Neotectonic activity in and around the southwestern Rhenish shield (West Germany): indications of a levelling comparison

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Abstract

Precise levelling data are re-examined in the southwestern Rhenish shield and its foreland by comparing them analytically along levelling profiles. Instead of generalizing regional vertical movement trends, this method emphasizes the activity of individual structural elements, which can be located with a high accuracy. It is shown that present-day vertical motions concentrate on fractures which cut the massif into a number of tectonic blocks. These undergo more or less independent movements. Significant measured displacements range from 1 to 3.5 cm over an average 20-year period and correspond mostly to aseismic slip. High displacements are found near pre-existing faults, sometimes also zones of joint concentration which are favourably oriented with respect to the current regional stress field. In the Mosel area, SW–NE-trending faults are predominantly reactivated as reverse faults. The motion inferred for the Hunsrück border fault is also consistent with the compressive regime presently observed in that area, with σ_1 oriented to the northwest. The direction of vertical motions along the western border fault of the upper Rhine graben changes from south to north in relation to the different azimuths of the central and northern segments of the graben, inducing a S–N-oriented transition from compressional to extensional shear. Within the graben itself, some N160°E-trending normal faults are identified, one of them having probably ruptured in a swarm of microearthquakes not long before the second survey was performed. The western Saar–Nahe trough is characterized by N–S-oriented fractures which cannot be related to mapped faults but show a close connection with photolineaments.

1. Introduction

There are strong geological and geomorphological indications that the western Rhenish shield has been uplifted since at least the Oligocene (Fuchs et al., 1983): Oligocene marine sands rest now on the highest parts of the Ardennes (Demoulin, 1989), the

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Eifel (Sonne and Weiler, 1984) and the Hunsrück mountains (Zöller, 1983), at altitudes of 700 m and more; Quaternary valleys are cut 200–300 m deep in the massif and many Quaternary terrace profiles are disturbed by recent faulting (Negendank, 1983). However, these data yield only a rough idea of the times of motion and its current amplitude and distribution. On the other hand, geodetic data supplies information on the present-day crustal movements, but needs to be interpreted in a detailed geological and geophysical frame. Attempts have been made
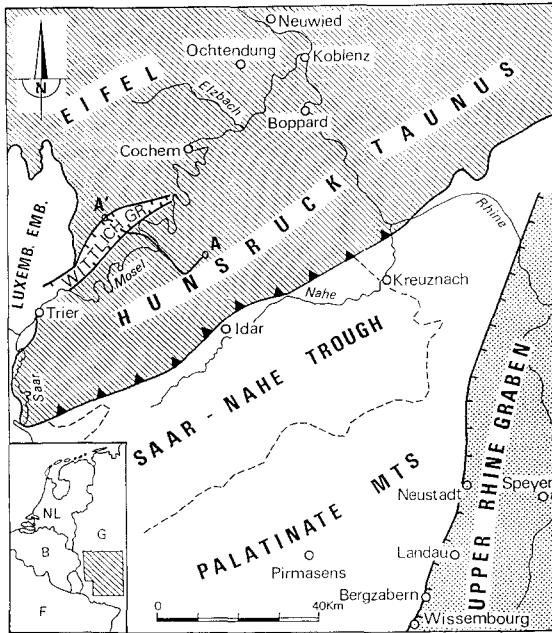
Fig. 1. Location of study area and places cited in the text. The line
A – A' corresponds to the profile shown in Fig. 3.

therefore to use available geodetic data, i.e., succes-
sive precise levellings, in order to determine and
quantify tectonic movements. For the southwestern
part of the Rhenish shield, the map drawn by Mälzer
et al. (1983) remains the best reference. They in-
ferred height changes and vertical movement veloci-
ties for the whole massif from comparison of at least
two successive precise levellings performed since
1921 in their study area. According to them, the
massif is not uplifted uniformly: the uplift motions
concentrate on limited areas, especially in the west-
ern Rhenish shield, whereas some parts of the massif
east of the Rhine river are even subsiding. The
highest uplift rates (up to 1.6 mm/yr) were observed
in the West Eifel (Fig. 1). The South Eifel is slightly
uplifting, while the Hunsrück is more or less stable,
with only a limited updoming east of Trier. The
Saar–Nahe trough and the Palatinate mountains dis-
play a more varied tectonic behaviour: a general
trend to uplift is particularly marked in their eastern
part, with movement rates up to 0.8 mm/yr on the
western shoulder of the upper Rhine graben, but one
notes also a subsidence area southwest of Idar-Ober-
stein, near the Hunsrück border fault. Superimposed
on these regional motions is an overall tilting to-

wards the Rhine valley, running from north to south
over the whole western Rhenish shield and its south-
ern foreland. Within the upper Rhine graben, Mälzer
et al. (1983) identify uplift motions west of the
Rhine river, due to compressional shear (Illies and
Baumann, 1982).

Similar work has also been completed in Belgium
and northern France. Fourniguet (1987) showed that
the Alsace, and, surprisingly, most of the Vosges
mountains too, are currently subsiding. This is in
contrast with the uplift motion of the Palatinate
mountains. In eastern Belgium, Jones (1950) ob-
served a considerable uplift of the Hautes Fagnes
plateau at a rate of 2 mm/yr during the first half of
the 20th century, but Pissart and Lambot (1989)
point out that, from 1948 to 1980, the same region
has subsided more than 40 mm, at a time when the
nearby Eifel mountains underwent continued strong
uplift!

All these studies have largely contributed to out-
line the current vertical crustal movement pattern of
the Rhenish shield and the adjacent areas. Unfortu-
nately, most of them do not supply information about
the present-day activity of individual structural fea-
tures on the shield, inasmuch as they provide only
smoothed maps of regional height change trends,
after having selected representative benchmarks
(Mälzer et al., 1983) or averaged the values for
geographically clustered benchmarks (Pissart and
Lambot, 1989). Much information is lost, therefore,
on local anomalous height-change variations, which
in some circumstances could betray current motion
of individual structural elements, especially faults.
To remedy this problem, we have processed the
adjusted rates of vertical movement in an analytical
way by direct interpretation of profiles along each
first-order levelling line before mapping. This method
has already been successfully applied, where either
faults were suspected to be presently active (Vysko-
cil et al., 1991; Ellenberg, 1992), or where a coseis-
mic movement had to be modelled (Stein and Barri-
entos, 1985), or systematically over wide areas
(Fourniguet, 1987; Colleau and Lenôtre, 1991; De-
moulin et al., 1992). Furthermore, such an analysis
supplies more reliable results since significance
thresholds are lowered by comparing adjacent bench-
marks, generally not more than 1 km away from
each other.

2. Database and method

The study area corresponds to that part of the Rhenish shield which belongs to the Rhineland–Palatinate land west of the Rhine river. Two precise levellings of first order are available in the complete network, the first one performed from 1949 to 1958, the second one achieved between 1968 and 1973. Meanwhile some single levelling lines have been repeated once more. The density of comparable benchmarks is approximately 1 per km along the levelling lines. Special data corrections of the observed height differences due to theoretical error influences (level collimation, rod calibration, temperature, atmospheric refraction, rod orientation relative to sunlight) are discussed in Zippelt (1988) but they are not considered here for lack of necessary data information. Schematically, the mean systematic error on parts of the German geodetic network is estimated not to exceed 20% of the random error (AdV, 1975); moreover, its systematic character is strong only over short distances, and is generally lost when considering longer lines. Correlating the determined height change variations to the levelling route topography, no significant extended regression coefficients were found. This indicates the absence of height-dependent systematic errors.

