Geol Rundsch (1997) 86:2–20

ORIGINAL PAPER

O. Oncken

Transformation of a magmatic arc and an orogenic root during oblique collision and it's consequences for the evolution of the European Variscides (Mid-German Crystalline Rise)

Received: 5 January 1996 / Accepted: 27 September 1996

Abstract The architecture of the European Variscides has been subdivided by Kossmat (1927) into paleogeographically coherent units which are presently interpreted as former plate fragments. The Mid-German Crystalline Rise (MGCR) separates two fragments (Rhenohercynian and Saxothuringian belts) at the site of an inferred plate boundary and reequilibrated orogenic root. The commonly favoured model interprets the MGCR as the magmatic arc on Saxothuringian crust above a south-dipping subduction zone in Upper Devonian and Carboniferous times. Data from the MGCR, the kinematic evolution of the Mid-European Variscides, and first order volume balancing suggest a reinterpretation of this unit which challenges classical views on the MGCR as well as on the subdivision of Variscan architecture. The MGCR is composed of two rock groups with different tectonic identity. A Lower Carboniferous low pressure-high temperature magmatic arc association on Lower Paleozoic basement rests tectonically on a stack of medium pressure-medium temperature rocks of inferred Rhenohercynian origin. The latter were tectonically accreted to the base of the overriding plate by tectonic underplating. The entire process was controlled by oblique convergence. This led to regional partitioning of the plate kinematic vector into contractional domains (lower Rhenohercynian plate and back-arc area of the upper Saxothuringian plate), bulk heterogeneous plate margin parallel extensional domains (MGCR), and plate margin parallel wrench domains (MGCR boundaries). During this process material was continually transferred from the lower plate to the upper plate, uplifted and exhumed by net crustal extension. The concomitant removal of parts of the former arc and the entire orogenic root necessitates a reappraisal of Variscan architecture and evolution.

O. Oncken
GeoForschungsZentrum Potsdam Telegrafenberg A 17,
D-14473 Potsdam, Germany
Tel.: 0331/2881310. Fax: 0331/2881370
E-mail: oncken@gfz-potsdam.de

Key words Mid-German Crystalline Rise · tectonic underplating · oblique collision · accretion · magmatic arc · root destruction · lithospheric deformation · subduction · strain partitioning

Introduction

Variscan Europe is traditionally subdivided into a number of zones which form more or less independent orogenic belts of Devono-Carboniferous age (Kossmat 1927; Fig. 1). The modern extension of Kossmats subdivision into zones defined as paleogeographically coherent units on the basis of stratigraphic and tectonometamorphic data relies on the validity of an important implicit assumption: With the advent of plate tectonics these zones were reinterpreted as independent microplates which basically retained their material integrity throughout the entire orogenic evolution. This general idea is challenged in the present paper using the Mid-German Crystalline Rise as a case study.

The northwest facing low to very low grade fold-thrustbelts on the northern flank of the Variscides (Rhenohercynian and Saxothuringian belts) are separated by a zone of crystalline basement, named the Mid-German Crystalline Rise (MGCR) by Scholtz (1930) and Brinkmann (1948). Recent interpretations emphasize that the Mid-German Crystalline Rise forms the laterally continuous, faulted basement wedge of an upper plate leading edge formed during the collision of two microplates in the European Variscides (e.g. Weber and Behr 1983, Lorenz and Nicholls 1984, Holder and Leveridge 1986, Matte 1986, 1991, Okrusch and Richter 1986, Ziegler 1986, Franke 1989, Franke and Oncken 1990, Krohe 1991, Flöttmann and Oncken 1992). The Rhenohercynian zone to the north, an inverted and stacked passive margin sequence (Franke and Oncken

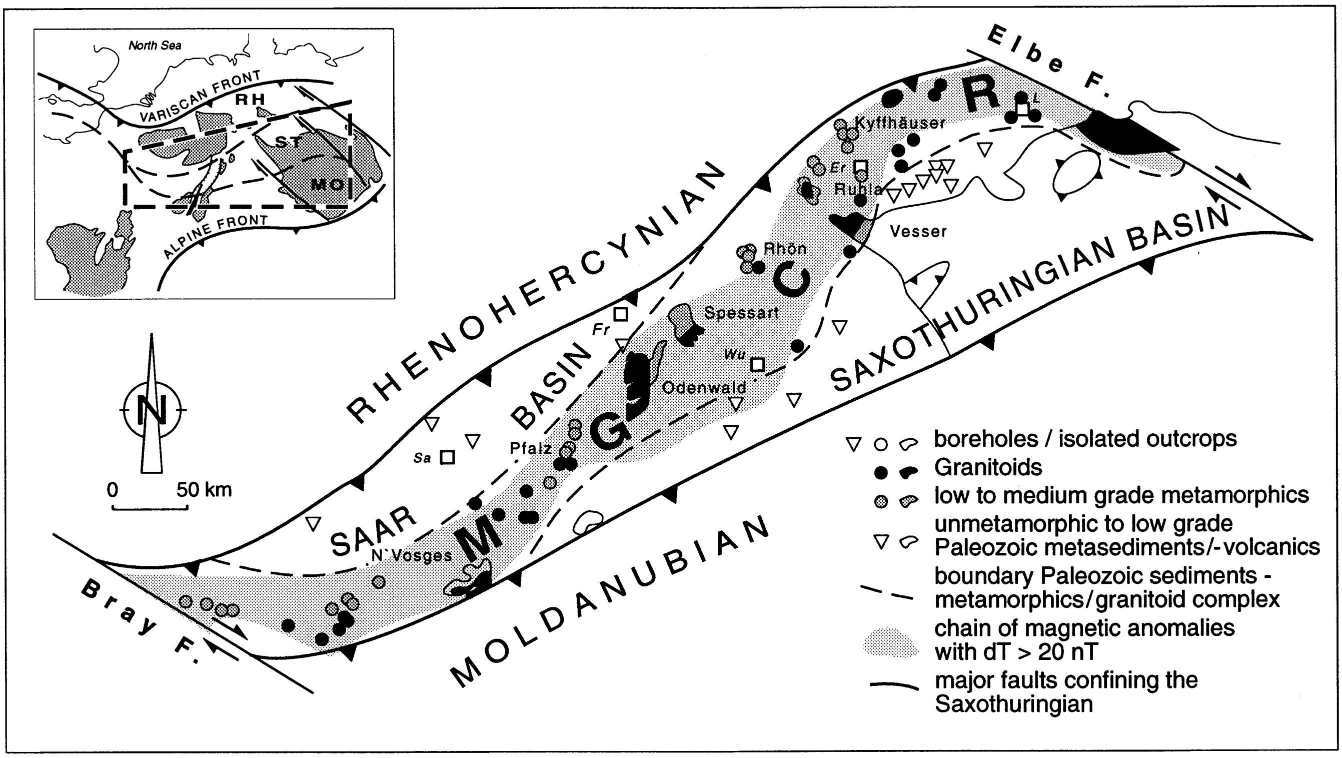


Fig. 1 Schematic map of Saxothuringian unit in central Europe showing MGCR outcrops and drilled occurrences. Shaded zone depicts area with positive magnetic anomalies with $\Delta T > 20$ nT (from Freeman and Mueller 1992). Drilled occurrences compiled from Behr 1966, Donsimoni 1981, Kämpfe 1984, Schmidt et al. 1986. Inset shows Variscan zones sensu Kossmat (1927) in central Europe (RH: Rhenohercynian, ST: Saxothuringian, MO: Moldanubian)

1990, Dittmar et al. 1994, Oncken et al. 1996) was underthrust beneath the so-called Saxothuringian zone to the south. One of the consequences expected is considerable thickening from crustal stacking in the collisional area which, during the Permo-Carboniferous, was reequilibrated to normal crustal thickness. This fact is highlighted by abundant seismic sections which reveal a flat Moho throughout Central Europe. Simple quantitative models led Behrmann et al. (1991) to the conclusion that parts of this thickened crustal root must have been lost by an as yet unresolved mechanism.

Apart from this major problem the continuous debate on the enigmatic nature of the MGCR is best highlighted by the following observations:

- age and composition of the detrital material in the synorogenic flysch basins on both sides of the Rise do not match that of the presently outcropping rocks of the MGCR;
- lateral heterogeneity of the MGCR along strike is extreme regarding rock types, metamorphic evolution, structure, and cooling ages;
- three seismic reflection and several seismic refraction lines crossing the system exhibit structures differing from one section to another although supposedly crossing the same tectonic setting;
- arc magmatism of Upper Devonian and Lower Carboniferous age is restricted to the western Rise and some eastern occurences; the central part is devoid of such magmatism;
- paleo-heat flow data and the absence of a paired metamorphic belt along most of the suture do not support a simple upper/lower plate twin.

An internally consistent set of explanations for the above features does not exist. Explanations for single features moreover are untestable in several cases, or are in conflict with other evidence. The as yet unknown mode of orogenic mass transfer during collision is estimated to be the most crucial parameter to resolve the case. The present paper is primarily based on such a reconstruction and on the reevaluation of data from the different MGCR units with the aim to determine the essential geometric constraints for the geodynamic evolution. In consequence, an opposing view of the above denoted geodynamic interpretation is proposed.

Geological and plate tectonic setting

The European Variscides and Caledonides were formed as the consequence of northward drift of Gondwana-derived microplates (Avalonia, Armorica, etc.)

from a near-southpolar position, and their sequential collision with Laurentia/Baltica in a near-equatorial position involving also Gondwana in the final stage (see Bachtadse et al. 1995, for compilation). The entire cycle lasted for some 200 Ma and started in Cambro-Ordovician times with rifting and subsequent rapid northward drift of these microplates until the Silurian.

Whereas the Saxothuringian unit (probably part of Armorica) fits this general picture, the Rhenohercynian marginal basin (the southern rim of Avalonia) is an extensional feature which evolved during Devonian times following drift and collision. The oceanic basin intervening between the Rhenohercynian and Saxothuringian zones equally has an age around the Lower/Mid-Devonian (Engel et al. 1983, Floyd 1984, Grösser and Dörr 1986). Remnants of this oceanic domain are preserved in the Giessen-Harz nappes.

Although the early crustal evolution of these microcontinents during northward drift suggests a setting of Andean type, very little magmatic addition to the crust is established. Minor arc magmatism occurred during the Ordovician-Silurian and during final collision in the Carboniferous. Within this scenario, the Mid-German Crystalline Rise and its western prolongation, the Normannian High (Holder and Leveridge 1986), are generally interpreted to reflect the deeply exposed basement of the northern Saxothuringian zone during the Upper Devonian and Lower Carboniferous time frame. The Rise is the only larger active magmatic margin identified thus far in the entire Variscan belt (Okrusch and Richter 1986, Franke 1989, Franke and Oncken 1990, Krohe 1991, Willner et al. 1991, Behrmann et al. 1991, Flöttmann and Oncken 1992). In the north, it is juxtaposed against the strongly deformed MP-LT-rocks of the Phyllite zone in the southern Rhenohercynian (Anderle et al. 1990, Klügel and Oncken 1994). The only exposure of the southern rim to the Saxothuringian fold thrust belt in the low grade Vesser unit exhibits rocks of unknown protolith age which also contain abundant MORB-type rocks (Bankwitz et al. 1994). The MGCR's incorporation into the Saxothuringian unit may thus be doubtful. The similarity in basement composition and evolution of Rhenohercynian and MGCR has led Franke and Oncken (1995) to suggest that their early proximity was disturbed by opening of the Devonian Giessen ocean.

General closure of the basins started during the Early Devonian and was completed in a final collisional stage in the Lower Carboniferous (see Matte 1986, Ziegler 1986, Franke 1989 for details). Carboniferous inversion and shortening of basins bordering Avalonia and parts of Armorica by some 50% resulted in thick continental crust (locally up to 50 km; Behrmann et al. 1991). Collision also resulted in an internal architecture of the Saxothuringian belt oblique to orogenic strike: the MGCR separates two different sedimentary basins (Saar basin and Saxothuringian basin, Fig. 1) and strikes NE–SW rather than the average ENE–WSW direction. Continental-scale wrenching and basin formation during the Upper Carboniferous overprinted the earlier sutures and the orogenic architecture (Arthaud and Matte 1977, Oncken 1988b).

Data base

Rocks, protoliths, and tectonometamorphic record

Although most of the MGCR is covered by Permo-Mesozoic and Cenozoic sediments its lateral continuation can be assessed from geomagnetic data (Fig. 1). In contrast to the magnetically quiet vicinity, the MGCR is traced by a chain of subelliptical anomalies which were shown to correlate with outcropping metamorphic and magmatic rocks of the MGCR (Flöttmann and Oncken 1992) and its southern margin (Vesser unit, DEKORP research group 1994). Summarising the basic aspects, the MGCR contains the following exposed units from west to east (Fig. 2; see Hirschmann 1995, Okrusch 1995 for compilations).

