Permo-Carboniferous magmatism and rifting in Europe: introduction

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An extensive rift system developed within the northern foreland of the Variscan orogenic belt during Late Carboniferous–Early Permian times, post-dating the Devonian–Early Carboniferous accretion of various Neoproterozoic Gondwana-derived terranes on to the southern margin of Laurussia (Laurentia–Baltica; Fig. 1). Rifting was associated with widespread magmatism and with a fundamental change, at the Westphalian–Stephanian boundary, in the regional stress field affecting western and central Europe (Ziegler 1990; Ziegler & Cloetingh 2003). The change in regional stress patterns was coincident with the termination of orogenic activity in the Variscan fold belt, followed by major dextral translation between North Africa and Europe.

Rifting propagated across a collage of basement terranes with different ages and thermal histories. Whilst most of the Carboniferous–Permian rift basins of NW Europe developed on relatively thin lithosphere, the highly magmatic Oslo Graben in southern Norway initiated within the thick, stable and, presumably, strong (cold) lithosphere of the Fennoscandian craton. The rift basins in the North Sea, in contrast, developed in younger Caledonian age lithosphere, which was both thinner and warmer than the lithosphere of the craton to the east.

A regional hiatus, corresponding to the Early Stephanian, is evident in much of the Variscan foreland, with Stephanian and Early Permian red beds unconformably overlying truncated Westphalian series (e.g. McCann 1996) (Fig. 2). Regional uplift coincides with the onset of voluminous magmatism across the region, raising the possibility that uplift could have been related to the presence of a widespread thermal anomaly within the upper mantle (i.e. a mantle plume or, possibly, several plumes). In detail, however, it is likely that uplift was induced by a complex combination of wrench-related lithospheric deformation, magmatic inflation of the lithosphere and thermal erosion of the base of the lithosphere (van Wees *et al.* 2000).

Stephanian–Early Permian (Autunian) wrench tectonics affected not only the Variscan foreland, but also the entire Variscan Orogen (Fig. 1). Within the orogen wrench faulting and associated magmatism were probably accompanied by detachment of subducted lithospheric slabs and partial delamination of thickened lithospheric roots (Ziegler 1990). Magmatic underplating of the base of the crust by ascending mafic magmas is likely to have been widespread (e.g. Downes 1993), providing the heat for partial melting of lower-crustal rocks. Available seismic reflection data provide strong support for such underplating of the crust. The presence of extensive ignimbrite sequences within parts of the North German Basin may be directly attributable to crustal melting induced in this way (e.g. Breitkreuz & Kennedy 1999).

Following the termination of wrench tectonics in the late Autunian two major intra-

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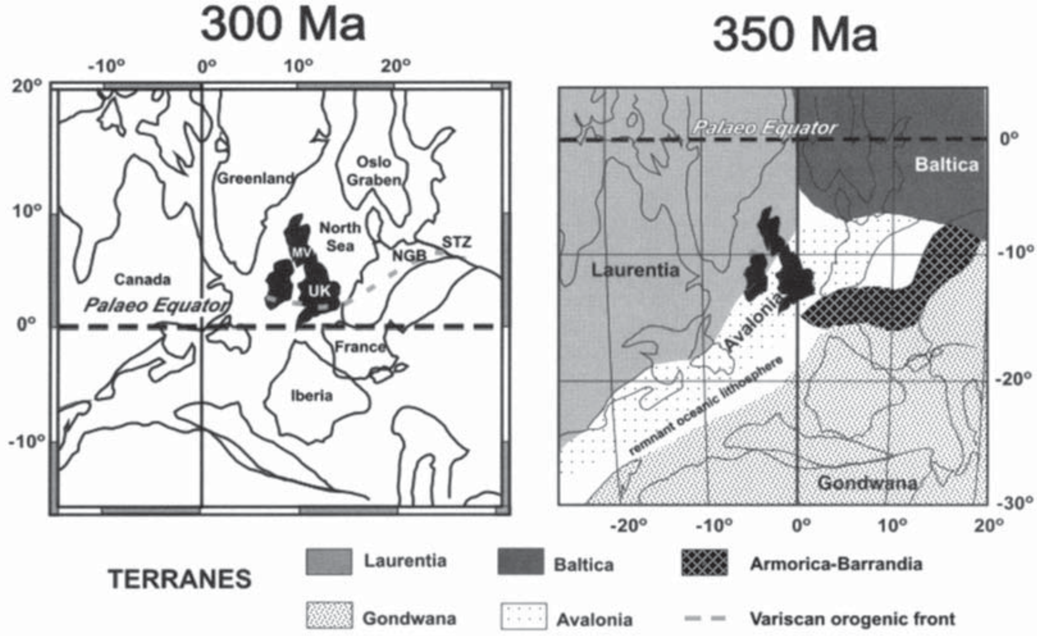

