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ANCIENT AND RECENT RIFTING IN THE RHINEGRABEN

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ABSTRACT

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The Rhinegraben is part of a western European rift system. Although of different ages and trend, these rifts are situated on pre-existing basement weakness zones. Signs of Rhinegraben subsidence occur in mid-Jurassic, but true rifting began in mid-Eocene. Boundary faults are complex systems of normal faults, dipping about 65°, perhaps flattening with depth. "Horizontal stylolite" orientations indicate an Eocene palaeostress field (related to Alpine plate collision) with its minimum component normal to the graben, i.e. ideal for rifting on the basement weakness zone. Rifting continued until Lower Miocene, but the depocentre shifted north with continued development of a mantle bulge in the south. Then, although crustal upwarping and volcanism continued, graben formation ceased – the stress field was no longer appropriately oriented. Graben activity restarted in Upper Pliocene and continues today. In-situ stress measurements indicate a sinistral shear component parallel to the graben, producing different tectonic reactions in the three slightly differently oriented graben segments. This shear motion is ascribed to continuing Alpine uplift and extension pushing northwestward the block east of the graben. The Rhinegraben and Lower Rhine Embayment are connected by a continuous seismotectonic belt where rifting is controlled by pre-existent basement fractures and regional stress.

INTRODUCTION

The Rhinegraben is the outstanding element of the Western European rift belt. The down-dropped block of the Upper Rhine plain, the conspicuous parallelism of its framing escarpments, the upwarped shoulders, and the equal amount of shoulder elevation on both sides mark, physiographically as well as geologically, a large-scale symmetric feature. This woodcut-like picture engraved upon the block mosaic of the Alpine foreland is considered to be the product of a two-stage process of continental rifting.

After discussing the regional tectonic setting and the preconditions of the graben formation, the opposing actions of graben subsidence and infill versus shoulder uplift and denudation will be analyzed in chronological order. It will be seen that rifting has evolved (1) basement controlled, (2) mantle or asthenolith controlled, and (3) stress field controlled. Moreover, the geologic history of the graben exhibits two stages of formation. The first involves the creation of a tensional rift valley, active from mid-Eocene through to Lower Miocene times (to explain this process mainly geological observations have been taken into account). The second is a period when the graben acts as a sinistral shear zone; this stage was initiated in Upper Pliocene times and is still active. To evaluate this latter process, a more direct analysis can be made, since geodetic measurements, in-situ stress determinations and seismotectonic observations are available to aid one's visual conception of rift valley formation.

REGIONAL SETTING OF THE RHINEGRABEN

The crust of the extra-Alpine part of Western Europe is traversed by a system of rift structures; geological history, size, and tectonic features of the individual grabens appear considerably different. Nevertheless, a preferred NNE-SSW ("Rhenish") to N-S orientation, as well as suggestions of a chainlike arrangement, indicate a coherent rift belt.

The North Sea Basin is longitudinally divided by the Viking-Central Graben; its main rifting activity took place in

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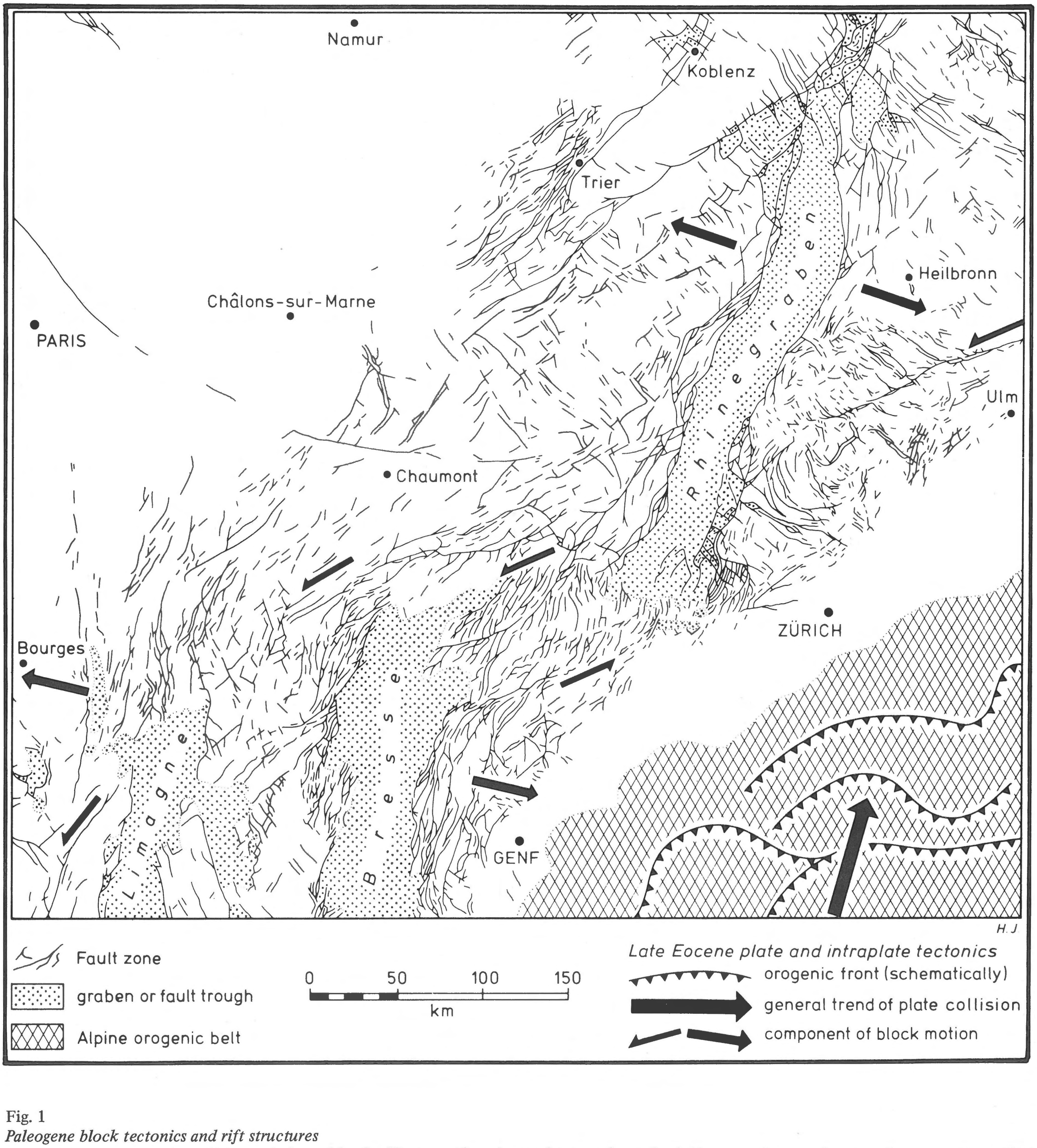

Fig. 1
Paleogene block tectonics and rift structures
About 36 m.y. ago plate collision culminated in the Western Alps. As can be seen from the fold axes and nappe fronts, a "pyrenean", i.e. E-W, general trend of compressional deformation is observed in the Alpine fold belt. In the foreland, and normal to the collision front, a system of pre-existent weakness zones responded to the stress conditions by reactivation. The rifting activity of the Rhinegraben and the Bresse and Limagne grabens, culminated simultaneously with the Alpine orogeny. The crustal extension across the individual grabens created a system of transcurrent of transform faults to release the shear strain along the lateral offsets that separate the different graben segments.
From: Illies & Greiner (1976).

Triassic to Jurassic times. Since this time the rift valley has been extinct, and epeirogenic movements formed a basin with much wider span, filled with thick Cenozoic sediments (Ziegler, 1975). An about 60 km westward offset leads up to the Central Graben of The Netherlands (Heybroek, 1974). This segment, which to the south runs into the Lower Rhine Embayment, first appeared during the Mesozoic; however, its present-day features are mainly the result of two stages of block tectonics, during the Lower Miocene and in Pliocene to Recent times (Teichmüller, 1974). Between the southern end of the Lower Rhine Embayment near Bonn and the Mainz basin of the northern Rhinegraben, some smaller fault basins, like those of Neuwied and Limburg, are found. Physiographically, the Mainz basin gives the impression of a triple rift junction between the Rhinegraben, the Lower Rhine Embayment and the Hessen depression. The Hessen depression, which is a less distinct branch of the rift system (Illies, 1974a), first appeared as an elongated trough element in Upper Permian and Lower Triassic times.

After episodes of block faulting in end-Triassic times and during the Upper Cretaceous, a new ingression of the Oligocene sea indicated a reactivation of subsidence. After widespread volcanic activity of Miocene age and a further downfaulting of the smaller Leine graben during the Pleistocene, tectonic activity ceased. North of the Hessen depression, in Lower Saxony and Holstein, a group of roughly N-S trending narrow basins is observed. The thick Mesozoic infill of the Gifhorn trough and the subsidence of the Hamburg basin during the Tertiary indicate rift valley propagation up to this area. No link can be established between these buried rifts in Northern Germany and extinct rift valleys in Southern Scandinavia, such as the Oslo and the Lake Vättern grabens. Both features had been active in Palaeozoic times, but no reactivation at a later date is recognized.

