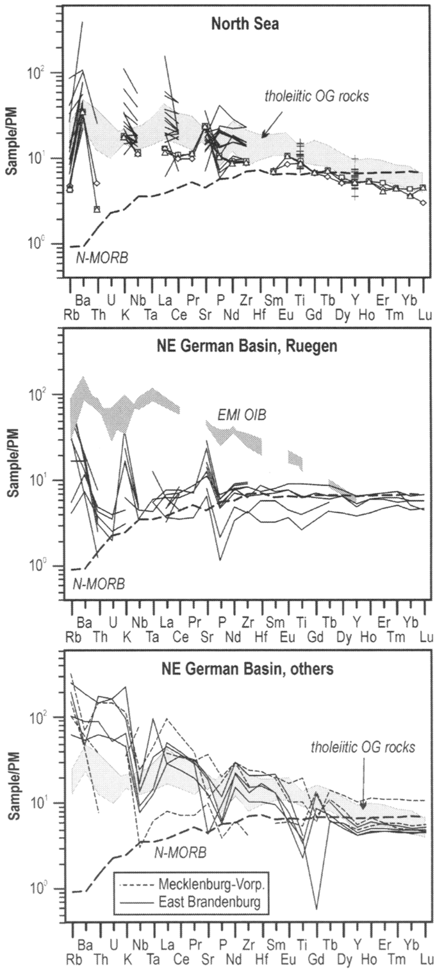

Fig. 12. Trace-element concentrations in mafic dykes in the North Sea (Aghabawa 1993), and mafic lavas in the NE German Basin (Benek *et al.* 1996; Heeremans *et al.* 2004*b*), normalized to the primordial mantle (PM) as defined by McDonough & Sun (1995). The fields of 'tholeiitic lavas and dykes' in the Oslo Graben (Fig. 8), EMI OIB and N-MORB are shown for comparison. References to EMI OIB and N-MORB are given in the text of Figure 7. The three North Sea lavas, for which almost complete data sets are available, show trace-element patterns that closely resemble those of tholeiitic Oslo Graben rocks. The most depleted rocks discussed here are the Ruegen lavas that show an affinity to N-MORB for all elements except Rb, Ba, K and Sr, which are highly enriched relative to the other incompatible trace elements; this may be the result of alteration or crustal contamination. Lavas from Mecklenburg–Vorpommern and East Brandenburg are highly enriched in the most incompatible trace elements relative to moderately incompatible elements, and are, in general, depleted in Nb–Ta relative to LREE. This clearly reflects a crustal component.

(Fig. 12). With the exception of positive K and Sr anomalies, these patterns resemble those obtained for the tholeiitic rocks in the Oslo Graben. In Figures 8 and 9 the North Sea basalts fall along a crustal contamination trend which, in Figure 8, appears to originate in the MORB field at the least enriched end of the OIB field. The relative enrichment in Ba and scatter of data points in Figure 9 may be due to mobilization of these elements during alteration processes.

Volume estimates

The most extensive lava sequences in the Central Graben are more than 500 m thick (Marx 1994). No attempts, however, have been made to estimate the volumes of the magmatic rocks. Gravity and refraction seismic data are not available to make conclusions about the deep-crustal structure.

The NE German Basin

Tectono-magmatic evolution and age relationships

The NE German Basin is part of a series of related basins extending from the North Sea into Poland and the Netherlands (Fig. 1). Volcanism was widespread, but the thickness of the lava sequences varies considerably across the area. The total thickness of extrusive rocks, as indicated by borehole cores, reaches a maximum of >2500 m south of Ruegen, 2360 m in Mecklenburg–Vorpommern in East Brandenburg, but only 200–500 m up to a maximum of 1000 m thick in East Brandenburg (Marx 1994; Benek *et al.* 1996 and references therein). Data on sedimentation and magmatism in different parts of the NE German Basin are available through a large number of well cores. SHRIMP zircon ages indicate that the magmatic activity in the NE German Basin was concentrated within a relatively short time-span of 302 ± 3 to 294 ± 11 Ma (Table 1), during the early part of basin development (Breitkreuz & Kennedy 1999). Benek *et al.* (1996) recognized five eruptive stages: (I) a Late Carboniferous (Stephanian) andesitic pre-ignimbrite stage; (II) a Permian (Lower Rotliegendes) explosive ignimbrite stage; (III) a post-ignimbrite stage; (IV) a late rhyolitic stage; and, after a hiatus, (V) a Permian (Upper Rotliegendes) late basalt stage.

