The Scott Simpson Lecture

Rheno-Hercynian belt of Central Europe: review of recent findings and comparisons with south-west England

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This paper summarizes results acquired in the German segment of the Rheno-Hercynian Belt during the past 20 years, comparisons with England, and important open questions. Newly discovered allochthonous units underlying the ocean-derived Giessen Nappe can be attributed to the strongly extended, passive northern margin of the Rheno-Hercynian Ocean. These allochthons include Ordovician through to early Devonian rocks with Armorican affinities. This suggests that the Rheno-Hercynian Ocean opened to the South of the Rheic suture between Avalonia and Armorica, and left a narrow belt of Armorican rocks stranded on its northern shore. The geodynamic causes for the opening of the Rheno-Hercynian ocean in a generally convergent setting remain controversial.

A conservative estimate yields ≥ 710 km of orthogonal shortening of continent-derived rocks involved in the Rheno-Hercynian Belt (the Mid-German Crystalline High included), and ≥ 2100 km for the entire mid-European Variscides. Hence, palinspastic restoration places all units formed south of the Rheno-Hercynian ocean far to the South-East, probably off the southern coast of Baltica. This explains the problem of important along-strike displacements in the Variscan belt which abut, today, against the south-western margin of Baltica, but may have operated freely in their original positions in the open sea.

Although the German and the English segments of the Rheno-Hercynian Belt match each other in great detail, the absence, in England, of a broad marine shelf between North Devon and the areas south of the Culm Synclinorium requires an explanation.

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Introduction

The Rheno-Hercynian Belt represents the northernmost orogenic belt in the terrane collage of the European Variscides (see the latest review in Franke, 2000). It is continued, westwards, via south-west England and southern Ireland as far as south Portugal, and, towards the East, around the Bohemian Massif into the Moravo-Silesian Belt of the Czech Republic (Figure 1). Recognition of the Rheno-Hercynian Belt goes back to the benchmark paper of Kossmat (1927), who defined a 'Rhenoherzynische Zone' named after the Rhenish Massif and the Harz Mountains. The southern, active margin of the Rheno-Hercynian orogen (in its modern definition) is contained in the northern part of Kossmat's Saxothuringische Zone (now termed Mid-German Crystalline High, see Kopp and Bankwitz (2003) for a review of the German segment of their 'Europäische Kristallinzone').

Correlation of the Rheno-Hercynian Variscides between Germany and SW-England has a long-standing tradition (Franke and Engel, 1982; Engel *et al.*, 1983; Franke and Engel, 1986; Floyd *et al.*, 1990, 1991; Holder and Leveridge, 1986; Matthews 1977a, b; Tunbridge *et al.*, 1987; Leveridge and Hartley, 2006). This paper summarizes results acquired in the German segment during the past 20 years, and presents a comparison with England, with a statement of important open questions.

Main features common to south-west England and Germany

It is largely agreed that the English and German segments of the Rheno-Hercynian Variscides share a very similar palaeogeographic and tectonic evolution. Summaries of the English and German terrains are available in Holder and Leveridge (1986), Leveridge and Hartley (2006) and Franke (1995, 2000). The main items include:

(1) Thick Devonian clastic sequences deposited at the southern margin of Laurussia + Avalonia (the 'Old Red Sandstone' Continent), although Avalonian basement remains to be proven in south-west England; (2) establishment of an Early Carboniferous limestone platform on the siliciclastic shelf; (3) Devonian and Early Carboniferous intra-plate volcanic assemblages within the passive margin; (4) formation of oceanic lithosphere in late lower Devonian (Emsian) time; (5) Grossly southward subduction of the Rheno-Hercynian basin floor and thinned passive margin, which brought about: (6) Devonian through to Namurian synorogenic greywacke turbidites derived from the active, southern margin of the Rheno-Hercynian basin (Normannian High in the English Channel, Mid-German Crystalline High on the continent), passing up-section and northwards into coal-bearing, fluvio-lacustrine sequences with coal seams (Namurian – Westphalian); (7) a grossly North-