The survey accuracy is thus strongly dependent on random errors. During levelling, the successive sections (distance between pairs of adjacent benchmarks) are generally surveyed twice, the forward and backward measured height differences between the benchmarks being usually slightly discrepant; the standard deviation of these discrepancies (whose distribution is assumed to be Gaussian in form) for all levelling sections indicates the accuracy of the levelling. Mälzer et al. (1983) computed standard deviations for all first-order levelling lines of both Rhineland–Palatinate surveys to be 0.2–0.5 mm/km$^{1/2}$. These were then used to obtain the cumulative random error on a levelling line, following the formula $\sigma = \eta L^{1/2}$ with σ = cumulative random error, $\eta \cong$ standard deviation and L = line length in kilometres (Bomford, 1971). If η_1 and η_2 denote, respectively, the standard deviations of the first and the second levelling, the cumulative random error for height changes (Δh) in that timespan is given by $\sigma_c = (\eta_1^2 + \eta_2^2)^{1/2} L^{1/2}$.

Our method of analytical levelling comparison, improved from the general principles exposed by Fourniguet (1987), is based on profiles which indicate changes of height differences of two adjacent benchmarks. However, because of highly variable timespan between the surveys for each benchmark, only a velocity model was suitable to model the point movements. Based on, and combined with a single-point model by Holdahl (1975), which yields adjusted time-dependent heights, different functional
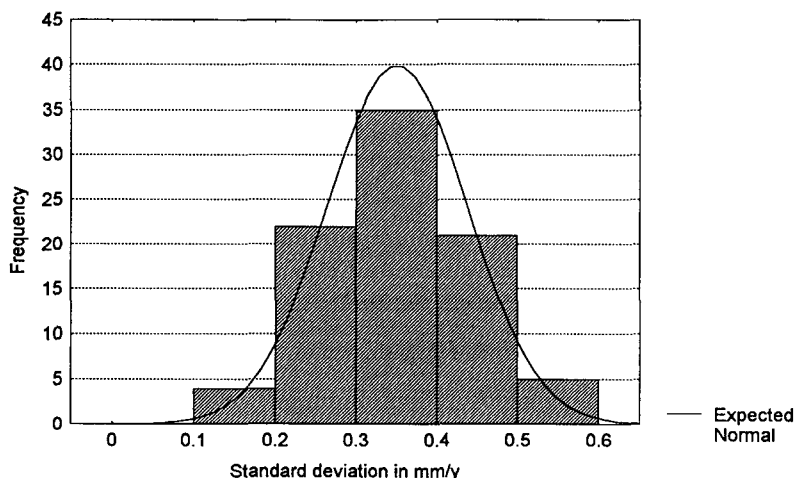

Fig. 2. Distribution of movement rate standard deviations (in mm/yr) for the junction points of the Rhineland–Palatinate first-order network used to compile the recent crustal movement map of the European geotraverse (after Zippelt, in Blundell et al., 1992).

models to estimate vertical motions have been dis-
cussed by Zippelt (1988), and a stepwise procedure
has been proposed to obtain information about the
height changes of the used benchmarks. After statis-
tically defining the best fitting model of the motions
by adjustment of all height differences, a network
composed of the junction points and of secondary
junction points defined where levelling has been
interrupted for a timespan exceeding one year, is
fixed by several representative benchmarks supposed
to be stable. The results of these computations are
used to investigate the whole network line by line
separately. By this way movement rates and standard
deviations of all comparable points are determined
along the levelling lines. Based on that procedure
(more extensively discussed in Mälzer et al., 1983),
Fig. 2 shows the distribution of movement rate stan-
dard deviations for the junction points used in south-
western Germany to compile the recent crustal
movement map of the European geotraverse (Blun-
dell et al., 1992). Thus, profiles representing individ-
ual movement rates for each point were drawn (Fig.
3). In order to express more clearly some movement
values (for instance the tilting of blocks), we have
further assumed that motions were linear on a period
of 20 years, averaging the timespan between succes-
sive measurements, and we have transposed the ve-
locity profiles on profiles giving the total amount of
movement over that 20-year period. Nevertheless,
the chart with the σ_c and $2\sigma_c$ curves (plotted against
L), which determine the significance thresholds for
the height change analysis, has been drawn at a scale
which is considered the worst possible situation (Fig.
3), i.e., some benchmarks may have been relevelled

only 11 years after their first measurement (1957–
1968).

Profile interpretation assumes that the levelling
lines are divided into a number of segments which
correspond to zones of different tectonic behaviour
and diverse movement. A mean profile line is thus
defined, composed of segments approaching, at best,
the real profile. Their delimitation and the signifi-
cance of their slope are defined on the basis of the σ_c
curve. The junctions between adjacent segments,
which we shall call motion discontinuities, can be
characterized only by simple inflexion points sepa-
rating segments of significantly different slope (at
the $1\sigma_c$ confidence level) or by vertical offsets,
either progressive, indicating the presence of flex-
ures, or abrupt when resulting from a fault move-
ment. Most of the motion discontinuities discussed
below are such segment junctions, characterized by a
sharp slope change associated with a significant ver-
tical displacement. However, fault movement may
also be indicated by abnormal points on the profile;
these points, interrupting abruptly the segment conti-
nuity, are defined as lying outside the $2\sigma_c$ curve
adjusted on the mean segment line. As the longest
segment identified in Rhineland–Palatinate is 74 km
long, the cumulative error on a segment never ex-
ceeds 6.1 mm (with $\eta_1 = \eta_2 = 0.5$ mm/km$^{1/2}$); at
the 95% confidence level, every anomalous point
which departs from the mean segment line of more
than $(2L)^{1/2}$ mm, with L counted in kilometres
from the starting point of the segment, is described
as a levelling anomaly; at a distance of 74 km, this is
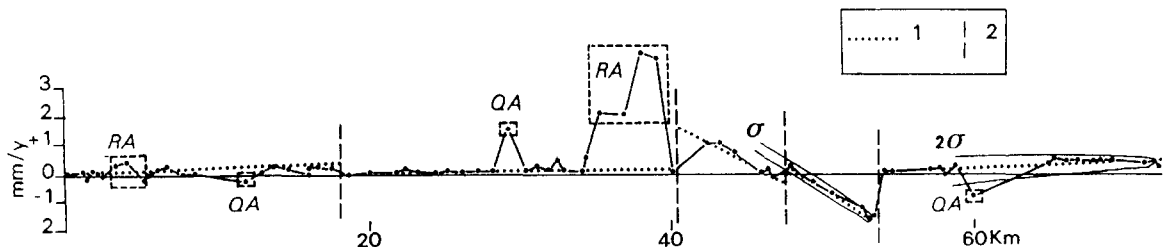at least 12.2 mm higher or lower than the segment
line.

