© 1981 GEOLOGIE EN MIJNBOUW 0016-7746/81/0300-0149 $ 2.50/0

THE STRUCTURAL DEVELOPMENT OF THE RHEINISCHE SCHIEFERGEBIRGE[1]

K. WEBER[2]

ABSTRACT

Weber, K. 1981 The structural development of the Rheinische Schiefergebirge. *In:* H. J. Zwart & U. F. Dornsiepen (eds.): The Variscan Orogen in Europe – Geol. Mijnbouw 60: 149-159.

The structural framework of the Rheinische Schiefergebirge is characterized by NW-facing folds with a more or less strongly developed slaty cleavage and by listric overthrusts. The listric overthrusts of the Subvariscan Foredeep often are folded. Nappe displacements are assumed for the southeastern Rheinische Schiefergebirge.

Based on their tectonic movement pictures two different types of listric overthrusts can be distinguished in the Rheinische Schiefergebirge:

(1) Listric overthrusts forming simultaneously with folding. As the upward decreasing displacement may be compensated by folding, the overthrusts may die out at higher tectonic levels. During folding and thrusting fold-axial planes and thrust planes are rotated to NW. As a result of uplift and rotation to NW, both being related to folding and thrusting, secondary structures occur: low dipping NW-facing overthrusts and, locally, a SE-dipping post-crystalline crenulation cleavage.

(2) Listric overthrusts which cut pre-existing NW-facing fold structures. This gives rise to an antithetic rotation of the overthrusted block and thus to a steepening of the originally NW-facing folds and cleavage planes. This rotation is intensified by further tectonic shortening and finally results in NW-dipping axial planes and cleavage planes. As a consequence of the SE-directed rotation of the overthrusted blocks a cleavage fan develops, which becomes overprinted by a predominantly flat-lying post-crystalline second cleavage.

The youngest tectonic fabrics are kink bands. They occur in areas of late tectonic uplift and must be interpreted as extension structures.

The character of metamorphism in the Rheinische Schiefergebirge is of a low pressure and high temperature with metamorphic temperatures not higher than 350 °C except in the metamorphic zone of the Taunus, where temperatures of 400-450 °C were reached.

The metamorphism in the Rheinische Schiefergebirge is syntectonical with respect to the folding and its associated first cleavage. According to radiometric datings the age of folding in the southernmost part of the Rheinische Schiefergebirge is about 330 Ma and increases continuously towards the north to about 300 Ma. Folding and metamorphic development are continuous processes without distinguishable phase-like events.

The Rheinische Schiefergebirge must be regarded as an ensialic orogen. Its geodynamic development is interpreted as being the result of A-subduction, i.e. subduction of lithospheric mantle below continental crust.

INTRODUCTION

The Rheinische Schiefergebirge is a part of the Rhenohercynian Zone (KOSSMAT, 1927). This Rhenohercynian Zone forms the northern external zone of the Hercynian Orogen, and is bordered to the south by the mid-German Crystalline Rise (Mitteldeutsche Schwelle, Fig. 1). The molasse basin of the Sub-Variscan Foredeep joins the Rhenohercynian Zone to the NW and extends continuously for over 400 km into the North Sea region.

The geosynclinal development of the Rheinische Schiefergebirge may be outlined here only briefly. Sedimentation starts in the Early Devonian with rapid accumulation of thick sequences of neritic sediments, derived from the Old Red

---

[1] This work forms part of the research programme of the Sonderforschungsbereich 48 'Entwicklung, Bestand und Eigenschaften der Erdkruste, insbesondere der Geosynklinalräume' at the University of Göttingen. Funds for this work were provided by the Deutsche Forschungsgemeinschaft.

[2] Geologisch-Paläontologisches Institut, Abteilung für Tektonik, Goldschmidt-Straße 3, 3400 GÖTTINGEN, Federal Republic of Germany.

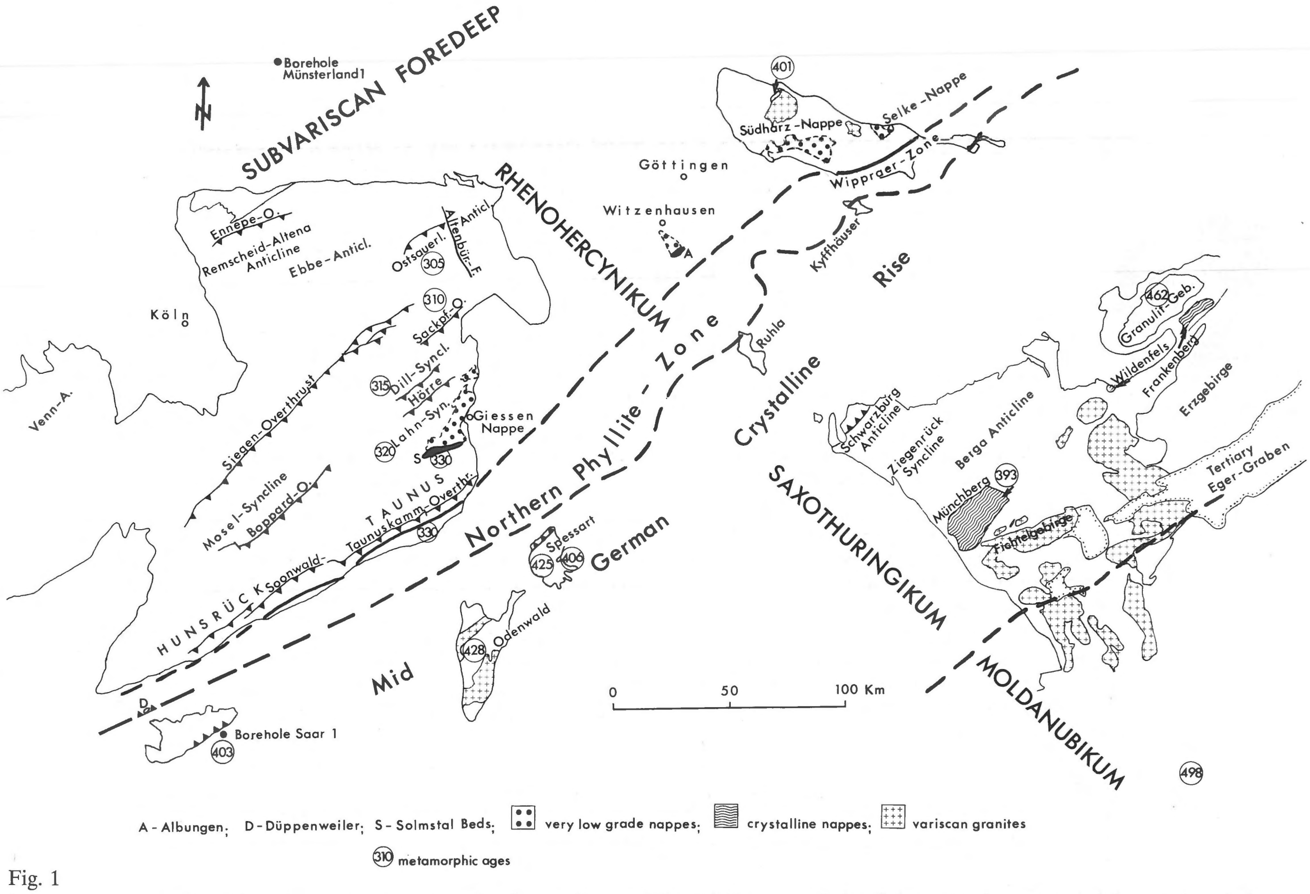


Fig. 1
Structural map of the Rhenohercynian and Saxothuringian Zones. The Rb/Sr ages of the Odenwald, Spessart and Saar 1 borehole are interpreted as intrusion ages of early orogenic granitoids. (Rb/Sr-ages are recalculated by using λ Rb^{87} = 1.47 × $10^{-11}y^{-1}$)

continent in the north. During the Early Devonian the main depocentres are positioned in the southern part of the Rheinische Schiefergebirge. They receded northwards during Devonian time, forming northwards-moving shelf basins with clastic sequences up to 5000 m. These sequences are interpreted by FRANKE ET AL. (1978) as belonging to the Caledonian Molasse

This phase was followed by a phase of stagnation with diminished subsidence and sedimentation (FRANKE ET AL., 1978). The condensed pelagic sequences have been deposited at water depths, probably less than 1000 m. Geosynclinal volcanism (keratophyres and tholeiitic basalts) was active from Emsian to Viséan, with main activities during the Givetian and Early Carboniferous. In the Lahn- and Dill-Syncline 600-700 m of Middle Devonian volcanoclastics are forming rises. On such sites thick reef limestones or condensed cephalopod limestones were accumulated. There is no evidence of a Rhenohercynian ocean.

