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Basement topography and thrust fault ramping, a model to explain cleavage fans in the Mosel area (Rheinisches Schiefergebirge)

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Abstract

The structure of the Mosel area is characterized by major NW-directed overthrust faults, that formed in a late stage of the deformation history, after two phases of ductile deformation. The traces of the major overthrust faults are indicated by discontinuities in stratigraphy, metamorphic grade and intensity of the pre-thrusting deformation structures. The thrust planes separate rock sequences that have rotated by foreland-directed movement on SE-dipping listric surfaces. Large scale normal and reverse cleavage fans have formed in the hanging wall of the main overthrust planes.

It is suggested that the overthrust planes, cleavage fans and the large scale rotations have formed in relation to bending of the detached sedimentary cover over pre-existing ramps in the crystalline basement. These ramps represent inherited normal faults, that formed during syn-sedimentary differentiation of the Lower Devonian sedimentary basin.

Introduction

The Mosel- Hunsrück- S.E. Eifel area is situated in the S.W. Rheinische Schiefergebirge and is part of the Rhenohercynian Zone of the Variscan orogenic belt in central Europe (Kosmatt, 1927). The Rheinische Schiefergebirge is bordered in the south by the late Variscan intramontane basin of the Saar-Nahe trough along a major fault zone (Hunsrück Südrand Verwerfung; Meissner et al., 1980). In the north folding gradually dies out in the accumulation of molasse deposits of the Subvariscan Foredeep (Franke et al., 1978).

Deformation in the Rheinische Schiefergebirge took place during the late Middle Carboniferous. The structural development is characterized by north-west directed tectonic transport. This is demonstrated by the NW migration of flysch basins (Franke et al., 1978) and by the dominance of NW-vergent fold structures, reverse faults and small nappe structures (Weber & Behr, 1983). Deformation intensity, metamorphic grade and the age of the syntectonic metamorphism progressively decreases in a NW direction.

Large scale cleavage fans are an important tectonic element in the southern Rheinische Schiefergebirge (Fig. 4). The fans are known since the early work of Leppla (1924) and Born (1927) and have been described in detail by Quiring (1939) and Hoeppener (1960). They occur both as upward divergent 'normal' fans (Fächer) and upward convergent 'reverse' fans (Meiler), which can be followed along the trend of the Rheinische Schiefergebirge for several tens of kilometres.

Formation and kinematic significance of the fans is poorly understood notwithstanding the large number of models that has been presented to explain them. The cleavage fans have been interpret-