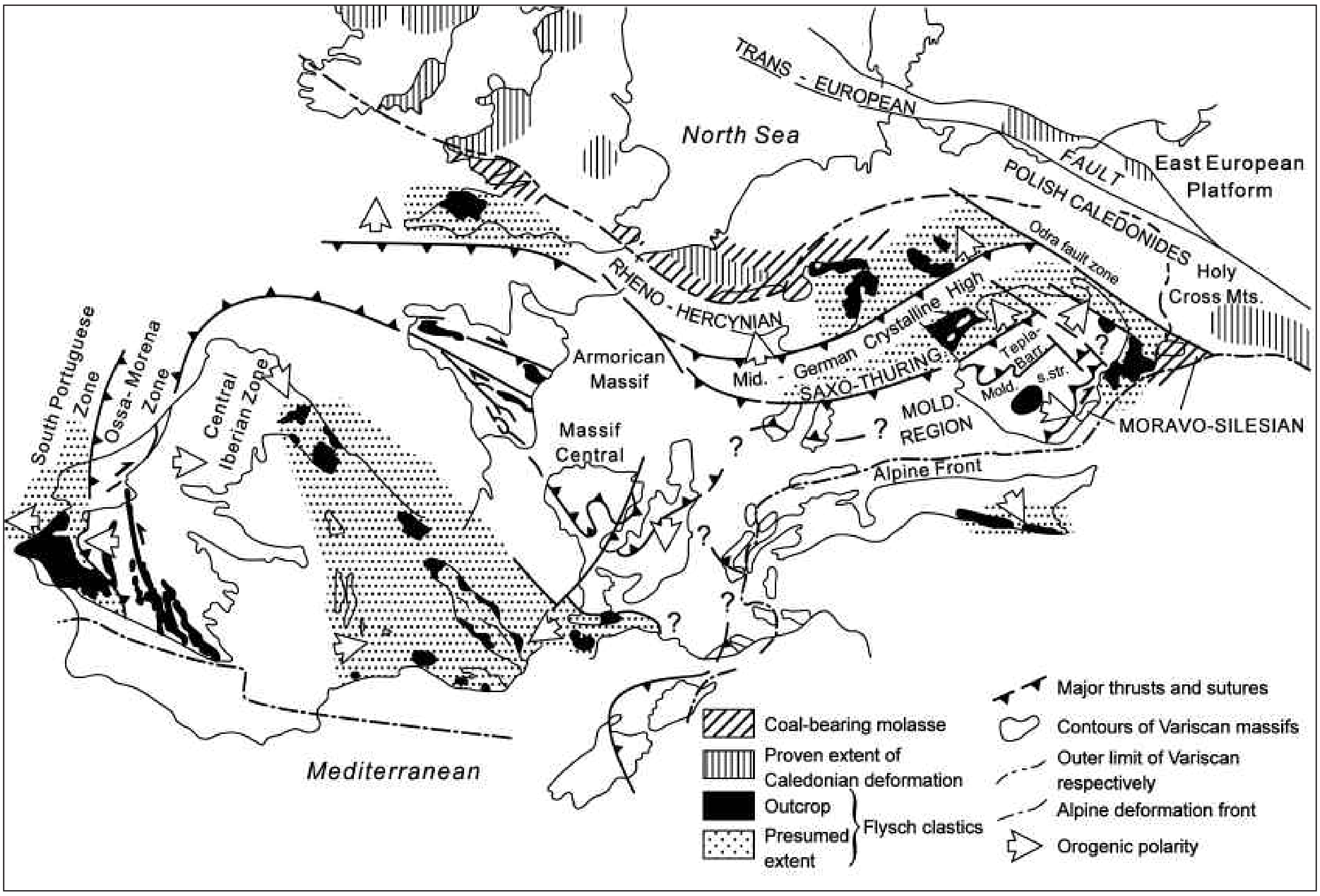

Figure 1. *Tectonic subdivision of the European Variscides (after Franke, 2000).*

vergent fold and thrust belt, with northward emplacement of thrust sheets mainly composed of fragmentary ophiolite sequences and their sedimentary cover; (8) reflection seismic documentation of north-directed thrusting (BIRPS and ECORS 1986; Chadwick *et al.*, 1983; DEKORP 2-N Research Group, 1990); (9) At the base or in deeper parts of the thrust stack Ordovician through to Early Devonian rocks with Armorican affinities (derived from the Rheno-Hercynian/Rheic suture zone to the south), now occurring as tectonic slices or else as clasts in olistostromes; (10) Late Carboniferous/early Permian granite batholiths and extensional basins.

News from the Continent

The main advancements of research into the German part of the Rheno-Hercynian orogen concern the age of the basement, the extent and subdivision of the allochthonous units, the evolution of metamorphic rocks, the deep structure of the belt as revealed by seismic profiling, and the succession of tectonic events. Many of these findings have repercussions on the palaeogeographic subdivision and evolution.

Basement

The pre-Variscan basement has been upthrusted at the southern margin of the Rhenish Massif West of the river Rhine. The Wartenstein Gneiss is a kyanite-bearing paragneiss dated at 574 ±3 Ma (Pb-Pb zircon evaporation, Molzahn *et al.*, 1998) and 550 ±20 Ma (K-Ar and Ar-Ar on hornblende and mica, Meisl *et al.*, 1989). On both sides of the Rhine, the oldest deposits are of Gedinnian age. In the Ardennes, they unconformably overly folded and weakly metamorphosed Cambrian and Ordovician rocks of a 'Caledonian' (or Acadian) basement (Pharaoh *et al.*, 1993; van Grootel *et al.*, 1997; Verniers *et al.*, 2002). In the Ebbe Anticline east of the Rhine, contacts between Ordovician, Silurian and early Devonian rocks are tectonically disturbed, but there is no indication of an unconformity (Gruppenbericht, 1981; Verniers *et al.*, 2002).

Autochthonous cover sequences

The Gedinnian through to Late Carboniferous deposits are dominated by shelf sequences. K-Ar dating of detrital micas in all shelf and shelf-derived clastic sediments has yielded ages between *c.* 440 and 420 Ma, which points to sources in the Scandinavian Caledonides (Huckriede *et al.*, 2004). The shelf margin is seen to retreat from a position South of the Rhenish Massif (Early Devonian) to the Ardennes (Late Devonian), giving way to pelagic shales and carbonates in the South-East. Sedimentation is punctuated by basaltic volcanic episodes at about the Givetian/Frasnian boundary and in the Early Carboniferous ('Deckdiabas'). Synorogenic grewacke turbidites (flysch) are detectable from the Late Tournaisian through to the Namurian C and pass northwards and up-section into the coal-bearing molasse of the Ruhr coal district. This evolution has been summarized by numerous papers in Martin and Eder (1983), Dallmeyer *et al.* (1995) and Franke *et al.* (2000). The Rhenish Massif and Harz Mountains share essentially the same evolution. The main difference lies with the higher level of erosion in the Harz, which brings about an areal predominance of allochthonous units (see Franke and Paech, 2003 and Huckriede *et al.*, 2004 for comparisons).

Allochthonous units

As revealed by recent studies, the Giessen – South Harz nappe is not the only thrust sheet of the German segment. In the southeastern Rhenish Massif, the following structural sequence has been established (Figures 2, 3):

Dill-Lahn autochthon

Early Devonian (up to Late Emsian) siliciclastic shelf sediments derived from Caledonian sources (Huckriede *et al.*, 2004) are overlain by hemipelagic shales, which extend into the Givetian. Volcanism (mainly basaltic) is prominent and widespread with peaks in the late Givetian and Tournaisian/early Viséan (review in Floyd, 1995 and Nesbor, 2004). Coral/stromatoporoid reefs occur on Givetian volcanic highs (e.g., Buggisch and Flügel, 1992). Condensed pelagic shales and carbonates of Givetian through to Famennian age laterally replace and overly the reef facies. The youngest beds are Tournaisian/Early Viséan shales and radiolarian cherts, overlain by greywacke turbidites (from the early Carboniferous III α 4 onwards).

Bicken Unit

Early Devonian shelf sediments are overlain by Eifelian hemipelagic shales (as in the autochthon). These are overlain by condensed pelagic limestones and shales extending into the Famennian. The youngest sediments are Tournaisian/early Viséan radiolarian cherts.

Hörre-Gommern Quartzite

The Hörre Quartzite is part of a laterally extensive unit, which extends from the Hörre via the Kellerwald and the Harz Mts. into the Flechtingen hills at Gommern near Magdeburg (Figure 2a), hence: 'Hörre-Gommern Quartzite'. Quartz arenites of Tournaisian through to early Viséan age (Jäger and Gursky, 2000), derived from Laurussian sources (Haverkamp *et al.*, 1992; Huckriede *et al.*, 2004). Parts of the sequence probably represent thin-bedded turbidites. More massive beds with large-scale cross bedding and granules around 2 mm at their base may represent contourites. Small, isolated tectonic slices of quartzite also exist in the Lahn area between the Hörre and Giessen nappes (not represented on Figure 2) and to the south-west of the Giessen Nappe (Limburg Klippen, ornamented as Hessische Schieferserie in Figure 2c). These isolated occurrences overlie rocks of the Hessische Schieferserie.