Major- and trace-element chemistry

Geochemical data for magmatic rocks in the NE German Basin are available for Ruegen island in the Baltic Sea, Mecklenburg–Vorpommern, East Brandenburg, Altmark, Niedersachsen and Emsland (Figs 1 and 2) (Marx 1994; Benek *et al.* 1996). The NE German Basin contains a wide variety of rock types, ranging from strongly alkaline to tholeiitic mafic rocks, to evolved trachytic, dacitic and rhyolitic rocks (Fig. 6e, f). According to Benek *et al.* (1996), and references therein, the magmatic rocks exhibit different degrees of post-magmatic alteration. It is, therefore, likely that some of the scatter in, for example, ($Na_2O + K_2O$) relative to SiO_2 seen in Figure 6e, f is due to alteration. However, there also appear to be systematic differences between magmatic series from the different areas that are preserved despite post-magmatic processes. In Ruegen the volcanism consists of subalkaline–transitional basalts (Fig. 6e). The Mecklenburg–Vorpommern volcanism is dominated by rhyolites low in alkalis, whereas the few analyses available for East Brandenburg show a wide range in compositions. A series of highly alkaline basalts together with a single rhyolite have been recovered in East Altmark, whereas the western part of Altmark shows a wide range in compositions dominated by andesites, dacites, and subalkaline trachytes and rhyolites. The Niedersachsen and Emsland areas further to the west (Fig. 2) are dominated by evolved magmatic rocks, mainly mildly alkaline–subalkaline basaltic trachyandesites and trachyandesites (Fig. 6f).

In Figure 12 we show PM-normalized trace-element patterns for rocks claimed by Benek *et al.* (1996) to represent samples that have suffered a minimum of alteration. The Ruegen lavas exhibit strong enrichment in Rb, Ba, K and Sr relative to other highly incompatible elements, and depletion in LREE relative to middle and heavy REE (MREE and HREE; e.g. $La_N = 3–8$; $Y_N = 5–7$; Fig. 12). Mafic lavas from Mecklenburg–Vorpommern and East Brandenburg are generally enriched in highly incompatible elements relative to mildly incompatible elements (e.g. $La_N = 8–97$; $Y_N = 4.4–10.7$), and show marked negative Nb–Ta and Ti anomalies. Using a much larger data set, Benek *et al.* (1996) found that, with the exception of basaltic rocks from Ruegen, depletion in Nb, Ta and Ti relative to other strongly incompatible trace elements is a common feature of the mafic lavas in the NE German Basin.

Strong enrichment in Rb, Ba, K and Sr relative to other highly incompatible elements, as found among the Ruegen lavas, is typical of sea-water alteration (e.g. Hart 1970; Jochum & Verma 1996). Disregarding these elements, Benek *et al.* (1996) concluded that the Ruegen lavas resemble normal MORB (N-MORB) from the Red Sea. However, N-MORB melts very rarely penetrate continental crust. In Figure 8 all mafic lavas from the NE German Basin, including the Ruegen lavas, fall outside the OIB and MORB fields, forming a trend towards crustal compositions. In Figure 9, the Ruegen lavas, with one exception, plot towards the depleted end of the mantle array within the MORB field. The other mafic lavas from the NE German Basin fall well within the field of destructive plate margins in Figure 9. The highest degree of crustal interaction is found among the East Brandenburg samples from the east-central part of the NE German Basin. The positive Rb–Ba, K and Sr anomalies exhibited by the Ruegen lavas are most probably linked to low-temperature alteration; however, they could also be caused by subduction-related fluid enrichment of their mantle source.

Volume estimates

The total volume of volcanic rocks in the NE German Basin is estimated to be *c.* 48 000 km^3, of which *c.* 70% are rhyolites and ignimbrites, *c.* 26% are andesitic rocks, and about 4% basalts and dolerites (Benek *et al.* 1996). Like the magmatism in the Oslo Graben, that in the NE German Basin is dominated by rocks of intermediate–highly evolved compositions. This implies the existence of dense cumulates, or dense residues after partial melting situated within the crust. Detailed petrological models similar to those developed for the evolved rocks in the Oslo Graben, or isotopic data that give information about the source rocks, are not available for the magmatism in the NE German Basin. We have therefore made no attempts to estimate the volume of deep crustal rocks in this area. However, it seems highly likely that the high-density, high-velocity layer in the deep crust beneath the central part of the NE German Basin represents magmatic underplating (Rabbel *et al.* 1995) and/or dense residues after partial melting in the crust.