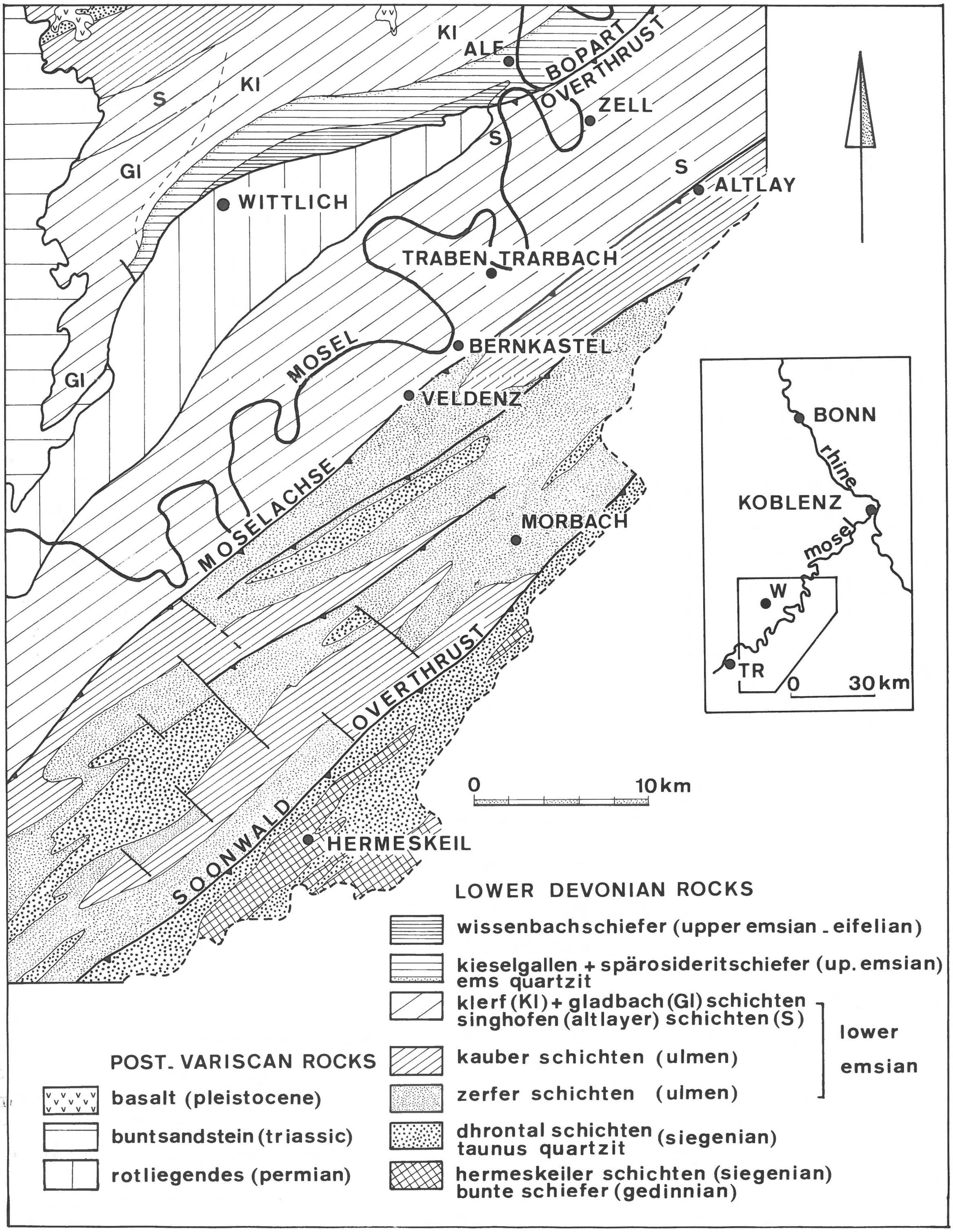

Fig. 1. Geological sketch map of the Middle Mosel and southern Hunsrück area. Compilation of published work of Geib et al. (in: Negendank, 1974), Stets, (1962), Solle (1976), Kneidl (1980), Mittmeyer (1980) and the present authors' observations.

ed to form as the result of large scale cleavage refraction in major fold structures (Engels, 1960) or by rotation of the limbs of the 'Moselmulde' during syn-tectonic subsidence (Hoeppener, 1960).

These models are open to criticism as has been shown by Gasser (1978) and more recently by Weijermars (1986). This last author presented an interpretation in which the variation of the cleavage planes through the fans is explained by large scale post-cleavage folding and SE-directed reverse faulting. Comparable post-cleavage fold models have been presented previously by Quiring (1939). A major disadvantage of many models presented so far is that they do not consider the stratigraphical data from the area, which are available from the work of amongst others Solle (1951, 1976) and Mittmeyer (1973, 1980). The model that is presented in this paper explains the structure of the Mosel area in terms of bending of the detached sedimentary cover during thrusting over pre-existing basement ramps. It is based on the structural and stratigraphical data of the area between the profile sections Bad Bertrich – Alf – Zell – Altlay – Hahn in the north and the Hinterbach section near Veldenz in the south (Fig. 1). It is consistent with recent geophysical data from other areas in the Rheinische Schiefergebirge (Meissner et al., 1981) and the crustal underthrusting (Subfluenz) model of Weber (1978).

Stratigraphy

The rocks that are exposed in the Mosel area are slates, metasandstones and quartzites of Lower Devonian age. They were deposited in the southern part of the SE-NW striking Rhenish sedimentary basin between the German Crystalline Rise (Brinkmann, 1948) in the south and the Old Red Continent in the north and north-west. Both areas supplied clastic sediments into the Rhenish basin, although their importance as a source area varied with time.