The Rhinegraben represents the central and most prominent segment of the whole system. Its subsidence set in during the Middle Eocene. After an interruption from Middle Miocene to Lower Pliocene, rifting started anew in Upper

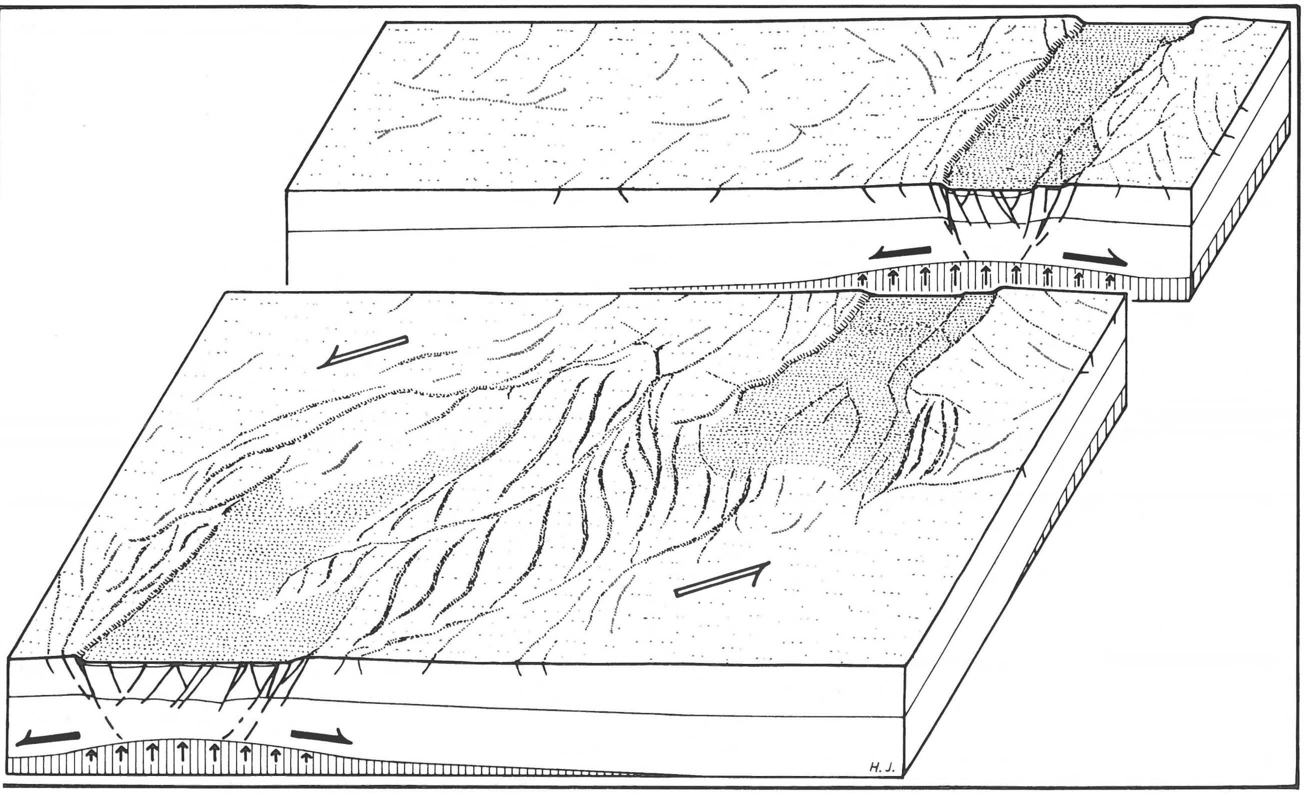

Fig. 2

Fault pattern development between Rhinegraben and Bresse graben

Cartoon to explain the fault pattern development between Rhinegraben (right) and Bresse graben (left). The two rift segments passed through a first climax of crustal extension in Lower Oligocene times. Since a lateral offset of about 150 km separates the southern end of the Rhinegraben from the northern end of the Bresse, the intervening crustal segment has been stressed by the relative block motions sideways away from the individual graben segments. A consequent dextral shear motion produced different sets of en échelon feather fissures and micro-grabens. This is the structural pattern along the southern slope of the Vosges Mts. This fault mechanism may be seen as a kind of transform faulting in the continental domain.
From: Illies (1972).

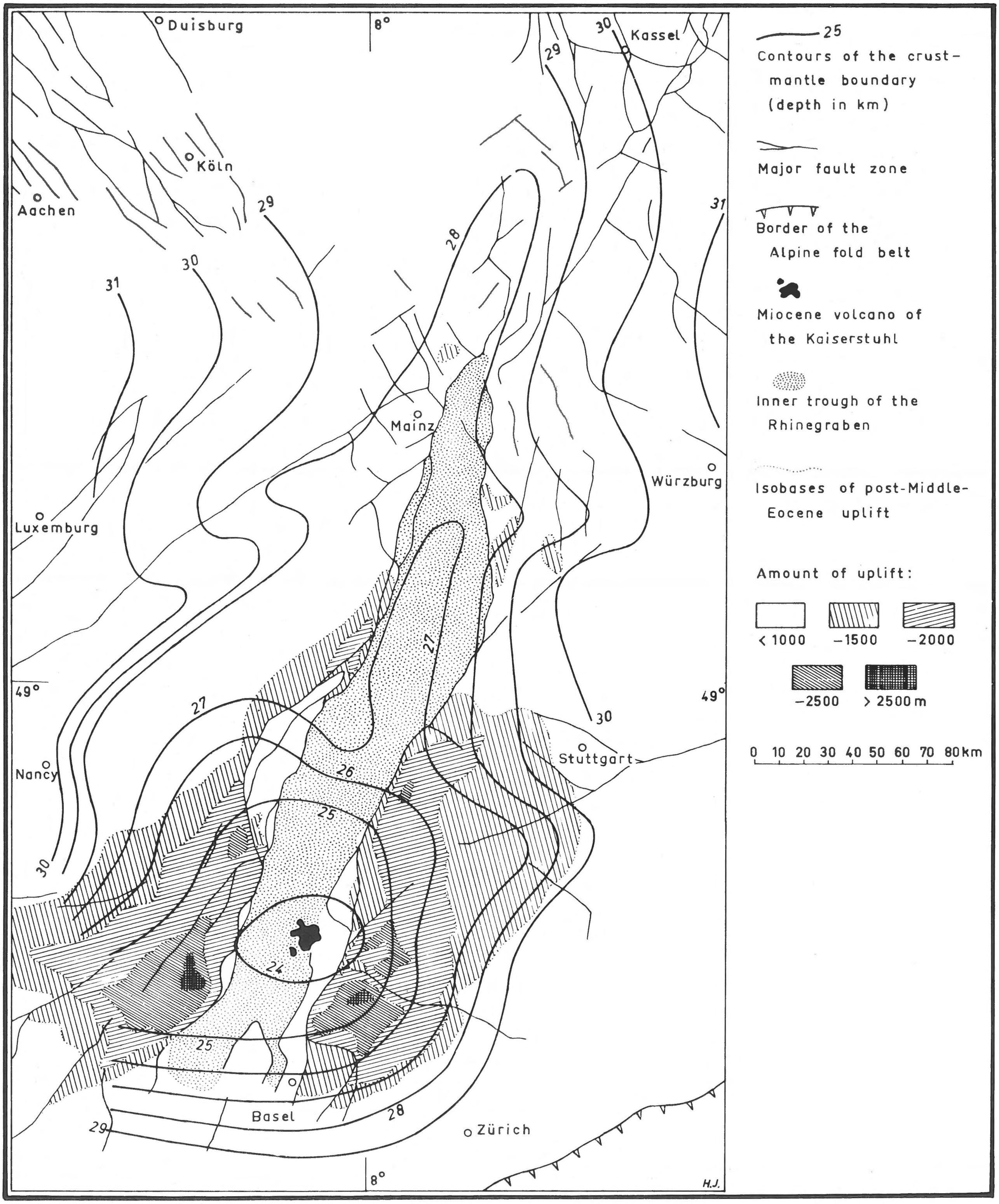

Fig. 3
Mantle bulge and shoulder upwarping
The Moho contours display a mantle bulge underneath the Rhinegraben rift system. Below the Miocene volcano of the Kaiserstuhl the mantle body comes nearest to the surface with a depth of 24 km. The first olivine-nephelinitic eruptions in this area occurred about 100 m.y. ago during mid-Cretaceous. Since that time mantle upwelling is indicated. The Kaiserstuhl mantle diapir forms an apophysis towards the northern end of the graben. This may explain the longitudinal sediment thickness distribution in the graben, which indicates that the Kaiserstuhl area acted as the primary spreading center of the rift valley. The isobases of post-Eocene shoulder upwarping follow to a large extent the contours of the mantle bulge underneath.
From: Illies (1975).

Pliocene times to continue to the present-day. East of the Rhinegraben, in Northern Bohemia, a graben striking about 060° is interposed between the Bohemian massif and the Erzgebirge Mts. The ages of violent volcanic eruptions and a browncoal bearing sediment fill, define the main stage of rifting as Middle and Upper Miocene. The southern Rhinegraben and Bohemian graben appear imperfectly linked together by a fault zone which is called the Swabian lineament.

South of the Rhinegraben, in eastern France, two grabens with prevalently Oligocene sediment fill mark the southern extension of the rift belt. The Bresse and the Limagne grabens are in the same trend as the Rhinegraben with offsets of 150 and 300 km westward, respectively (Fig. 1). A dense pattern of shear or transcurrent fractures connects the southern end of the Rhinegraben and the northern ends of the Bresse and Limagne grabens (Fig. 2). Kinematically, this may be comparable with transform faults in the oceanic realm (Illies, 1972). The Oligocene to sub-Recent volcanic activity, which is concentrated along the western rim of the Limagne graben, indicates that processes in the upper mantle remained active for a longer period than the rifting of the crust. The extension of the rift belt further south appears less distinct. In southern France the approximately NE-SW trending graben zone of Alès might lead to the El Panades graben near Barcelona. More to the south the Tirso and the Campidano grabens of Sardinia might be seen as a branch of the Tertiary graben system in the Western Mediterranean.