Fig. 3. Height change variation profile between Gödenroth (Hunsrück) and Wittlich (southern Eifel). *1* = smoothed line of a profile
segment, corresponding to a zone of homogeneous height change; *2* = segment junction; *RA* = reliable motion anomaly ($|\Delta h| > (2L)^{1/2}$
mm relative to the segment line, see further explanation in text); *QA* = questionable anomaly (geodetically significant but tectonically
uncertain). The σ and 2σ curves in the right part of the profile highlight quality of data and significance of the proposed segmentation.
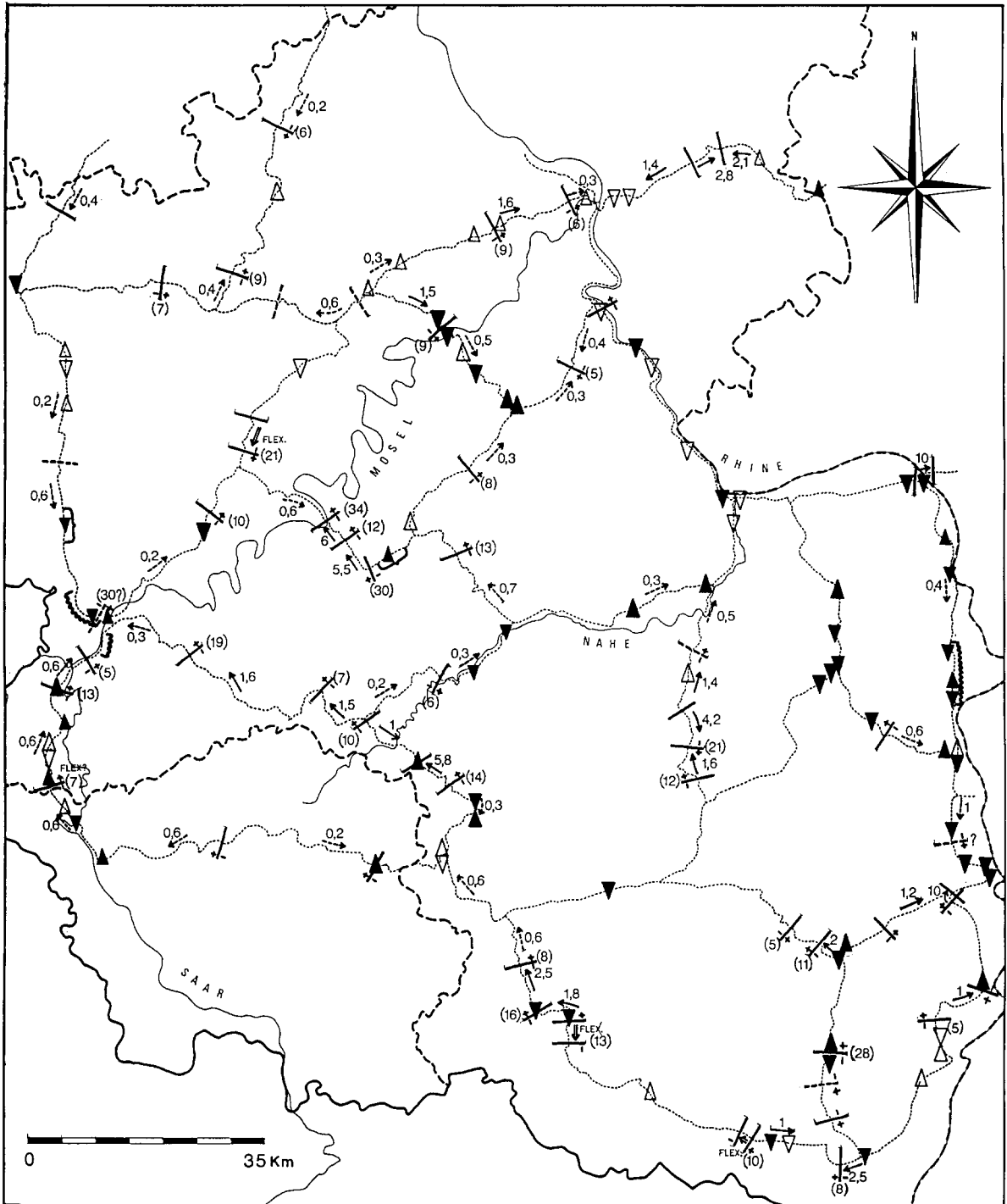
Fig. 4. Map of the motion discontinuities and anomalies. A bar on a profile denotes a motion discontinuity; if accompanied by + / −, a vertical displacement whose value in mm for a 20-year period is given in brackets. Solid triangles denote reliable local anomalies, positive or negative; open triangles are for questionable anomalies. Arrows point down to the tilted segments; tilt value is given in mm/km for a 20-year period.

These geodetically significant anomalies must furthermore be tested for their tectonic significance; their reliability was first assessed by field checking of the benchmarks, by considering the direction of the anomalous motion and by the number of clustered anomalous points. Every isolated benchmark displaying height change 100 mm larger than adjacent benchmarks has further been eliminated, except if it belonged to a special segment configuration (see, for instance, profile A′–A″ in Fig. 7). Lastly, subsidence effects induced by a progressively lowering water table have been analysed by Hein (1978) in the northern Rhine graben, but such subsidence appears unlikely in most of the study area (Rhenish shield, Saar–Nahe trough and Palatinate mountains).

In a second step of the analysis, all discontinuities and tectonically significant anomalies identified on the profiles are mapped (Fig. 4) and relationships are established between them, the interpolation within the levelling polygons being carefully carried out with reference to the type of discontinuity or anomaly and the regional structural pattern.

3. Analysis of the map of motion discontinuities

The analysis of motion discontinuities and anomalies leads us to split up the western Rhenish shield and its southern foreland into a number of different tectonic blocks, separated by motion discontinuities mostly occurring on faults (Fig. 5). At first sight, the fracture pattern characterizing the whole study area (including Rhenish massif, foreland and even the northwestern Rhine graben) is uniform: alternating homogeneous, more or less stable zones, with densely fractured zones of tilted blocks. In detail however, the dominant fracture direction and the nature of the movement are particular to each zone.

North of the Mosel river, the southwestern Eifel mountains can be considered as a relatively homogeneous and stable region with at most a slight downwarping to the southwest. It is traversed, however, by some NW–SE-trending discontinuities with minor displacements. Further south, the Mosel trough is cut in longitudinal tectonic blocks, oriented southwest–northeast and asymmetrically tilted towards the river. On the northern valleyside a broad block ex-

tending from Trier to Koblenz gently slopes to the southeast. Its faulted northwestern edge is locally accompanied by a secondary flexure. Coming nearer to the Rhine valley, that block is cut across by NNW–SSE-oriented fractures defining orthogonal blocks inclined towards the Rhine axis. Such local NNW–SSE-trending blocks are also observed on the opposite side of the Rhine valley. South of the Mosel, narrow SW–NE-oriented blocks strongly tilt in a step-like manner down to the river, with tilt values up to 6 mm/km in a 20-year timespan. They are separated by sharp motion discontinuities occurring on faults whose vertical slip is up to 34 mm in 20 years. Similar SW–NE-trending blocks, tilted to the northwest, characterize also the western half of the Hunsrück mountains. The individual block tiltings in the Hunsrück are, however, compensated for by fault vertical countermovements, so that this massif as a whole experiences an almost pure vertical motion. The levelling-derived data show moreover, that its eastern part behaves homogeneously and is devoid of significant discontinuities. The Rhine cutting through the southern part of the Rhenish shield up to Koblenz is also tectonically quiet, except for a minor transverse fault at Boppard.

In the southern foreland of the Rhenish shield, the lack of data within a large levelling polygon does not permit investigation of the current tectonic behaviour of the central part of the Permian Saar–Nahe trough. To the west, this region is cut by N–S-trending fractures separating blocks differently raised, with only locally a tilt component in the vicinity of the Hunsrück border, toward a lowered area. In its eastern part, two outward-sloping segments connecting in a simple inflexion point suggest the motion of a SW–NE-trending anticline, whose flanks are furthermore limited by fractures with vertical displacements up to 21 mm in 20 years. These fractures extend possibly into the northern part of the Rhine graben, which is otherwise rather quiet and stable, except for an anomalous zone along the Rhine river clearly due to groundwater pumping (Fahlbusch et al., 1983). South of the study area, the Triassic region of the Palatinate mountains appears also as a homogeneous zone, with uplift relative to the adjacent areas. However, this en-bloc movement is disturbed on its western limit by a succession of approximately ENE–WSW-oriented faults and a flexure determining a

step-like lowering toward the northwest of strongly tilted blocks (up to 2.5 mm/km in 20 years).