Very little is known about the paleogeographical configuration during the Gedinnian although Meyer (1975) has described the occurrence of multicoloured slates (Bunte Schiefer) with fragments of a nearby crystalline area in the Southern Hunsrück. In the Siegenian large parts of the northern Rhenish basin were filled with marine to brackish near-coast clastics, but the coast of the Old Red Continent was situated too far to the NW to play an important role as a source area for the sediments of the Hunsrück-Mosel area. In the SE Eifel sedimentation took place in an open marine environment with a pelagic (Hercynian) fauna (Fuchs, 1974), while the sediments in the Hunsrück area were mainly derived from the German Crystalline Rise and deposited in a higher energetic marine shelf environment (Südfazies; Meyer & Stets, 1980). This was the depositional area of the lower Siegenian quartzites and sandstones of the Hermeskeiler Schichten (Meyer, 1975) and the overlying, up to 1200 m thick middle to upper Siegenian Taunus quartzites and Dhrontal Schichten.

In the lowermost Emsian (Ulmen age) the overlying series of the Hunsrückschiefer s.s. (Mittmeyer, 1980) were deposited in strongly subsiding shelf basins, which locally received up to 3000 m of sediment. The lower part of the Hunsrückschiefer contains well-bedded sandy slates with many flaser structures and dark greywacke beds (Zerfer Schichten). In the upper part there is an increasing amount of thick series of black-blue fine grained roof slates (Kauber Schichten).

On top of the Hunsrückschiefer s.s. rests the thick shale series of the Singhofen or Altlayer Schichten (Mittmeyer, 1980). The lower boundary of this series is not well defined but is generally taken at the first occurences of thin porphyroid tuffs, which characterise the series and which have been described for example from near Altlay (Engels, 1960).

The Singhofen or Altlayer Schichten have a middle Lower Emsian age. They are exposed among other places in the profile section between Altlay and Zell and in the Mosel valley, where they have been differentiated (Solle, 1976) into three units: (1) a lower series of homogeneous dark grey slates with no obvious bedding planes (exposed between the bridge near Bullay and Alf); (2) a middle series characterized by cyclic sedimentation with rhythmic sandstone-shale repetitions at a scale of centimetres up to 1 decimetre (visible in many exposures

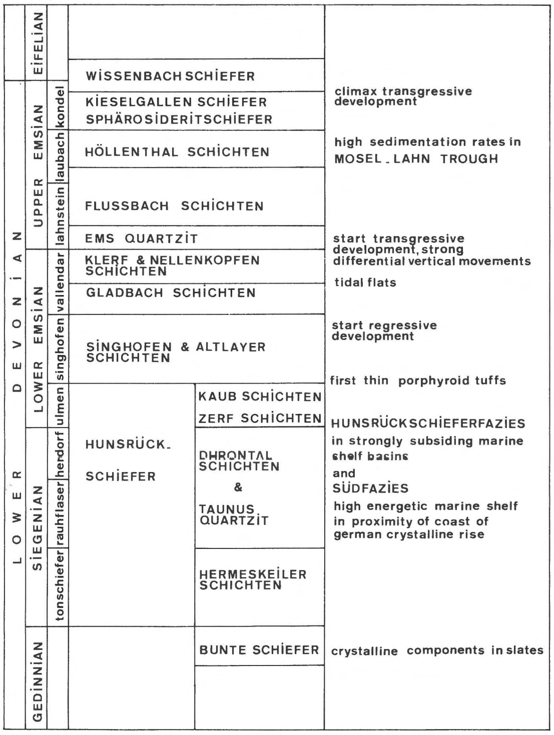

Fig. 2. Schematic diagram showing the main stratigraphic units of the Middle Mosel and southern Hunsrück, their age and sedimentary facies. After Solle (1976), Mittmeyer (1980) and Meyer & Stets (1980).

in the Mosel valley; Fig. 3b); (3) an upper series with greywacke and sandstone beds with a thickness of 1–3 decimetre up to 1 metre (e.g. Reiler Hals; Fig. 3a).

The sedimentary facies of the lower and middle Singhofen Schichten is comparable with the facies of the underlying Hunsrückschiefer s.s. The upper Singhofen Schichten, however, represent shelf deposits with strong currents in quickly changing directions. This indicates the start of a regressive cycle and a stronger influence of the Old Red Continent during the upper part of the Lower Emsian. The regression and the associated southward shift of the coast line of the Old Red Continent, culminates in the deposition of the non-marine tidal flat deposits of the Klerf Schichten, which are well exposed in road cuts SE of Bad Bertrich.