Chemical characteristics of mantle and crustal sources

In previous sections we have demonstrated that there are significant differences in the geochemical characteristics of the Carboniferous–Permian basaltic lava and dyke series discussed above. Some differences in trace-element ratios may be induced through different degrees of partial melting. Low degrees of partial melting are expected to produce highly alkaline melts with relatively low $(Zr/Nd)_N$ and $(Nb/Ce)_N$, and high Ta/Yb and Th/Yb, ratios, whereas high degrees of partial melting produces tholeiitic magmas with relatively high $(Zr/Nd)_N$ and $(Nb/Ce)_N$, and low Ta/Yb and Th/Yb, ratios. However, in the Oslo Graben it is very difficult to associate the differences in trace-element characteristics observed among the mafic lavas with different degrees of partial melting. The 'highly alkaline' and 'alkaline' groups are both very voluminous relative to the 'tholeiitic group' (see above), suggesting significantly larger amounts of magma production. This is supported by much larger positive gravity anomalies over the southern than over the northern part of the Oslo Graben (Fig. 3). Furthermore, there is a shift in initial Sr–Nd isotope ratios from the highly alkaline B1 basalts at the base of the Skien lava series (Fig. 10), to the mildly alkaline basalts, RP lavas and larvikites that make up the major volumes of mafic–intermediate magmatic rocks in the Oslo Graben (Table 2). We therefore consider that the observed contrasts in trace-element characteristics among the basaltic rocks in the Oslo Graben reflect the involvement of different mantle source components in the petrogenesis of the parental mafic magmas; in addition, the parental magmas may locally have experienced crustal contamination during their storage in crustal magma chambers. The importance of local heterogeneities within both the crustal and mantle parts of the lithosphere in fingerprinting the geochemical characteristics of the mafic magmas is strongly supported by the clear correlation between their trace-element characteristics and geographical location.

The strong enrichment in highly incompatible elements relative to moderately incompatible elements, and positive anomalies (or no anomalies) in Nb and Ta exhibited by many of the Carboniferous–Permian basaltic rock series discussed here (Figs 7, 11 and 12), are typical of alkaline intra-plate magmas (e.g. Weaver 1991; $[Nb/Ce]_N \geq 1.0$ and $La_N/Nb_N \leq 1.0$). The range of trace-element ratios characteristic of basaltic lavas erupted in modern-day ocean islands (OIB) is shown in Figures 8 and 9 for comparison with the available data for the Carboniferous–Permian basalts. OIB are extruded on relatively young oceanic lithosphere and are not, therefore, influenced by continental crustal contamination, nor are their mantle sources typically modified by subduction processes. Similar trace-element characteristics in continental basalts to those of OIB are often used as an argument in support of their derivation from sublithospheric mantle sources.

When groups of basaltic rocks occupy different positions within the OIB trace-element field (Figs 8 and 9) this may suggest either derivation from mantle sources with different geochemical characteristics, the influence of different melting processes/mantle source mineralogies and/or different degrees of partial melting of inhomogeneous sources. It should be stressed, however, that the OIB field shown in Figures 8 and 9 does not include all known ocean island basalts; some mantle components may lie outside the OIB field plotted in Figures 8 and 9. We cannot exclude the possibility that mantle sources may exist that are unique to the petrogenesis of continental basalts, which reside, for example, within old continental lithospheric mantle.

The degree of light REE (LREE) enrichment (e.g. the La_N/Lu_N ratio) is positively correlated with the degree of incompatible trace-element enrichment in the mantle source, and negatively correlated with the degree of partial melting. Furthermore, elements with similar mineral/melt distribution coefficients for mantle–melt systems (elements that plot close to one another in Figs 7, 11 and 12; e.g. Nb/Ce, Zr/Nd) are not significantly fractionated relative to one another during partial melting processes or by moderate degrees of fractional crystallization. When basaltic magmas exhibit significantly different ratios between such elements, this is therefore strong evidence that they are derived from different mantle sources. Furthermore, OIB with Sr–Nd–Pb isotope compositions believed to represent different mantle source components also have different trace-element signatures, resulting in different trace-element ratios (e.g. Weaver 1991). Mafic lavas extruded in purely oceanic settings (OIB and MORB), and thus unaffected by continental rocks, are characterized by $(Nb/Ce)_N \geq 1.0$ (Fig. 8). MORB and OIB define a distinctive array in a plot of Th/Yb v. Ta/Yb (Fig. 9) consistent with increasing enrichment of the mantle source from MORB to OIB. Crustal contamination and subduction-related processes (which transfer the signature of subducted crustal components to the mantle lithosphere) are typically reflected in negative Nb anomalies in mantle-normalized trace-element plots (e.g. Pearce 1982) resulting in $(Nb/Ce)_N$ ratios significantly below unity, and significantly higher Th/Yb than Ta/Yb ratios, as exhibited by the SE Norwegian crustal rocks (SENC in Fig. 8) and the field of destructive plate margin basalts in Figure 9.