The central segment of the Rhine graben, whose western border is clearly marked by a double discontinuity, either flexured or faulted, is intensely fractured by NW–SE- to NNW–SSE-trending disconti-nuities. The vertical displacements along the border fault amount to 10–11 mm in 20 years: in the north, the graben is still subsiding but in the south, its western margin is in uplift with regard to its shoulder. The inner fractures delimit small blocks, more or less tilted, acting as minor horsts and grabens.
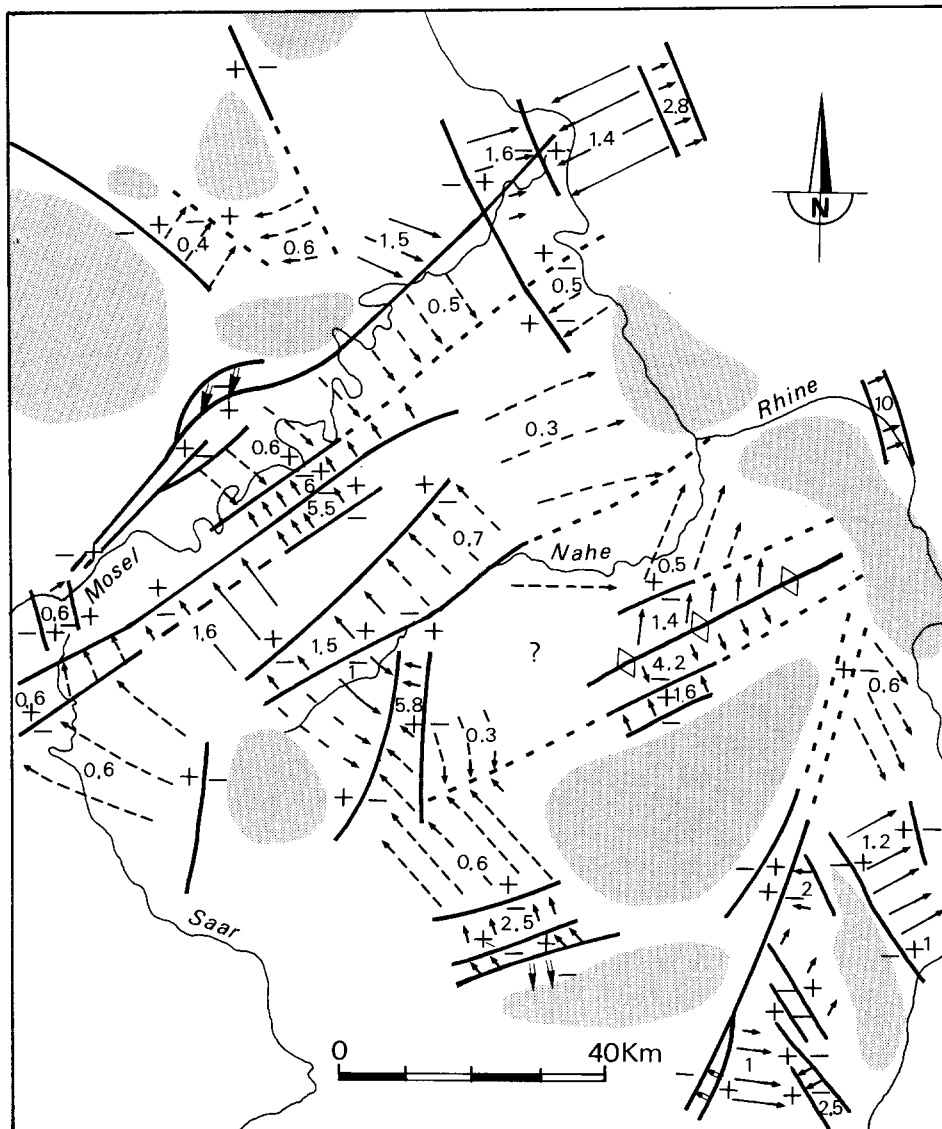

Fig. 5. Map of tectonic blocks and current motions inferred from the levelling comparison. Heavy solid and dashed lines correspond to proved and supposed faults (+ / − mentioned in places of observed discontinuities give the movement direction). Arrows point to the lowered side of tilted blocks (tilt values in mm/km for a 20-year period). The areas undergoing pure vertical motion without faulting are figured in light gray.

North of Landau, one of these motion discontinuities displays the typical profile for a coseismic movement on a high-angle planar normal fault (Stein and Barrientos, 1985), with a superficial displacement on the fault plane approximately fifteen times greater than the relative block movement. Provided only a single sudden motion accounted there for the total height change between both levellings, then that vertical movement would have amounted to 0.3–0.4 m on the fault plane at the surface. Moreover, two adjacent minor motion anomalies can be interpreted as the traces of conjugate faults.

4. Geological interpretation of structures and motions

Most motion discontinuities are sharp changes of segment slope associated with significant vertical displacements. They are interpreted as active faults. However, these motions, though significant, do not generally exceed 34 mm in about 20 years, and correspond to creep. It is furthermore evident that these geodetically inferred movement rates (0.5–1.7 mm/yr) are not consistent with rates on geologic timespans. This is a well-known fact (Mälzer et al., 1979; Sychev et al., 1986; Demoulin et al., 1992) which could be linked to periodicity of the crustal movements and which excludes any extrapolation of the current rates on longer periods. Moreover, the fault movements are mostly coupled with tilting of the blocks they delimit, in contrast with the purely vertical movements of unfaulted areas. Many motion discontinuities are superposed on either structural or related features, as for instance the NW–SE-oriented alignment of the Quaternary West Eifel volcanoes. Among the major identified structures, the levelling comparison points out the current activity of the Wittlich graben and other tectonic elements along the Mosel valley, the western border fault of the Rhine graben, the Hunsrück border fault and another prominent Variscan fault in the Pirmasens area. Fold reactivation is also sometimes indicated by geodetic data, as for example, a SW–NE-trending anticline axis south of Kreuznach. But motion discontinuities also demonstrate the frequent existence of geologically unknown structures, either extending the influence area of the main fault systems or revealing

neotectonic features which are in no way linked to the pre-existing structural framework.

4.1. The Mosel valley

In this area, the main active structures extend parallel to the valley, in the SW–NE Variscan direction. The faults bordering the Permian Wittlich graben, north of the Mosel, are presently moving at a rate up to 1 mm/yr, resulting in a graben uplift with respect to its shoulder. The axis of relative subsidence (or better, of slowest uplift) is about 13 km further south, on the southern valleyside of the Mosel. The tectonic inversion of the graben, inconsistent with its presumed subsidence of 5–15 and even 35–50 m in the west since the middle Pleistocene (Negendank, 1977, 1983), is, however, corroborated by similar motions occurring on reactivated Paleozoic faults south of the Mosel river. These high-angle faults, steeply dipping to the northwest in the antivergent zone of the Variscan Mosel syncline (Hoeppener, 1960; Gasser, 1978; Weijermars, 1986), now act as reverse faults, giving rise to a step-like arrangement of NW-tilted blocks. Moreover, they are seismically active, as indicated by some minor earthquakes recorded along their trace in the 1927–1935 period (Ahorner and Murawski, 1975). The inferred compressive regime could be easily understood in the general stress field of northwestern Europe, with $\sigma_H = \sigma_1$ oriented from southeast to northwest. But the in situ stress measurements performed in the Rhenish shield reveal an extensional stress regime for that area (Baumann and Illies, 1983), so we must consider the possibility of either a temporary or a local change in the stress regime along the Mosel valley, with σ_1 turning horizontal. The local character of such a modification is more probable, inasmuch as the general pattern of a crumpled structure south of the Mosel, with block tilting compensated by fault motions, indicates also a predominantly horizontal push exerted on the massif. Moreover, the focal mechanisms of some recent earthquakes in the nearby mountains (Baier and Wernig, 1983) corroborate the compressive type of the stress field at least in parts of the massif. Thus, the extensional regime claimed by Baumann and Illies (1983) for the Rhenish shield as a whole should certainly be restricted to the Eifel area, where an anomalous body of low-

velocity material has been observed at the mantle–crust boundary, best modelled as a mechanical diapir due to density instability in the asthenosphere (Fuchs et al., 1983).