At the beginning of the Upper Emsian a new paleogeographical configuration set in with the development of a number of relatively small subsiding basins (Meyer & Stets, 1980). From then on there is a strong contrast between the high sedimentation rates in the Mosel-Lahn trough, starting with the transgressive Ems quartzite, and the absence of sedimentation in the Hunsrück-Taunus area. The youngest sediments in the area are the Upper Emsian to lowermost Eifelian pelagic shales of the Wissenbach Schiefer(Solle, 1976).

Structure

Analysis of the structure of the Mosel area on the basis of overprinting shows that the rocks have been subjected to three successive phases of deformation. These deformation phases (D_1, D_2 and D_3) are treated here separately although their coaxiality may indicate a continuous deformation sequence.

During the D_1 deformation phase NW-vergent folds and reverse faults of bedding developed on a mesoscopic scale. The folds are characterized by more or less parallel shallow plunging fold axes with a ENE-WSW trend and may be observed – or reconstructed on the basis of cleavage/bedding relationships – in most areas where the lithological succession contains sufficient meta-sandstone layers.

D_1 structures contain a well developed axial plane cleavage (S_1) which refracts through meta-sandstone layers (Fig. 3b). On a microscopic scale it has the characteristics of a domainal slaty cleavage (Hobbs, et al., 1976; Roy, 1978).

Deformation took place under anchizonal to lowermost greenschist facies conditions. In the SE part of the area greenschist facies conditions are indicated by the presence of chlorite and white mica porphyroblasts in a paragenesis with feldspar and quartz. Numerous quartz segregations and syn-tectonic veins indicate that deformation essentially took place in the field of pressure solution deformation (White, 1976).

In the SE part of the area, approximately SE of a line from Veldenz to the Peterswalder Bach along the road section from Zell to Altlay, D_1 structures are overprinted by D_2 deformation structures. Dur-

Fig. 3a. Ball and pillow structures in Singhofen Schichten in the Mosel valley south of Reil.

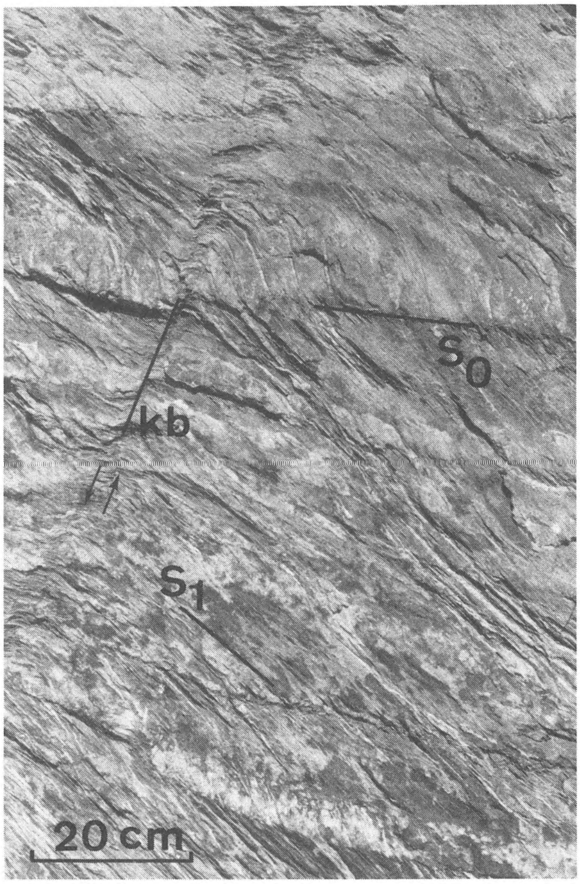

Fig. 3b. Refraction of S_1-cleavage through sedimentary layering (S_0) southeast of Zell – Singhofen Schichten.

ing this deformation phase the sedimentary bedding and the previously formed S_1 cleavage were folded into small scale folds with maximum amplitudes of several metres. These folds are again NW-vergent and have been described as 'Kauber Walzen' on the basis of their swinging asymmetry (Engels, 1960). Parallel to the axial plane of the D_2 folds there is a well developed discrete S_2 crenulation cleavage (Talbot, 1965). The spaced character of the cleavage and the presence of quartz segregations parallel to S_2 shows that pressure solution deformation mechanisms prevailed during D_2.