The graben elements traversing Western Europe, although showing different ages, trends, and structures, did not behave as completely independent tectogenes. Connecting fault systems, volcanic provinces which overlap, as well as continuous seismic belts demonstrate mutual interrelations of different graben segments in time and space. It is believed that three sets of circumstances controlled the structural evolution of the various rift elements. Only when the corresponding three sets of conditions, outlined below, were fulfilled did graben formation take place, and this resulted in the common features of the separate elements.

(1) The course of rifting is proved to be basement controlled. All rift valleys have followed pre-existent weakness zones in the Hercynian or Caledonian basement. Rhinegraben rifting followed a sinistral shear zone in the Hercynian socle; the graben of northern Bohemia developed along a longitudinal weakness element of the Hercynian fold belt; and the Lower Rhine Embayment reflects a reactivated set of cross faults in the basement.

(2) Rifting is proved to be a stress-controlled tensional process. A reactivation of pre-existent weakness elements implies regional stress conditions with the direction of maximum compression running closely parallel to, and the minimum component normal to, the graben axis. For example, Rhinegraben rifting began in mid-Eocene times, when regional stress field and basement anisotropy were compatible. Recent stress conditions cause the Rhinegraben to react by left-lateral strike-slip motion, whilst the Lower Rhine Embayment undergoes crustal extension.

(3) Rifting, if combined with shoulder upwarping and volcanic activity, is controlled by mantle rise. Mantle cushions or asthenolithic bodies are observed below several segments of the described rift system. Under the southern part of the Rhinegraben the crust-mantle boundary rises to a depth of only 24 km (Fig. 3). The upwelling mantle material conditioned the domed crust to react by rifting and gravity sliding away from the bulge, when conditions (1) and (2)

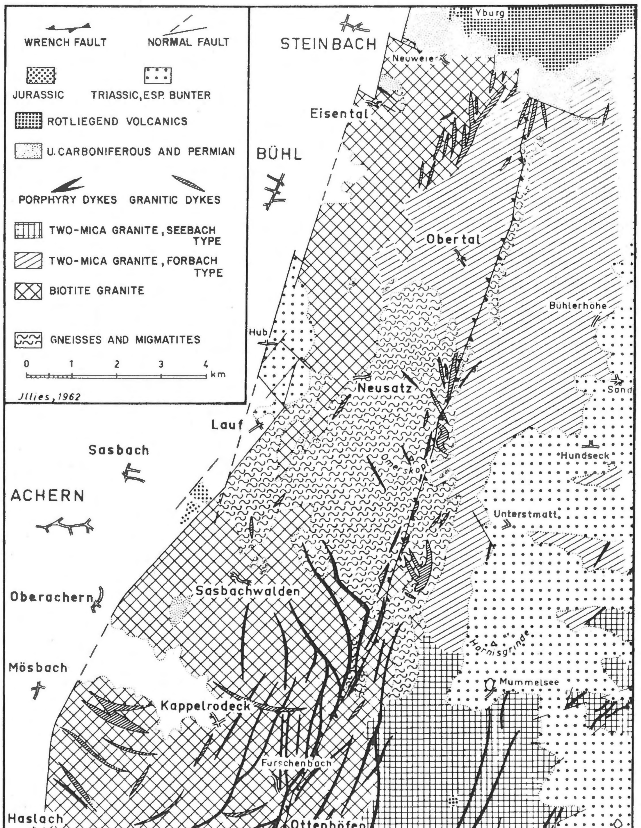

Fig. 4

Hercynian shear zone in the northern Black Forest

During the Asturian phase of the Hercynian orogeny (late Westphalian, Upper Carboniferous) a regional stress field governed the Rhinegraben area; its components were nearly identical to those of present-day tectonics. A belt of sinistral shear zones was formed parallel to the future graben. This pre-existent element partly controlled Rhinegraben rifting when, in mid-Eocene times, the weakness belt and the direction of maximum compressive stress fitted together. The structural map shows the rim of the northern Black Forest south of Baden-Baden. A Hercynian shear zone traverses the basement parallel to the eastern master fault of the graben at a distance of about 4 to 5 km. Such weakness zones were reactivated by the Cenozoic graben tectonics.

From: Illies (1962).

above were fulfilled. Furthermore the mantle bulges acted as the spreading centers from which the subsequent process of linear rift valley propagation started.

THE PRE-TAPHROGENIC PERIOD

In 1922 Hans Cloos was the first to describe a Hercynian shear zone (in the northern Black Forest) which runs parallel to the eastern fault scarp of the Rhinegraben at a distance of about 4 km. In 1948 the same author showed that the whole graben followed a pre-existent suture line.

A special mapping project on both graben flanks, where the Hercynian basement is well exposed, confirmed the existence of shear elements, mylonites and dike swarms parallel to the Tertiary graben (Illies, 1962). The most prominent pre-existent weakness zones are the Otzberg fault in the Odenwald Mts., the Bühlertal (Fig. 4) and the Schweighof lineaments in the Black Forest, and the Sainte-Marie-aux-Mines fault in the Vosges. All these lineaments acted as sinistral shear zones. In some parts, coal measures of the Westphalian stage are displaced, but are unconformably overlain by strata of Stephanian age. Therefore, it is assumed that the main shear displacement evolved during the Asturian (= Upper Silesian) phase of the Hercynian orogeny. Basaltic and rhyolitic extrusions of Lower Permian (= Rotliegend) age are strung along some segments of the shear belt. Unlike these features, the thickness distributions of the Upper Permian to Liassic series of the sedimentary cover do not show any relation to the "Rhenish" weakness zone in the basement (Boigk & Schöneich, 1974). The isopach lines predominantly follow the northeastward axial trend of the Hercynian basement (Fig. 5), i.e. oblique to the future graben. The suture line in the basement remained seized up during this period. Only in Bajocian to Oxfordian times did this tendency begin to be complicated by subsidence of the area of the future graben. The sediments of this series are about 100 to 200 m thicker and there are some facies changes in comparison to the equivalent beds that overlay the future graben shoulders (which acted as submarine swells at that time). At the base of the Bathonian some local unconformities (Fig. 6) are observed parallel to the rim of the Cenozoic graben (Illies, 1956). After these first labour pains of graben formation, the sea withdrew from the whole area after the Oxfordian stage. No indications are known concerning the further physiographic evolution up to the beginning of graben inundation in mid-Eocene times.

To evaluate the question as to how far the formation of the Cenozoic Rhinegraben has been basement controlled, the following statements can be made.

(1) The general trend of the graben feature followed a pre-existent weakness zone in the basement, and it can be shown that some basement faults were reactivated by graben tectonics (Illies, 1962).

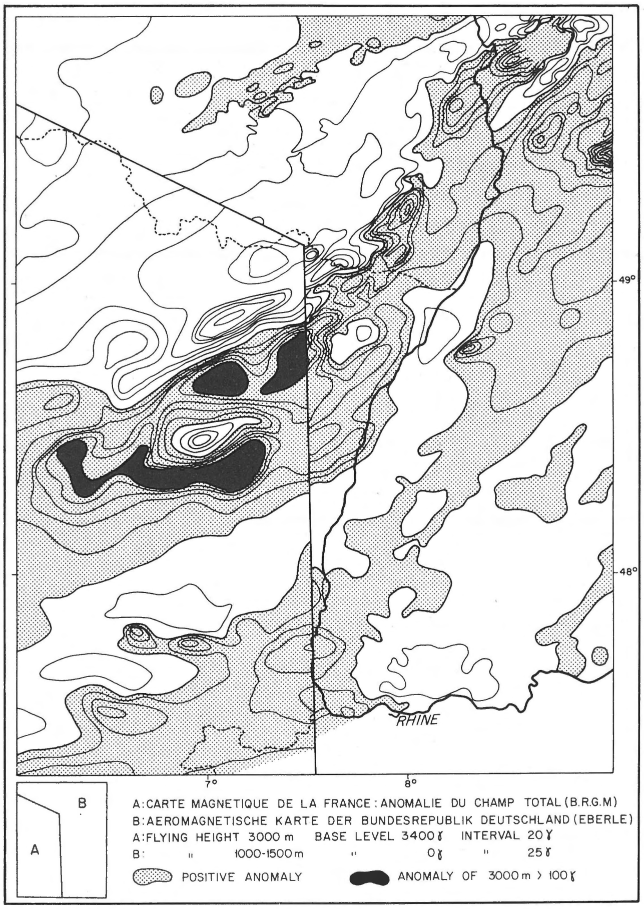

Fig. 5
Magnetic anomalies of the Rhinegraben area
The total intensity is predominantly determined by both the susceptibility of the basement rocks and their depth of submergence below Mesozoic cover and Cenozoic graben sediments. The general SW-NE trend of the dominant strike of the Hercynian rock units is clearly visible. Parallel to the Rhine river, some indication of a sinistral offset of those features may be recognized. This is the influence of the pre-existent sinistral shear zone in the Hercynian basement. Major parts of the Cenozoic fault trough appear as a magnetically smooth zone. The positive anomalies near the southern end of the graben are produced by the basic volcanics of the Kaiserstuhl.
From: Edel (Thèse, Strasbourg 1975).

(2) The geometry of the down-thrown wedge block with its constant width of about 36 km and the strong parallelity of the framing master faults is a consequence of Tertiary rift tectonics and had no precedent in the Hercynian structure. The Palaeozoic block motions mainly resulted from transcurrent fault movements; the fracture pattern of the Hercynian shear zone was scattered over a wider area than the actual physiographical graben. In this way parts of the old shear belt became upthrown by shoulder upwarping, others downthrown by graben subsidence.