Fig. 1. Plate tectonic reconstructions for the Variscan belt and its foreland between 350 and 300 Ma, indicating the locations of the major basement terranes. Significant northward drift occurred during this period (Torsvik 1998). Plate reconstructions were made using PGIS/Mac (©2000 PALEOMAP project; http://www.paleomap.com). Terrane boundaries are based on Pharaoh (1999) and Banka *et al.* (2002). Avalonia was accreted in the latest Ordovician, while the various components of the Armorica–Barrandia terrane were accreted during Devonian and Carboniferous times, climaxing in the Variscan orogeny. Abbreviations: STZ, Sorgenfrei–Tornquist Zone; NGB, North German Basin; MV, Midland Valley of Scotland.

continental sedimentary basins, generally referred to as the Northern and Southern Permian basins, began to subside within western and central Europe in response to thermal contraction of the lithosphere (e.g. Ziegler 1990; van Wees *et al.* 2000). The Northern Permian Basin extends over 1000 km in an E–W direction from Scotland, across the central North Sea into northern Denmark; the much larger Southern Permian Basin extends over a distance of 1700 km from England, across the southern North Sea and through northern Germany into Poland and the Baltic States. Both the Northern and Southern Permian basins initiated as broad crustal downwarps with little associated faulting. They developed within a mosaic of basement terranes of different ages and geodynamic histories, their geometries apparently showing little evidence of control by pre-existing basement structures (van Wees *et al.* 2000). The western parts of the Northern Permian Basin are located on Caledonian crust, while the eastern parts developed on Late Precambrian crust. The Southern Permian Basin subsided in the foreland of the Variscan orogenic belt, extending across the orogenic front in its eastern part. The intensity of the preceding Stephanian–Autunian phase of lithospheric destabilization may have exerted a first-order control on the subsequent subsidence history of the two basins (van Wees *et al.* 2000).

Whilst on a regional scale the Stephanian–early Permian magmatic event appears the most significant, locally it was pre-dated by a Visean magmatic phase (e.g. in the Midland Valley of Scotland, Wales, English Midlands, Central Ireland, SW England and the Baltic Sea; Fig. 2), which may have had a different geodynamic setting. This magmatism was contemporaneous with the later stages of a 45 Ma period of Late Devonian–Early Carboniferous (375–330 Ma) tholeiitic flood basalt volcanism in the Maritimes Basin of eastern Canada, which has been inferred to be plume-related (Dessureau *et al.* 2000). Dessereau *et al.* (2000) have suggested that plume-related magmatic activity may have gradually migrated eastwards during Late Devonian–Permian times, from the Maritimes Basin through Scotland to Norway and northern Germany. Plate tectonic reconstructions