The Carboniferous–Permian basaltic rocks from southern Scandinavia, the North Sea and the NE German Basin plot: (i) inside the OIB field; (ii) between the OIB and continental crustal fields; or (iii) within the continental crust or destructive plate margin basalt fields (Figs 8 and 9). The geochemical characteristics of the parental magmas of types (ii) and (iii) are believed to be influenced by crustal components, either through crustal contamination or through interaction with mantle lithosphere that has been metasomatically enriched by subduction-related processes. The importance of crustal components appears to increase from Scandinavia to the central part of the NE German Basin.

A large proportion of the 'highly alkaline' and the 'mildly alkaline OG groups' and the 'highly alkaline Scania dykes' fall within the OIB field, and appear to have suffered only minor crustal contamination. Subalkaline–tholeiitic rocks in the Oslo Graben, Scania and the North Sea, as well as the mildly alkaline dykes from Bornholm, plot between the high-$(Zr/Nd)_N$ end of the OIB field and the SENC field in Figure 8. In Figure 9 these rocks fall outside the OIB field towards the depleted (MORB) end of the mantle array. They plot in the general area of the average lower continental crust (LC), and fall partly inside, partly to the high-Th/Yb side of the 'mantle array'. The Ruegen lavas have significantly lower $(Nb/Ce)_N$, Th/Yb and Ta/Yb ratios than the other subalkaline–tholeiitic lavas, suggesting derivation from a more depleted mantle source combined with crustal contamination. This suggests significant interaction with crustal components in all these rocks. Basaltic rocks from Mecklenburg–Vorpommern and East Brandenburg in the central part of the NE German Basin plot between the OIB and SENC fields or within the SENC field in Figure 8, and well within the field of subduction-related lavas in Figure 9, thus showing the strongest evidence of crustal interaction among the rocks discussed here.

There are significant compositional contrasts among the rocks that plot within the OIB field in Figures 8 and 9 (e.g. different $(Zr/Nd)_N$, Th/Yb and Ta/Yb ratios). The 'highly alkaline rocks' in the Oslo Graben and Scania are characterized by $(Zr/Nd)_N < 0.63$; the 'mildly alkaline OG group' has intermediate ratios; while the 'subalkaline Scania dykes' have $(Zr/Nd)_N \approx 1.0$, similar to N-MORB (Fig. 8), implying derivation from mantle sources with different geochemical characteristics. This is supported by the crustal contamination trends defined by the different rock groups in Figure 8. The 'highly alkaline OG group' that, together with the 'highly alkaline Scania dykes', has the most enriched trace-element compositions (highest $[Nb/Ce]_N$ and $[Zr/Nd]_N$ ratios) defines a trend from the central part of the OIB field towards the SENC field. The 'tholeiitic OG group', together with basaltic rocks from Bornholm, the North Sea and Ruegen, defines trends from the area of the highest, almost MORB-like, $(Zr/Nd)_N$ ratios within the OIB field. The Mecklenburg–Vorpommern and East Brandenburg lavas may lie on an intermediate trend.

On the basis of the above, at least two distinct mantle sources appear to be involved in the Carboniferous–Permian magmatism in the general area of southern Scandinavia, the North Sea and northern Germany. These are: (a) a mantle source strongly enriched in incompatible trace elements involved in the petrogenesis of the highly alkaline magmatism in the Oslo Graben (Skien) and Scania; and (b) a mildly enriched mantle source, isotopically similar to PREMA, which is involved in the petrogenesis of the mildly alkaline–subalkaline magmatism in the Oslo Graben, Scania, Bornholm and the North Sea. A third, highly depleted source component similar to the source of MORB is required to explain the geochemical characteristics of the most depleted tholeiites (e.g. Ruegen). The conclusion that the formation of the highly alkaline and the mildly alkaline basalt groups in the Oslo Graben basalts involved two mantle sources with different geochemical characteristics is in complete agreement with the conclusions based on Sr–Nd–Pb isotopic evidence (Anthony *et al.* 1989; Dunworth *et al.* 2001) (Fig. 10).