Hörre Unit (main part)

The main part of the Hörre Unit consists of deep-water clastic sediments: Famennian greywackes, late Famennian through to Tournaisian shales and radiolarian cherts with fine-grained limestone turbidites and few intercalations of sandstones, overlain by late Tournaisian through to Viséan greywacke turbidites (Bender and Homrighausen, 1979).

Hessische Schieferserie

This unit forms a horshoe-like belt of outcrop, which fringes the half-window between the Hörre unit and the Giessen Nappe (Figure 2c). It has the same tectonic position as the Bicken Unit (under allochthonous greywacke sequences), and a very similar stratigraphic record although it contains more shales and fewer limestones than the Bicken rocks. Extrusive volcanic rocks are absent. Sparse intrusive metabasalts are probably of early Carboniferous age.

Armorican fragments (Lindener Mark)

In the western part of Giessen and further south (around Linden), mining outcrops have revealed a dismembered sequence of sedimentary rocks with Armorican faunal affinities (Franke and Oncken 1995, and literature therein). The association comprises early Ordovician sandstones and Silurian and early Devonian limestones. The different rock types occur as sedimentary clasts in an early Devonian debris flow, which, in its turn, forms a tectonic slice at the base of the Giessen

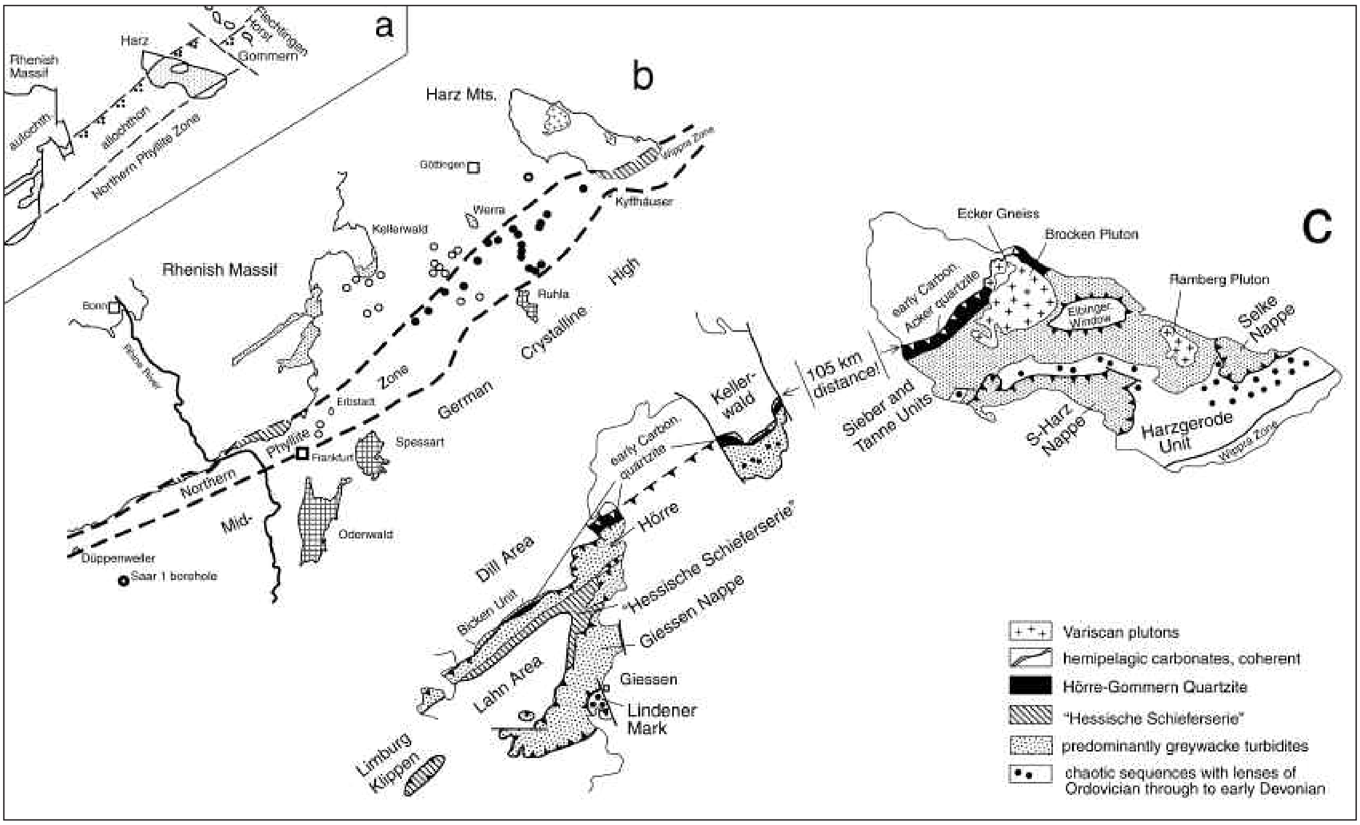

Figure 2. *Allochthonous units in the Rheno-Hercynian belt. (**a**) Allochthons in eastern part of Rhenish Massif, Harz Mountains and Flechtingen Horst, the latter including outcrop of early Carboniferous Gommern Quartzite. (**b**) Outcrop of allochthons in eastern Rhenish Massif, Werra and Harz Mountains (stipple), Northern Phyllite Zone (hatched) and Mid-German Crystalline High (empty contours). Note outcrop of greywacke at Erbstadt (NE of Frankfurt) and in boreholes (open circles). Boreholes with rocks of Northern Phyllite Zones: full circles. (**c**) Close-up of allochthons in eastern Rhenish Massif and Harz Mountains.*

Nappe. Since contacts with the Hörre Quartzite or the Hessische Schieferserie are nowhere exposed, the relative tectonic (and palinspastic) position of the Linden rocks remains uncertain.

Giessen Nappe

MORB-type metabasalts (Grösser and Dörr, 1986) are overlain by condensed shales and radiolarian cherts (Emsian through to early Frasnian, Birkelbach *et al.*, 1988). The main part of the unit consists of Frasnian to early Carboniferous greywacke turbidites (Dörr, 1990).