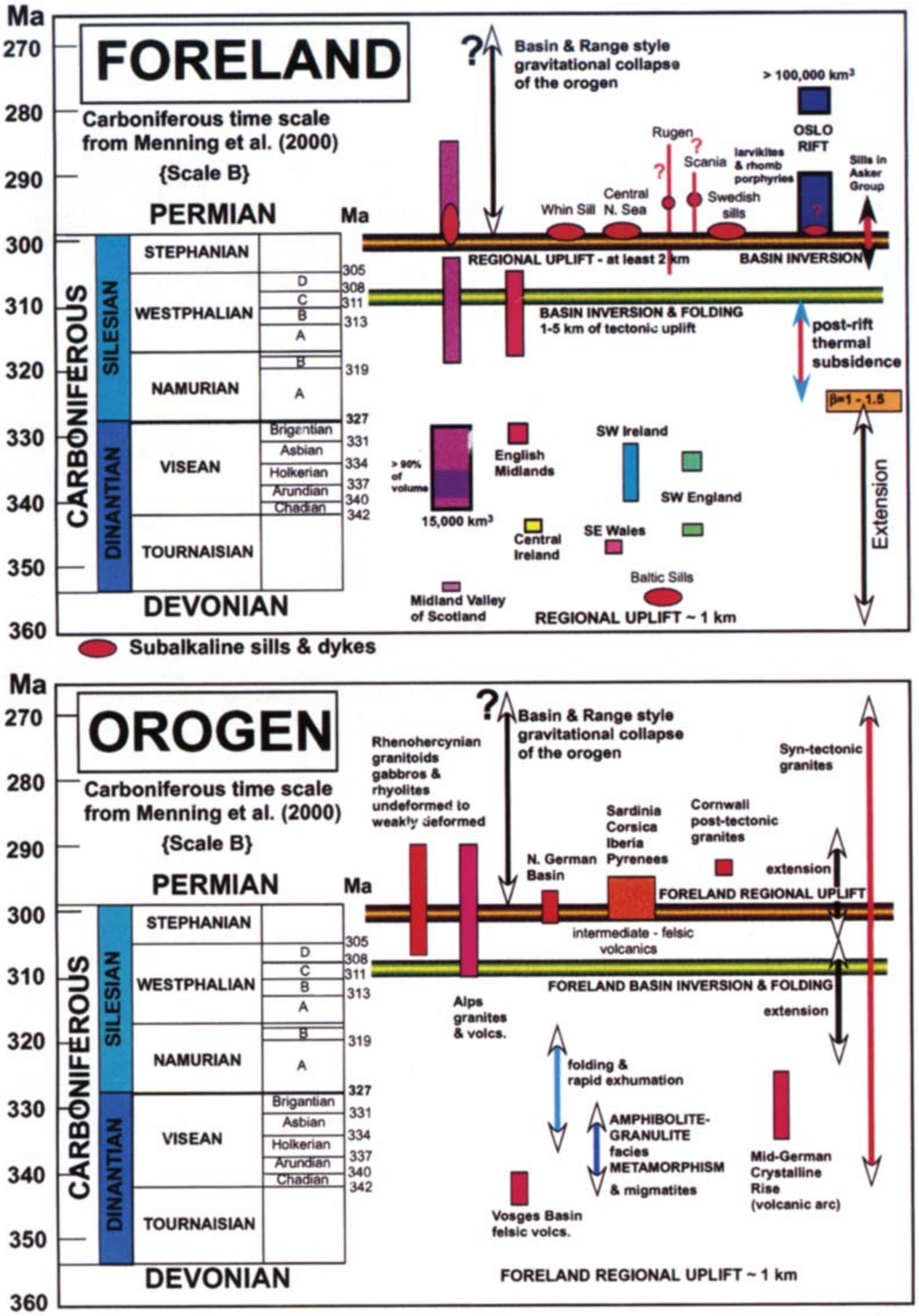

Fig. 2. Relative timing of Permo-Carboniferous magmatism, extensional tectonics, basin inversion and regional uplift within the Variscan orogenic belt and its northern foreland. Data have been compiled from all of the papers within this volume, and the timescale used is from Menning *et al.* (2000).

(Fig. 1), however, suggest that there was rapid northward plate motion during the Carboniferous which, when combined with the end-Carboniferous phase of wrench tectonics, makes it difficult to constrain potential hot-spot tracks. Consequently, such a hypothesis remains highly speculative.

The PCR Project

Many of the contributions to this volume represent the results of research conducted as part of a multi-disciplinary research project 'Permo-Carboniferous Rifting in Europe' or 'PCR' funded by the European Commission between 1997 and 2001. The aim of the PCR project was to further our understanding of the geodynamics of Carboniferous–Permian rifting and associated magmatism within the northern foreland of the Variscan orogenic belt. As part of the project we have produced a new Late Carboniferous–Permian tectono-magmatic map of NW Europe, based mainly on seismic and well data.

The main objectives of the PCR project were to:

- Determine the relationship between the onset of magmatism, regional uplift and extensional tectonics.
- Constrain, by high-quality Ar–Ar and U–Pb zircon dating, the chronology of magmatic events within the province.
- Assess the role of thermally anomalous mantle (i.e a mantle plume or superplume) in the petrogenesis of the magmas and to evaluate the excess mantle temperature via geochemical, He–Ne–Ar and Sr–Nd–Pb isotopic studies of the most primitive mafic magmas erupted within the province.
- Describe the onset and magnitude of uplift and thermal subsidence across the area, in order to evaluate the magnitude of any thermal pulse.
- Develop rheological models to understand the thermo-mechanical controls on rift development, magmatism and subsequent crustal evolution.
- Integrate petrological–geochemical data with both onshore and offshore geophysical (seismic, gravity, magnetic) and geological data to understand the dynamics of the Carboniferous–Permian rifting and its associated magmatism.
- Understand the thermal evolution of the lithosphere in the northern foreland of the Variscan Orogen during Carboniferous–Permian times.

Geochemical studies of the magmatic rocks were aimed at addressing the following fundamental questions:

- What was the nature of the mantle source of the magmas – lithosphere or asthenosphere?
- Was there one (or more) mantle plumes beneath Europe during Late Carboniferous–Early Permian times?
- How did variations in the age and thickness of the lithosphere influence the magmatism?
- How did the magmas interact with the lithosphere during migration from source to surface?

Although the main emphasis of PCR was on the northern foreland of the Variscan orogenic belt, petrological–geochemical studies were also conducted of post-collisional magmatic rocks within the orogen (principally in Iberia and central France). The aim of these studies was to investigate which parts of the mantle (i.e. lithosphere, depleted sublithospheric mantle, enriched sublithospheric mantle) generated magmas in the inner part of the Variscan Orogen during Carboniferous–Permian times and to evaluate if there are any similarities with the source of magmas of the same age from the foreland areas in northern Europe.

What is the relationship between Carboniferous–Permian magmatism and rifting in Europe?