The western MGCR is exposed along both escarpments of the Rhine graben (Pfalz, northern Vosges, and western Odenwald, Bergstraße; Fig. 1). It comprises orthogneisses and amphibolites of partly Late Ordovician protolith age (Reischmann, pers. comm.), Paleozoic metagreywackes, quartzites and metapelites with pyroclastic intercalations, and some marbles of Mid-Devonian age (Mehl, pers. comm.). Abundant syn- to late-orogenic calcalcaline intrusives of Lower Carboniferous age intruded into the previously metamorphosed volcano-sedimentary sequence (Montigny et al. 1983, Wickert and Eisbacher 1988, Hess, pers. comm., Henes-Klaiber 1989, Laue et al. 1990, Wildberg 1990; see Flöttmann and Oncken 1992, for a more detailed description; see also Donsimoni, 1981, for drilled occurrences).

The western rise is characterised by upright, NW–SE-trending, open to tight folds with subvertical foliation and mostly subhorizontal stretching lineations on both sides of the river Rhine (Krohe 1991, Flöttmann and Oncken 1992). Deformation occurred near peak metamorphic conditions with peak, low to medium-grade temperatures outlasting deformation (Willner et al. 1991, Flöttmann and Oncken 1992). Apart from some indications of an early start of deformation in the metavolcanics/-sediments (ca. 370 Ma, Kreuzer and Harre 1975, Kirsch et al. 1988) most isotopic ages record cooling from a HT/LP event which probably is related to peak intrusive activity (325–340 Ma; Kreuzer and Harre 1975, Montigny et al. 1983). The intrusives show some solid state deformation and a steep magmatic foliation with an elongation of mafic enclaves parallel to orogenic strike (plane strain geometry in map view with aspect ratios of

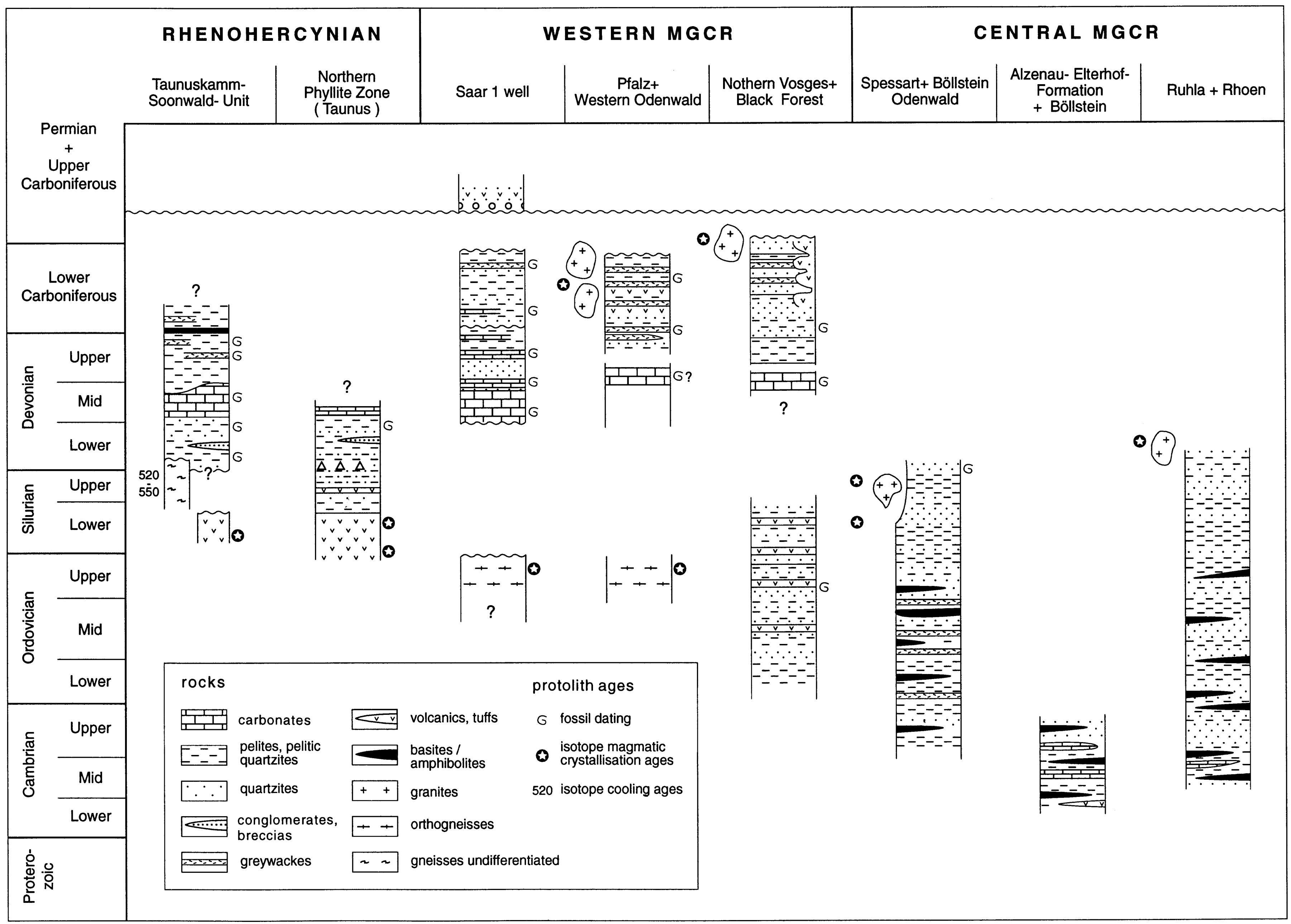


Fig. 2 Schematic time chart for southern Rhenohercynian and Mid German Crystalline Rise. Only general protolith types and age data are recorded (see text for sources)

1.5–2.5 on average). Syn-intrusive kinematics also show orogen-parallel wrenching which segments the entire rise (Krohe 1991). All mentioned units are affected by a conjugate set of late brittle strike-slip faults which has the same extension direction as the earlier fabrics.

Towards the northwest, the Saar 1 well on the northwestern boundary of the rise has drilled a thin sequence of marine Mid-Devonian to Lower Carboniferous sediments. The undeformed and unmetamorphosed sequence overlies a weakly metamorphic granite of Late Ordovician isotopic age (Sommermann 1993). It is overlain disconformably by the shallow marine to continental Westphalian to Lower Permian molasse-type clastic fill of the Saar-Nahe basin (see Hering and Zimmerle, 1976, Schäfer, 1989, for details).

The eastern Odenwald (Böllstein), the Spessart mountains, drilled rocks in the Rhön area, and the Ruhla unit consist of several metapelitic and metavolcanic sequences, probably of mostly Lower Paleozoic age (Reitz 1987, Hirschmann and Okrusch 1988, Altenberger and Besch 1993), but of different plate tectonic setting. The uppermost tectonic unit (Alzenau-Elterhof) consists of a variegated series of amphibolites (partly MORB-type), marbles, calcschists, and metapelites. All metasedimentary piles are intruded prior to their metamorphism by Silurian-Lower Devonian metagranitoids with shallow intrusion depths and with subduction-related affinities (Lippolt 1986, Okrusch and Richter 1986, Henneberg et al. 1994, Dombrowski et al. 1995). With exception of a diorite in the southern Spessart, no Variscan synorogenic magmatic features like those observed further west have been identified. Late-to post-orogenic granites may obscur the orogenic boundaries (e.g. Ruhla unit).

In the west, the central MGCR is separated from the western MGCR by the important Otzberg and Michelbach fault zones with sinistral transtensional slip (Hirschmann and Okrusch 1988, Weber and Juckenack 1990, Krohe 1991, 1992). East of this boundary, all units form domal or antiformal structures resulting from large scale folding of nappe stacks overprinted by extension (Weber and Juckenack 1990, Krohe 1992, Altenberger and Besch 1993, Zeh 1995). A pervasive stretching lineation developed throughout near peak conditions (E–W in the eastern Odenwald with sense of shear top to the west, Krohe 1991, 1992, Altenberger and Besch 1993; NE–SW in the Spessart and Ruhla, Weber and Juckenack 1990, Zeh 1995, with post-peak metamorphic SW-directed low angle extensional displacement). Earlier thrust-associated fabrics are often obliterated – only few indicators of sense of shear are reported with consistent NW-facing asymmetric folds and sense of shear in the Spessart and Ruhla and some S-dipping stretching lineations (Weber and Juckenack 1990, Zeh 1995).

Pervasive deformation mostly predated peak metamorphic conditions with some localised deformation during decompression and cooling. PT-conditions are typically Barrovian with upper greenschist to upper amphibolite conditions at 4–8 kb (see Okrusch 1995 for compilation; Willner et al. 1991, Franz & Seifert 1997). All geochronologic data measured on hornblende, muscovite, and biotite fall within the same range at 318–324 Ma in the eastern Odenwald, Spessart, and Rhön indicating very rapid cooling following peak metamorphism (Nasir et al. 1991, Lippolt 1986, Schmidt et al. 1986). These ages are identical to peak metamorphic ages dated for the northern Phyllite zone in the juxtaposed southern Rhenish Massif (Klügel 1995). In the Ruhla unit cooling ages are somewhat older with around 335–355 Ma (see Zeh 1995 for compilation) and are again identical to the mineral ages reported for the northern adjoining Phyllite belt in the Harz mountains (Ahrendt et al. 1995).

The easternmost exposed part of the MGCR (Kyffhäuser) is dominated by HT-LP metagranitoid and metadioritic rocks with only some intercalated metasediments of unknown age (Neumann 1966). Drillholes along the burried eastern MGCR show a similar rock content with a predominance of granitoids of Cambrian age and weakly metamorphic Lower Paleozoic sediments (Behr 1966, Röllig et al. 1995, Linnemann & Buschmann 1995). Reischmann (pers. comm.) and Wenzel et al. (1993) have recently found Late Lower to Upper Carboniferous ages from drilled granodiorites near Leipzig/Delitzsch and for the exposed Meissen pluton at the Elbe fault. Synintrusive shearing along the Elbe fault occurred during much of the intrusion history of this pluton at PT-conditions of no more than a low-P greenschist facies environment (Wenzel et al. 1993, Mattern 1996). The Kyffhäuser unit is separated from the Ruhla unit by a narrow, roughly NS-trending transition inferred from drilled phyllonitic rocks (Behr 1966).

The southernmost imbricates of the Rhenohercynian passive margin to the northwest (Phyllite zone) show a partly similar development: Ordovician-Silurian calc-alkaline volcanics or metamorphic basement of Cambrian cooling age are overlain by mostly marine Devonian and some Lower Carboniferous sediments (Klügel et al. 1994, Dittmar 1995). The southern Harz passive margin sequence is probably covered by relics of the Carboniferous accretionary wedge. Accretion and imbrication took place under greenschist facies conditions at slightly elevated pressures (Siedel and Theye 1993, Klügel 1995) and was overprinted by significant orogen-parallel stretching with changing senses of shear (Klügel 1995).

In summary a threefold subdivision of the MGCR is obvious. All parts – including the southern Rhenohercynian – have evolved on top of relics of an Ordovician-Silurian magmatic arc (Franke and Oncken 1995). The western MGCR (west of Rhine river, western Odenwald) is a moderately deformed, but strongly intruded part of a Lower Carboniferous magmatic arc with temperature-dominated metamorphism. From west to east a continuously deeper level of this arc relic has been exhumed (Krohe 1992), Flöttmann and Oncken 1992). Through plate convergence the Saar basin as the northwestern part of this crustal unit apparently occupied the position of a forearc basin riding piggy-back on the edge of the evolving active margin. The weakly exposed eastern MGCR shows similar, although as yet less well identified features as its western counterpart. Across the tectonic boundary of the Otzberg shear zone to the central MGCR (eastern Odenwald to Ruhla, Fig. 1) the fundamental change in all features does not support continuation of a Carboniferous magmatic arc. An antiformal thrust stack with no or little synkinematic magmatism controls this area (see Fig. 3 for different types of PT-paths). The degree of exhumation derived from peak pressures of rocks at the present surface varies significantly along strike and shows a central MP- and a western and eastern LP-domain of the MGCR (Fig. 4). A similar subdivision of the MGCR is suggested by the Nd model ages from Anthes & Reischmann (1995). All units show evidence of strong orogen-parallel extension and wrenching starting at peak metamorphic conditions and lasting through exhumation. Postorogenic undeformed granites and lamprophyric dykes of early Upper Carboniferous age crosscut all units and seal all faults.