Ecker Gneiss of the Harz Mountains

A hitherto unique allochthonous unit occurs in the northwestern Harz Mountains. The Ecker Gneiss, a raft of paragneiss, appears to float upon the lower, gabbroic, portion of the Brocken pluton (Figure 2c), which was emplaced – similar to the Cornish granites – at *c.* 295 Ma (Baumann *et al.*, 1991). Peak metamorphism in the granulite facies (720-780 °C/ 0.67 - 0.83 GPa, Franz *et al.*, 1997) indicates formation of the Ecker Gneiss in the middle or lower crust. On the basis of multigrain zircon data, Baumann *et al.* (1991) had considered a Cadomian age for the gneiss, which would have been compatible with its interpretation as uplifted autochthonous basement. However, the paragneiss has recently been shown to contain detrital zircons of Silurian to early Devonian age (436 to 410 Ma, SHRIMP data by Geisler *et al.*, 2005). Therefore, both the age of the sedimentary protolith and the age of metamorphism must be Devonian or younger. If the Ecker Gneiss were an uplifted part of basement, it would have had to be formed at *c.* 25 km (0.7 GPa) depth, at the bottom of a Devonian/Early Carboniferous sedimentary basin, while sedimention continued at the surface. Hence, the Ecker Gneiss is more readily explained as a remnant of a thrust sheet imported together with the allochthonous Acker Quartzite (a segment of the Hörre-Gommern Quartzite), which is present directly to the Northeast and Southwest of the gneiss raft (Figure 2c). In this instance, the Ecker Gneiss would be derived from a position to the South of the exposed Rheno-Hercynian massifs.

Derivation of the Rheno-Hercynian allochthons from a position to the South-East of the Rhenish Massif and Harz Mountains can be deduced from local occurrences, in boreholes and small surface outcrops, of weakly metamorphosed greywackes and local metabasalts in a narrow belt set between the Northern Phyllite Zone and the Mid-European Crystalline High (Figure 2b, Erbstadt outlier and drillholes; see also Anderle *et al.*, 1995).

Evolution of metamorphic units: Northern Phyllite Belt and Mid-European Crystalline High

The Northern Phyllite Belt is composed of meta-sedimentary and meta-volcanic rocks, which underwent pressure-dominated metamorphism (Massonne, 1995) during underthrusting beneath the Mid-European Crystalline High. In its western segment, west of the Rhine (South Hunsrück), the protoliths are reminiscent of the early Devonian of the Rhenish Massif. East of the Rhine, the Northern Phyllite Belt contains metavolcanic rocks whose composition indicates a subduction setting (Meisl, 1995). These rocks were probably formed by northward intra-oceanic subduction during the closure of the Rheic Ocean (Franke, 2000). Isotopic ages (mostly multigrain zircon data) have large error bars, but consistently yield ages between 442 and 426 Ma (late Ordovician/Silurian; e.g., Sommermann *et al.*, 1994 and the compilation in Franke, 2000). Phyllites in a drillhole have yielded acritarchs of early Ordovician age with cold-water affinites (Reitz *et al.*, 1995). The Harz segment of the Northern Phyllite Belt (Wippra Zone) contains Ordovician and Silurian meta-sediments and within-plate metavolcanic rocks (review in Anderle *et al.*, 1995). These findings suggest that the Rheic suture is contained within the Northern Phyllite Zone, and is truncated by the Variscan structural boundaries at an acute angle. Remnants of Giessen Greywackes in the southern part of the Northern Phyllite Zone have already been mentioned above.

It is tempting to correlate the Northern Phyllite Zone with the metamorphic rocks of the Start Complex in south-west England, but the protolith ages of the latter are unknown.

The Mid-German (or European) Crystalline High is dominated by subduction-related granitoids (rarely gabbros) ranging in age between *c.* 370 and 320 Ma (compilations in Anthes, 1998; Franke, 2000; Kopp and Bankwitz, 2003). Locally, the Mid-German Crystalline High contains calc-alkaline orthogneisses and xenocrysts in younger granitoids, which have yielded zircon ages between 439 and 398 Ma. These rocks probably correspond to the Silurian volcanic arc rocks in the Northern Phyllite Zone. After Oncken (1997), these rocks are not an original part of the Mid-German Crystalline High, but owe their present position to collisional underplating and subsequent exhumation.

Data on pre-Devonian events in the Mid-German Crystalline High are scarce. Zircon from a granite gneiss in the Kyffhäuser uplift (South of the Harz Mountains) has yielded a zircon evaporation age of 588 Ma (Anthes and Reischmann, 1996). Unmetamorphosed volcanic pebbles in a Rheno-Hercynian flysch conglomerate give late Proterozoic U-Pb multi-grain zircon ages (Sommermann, 1990). Frasnian through to early Carboniferous greywackes contain muscovite populations with late Proterozoic K-Ar ages (Huckriede *et al.*, 2004). A borehole within the Elbe Zone has yielded a gabbro dated at *c.* 490 Ma (Sm-Nd mineral isochrons, Hammerschmidt *et al.*, 2003). These late Proterozoic and early Palaeozoic events are in accord with derivation of at least parts of the later Mid-German Crystalline High from the Armorican Terrane Assemblage. A late Silurian microflora from a quartzite in the northern Spessart Mountains (Reitz, 1987) appears to be unique in continental Europe. Ordovician and Silurian protolith ages of the Mid-German Crystalline High also occur in south-west England (Sandeman *et al.*, 1997; Dörr *et al.*, 1993).

Metamorphism of the Mid-German Crystalline High spans a wide range of ages. Detrital white mica populations in Late Devonian and Carboniferous flysch greywackes consistently yield middle and late Devonian K-Ar ages (390 and 370 Ma, Huckriede *et al.*, 2004), partly with Si/Al ratios indicative of pressure-dominated metamorphism. These micas clearly pre-date collision between the Mid-German Crystalline High and its foreland, which is dated by the first onlap of south-derived greywacke turbidites on the autochthonous foreland in the Tournaisian (Franke and Engel, 1986; Franke, 2000). Since mid-Devonian metamorphism documented in the micas clearly pre-dates collision, it is best explained by subduction erosion, metamorphism and subsequent exhumation of rocks derived from the upper plate (Franke, 2000; Huckriede *et al.*, 2004; see Oncken, 1997 for a model of subduction erosion in the Crystalline High). Metamorphism of rocks exposed at the surface is mostly of amphibolite facies grade. K-Ar and zircon ages from the Odenwald segment document metamorphism around 370 Ma, whereas the easterly segments of the Mid-German Crystalline High have yielded K-Ar ages ranging between *c.* 340 and 320 Ma (compilation in Franke, 2000 and Stein, 2001). High pressure metamorphism (relict eclogite facies) is only known from one single locality in the eastern Odenwald (Will and Schmaedicke, 2001), which has yielded ages of 357 ±7 and 353 ±11 Ma (Lu-Hf garnet – whole rock, Scherer *et al.*, 2002).

Devonian metamorphism in the Mid-German Crystalline High is also documented in the Kennack Gneiss of the Lizard Complex (Sandeman *et al.*, 1995, 2000).

Tectonic evolution

Unpublished mapping and structural studies in the south-eastern Rhenish Massif over the past 20 years have revealed three phases of tectonic deformation. K-Ar dating on slaty cleavage (Ahrendt *et al.*, 1983) indicates that these events occurred in time between *c.* 325 and 305 Ma.