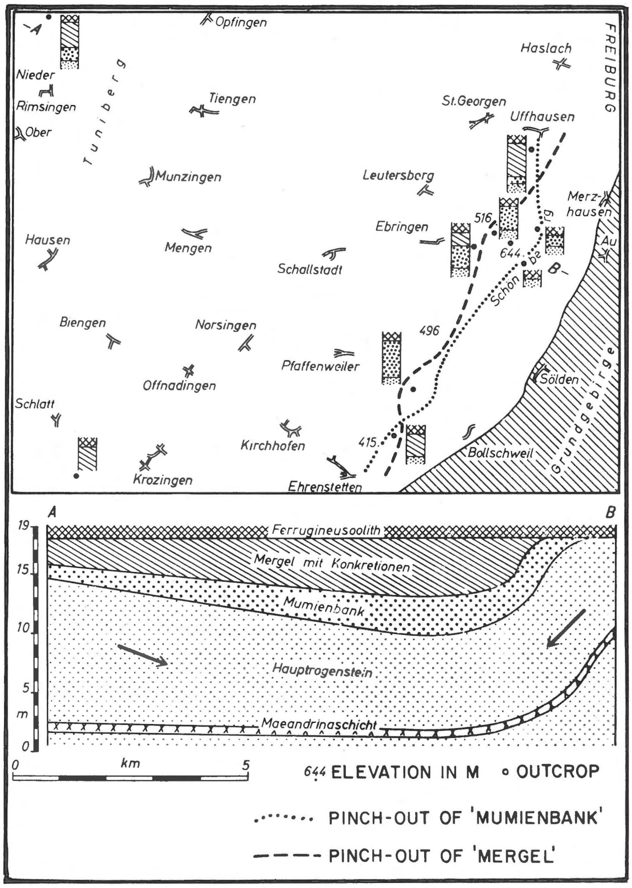

Fig. 6

First signs of subsidence in Middle Jurassic in the Freiburg area

The thickness distribution of the Upper Permian to Lower Jurassic sedimentary cover does not show any relation to the "Rhenish" weakness zones in the basement. The isopach contours follow mostly the longitudinal, NE trend of the Hercynian mountain range. Not until Bajocian/Bathonian times (Middle Dogger) do some indications of a preferred epeirogenic subsidence of the future graben appear. The map shows the rim of the Black Forest south of Freiburg, where individual strata of this age pinch out parallel to the future main escarpment. The local unconformity corresponds stratigraphically to the Bajocian-Bathonian boundary.
From: Illies (1956).

(3) The Palaeozoic basement fractures are exclusively vertical shear faults; the graben fractures, however, are inclined dip-slip faults of mostly listric configuration. The frequent unilateral tilt block dip towards one side of the graben does not show any relation to the basement structure.

(4) The graben formation was controlled by a grossly different tectonic setting to that which caused the shear zone in Hercynian times. Mantle bulge, thermal rise, the mantle-derived graben volcanism, the break-up of the crust to form the graben segment, the crustal extension, the subsidence of the graben wedge block, the internal tilt block mechanism and the shoulder upwarping were governed by the interrelations between Alpine plate tectonics and consequent intraplate reactions in the foreland, by a regional stress field and by processes in the upper mantle fundamentally different from those which controlled the formation of the Hercynian shear belt. The weakness zone in the basement facilitated and localised rifting like a predetermined breaking point in mechanical stress tests. Regional stress conditions during the rifting process, fitting closely the anisotropy of the pre-existent fracture zones, were the most essential prerequisites for the first break-up of the crust.

Before the regional stress field became compatible with the basement anisotropy in Eocene times, the new tectonic regime of taphrogenesis had been announced by a long-lasting period of mantle rise and surface volcanic eruptions. Starting about 100 m.y. ago, i.e. in mid-Cretaceous times, volcanic activity set in, widespread over the future graben and its shoulders but not noticeably concentrated on its main fracture zones (Baranyi, Lippolt & Todt, 1976). Nearly all the volcanics are derived from an olivine-nephelinitic magma source, i.e. corresponding to the composition of the mantle layer, presumably ranging in depth between about 80 and 100 km. This volcanic activity continued until the first rifting became apparent at the surface in mid-Eocene times or about 48 m.y. ago.

THE FORMATION OF THE TENSIONAL RIFT VALLEY (MIDDLE EOCENE TO LOWER MIOCENE)

Eocene

The beginning of rift valley subsidence is indicated by freshwater deposits of mid-Eocene (Lutetian) age, mostly less than 100 m thick. A disconnected chain of freshwater lakes started to cover the end-Cretaceous peneplain roughly between Basel and Frankfurt, but not exactly restricted to the configuration of the future graben trough. The vertical movements causing the inundation of this segment were accomplished by fault action: at several places dip-slip faults are described to be at least as old as the deposition of the earliest strata of the graben fill (Doebl, 1971). Since upwelling mantle material had stressed the crust at its base, the observed faulting might have been facilitated by updoming of the graben area. The roughly constant width of the graben block (33 to 38 km) suggests that the planes of the boundary faults may come together to a common baseline at the crust/mantle boundary, thus enclosing a triangular wedge block (Illies, 1967).

Rifting, i.e. dip-slip displacements along convergent normal faults, requires a lateral yielding of the confining abutments of the graben. For such kinematic conditions a regional stress field is required with its maximum horizontal component parallel to, and its minimum component normal to, the graben feature. Relevant stress conditions have been deduced from the observation of "horizontal" stylolites. "Vertical" stylolites are considered to be caused by partial

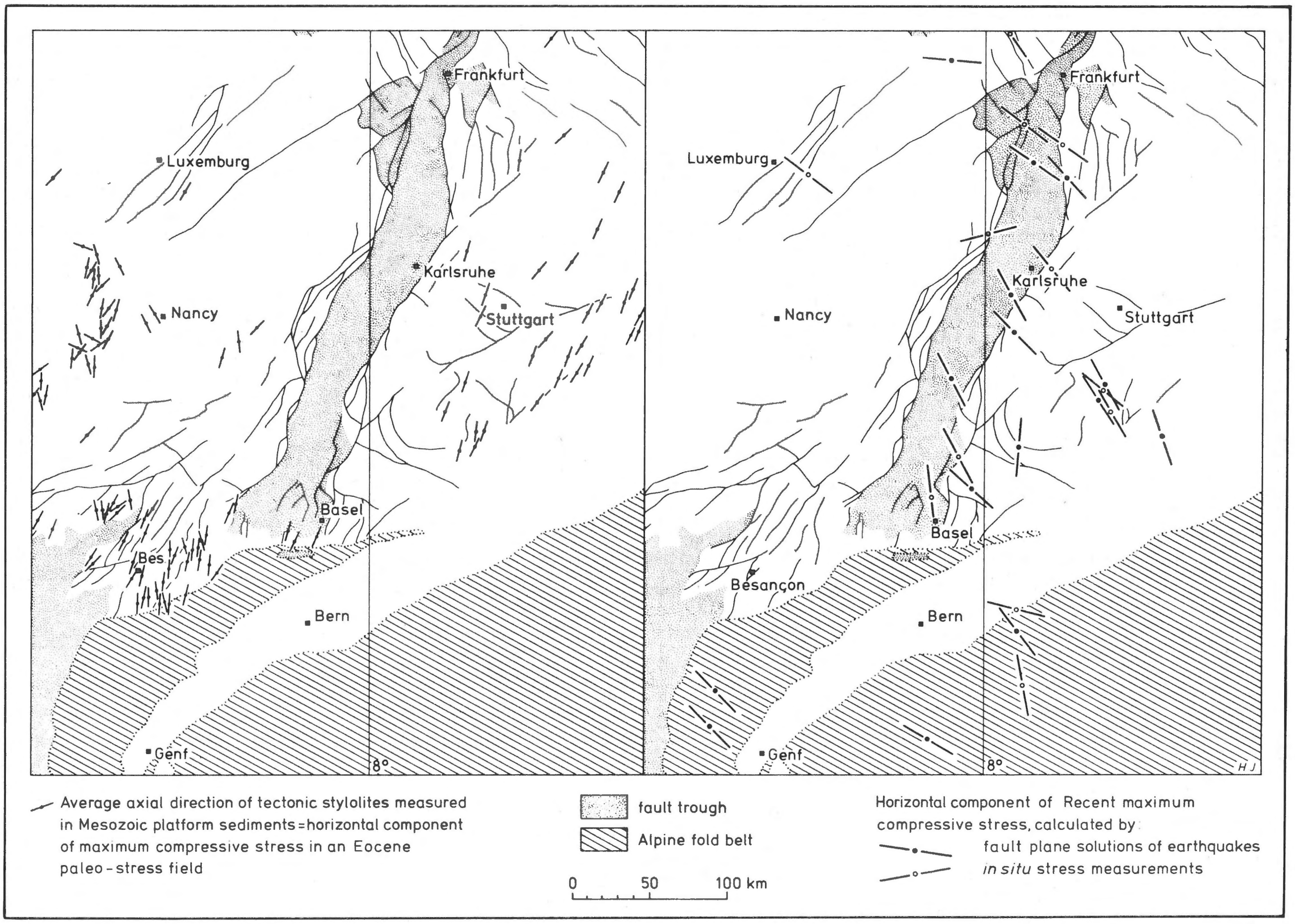

Fig. 7

Eocene and Recent stress conditions

The Paleogene rift valley formation and the Recent activity along the graben were controlled by totally different regional stress fields. The average axial directions of horizontal stylolites, as measured at many places in the Mesozoic cover, reflect the pattern of compressive stress which caused the first break-up of the graben in mid-Eocene times (left). σ_1 at that time was roughly parallel to the graben feature, resulting in tensional rift valley. The present-day maximum compressive stress is oblique to the graben axis which now coincides with the sinistral shear component of the Recent stress field (right). Consequently, the Recent crustal movements of the graben are controlled by sinistral strike-slip motions.