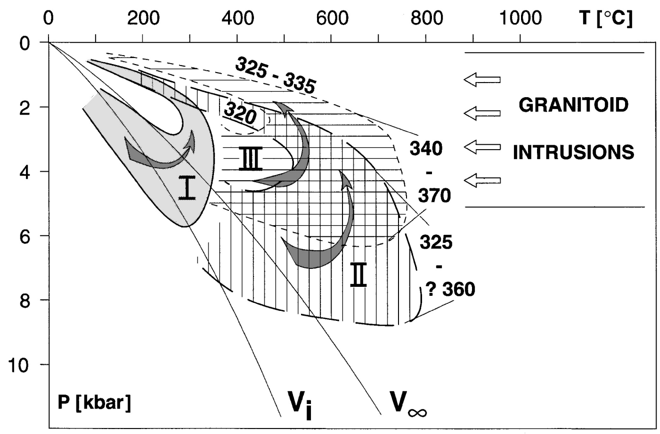
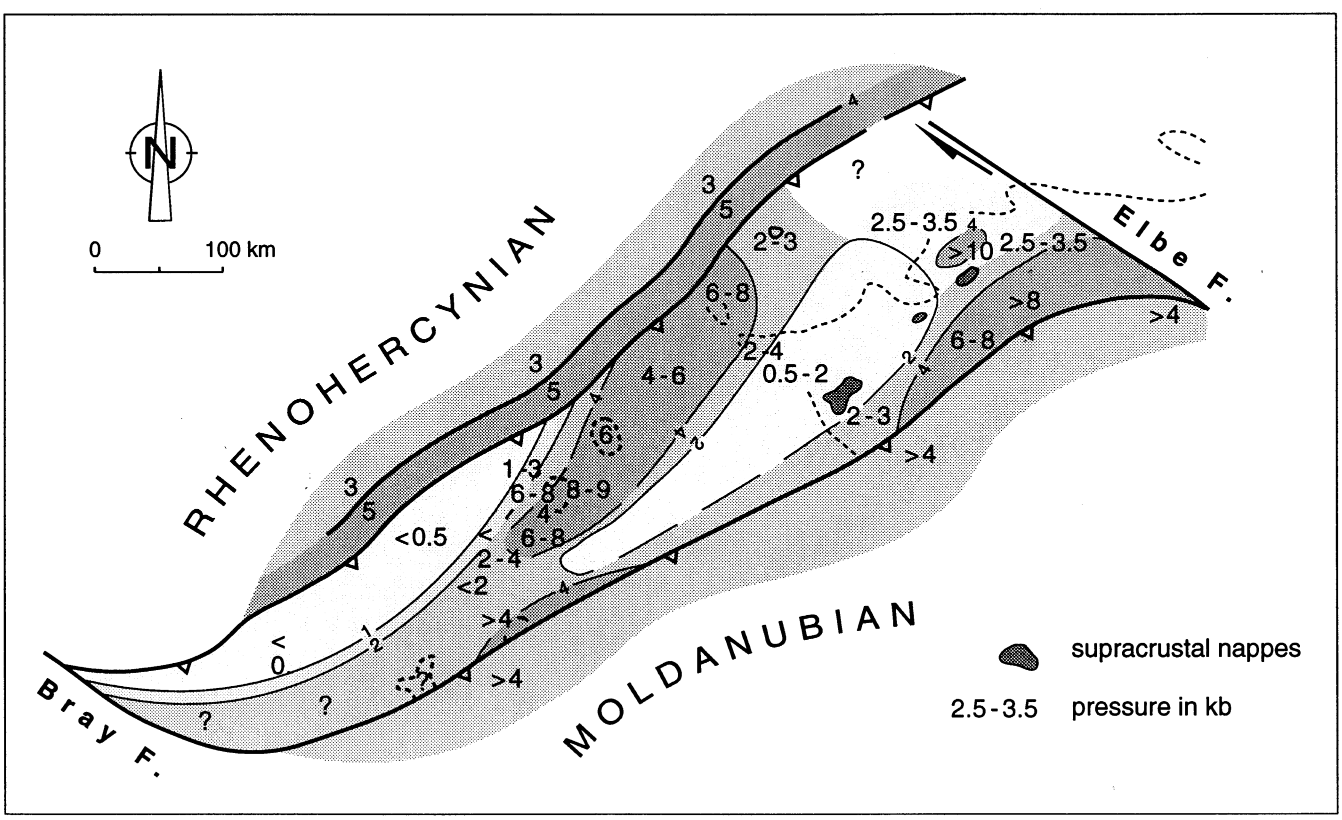


Fig. 3 Compiled PTt-paths of southernmost Rhenohercynian zone (I), central MGCR (II: eastern Odenwald, Spessart, Rhön, Ruhla), and western and eastern MGCR (III: Pfalz, western Odenwald, Kyffhäuser). See text for references. Depth interval of granite intrusions into the western MGCR derived from barometric data. Stable continental (Vi) and post-thickening equilibrated continental geotherms (V∞) are included

Large scale structure and seismics

The entire MGCR is crossed by a number of reflection and refraction seismic lines which exhibit quite

Fig. 4 Exhumation map of Saxothuringian microplate showing the degree of unroofing following peak metamorphic conditions during Variscan orogeny in kb (see text for references)



different features (Fig. 5). In the west, the Saar basin and western MGCR are crossed by lines DEKORP 1C and 9N (DEKORP research group 1991, Wenzel and Brun 1991). Below the Permo-Carboniferous half-graben fill the flatlying and undeformed Mid-Devonian to Lower Carboniferous sequence rests unconformably on a seismically transparent wedge-shaped basement complex (drilled in the Saar 1 well) which can be observed to continue some distance towards the southeast (Henk 1993). The transparency can be tied to the Lower Paleozoic arc, the typically upright structures of the western rise and their abundant intrusion by Lower Carboniferous granites. The wedge shaped structure is underlain by a midcrustal 10–20° SE-dipping highly reflective broad band which has been interpreted as tectonic slivers of the oceanic crust trapped in between the upper plate of the MGCR and the underthrust Rhenohercynian crust (DEKORP research group 1991, Oncken et al. 1997). This rock association crops out in the southernmost imbricates of the western Rhenish Massif and comprises a sequence of MOR-type volcanics with intercalated metasediments (Meisl 1990).

The sections DEKORP 2S and DEKORP 3B (DEKORP research group 1985, Behr and Heinrichs 1987, DEKORP research group 1994) cross the MGCR in the Spessart and Rhön area respectively (Fig. 5). Both show weakly SE-dipping reflection bands at mid-crustal depth which probably reflect the basal detachment above which the passive margin sequence has been telescoped (Behrmann et al. 1991). The Spessart antiform stack and the Rhön area are underlain by numerous reflections with similar antiform geometry down to the middle crust. South of the Spessart and Rhön area, a major NW-dipping reflection band which links up with the exposed Vesser unit reflects the termination of the MGCR at the boundary to the deformed Saxothuringian basin sediments (comp. Fig. 1).

Refraction work – DEKORP 3B and EGT lines (Aichroth et al. 1992, DEKORP research group 1994) – shows the upper crustal MGCR to be a homogeneous medium velocity unit (vp: 6 km/s). This is opposed to the Rhenohercynian and Saxothuringian thrust belts which show a continuous increase of velocities to an intracrustal discontinuity at some 10–20 km depth. The lower crust under the MGCR shows the same features as the Rhenohercynian lower crust below a weakly SE-dipping velocity boundary. In conclusion, seismic interpretation shows two important aspects: a two-fold subdivision of the MGCR into a western and a central part is evident again; the MGCR appears to be underlain by Rhenohercynian material and is overthrust in pop up mode towards the north and south.

Large scale kinematic pattern

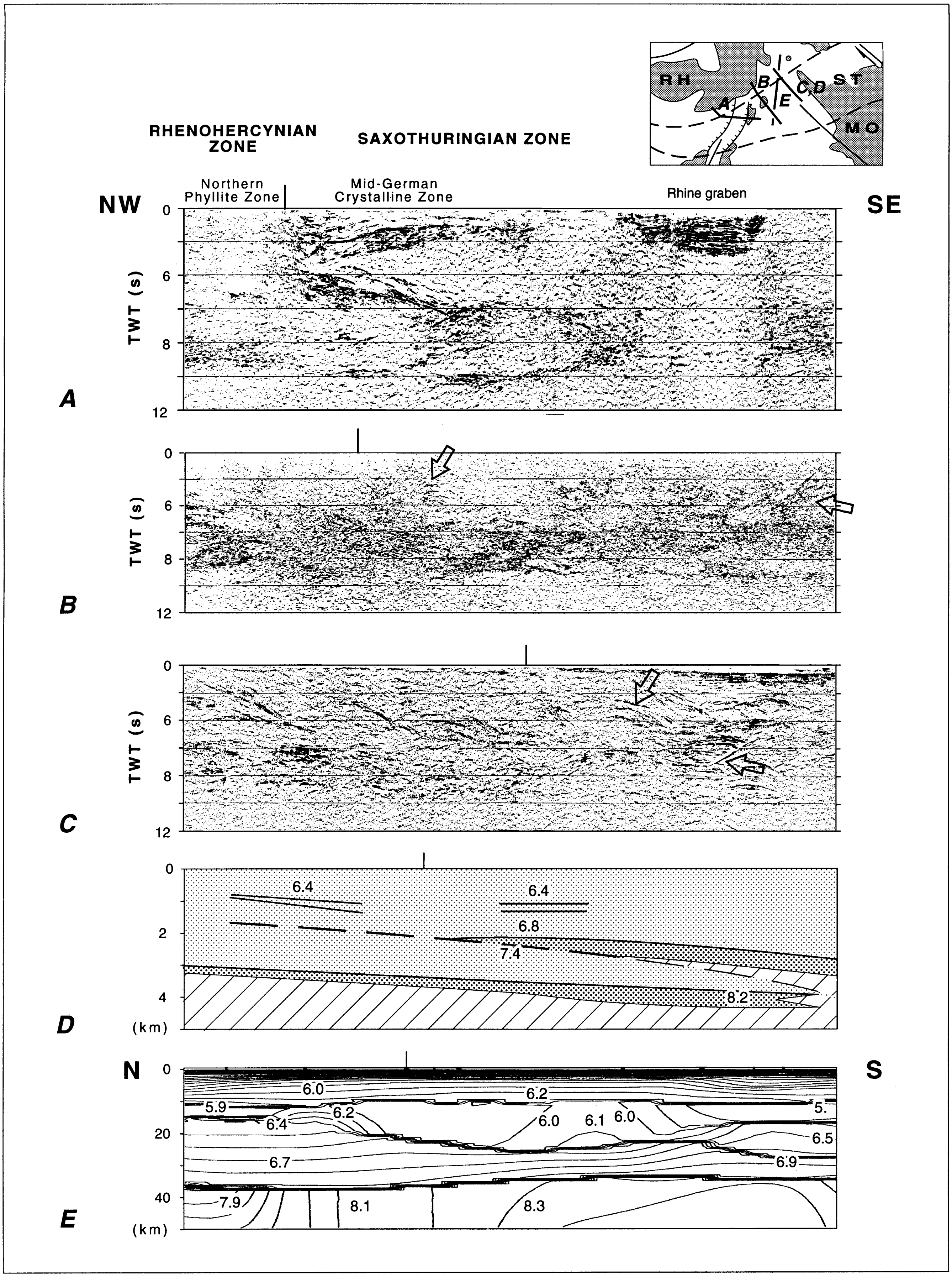
Fig. 6 summarizes the available data on the kinematics of the crustal units involved in the Carboniferous collision process between the Saxothuringian and Rhenohercynian zones. Precollisional information is lacking due to the nearly complete subduction of the intervening oceanic plate and to nearly complete erosional removal of the obducted accretionary wedge. The remaining rocks bear a kinematic memory starting at some 360 Ma, roughly equivalent to the onset of collision, until some 300 Ma at the end of deformation. The presentation only makes use of the following types of age data which may be interpreted kinematically:

- K–Ar and Ar–Ar ages of fabric-forming mica and hornblendes from rocks which never exceeded lowermost greenschist conditions thus recording their crystallisation ages;
- ages from the same minerals in retrograde shear zones from rocks which had reached amphibolite facies and higher conditions above the minerals closing temperatures;
- crystallisation ages of synkinematic intrusives and dykes (mostly U-Pb from zircons) and of the oldest postkinematic magmatic rocks;
- ages of hornblende and mica in magmatic rocks deformed during cooling;
- stratigraphic ages of synorogenic sediments.

The Rhenohercynian proper shows evidence of foreland-directed thrusting followed in the more internal parts by increasingly W-directed thrusting (Oncken 1988a, 1989, Dittmar et al. 1994). Cleavage dating and flysch ages indicate an orogenic wedge propagating NW from 370 until 300 (Ahrendt et al. 1983, Engel and Franke 1983, Ruchholz 1989). The southern part of the wedge exhibits a late stage sinistral shearing at 312 Ma with significant orogen-parallel stretching, and subsequent dextral shearing (Klügel 1995). This kinematic picture of the detached Rhenohercynian sediments has been interpreted as evidence of oblique convergence with the Saxothuringian upper plate (Oncken 1988a, 1989, Dittmar et al. 1994, Klügel 1995).