During the D_3 deformation phase large scale rotations of rock sequences took place, which changed the orientation of the previously formed D_1 and D_2 folds and their respective axial plane cleavages. The rotation axes of these movements are subhorizontal and coaxial with the D_1 and D_2 fold axes. The rotated cleavage planes define a number of large scale cleavage fans (Fig. 4).

In the Mosel area a 'normal' divergent upward fan is present along the line Veldenz – Bernkastel – Traben Trarbach – Starkenborger Mühle – Altlay (Moselachse; Scholtz, 1930). Here the SE-dipping S_2 cleavage planes and NW-vergent D_2 and D_1 structures at the north-west side of the line have rotated passively through the vertical into a general NW dip on the southeastern side. A 'reverse' convergent upward fan is present along the line from Bullay/Merl in the Mosel valley to Oberlahnstein am Rhein (Quiring, 1939; Hoeppener, 1955, 1960). The fan south of Bullay is situated north-west of the

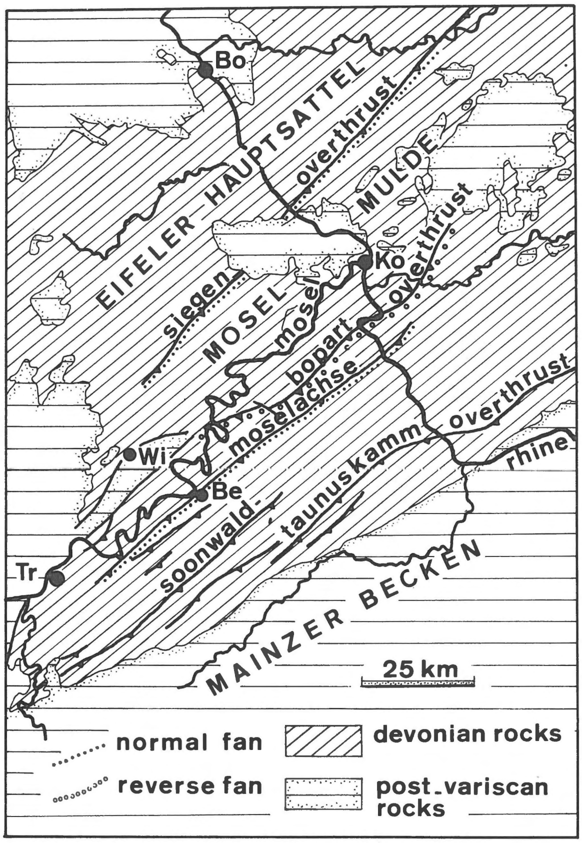

Fig. 4. Tectonic map of the SW Rheinische Schiefergebirge indicating the position of the major overthrust faults, cleavage fans and assumed basement culminations (Sättel) and depressions (Muldes).

area that is influenced by D_2 deformation. Along this line flat-lying S_1 planes and associated D_1 folds in the SE rotate through the vertical near Alf into steep overturned folds with a NW dipping cleavage in the profile section from Alf Fabrik to Bad Bertrich.

Finally another 'normal' fan has been described NW of the investigated area along the line Kaisersesch-Andernach (Quiring, 1939). North of the fan the S_1 cleavage planes dip at approximately 60° to the SE. In a SE direction they rotate through the vertical to a dip of approximately 60° to the NW in the area between Andernach and Koblenz.

Interpretation of the cleavage fans

Three important characteristics of the cleavage fans may form a basis for their tectonic interpretation and are discussed below.

1. The cleavage fans are closely associated with major discontinuities in the stratigraphy and locally with the deformation intensity and metamorphic grade. This is particularly clear along the SW part of the Moselachse near Veldenz, where Zerfer Schichten of lowermost Emsian (Ulmen) age on the SE side of the line are in contact with middle Lower Emsian (Singhofen) slates in the Mosel valley on the NW side of the line.