The chapters included in this volume are broadly arranged in a geographical context, focusing on different aspects of this fundamental question. Emphasis initially is on the orogenic foreland in the UK, Scandinavia and the North Sea; subsequent chapters include discussions of the changing style of magmatism as the orogenic front is crossed in Germany and Poland, and within more internal parts of the orogen in France and the Iberian peninsula.

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. **Neumann *et al.*** demonstrate that 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. Peak magmatic activity was concentrated in a narrow time-span from *c.* 300 to *c.* 280 Ma. The magmatic provinces developed within basement terranes of different ages and lithospheric characteristics (including thickness) brought together during the preceding Variscan orogeny. This suggests that the magmatism may represent the local expression of a common tectono-magmatic event with a common causal mechanism.

Timmerman reviews the timing, geodynamic setting and characteristics of Early Carboniferous–Permian magmatism in the foreland of the Variscan Orogen in NW Europe. During the Early Carboniferous, final closure of the Rhenohercynian Ocean, accretion of a magmatic arc and docking of microcontinents caused fault reactivation, extension and fault-controlled basin subsidence in the foreland. Lithospheric stretching locally resulted in eruption of mildly alkaline basaltic volcanism that peaked in the Visean (Fig. 2). In the internal Variscides, rapid uplift and granitoid plutonism shortly followed continental collision and was probably due to slab detachment(s) or removal of orogenic root material.

A regional-scale, E–W-oriented stress field was superimposed on the collapsing orogen and its foreland from the Westphalian onwards. In the Stephanian–Early Permian, a combination of outward propagating collapse, mantle or slab detachment, and the regional stress field resulted in widespread formation of fault-controlled basins and extensive magmatism dated at 290–305 Ma. In the foreland, large amounts of felsic volcanic rocks erupted in northern Germany, accompanied by mafic–felsic volcanics and intrusions in the Oslo Rift, and dolerite sills and dyke swarms in Britain and Sweden. In the internal Variscides, mafic rocks are rare and felsic–intermediate compositions predominate; typically, these have a distinctive subduction-related trace-element geochemical signature that may have been inherited from partial melting of subduction-modified (metasomatized) lithospheric–asthenospheric mantle sources and/or caused by extensive assimilation of continental crust by mafic mantle-derived magmas.

Latest Carboniferous–earliest Permian doleritic dykes, sills and flows from Britain to Scandinavia yield ages in the range 295–305 Ma (Fig. 2), confirming that the magmatism was broadly coeval with voluminous rhyolitic–andesitic volcanism in the North German Basin (*c.* 302–297 Ma based on U–Pb zircon ages; Breitkreutz & Kennedy 1999). Younger, 270–285 Ma, crystallization ages obtained for post-tectonic dykes and sills in Scotland and Norway indicate that magmatic activity, although small in volume and different in composition (alkaline), continued into the Permian. Latest Permian–earliest Triassic ages (*c.* 240–245 Ma) for syenitic–granitic intrusions in the northwestern and eastern parts of the Oslo Rift probably reflect a separate magmatic event of limited extent and duration.

One of the goals of the PCR project was to produce a new map of northern Europe (**Heeremans *et al.***) showing the distribution of Late Carboniferous–Early Permian (Lower Rotliegend) volcanics, dykes and sills, and the pattern of faulting associated with the Southern and Northern Permian basins. Production of this map required an overview of all the available seismic and borehole data, including unpublished data provided by our industrial partners.

Praeg investigates models of orogenic collapse involving diachronous tectonism in which crustal uplift and extension are compensated by peripheral compression. He tests first-order predictions against published data on late-orogenic extensional and compressive structures along a 1500 km-transect from the Variscan central internides in France to the foreland in the Irish Sea area. The collapse of the Variscan Orogen is shown to have expanded northward over time, via three main stages:

- *collapse of the central internides* (late Visean–mid-Westphalian, *c.* 335–310 Ma);
- *reorientation and expansion of collapse* (mid-Westphalian–late Stephanian, *c.* 310–300 Ma);
- *collapse of the foreland* (late Stephanian–Early Permian, *c.* 300–290 Ma).

These three stages are argued to support a model of Variscan late-orogenic collapse in response to three successive detachments of negatively buoyant lithospheric material: a collisionally thickened orogenic root and two (Rheic) oceanic slabs, subducted, respectively, southward (beneath the orogen) and northward (beneath the foreland). Multiple detachments are a predictable consequence of ocean closure and continental collision, so that episodic collapse may be a common process in the rise and fall of orogenic belts, and the tectonic evolution of their forelands.