The MGCR shows significant orogen-parallel extension during cooling with only minor concomitant orogen-perpendicular shortening as recorded from deformation of synorogenic intrusives. Relics of an earlier NW-directed stacking stage are only reported from the Spessart. This entire period lasted from 360–325 Ma (Kreuzer and Harre 1975, Montigny et al. 1983, Lippolt 1986, Schmidt et al. 1986, Hess and Schmidt 1989, Nasir et al. 1991, Zeh 1995). It is largely finished at the onset of subduction of continental material from the lower plate as reflected from undeformed lamprophyric dykes and granites which intrude the final brittle strike slip fault system. The ages of the major bounding

Fig. 5 Seismic sections across the MGCR. A: DEKORP 1C + 9N, B: DEKORP 2N, C: DEKORP 3B, D: Refraction line parallel to DEKORP 3B, E: EGT European Geo Traverse refraction line. Inset shows location of lines (see text for references). Arrows mark important structures in MGCR and its boundary to retrowedge


RH
B
C,D
ST
A
E
MO
RHENOHERCYNIAN ZONE
SAXOTHURINGIAN ZONE
Northern Phyllite Zone
Mid-German Crystalline Zone
Rhine graben
NW
SE
TWT (s)
A
B
C
D
E
(km)
N
S
6.4
6.4
6.8
7.4
8.2
6.0
6.2
5.9
6.2
6.4
6.0
6.1
6.0
6.5
6.7
6.9
7.9
8.1
8.3

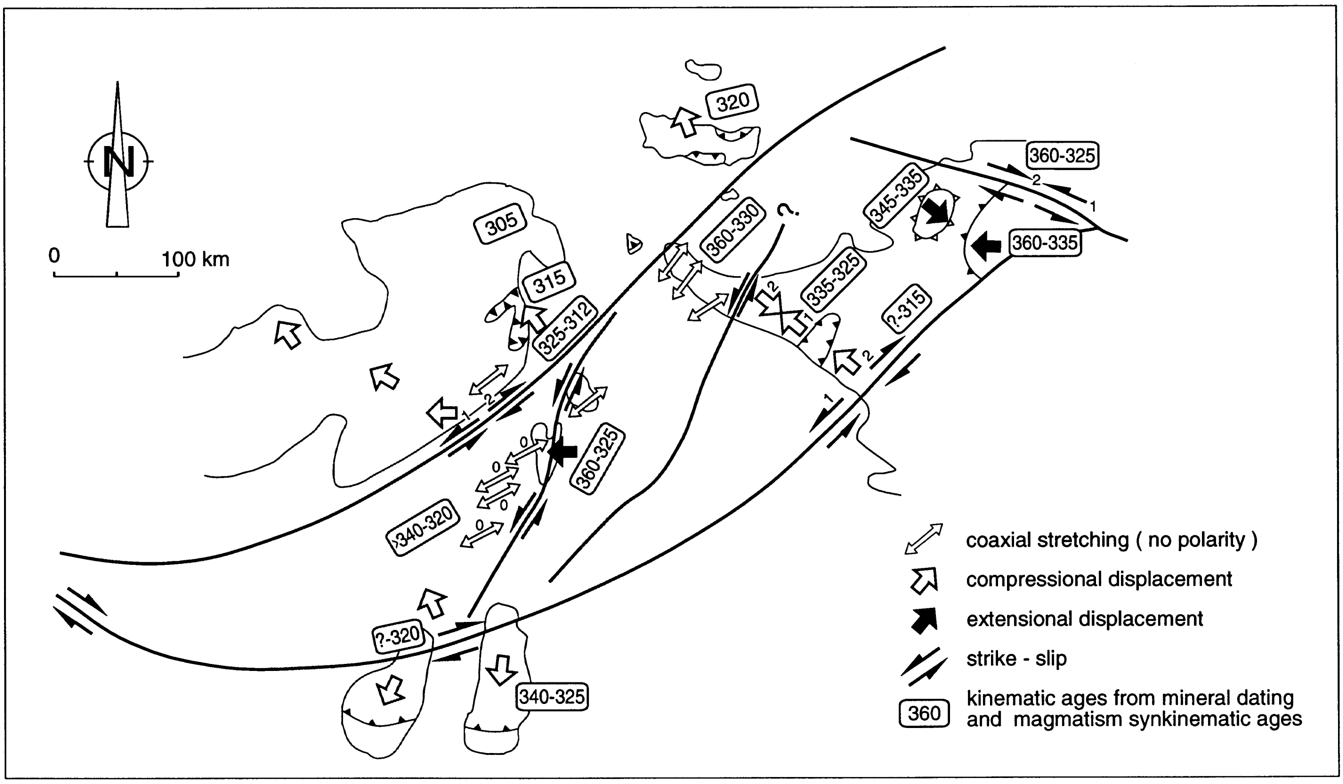


Fig. 6 Kinematics of the Rhenohercynian-Saxothuringian lower-upper plate system during and after collision in Carboniferous times based on average displacement orientation and most pervasively developed lineations (see text for references). In cases of reversal of shear 1 indicates the earlier increment

sinistral faults are similar as far as known (Hess and Schmidt 1989). The Devonian Saar precursor basin is escaping deformation towards the SW along its border faults which are operating successively. The Saxothuringian basin south of the MGCR is shortened perpendicular to the orogenic trend in two stages: an earlier thrust wedge (carrying HP-rocks from the upper plate Münchberg nappes in piggy-back mode) propagates NW at around 325 Ma (Ahrendt et al. 1986, Franke 1989) and tapers out in the central part of the basin. A second slightly younger fold-thrust belt evolves in a retrowedge position south of the MGCR and propagates towards the SE with its basal detachment cutting across the front of the earlier wedge (Schäfer and Oncken 1996). The two Saxothuringian belts overprint the Granulite Massif, a metamorphic core complex (Franke 1993) with HP-rocks metamorphosed at 340–350 Ma. It was exhumed to the base of the Saxothuringian basin fill along an extensional detachment during early plate convergence.

The steeply dipping Elbe fault in the NE of the Saxothuringian shows mainly dextral strike slip spanning at least the entire period of magmatic activity (330–300 Ma, Wenzel et al. 1993, Mattern 1996). The Erbendorf line and its southwestern continuation, the Baden-Baden and the Lalaye-Lubine fault, which separate the Saxothuringian belt from the Moldanubian, stop their dextral motion around 320 Ma (Teufel 1988, Wickert and Eisbacher 1988, Wickert et al. 1990, Zulauf 1993). The age of the earlier sinistral motion is not constrained so far.

The complex kinematic pattern derived from these data emphasizes an important point: Most, if not all, syncollisional kinematic regimes and displacements partly or entirely overlap in time. Consequently, the major faults and the diffusely deforming intervening domains must form a kinematically linked system. While deformation of the upper crust of the Rhenohercynian lower plate involved plate margin-perpendicular to -oblique contraction, the upper plate leading edge deformed by weak (western MGCR) to average (central MGCR) contraction and concomitant orogen parallel extension at all levels. The back arc area on the upper plate again deformed by plate margin perpendicular contraction. The deep back arc lithosphere appears to have been significantly extended perpendicular to the plate margin in the early stage in an overall convergent scenario. In the intervening boundaries strain compatibility was established by wrenching. These observations can easily be explained by domainal partitioning of deformation during an oblique collision process.

The rate of flysch propagation and propagation of the metamorphic front across the Rhenohercynian lower plate (data from Engel and Franke 1983, Ahrendt et al. 1983) yield the plate margin perpendicular velocity component of the upper plate orogenic wedge during collision. The shelf thus contracted by 15 to 22 mm/a during the entire Upper Carboniferous (comp. Henk 1996). Uplift rates in the upper plate were modelled by Henk at around 3 mm/a in the earliest Upper Carboniferous for the central MGCR (Spessart and eastern Odenwald) decreasing to 0.2 mm/a until the end of the Carboniferous. Exhumation in the western Odenwald was slower (1.3 mm/a to 0.2 mm/a) from the late Lower Carboniferous until the end of Carboniferous. Data for the orogen-parallel extension rates of the MGCR are less conclusive. The minimum strain estimates ($>60\%$ stretching from mafic enclaves) and the minimum time frame of 360–325 Ma suggest that the averaged extension rate ranges between the overall convergence and the uplift velocities at some 8–10 mm/a. Consequently, the velocities at the major wrench zones confining the MGCR must be smaller (to enable shearing along the zone and stretching of the upper plate). In the case of the MGCR-Rhenohercynian boundary (active from 325 to 312 Ma), this would result in a partitioning-controlled component of less than 100 km average orogen-parallel wrench displacement (varying regionally from possibly 0 to as much as 300 km due to upper plate stretching relative to the lower plate). Additional wrench displacements controlled by plate boundary forces are possible, although the arcuate Variscan architecture in Europe does not allow for large values during the collision stage.

The complex 3D-deformation patterns on all scales naturally precludes any quantitative considerations or reconstructions of the entire system in 2D-space.

Geometric considerations

The destruction of crustal roots below the Variscan belt of Central Europe is usually attributed to postcollisional reequilibration of the orogen (e.g. Rey 1993). The processes involved, however, are a matter of debate. The lack of eclogites in xenolith populations from the former root does not support the presence of an eclogitized, seismically invisible root (Mengel 1990, Mengel and Kern 1990, Franz pers. comm.). The degree of extension observable at the surface ($<30\%$, Henk 1993) is insufficient to remove the roots. Mantle xenoliths do not show evidence of significant assimilation of crustal material (Franz, pers. comm.) Further possibilities like lateral flow of the roots without lithospheric extension, or delamination of the lithosphere with parts of the lower crust, which would moreover have resulted in a net loss of crustal material, are not supported by convincing evidence. For the area under consideration Behrmann et al. (1991) have calculated an average thickness of the root below the MGCR of some 50 km at a width of some 80 km from balancing studies. Recent analyses rather suggest that these values are minimum values (Oncken et al. 1997). These considerations, which rely on 2D-data, are reevaluated in the following taking into account the above kinematic data. The calculations in parts clearly have a large error, but, since all values derived from balancing etc. are conservative data, will still yield the minimum values for crustal volume, shortening, basin width, etc..

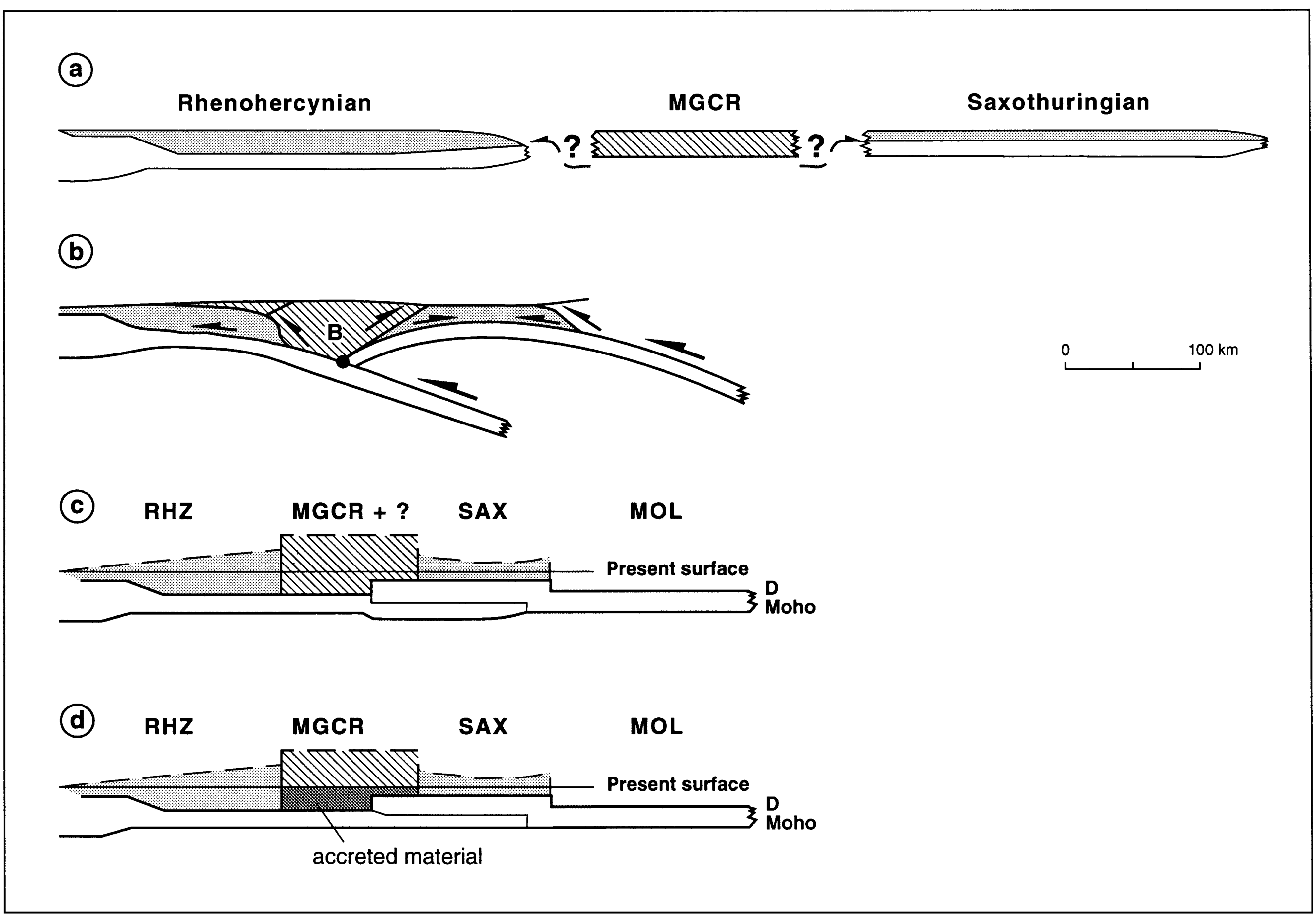
The Rhenohercynian upper crust has been shortened by 52% on average starting from a more than 350 km wide shelf (Dittmar et al. 1994, Oncken et al. 1997). The preservation of slope and rise sediments in the southernmost imbricates indicates that no shelf material was lost by subduction (Dittmar 1995). The detachment was identified from balancing exercises and from reflection seismic data at an average midcrustal depth of 10–12 km below top of sediments before deformation. Calculation of crustal thickness is derived from analysis of subsidence, basin flexure, and heat flow (Heinen 1996) and yields a 25–35 km thick crust (average: 29) in the Lower Carboniferous (basement + sediments). This is also the present average thickness from the foreland to the former suture. Because the present day detachment depth is again 10–15 km on average, lower crustal material below the present Rhenish Massif cannot have been deformed significantly during and after collision. The basement of 52% of the telescoped basin fill, i.e. some 180 km, must therefore be sought south of the boundary to the MGCR. Cross sectional area of underthrust lower Rhenohercynian crust thus amounts to a minimum of $2370\,km^2$ which is equivalent to ca. $1.9\cdot10^6\,km^3$ for the entire length of the Mid-European Rhenohercynian (some 800 km) between the present position of the Elbe and the Bray faults. These faults form the lateral boundaries with no evidence of material transfer across these faults. As the distance between the two faults which were active throughout upper plate deformation (see above) must have changed due to the established along strike extension by possibly as much as a factor of 1.6–2 (using the above strain data), the length of underthrust lower plate material overlapped by the extending Saxothuringian upper plate must have grown during collision.