The discontinuous character of the contact is further demonstrated by the sudden increase in the intensity of D_2 structures, specifically the penetrative S_2 crenulation cleavage SE of the line Veldenz-Altlay, and by the fact that lower greenschist facies rocks in the SE are in direct contact with anchizonal slates in the Mosel valley NW of the line. In the Mosel area this indicates an estimated vertical displacement of several kilometres. These observations lead to the conclusion that the line Veldenz-Altlay represents the trace of a major post-D_2 fault plane along which rocks from a deeper stockwork from the SE are in contact with rocks from a higher structural level in the NW. These stratigraphic and structural relationships and the rotation of the SE block can only be explained by assuming NW-directed movement along a SE-dipping listric reverse fault.

The cleavage fan near Alf is situated directly SE of an even more pronounced discontinuity in the stratigraphy. The stratigraphic sequence NW of the fan has an uppermost Emsian (Kondel) to lowermost Eifelian age. The series is vertical to slightly overturned facing towards the SE. The youngest rocks exposed are the Upper Emsian to Lower Eifelian Kieselgallen and Wissenbach Schiefer, which are in direct contact with Lower Emsian slates of Singhofen age directly south of Alf (Solle, 1976). The fault is a SE-dipping reverse fault which continues in a NE direction, where it is known as the Bopard Overthrust. It has been described along the Rhine profile (Meyer & Stets, 1975) and in the Westerwald (Hannak, 1959).

Finally the northern 'normal' fan along the line Kaisersesch-Andernach is associated with another major overthrust fault (Siegen Overthrust; Hoeppener, 1957). In the Rhine profile the fan is situated in the overlying block, directly SE of a SE-dipping reverse fault that separates rocks of upper middle Siegenian age on the NW-side from lower Siegenian Hunsrückschiefer in the SE, indicating a minimum vertical displacement of 3 km (Meyer & Stets, 1975).

2. The cleavage fans coincide with fundamental facies boundaries during Lower and Upper Emsian differentiation of the southern Rhenish sedimentary basin (Fig. 4). The Lower Siegenian rocks that are exposed north of the Siegen Overthrust indicate a relatively high elevation of the underlying crystalline basement. In contrast the 'Moselmulde' south of the Siegen Overthrust is characterized by an enormous thickness of Upper Emsian and lower Eifelian rocks and apparently represents an area of significant subsidence during the Upper Emsian. Consequently the basement was relatively deep down during the Carboniferous phase of crustal shortening. South of the Moselmulde, the Hunsrück-Taunus Schwelle represented a high area in the Upper Emsian paleogeography. In this area, however, at that time the basement was already situated at a different depth as the result of previous, Lower Emsian differentiation. Then, during the Ulmen substage, a number of rapidly subsiding basins were formed, which received up to 3000 m of Hunsrückschiefer, in contrast to domains with significant less subsidence like the Idarwald and Soonwald Schwelle.

3. The normal fans are extensional structures. This is illustrated by the frequent occurence of small normal faults parallel to the S_1 cleavage planes (Schieferungsparallelle Abschiebungen; Hoeppener, 1960) and by the pattern of movement of conjugate sets of kinkbands in the central parts of the fans where the S_1 cleavage planes are vertical.

In the past few years several authors have drawn attention to the importance of listric overthrust planes and imbricate structures in the 'thin skinned tectonis' of the Rheinische Schiefergebirge. In the northern Schiefergebirge Meissner et al. (1981) interpreted a prominent seismic reflector at 3–4 km depth near Aachen as a well lubricated thrust fault along which large horizontal nappe emplacements took place during the last stages of the Variscan orogeny. Weber (1978) and Weber & Behr (1983) interpreted the imbricate structure of the southern Schiefergebirge as the result of south-directed underthrusting of the lower crust underneath the crystalline rocks of the German Crystalline Rise and the associated decoupling and north directed thrusting of the suprastructure (Subfluenz model). According to these authors the normal cleavage fans formed as the result of backward rotation of the overriding block over SE-dipping listric surfaces during NW-directed thrusting of the detached suprastructure. However the interpretation of Weber & Behr (1983) does not satisfactory explain the extensional character of the normal cleavage fans, nor the formation of reverse fans in the hanging wall of reverse faults like the Bopard Overthrust.