After the occurrence of precursory greywackes in the southern Rheinische Schiefergebirge and the southern Harz Mountains during Late Devonian time and olisthostromes of Late Devonian age (STOPPEL, 1977) or Early Carboniferous age (SCHWAB, 1974; LUTZENS, 1975) in the southern Harz Mountains, the main phase of flysch sedimentation starts in the Upper Viséan (cd III α). The source area of the Rhenohercynian flysch was the mid-German Crystalline Rise (Mitteldeutsche Schwelle). The Upper Viséan flysch fills up the submarine relief and enlarges the flysch basin to the north. After FRANKE ET AL. (1978) accumulation outdoes subsidence by late Namurian times and sedimentation is continued in paralic environments. The depocentre of the molasse basin continues to migrate northwards through the Late Carboniferous. 'It is only a quantitative change that switches the system from flysch to molasse and there is no need to look for new geodynamic factors' (FRANKE ET AL., 1978, p. 212) (see more details in WALLISER, this issue).

Like the sedimentary development, the structural and metamorphic development of the Rheinische Schiefergebirge and the Subvariscan Foredeep are characterized by strong NW-polarity. The structures of the Rheinische Schiefergebirge continue below the Cretaceous cover to the Münsterland Basin. The Hercynian structures are well-known, particularly in the western part of the Subvariscan Foredeep, i.e. in the Ruhr-District (Fig. 2). Here the folding gradually fades (PAPROTH & TEICHMÜLLER, 1961; HOYER ET AL., 1974).

The northern part of the Ruhr-Basin is characterized by wide synclinal and narrow anticlinal structures. To the SE deformation increases and NW-facing folded listric over-

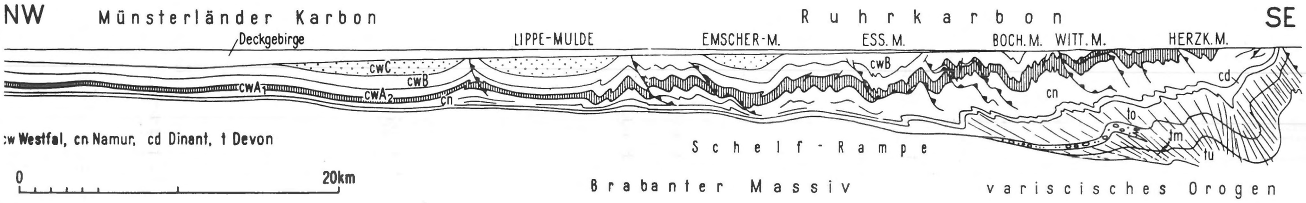


Fig. 2
Cross-section through the Subvariscan Foredeep. (After PAPROTH & TEICHMÜLLER, 1961).

thrusts are frequent (Fig. 2). As shown by the result of the borehole Münsterland 1 deformation increases with depth. In the region of the Münsterland 1 borehole slaty cleavage develops at approximately 4000 m and becomes more intense downward (TEICHMÜLLER ET AL., 1979; FÜCHTBAUER, 1963). At the southern margin of the Subvariscan Foredeep the structural level showing slaty cleavage is exposed. Metamorphism grades from diagenesis to the lower anchizone (TEICHMÜLLER ET AL., 1979).

The cross-section presented here is predominantly based upon literature. The following publications are used for drafting of the cross-section: AHLBURG (1918), AHRENDT ET AL. (1977), DENCKMANN & QUIRING (1923), EBERT (1961, 1968), KEGEL (1929, 1934), KÜHNE (1978), LIESCHE (1979), LIPPERT ET AL. (1970), LEUTERITZ (1972), MEYER (1962), MITTMEYER (1962), REICH (1928), SAUERLAND (1980), SCHMIERER (1930), THOME (1968), WOHLBURG (1933).

The structural cross-section (Fig. 3) approximately follows the cross-section of the facies development represented by WALLISER (this issue).

DESCRIPTION OF THE CROSS-SECTION THROUGH THE RHEINISCHE SCHIEFERGEBIRGE

The structural style of the Rheinische Schiefergebirge east of the River Rhine is characterized by NW-facing folds and overthrusts.

In the most northern part of the cross section A-A', in the area of the Nuttlar Syncline, the fold-envelope dips approximately at 30° to the NW. This plunge is most clearly apparent in the southern part of the Nuttlar Syncline (sheet Meschede: THOME, 1968; and sheet Eversberg: EBERT, 1961).

The East Sauerland Anticline which succeeds it on the south, forms the dominant anticlinal structure in the NE Rheinische Schiefergebirge. It displays strongly developed slaty cleavage (BEHREND & PAECKELMANN, 1937; PAECKELMANN, 1933; EBERT, 1955, 1968; HELLERMANN, 1965; WEBER, 1972, 1976, 1978).

The East Sauerland Anticline forms a NW-facing, large-scale fold with axial plunges to both NE and SW. The strongly overturned northwestern limb is cut by numerous overthrusts of different ages and attitudes. An older sequence of overthrusts is coeval with the folding. These are interpreted as listric overthrusts (WEBER, 1978). Since their throw, decreasing upward, may be compensated by folding, the overthrusts die out at high tectonic levels (Fig. 4).

During folding and thrusting fold-axial planes and thrust-planes were rotated to the NW. In response to uplift and rotation to the NW, secondary structures were formed. These are low dipping NW-facing overthrusts (which are widespread in other parts of the Rheinische Schiefergebirge also) and a SE-dipping post-crystalline crenulation cleavage, similar to that found in the northern part of the Taunus Anticlinorium (see Fig. 5). Both structures contributed to the NW-directed tectonic transport which was in effect during advanced stages of the folding. The youngest tectonic fabrics are north-dipping kink bands and south-dipping normal faults of the same ages. They form a shear system with shear planes which differ in their morphology depending on their different attitudes to the anisotropy represented by the slaty cleavage. The relative movement along these shear planes indicates a more or less horizontal extension during late tectonic uplift (WEBER, 1978).

On the south a number of smaller synclinal and anticlinal structures follow, forming the western continuation of the Waldeck Syncline. The fold-axial planes dip more steeply to the south and reach a more or less vertical attitude in the Latrop Anticline and in the Wittgenstein Syncline. In the Wittgenstein Syncline local weak SE-vergence occurs.

In the southern part of the Wittgenstein Syncline, which is limited on the south by the Sackpfeifen Overthrust, NW-facing folds occur again. Along the eastern border of the Rheinische Schiefergebirge, the relatively small Sackpfeifen Anticline separates the Wittgenstein Syncline from the Dill Syncline.