Evaluation of the different seismic sections only yields cross sectional area for the underthrust lower plate crust varying between some 1000 to $1500\,km^2$ (equivalent to some $0.8–1.2\cdot10^6\,km^3$) depending on the identification of the upper-lower plate boundary. This leaves a gross difference of some $1300\,km^2$ (or $1\cdot10^6\,km^3$) or approximately 50% of continental Rhenohercynian crustal material for which there is no account. Since the existence of eclogitized crustal material is not corroborated and since extension would not have affected crustal volume, its apparent disappearance must be controlled by other mechanisms.

A simple area-balanced cartoon across the central part of the MGCR (parallel to line DEKORP 2 which crosses the central MGCR) helps to illustrate these aspects and to highlight further consequences. The crustal units involved in collision are shown with their respective restored cross sectional areas in Fig. 7a. The width of the former Saxothuringian basin and the depth of the syncollisional detachments is estimated from first order considerations of Behrmann et al. (1991) and Schäfer & Oncken (1996). Because most of its sedimentary evolution clearly is pelagic in nature, the former crustal thickness is estimated to be somewhat less than that of the Rhenohercynian. Shortening of the Saxothuringian sediments amounts to some 50%. The magmatic arc MGCR is reconstructed by taking its present width, an arbitrary shortening of ca. 40% (which is more than that observed in deformed mafic enclaves, but roughly corresponds to values calculated from average fold opening angles of 60°) and an average precollisional crustal thickness of 20 km or some 6–8 kb, thus allowing for marine sedimentation. This results in a width of 150 km for the former MGCR or some 3000 km^2 cross sectional area prior to collision. Collision of all units should yield a scenario similar to that in Fig. 7b (subduction angle and major detachment positions taken from seismic sections). This highlights the nature of the kinematically linked system of faults in 2D which appear at surface and act simultaneously (comp. Fig. 6).

The scenario in Fig. 7b is simplified to Fig. 7c applying three operations: 1) Simplifying unit geometry while conserving area (justified also by actual steep dip of boundaries), 2) unroofing by the values established from geobarometry of present surface rocks, 3) removing the possible but not definitely proven mantle wedge. This leads to the superposition of all units in Fig. 7c. It becomes clear that most, if not all of the upper plate must be underlain by the underthrust Rhenohercynian material if the latter were undeformed. Reduction in cross sectional area by removal of material out of section from especially the upper plate, as is implied by the deformation pattern (Fig. 6), does not significantly change this picture with exception of one important aspect. Upper plate area (especially MGCR area) is considerably reduced (the above shortening values are applied with close to plane strain conditions in map view as suggested by deformed xenoliths: minor shortening by some 40% with no significant vertical thickening and all shortening compensated by along

Fig. 7 Volumetric crustal balance in 2D-space based on bulk deformation of crustal units in the vicinity of lines DEKORP 2 and EGT across the central MGCR (see text for explanation)



strike stretching; algorithms from Winterfeld and Oncken 1995). Magmatic addition to the crust during subduction counteracts this aspect by increasing cross sectional area and volume during orogeny. It is included in Fig. 7d with a volumetric increase of 30% which is probably at the upper limit. The crustal area of the upper plate leading edge which remains after this correction (2000 km^2, identical to the present western MGCR cross sectional area!) now has its base near the present erosional level. This implies that the area from the surface down to the seismically identified base of the central MGCR (some 1000 km^2, see marked area in Fig. 7d) must be replaced by other material. At the same time, the subducted or underplated lower Rhenohercynian material which underlied the present Moho depth in Fig. 7c has to be accounted for. Interestingly, surplus and lacking areas in both plates are in the same order of magnitude. Or total crustal material roughly seems to balance on first order, although the different plates do not balance internally when the boundary identified from seismic and section balancing studies is accepted.

A simple way out of this dilemma follows from orogenic wedge theory (i.e. Davis et al. 1983, Platt 1986, Barr and Dahlen 1989). Orogenic wedges which evolve during subduction of a lower plate grow by incorporation of parts of the latter's sedimentary cover (and basement at times). Growth may either occur by frontal accretion at the tip of the wedge or by adding lower plate material by tectonic underplating or offscraping anywhere at the base of the wedge (Fig. 8). Particle paths may thus easily lead lower plate material into the upper plate.

In the present case, Oncken et al. (1997) presented evidence that the mode of accretion of the former Rhenohercynian passive margin sequence went through two stages as suggested by the regional distribution of synkinematic pressures. In a first stage, the southernmost exposed part (>70 km, $P = 2$–6 kb) was underthrust below the upper plate wedge (retained in the Giessen nappe relics). Sequential footwall collapse incorporated this sequence with parts of its basement into the wedge. After consumption of part of the margin the mode changed to frontal accretion with imbricate fans ($P < 2$ kb). Consequently, a similar accretionary mode for the deeper, underthrust parts of the Rhenohercynian crust from below the offscraped Devonian basin fill may have operated. The seismically visible suture would then only reflect its trace during the final motions. Part of its hangingwall would be constituted by former Rhenohercynian material. This has further consequences: most of the crustal thickening would be reduced by synorogenic and later unroofing at the top (as indicated in Fig. 7d which shows a flat Moho parallel to the present Moho if part of the underthrust material is accreted to the MGCR). Apart from erosion (into the flysch basins), orogen-parallel extension of the upper plate had a major role in this process and has helped to thin the growing crustal bulge.

The kinematic pattern of the MGCR and its variably exhumed crustal levels moreover suggest that stretching along strike is not homogeneous but rather dissects the upper plate into subsiding units (Saar precursor basin), units with only very minor uplift and exhumation (western MGCR and parts of the eastern Rise),

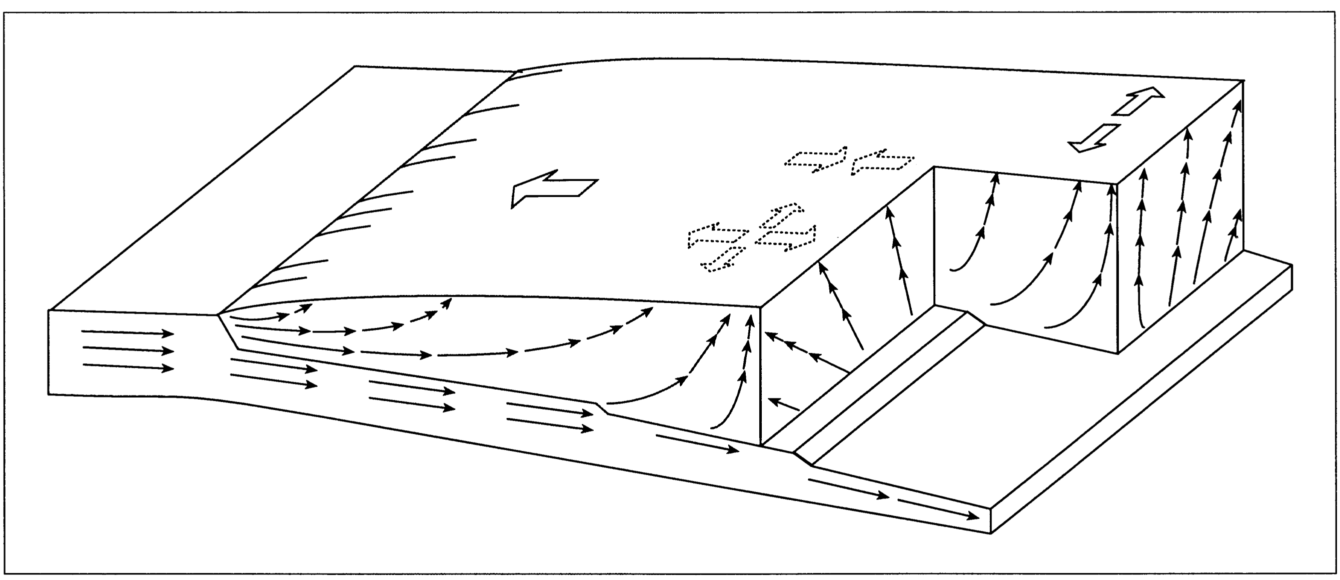


Fig. 8 Idealised particle displacement field in a propagating isotropic orogenic wedge showing frontal and basal accretion during oblique collision with reference to a coordinate system at the centre rear of the wedge. Length of arrows schematically depicts varying displacement rates. Arrows on top of wedge depict possible kinematic regimes in upper part of wedge depending on its taper and dynamic properties

and units which show unroofing by as much as 25–30 km. In the west, the 2000 km^2 cross sectional area of the deformed upper plate still fills the area down to the well visible basal detachment (calculated from eroded thickness plus thickness down to seismically identified base). In the central MGCR, this area is uplifted above the present surface (see Fig. 7d). The remaining 1000 km^2 between the eroded MGCR and the basal detachment in the section thus must be replaced from another source. This is roughly the amount of unaccounted for Rhenohercynian material (see above) in this section. Removal of most of the original arc crust during and after collision clearly has the consequence that part of the lower plate material, originally accreted at the base of the upper plate, may have reached surface. Parts of the present MGCR should be formed by metamorphosed Rhenohercynian crust replacing the former upper plate.

The volume accreted to the upper plate can be estimated from the material which is different from the Carboniferous magmatic arc identified in outcrop and seismically (i.e. eastern Odenwald, all or major parts of the Spessart, Rhoen area, Ruhla unit). Error in this calculation depends on uncertainties regarding identification of boundaries and estimating the amount of erosion of accreted material. The latter is believed to be of only minor importance: The rocks at the surface only expose allegedly Rhenohercynian basement of Lower Paleozoic age – no older or originally deeper basement has been identified thus far. This Lower Paleozoic material should thus be material from below the detached Rhenohercynian Devonian rocks. Removal of this Lower Paleozoic accreted material is estimated to be less than 1 kb. The resulting amount of accreted material is some $0.4 \cdot 10^6$ km^3. This is a minimum value because the lateral boundaries of the accreted bodies are included as steep boundaries in the Odenwald and west of the Kyffhäuser. This value is also considerably smaller than the above stated volume lost from the lower plate. Minor accretion below the other parts of the present MGCR may increase this value by as much as 60%. Roughly 2/3 of the unaccounted for Rhenohercynian material may thus be part of the present MGCR. Consequently, this also means that parts of the much debated Variscan root of this suture are literally at the surface.

Discussion

MGCR evolution and material paths

The former controversies and discrepancies between data and the standard model as summed up in the introduction are thus resolved when a composite nature of the MGCR is argued. The analysis suggests that the rock association of the present MGCR falls into two groups, each with a characteristic set of features. The Saxothuringian part of the MGCR represents relics of a Carboniferous magmatic arc which evolved on the relics of an older arc (also see Franke and Oncken 1995, Dombrowski et al. 1995). The alleged Rhenohercynian part of the MGCR rather reflects features typical of crustal stacking of a Lower Paleozoic sedimentary sequence, equally with relics of an older arc. The contacts between these contrasting two sequences are extensional or strike slip where established, the Saxothuringian MGCR always forms the upper plate.