In the present authors' view the formation of listric overthrust faults and cleavage fans in the southern Rheinische Schiefergebirge is controlled by the pre-thrusting structure of the crystalline basement underlying the wedge of Lower Devonian clastic sediments. The concept is illustrated in Fig. 6.

Assuming NW-directed transport of the supracrustal thrust sheets – as was proposed by Weber's (1978) Subfluenz model – the basement topography is likely to have influenced the detached Lower Devonian sediments in several ways. Movement of the rock mass over a ramp will result in translation, rotation and strain of the overriding rock sequence, in which specific areas of extension and compression are created. (Wiltschko, 1981). Assuming 'neutral surface bending' of the thrust mass, a material element on the lower surface will experience extension as it is bent into the lower hinge of the ramp, and shortening when it conforms to the top hinge of the ramp. In the same way a material element above the neutral surface of the thrust mass will be shortened where the thrust mass steepens up the ramp, and extend where the thrust mass flattens out again (Fig. 5).

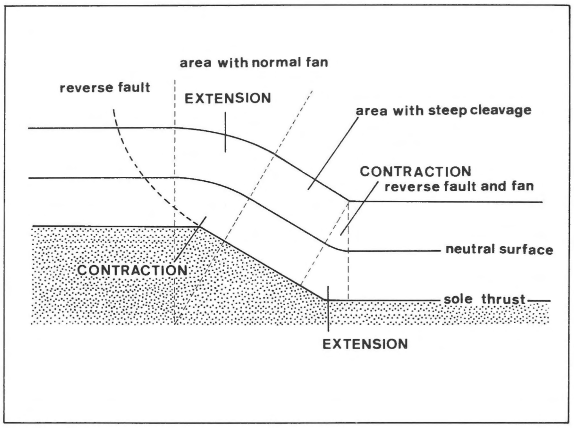

Fig. 5. Simplified model of neutral surface bending of a thrust mass over a basement ramp.

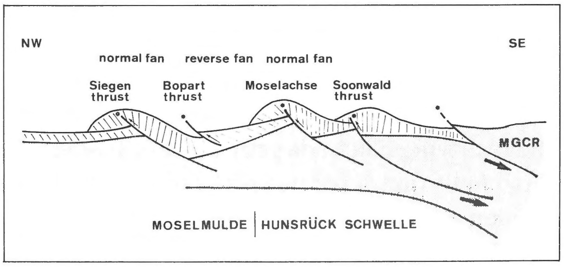

Fig. 6. Conceptual profile of the structure of the Hunsrück-Mosel-S.E. Eifel (not to scale). Crustal underthrusting of the basement (stippled) underneath the Mid German Crystalline Rise (MGCR) and detachement of the Lower Devonian cover. Thrust faults in the cover are formed at pre-existing ramps in the basement. Rotation of pre-existing structures in cleavage fans (S_1-plane indicated) by movement on listric reverse faults. Extensional structures in outer arc of roll-over antiforms. Abrupt or continuous variation in cleavage orientation within the normal fans depends on the depth of the section.

The reverse fan is developed where the thrust mass steepens at the lower hinge of the ramp and the originally approximately 60° SE-dipping cleavage planes rotate into a vertical and even overturned position. The normal fans are formed near the top hinge of the ramp, where the thrust mass flattens again and the cleavage planes rotate back into a SE-dipping position.

The areas of compression also represent the sites where reverse faults may form to maintain bed length during deformation. At the lower surface of the thrust mass such reverse faults may develop near the top hinge of the ramp as splays from the sole thrust and climb up from there towards the surface in front of the normal fans.

In the area of shortening above the neutral surface another reverse fault may develop directly in front of the reverse fan. Shortening in the outer arc of a thrust mass, steepening up the lower hinge of a ramp, may thus be a likely explanation for the development of a major reverse fault like the Bopard Overthrust. Finally, extensional structures are expected to develop in the outer arc of the thrust mass where it tends to flatten again. These are the areas where the normal fans are present and where normal faults, 'Schieferungsparallelle Abschiebungen' and the observed sets of kink bands illustrate the extensional character of the deformation.

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