The mantle source of the highly alkaline magmatism

Trace-element characteristics similar to those of the oldest part of the 'highly alkaline OG group' and the 'highly alkaline Scania dykes' (high La_N/Lu_N; relatively high $[Nb/Ce]_N$ and low $[Zr/Nd]_N$ ratios; Figs 7–9, 11 and 12) resemble those of recent HIMU OIB (Weaver 1991), which must have inherited these characteristics from their mantle source. It is worth noticing, however, that these rocks are more strongly depleted in Zr–Hf relative to REE than HIMU OIB. It is difficult to tell if they are isotopically similar to HIMU as we have few constraints on the parent–daughter ratios of the HIMU mantle end-member, which are required to calculate the isotopic characteristics of HIMU at 300 Ma. HIMU has been considered to represent an ancient recycled subducted oceanic crustal component within the convecting mantle (e.g. Hofmann 1997 and references therein). However, similar trace-element characteristics are frequently observed in lithospheric mantle xenoliths entrained within both continental and oceanic alkali basalts, and have been considered by some authors to represent the signature of mantle metasomatized by carbonatitic fluids and melts (e.g. Green & Wallace 1988; Hauri *et al.* 1993). In the context of the tectonomagmatic evolution of the Oslo Graben, it seems likely that the highly alkaline basalts formed from a lithospheric mantle source that had a previous history of carbonatite metasomatism. There is also evidence for lithospheric metasomatism as a precursor to the Permo-Carboniferous magmatism in Scotland (Upton *et al.* 1999, 2001).

Detailed studies of clinopyroxene phenocrysts and xenocrysts, and their melt inclusions, from the 'highly alkaline OG lavas' in the Skien area have shown that magma generation processes were extremely complex (Dunworth *et al.* 2001; Kirstein *et al.* 2002). Zoning in the studied clinopyroxenes reflects multiple generations of crystal growth in different chemical environments. Their trace-element and Sr–Nd isotopic compositions imply that during ascent the magmas that crystallized the pyroxenes experienced varying degrees of fractional crystallization, mixing between evolved and mafic magma batches, and crustal contamination in magma chambers in the deep–middle crust (Dunworth *et al.* 2001; Neumann *et al.* 2002). Melt inclusions trapped at different stages of pyroxene growth show a change in the types of trapped melts. The oldest inclusions, trapped in the central parts of phenocrysts, are of two types: one type represents low-degree partial melts formed from fertile peridotite in the spinel stability field, at about 1 GPa (in the upper part of the lithospheric mantle); the other consist of melts formed within the garnet stability field (Kirstein *et al.* 2002). Towards the outer parts of the phenocrysts the melts generated in the garnet stability field become dominant, and show differentiation through fractional crystallization of clinopyroxene and olivine during the migration of these melts to the surface. We interpret the earliest melt inclusions as a combination of melts formed in the main mantle source, and melts formed in metasomatized, relatively shallow, parts of the lithospheric mantle. A higher content of volatiles in the metasomatized shallow lithospheric mantle than in the deeper parts might cause contemporaneous melting at different depths. With time the shallow lithospheric mantle became exhausted in the easily melted, metasomatic components, and melts from the main source became dominant.

The mantle source(s) of the mildly alkaline and tholeiitic magmatism

The 'mildly alkaline OG group' (the majority of the basaltic rocks in the Oslo Graben, including B1-basalts in Vestfold and Jeløya; Fig. 4) and the parental magmas of most of the evolved Oslo Graben rocks (e.g. rhomb porphyry lavas and larvikites) were derived from a mantle source moderately enriched in incompatible trace elements (Figs 7, 11 and 12), and with a Nd–Sr isotopic signature resembling that of PREMA at 300 Ma (Fig. 10) (Stein & Hofmann 1994; Dunworth *et al.* 2001). The limited Nd isotope and trace-element data available (Obst *et al.* 2004) suggest that a similar mantle source component may have also contributed to the highly alkaline magmatism in Scania. The tholeiitic OG group and the subalkaline Scania dykes require the involvement of a more depleted mantle source component combined with crustal contamination that has significantly affected the isotopic compositions and trace element signatures in many of these rocks (Figs 8–11). The Bornholm dykes and the North Sea basalts also require a depleted source component in their petrogenesis. The basaltic rocks from Ruegen appear to be derived from an even more strongly depleted source component similar to MORB-source mantle; Nd–Sr isotope data are needed to evaluate this possibility.