From: Illies & Greiner (1976).

solution of fine-grained limestones, in accordance with Riecke's law, due to the vertical pressure of the overburden. Following the same principle, those stylolites with horizontal axes are ascribed to a horizontal tectonic compression at the time of the formation of the features. Horizontal stylolites have been measured in limestone beds of the Mesozoic sedimentary cover over wide areas of Central Europe (Beiersdorf, 1969). The formation of tectonic stylolites requires a crustal shortening of about 0.5 to 2% parallel to their average axial direction. Since horizontal stylolites are found in different Mesozoic strata, but are absent in the sediment fill of the graben, they are believed to belong to a paleo-stress field active at the time of the first graben formation. Their average axial direction appears parallel to the Rhinegraben, the Hessen depression, the Bresse and Limagne grabens (Fig. 7). This implies an Eocene stress field with a horizontal component of maximum compressive stress in about 015° (NNE), similar to the trend of the weakness zones in the basement underneath. These specific stress conditions triggered the beginning of graben formation. The graben trend of about 015° is believed to be roughly normal to the general direction of the plate collision front at the time of graben initiation. This direction is reflected by the WNW-ESE trend of the Pyrenees, and of some anticlines with "pyrenean" strike in the Western Alps (Caby, 1975), which were folded in Eocene times. Thus plate collision and continental rifting are seen to be related in time and space (Fig. 1).

During the deposition of the Upper Eocene *Lymnaea*

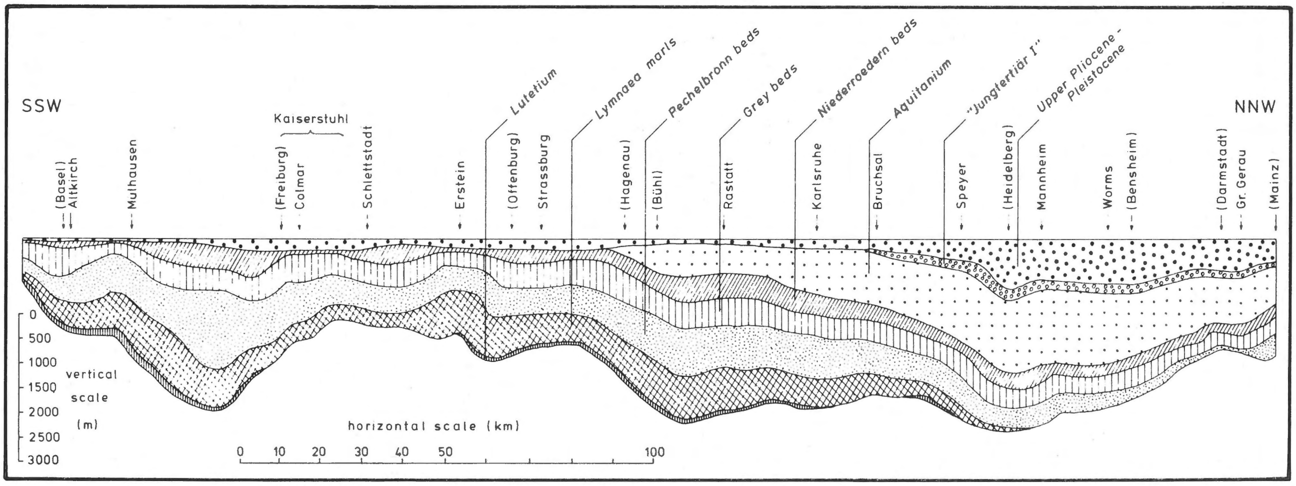

Fig. 8
Moving subsidence centre
Longitudinal section through the sediment fill of the Rhinegraben. The subsidence started in Eocene times near the southern end of the graben. During further fault trough development the maximum of sediment thickness shifted progressively towards the North. Between the Jungtertiär I (mainly Burdigalian) and the Upper Pliocene-Pleistocene sedimentation cycle, a stratigraphic gap of about 15 m.y. is observed. During that time graben subsidence was interrupted.
From: Illies (1975)

marls, the advancing process of crustal extension accelerated the subsidence of the graben wedge block. This series is up to about 900 m thick near the southern end of the graben but pinches out northward near Heidelberg (Doebl, 1970). Evidently, the southernmost segment of the graben acted as a primary spreading center (Fig. 8). This is in agreement with the crust and mantle structure of this area. Actually, underneath the southern graben and the surrounding area of the Black Forest and the Vosges Mts., a mantle diapir is found (Fig. 3) which comes nearest to the surface below the Kaiserstuhl area at a depth of only 24 km (Edel *et al.,* 1975). The isobases of post-Eocene uplift of the shoulders generally fit the contours of the mantle bulge (Illies, 1975). The radiometric ages of the volcanics on top of the diapir demonstrate that mantle upwelling evolved since mid-Cretaceous times (Baranyi *et al.*, 1976). A tendency for gravitational sliding, away from the rising mantle dome, evidently propagated the rifting of the overlying crust.

Oligocene

Rift valley propagation continued during the sedimentation of the Lower Oligocene Pechelbronn beds. This series covers the whole Rhinegraben lagoon and extends northward to the Hessen depression. The maximum thickness of the Pechelbronn beds reaches about 1600 m – still near the southern end of the graben (Doebl, 1970). Growth faults are observed at many places, demonstrating that crustal extension reached its first climax during this time. As described by Trümpy (1973), folding and nappe formation culminated during the same stratigraphic period in the Western Alps. Plate collision in the Alps, and Rhinegraben rifting in the foreland were associated with the same regional stress conditions (Fig. 1).

Banks of coarse conglomerates, intercalated in the marly or evaporitic facies of the Pechelbronn beds, mark the coastlines of the former lagoon. The lowermost layers of these conglomerates consist of pebbles of the same Jurassic limestones that form the base of the Cenozoic graben infill. Higher in the series pebbles of Muschelkalk and Bunter are added; towards the top, components of the Hercynian basement are found, equivalent to rocks now exposed in the Black Forest and the Vosges. The results of this pebble analysis demonstrate that the graben shoulders became upwarped at that time, and the Mesozoic cover came under erosion layer by layer. Streams transported the debris down to the coast of the lagoon where gravel fans became interbedded with the fine-grained lagoonal sediments. The Mesozoic strata covering Black Forest and Vosges had been about 1000 m thick before rifting began in mid-Eocene times. The presence of Hercynian basement pebbles demonstrates that the top of the basement had then become elevated and locally eroded at a higher level than the lagoon; i.e. a shoulder upwarping of more than 1000 m at that time is indicated (Illies, 1965). Graben subsidence and shoulder uplift culminated in this segment during the same period. Consequently the conveyor belt mechanism of a relatively short erosion/sedimentation cycle, supplied the sinking graben floor with a nearly synchronous replenishment of new sediments. Both graben infill (totally up to about 3500 m) and shoulder denudation (in the valleys up to 2000 m) triggered isostatic readjustments (Fig. 9), and thus modified the energy balance of the rifting process (Illies, 1965).