This compositional evolution must have been controlled by the kinematic and rheological boundary conditions during collision. Internal kinematics of the MGCR during cooling and exhumation involve orogen-parallel extension of the entire composite MGCR in contrast to the earlier stacking history recorded only in the newly accreted parts. The mode of large scale crustal deformation in the upper plate during collision is adopted by the accreted rocks following their addition to the upper plate. The entire kinematic pattern observed obviously is the consequence of oblique collision with a domainal partitioning of the plate kinematic vector into domains of plate margin perpendicular contraction and plate margin parallel extension or wrenching. The degree of partitioning has been shown to be strongly controlled by the rheology of a plate couple (e.g. Platt 1993, Ellis et al. 1995). Weak zones – such as hot magmatic arcs – are especially susceptible for taking up the plate margin parallel strains. In a number of recent settings (New Zealand, Sumatra arc, Aleutian arc, San Andreas fault) oblique collision can be seen to produce similar patterns of deformation (e.g. Hickman 1990, Jackson 1992, Cashman et al. 1992, Mount and Suppe 1992). The pattern observed in the northern Variscides suggests a soft plate boundary zone and a partly soft upper plate during the Lower Carboniferous. Candidates for these units are the pelite-dominated phyllite belts to the north and south of the MGCR and the magmatically heated and thermally softened MGCR itself.

Within this kinematic framework mainly two aspects are of importance: Material transfer from the lower to the upper plate by basal accretion leads to a loss or 'switch of identity' of material with respect to plate provenance and forces to abandon the often implicitly held idea of an 'impermeable' plate boundary at depth. Vertical particle paths in the upper rear part of the orogenic wedge are overprinted by a significant horizontal component due to the established kinematic partitioning which leads to divergent displacement fields (Fig. 8). Consequently, the upper plate was thinned in cross section. Due to heterogeneous thinning and lateral basal accretion upper plate arc material may be preserved in structural depressions (as in the case of parts of the western MGCR). In structural highs arc material was lost from the top of the wedge by erosional removal and tectonic unroofing.

Laterally heterogeneous accretion also controls another aspect of MGCR evolution. Bivergent out of sequence thickening with fastest uplift rates at the site of the former arc (see also Henk 1996) must have caused the juxtaposition of the central part of the MGCR to the low grade wedges on both sides. It is interesting to note that this period of rapid uplift and inferred tectonic unroofing is confined to the early stage of underthrusting of the Rhenohercynian continental crust under the upper plate (330–320 Ma) and to formation of the retrowedge. The resultant destabilisation of the critical taper of the prograding wedge and pervasive deformation of the MGCR itself is nearly stopped after 325 Ma when deformation is transferred to the pro- and retrowedge couple on the flanks of the MGCR.

Laterally heterogeneous accretion into the MGCR also suggests that accretion conditions were not identical along the entire plate margin. The southern Rhenohercynian margin shows significant changes along strike: in the west (southern Hunsrück west of the river Rhine) Dittmar and Oncken (1992) and Dittmar (1995) have shown that a complete Devonian passive margin including the slope and rise part is exposed. Further east, the southern Taunus shows shelf margin units (Klügel et al. 1994, Klügel 1995) with only some hints to the proximity of an oceanic basin (isolated occurences of dykes with MORB affinity). In the southern Harz area and further east details of the former margin paleogeography are still lacking, the widespread occurence of olistostromatic rocks and nappes suggest that major parts or all of the passive margin is still covered by upper plate rocks (Lutzens 1991, Franke and Oncken 1995). In addition, pre-Devonian basement along strike also varies: medium grade Cadomian basement in the west, a thick unmetamorphic Lower Paleozoic volcano-sedimentary sequence (!) further east. These joint aspects suggest differences in margin width as well as mechanical properties and may thus be the reason for the observed lateral difference in accreted volume.

The bulk geometrical and kinematic evolution is summarised in Fig. 9. Magmatic input in the upper plate is shut off at the initiation of continental subduction. This is probably due to loss of the asthenospheric source because of reduction in the angle of subduction. The subsequent onset of addition of continental lower plate material to the upper plate by tectonic underplating was stopped when the important detachment branch line linking pro- and retrowedge migrated northwards below the MGCR and shut off its connection to the material source. Further underplating may now either have occurred further northwards (which is corroborated by the observations of Oncken et al., 1997, on the Rhenohercynian prowedge) and by accretion below the Saxothuringian basin (which is suggested by the seismic images). Moreover, the lack of HP-data in the prowedge (3 kb in the southern Rhenohercynian, 5–6 kb in the adjoining Phyllite belt, 5–9 kb in the accreted part of the MGCR) and the absence of eclogites seems to suggest that subduction geometry must have been such that supra-detachment rocks were not transported to greater depth. This implies a flat SE-dipping subduction zone until at least the southern margin of the MGCR not exceeding some 10° and/or a maximum depth of 10 kb for the migrating pro-retrowedge branch line.

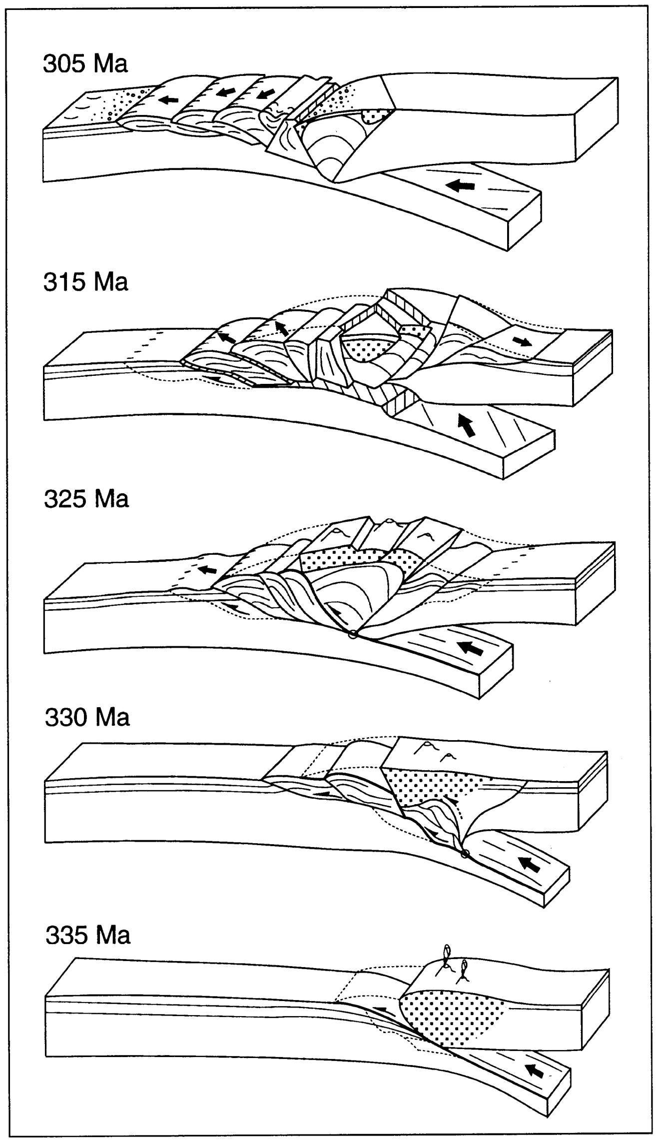


Fig. 9 Schematic sequential steps of syn- to postcollisional MGCR evolution during the Carboniferous showing material paths and kinematic evolution of the entire pro- and retrowedge system (section crossing boundary western-central part of the rise). Original magmatic arc and forearc material is shown in shaded mode. Eroded accretionary wedges on both sides are shown transparent with dashed boundaries only. Arrow on subduction zone shows inferred plate kinematic vector of upper plate. Observe motion of main detachment branch point and its control on the changing geometry of accretion. See text for further discussion

These considerations altogether suggest that the Variscan upper crustal sutures do, as a rule, not coincide with the lithospheric sutures. Lithospheric contraction is transferred to the subduction zone by a detachment system linking both wedges. Earlier traces of the suture, formerly at the top of the accreted material have been brought to the present surface as inactivated thrusts. A possible example of these might be the mylonitic zone with MORB-type amphibolites in the southern Spessart (Elterhof Series, Hirschmann and Okrusch 1988) which separates the alleged accreted Rhenohercynian rocks from Odenwald-type calc-alkaline rocks in the hangingwall. The MGCR as a composite crustal unit floats as a major rootless unit, deprived of its former mantle lithosphere, on underthrust lower crust from the Rhenohercynian and the Saxothuringian zones. Moreover, Fig. 7 suggests that the Saxothuringian and Moldanubian zones have lost their mantle lithosphere during progressive orogenic contraction. In order to accomodate the shortening observed, and to produce a flattened Moho, the inferred mantle lithosphere wedges of the respective upper plates must be completely removed and replaced by lower plate lithosphere. The Variscan Internides would thus form huge far-travelled crustal nappes without their original mantle lithosphere, and rest on parts of the former lower plate.

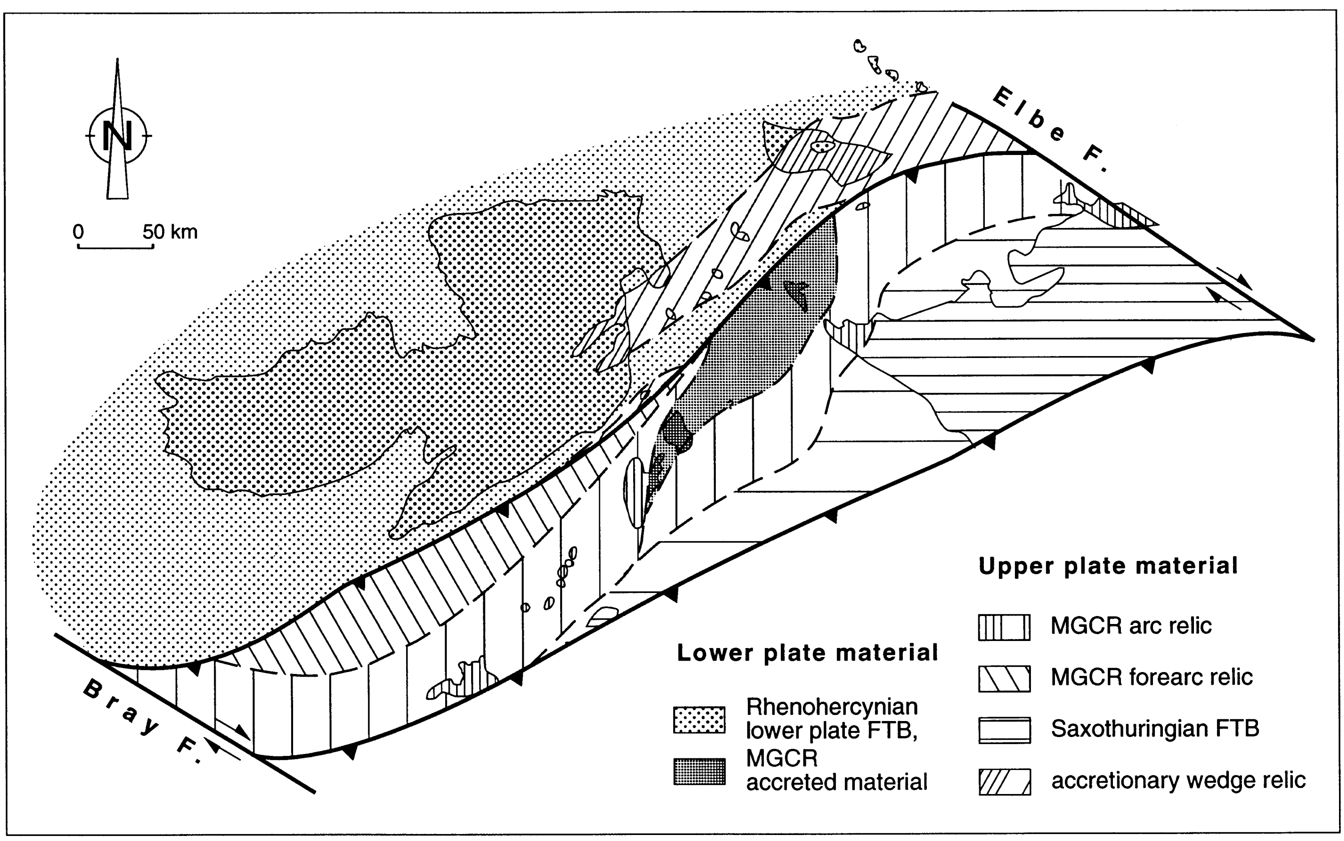
Solutions and Predictions

The discussed model can claim to solve most open questions listed in the introduction: the orogenic root aspect, the nature of lateral heterogeneity, the variable seismic patterns, the lack of a throughgoing paired metamorphic belt. A major consequence is a redefinition of the exposed rocks in Kossmat's (1927) paleogeographic zones based on the identification of geodynamic provenance as shown in Fig. 10 which emphasizes the role of material transfer as opposed to the notion of geodynamic units with constant identity.

Further implicit predictions may decide on the fate of this revised interpretation:

- This model predicts that future protolith dating in the accreted part of the MGCR should only yield Lower Paleozoic and older ages because the rocks accreted must be derived from below the basal detachment of the southern Rhenohercynian fold-thrust-belt. Balancing by Oncken et al. (1997) shows that this must be Pre-Devonian as a rule.