Crustal components

The majority of the Carboniferous–Permian magmatic rocks within the province show some evidence for the involvement of crustal components in their petrogenesis (Figs 8–12). These components appear to be least significant in the Oslo Graben and Scania, and to increase southwards into the NE German Basin. As pointed out by Benek *et al.* (1996), all the lavas in Mecklenburg–Vorpommern and East Brandenburg have trace-element characteristics typical of extensive crustal contamination or derivation from subduction-modified mantle sources. It should be recognized, however, that the crust in Germany is not likely to be identical to that in SE Norway. It is therefore impossible to make quantitative estimates of the extent of crustal influence on basaltic rocks in the NE German Basin. Benek *et al.* (1996) proposed that crustal contamination increases from the outer parts towards the centre of the NE German Basin. Our research reveals an even more extensive pattern of southwards increase in the importance of crustal contamination in the petrogenesis of the Carboniferous–Permian magmas from the external to the more internal parts of the Variscan Orogen.

The subduction-like trace-element characteristics of the lavas in Mecklenburg–Vorpommern and East Brandenburg (Fig. 12) are clearly at variance with their Permo-Carboniferous intraplate tectonic setting. Crustal contamination cannot be excluded, but it should be noticed that, if this has taken place, the contaminant was much more enriched in K and REE relative to Nb than estimated averages for the continental crust (e.g. Weaver 1991; Rudnick & Fountain 1995). Benek *et al.* (1996) associate the geochemistry of the magmatic rocks in the NE German Basin with their position relative to the Variscan foredeep and the Rhenohercynian orogenic zone (Fig. 2), implying the presence of pre-existing subduction-modified lithospheric mantle in the area. The lithospheric mantle may have been locally metasomatized by subduction-related fluids during the Variscan orogeny. In this context it is significant that the East Brandenburg lavas that exhibit the strongest evidence of crustal contamination lie behind the North Variscan Deformation Front (Fig. 2).

The magmatic rocks in the Oslo Graben and the subalkaline dykes in Scania and the North Sea also have trace-element and Nd–Sr isotopic compositions that show the influence of crustal components (Figs 8–10). Scania and the southern–central Oslo region lie outside the Caledonian Deformation Front, suggesting that the crustal component seen in these rocks is due to contamination by the continental crust rather than subduction-modified lithospheric mantle. In the Oslo region the trace-element characteristics of the magmas are compatible with different degrees of contamination by crustal rocks chemically similar to 1.67–2.05 Ga-old amphibolite–granulite facies rocks now exposed in the Bamble sector, south of the Oslo Graben (Knudsen *et al.* 1997; Knudsen & Andersen 1999; Neumann *et al.* 2002); Sr–Nd isotopic ratios suggest that crustal components are involved that exhibit both moderate and strong enrichment in radiogenic Sr combined with low Nd isotopic ratios (Fig. 10). The highest initial $^{87}Sr/^{86}Sr$ ratios are seen in shallow syenitic and granitic intrusions emplaced during the later part of the magmatic period (Figs 5 and 10). We believe these rocks to have suffered significant contamination in the shallow crust. The moderately high initial Sr isotopic ratios combined with low initial Nd ratios (Fig. 10) observed in many rocks of mafic–intermediate composition are believed to reflect contamination in the deep crust. Among the basaltic rocks in the Oslo Graben, the tholeiitic B1 lava at Krokskogen and the tholeiitic dykes appear to be the most strongly contaminated (Figs 8–10); crustal contamination makes it difficult to identify the isotopic characteristics of the mantle source of the primary magmas.

The North Sea lies inside the Caledonian Deformation Front (Fig. 2), and therefore it is difficult to evaluate if these rocks have suffered crustal contamination or have inherited a subduction-related component from the lithospheric mantle.