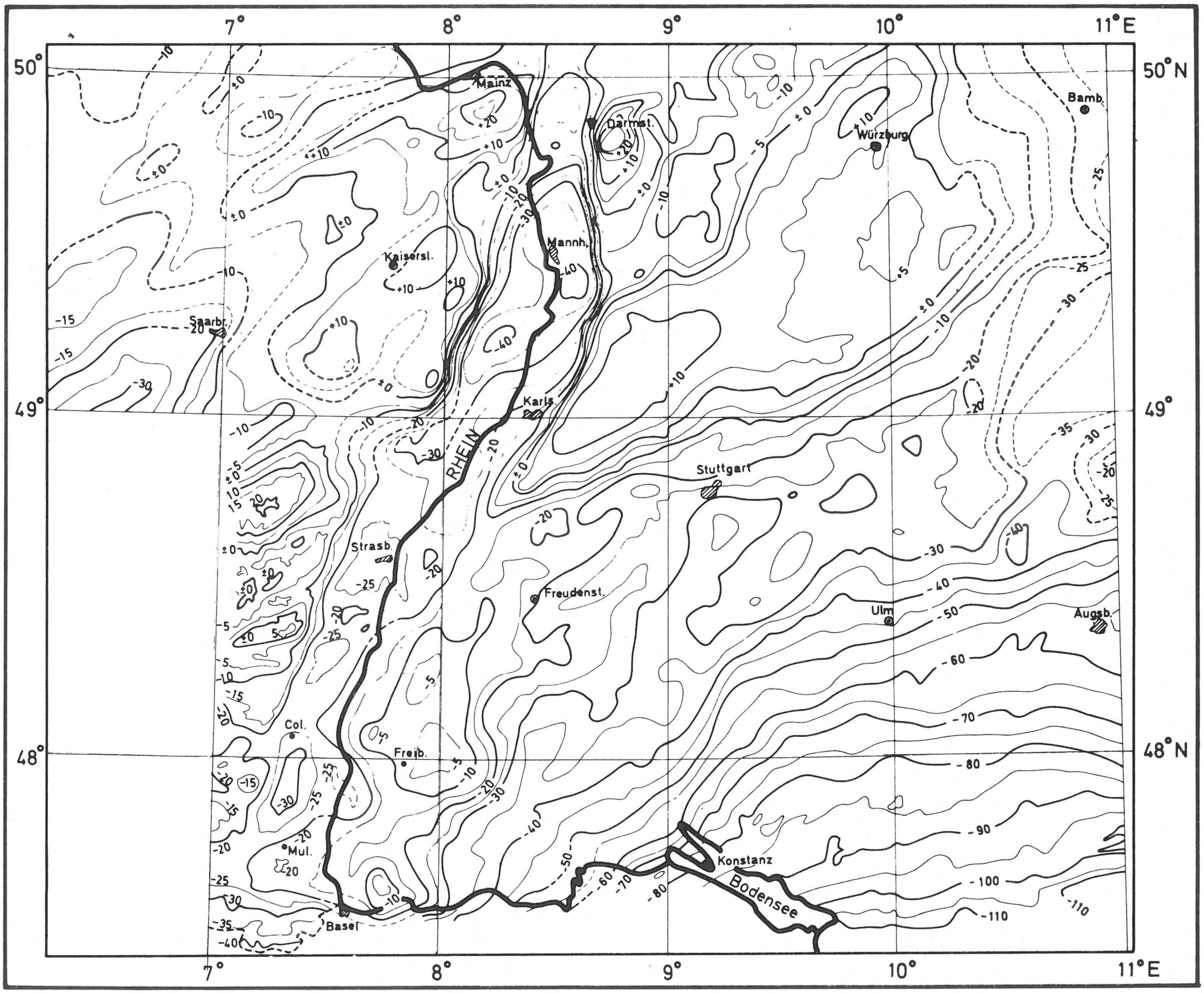

Fig. 9

Gravity anomalies

Outside the rift valley a regional NE-SW trend of the anomalies may be clearly seen. This is the influence of the different lithological units in the Hercynian basement with their general northeasterly strike. The graben trough appears as a negative anomaly belt, whose contours are of almost the same shape as the isopach lines of the Cenozoic sediment fill. Local effects of the underlying basement features may be recognized superimposed on the negative anomalies of the poorly consolidated sediment fill.
From: Mueller & Rybach (1974).

Zones of intense faulting provided a mobile zone between shoulder uplift and graben subsidence. The main or master faults are dip-slip faults, with grabenward inclination near the surface ranging between 55° and 80°. The most frequent values occur between 60° and 65° (Illies, 1967). At depth, a slight listric flattening can sometimes be observed (Erlinghagen & Dohr, 1974). By means of reflection seismic, the master fault of the Black Forest scarp could be traced down to a depth of about 7 km only (Dohr, 1957). Similarly, the depths of earthquake foci in the graben proper do not exceed 12 km. It is assumed that these observations are the consequence of thermal rise and partial melting of crustal material during the advancing process of rifting. At the early stage of rifting, rupture down to the crust/mantle boundary is considered possible.

Locally, the main boundary fault is seen to be replaced by two parallel master faults. These enclose wide zones of "foot-hill" structures within which sets of synthetic and antithetic step faults are present. The patterns of these faults are reminiscent of – but not necessarily genetically identical to – the slip planes seen in large landslides (Fig. 10).

The early Oligocene culmination of rifting, crustal extension, fault trough subsidence and shoulder upwarping was followed by a period of more steady graben development.

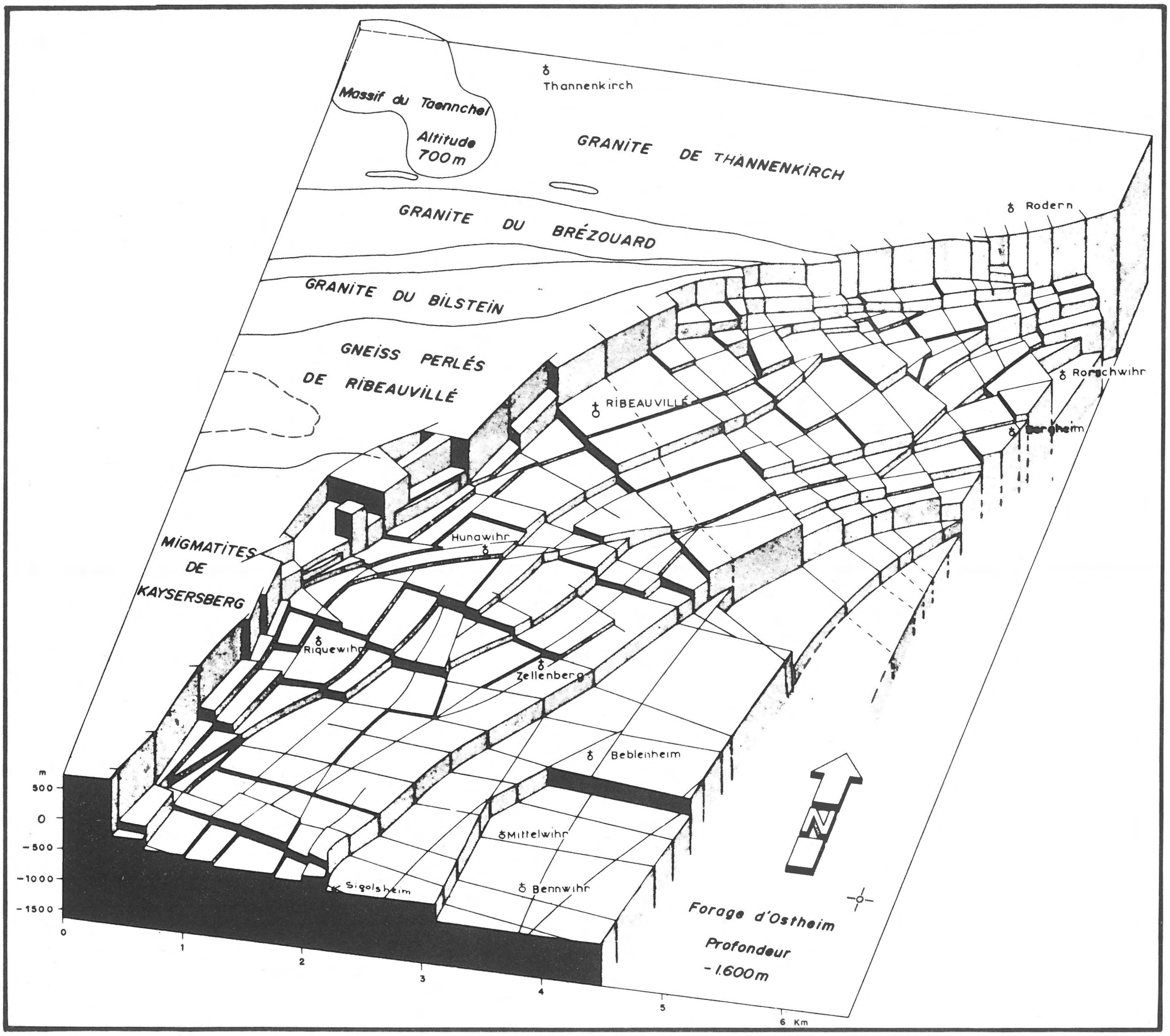

Fig. 10

Fault pattern of Ribeauvillé

Wide zones of foothills often are intercalated between the down-thrown graben and the upwarped shoulder of the Vosges. A dense pattern of synthetic and antithetic block faulting gives the impression of large landslides. Excess of lateral space has been compensated by rotational motion of the individual blocks. Measured fault dips range mostly between 60° and 70°; the vertical planes indicated in the cross sections are the result of the enlarged vertical scale of the block diagram.

From: Hirlemann (1974)

The sediments of the Middle and Upper Oligocene exhibit a more uniform thickness distribution over the whole trough, attaining a maximum of about 1000 m in the central segment of the graben. Shoulder upwarping now appeared to have moved to the northern part of the graben, since conglomeratic intercalations are restricted to the rims of this segment.

The first brackish to marine ingressions influenced facies and fauna in Late Eocene and Early Oligocene times. These ingressions came from the Helvetian trough, narrowed and displaced northward by simultaneous Alpine folding. From Middle Oligocene times onward, parts of the foreland were flooded by the sea of the Molasse trough. Paleogeographically the Rhinegraben lagoon then became an appendage of the Molasse foredeep; facies, fauna and salinity became common to both sedimentary basins. During the Middle Oligocene Rupelian stage, a marine transgression extended to the Hessen depression. A narrow graben sea connected the Molasse trough with the enlarged North Sea Basin in Lower