Judging by its fabric development, the Sackpfeifen Overthrust can be interpreted as a listric overthrust which cuts pre-existing NW-facing fold structures. This gives rise to an antithetic rotation of the overriding block and leads to steepening of the originally NW-facing folds and cleavage planes. The rotation is intensified by further tectonic shortening and may finally produce axial planes and cleavage planes dipping to the NW.

The cross section C-C′ starts in the eastern part of the Siegerland Anticline. Here the important NW-facing Siegerland Overthrust splits up into a number of smaller overthrusts. Such fold- and schuppen-structures, more intensively developed in the middle and southern parts of the Rheinische Schiefergebirge than in the northern part, continue to occur,

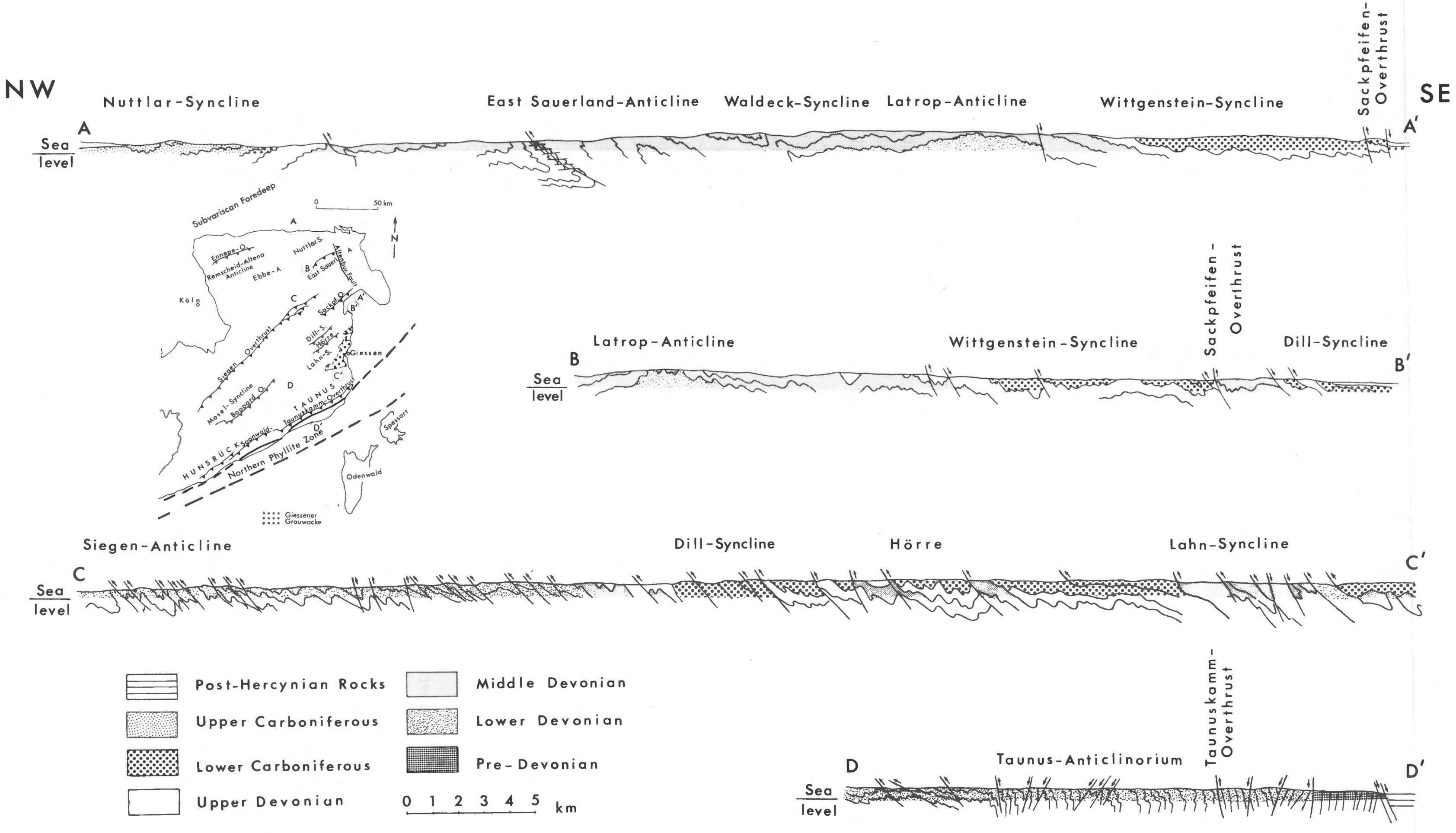


Fig. 3
Cross-section through the Rheinische Schiefergebirge.

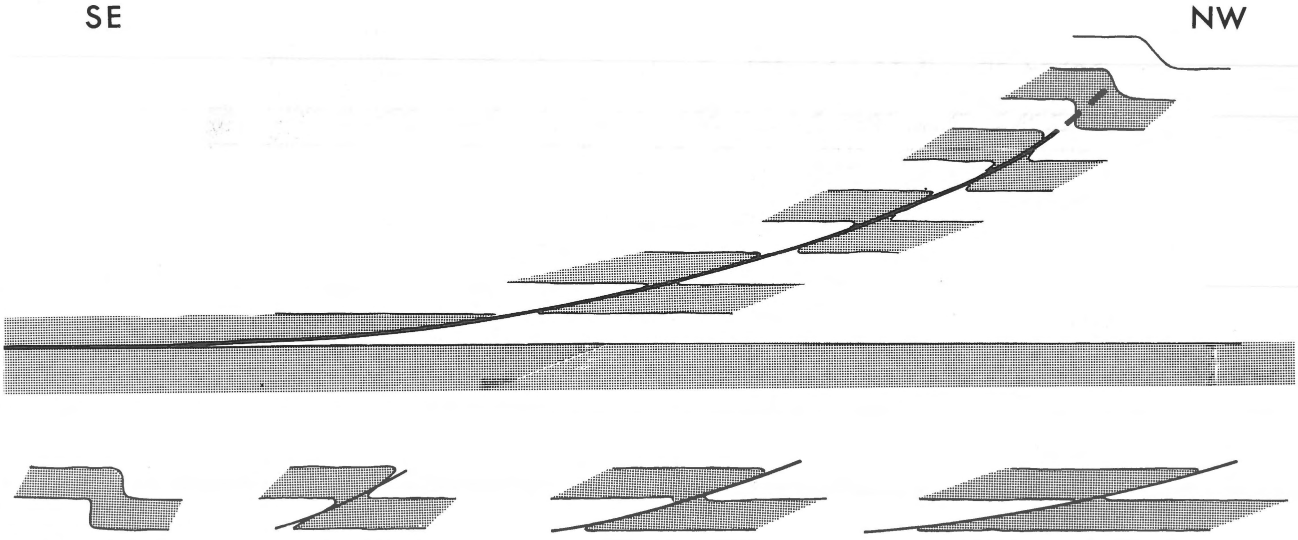


Fig. 4
Diagrammatic representation of the development of a listric overthrust.

with varying intensity of development to the southern border of the Rheinische Schiefergebirge.

The Hörre with its northern and southern schuppen-zones (Eiternhöll- and Bickener Schuppe in the north and the Weidbacher Schuppe in the south) forms a small anticlinal zone between the Dill Syncline on the north and the Lahn Syncline on the south. If compared with the Lahn and Dill Synclines, the Hörre is seen to have a different facies development. The facies of the Hörre is characterized by a lack of Middle and Late Devonian volcanoclastics, spilites and also of Early Carboniferous spilitic rocks. The volcanic suites are of considerable thickness in the Lahn- and Dill-Synclines. The tectonic structures of these two are similar, but in the Lahn Syncline flat lying overthrusts are more frequent (KAYSER, 1911; AHLBURG, 1912; KEGEL, 1934). These flat-lying overthrusts are similar to those in the northern limb of the East Sauerland Anticline. They cut the cleavage of the slates. The formation of these overthrusts may be explained by late tectonic uplift of the Taunus Anticlinorium and continuing depression of the Lahn Syncline during tectonic shortening.