Pascal *et al.* use finite-element modelling to investigate the role of changing lithospheric thickness as a first-order control on the localization of major rifts such as the Oslo Graben and the focusing of magmatic activity. Compared to other Permo-Carboniferous rift basins within NW Europe, the Oslo Graben has two distinct characteristics. First, it initiated inside cold and stable Precambrian lithosphere, whereas most of the Permo-Carboniferous basins developed in weaker Phanerozoic lithosphere, and, second, it is characterized by large volumes of magmatic rocks despite relatively little extension. The Oslo Graben appears to have evolved at the transition between two lithospheric domains with contrasting thickness. Seismic reflection surveys show that the crust thickens from southern Norway to southern Sweden, the most significant Moho deepening occurring from the Oslo region eastwards. Deep seismic studies also suggest that the base of the lithosphere deepens markedly eastwards from the Oslo region. Such a long-wavelength lithospheric geometry cannot be explained by the Permian or post-Permian evolution of the area. Numerical thermo-mechanical modelling is applied to test if this transitional position can influence the dynamics of rifting and facilitate melting of the mantle. Different models with varying lithosphere thickness contrast are considered; those with a crust and lithosphere thickness contrast comparable to that of the Oslo region predict rifting and focusing of magmatism in a narrow zone with minor thinning of the crust.

Heeremans & Faleide and **Heeremans *et al.*** discuss the relationship between magmatism and rifting in the Skagerrak, Kattegat and North Sea. Special attention is paid to the distribution of intrusive and extrusive magmatic rocks in relation to fault geometries, based upon an extensive database of industrial seismic and well data. Rift structures (with characteristic half-graben geometries) and the distribution of magmatic rocks (intrusives and extrusives) were mapped using seismic and potential field data. In the Sorgenfrei–Tornquist Zone and the North Sea additional constraints are provided by well data. The rift structures in the Skagerrak, which represents the offshore continuation of the Oslo Graben, can be linked with extensional structures in the Sorgenfrei–Tornquist Zone in which similar fault geometries are observed. Both in the Skagerrak and the Kattegat, lava sequences were deposited that generally parallel the underlying Lower Palaeozoic strata. This volcanic episode, therefore, pre-dates the main fault movements and the development of half-grabens filled with Permian volcaniclastic material. Upper Carboniferous–Lower Permian extrusives and intrusives have been penetrated in wells in the Kattegat, Jutland and the North Sea (Horn and Central grabens). Particularly in the latter area, the dense seismic and well coverage permits detailed mapping of the distribution of Upper Palaeozoic magmatic rocks, although the presence of salt often conceals the seismic image of the underlying strata and structures.

The Carboniferous–Permian evolution of the central North Sea is characterized by three main geological events: (1) the development of the West European Carboniferous Basin; (2) a period of basaltic volcanism during the Lower Rotliegend (latest Carboniferous–early Permian); and (3) the development of the Northern and Southern Permian basins in Late Permian times. The timing of the Late Carboniferous–Permian basaltic volcanism in the North Sea is poorly constrained, as is the timing of extensional tectonic activity following the main phase of inversion during the Westphalian (Fig. 2) due to the propagation of the Variscan deformation front. Results of high-precision Ar–Ar dating on basalt samples taken from a core from exploration well 39/2–4 (Amerada Hess), in the UK sector of the central North Sea, suggests that basaltic volcanism was active in the Late Carboniferous, at *c.* 299 Ma. The presence of volcanics below the dated horizon suggests that the onset of Permo-Carboniferous volcanism in the central North Sea commenced earlier, probably at *c.* 310 Ma (Westphalian C). This is contemporaneous with observations of tholeiitic volcanism elsewhere in NW Europe, including the Oslo Graben, the NE German Basin, southern Sweden and Scotland. Interpretations of available seismic data show that the main extensional faulting occurred after the volcanic activity, but the exact age of the fault activity is difficult to constrain with the data available.

Extensional tectonics to the north of the Variscan front during the Early Carboniferous generated fault-controlled basins across the British Isles, with accompanying basaltic magmatism (Fig. 2). **Upton *et al.*** demonstrate that in Scotland Dinantian magmatism was dominantly of mildly alkaline–transitional basaltic composition. Tournaisian activity was followed by widespread Visean eruptions, largely concentrated within the Scottish Midland Valley where the lava successions, dominantly of basaltic–hawaiitic composition, attained thicknesses of up to 1000 m. Changing stress fields in the late Visean coincided with a change in the nature of the igneous activity; subsequently, wholly basic magmatism persisted into the Silesian. As sedimentary basin fills increased, sill intrusion tended to dominate over lava extrusion. In the Late Carboniferous (Stephanian) a major melting episode, producing large volumes of tholeiitic magma, gave rise to a major dyke swarm and sills across northern England and Scotland. Alkali basaltic magmatism persisted into the Permian, possibly until as late as 250 Ma in Orkney. Geochemical data suggest that the Carboniferous–Permian magmas were dominantly of asthenospheric origin, derived from variable degrees of partial melting of a heterogeneous mantle source; varying degrees of interaction with the lithosphere are indicated. Peridotite, pyroxenite and granulites-facies metabasic rocks entrained as xenoliths within the most primitive magmas provide evidence for metasomatism of the lithospheric mantle and high-pressure crystal fractionation.