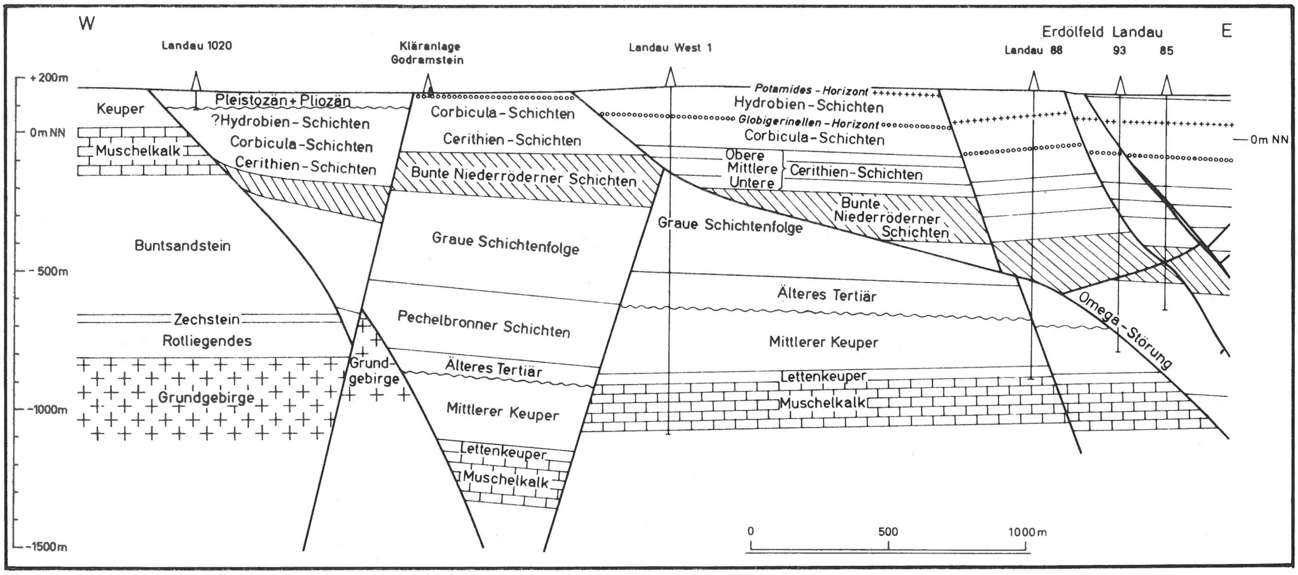

Fig. 11
Section, Landau oilfield
Cross section of the Landau oilfield near the western margin of the graben. All faults are of a dip-slip character and confine tilt blocks that rotated antithetically. Most of the fault planes are curved, sometimes listric (= shovel-like), sometimes "antilistric". Abruptly changing thicknesses indicate synsedimentary fault action. Growth faulting evolved in this segment principally during the sedimentation of the Pechelbronn, Cerithium, Corbicula and Hydrobia beds. Some of the faults became reactivated in Plio-Pleistocene times. The main fault element is the "Omega-Störung", striking about 170°. The sigmoidal curvature of its plane seems typical for growth faults that have been active over a long period.
From: Doebl, in v.d. Brelie et al. (1973).

Saxony via the rift system, and the same environmental conditions controlled facies and fauna in both areas.

Lower Miocene

Around the Oligocene/Miocene boundary (= Chattian/Aquitanian) some paleogeographical changes evolved. The southern part of the Rhinegraben, south of the city of Haguenau, became dry land; another regression is observed in the Hessen depression. Sedimentation continued in the northern segment of the Rhinegraben and the funnel-like enlargement near its northern end (consisting of the Mainz basin, the Hanau depression and the area of the future Vogelsberg volcano). These alterations of the main paleogeographic features were accompanied by a reactivation of strong taphrogenic activity. In the northern segment of the graben, high rates of subsidence were observed during the Aquitanian stage. Near Mannheim the corresponding sediments reach a thickness of 1600 m. Many of the internal graben faults were active as growth faults (Fig. 11), causing abrupt changes in thickness and, to a lesser extent, facies of the sediments (Schad, 1964). Most of these faults are of antithetic character. Their dip often appears relatively flat: near the graben rims mostly about 60°, but in the inner graben down to about 40° inclination. In some oilfields a substantial flattening with depth is observed; for instance Doebl & Bader (1971) described from Landau nearly horizontal fault planes at depths between 500 and 1000 meters. Most of these faults demonstrate a typical listric (= shovel like) configuration. "Antilistric" dip-slip faults, steepening with depth, have been recognized as well (Fig. 11). The antithetic block-faulting can be quite regular in appearance. Locally, sizeable graben areas are characterised by sets of fault planes all dipping towards the same side of the graben. Dip to the west is more common than to the east (Fig. 12). Such unilateral tilt of blocks is ascribed to unequal outward movement of the two shoulder blocks which bound the graben (Illies, 1972).

The formation of the observed structures requires high rates of crustal extension, i.e. yielding of the framing blocks (Fig. 13). By means of a palinspastic restoration, an average amount of dilatation of about 4.5 to 5 km during the entire evolution of the graben is found. In Lower Miocene times the direction of tension was oriented about WSW-ENE, i.e. oblique to the graben axis. This may be deduced from the prevailing trend of synsedimentary faults and basaltic dikes of that age. Tensional fractures are observed on both graben shoulders as well. Swarms of mineral veins, mostly barite and fluorite, but in some areas sulfide and oxide ores, traverse both the basement and the Mesozoic cover of the uplifted shoulders. Approximately parallel sets of the same kind of

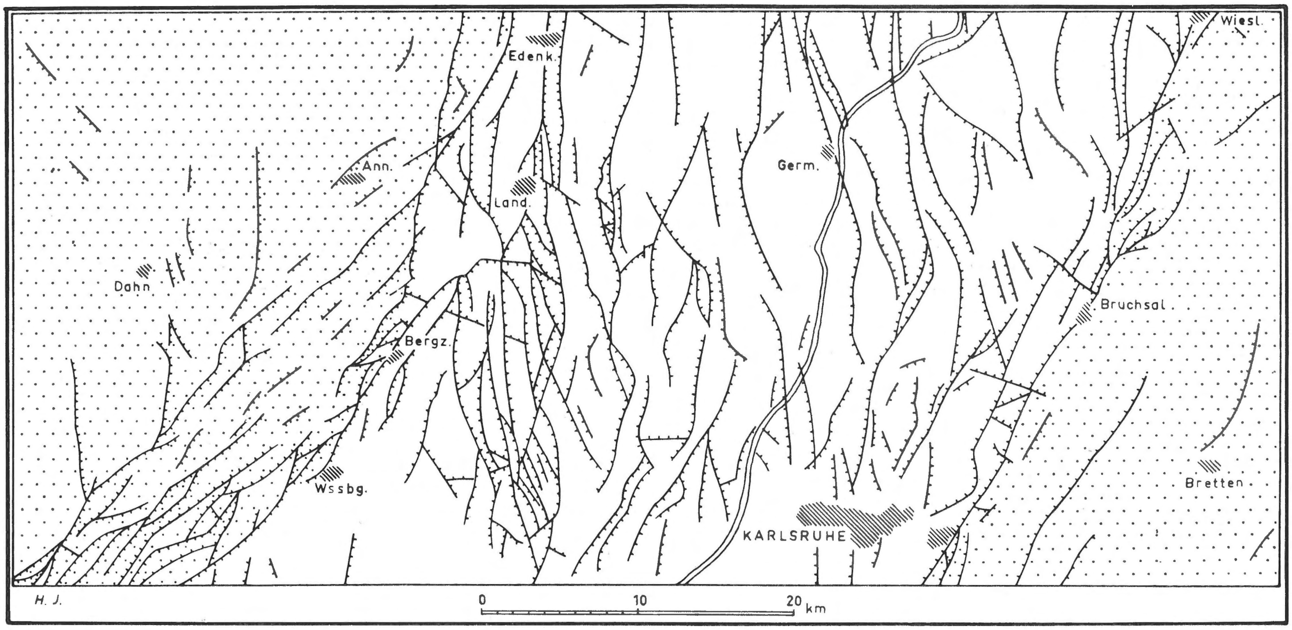

Fig. 12
Detailed fault pattern
The fault pattern of the Karlsruhe segment exhibits some features that appear characteristic for the whole rift system. Internal graben faults and external master faults follow divergent trends, but also within the graben, fault systems of different trend are found. The first block faulting was identified from the mid-Eocene. Growth faulting in this segment is mainly observed in Upper Eocene to Lower Oligocene, in Lower Miocene and in Upper Pliocene to Pleistocene. Growth faulting during a single period produces predominantly parallel sets of faults. Therefore, the divergently striking fault systems may be explained by varying regional stress conditions in time.
From: Illies (1965).

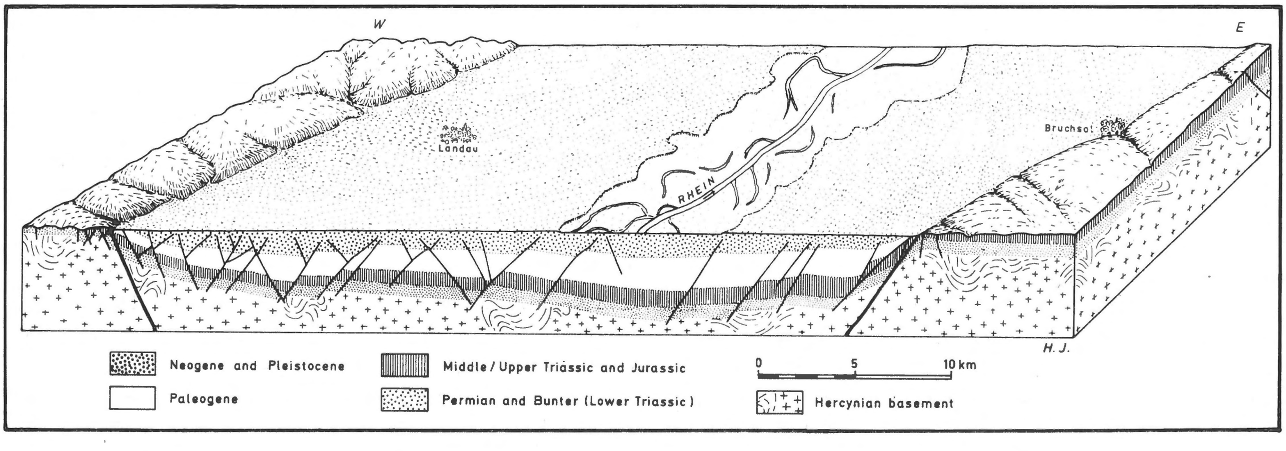

Fig. 13
Rhinegraben cross section
Block diagram of the Karlsruhe segment of the Rhinegraben. The graben as a whole is a wedge block with convergent master faults. Internal dip-slip faulting is of antithetic character. A palinspastic reconstruction of the whole process of graben tectonics demonstrates a total amount of crustal extension between 4.5 and 5 km. The sediment fill of the fault trough was supplied mostly by the equivalent denudation of the uplifted shoulders.
From: Illies (1974a).

mineralization are scattered over the Northern Black Forest and the Pfaelzerwald Mts. (Illies, 1965).