At the southwestern end of the longitudinal tectonic blocks parallel to the Mosel valley, the levelling comparison indicates motion taking place on a number of minor NNE–SSW- to N–S-trending faults belonging to the eastern flank of the Luxemburg Embayment, northwest of Trier. These are seemingly moving as oblique-slip faults, combining sinistral shear and extension for a vertical movement rate of up to 1 mm/yr. Transverse fault activity is also identified at the other end of the longitudinal Mosel blocks, on the western and southern margins of the Neuwied basin. In that area, the Mosel terraces already suggest the existence of these transverse faults but do not locate them as accurately as proposed here (Negendank, 1983; Bibus, 1983). In particular, a vertical motion of about 40–50 m during the Quaternary was inferred either in the Cochem area (Bibus, 1983) or along the Elzbachtal line (Negendank, 1983). Considering present-day vertical movements, the motion discontinuity that we map is located 10 km further east and corresponds exactly to the southern continuation of the NW–SE-oriented Niedermendig fault. The activity of that fault is furthermore proved by the many micro-earthquakes recorded near Ochtendung between 1977 and 1981, whose distribution and focal mechanisms clearly indicate a purely tensional dip-slip dislocation along a NW–SE-striking and 60°NE-dipping plane (Ahorner, 1983). However, the height change trend suggested by the relative position of the levelling segments on each side of the fault for the 1934–1973 period corresponds surprisingly to an opposite movement, by far more important than the seismotectonic slip rate computed from seismic moments of the earthquakes (0.25–0.50 mm/yr against 0.004–0.027 mm/yr)! Such short-term oscillations of vertical motion, though frequently observed at a regional scale (Sychev et al., 1986), remain largely unexplained at the single fault scale.

4.2. The Hunsrück border fault

The present-day activity of the Hunsrück border fault is clearly revealed by the levelling comparison.

It is characterized by vertical motions of up to 0.5 mm/yr and by a number of local anomalies. The fault movement direction is varying, depending on the place where it is considered: this is probably due to the fact that, in this broad fault zone, the geodetic data indicate in some places the main fault activity and in others minor displacements on conjugate faults. However, the global trend is undoubtedly an uplift of the Hunsrück massif with respect to its southern foreland, in agreement with the Plio-Quaternary upheaval of that area. In the upper 10 km of the crust, the Hunsrück border fault has a high-angle fault character, steeply dipping to the northwest, so that its geodetically inferred vertical motion is compressive, corroborating the NW–SE orientation of the maximum horizontal compression established by in situ stress measurements for that part of northwestern Europe (Baumann and Illies, 1983). Nevertheless, a contradiction arises when considering the focal mechanisms calculated for some earthquakes which recently shook this fault zone. At a depth of 10–15 km, they correspond to extensional dip-slip movements, with a minor right-lateral shear component on a 48°SE-sloping plane (Ahorner and Murawski, 1975). This is easily explained by the geometry of the Hunsrück border fault (Murawski, 1975), a listric fault which is overturned with respect to the σ_1 axis in the upper 10 km of the crust (Fig. 6): compression in the upper part of the crust necessarily turns to extension at depth. But one has still to investigate what term of this couple is the driving mechanism of the fault motion. Considering that no deep structure or mantle anomaly has been found in that area to cause primary extension and uplift like in the West Eifel (Neugebauer et al., 1983; Fuchs et al., 1983), we propose that the main tectonic stress acting in the southern Rhenish shield area is a near-surface SE–NW-oriented compression due to the gravitational push of the Alpine arc on its foreland. Moreover, normal faulting at depth (in the middle part of the crust) revealed by focal mechanisms of earthquakes should be considered as a secondary effect of that compression, due to the fault geometry. This is in agreement with the opinion of Zoback et al. (1993), who suggest that "plate driving forces in the continental lithosphere in this part of western Europe are transmitted principally through the upper crust".
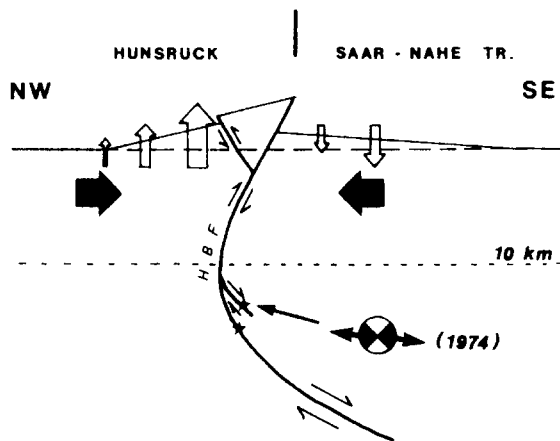
Fig. 6. Diagrammatic sketch showing a cross section of the Hunsrück border fault (*HBF*). Due to the fault geometry, near-surface compression turns to extension at depth. Stars indicate earthquake hypocenters. The Kirn earthquake, 1974, focal mechanism is drawn after Ahorner and Murawski (1975). White arrows describe the vertical crustal motions inferred from geodetic data. The compressive stress in the upper crust is figured by black arrows.

4.3. The upper Rhine graben

The activity of the main western border fault of the upper Rhine graben in the Bad Bergzabern–Neustadt a.d. Weinstrasse area is clearly shown by the geodetic data. In that northern half of the N35°E-striking central segment of the graben, opposite fault motions are observed from south to north. In Bad Bergzabern, the western margin of the graben is in uplift with regard to its shoulder (profile A–A', Fig. 7); moreover, it is tilted toward the graben axis; the movement which appears flexural in the levelling profile, is probably distributed over two or three major faults. On the contrary, in Neustadt, 30 km further north, the graben is still in relative subsidence, at a rate of 0.5 mm/yr, concentrated on a single fracture. Its margin is strongly tilted toward the active western border fault. These opposite vertical motions are understood to be a consequence of moving from the central segment of the graben, deflected towards the σ_3 direction with respect to the regional shear direction (N20°E) and thus submitted to compressional shear, towards the more or less N–S-trending northern segment, where extensional

shear enables further subsidence of the graben (Illies and Baumann, 1982).