Fig. 10 Reinterpreted geodynamic map of Mid-European Variscides in terms of geodynamic provenance and setting of involved crustal units from plate couple during Carboniferous collision (FTB: fold thrust belt)



- Age of peak metamorphic conditions in the accreted part of the MGCR should decrease with structural depth (due to sequential accretion and exhumation) and should be Late Lower Carboniferous (later than the onset of collision and accretion of the southernmost Rhenohercynian rocks to the north). Deformation and metamorphic ages of the original upper plate MGCR may have a larger spread between the onset of subduction (early Upper Devonian) and the end of MGCR deformation (early Upper Carboniferous).
- Xenolith populations collected from Rhenohercynian basement north of the boundary to the MGCR should not significantly differ from the populations collected from sites of accreted MGCR (but out of sequence stacking may have produced a mix of rocks of old and accreted material !). Xenoliths collected from sites of preserved arc MGCR may be different (not necessarily if the basement is similar as suggested by Franke and Oncken 1995).
- Synorogenic flysch in neighbouring basins should record the switch in provenance with respect to detrital composition and ages as soon as the original upper plate is completely removed. Detrital data from the Rhenohercynian and allochthonous flysch of the Giessen-Harz nappe pile suggest that a magmatic arc is eroded (Floyd et al. 1990) during the Upper Devonian/Lower Carboniferous and that the material does not coincide compositionally with much of the present MGCR outcrop.
- Geometry, location, and volume of the flysch fan evolving north of the MGCR should record its variable exhumation and laterally heterogeneous accretion. Interestingly, preserved flysch thickness in the eastern Rhenish Massif and Harz mountains (both juxtaposed to the central MGCR) amount to several km while no significant flysch sediments are present in the western Massif (which is juxtaposed to the western MGCR).
- Most if not all of the Saxothuringian zone should be underlain by underplated Rhenohercynian material at a depth of some 20 ± 5 km. Traces may be found in petrological or geochemical features of xenolith populations or late- to post-orogenic crust-derived melts. If, as suggested in Fig. 7, also relics of the mantle wedge are involved, properly designed seismic studies should image this ‘sandwiching’.

Problems and perspectives

Several problems remain unsolved. The precollisional mode of material transfer may bear interesting implications. There is no evidence for significant accretion of oceanic crust to the upper plate in this stage. However, the actual proximity of the former magmatic arc to the lower plate and the acute wedge-shape of the upper plate leading edge in section DEKORP 1C (Fig. 5A) suggest that material from the upper plate must have been eroded tectonically prior to collision. In this case material from the upper plate changed into the lower plate by subduction erosion and must have been transported further south. Its whereabouts are unknown.

Last not least, unaccounted for Rhenohercynian material from the above crude volume balancing of some $0.3 \cdot 10^6$ km^3 – though significantly less than the original $1 \cdot 10^6$ km^3 – still leaves a problem with unclear meaning. Larger erosion of accreted material after its exhumation would reduce this figure by increasing the accreted volume. Rhenohercynian material reaching as far south as the Moldanubian would reduce the figure by increasing the amount of still present lower plate material underplated below the internal Variscan zones. The expected error in the above calculations as well as the operation of one or the other of the above listed root and crust-destructing mechanisms (lithospheric delamination, etc.) may both be further viable alternatives at present.

Within the Variscides the rather small arc of the MGCR only marks a minor feature related to the closure of a minor basin. This evolution is superposed on the large-scale plate-kinematic pattern of the Gondwana–Laurasia–Baltica collision and the intervening Variscan microplates (Ziegler 1986, Matte 1986, 1991). Several parts of the Variscan plate collage around Europe show relics of former upper-lower plate twins, especially in the more internal zones, the Saxothuringian and Moldanubian belts. Possibly thus, the mechanisms discussed in this paper may have operated and problems regarding rock distribution and crustal volumes may be resolved in a similar way. Fig. 7 clearly shows that Saxothuringian lower crust and mantle lithosphere should underlie most of the Moldanubian zone s.l.. Within the latter only the Tepla-Barrandian unit has the characteristics of an upper plate unit – i.e. a complete Paleozoic weakly to unmetamorphic sedimentary cover on Cadomian basement (Franke 1989). This unit and its offsprings (e.g. Münchberg nappes, etc.) overlie the Moldanubian s.str. and the southern Saxothuringian above an important shear zone which includes serpentinites and ultrabasic slivers. The Moldanubian s..str. is characterised by relic HP-HT-rocks overprinted by a regional HT-LP-event and thus has gone through a subduction cycle. The above discussion of particle paths in the MGCR suggests that also in this case lower plate material may have reached surface but has not been properly identified. Much if not all of the Mid-European Moldanubian s.str. may thus form a composite unit assembled from underthrust material of Saxothuringian provenance (from the north), of Rhenohercynian–Moravian provenance (from the east and southeast), and of Southern Black Forest–Morvan zone provenance (from the south), all accreted to the base of the Tepla-Barrandian. The Moldanubian zone thus cannot constitute a plate fragment with an own material identity.

In consequence, Kossmat's Variscan zones have no straightforward and unequivocal geodynamic identity during convergence and collision. Adherence to this concept with the commonly favoured geodynamic connotation moreover is prone to create pseudoproblems – such as the long quest for the Variscan roots – because orogenic mass transfer and material path lengths easily reach crustal scale dimensions. The notion of zones merely retains a geographic meaning of questionable scientific value unless paleogeographic coherence and geodynamic identity can be established. This however, can thus far only be claimed for subunits within the former zones as shown in Fig. 10.

Acknowledgements The present paper has greatly benefited from discussions with a number of people, especially from constructive criticisms by L. Franz, A. Henk, and W. Kramer. Careful reviews by J. Behrmann and W. Franke have greatly helped to elucidate the manuscripts contents. The support of all is gratefully acknowledged.

References

Ahrendt H, Clauer N, Hunziker JC, Weber K (1983) Migration of Folding and Metamorphism in the Rheinisches Schiefergebirge Deduced from K-Ar and Rb-Sr Age Determinations. In Martin H, Eder FW (eds) Intracontinental Fold Belts. Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia. Springer, Berlin Heidelberg New York pp 323–338

Ahrendt H, Clauer N, Franke W, Hansen BT, Teufel S (1986) Oberpfalz Geochronologie. Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland KTB, 2. KTB-Kolloquium 19.9.-21.9.1986, Seeheim/Odenwald, Poster-Programm

Ahrendt H, Franzke HJ, Marheine D, Schwab M, Wemmer K (1997) Zum Alter der Metamorphose in der Wippraer Zone/Harz – Ergebnisse von K/Ar-Datierungen an schwach metamorphen Sedimenten. Z dt Geol Ges (in press)

Aichroth B, Prodehl C, Thybo H (1992) Crustal structure along the central segment of the EGT from seismic-refraction studies. In Freeman R, Mueller S (eds) The European Geotraverse, Part 8. Tectonophysics 207 : 43–64

Altenberger U, Besch T (1993) The Böllstein Odenwald: evidence for pre- to early-Variscan plate convergence in the Central European Variscides. Geol Rundschau 82 : 475–488

Anderle HJ, Massonne HJ, Meisl S, Oncken O, Weber K (1990) Southern Taunus Mountains. In: Field Guide "Mid German Crystalline Rise, Rheinisches Schiefergebirge" (Internat. Conf. on Paleozoic Orogens in Central Europe), Göttingen-Gießen 1990, pp 125–148

Anthes G, Reischmann T (1995) Regional variations of Nd and Sr isotopes of the Mid German Crystalline Rise. Beitragszusammenfass. des 4. Koll. im DFG-SPP 'Orogene Prozesse', Terra Nostra 95/8 : 78

Arthaud F, Matte P (1977) Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Results of a right-lateral shear zone between the Appalachians and the Urals. Geol Soc Amer Bull 88 : 1302–1305

Bachtadse V, Torsvik TH, Tait JA, Soffel HC (1995) Paleomagnetic constraints on paleogeographic evolution of Europe during the Paleozoic. In: Dallmeyer D, Franke W, Weber K (eds) Pre-Permian Geology of Central and Western Europe. Springer, Berlin Heidelberg New York, pp 567–578

Bankwitz P, Bankwitz E, Kramer W, Pin C (1994) Early Paleozoic bimodal volcanism in the Vesser area, Thurigian Forest. Zbl. Geol. Paläont. Teil I 1992 : 1113–1132

Barr TD, Dahlen FA (1989) Brittle frictional mountain building; 2, Thermal structure and heat budget. J Geophys Res B 94 (4): 3923–3947

Behr HJ (1966) Das metamorphe Grundgebirge im Thüringer Becken. Ber dt Ges Geol Wiss Geologie und Paläontologie A11 : 39–56

Behr HJ, Heinrichs T (1987) Geological interpretation of DEKORP 2-S; a deep seismic reflection profile across the Saxothuringian and possible implications for the late Variscan structural evolution of Central Europe. Tectonophysics 142 : 173–202

Behrmann J, Drozdzewski G, Heinrichs T, Huch M, Meyer W, Oncken O (1991) Crustal-scale balanced cross sections through the variscan fold belt, Germany: the central EGT-segment. Tectonophysics 196 : 1–21.

Brinkmann R (1948) Die Mitteldeutsche Schwelle. Geol Rundschau 36 : 56–66

Cashman S, Kelsey HM, Erdman CF, Cutten HNC, Berryman KR (1992) Strain partitioning between structural domains in the forearc of the Hikurangi subduction zone, New Zealand. Tectonics 11 : 242–257

Davis D, Suppe J, Dahlen FA (1983) Mechanics of fold-and-thrust belts and accretionary wedges. J Geophys Res B 88 : 1153–1172

DEKORP Research Group (1985) First results and preliminary interpretation of deep-reflection seismic recordings along profile DEKORP 2-South. J Geophys 57 : 137–165

DEKORP Research Group (1991) Results of the DEKORP 1 (BELCORP-DEKORP) deep seismic reflection studies in the western part of the Rhenish Massif. Geophys J Int 106 : 203–227

DEKORP Research Group (1994) The deep reflection seismic profiles DEKORP 3/MVE-90. Zt f Geol Wiss 22 : 623–825

Dittmar U (1995) Profilbilanzierung und Verformungsanalyse im südwestlichen Rheinischen Schiefergebirge – Zur Konfiguration, Deformation und Entwicklungsgeschichte eines passiven varistischen Kontinentalrandes. Unpubl. PhD thesis Univ Würzburg, pp 1–465

Dittmar U, Oncken O (1992) Anatomie und Kinematik eines passiven varistischen Kontinentalrandes – Zum Strukturbau des südwestlichen rheinischen Schiefergebirges. Frankf geowiss Arb, A 11 : 34–37

Dittmar U, Meyer W, Oncken O, Schievenbusch T, Walter R, von Winterfeld C (1994) Strain partitioning across a fold and thrust belt: the Rhenish Massif, Mid-European Variscides. J Struct Geol 16 : 1335–1352

Dombrowski A, Henjes-Kunst F, Höhndorf A, Kröner A, Okrusch M, Richter P (1995) Orthogneisses in the Spessart Crystalline Complex, Northwest Bavaria: Silurian granitoid magmatism at an active continental margin. Geol Rundschau 84 : 399–411

Donsimoni M (1981) Le Bassin Houiller Lorrain. Mèm Bur Rech Geol Min 117, Orléans CEDEX, pp 1–102

Ellis S, Fullsack P, Beaumont C (1995) Oblique convergence of the crust driven by basal forcing: implications for length-scales of deformation and strain partitioning in orogens. Geophys J Int 120 : 24–44

Engel W, Franke W (1983) Flysch-Sedimentation: Its Relations to Tectonism in the European Variscides. In: Martin H, Eder FW (eds) Intracontinental Fold Belts. Case Studies in the Variscan Belt of Europe and the Damara Belt in Namibia. Springer, Berlin Heidelberg New York pp 289–321

Engel W, Franke W, Langenstrassen F (1983) Palaeozoic sedimentation in the northern branch of the Mid-European Variscides; Essay of an interpretation. In: Martin H, Eder FW (eds) Intracontinental Fold Belts. Springer Verlag Berlin Heidelberg New York, pp 9–41

Floettmann T, Oncken O (1992) Constraints on the evolution of the Mid German crystalline rise; a study of outcrops west of the River Rhine. Geol Rundschau 81 : 515–543

Floyd PA (1984) Geochemical characteristics and comparison of the basic rocks of the Lizard Complex and the basaltic lavas within the Rhenohercynian troughs of SW England. J Geol Soc London 141 : 61–70

Floyd PA, Leveridge BE, Franke W, Shail R, Dörr W (1990) Provenance and depositional environment of Rhenohercynian synorogenic greywackes from the Giessen Nappe, Germany. Geol Rundschau 79 : 611–626

Franke W (1989) Tectonostratigraphic units in the Variscan belt of Central Europe. Geol Soc Amer Spec Pap 230 : 67–90

Franke W (1993) The Saxonian granulites; a metamorphic core complex?. Geol Rundschau 82 : 505–515

Franke W, Oncken O (1990) Geodynamic evolution of the North-Central Variscides – a comic strip. In: Freeman R, Giese P, Mueller S (eds) The European Geotraverse: Integrative Studies (eds), Results from the 5th Study Centre 26.3–7.4.1990, European Science Foundation, Strassbourg, pp 187–194

Franke W, Oncken O (1995) Zur prädevonischen Geschichte des Rhenohercynischen Beckens. Nova Acta Leopoldina NF 71, 291 : 53–72