Location of the mantle sources

The simultaneous onset of magmatism and tectonic activity at about 305 Ma over a large area within northern Europe strongly suggests a common triggering mechanism. This mechanism is most probably an extension of the lithosphere north of the Variscan Front (e.g. Ziegler 1990, 1992 and references therein). Pascal *et al.* (2003) propose that the voluminous magmatism associated with highly localized rifting that took place along the Oslo–Skagerrak Graben is a response to stretching and decompression in an area of rapidly changing lithosphere thickness at the margin of the Baltic Shield. Similarly, Obst *et al.* (2004) explain the geographical location and trend of the Scania dykes as the result of decreasing crustal and lithospheric thicknesses from the Baltic Shield towards the SW. Variations in lithospheric thickness, physical properties and geochemical characteristics are likely to contribute significantly to regional variations in the intensity of Carboniferous–Permian magmatic activity within southern Scandinavia, the North Sea and the NE German Basin (Fig. 1, Table 2).

The lithospheric thinning model of Pascal *et al.* (2004) suggests that melt generation in the Oslo Graben could have initiated within 2–3 Ma of the onset of rifting by decompression melting of the base of the lithosphere and within the underlying convecting mantle (asthenosphere) at relatively high stretching rates of 5–8 cm year^{-1}. Their model assumes a normal mantle potential temperature, T_p, of 1300 °C, and that both the mantle lithosphere and asthenosphere were essentially dry (anhydrous). Unfortunately, because of the nature of the numerical simulation, Pascal *et al.* (2004) had to terminate their model runs just before the onset of partial melting. They suggest, however, that for a small additional increment of strain violent decompression of the base of the lithosphere could occur, locally explaining the generation of high-degree partial melts (e.g. Krokskogen tholeiites) early in the rift history. Decreasing strain rates after the initial rift phase could account for the return to smaller degrees of partial melting (basanites, alkali basalts). Their model predicts significant differential stretching between the mantle and the crust in the first 1 Ma of rifting with the mantle part of the lithosphere thinning by 50–65% while the crust thins by 25–35%.

As indicated above, there is strong geochemical evidence that at least two mantle source components were involved in generating the parental mafic magmas within the geographically restricted area of the southern Oslo Graben (Fig. 1). Partial melts of a highly enriched source component, with HIMU OIB-like trace-element characteristics, gave way progressively to more PREMA-like magmas with time. Available trace-element data also suggest that two distinct mantle source components were involved in the generation of the highly alkaline and the subalkaline Scania dykes (Fig. 10). We suggest that the highly enriched component resides within the lithosphere, whereas the more depleted component resides within the convecting mantle. It thus seems likely that the asthenospheric mantle beneath southern Scandinavia had PREMA-like characteristics, whereas the HIMU component represents a localized zone of enriched mantle within the lithospheric mantle beneath the southern Oslo Graben. We consider it likely that the HIMU-like source component is the product of local metasomatic enrichment by migrating carbonatite fluids in the earliest Palaeozoic (*c.* 600 Ma). If the HIMU mantle was more volatile-rich than the PREMA mantle it would be the first part of the system to partially melt, accounting for the early eruption of the Skien basalts in the Oslo Graben. As the HIMU mantle component was progressively exhausted, melting became dominated by the PREMA-like mantle component.

The lithosphere beneath the NE German Basin appears to be dominated by subduction-related chemical components that contribute significantly to magma generation processes; the involvement of a PREMA-like asthenospheric component is also permitted by the data.

The above discussion implies that the observed differences in geochemical characteristics within the Carboniferous–Permian magmatic provinces in southern Scandinavia, the North Sea and northern Germany primarily reflect partial melting processes spanning the lithosphere–asthenosphere boundary and chemical differences between parts of the lithospheric mantle with different evolutionary histories. It is highly unlikely that the dominant magma source resides within the lithosphere; the degree of lithospheric extension indicated by both geolo-