In the graben itself, the motion discontinuities mapped in the Landau area are also interesting (profile A'–A'', Fig. 7). The major one is interpreted as a NNW–SSE-trending, WSW-dipping normal fault running across the village of Nussdorf, north of Landau. South of it, two minor anomalies correspond probably to antithetic faults. Further north, another NW-striking fault is inferred from two motion discontinuities located west of Speyer. These structures have already been mentioned by Illies and Baumann (1982), who consider them to be extensional faults resulting from a mechanism similar to feather jointing and separating narrow N160°E-trending horsts and grabens. Oblique to the direction of left-lateral shearing, these pinnate fractures are furthermore confirmed by similarly oriented small scarps, generally 10–15 m high and by minor offsets of local Rhine tributaries. It is also worth noting that these NNW–SSE-trending extensional faults within the graben concentrate on its western margin between Wissembourg and Neustadt a.d. Weinstrasse, where they are probably initiated by the main western border fault geometry: in that area, the azimuth of the border fault changes from N45°E in the south to N25°E in the north, inducing a change in the stress regime, with the transition from compressional shear to simple shear and then rapidly to extensional shear northwards.

Moreover, the signal displayed by the vertical movement profile in the vicinity of Landau (profile A'–A'', Fig. 7) is problematical. Occurring on the small Nussdorf fault, that signal corresponds to a motion of about 40 cm. Such a movement could be ascribed to a levelling error; but even if we accept that the sharp positive spike on the profile may be not valid, a roughly similar signal remains, with fault motion amounting to 20 cm. Compaction of the unconsolidated Neogene sediments of the upper Rhine graben, eventually reinforced by oil pumping, seems also unable to explain that very localized phenomenon, whose lowered part has its uplifted counterpart.

The observed movement should thus be of tectonic origin. In fact, while flexural isostatic response to fault motion, as proposed by Kusznir and Ziegler (1992) to determine that type of profile, appears
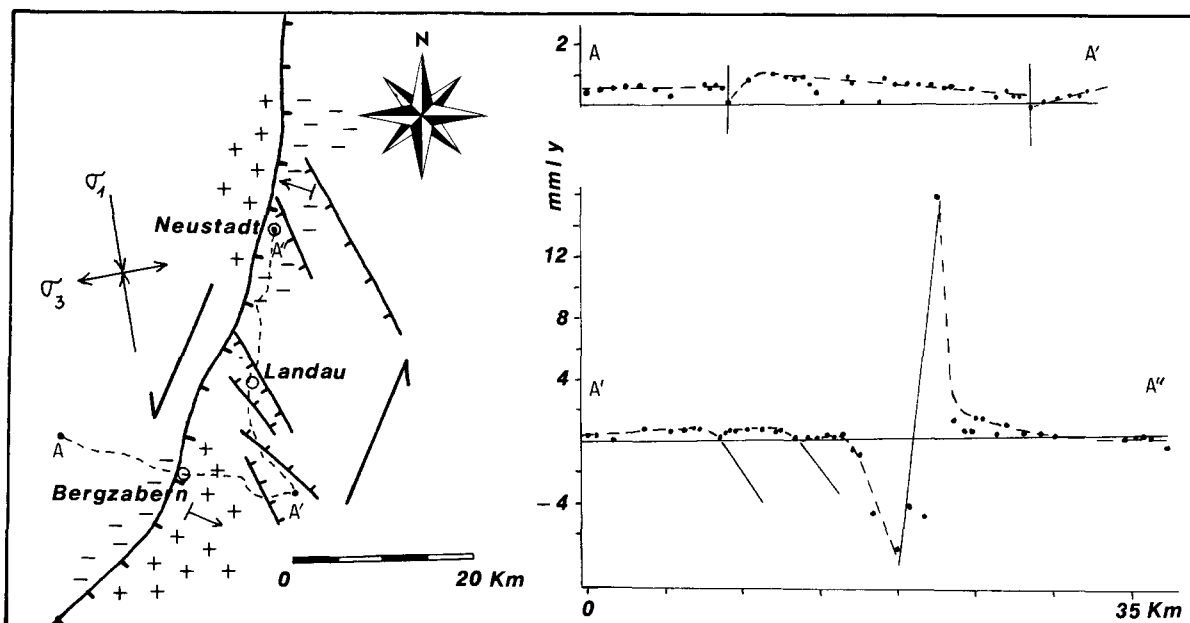
Fig. 7. Relative vertical movements (+ / −) at the western Rhine graben border fault in the Landau area, related to the present-day stress field. Arrows indicate the local sense of tilting. The height change variation profiles A–A' and A'–A" clearly show the fault motions discussed in the text.

unlikely at such a small scale, it looks very like the coseismic movement modelled and observed by Stein and Barrientos (1985) for the Borah Peak earthquake, 1983, on a high-angle planar normal fault of the Basin and Range Province (USA). There is a well-marked antithetic flexure (roll-over) of the hanging wall and a corresponding, though less certain rise of the footwall. Relying on this analogy means that the observed movement in Landau is predominantly due to a sudden slip, which has obliterated the long-term fault displacement. Indeed, the Nussdorf fault is a normal fault whose geometry supports an elastic dislocation model fitting the profile A'–A" (Fig. 7). However, no important earthquake was registered in the Landau area during the inter-levelling period, to produce a motion that is at least two orders of magnitude higher than ground motion expected from tremors commonly occurring in that part of the Rhine graben. We suggest therefore as a hypothesis that an unrecorded swarm of shallow microearthquakes on the Nussdorf fault may be responsible for the vertical movement defined by

the levelling comparison near Landau. Since no post-seismic compensation of the coseismic elastic rebound is apparent, this earthquake swarm probably occurred in the late sixties, just before the second survey was performed.

In contrary to the form of the motion, its size remains, however, inconsistent with that hypothesis. The underground presence of oil must probably be taken into account: due to the lubricating effect of oil on the fault plane, the fault may be much weaker than theoretically expected; the ruptures may also propagate in the near-surface realm more easily. Anyway, such a discrepancy in amount between observed and calculated motion has already been noted elsewhere (Castle et al., 1977), but without receiving any satisfying explanation.

4.4. The Saar–Nahe trough

In the northwestern part of the Saar–Nahe trough, where few faults, and especially no important fault favourably oriented for a reactivation in the present-

day stress field are recognized in the Paleozoic base-
ment, the motion discontinuities are by no means
less numerous than in the rest of the study area.
Since the N–S-trending fractures inferred from the
geodetic data could not be related here to known
structures, they have been compared to photolinea-
ment maps drawn from Landsat2 image analysis
(Wahba and Zöller, 1983). On a test area covering
the Hunsrück and the western Saar–Nahe trough,
such a comparison shows a close relationship be-
tween motion anomalies and photolineaments (Fig.
8). However, neither relate to mapped faults. 81.5%
of the significant motion discontinuities coincide with
the crossing of a levelling line by a lineament identi-
fied on Landsat2, and conversely 43% of the places