Freeman R, Mueller S (eds) (1992) A continent revealed: the European Geotraverse. Cambridge University Press: pp 164–179

Grösser J, Dörr W (1986) MOR-Typ-Basalte im östlichen Rheinischen Schiefergebirge. N Jb Geol Paläont Mh 12 : 705–712

Heinen V (1996) Simulation der präorogenen devonisch-unterkarbonischen Beckenentwicklung und Krustenstruktur im Linksrheinischen Schiefergebirge. Aachener Geowiss Beitr 15 : 1–161

Henes-Klaiber U (1989) Der Odenwald: Hinweise auf einen variszischen Arc-Magmatismus? Beih Europ J Mineral 1/1 : 66

Henk A (1993) Late orogenic basin evolution in the Variscan Internides; the Saar-Nahe Basin, Southwest Germany. Tectonophysics 223 : 273–290

Henk A (1995) Late-Variscan exhumation histories of the southern Rhenohercynian Zone and western Mid-German Crystalline Rise – results from thermal modeling. Geol Rundschau 84 : 578–590

Henneberg E, Pilot W, Werner CD (1994) Neue Datierungen an Einzelzirkonen nach der Evaporationsmethode von verschiedenen Einheiten des Ruhlaer Kristallins. Ber dt min Ges 1/1994 : 103

Hering O, Zimmerle W (1976) Petrographische Beschreibung und Deutung der erbohrten Schichten (Saar 1). Geol Jb A 27 : 91–306

Hess JC, Schmidt G (1989) Zur Altersstellung der Kataklasite im Bereich der Otzberg-Zone, Odenwald. Geol Jb Hessen 117 : 69–77

Hickman SH (1990) The strength of active faults in the Earth's crust and the high stress/low stress controversy. Eos 71 (43) : 1579–1580

Hirschmann G (1995) Mid German Crystalline High – Lithological Characteristics. In: Dallmeyer RD, Franke W, Weber K (eds) Tectonostratigraphic Evolution of the Central and East European Orogens, Springer, Berlin Heidelberg New York, pp 155–166

Hirschmann G, Okrusch M (1988) Spessart-Kristallin und Ruhlaer Kristallin als Bestandteile der Mitteldeutschen Kristallinzone; ein Vergleich. N Jb Geol Palaeont Abhandlungen 177 : 1–39

Holder MT, Leveridge BE (1986) Correlation of the Rhenohercynian Variscides. J Geol Soc London 143 : 141–147

Jackson J (1992) Partitioning of strike slip and convergent motion between Eurasia and Arabia in eastern Turkey and the Caucasus. J Geophys Res B 97 : 12471–12479

Kämpfe C (1984) Tiefbohrungen in Baden-Württemberg und umgebenden Ländern. Arb Inst Geol Paläont Univ Stuttgart NF 80, pp 1–313

Kirsch H, Kober B, Lippolt HJ (1988) Age of intrusion and rapid cooling of the Frankenstein gabbro (Odenwald, SW Germany) evidenced by $^{40}Ar/^{39}Ar$ and single zircon $^{207}Pb/^{206}PB$ measurements. Geol Rundschau 77 : 693–711

Klügel T (1995) Geometrie und Kinematik einer varistischen Plattengrenze – der Südrand des Rhenoherzynikums im Taunus. Unpubl. PhD thesis Univ Würzburg, pp 1–165

Klügel T, Oncken O (1994) Geometrie und Deformationsgeschichte der Phyllit-zone/Taunussüdrand. Abstract TSK V, Göttingen, pp 179–181

Klügel T, Ahrendt H, Oncken O, Käfer N, Schäfer F, Weiss B (1994) Alter und Herkunft der Sedimente und des detritus der nördlichen Phyllit-Zone (Taunussüdrand). Z dt Geol Ges 145 : 172–191

Kossmat F (1927) Gliederung des varistischen Gebirgsbaues. Abh sächs geol Landesamt 1 : 1–39

Kreuzer H, Harre W (1975) K/Ar-Altersbestimmungen an Hornblenden und Biotiten des Kristallinen Odenwaldes. Aufschluß 27 (Sonderband Odenwald): 71–77

Krohe A (1991) Emplacement of synkinematic plutons in the Variscan Odenwald (Germany) controlled by transtensional tectonics. Geol Rundschau 80 : 391–409

Krohe A (1992) Structural evolution of intermediate-crustal rocks in a strike-slip and extensional setting (Variscan Odenwald, SW Germany); differential upward transport of metamorphic complexes and changing deformation mechanisms. Tectonophysics 205 : 357–386

Laue S, Reischmann T, Emmermann KH (1990) Geochemical variation of granitoid rocks from the NW margin of the Rhinegraben. Beih Europ J Mineral 2/1 : 156

Lippolt HJ (1986) Nachweis altpaläozoischer Primäralter (Rb-Sr) und karbonischer Abkühlalter (K-Ar) der Muscovit-Biotit-Gneise des Spessarts und der Biotit-Gneise des Odenwaldes. Geol Rundschau 75 : 569–583

Linnemann U, Buschmann B (1995) Terrane der Saxothuringischen Zone. Beitragszusammenfass. des 4. Koll. im DFG-SPP 'Orogene Prozesse', Terra Nostra 95/8 : 115

Lorenz V, Nicholls IA (1984) Plate and intraplate processes of Hercynian Europe during the Late Paleozoic. Tectonophysics 107 : 25–56

Lutzens H (1991) Flysch, Olisthostrome und Gleitdecken im Unter- und Mittelharz. Zt f Geol Wiss 19 : 617–623

Matte P (1986) Tectonics and Plate Tectonics Model for the Variscan Belt of Europe. Tectonophysics 126 : 329–374

Matte P (1991) Accretionary history and crustal evolution of the Variscan belt in Westem Europe. Tectonophysics 196 : 309–337

Mattern F (1996) : The Elbe zone at Dresden – a Late Paleozoic pull-apart intruded shear zone. Z dt Geol Ges 147 : 57–80

Meisl S (1990) Metavolcanic rocks in the "Northern Phyllite Zone" at the southern margin of the Rhenohercynian Belt. In: Field Guide "Mid German Crystalline Rise, Rheinisches Schiefergebirge" (Internat. Conf. on Paleozoic Orogens in Central Europe), Göttingen-Gießen 1990, pp 25–42

Mengel K (1990) Crustal xenoliths from Tertiary volcanics of the northern Hessian Depression; petrological and chemical evolution. Contrib Mineral Petrol 104 : 8–26

Mengel K, Kern H (1990) Petrologic versus seismic Moho and crustal root mysteries of the Hercynian orogen. In: Freeman R, Giese P, Mueller S (eds) The European geotraverse: Integrative Studies. Results from the fifth study centre, pp 169–176

Montigny R, Schneider C, Royer JY, Thuizet R (1983) K-Ar dating of some plutonic rocks of the Vosges. Terra Cognita 3 : 201

Mount VS, Suppe J (1992) Present-day stress orientations adjacent to active strike slip faults: California and Sumatra. J Geophys Res B 97 : 11995–12013

Nasir S, Okrusch M, Kreuzer H, Lenz H, Höhndorf A (1991) Geochronology of the Spessart Crystalline Complex, Mid-German Crystalline Rise. Mineral Petrol 44 : 39–55

Neumann W (1966) Versuch eines lithostratigraphischen Vergleiches von Grundgebirgsanschnitten im Bereich der Mitteldeutschen Kristallinschwelle. Geologie Berlin 15 : 942–962

Okrusch M (1995) Mid German Crystalline High – Metamorphic Evolution. In: Dallmeyer RD, Franke W, Weber K (eds) Tectonostratigraphic Evolution of the Central and East European Orogens, Springer, Berlin Heidelberg New York

Okrusch M, Richter P (1986) Orthogneisses of the Spessart Crystalline Complex, Northwest Bavaria: Indicators of the geotectonic environment? Geol Rundschau 75 : 555–568

Oncken O (1988a) Geometrie und Kinematik der Taunuskammüberschiebung, Beitrag zur Diskussion des Deckenproblems im südlichen Schiefergebirge. Geol Rundschau 77 : 551–575

Oncken O (1988b) Aspects of the reconstruction of the paleostress history of a fold and thrust belt (Rhenish Massif, FRG). Tectonophysics 152 : 19–40

Oncken O (1989) Geometrie, Deformationsmechanismen und Kinematik großer Störungzonen der hohen Kruste (Beispiel Rheinische Schiefergebirge). Geotektonische Forschungen 73 : 1–215
Oncken O, Winterfeld Cv, Dittmar U (1997) Inversion and telescoping of a passive margin sequence – the Rhenohercynian belt (central European Variscides). Tectonics (submitted)
Platt JP (1986) Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geol Soc Amer Bull 97 : 1037–1053
Platt JP (1993) Mechanics of oblique convergence. J Geoph Res B 98 : 16239–16256
Reitz E (1987) Palynologie in metamorphen Serien: I. Silurische Sporen aus einem granatführenden Glimmerschiefer des Vor-Spessart. N Jb Geol Paläont Mh 1987 : 699–704
Rey P (1993) Seismic and tectonometamorphic characters of the lower continental crust in Phanerozoic areas; a consequence of post-thickening extension. Tectonics 12 : 580–590
Roellig G, Kampe A, Steinbach V, Ehling BC, Wasternack L (1995) Der Untergrund des Mitteldeutschen Braunkohlereviers. Z Geol Wiss 23 : 3–26
Ruchholz K (1989) Entwicklung und gerichtete Transformation von oberdevonisch-unterkar-bonischer Flyschsedimentation und Olisthostromen im oestlichen Rhenoherzynikum (Harz). Zt Geol Wiss 17 : 581–588
Schäfer A (1989) Variscan molasse in the Saar-Nahe basin (W-Germany), Upper Carboniferous and Lower Permian. Geol Rundschau 78 : 499–524
Schmidt FP, Gebreyohannes Y, Schliestedt M (1986) Das Grundgebirge der Rhoen. Zt dt Geol Ges 137 : 287–300
Scholtz H (1930) Das varistische Bewegungsbild. Fortschr Geol Paläont VIII/25 : 235–316
Siedel H, Theye T (1993) Very low-grade metamorphism of pelites in the Wippra metamorphic zone, Harz Mountains, Germany. N Jb Mineral Monatshefte 1993 : 115–132
Sommermann AE (1993) Zirkonalter aus dem Granit der Bohrung Saar 1. Beih Europ Journ Mineral 5/1 : 145
Teufel S (1988) Vergleichende U-Pb- und Rb-Sr-Altersbestimmungen an Gesteinen des Übergangsbereichs Saxothuringikum/Moldanubikum, NE-Bayern. Gött Arb Geol Paläont 35, Göttingen, pp 1–87
Weber K, Behr HJ (1983) Geodynamic interpretation of the mid European Variscides. In: Martin H, Eder FW (eds) Intracontinental Fold Belts. Springer, Heidelberg New York, pp 427–469
Weber K, Juckenack C (1990) The structure of the Spessart Mts. crystalline basement and it's position in the frame of the European Variscides. In: Field guide, Mid-German Crystalline Rise and Rheinisches Schiefergebirge, Int. Conf. Paleozoic Orogens in Central Europe, Göttingen-Giessen, pp 101–114
Wenzel F, Brun JP, ECORS-DEKORP working group (1991) A deep seismic reflection line across the Northern Rhine Graben. Earth Planet Sci Lett 104 : 140–150
Wenzel T, Hengst M, Pilot J (1993) The plutonic rocks of the Elbe Valley-zone (Germany); evidence for the magmatic development from single-zircon evaporation and K-Ar age determinations. Chemical Geology 104 : 75–92
Wickert F, Eisbacher GH (1988) Two-sided Variscan thrust tectonics in the Vosges Mountains in northeastern France. Geodin Acta 2/3 : 101–120
Wickert F, Altherr R, Deutsch M (1990) Polyphase Variscan tectonics and metamorphism along a segment of the Saxothuringian-Moldanubian boundary: The Baden-Baden Zone, northern Schwarzwald (F.R.G.). Geol Rundschau 79 : 627–647
Wildberg HGH (1990) Granitoide aus den saxothuringischen und moldanubischen Vogesen: Zeugen einer Entwicklung von Subduktion zu Kollision. Beih Europ J Mineral 2/1 : 280
Willner A, Massonne HJ, Krohe A (1991) Thermal evolution of a Variscan magmatic arc: The Odenwald (FR Germany) as an example. Geol Rundschau 80 : 369–390
Winterfeld Cv, Oncken O (1995) Strain and the restoration of balanced sections. J Struct Geol 17 : 447–450
Zeh A (1995) Die Druck-Temperatur-Deformations-Entwicklung des Ruhlaer Kristallins (Mitteldeutsche Kristallinzone). Unpubl. PhD thesis Univ Würzburg, pp 1–254
Ziegler PA (1986) Geodynamic Model for the Paleozoic Crustal Consolidation of Western and Central Europe. Tectonophysics 126 : 303–328
Zulauf G (1993) The Moldanubian/Saxothuringian boundary at the western border of the Bohemian Massif – a polyphase strike-slip zone. Zt dt Geol Ges 144 : 68–87