The Taunus Anticlinorium (cross section D-D′) forms a large cleavage fan (Fig. 5). In the northern part i.e. in the transition zone into the Lahn Syncline, the Taunus Anticlinorium is characterized by strongly NW-facing folds with gently SE-dipping fold-axial planes and cleavage planes. To the south the fold-axial planes and cleavage planes go over into vertical and finally NW-dipping attitudes. Fold geometry shows plainly that these are not originally south-facing folds. The Taunus Anticlinorium cannot be explained as one single large anticlinal structure. It is necessary instead to envisage its development as a sequence of NW-facing folds and listric overthrusts (Fig. 5). As in the case of the Sackpfeifen Overthrust (Fig. 1) displacement along listric overthrusts gave rise to antithetic rotation of the overriding blocks and led to a steepening of the originally NW-facing folds and cleavage-planes. Further tectonic shortening gave rise to an uplift in the area of the Hohenstein Anticline (Fig. 5). As a result, southeastern parts of the Taunus Anticlinorium are seen to have been rotated to the SE and the northwestern parts rotated to the NW.

Production of cleavage fan led to formation of extension structures developed under the force of gravity. In the area of the Hohenstein Anticline these extension structures are kink bands, formed simultaneously with a crenulation cleavage showing horizontal fold-axial planes.

In the northwestern part of the Taunus Anticlinorium, small zones paralleling the general strike of the folds show a local SE-dipping crenulation cleavage. In such zones, which take the place of overthrusts, the first cleavage is strongly crenulated and rotated into a horizontal or NW-dipping attitude (Fig. 5). Steeply NW-dipping kink bands are younger than this crenulation cleavage. As in the East Sauerland Anticline, these kink bands take the place of normal faults; they must be interpreted as late tectonic extension structures.

In the southern part of the Taunus Anticlinorium the first and second cleavage planes dip northward and the crenulation cleavage is much more frequent than in the northern part. The first cleavage is deformed into small-scale monoclinal folds by a second cleavage which is more or less homogeneously distributed in the rock (Fig. 5) or else the crenulation cleavage is developed in narrow, strike-parallel zones, which are similar to broad kink bands. Within these zones the first cleavage is strongly crenulated (Fig. 5). These kink-band-like zones in the southern and northern part of the Taunus Anticlinorium are geometrically equivalent. However, they are different kinematically, since they replace overthrusts in the north and normal faults in the south.

The youngest fabrics, SE-dipping kink bands, show relative movement which indicates a more or less horizontal extension during late tectonic uplift.

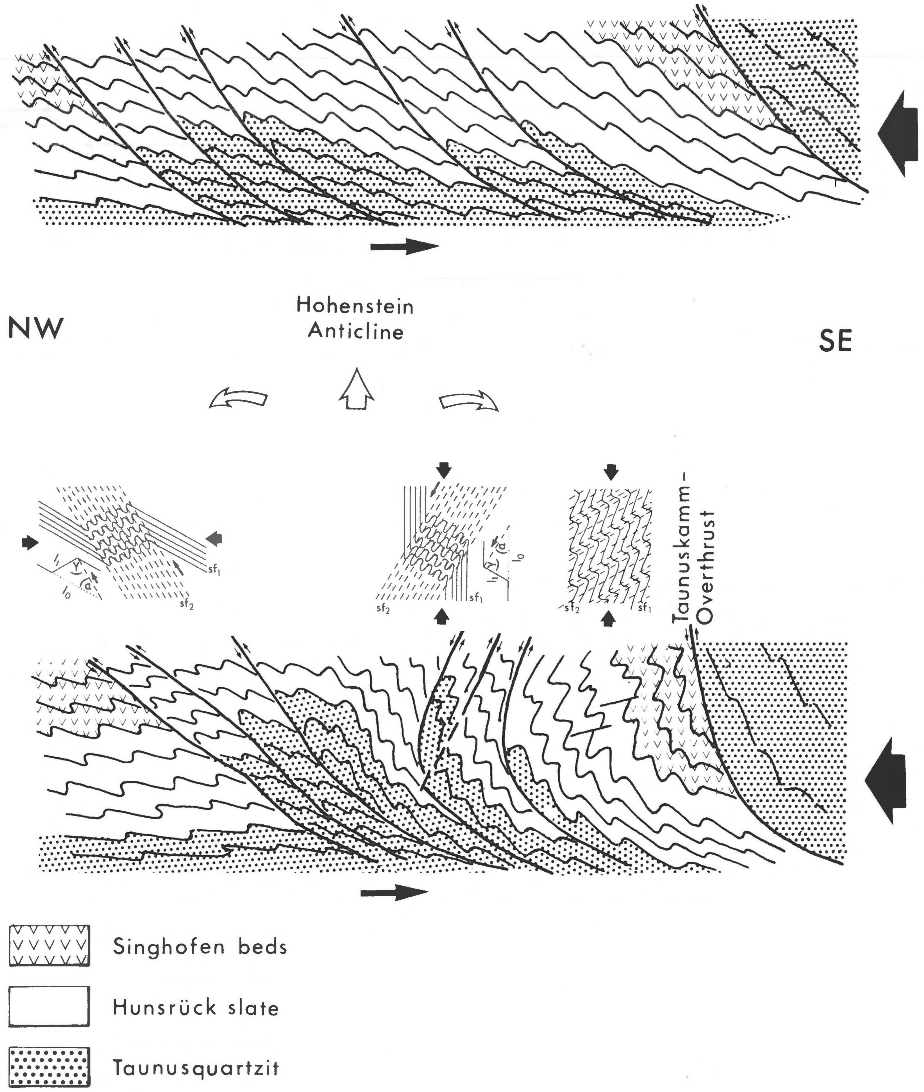


Fig. 5
Structural development of the Taunus Anticlinorium.

The structural character of the Taunus Anticlinorium can be traced into the metamorphic zone of the Taunus pre-Devonian. These pre-Devonian rocks are metavolcanics of acidic to intermediate composition, metapelites and metagreywackes.

Nappe movements are suggested to exist in the southeastern Rheinische Schiefergebirge. Here an unconformity exists between the Gießen Greywacke (Fig. 1) and the underlying Devonian beds. The Gießen Greywacke shows intensive internal deformation with NW-facing folds and the basal parts have a mylonitic character. KEGEL (1934) and HENNINGSEN (1974) have interpreted the Gießen Greywacke as a transgressive deposit, overlying folded (early Variscan) basement. KOSSMAT (1927), KREBS & WACHENDORF (1974) and WEBER (1978) prefer to interpret the structure as a tectonic nappe.

Structural levels

In the Rheinische Schiefergebirge three structural levels or ‘Stockwerke’ may be distinguished.

(1) The uppermost structural level is uncleaved. The main mechanism of folding are flexural slip and flexural flow. In the Subvariscan Foredeep this level can be traced to a depth of approximately 4000 m. Below that, slaty cleavage develops. Within the Rheinische Schiefergebirge slaty cleavage forms at shallower depths because of the higher geothermal gradient (TEICHMÜLLER ET AL., 1979).

(2) In the upper part of the stockwerk with slaty cleavage, for example in the Carboniferous beds of the Nuttlar Syncline, the first cleavage is developed as a very closely spaced crenulation cleavage, i.e. without recrystallization of phyllo-

silicates (WEBER, 1976, 1978). At greather depth, solution processes along cleavage planes can be observed and recrystallization of phyllosilicates begins. Strong synkinematic recrystallization occurs within a relatively narrow temperature interval slightly above 300 °C, as for example in the East Sauerland Anticline (WEBER, 1976, 1978). With increasing depth the original dip of the cleavage planes is progressively less and transition into the phyllite stockwerk takes place.