where such a lineament cuts a levelling line are
characterized by a geodetic anomaly. Taking into
account the anomalies whose reliability is more
questionable (for instance because it is recorded by a
single benchmark), the percentage of photolineations
correlating to motion discontinuities even approxi-
mates 60%. These currently moving lineaments fol-
low two major directions: the first is the Variscan
direction (N60°E), frequently observed in the
Hunsrück massif, and the second is a mean N–S
direction with fanwise-arranged NW–SE- to NNE–
SSW-oriented lineations, especially in the northwest-
ern Saar–Nahe trough. Since field checking of pho-
tolineaments demonstrates that, if not related to
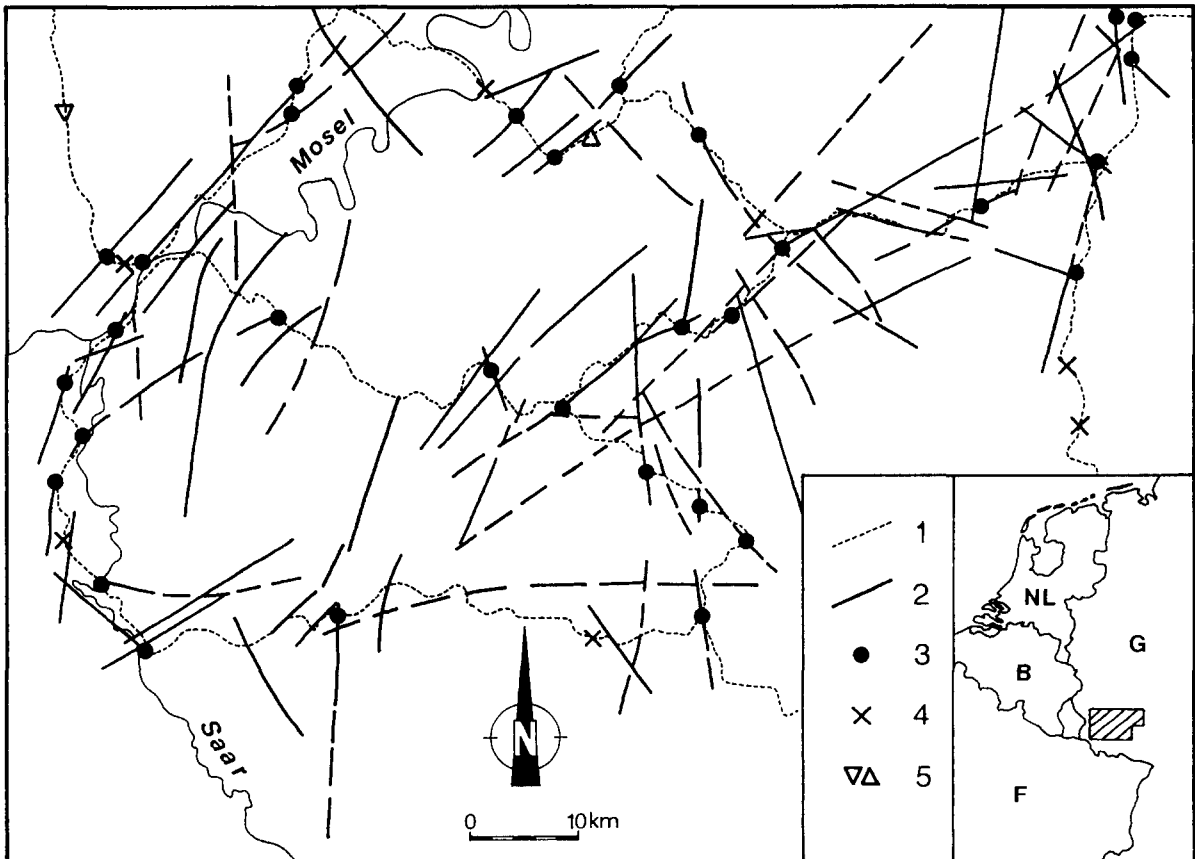faults, they correspond in most cases to zones of

Fig. 8. Close relationship between structural features inferred from the levelling comparison and photolineaments identified on Landsat2
images in the region centred on the Hunsrück. 1 = first-order levelling line; 2 = photolineament (after Wahba and Zöller, 1983); 3 = motion
discontinuity or anomaly coinciding with a photolineament; 4 = motion discontinuity; 5 = local motion anomaly.

joint concentration (Kronberg, 1977), it is proposed that in areas more or less devoid of major faults favourably oriented for present-day stress relaxation, the tectonic stresses are primarily released by creep on (generally pre-existing) joint systems. In the Saar–Nahe trough, the NW–SE to NNW–SSE-oriented jointing is probably of Hercynian origin, whereas the N–S-oriented joint system is related to the still older N–S-trending Eifel Depression. According to the current stress field in northwestern Europe (Bergerat, 1987), they are normally undergoing more or less extensional shearing, with predominant strike-slip movements: this is in agreement with the fact that many motion discontinuities related to photolineaments in that area are only local anomalies without any other disturbance, and especially without any relative vertical displacement between the two parts of the segment they interrupt.

5. Conclusion

The analytical comparison of geodetic data along levelling profiles is useful as an aid to regional-scale neotectonic studies in intraplate regions. It provides a detailed picture of relative vertical motions and points out movement of individual structural elements, thereby accurately locating the active fractures. In the case of the southwestern Rhenish shield, a complicated active fault pattern is revealed, dividing the massif into a number of tectonic blocks. These display every type of movement (relative subsidence or uplift, tilting). Most faults that are undergoing movement are reactivated, principally along the Variscan trend with compressive motion (Mosel valley, Hunsrück border fault), but movement also occurs in the transverse NW–SE direction or NNE–SSW shear direction of the upper Rhine graben. Some recent, "neotectonic" features could be the extensional faults within the Rhine graben in the Landau area (Villemin and Bergerat, 1987), and possibly the N–S-trending fractures of the Saar–Nahe trough, which we explain as former joints now experiencing some displacement. Though the movement rates inferred from the levelling comparison correspond generally to aseismic slip, the faults on which they are observed can also sometimes rupture in minor earthquakes (Landau, Ochtendung, Mosel area).

References

AdV, 1975. Arbeitsgem. d. Vermessungsverw. d. Länder der BRD: Nivellementnetz 1960. Bayer. Landesvermessungsamt, München.

Ahorner, L., 1983. Historical seismicity and present-day microearthquake activity of the Rhenish massif, central Europe. In: K. Fuchs, K. von Gehlen, H. Mälzer, H. Murawski and A. Semmel (Editors), Plateau Uplift. The Rhenish Shield. A Case History. Springer, Berlin, pp. 198–221.

Ahorner, L. and Murawski, H., 1975. Erdbebentätigkeit und geologischer Werdegang der Hunsrück-Südrand-Störung. Z. Dtsch. Geol. Ges., 126: 63–82.

Baier, B. and Wernig, J., 1983. Microearthquake activity near the southern border of the Rhenish massif. In: K. Fuchs, K. von Gehlen, H. Mälzer, H. Murawski and A. Semmel (Editors), Plateau Uplift. The Rhenish Shield. A Case History. Springer, Berlin, pp. 222–227.

Baumann, H. and Illies, J.H., 1983. Stress field and strain release in the Rhenish massif. In: K. Fuchs, K. von Gehlen, H. Mälzer, H. Murawski and A. Semmel (Editors), Plateau Uplift. The Rhenish Shield. A Case History. Springer, Berlin, pp. 177–186.

Bergerat, F., 1987. Stress fields in the European platform at the time of Africa–Eurasia collision. Tectonics, 6(2): 99–132.

Bibus, E., 1983. Distribution and dimension of young tectonics in the Neuwied basin and the Lower Middle Rhine. In: K. Fuchs, K. von Gehlen, H. Mälzer, H. Murawski and A. Semmel (Editors), Plateau Uplift. The Rhenish Shield. A Case History. Springer, Berlin, pp. 54–61.

Blundell, D., Freeman, R. and Mueller, S., 1992. A Continent Revealed. The European Geotraverse. Cambridge Univ. Press, Cambridge, 288 pp.

Bomford, G., 1971. Geodesy. Oxford Univ. Press, New York, NY, 731 pp.

Castle, R.O., Church, J.P., Elliott, M.R. and Savage, J.C., 1977. Preseismic and coseismic elevation changes in the epicentral region of the Point Mugu earthquake of February 21, 1973. Bull. Seismol. Soc. Am., 67(1): 219–231.

Colleau, A. and Lenôtre, N., 1991. A new digital method for analysis of neotectonics applied to the Bonnevaux–Chambaran area, France. Tectonophysics, 194: 295–305.