Province	Location / stage	Magma type	Age (Ma)	Volume (km^3)	Melt source
Oslo Graben	Stage 1 - Initial rifting	B1 tholeiite (N)	305-299	120 000?	
		B1 highly alkaline-mildly alkaline bas. (S)			HIMU-PREMA
	Stage 2 - Main rifting period	RP lavas Larvikitic intr.	299-292		PREMA
	Stage 3 - Central volcanoes	Basanite-trachytes-rhyolites	280-243		
	Stage 4 - Composite batholiths	Trachytes-rhyolites	273-241		
Skagerrak Graben				4000?	
Scania	Dykes	Highly alkaline basalts	294-274	4000	PREMA
		Subalkaline basalts Trachyandesites-trach.			
Bornholm	Dykes	Mildly alk. basalts			PREMA?
North Sea	Central Graben	Mildly alk. trachybasalts	299-280		
	Horn Graben	Subalkaline basalts Rhyolites	284-260		
S Denmark		Dacites			
NE German Basin	Ruegen	Subalk. basalts	302-294	48 000	Lithospheric mantle w. subduction-related composition
	E Altmark	Strongly alk. basanites			
	Altmark	Trachybas.-andesite-rhyolite			
	Niedersachsen	Highly alk.-thol. basalts-rhyolites			
	Emsland	Basanites-dacites			

Fig. 13. A summary of the magma types, periods of magmatism, estimated volumes of magmatic rocks and melt sources in the different magmatic provinces discussed in this paper.

gical and geophysical data seems insufficient to produce the enormous volume of magma estimated to have been generated beneath the Oslo Graben (> 120 000 km^3). An unresolved problem, however, concerns the origin and location of the PREMA component. PREMA (or analogue mantle components) is a common source component in OIB petrogenesis; this provides some of the strongest support that a mantle plume might have been involved in triggering the widespread Carboniferous–Permian magmatism within northern Europe. An important question, therefore, is whether there is any evidence for the existence of late Carboniferous mantle plume upwelling beneath the base of the lithosphere. Ernst & Buchan (1997) proposed that the *c.* 300 Ma-old dyke swarms in NE England and the Scottish Midland Valley (Upton *et al.* 2004; Wilson *et al.* 2004), the Oslo Graben and Scania, radiate from a triple junction in the northernmost part of Jutland, Denmark, and that this triple junction marked the axis of a deep-mantle plume centred in this area. At present, insufficient geochemical data are available to test this hypothesis properly.

Summary

A summary of magma types, duration of magmatism, estimated volumes of magmatic rocks and magma sources in the main magmatic provinces in an area extending from southern Scandinavia, through the North Sea, into northern Germany is given in Figure 13. The magmatism covers a wide range in rock types both on a regional and a local scale (from highly alkaline to tholeiitic basalts to trachytes and rhyolites). The most intensive magmatism took place in the Oslo Graben (possibly > 120 000 km^3) and in the NE German Basin (48 000 km^3). In both these areas a large proportion of the magmatic rocks are highly evolved (trachytes–rhyolites).

The magmatism appears to have started approximately contemporaneously about 300 Ma ago in the different areas. In the Oslo Region available Rb–Sr age determinations suggest that magma generation may have continued until about 240 Ma. However, there is evidence from U–Pb age determinations that the Rb–Sr method may give ages that are too young and that the duration of the main magmatic phase was considerably shorter. More age determinations by the U–Pb method are clearly needed, both in the Oslo Graben and elsewhere in the area.

Trace-element and limited Sr–Nd isotope data imply that at least three mantle components were involved in the petrogenesis of the magmas. The oldest basaltic lavas in the southern Oslo Graben appear to have been derived from a HIMU-like enriched mantle source. This source is believed to be located in the lithospheric mantle and to be the result of metasomatism by carbonatitic melts, possibly associated with the Fen carbonatite event about 580 Ma ago. The main mantle source for the magmatism in the Oslo Graben, Scania and possibly the North Sea was PREMA-like. The location and origin of this source component is somewhat equivocal. It may represent the general composition of the base of the lithospheric mantle and the asthenosphere beneath this area, which partially melted in response to localized thinning of the lithosphere due to regional extension north of the Variscan Front. An alternative scenario involves a mantle plume with PREMA-like characteristics actively upwelling beneath the lithosphere in the Late Carboniferous. The numerical model of Pascal *et al.* (2003) does not require a thermal anomaly within the convecting mantle in order to initiate partial melting, although it does not preclude one. If a mantle plume was involved, therefore, there is no requirement that it was substantially hotter than ambient mantle.

In northern Germany the mafic magmatic rocks exhibit the strong geochemical fingerprint of a crustal component. This component is most likely to be located within a lower part of the lithospheric mantle metasomatically enriched by subduction-related fluids during the Variscan orogeny. The contribution of this crustal component increases southwards within the NE German Basin. In all the magmatic provinces many of the magmatic rocks have also suffered crustal contaminations, a consequence of the assimilation of local crustal rocks.

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