Monaghan & Pringle report new $^{40}Ar/^{39}Ar$ step-heating age determinations on mineral separates from intrusive and extrusive Carboniferous and Permian igneous rocks in the Midland Valley of Scotland. These ages resolve inconsistencies between existing K–Ar dates on the same samples and stratigraphical constraints correlated to recently published timescales. Twenty-one precise $^{40}Ar/^{39}Ar$ dates are stratigraphically constrained to stage level and contribute important new Carboniferous timescale tie points at the Tournaisian–Visean boundary, within the Visean and at the Carboniferous–Permian boundary. Two distinct phases of extension-related transitional to alkaline volcanism are recognized in the Dinantian: the Garleton Hills Volcanic Formation in the eastern Midland Valley near the Tournaisian–Visean boundary at *c.* 342 Ma and the Clyde Plateau Volcanic Formation in the western Midland Valley during the mid Visean (335–329 Ma). Alkaline basic sills near Edinburgh, previously thought to be Namurian, appear to be coeval with the Clyde Plateau Volcanic Formation at *c.* 332–329 Ma. The new ages allow correlation between these short-lived Dinantian magmatic pulses and extensional and magmatic phases in the Northumberland–Solway and Tweed basins further to the south. After a phase of late Westphalian compression (Fig. 2) and the regionally important tholeiitic intrusive phase at *c.* 301–295 Ma, alkaline magmatism related to post-Variscan extension occurred in the central and western Midland Valley until at least 292 Ma.

Kirstein *et al.* present the results of a noble gas isotope study of well-characterized spinel peridotite facies lithospheric mantle xenoliths and garnet megacrysts entrained within Scottish Permo-Carboniferous dykes, sills and vents in an attempt to evaluate whether a high $^{3}He/^{4}He$ lower-mantle plume could have been involved in the petrogenesis of the host magmas. The samples were collected from the Northern Highland and the Midland Valley basement terranes, which vary from Archaean–Proterozoic to Proterozoic–Palaeozoic in age. The He isotope data suggest that the mantle lithosphere beneath Scotland during the late Palaeozoic had experienced time-integrated U–Th enrichment. This enriched mantle was preferentially melted following the transition from early Palaeozoic compression to late Palaeozoic extensional tectonics. The helium isotope data provide no evidence for the presence of primordial plume-type mantle beneath this part of Scotland during the late Carboniferous–early Permian.

Permo-Carboniferous rifting in Europe was accompanied by the widespread emplacement of mantle-derived magmas in regional dyke swarms and sills in northern England, Scotland, Norway and southern Sweden during the late Stephanian and early Permian (Autunian). **Obst *et al.*** note that the regional trends of the dyke swarms intersect at a focal point in the Kattegat south of the Oslo Graben, and suggest that the dykes could all emanate from a single magmatic centre. They show that the WNW- to NW-trending dyke swarm at the SW margin of the Fennoscandian Shield in southern Sweden is composed mainly of tholeiitic dolerites, with lesser amounts of alkaline mafic rocks (camptonites, alkali basalts and spessartites) and trachytes. The alkaline mafic rocks are enriched in Ba, Sr, Nb, P and CO_2, implying a metasomatic enrichment of their upper mantle source prior to melting. After generation of alkaline melts by relatively small degrees of partial melting, increased extension was accompanied by the formation of subalkaline tholeiitic magmas. Two groups of tholeiitic dolerites can be distinguished that exhibit slight differences in their mantle-normalized trace-element patterns and Nb/La ratios, suggesting that they were generated from different mantle sources. Group I dolerites appear to have been formed from a sublithospheric garnet-bearing mantle source, whereas group II dolerites were formed by mixing of asthenosphere-derived magmas with lithospheric partial melts.

Ziegler *et al.* consider the post-Variscan evolution of the lithosphere in the Rhine Graben area of central Germany based on subsidence modelling. The Cenozoic Rhine Graben rift system transects the deeply truncated Variscan Orogen with its superimposed system of Permo-Carboniferous wrench-induced troughs, and Late Permian and Mesozoic thermal sag basins. Ziegler *et al.* propose that at the time of its Westphalian consolidation, the Variscan Orogen was probably characterized by 45–60 km-deep crustal roots that were associated with the main Rheno-Hercynian–Saxo-Thuringian, Saxo-Thuringian–Bohemian and Bohemian–Moldanubian tectonic sutures. During Stephanian–Early Permian wrench-induced disruption of the Variscan Orogen, they propose that subducted lithospheric slabs were detached, causing upwelling of hot mantle material. As a consequence of the resulting thermal surge, partial delamination and/or thermal thinning of the continental mantle–lithosphere induced regional uplift. Contemporaneously, the Variscan orogenic roots were destroyed and crustal thicknesses reduced to 28–35 km in response to the combined effects of mantle-derived melts interacting with the lower crust, regional erosional unroofing of the crust and, on a more local scale, by its mechanical stretching. Towards the end of the Early Permian, the temperature of the asthenosphere is considered to have returned to ambient levels. Subsequently, regional, long-term subsidence of the lithosphere commenced, controlling the development of a new system of Late Permian and Mesozoic thermal sag basins. The evolution of these basins was repeatedly overprinted by minor short-term subsidence accelerations related to the build-up of far-field stresses linked to rifting in the Tethyan and Atlantic domains.