(3) The phyllite stockwerk crops out only in the metamorphic zone of the Taunus and Hunsrück, forming part of the Northern Phyllite Zone. This Northern Phyllite Zone represents a huge geotectonic boundary along which the Saxo-Thuringian Zone of the Variscan Orogen is thrust onto the Rhenohercynian Zone (BEHR, 1978; WEBER, 1978). The phyllite stockwerk shows an originally subhorizontal often more or less bedding-parallel slaty cleavage and strongly asymmetrical small-scale folds. During the formation of first cleavage the rocks of the Northern Phyllite Zone were syntectonically recrystallized, but they suffered post-crystalline overprinting during progressive uplift and rotation into a more or less vertical attitude.

Metamorphism

The character of the metamorphism in the Rheinische Schiefergebirge indicates low pressure and high temperature. The metamorphic grade of the Devonian and Carboniferous rocks corresponds to 'the very low grade' sensu WINKLER (1976) or the 'anchi-zone' sensu KUBLER (1967) with metamorphic temperatures not higher than 350 °C (SCHERP, 1959; MEISL, 1970; WEBER, 1972; WOLF, 1972; TEICHMÜLLER ET AL., 1979). In the Subvariscan Foredeep very low grade metamorphism grades into the diagenetic zone towards the north.

In the metamorphic zone of the southern Taunus the rocks belong to the quartz-albite-muscovite-chlorite-subfacies of the greenschist-facies with metamorphic temperatures of about 400-450 °C (MEISL, 1970). Quartz recrystallization starts in the Early Devonian of the northern Taunus and increases to the south (KOSCHINSKI, 1979).

The age of folding

Along a N-S traverse from the East Sauerland Anticline to the southern border of the Taunus Anticlinorium the radiometric age of this metamorphism has been determined by the K/Ar-method (AHRENDT ET AL., 1978) (Fig. 1). For purposes of age determination, only rock samples with phyllosilicate fabrics of purely metamorphic origin were selected.

Because of the very low degree of metamorphism it can be assumed that the blocking temperature for the K/Ar system of white micas was not exceeded, exept in the 'Taunus pre-Devonian'. Therefore these age determinations do not give cooling ages but date the peak of metamorphism. According to these datings the age of metamorphism in the northeastern Rheinische Schiefergebirge is about 300 Ma, whereas it increases towards the south to 315 Ma and up to 330 Ma in the Taunus.

The 'Taunus pre-Devonian' rocks, following to the south, have yielded younger ages which are interpreted as cooling ages, because during metamorphism the temperatures in this area exceeded the blocking temperatures for the K/Ar system of the micas. The ages of about 330 Ma in the Lahn Syncline were measured on phyllitic slates (Fig. 1). These rocks were probably brought to their present position by nappe movement proceeding from the southern margin of the Schiefergebirge and therefore have the higher ages characteristic of the southern margin.

The metamorphism is syntectonic with respect to the folding and its associated first cleavage (WEBER, 1976). For that reason the ages give not only the peak of metamorphism but also the date of deformation. Deformation, however, continued beyond the peak of metamorphism, as the widespread development of a post-crystalline second cleavage shows.

The K/Ar datings are in accord with the suggestion that folding migrated from the south to the north. This synmetamorphic wave of folding proceeded from the south to the north in approximately 30 million years, which corresponds to a 'wave-velocity' of (on average) 0.5 cm per year if one assumes a mean tectonic shortening of 42%, following WUNDERLICH (1964).

In the Rheinische Schiefergebirge (outside the Northern Phyllite Zone), accepting the premise that heat-flow was relatively high (50-80 °C/km), the very low grade metamorphism can adequately be explained by the thickness of the sediment pile. This, however, is not possible in the case of the Phyllite Zone. There, in the southern Hunsrück and Taunus, at least 5000-6000 m of sedimentary cover would be required; but the chances are that the cover, at a maximum, was of the order of 2000 m.

According to MOTTANA & SCHREYER (1977) the occurrence of carpholite in the Wippra Zone of the southern Harz Mountains can be taken as an indication of relatively high pressure in the Northern Phyllite Zone.

The metamorphic rocks of the Northern Phyllite Zone must have been deeply buried, in contrast to the very low grade metasedimentary rocks of the other parts of the Rheinische Schiefergebirge and in yet clearer contrast to the completely non-metamorphic Middle and Late Devonian rocks which, as the Saar 1 borehole and the Düppenweiler boreholes have revealed, overlie the Mitteldeutsche Schwelle SE and NW of Saarbrücken. Grain-fabric studies have shown that the rocks of the Northern Phyllite Zone are synkinematically recrystallized but suffered post-crystalline overprinting during progressive uplift.

Folding and metamorphic development of the Rheinische Schiefergebirge are continuous processes without distinguishable phase-like events.

Geodynamic interpretation

Orogenic development of the Rheinische Schiefergebirge should be discussed within the context of the tectonic evolution of the whole European Variscan Orogen. Such a wide-reaching review would, however, go well beyond the scope of the present discussion and is best reserved for another occasion (WEBER & BEHR, in press). The attempt here to develop a geodynamic interpretation refers particularly to the Rheinische Schiefergebirge or the Rhenohercynian Zone.

Any geodynamic interpretation of the tectonic and metamorphic development of the Rheinische Schiefergebirge must account for the following facts:

(1) There are no indications of the existence of an ocean. The Devono-Carboniferous volcanism displays bimodal character. The spilites are tholeiitic basalts and do not represent ocean floor (HERRMANN & WEDEPOHL, 1970; WERNER & RÖSLER, 1979). The intercalated sediments produce no unequivocal indication of deep-water character. Reefs have grown on top of 600-700 m thick piles of volcaniclastic material.

(2) The metamorphism is of low-pressure, high-temperature character, suggesting geothermal gradients of the order of 50-70 °C/km and locally perhaps as high as 100 °C/km.

(3) With the exception of the metamorphic zone at the southern margin of the Rheinische Schiefergebirge (and the Harz) there is no basis for suggesting that tectonic deformation led to any considerable crustal thickening. Otherwise, isostatic adjustment would have led to exposure of metamorphic rocks of higher grade than any now found in the Rheinische Schiefergebirge.

(4) The kinematics of fabric development indicate that the tectonic levels exposed suffered tangential transport directed from SE to NW. Palinspastic considerations would argue against any suggestion that there had been widespread gravitative transport. The mid-German Crystalline Rise, nearby to the south, cannot be regarded as a possible tectonic source-area, for it has, in its southwestern part at least, sedimentary rocks which are of the same ages as those in the Schiefergebirge and which are, in addition, non-metamorphic.

(5) Migration of the wave of folding from SE to NW. Here it must be understood at the outset that the fold-wave arose in the region of the Northern Phyllite Zone, in front of the mid-German Crystalline Rise, and that the prograde metamorphism in the mid-German Crystalline Rise is earlier than the beginnings of folding in the Rheinische Schiefergebirge. This is shown not only by the radiometric dates (Fig. 1) which indicate late Silurian or early Devonian metamorphism in the region of the mid-German Crystalline Rise (KREUZER ET AL., 1973; LIPPOLT ET AL., 1976; LENZ & MÜLLER, 1976), but also by the occurrences of 'early', Late Devonian greywackes in the Rheinische Schiefergebirge and by the non-metamorphic state of the Middle and Late Devonian rocks penetrated in the Saar 1 and the Düppenweiler boreholes (ZIMMERLE, 1976; MÜLLER, 1978). During the time of the Late Carboniferous folding in the Rhenohercynian Zone, the mid-German Crystalline Rise was affected by a retrograde metamorphism and SE-vergent thrusts developed along its NW margin, such as the Michelbacher Thrust in the northern part of the Spessart and the Düppelnweiler Thrust in the northern part of the Saar region. The age of the Düppenweiler Thrust, which brings phyllitic rocks with retrograde metamorphism over non-metamorphic Upper Devonian, is given by a K/Ar cooling age (determined by Dr. Hunziker, Bern) of 302 ± 9 Ma.