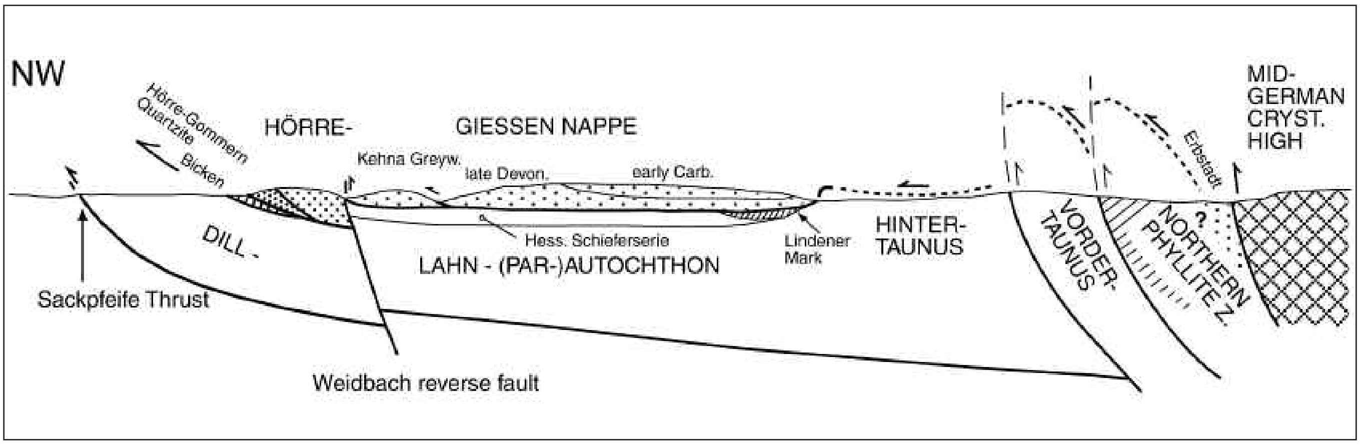

Figure 3. *Diagrammatic section across the southeastern Rhenish Massif (after Franke, 2000).*

D1 has produced NW-vergent folds and thrusts. The associated slaty cleavage was associated with anchizonal peak metamorphism (illite crystallinity; Weck, 1995).

D2 is associated with the emplacement of the Hörre-Giessen allochthon along (today) horizontal brittle faults, which truncate D1 folds and slaty cleavage. Transport was still directed towards the NW (Weck, 1995). This event is also responsible for subhorizontal faulting in the autochthon, which has been dismembered into slices of a few hundreds of metres thickness dragged along at the main nappe base over distances in excess of 10 km.

With respect to the northwestern Lahn area, emplacement of the allochthon has effected inversion of very low grade metamorphism. However, anchizonal metamorphism of the allochthon is lower than that of the Early Devonian rocks of the Hintertaunus adjacent to the Southeast. These relationships can be explained by gravitational sliding of the allochthon from an original position in the upper part of the Rheno-Hercynian tectonic wedge, producing inversion in the foreland and reduction of the metamorphic profile in the hinterland.

D3 brought about local reverse faulting and folding of earlier structures and fabrics in the Lahn area, D3 is responsible for the uplift of the Giessen nappe and the underlying autochthon with respect to the Hörre Zone adjacent to the Northwest, thus producing a halfwindow of autochthonous rocks which – due to the Northeastward tectonic plunge – closes toward the Northeast (Figures 2b, c). It can be speculated that D3 has also effected brittle upthrusting of the Northern Phyllite Zone at the southern margin of the Rheno-Hercynian Zone (Figure 3). Steepening of bedding and cleavage during D3 effected an extensional cleavage (D2 of Weber, 1981).

The seismic reflection lines DEKORP 2-N (DEKORP Research Group, 1990) crossed the Rhenohercynian foreland from its southern margin to a position near the Variscan deformation front near Münster. High quality vibroseis data have revealed a thick-skinned fold and thrust belt, with thrust faults represented by curved reflections which root in a mid-crustal transparent zone (Figure 4). Because of its deep structural position, the decollement zone is probably situated in unknown basement under the floor of the Rheno-Hercynian basin, and controlled by a rheological boundary. At a geothermal gradient of 35 °C/km, 15 km depth would correspond to *c*. 525 °C, i.e., close to the critical temperature for the superplastic behaviour of feldspar.

The set of thrust faults is not uniform (Figure 4): a southern group of curved reflections appears to have a slightly shallower decollement level, and its northern front can be identified, at the surface, with the 'Sackpfeife Thrust'. The reflections adjacent to the North show a common, deeper decollement level. It is possible that the southern, 'Sackpfeife' set of reflections correlates with D1 in the southeastern Rhenish Massif, whereas the northern reflections were formed during D3. This remains to be tested by more refined K-Ar dating on slaty cleavage.

Deeper reflections are difficult to interpret. Underneath the decollement zone, a poorly defined band of stronger reflections which correlates with higher seismic velocities (Giese *et al.*,

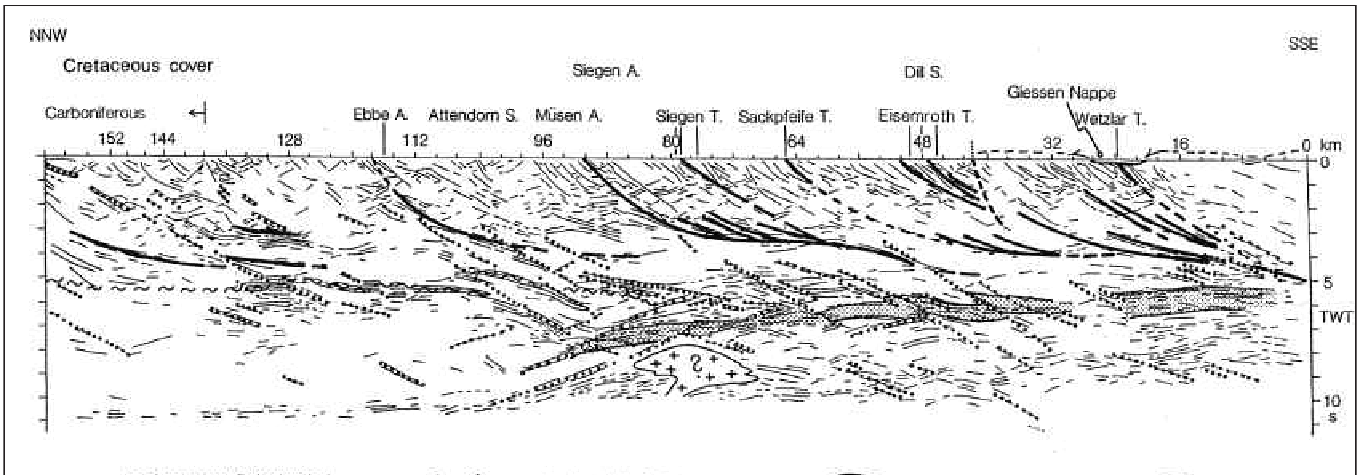

Figure 4. *Line drawing of the seismic line DEKORP 2-N (from DEKORP 2-N Working Group, 1990).*