Zeh & Brätz discuss the relationship between Late Carboniferous–Early Permian magmatism and transtensional tectonics in the Thuringian Forest region of Germany. Here, dextral transtensional movements along a NW-trending fault system caused complex block faulting accompanied by intense magmatism. The age of this tectono-magmatic activity is well constrained by geochronological data (^{207}Pb/^{206}Pb single zircon, SHRIMP, ^{40}Ar/^{39}Ar mica, zircon fission-track ages) and field relationships. NE-trending structures appear to have formed between 300 and 294 Ma, with formation or re-activation of W- to NW-trending structures between 290 and 275 Ma.

Von Seckendorff *et al.* report the results of a programme of ^{40}Ar/^{39}Ar step-heating dating of mineral separates from lamprophyre dykes (spessartites, minettes and kersantites) from the Saxothuringian Zone of the Variscan Orogen. These dykes give Visean–Namurian (334–323 Ma) and Stephanian–early Permian (295–297 Ma) crystallization ages indicating magma generation over a period of some 30 Ma. In many cases, dyke emplacement was controlled by faults. Many of the dykes are composite or show evidence for mingling of primitive mantle-derived and more evolved magmas, and, in some cases, contamination with crustal melts. Kersantites and minettes have similar incompatible trace-element characteristics and appear to have originated from partial melting of deeper mantle sources than the associated spessartites; negative Ta, Nb and Ti anomalies are common in mantle-normalized trace-element patterns and may reflect derivation of the parental magmas from a mantle source that was metasomatized during an earlier (Devonian?) subduction event. Magma generation may have been triggered by decompression partial melting of the mantle due to delamination of the base of the lithosphere and its replacement by upwelling hotter asthenospheric mantle. Lithospheric mantle detachment may have caused post-collisional, Namurian uplift and cooling of the crust, and facilitated emplacement of lamprophyre dykes along fault zones at high crustal levels.

Von Seckendorff *et al.*, in their second chapter, review the magmatism of the Saar–Nahe Basin in Germany. This is a late Variscan intermontane basin that developed on the site of an earlier island arc, the Mid-German Crystalline Rise. A wide variety of igneous rocks was emplaced into the thick continental sedimentary fill of the basin over a period of *c.* 4 Ma, from 296 to 293 Ma, as high-level intrusions and lava flows, extrusive domes, diatremes and pyroclastic deposits, ranging in composition from basalt and basaltic andesite to rhyodacite, rhyolite and trachyte. Composite intrusive–extrusive complexes consist of andesite, rhyodacite and trachyte. The geochemical characteristics of the most primitive mafic magmas indicate derivation from a slightly enriched upper-mantle source modified by subduction-related fluids. Nd–Sr–O isotope data indicate that crustal contamination was important in the petrogenesis of the more differentiated magmas.

Dubińska *et al.* focus on the problems associated with geochemical studies of Permian volcanic rocks in NW Poland where intense low-grade metamorphism, of probable Upper Jurassic age, has partially obliterated the primary magmatic signature. Despite the degree of alteration, they consider that the geochemical characteristics of the most mafic rocks are consistent with derivation from an enriched mantle source.

Perini *et al.* consider the petrogenesis of the most primitive mafic magmas within the Variscan belt of Spain and France, in particular the nature of the mantle source of the magmas. Carboniferous–Permian magmatism in the Spanish Central System, Iberian Ranges, Cantabrian Chain, Pyrenees and the French Massif Central includes a range of mafic calc-alkaline and shoshonitic rock types, as well as amphibole-bearing lamprophyres (spessartites) and minor alkaline lamprophyres (camptonites). Subalkaline basalts, with intermediate characteristics between enriched mid-ocean ridge basalts (E-MORB) and the mafic calc-alkaline rocks, also occur in the Pyrenees. The incompatible trace-element characteristics of the least differentiated subalkaline rocks and lamprophyres indicate that variably enriched mantle sources were involved in their petrogenesis; the trace-element signatures of the calc-alkaline and shoshonitic rocks require either assimilation of crustal rocks plus fractional crystallization (AFC) of the parental mafic magmas or melting of a previously subduction-modified mantle source. In the Cantabrian Chain and the Massif Central melting of a subduction-modified mantle source seems the most likely process. In the Central System, Iberian Ranges and Maladeta area of the Pyreneees, the lack of any evidence for a contemporaneous subduction system suggests that AFC processes were probably responsible for the crustal signature of the magmas. The alkaline camptonites from the Central System appear to have been generated from an enriched mantle source that was distinct from the source of the older calc-alkaline magmas from the same area. The incompatible trace-element patterns and ratios (e.g. Y/Nb, Zr/Nb) of the subalkaline basalts from Panticosa, Cinco Villas and La Rhune suggest that they were generated from similar parent magmas, formed by mixing of partial melts of an asthenospheric mantle source and a crustal component.