Demoulin, A., 1989. Les transgressions oligocènes sur le massif Ardenne–Eifel. Ann. Soc. Géol. Belg., 112: 215–224.

Demoulin, A., Lenôtre, N., Moxhet, J. and Pissart, A., 1992. Les

régions néotectoniques de la Belgique définies par la compara-
ison de nivellements. Ann. Soc. Géol. Belg., 115: 99–111.

Ellenberg, J., 1992. Recent fault tectonics and their relation to the
seismicity of East Germany. Tectonophysics, 202: 117–121.

Fahlbusch, K., Hein, G. and Kistermann, R., 1983. Rezente
Bewegungen im nördlichen Oberrheingraben. Verknüpfung
von Messdaten aus Geodäsie, Geologie und Bodenmechanik.
Neues Jahrb. Geol. Paläontol. Monatsh., pp. 460–476.

Fourniguet, J., 1987. Géodynamique actuelle dans le nord et le
nord-est de la France. Mém. BRGM 127, 160 pp.

Fuchs, K., Von Gehlen, K., Mälzer, H., Murawski, H. and Sem-
mel, A., 1983. Epilogue: mode and mechanism of Rhenish
plateau uplift. In: K. Fuchs, K. von Gehlen, H. Mälzer, H.
Murawski and A. Semmel (Editors), Plateau Uplift. The Rhen-
ish Shield. A Case History. Springer, Berlin, pp. 405–411.

Gasser, U., 1978. Zur tektonischen Problematik der Moselmulde
(Rheinisches Schiefergebirge). Geotektonische Forsch., 54:
1–84.

Hein, G., 1978. Multivariat Analyse der Nivellementsdaten im
Oberrheingraben   und   Rheinischen   Schild.   Z.
Vermessungswes., 103: 430–435.

Hoeppener, R., 1960. Ein Beispiel für die zeitliche Abfolge
tektonischer Bewegungen aus dem Rheinischen Schieferge-
birge. Geol. Mijnbouw, 39: 181–188.

Holdahl, S.R., 1975. Models and strategies for computing vertical
crustal movements in the United States. Int. Symp. Recent
Crustal Movements, Grenoble.

Illies, J.H. and Baumann, H., 1982. Crustal dynamics and mor-
phodynamics of the western European rift system. Z. Geomor-
phol. Suppl., 42: 135–165.

Jones, L., 1950. Les premiers résultats de la comparaison du
Deuxième Nivellement Général (1948) avec les nivellements
anciens. Bull. Soc. Belge Géol. Paleontol. Hydrol., 59: 156–
162.

Kronberg, H., 1977. Die regionale und überregionale Bruchtek-
tonik Mitteleuropas. Bestandsaufnahme und Interpretationen.
Geotektonische Forsch., 53: 7–41.

Kusznir, N.J. and Ziegler, P.A., 1992. The mechanics of continen-
tal extension and sedimentary basin formation: a simple-
shear/pure-shear flexural cantilever model. Tectonophysics,
215: 117–131.

Mälzer, H., Schmitt, G. and Zippelt, K., 1979. Recent vertical
movements and their determination in the Rhenish massif.
Tectonophysics, 52: 167–176.

Mälzer, H., Hein, G. and Zippelt, K., 1983. Height changes in the
Rhenish massif: determination and analysis. In: K. Fuchs, K.
von Gehlen, H. Mälzer, H. Murawski and A. Semmel (Edi-
tors), Plateau Uplift. The Rhenish Shield. A Case History.
Springer, Berlin, pp. 164–176.

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

Negendank, J.F.W., 1977. Argumente zur känozoischen
Geschichte von Eifel und Hunsrück. Neues Jahrb. Geol.
Paläontol. Monatsh., pp. 532–548.

Negendank, J.F.W., 1983. Cenozoic deposits of the Eifel–
Hunsrück area along the Mosel river and their tectonic impli-
cations. In: K. Fuchs, K. von Gehlen, H. Mälzer, H. Murawski
and A. Semmel (Editors), Plateau Uplift. The Rhenish Shield.
A Case History. Springer, Berlin, pp. 78–88.

Neugebauer, H.J., Woidt, W.D. and Wallner, H., 1983. Uplift,
volcanism and tectonics: evidence for mantle diapirs at the
Rhenish massif. In: K. Fuchs, K. von Gehlen, H. Mälzer, H.
Murawski and A. Semmel (Editors), Plateau Uplift. The Rhen-
ish Shield. A Case History. Springer, Berlin, pp. 381–403.

Pissart, A. and Lambot, P., 1989. Les mouvements actuels du sol
en Belgique; comparaison de deux nivellements IGN (1946–
1948 et 1976–1980). Ann. Soc. Géol. Belg., 112: 495–504.

Sonne, V. and Weiler, H., 1984. Die detritischen alttertiären
(oligozänen) Faunen- und Florenelemente in den Sedimenten
des Meerfelder Maares. In: G. Irion and J.F.W. Negendank
(Editors), Das Meerfelder Maar. Untersuchungen zur Entwick-
lungsgeschichte eines Eifelmaares. Courr. Forschungsinst.
Senckenberg, 65: 87–95.

Stein, R.S. and Barrientos, S.E., 1985. Planar high-angle faulting
in the Basin and Range: geodetic analysis of the 1983 Borah
Peak, Idaho, earthquake. J. Geophys. Res., 90(B13): 11,355–
11,366.

Sychev, P.M., Zacharov, V.K. and Semakin, V.P., 1986. On the
origin of recent and modern vertical movements in the island
systems of northeastern Asia. Tectonophysics, 122: 283–305.

Villemin, T. and Bergerat, F., 1987. L'évolution structurale du
fossé rhénan au cours du Cénozoïque: un bilan de la déforma-
tion et des effects thermiques de l'extension. Bull. Soc. Géol.
Fr., 8, III, 2: 245–255.

Vyskocil, P., Tealeb, A. and Mohamed, A.S., 1991. Recent crustal
movement studies at Seiyal area, northwest of Aswan Lake,
Egypt. J. Geodyn., 14: 263–276.

Wahba, Y. and Zöller, L., 1983. Terrassenverstellungen und tek-
tonische Analyse von Satellitenbildern. Ein methodischer Ver-
such, dargestellt an Beispielen aus dem Mosel–Saar–Nahe-
Raum. Eiszeitalter Ggw., 33: 31–30.

Weijermars, R., 1986. S_1-cleavage fans in the Moselmulde of the
Rheinische Schiefergebirge (Federal Republic of Germany)
may be due to a D_3-tectonic event: open folding and reverse
faulting. Geol. Rundsch., 75(2): 323–332.

Zippelt, K., 1988. Modellbildung, Berechnungstrategie und
Beurteilung von Vertikalbewegungen unter Verwendung von
Präzisionsnivellements. Dtsch. Geod. Komm. 343, 153 pp.

Zoback, M.D., Apel, R., Baumgärtner, J., Brudy, M., Emmer-
mann, R., Engeser, B., Fuchs, K., Kessels, W., Rischmüller,
H., Rummel, F. and Vernik, L., 1993. Upper-crustal strength
inferred from stress measurements to 6 km depth in the KTB
borehole. Nature, 365: 633–635.

Zöller, L., 1983. Neotectonic movements at the southern and
western boundary of the Hunstrück mountains (southwestern
part of the Rhenish massif). In: K. Fuchs, K. von Gehlen, H.
Mälzer, H. Murawski and A. Semmel (Editors), Plateau Uplift.
The Rhenish Shield. A Case History. Springer, Berlin, pp.
89–92.