1990), possibly represents mafic rocks. This invites comparisons with the IBERSEIS seismic line, which traverses the Central Iberian, Ossa Morena and South Portuguese zones of the Iberian Variscides (Simancas *et al.*, 2003). The tectonic units covered by IBERSEIS correspond to the Saxo-Thuringian and Rheno-Hercynian orogens of the German segment. The IBERSEIS line likewise contains a reflective band at about the base of the middle crust, which – in Iberia – has been interpreted to represent mafic layered intrusions relating to the Early Carboniferous magmatic phase widespread in surface outcrops of SW Iberia (e.g., Castro *et al.*, 2002). This interpretation might also apply to the German section, since Tournaisian to mid-Viséan metabasalts ('Deckdiabas') are widespread in the central and southern parts of the Rhenish Massif and also occur in the northwestern Harz Mountains (e.g., Meischner and Schneider, 1970).

Post-Variscan events include, both in south-west England and Germany, emplacement of granitoids and the formation of sedimentary basins. The Cornubian granites were emplaced between 290 and 270 Ma (Chen *et al.*, 1993; Chesley *et al.*, 1993), and the Brocken pluton (Figure 2) around 295 Ma (Baumann *et al.*, 1991).

A mantle origin for all these granites is generally accepted (e.g. Shail *et al.*, 2003). The outline of the contact aureoles of the German granites (Harz Mountains, Friedel *et al.*, 1995) suggests that the granites were intruded along NNE-trending fractures, which probably parallel the main horizontal stress during the post-collisional stage.

Palinspastic restoration

The palinspastic restoration of tectonic units in the south-eastern Rhenish Massif (Figure 2) is based upon the tectonic cross section shown in Figure 3. The allochthonous units must be derived from a position between the Northern Phyllite Zone and the Mid-European Crystalline High. Within the allochthonous assemblage, structurally higher members must have occupied more south-easterly positions. This places the Hörre and Giessen greywackes (with their oceanic basement) to the southeast of the Hörre-Gommern quartzite, which, in its turn, must be positioned to the southeast of the – today underlying – Hessische Schieferserie. The Hessische Schieferserie probably represents a more distal equivalent of the Bicken limestone unit.

Since the Armorican fragments of the Lindener Mark have been transported at the base of the Giessen nappe, they must have been positioned to the northwest of the Rheno-Hercynian ocean. If the Siluro-Devonian arc, now contained in the Northern Phyllite Zone, was formed by intra-oceanic subduction of the Rheic Ocean between Avalonia and Armorica, the Armorican fragments must have been situated to the southeast of the arc. The position of the Armorican fragments relative to the Hessische Schieferserie is uncertain. They might either form part of, or either (as depicted in Figure 5) have been adjacent to the Schieferserie.

This scenario permits us to reconstruct the plate tectonic evolution during the Silurian and Devonian (Figure 6): northward subduction of oceanic crust within the Rheic Ocean created an island arc, which was later accreted to the southern margin of Avalonia. Northward subduction is suggested by the absence of Silurian/Early Devonian flysch sediments and deformation from the Rhenish Massif. Northward subduction and back-arc extension would also explain deposition of the earliest (Gedinnian to Siegenian) sediments in the Rhenish Massif, which pre-date the formation of oceanic crust further to the South, in Emsian time (Franke, 2000). Later still, a northern part of the Armorican terrane assemblage was docked or closely juxtaposed to the Rheic arc. Traces of this event were probably destroyed during the Variscan collision, when the Silurian arc was overridden by the active southern margin of the Rheno-Hercynian Ocean (today the Mid-German Crystalline High).

Opening of this Rheno-Hercynian Ocean, which is detectable from the Emsian onwards, did not exactly reproduce the trace of the Rheic, but left a small Armorican fragment stranded on its northern shore, from where it was later dragged into its present position (Lindener Mark) at the base of the Giessen Nappe.

The above scenario leads to a new assessment of the amount of shortening of the blocks of continental crust involved in the Rheno-Hercynian collision. From the structure of the autochthon in the Rhenish Massif, Oncken *et al.* (2000) derive shortening down to 50%, so that the present width of 175 km expands to 350 km before shortening. For the Kellerwald segment of the Hörre-Gommern Zone (Figures 2,3), Meischner (personal communication, 2006) proposes shortening down to 25%. This estimate should also be valid for the Hörre-Gommern Quartzite, Hessische Schieferserie (including the Bicken Unit) and the Lindener Mark, for which the preserved widths (20 + 25 + 25 km) expand to 70 x 4 = 280 km. For a crude conservative approximation, the same shortening factor is proposed for the metamorphic units (Northern Phyllite Zone, Mid-German Crystalline High). The outcrop of these units would then expand to 25 x 4 = 100 km and 60 x 4 = 240 km. In total, the continental crust incorporated into the Rheno-Hercynian orogen – today 260 km wide – would have covered, before tectonic shortening, 970 km perpendicular to the later tectonic trend. This implies shortening by 710 km. It should be recalled that this estimate only considers sequences underlain by (thinned) continental crust and only the present-day outcrop of the tectonic units, i.e., makes no allowances for eroded parts of the allochthons.