Lago *et al.* in their first chapter, discuss the relationship between Permian magmatism and basin dynamics in the Pyrenees during the transition from late Variscan transtension to early Alpine extension. They provide evidence for two compositionally distinct, consecutive, magmatic episodes: a calc-alkaline–transitional phase (andesites) and a mildly alkaline phase (basalts and dolerites). These two magmatic events are related to the attenuation of late Variscan transtensional tectonics and the onset of extension related to regional rifting. The strike-slip fault systems that affected the Pyrenees in late Variscan times initially controlled the development and morphology of the sedimentary basins. These were periodically affected by phases of extension, which controlled basin subsidence and the emplacement of magmas. The whole-rock trace-element and isotopic signature of the andesites suggests that their parent magmas were derived from the upper mantle but were subsequently hybridized with late-orogenic crustal melts, whereas the alkaline basalts could have been derived from a lithospheric mantle source, enriched as a consequence of Variscan subduction processes, with a contribution in some areas of an enriched (asthenospheric) mantle source component.

The second chapter by **Lago *et al.*** focuses on the Late Variscan magmatism within the Iberian Chain of Central Spain, which includes both pyroclastic units and high-level intrusions (sills and dykes) emplaced in a transtensional, post-orogenic tectonic setting. A variety of subalkaline igneous rocks occur in this region, ranging from basalt to rhyolite; andesitic rocks are, however, dominant. The pyroclastic units contain plant fossils and pollen that suggest an Autunian age, consistent with available K–Ar radiometric age data (283–292 Ma) for the hypabyssal intrusions. Significant crustal assimilation appears to have been involved in the petrogenesis of the intermediate magmas. A significant hiatus, spanning the Middle Permian and most of the Upper Permian, separates this Lower Permian magmatism from subsequent episodes of Triassic and Jurassic alkaline magmatism that represent later rifting events which affected the Iberian Chain, progressively thinning the Variscan crust as the Alpine cycle began.

Summary

The results of the PCR project have provided important new constraints on the relative roles of far-field stresses v. dynamic upwelling of the upper mantle (i.e. mantle plumes) in the initiation of the Permo-Carboniferous rift system of northern Europe and in the petrogenesis of the resulting magmas. Magmatism and regional tectonics are intimately linked, and heterogeneities in lithospheric thickness clearly play an important role in localizing sites of decompression partial melting. The magmatic rocks emplaced within the orogen and its northern foreland exhibit a wide spectrum of geochemical characteristics, consistent with melt generation in a number of distinct geodynamic settings.

The majority of the most primitive Permo-Carboniferous lavas in the Oslo Rift, southern Scotland, northern England and parts of Ireland appear to be small-degree partial melts of one or more sublithospheric mantle sources. The rising mantle-derived magmas, however, have often been modified subsequently by shallow-level processes, including magmatic differentiation and lithospheric (both crust and mantle) contamination, that mask the geochemical signature of the mantle source. The enriched asthenospheric mantle source of the most primitive magmas in many areas bears some similarity to the source of modern-day Hawaiian–Icelandic basalts, which are generally assumed to be plume-related. Whilst the limited He isotope data available from Scotland could be considered to be consistent with the involvement of a low ^{3}He/^{4}He mantle plume (or several plumes), similar to the source of present-day HIMU (High-μ) ocean island basalts (Hofmann 1997), in the petrogenesis of the magmas, it seems much more likely that magma generation was a complex response to far-field stresses and the tectonic collapse of the Variscan Orogen.

Geochemical and structural studies of regional dyke swarms in Scotland, Norway and Sweden suggest that there were at least five different intrusive events. One of the most extensive is the widespread emplacement of tholeiitic dykes and sills over a short time interval close to the Carboniferous–Permian boundary (*c.* 300 Ma). These intrusions appear to reflect a short-lived, high-degree melting event over a wide region that may have been tectonically induced by wrench faulting.

Within the Variscan Orogen, the earlier subalkaline post-orogenic magmas appear to be derived from partial melting of subduction-modified mantle lithosphere. Later, alkaline mafic magmas appear to be derived from an asthenospheric mantle source, similar to that beneath the northern foreland.

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