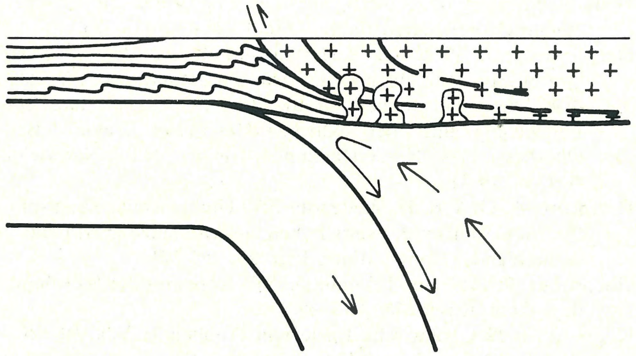
The whole range of geosynclinal, tectonic and metamorphic evidence consistently indicates ensialic character for the Variscan Orogen. This means that the Rheinische Schiefergebirge, from the geosynclinal stage through to folding and metamorphism, developed on continental crust. The major boundary along the northern margin of the mid-German Crystalline Rise, evident in the special character of the Northern Phyllite Zone, is not to be interpreted as the result of subduction of oceanic crust leading to continent-continent collision. What is involved here is, instead, a large-scale ensialic overthrust which brought the mid- German Crystalline Rise to rest on the Rhenohercynian Zone (WEBER, 1978). Overthrusts on this scale, penetrating the continental crust and bringing high-grade metamorphic rocks to rest on weakly-metamorphosed or non-metamorphic rocks, are present in various regions within the European Variscan Orogen. BEHR (1978) and WEBER (1978) have called them 'subfluence zones'.

Rhenohercynian folding began in the subfluence zone situated in the foreland of the mid-German Rise. The total shortening involved in the major overthrust is not known, but the possibility of thrusting involving more than 100 km of transport cannot be excluded. The clear NW vergence and the polarity evident in the whole tectonic development of the Rhenohercynian Zone are in good accord with the suggestion of a subfluence zone at the southern margin of the Schiefergebirge.

The cause of the tectonic shortening must lie in tangential transport. Purely gravitative transport may, but only locally, be of some significance – one thinks of possible nappe-transport of this kind in the southern part of the Rheinische Schiefergebirge and in the southern Harz. Gravitative transport cannot be thought to be the cause of the whole history of deformation seen in the Rhenohercynian Zone.

Kinematic analyses of the exposed suprastructure show (WEBER, 1978) that the frequent, NW-vergent overthrusts in the Rheinische Schiefergebirge are listric overthrusts. These overthrusts arise at different depths out of the horizontal thrust planes. Major structures can be related to shear planes, at 6-10 km depth, which lie parallel to the subhorizontal layering in the infrastructure below (WEBER, 1978). At depths less than 10 km, where the rocks are strongly folded, there are no particularly clear seismic reflectors. At depths beyond 10 km, there are progressively clearer returns from approximately flat-lying features of the deep structures (BOSUM ET

A-Subduction



B-Subduction

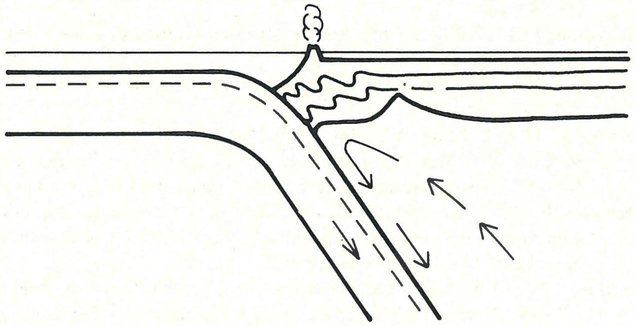


Fig. 6
Cartoon showing A-subduction (Subduction of lithospheric mantle below continental crust) and B-subduction (subduction of oceanic lithosphere).

AL., 1971; AHORNER & MURAWSKI, 1975; MURAWSKI, 1975; MEISSNER ET AL., 1980). According to Jödicke & Untiedt (pers. comm.) two horizons of high magnetotelluric conductivity and southward inclined, can be recognized at depths in the range between 10 km and 30 km. It is possible that these are major shear surfaces.

It is therefore probable to suggest that at deep, highly metamorphic levels in the continental crust there is a subhorizontal flow regime, perhaps an extensional flow in PRICE's (1972) sense. The subhorizontal layering found in exposed sections of relatively deep crustal material can be interpreted as an expression of such a subhorizontal flow-regime. The cause of the subhorizontal flow-regime may be relative movement of crust and lithospheric mantle. Lithospheric mantle of peridotitic composition behaves, under Moho conditions of temperature, in a brittle fashion as compared with the behaviour of the quartz-feldspar-rich crustal rocks. In the neighbourhood of the Moho there may therefore be a well-developed rheological boundary, which provides for movement of crust relative to lithospheric mantle, and which may also allow uncoupling of crust from lithospheric mantle (see more details in WEBER & BEHR, 1981). This would introduce the possibility of a subduction of lithospheric mantle under continental crust. The crust, because of its relatively low density, cannot take part in such a subduction process and the result is a separation of lithospheric mantle from crust along the rheological boundary in the Moho region.

Subduction of lithospheric mantle leads to establishment of an Andrews-Sleep-Cell, in which renewed input of hot asthenospheric material reaches the base of the lower crust and brings into being the synorogenic heat front. Such an ascent of hot asthenospheric material in advance of the front of the subducted lithospheric mantle is akin to what BIRD (1978, 1979) has called delamination. This delamination process appears to be readily applicable to the problem of explaining the extremely high syntectonic heat flow evident in the European Variscides.

Subduction of lithospheric mantle under continental crust brings about mass transport in the ductile lower part of the crust. BEHR (1978) and WEBER (1978) have applied to this process the term 'subfluence', used earlier by AMPFERER (1906), SCHWINNER (1920) and KRAUS (1958). Folds and imbricate structures are characteristic features of deformation in the suprastructure because of the high mechanical anisotropy existing there. Rocks at this level are overtaken by deformation only when the orogenetic heat front has sufficiently reduced the strenght of the crust and only if the slab of subducted lithospheric mantle is long enough to ensure transmission of sufficient frictional stress into the continental crust (WEBER & BEHR, 1980). If these conditions are not satisfied syntectonic metamorphic effects may be confined to deep crustal levels.

Crustal thickening may be expected to develop where a subfluence zone is active and will occur too in the central parts of the Variscan Orogen. A result of such thickening is widespread occurrence of granitoids in the central zone of the orogen.

Subfluence may be regarded as the reaction of continental crust to subduction of the underlying lithospheric mantle. BEHR & WEBER(1980) have proposed that subduction of this character, specifically a process involving a subduction of *lithospheric mantle* and operating *underneath* continental crust, be termed Ampferer subduction (A-subduction). It should be seen to differ from Benioff subduction (B-subduction), which involves subduction of oceanic lithosphere (Fig. 6).

The two mechanisms closely resemble one another, both geometrically and kinematically but are different in their effects on the sedimentary, magmatic, metamorphic and tectonic development of an orogen. In the case of the Rheinische Schiefergebirge a number of differences from what is found in the circum-Pacific orogenes and in island arcs are immediately obvious.