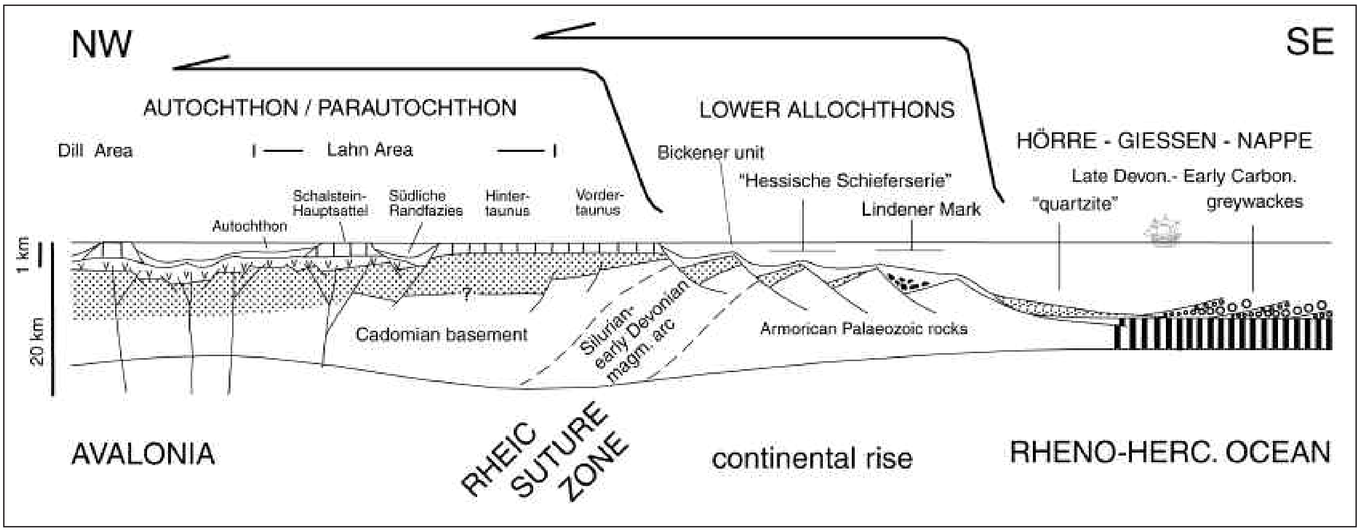

Figure 5. *Palinspastic restoration of tectonic units in the southern part of the Rheno-Hercynian belt (after Franke, 2000).*

The remainder of the central European Variscides, from the southern margin of the Mid-German Crystalline High down to the southern tip of the Bohemian Massif is, today, *c.* 400 km wide (see appendix map in Franke *et al.*, 2000). If one applies the shortening factors for the Rheno-Hercynian orogen used above and add *c.* 100 km of backthrusting of the Mid-German Crystalline High over the Saxo-Thuringian Belt (Schäfer *et al.*, 2000), these areas expand to 1790 km. In total, original width of the preserved part of the Variscides expands to 2760 km. By comparison with the present-day extent of 660 km, this implies shortening by ≥2100 km.

Today, the Variscan terranes are packed into the embayment between the south-western margin of Baltica and the southern margin of Avalonia. In the Bohemian Massif, terrane boundaries are curved through 90° (Franke and Żelaźniewicz, 2000). In this configuration, it is difficult to explain dextral displacements along the Variscan sutures, especially the large-scale transpressional shear zone ('Moldanubian Thrust') between the Moldanubian crystalline block and the Moravo-Silesian Unit adjacent to the Southeast (Matte, 2001). In their present position, these orogen-parallel shear zones abut against the south-western margin of Baltica. Dextral movements along these faults would imply either north-eastward thrusting of the north-western blocks over Baltica, or else displacement of the south-eastern blocks away from the platform, which would create sedimentary basins in the rear. None of these features can be identified in the field. As discussed by Franke and Żelaźniewicz (2002), this problem can be solved, if one considers the important amount of orthogonal shortening discussed above: during early stages of collision, i.e., in late Devonian/Carboniferous times, the Variscan terranes must have occupied positions far to the south-east, and probably in the open sea off the south coast of Baltica, where dextral strike-slip movements were mechanically unimpeded.

Open questions

Origin of the Rheno-Hercynian Basin

One of the most important questions concerns the origin of the Rheno-Hercynian Basin, shortly after the docking of Armorica with Avalonia. Against the general background of Devonian/early Carboniferous plate convergence, this extensional event appears untimely late. Several authors (e.g., Ziegler and Dézes, 2005) have suggested back-arc-extension above a north-dipping subduction zone of Rheic Ocean crust. In fact, such a scenario may be invoked for the origin of the Silurian arc, and for the early (Gedinnian to Siegenian) part of the extensional history in the main part of the Rhenish Massif, north of the arc (see Figure 6 and the text above). Northward subduction cannot, however, explain the formation of Rheno-Hercynian oceanic crust south of the present-day Rhenish Massif, in a position not only south of the arc, but also south of the stranded Armorican fragment (Figure 6).

However, Rheno-Hercynian back-arc spreading in this position is conceivable if remnant Rheic Ocean crust from south of the Silurian arc was subducted toward the south, down under the northern margin of the Armorican Terrane Assemblage (as defined by Tait *et al.*, 2000). In another variant of this model, the Rheno-Hercynian basin might have originated from southward subduction of the former spreading ridge of the Rheic Ocean, in a situation much resembling the modern Gulf of California (Franke, 2006). In any such model involving a second, southward subduction zone, the widespread presence of Armorican rocks to the North of the Rheno-Hercynian Ocean would be an intrinsic feature, instead of being simply incidental. In such a scenario, the Silurian