A-subduction produces no trench in the sea floor. Deep-sea sediments and obduced ophiolite sequences need not be expected to occur. The process does not involve subduction of large volumes of water-rich rocks, as B-subduction does, and this explains the lack of calc-alkaline (andesitic) magmas, such as are characteristic of B-subduction, in the Rhenohercynian Zone.

Since crustal rocks are not involved, no high-pressure/low-temperature metamorphic rocks result. Because of the delamination, metamorphism has, instead, a high-temperature, low-pressure character.

BIBLIOGRAPHY

Ahlburg, J. 1918 Geologische Karte von Preußen, 1:25000 Bl. 5516 Weilmünster mit Erläuterungen – Preuß. Geol. L. – Amt (Berlin).

Ahorner, L. & H. Murawski 1975 Erdbebentätigkeit und geologischer Werdegang der Hunsrück-Südrand-Störung – Z. dt. geol. Ges. 126: 63-82.

Ahrendt, H., H. -J. Anderle, H. -J. Behr, S. Meisl & K. Weber 1977 Exkursionsführer Geotagung 77, I, Exkursion G. (Göttingen) – Geol. – Paläont. Inst. Museum Univ. Göttingen: 93-169.

Ahrendt, H., J. C. Hunziker & K. Weber 1978 K/Ar-Altersbestimmungen an schwach-metamorphen Gesteinen des Rheinischen Schiefergebirges – Z. dt. geol. Ges. 129: 229-247.

Ampferer, O. 1906 Über das Bewegungsbild von Faltengebirgen – Jb. geol. R. – Aust. 56: 539-622.

Anderle, H. J. 1976 Der Südrand des Rhenoherzynikums im Taunus – Geol. Jb. Hessen 104: 279-284.

Behr, H. J. 1966 Das metamorphe Grundgebirge im Thüringer Becken – Ber. dt. Ges. geol. Wiss. A. Geol. Paläont. 11: 39-56.

——1978 Subfluenzprozesse im Grundgebirgsstockwerk Mitteleuropas – Z. dt. geol. Ges. 129: 291-326.

Behr, H. J. & K. Weber 1980 Subduktion oder Subfluenz im mitteleuropäischen Varistikum? – Berliner Geow. Abh. Reihe A/B 19 (Intern. A. Wegener-Symposium, Berlin): 22-23

Behrend, F. & W. Paeckelmann 1937 Der geologische Bau und die Lagerstätten des Ramsbecker Erzbezirkes – Arch. Lagerstättenforsch. 64: 198 pp.

Bird, P. 1975 Continental delamination and the Colorado Plateau – J. Geophys. Res. 84: 7561-7571.

——1978 Initiation of intracontinental subduction in the Himalaya – J. Geophys. Res. 83: 4975-4987.

Bosum, W., J.-H. Dürbaim, W. Fenchel, J. Fritsch, M. Lusznat, H. Nickel, S. Plaumann, A. Scherp, C. Stadler & H. Vogler 1971 Geologisch-lagerstättenkundliche und geophysikalische Untersuchungen im Siegerländer Spateisenbezirk – Beih. geol. Jb. 90: 1-139.

Denckmann, A. & H. Quiring 1923 Geologische Karte von Preußen 1:25000 Blatt 5114 Siegen mit Erläuterungen – Preuß. geol. L. – Amt (Berlin).

Dufour, J. 1925 Die Grube 'Königsberger Gemarkung' und ihre Beziehung zur Stratigraphie und Tektonik der östlichen Lahnmulde – Diss. Univ. Giessen.

Ebert, A. 1955 Das untere Mitteldevon und der Bau des westlichen Ostsauerländer Hauptsattels – Geol. Jb. 69: 1-10.

——1961 Geologische Karte von Nordrhein-Westfalen 1:25000, Blatt 4616 Eversberg mit Erläuterungen – Geol. Landesamt NRW (Krefeld): 107 pp.

——1965 Das untere Mitteldevon und der Bau des westlichen Ostsauerländer Hauptsattels – Fortschr. Geol. Rheinl. Westf. 9: 589-620.

——1968 Geologische Karte von Nordrhein-Westfalen 1:25000 Blatt 4716 Bödefeld mit Erläuterungen – Geol. Landesamt NRW (Krefeld): 112 pp.

Franke, W., W. Eder, W. Engel & F. Langenstrassen 1978 Main aspects of geosynclinal sedimentation in the Rhenohercynian Zone – Z. dt. geol. Ges. 129: 201-216.

Füchtbauer, H. 1963 Petrographische Untersuchungen des Unterkarbons und Devons der Bohrung Münsterland 1 – Fortschr. Geol. Rheinl. Westf. 11: 353-364.

Hellermann, E. 1965 Schiefrigkeit und Gebirgsbau im östlichen Rheinischen Schiefergebirge – Geol. Mitt. 4: 333-396.

Henningsen, D. 1962 Die Lagerungsverhältnisse der Gießener Grauwacke – Notizbl. hess. L.–Amt Bodenforsch. 90: 273-286.

——1966 Die paläozoischen Grauwacken bei Gießen und ihre Fortsetzung unter der südlichen Hessischen Senke – Ber. Oberhess. Ges. Natur-Heilkunde Gießen, N.F., Naturwiss. Abt. 34: 19-31.

Herrmann, A. G. & K. H. Wedepohl 1970 Untersuchungen an spilitischen Gesteinen der varistischen Geosynklinale in Nordwestdeutschland – Contr. Miner. Petr. 29: 255-274.

Hoeppener, R. 1957 Zur Tektonik im SW-Abschnitt der Moselmulde – Geol. Rdsch. 46: 318-348.

Kegel, W. 1929 Geologische Karte von Preußen 1:25000 Bl. 5517 Kleeberg-Kirchgöns mit Erläuterungen – Preuß. geol. L.– Amt (Berlin).

——1934 Geologie der Dill-Mulde – Abh. preuß. geol. L.–Amt N.F. 160: 48 pp.

Kossmat, F. 1927 Gliederung des varistischen Gebirgsbaues – Abh. Sächs. Geol. L. Anst. 1: 39 pp.

Kraus, E. C. 1958 50 Jahre Unterströmungs-Theorie–Z. Geol. 7: 261-283.

Kreuzer, H., H. Lenz, W. Harre, S. Matthes, M. Okrusch & P. Richter 1973 Zur Altersstellung der Rotgneise im Spessart – Rb/Sr Gesamtgesteins-Datierungen – Geol. Jb. A9: 69-88.

Kubler, B. 1967 La cristallinité de l'illite et les zones tout a fait supérieures du metamorphisme. In: Etages tectoniques – Coll. Neuchâtel 18-21 (4.1966): 105-122.

Kühne, F. 1978 Geologische Karte von Nordrhein-Westfalen 1:25000 Blatt 4514 Möhnesee mit Erläuterungen – Geol. L. – Amt NRW (Krefeld), 2. Aufl.

Langheinrich, G. 1976 Verformungsanalyse im Rhenoherzynikum – Geotekt. Forsch. 51: 1-127.

Lenz, H. & P. Müller 1976 Radiometrische Altersbestimmungen am Kristallin der Bohrung Saar 1 – Geol. Jb. A 27: 429-432.

Leuteritz, K. 1972 Geologische Karte von Nordrhein-Westfalen 1:25000, Blatt 4817 Hallenberg mit Erläuterungen – Geol. L.-Amt NRW (Krefeld): 215 pp.

Liesche, S. 1979 Die tektonische Gesteinsdeformation im Raume des Latroper Sattels und der Wittgensteiner Mulde am Ostrand des Rheinischen Schiefergebirges – Diss. Univ. Göttingen.

Lippert, H. -J., H. Hentschel & A. Rabin 1970 Geologische Karte von Hessen 1:25000 Blatt 5215 Dillenburg mit Erläuterungen – Hess. L.-Amt Bodenf. (Wiesbaden): 550 pp.