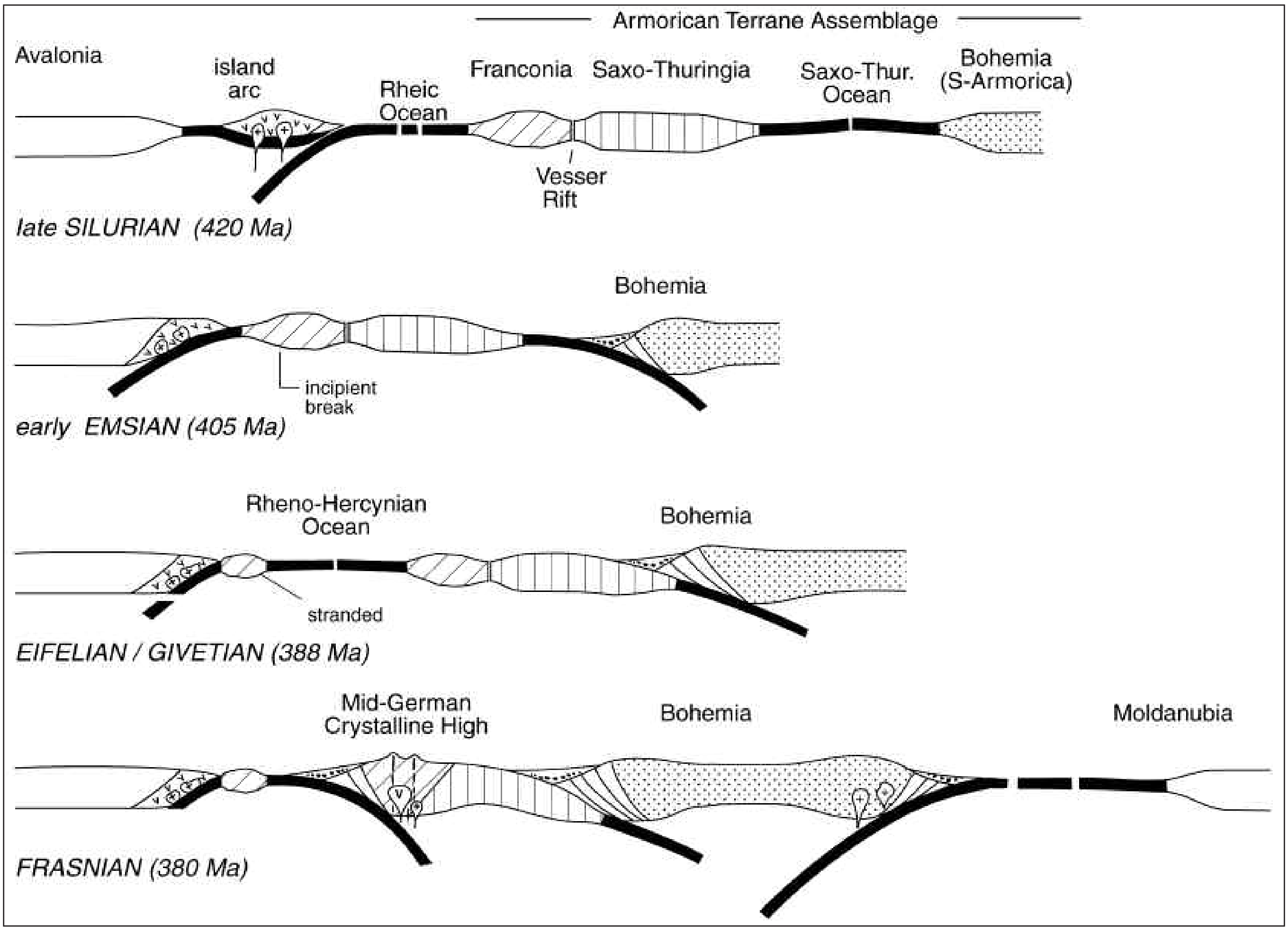

Figure 6. *Plate kinematic scenario for the evolution of the Rheic and Rheno-Hercynian oceans (Silurian through to Late Devonian) after Franke (2000).*

I-type granitoids contained in the Mid-German Crystalline High (see above) would not represent underplated parts of the northern, but a second, independant arc. The metamorphic grade and incomplete preservation of early Palaeozoic protoliths in the Mid-German Crystalline High do not permit to expand upon this model.

Opening of the Rheno-Hercynian basin by ridge-subduction has already been proposed earlier (Matthews 1978), although this author suggested southward subduction of the Iapetus (and not the Rheic) mid-ocean ridge.

Another explanation for the untimely opening of the Rheno-Hercynian ocean might be found by considering a larger-scale geodynamic context, which includes other Variscan zones of Devonian/early Carboniferous extension and magmatism as well as extra-Variscan extensional belts, such as the Dnjepr-Donez-aulacogen (Stephenson *et al.*, 2006). From this perspective, all these features might relate to a group of mantle plumes, which are independant from Variscan plate tectonics proper (Franke, 2006). A similar, incidental relationship might hold for Variscan geodynamics and Permo-Carboniferous magmatism.

Origin of basaltic volcanism

The origin of basaltic volcanism in the Rheno-Hercynian belt is as difficult to understand as the geodynamic causes for the opening of the basin. From the pre-plate tectonic perspective, these volcanic rocks were referred to as an 'initial' magmatic phase directly related to basin formation. However, the palinspastic restoration laid out above reveals that the main belt of outcrop of these rocks, in the Dill-Lahn autochthon and corresponding parts of the Harz Mountains, was not situated near the Rheno-Hercynian spreading axis, but hundreds of kilometres further north, in a much more proximal part of the extended margin. Similarly, the age of the volcanic rocks (late Givetian through to early Carboniferous) is clearly younger than that of the oceanic crust (Emsian), while Early Devonian volcanicity is only represented by some felsic tuffs (Kirnbauer, 1991). These findings suggest that basaltic volcanism is not related, either in space nor in time, to the opening of the Rheno-Hercynian Ocean.

Possibly, Rheno-Hercynian basaltic magmatism relates to the same major plume (or cluster of plumes) suggested for the opening of the Rheno-Hercynian ocean (see above).

Palaeogeographical misfits between Germany and England

Some of the apparent differences between England and the continent are easily explained. While both segments of the Rheno-Hercynian Belt contain thrust sheets with MORB-type metabasalts and overlying oceanic sediments (the Carrick resp. Gießen Nappe, Floyd *et al.*, 1990, 1991), the German segment lacks equivalents of the overlying Lizard Nappe (oceanic lower crust and mantle). These rocks may well have been present in Germany, and later been eroded.

One of the most important differences between the segments of the belt lies with the broad clastic shelf, which intervenes, on the continent, between the fluvio-lacustrine Old Red Sandstone facies and the pelagic realm further South. In the early Devonian of the Rhenish Massif East of the Rine, the shelf facies occupies a belt of *c.* 150 km. During the middle and late Devonian, the shelf margin receded towards the Northwest, so that late Devonian clastic shelf sediments are restricted to the Ardennes. However, shelf-derived sandstone turbidites still reached the Lahn-Dill area (see maps and references in Franke, 1995).

In south-west England, early Devonian shelf clastics reached southwards as far as the Gramscatho Basin. However, the middle and especially late Devonian sequences of South Devon contain only slates, limestones and volcanic rocks (Leveridge and Hartley, 2006), although thick fluvial to shallow marine deposits are available near-by, in the North Devon succession just North of the Culm Synclinorium. The North Devon association reminds the inner shelf of Langenstrassen (1983), in which fluvial to brackish environments alternate with marine sequences. There is no equivalent, in south-west England, of the late Devonian marine outer shelf and turbidite sandstones widespread on the continent.

Anyhow, the relatively small volume of shelf sandstones south of the Culm Basin has had important repercussions on the style of tectonic deformation in south-west England: in the absence of a thick clastic cover, synsedimentary extensional faults in South Devon controlled not only submarine topography, but also tectonic vergence: during orogenic shortening, the infill of extensional half grabens was expelled and transported across the flanks of the adjacent graben shoulders, thus causing changes in tectonic vergence (Leveridge and Hartley, 2006).

Synorogenic sedimentation in south-west England is related, as in Germany, to the advancing thrust load (Leveridge and Hartley, 2006). However, the German synorogenic flysch and molasse sediments appear to have been derived, until the late Westphalian and Stephanian, by a source producing white mica fractions with ages between 396 and 320 Ma (Neuroth, 1997; Küstner, 2000). These micas are undoubtedly derived from a Variscan source to the South like the Mid-German Crystalline High. In England, a change towards a source producing more mature sediments occurred already during the mid-Namurian/-early Westphalian Crackington Formation, and a northerly source established itself during deposition of the Bude formation (Westphalian B/C).

Differences in both the pre- and synorogenic clastic sedimentation deserve further attention.

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