Lippolt, H. J., J. Barany & J. Raczek 1976 Rb/Sr chronology of orthogneisses in the eastern Odenwald and southern Spessart (Germany) – Abstr. ECOG IV (Amsterdam).

Lutzens, H. 1975 Ein Beitrag zur Geologie des Unter- und Mittelharzes – Geol. Beih. 74: 1-105.

Meisl, S. 1970 Petrographische Studien im Grenzbereich Diagenese-Metamorphose – Abh. hess. L.-Amt Bodenf. 57: 1-93.

Meissner, R., H. Bartelsen & H. Murawski 1980 Seismic reflection and refraction studies for investigating fault zones along the Geotraverse Rhenohercynikum – Tectonophysics 64: 59-84.

Meyer, K. 1962 Das Untere Mitteldevon zwischen Winterberg und Wiemeringhausen im östlichen Sauerland – N. Jb. Geol. Paläont. Abh. 114: 273-290.

Meyer, W. & J. Stets 1975 Das Rheinprofil zwischen Bonn und Bingen – Z. dt. geol. Ges. 126: 15-29.

Mittmeyer, H. -G. 1962 Die Hunsrückschiefer des südlichen Aartales (Rheinisches Schiefergebirge) – Diss. Univ. Hamburg.

——1965 Die Bornicher Schichten im Gebiet zwischen Mittelrhein und Idsteiner Senke (Taunus, Rheinisches Schiefergebirge) – Notizbl. hess. L. Anst. Bodenkunde 93: 73-98.

Mottana, A & W. Schreyer 1977 Carpholite crystal chemistry and preliminary experimental stability – N. Jb. Miner. Abh. 129: 113-138.

Müller, E. 1978 Ergebnisse der Forschungsbohrungen Düppenweiler/Saar – Nachr. dt. geol. Ges. 19: 32-33.

Murawski, H. 1975 Die Grenzzone Hunsrück/Saar-Nahe-Senke als geologisch-geophysikalisches Problem – Z. dt. geol. Ges. 126: 49-62.

——1976 Raumproblem und Bewegungsablauf an listrischen Flächen, insbesondere bei Tiefenstörungen – N. Jb. Geol. Paläont. Mh. Jg. 1976: 209-220.

Paeckelmann, W. 1933 Grundzüge der Tektonik des östlichen Sauerlandes – Jb. preuß. geol. L.-Anst. 54: 217-260.

Paproth, E. & R. Teichmüller 1961 Die paläogeographische Entwicklung der subvaristischen Saumsenke in Nordwestdeutschland im Laufe des Karbons – C.R. 4e Congr. Strat. Géol. Carbonifère (Heerlen, 1958): 471-491.

Price, R. A. 1972 The distinction between displacement and distortion in flow, and the region of diachronism in tectonic overprinting in orogenetic belts – 24th Int. Geol. Congr. Sect. 3: 545-551.

Reich, H. 1928 Geologische Karte von Preußen 1:25000 Bl. 4916 Berleburg mit Erläuterungen – Preuß. geol. L.-Amt (Berlin).

Sauerland, V. 1980 Tektonische Entwicklung des westlichen Taunus zwischen Taunuskammüberschiebung und Lahnmulde – Diss. Univ. Göttingen (in prep.).

Schmierer, Th. 1930 Geologische Karte von Preußen 1:25000 Bl. 5017 Biedenkopf mit Erläuterungen – Preuß. geol. L.-Amt (Berlin).

Scholtz, H. 1930 Das varistische Bewegungsbild, entwickelt aus der inneren Tektonik eines Profils von der Böhmischen Masse bis zum Massiv von Brabant – Fortschr. Geol. Paläont. 8: 235-316.

Schwab, M. 1974 Harz – verkehrt gestapelt. Neue Theorien zum Gebirgsbau des Harzes – Wiss. Fortschr. 24: 85-89 + 140-145.

Schwinner, R. 1920 Vulkanismus und Gebirgsbildung – Ein Versuch – Z. Vulkan. 4: 175-230.

Stoppel, D. 1977 Schlammstrom-Sedimente im Oberdevon des Südwestharzes und des östlichen Kellerwaldes – Z. dt. geol. Ges. 128: 81-98.

Teichmüller. M. & R. Teichmüller 1950 Spuren vorasturischer Bewegungen am Südrand des Ruhrkarbons – Geol. Jahrb. 65: 497-506.

Teichmüller, R., M. Teichmüller & K. Weber 1979 Inkohlung und Illit-Kristallinität. Vergleichende Untersuchungen im Mesozoikum und im Paläozoikum von Westfalen – Fortschr. Geol. Rheinl. Westf. 27: 201-276.

Thome, K. N. 1968 Geologische Karte von Nordrhein Westfalen 1:25000, Blatt 4615 Eversberg mit Erläuterungen – Geol. Landesamt NRW (Krefeld): 148 pp.

Walliser, O. H. 1977 Probleme der geotektonischen Einordnung der Variskiden – Z. angew. Geol. 23: 459-463.

Weber, K. 1972a Notes on determination of illite crystallinity – N. J. Miner. Mh. 1972: 267-276.

——1972b Kristallinität des Illits und andere Kriterien schwacher Metamorphose im nordöstlichen Rheinischen Schiefergebirge – N. Jb. Geol. Palönt. Abh. 141: 333-363.

——1976 Gefügeuntersuchungen an transversalgeschieferten Gesteinen aus dem östlichen Rheinischen Schiefergebirge (Ein Beitrag zur Genese der transversalen Schieferung) – Geol. Jb. D15: 3-98.

——1977 Bau und tektonische Entwicklung des Ostsauerländer Hauptsattels und der varistischen Ramsbecker Blei-Zinkerzlagerstätte. Zu: Lagerstätten und Mineralisationen im Sauerland – Fortschr. Miner. 55: 48-63

——1978 Das Bewegungsbild im Rhenoherzynikum-Abbild einer varistischen Subfluenz – Z. dt. geol. Ges. 129: 249-281.

Weber, K. & H. J. Behr 1981 A cross-section through the mid-European Variscides and its geodynamic interpretation – J. Struct. Geol. (in press).

Werner, C.-D. & H. J. Rösler 1979 Aussagemöglichkeiten der initialen Magmatite für die Klärung struktueller Verhältnisse am Beispiel des mitteleuropäischen Variszikums – Z. geol. Wiss. 7: 353-366.

Winkler, H. G. F. 1976 Petrogenesis of metamorphic rocks – Springer (New York, Heidelberg, Berlin): 334 pp.

Wolburg, J. 1933 Das Devon im Gebiet der oberen Lenne – Abh. preuß. geol. L.-Anst. (Berlin) N.F.: 151 pp.

Wolf, M. 1972 Beziehung zwischen Inkohlung und Geotektonik im nördlichen Rheinischen Schiefergebirge – N. Jb. Geol. Paläont. Abh. 141: 222-257.

Wunderlich, H. G. 1964 Maß, Ablauf und Ursachen orogener Einengung am Beispiel des Rheinischen Schiefergebirges, Ruhrkarbons und Harzes – Geol. Rdsch. 54: 561-882.

Zimmerle, W. 1976 Petrographische Beschreibung und Deutung der erbohrten Schichten. In: Die Tiefbohrung Saar 1 – Geol. Jb. Reihe A 27: 21-305.

Zwart, H. J. 1969 Metamorphic facies series in the European orogenic belts and their bearing on the causes of orogeny – Geol. Assoc. Canada Sp. Paper 5: 7-16.

Zwart, H. J. & U. F. Dornsiepen 1978 The tectonic framework of central and western Europe. In: A. J. van Loon (ed): Key-notes of the MEGS-II (Amsterdam, 1978) – Geol. Mijnbouw 57: 627-654.