During the Aquitanian stage, two marine to brackish ingressions had reached the northern Rhinegraben. Since the influence of marine environments decreases from the Mainz basin towards the southern end of the lagoon, it seems likely that the transgressions invaded from the Lower Rhine Embayment. As the faunas of the Rhinegraben lagoon are of an endemic character, the stratigraphic correlation with the equivalent series of the Lower Rhine Embayment remains obscure. Therefore it is controversial whether the late Chattian and early Hemmoorian transgressions in the latter correspond with the marine stages of the *Cerithium* and the *Hydrobia* beds respectively in the northern Rhinegraben.

AN EXTINCT RIFT VALLEY (MIDDLE MIOCENE TO LOWER PLIOCENE)

In about end-Aquitanian times the graben subsidence temporarily came to an end. A flat freshwater lagoon continued to exist during the Burdigalian stage in the northern segment between Karlsruhe and Darmstadt; up to 200 m of marls and limestones filled up the remaining depression. Then followed a period of tectonic stabilization of about 15 m.y. Parts of the graben fill underwent fluvial erosion, and only scarce and thin relics of sediments are known from the Upper Miocene and Lower Pliocene. At the same time the graben shoulders were denuded and became part of the so-called Pontian peneplain.

Whilst wedge block subsidence and antithetic faulting remained inactive, the upwelling tendency of the mantle bulge underneath continued during this period. Between 19 and 13 m.y. ago the mantle body had produced the magmatic cycle of the composite volcanic massif of the Kaiserstuhl (Baranyi *et al.*, 1976). The uppermost part of the mantle diapir acted as a long-lived magma chamber, in which olivine-nephelinitic parent magma produced (by fractionalization) the basic to ultrabasic magmas as well as the carbonatites of the central Kaiserstuhl. Renewed mantle rise caused a large-scale updoming of the Black Forest, the Vosges and perhaps the enclosed graben segment too. Coarse conglomeratic intercalations in the Upper Miocene freshwater molasse, the so-called "Juranagelfluh", indicate an increasing gradient on the eastern slope of the Southern Black Forest. As shown by refraction seismic data (Edel *et al.*, 1975) and by the distribution of Tertiary volcanic activity (Baranyi *et al.*, 1976), the limits of the areas of physiographic shoulder upwarping and of the subcrustal mantle bulge roughly coincide (Fig. 3). Since the olivine-nephelinitic parent magma of most of the Rhinegraben volcanics is primarily derived from a mantle layer between about 80 and 100 km depth, it is concluded that the mantle bulge consisted of a laccolithic or asthenolithic cushion, intercalated between crust and mantle (Illies, 1974b). In the transition area between the Rhinegraben and Hessen depression, the Vogelsberg volcano was active about 20 m.y. ago, constructing the largest shield volcano of Central Europe. South of it, in the Frankfurt area, flood basalts were extruded from fissure systems in Late Miocene times. The Vogelsberg volcano and the trap formation were fed by magma sources of mixed composition, some of them tholeiitic and some alkaline basalts.

THE RHINEGRABEN AS A SHEAR ZONE (UPPER PLIOCENE TO RECENT)

In Middle Miocene to Lower Pliocene times mantle rise proceeded although crustal rifting remained extinct. The changed regional stress conditions did not fit the fault pattern of the Rhinegraben, with the result that vertical block motions became impossible. This extinct rift valley stage ended at the beginning of the Upper Pliocene. Dense clusters of seismic epicenters, high rates of Recent crustal movements, damage to buildings sited upon active faults and high heat flow values demonstrate that Rhinegraben tectonics are still active today.

The northern graben segment continued to subside with the highest rates (Fig. 8). The maximum thickness of Pliocene sediments, mostly of Upper Pliocene age, is observed near Heidelberg, where there are about 760 m (Doebl, 1967) of mostly fluviatile sands and gravels. From the same area the culmination of Pleistocene sediment accumulation (about 380 m) has been reported. In the southern graben segment block subsidence was reactivated locally. Following Bartz (1974), Pleistocene gravels SSW of the Kaiserstuhl were found up to 243 m thick, and south of Strasbourg more than 150 m thick. The isopach map of the Pleistocene sediments given by Bartz (Fig. 14) illustrates considerable similarities to the contours of geodetically calculated rates of recent vertical movements. Schwarz (1976) presented an excellent map of the height differences obtained by precision levellings for the northern graben segment, and Mälzer & Schlemmer (1975) did the same for the German part of the southern segment.

As shown by morphological studies, substantial shoulder uplift continued in Upper Pliocene to Pleistocene times. For the highest parts of the Black Forest and the Vosges an additional uplift of about 800 m or more was estimated by several authors. Contrary to these statements, the geodetic height variations in parts of the Black Forest appear negative (Mälzer & Schlemmer, 1975), and some river valleys are filled up with young gravel accumulations up to 40 m thick (Bartz, 1974). Seemingly, shoulder upwarping was recently replaced by downwarping, introducing a future period of tectonic inversion. This might be explained by diminished activity of the heat-generating mantle structure underneath, as the volcanic activity supported by it has slowed down since Pliocene times (Baranyi *et al.*, 1976). The shoulder elevation might be a function of density variations in the crust and upper mantle caused by thermal anomalies, analogous with some models to explain the topo-

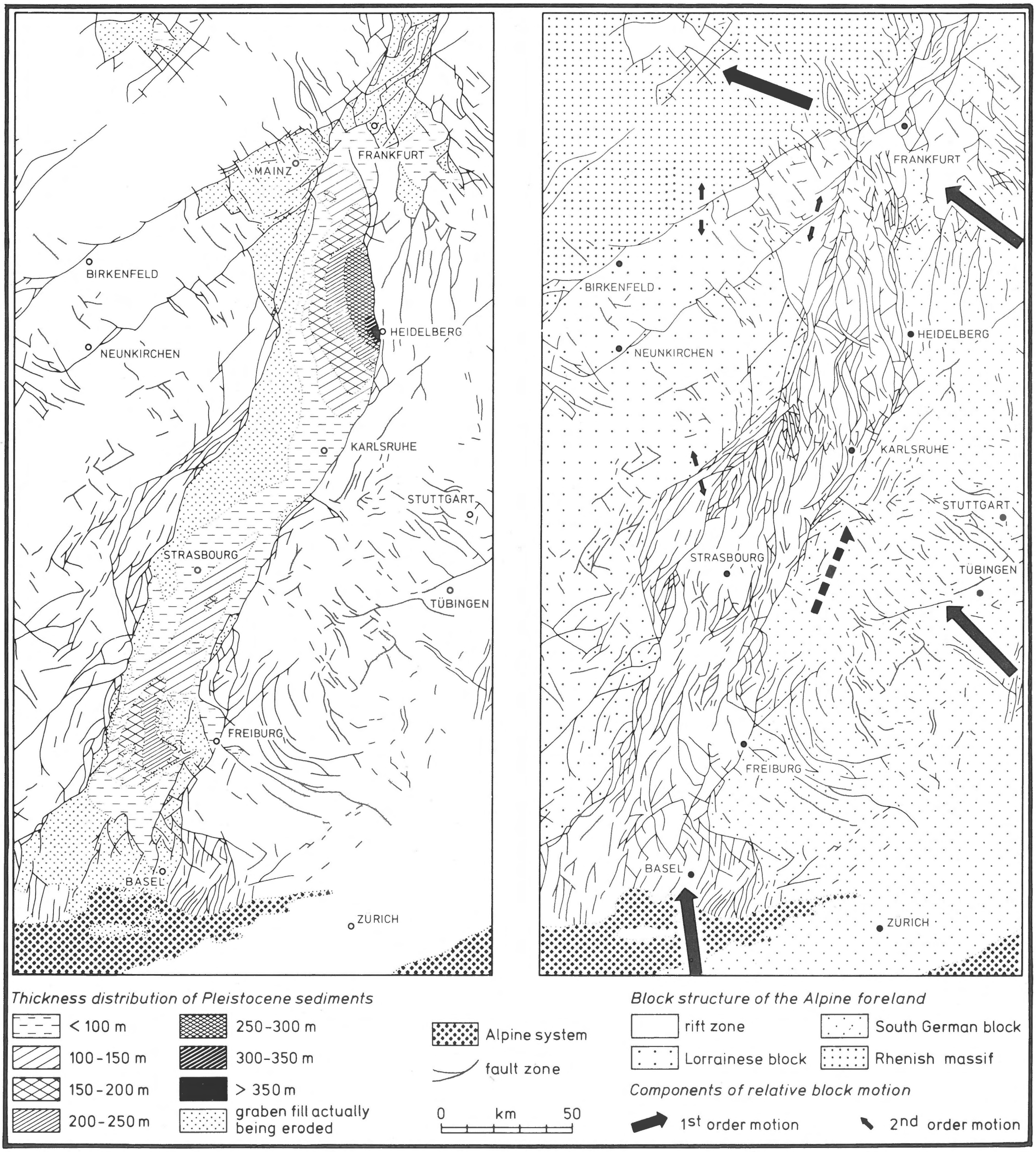

Fig. 14

Neotectonic features of the Rhinegraben

Today the Rhinegraben acts as a sinistral shear belt within the block mosaic of the Alpine foreland. The strike-slip mechanism parallel to the graben axis controls secondary normal faulting, mainly of N-S trend, following the principle of Riedel shear (right-hand diagram). Since the graben consists of three differently striking segments, the tectonic reactions to the general shear motion vary between the individual segments. In the southern segment local grabens and horsts are observed. The central part is mainly under compression, and reacts by local thrusting, uplift and erosion of the graben fill. In the northern segment the highest rates of subsidence and a number of active normal faults have been observed (left-hand diagram).

From: Illies & Greiner (1976).

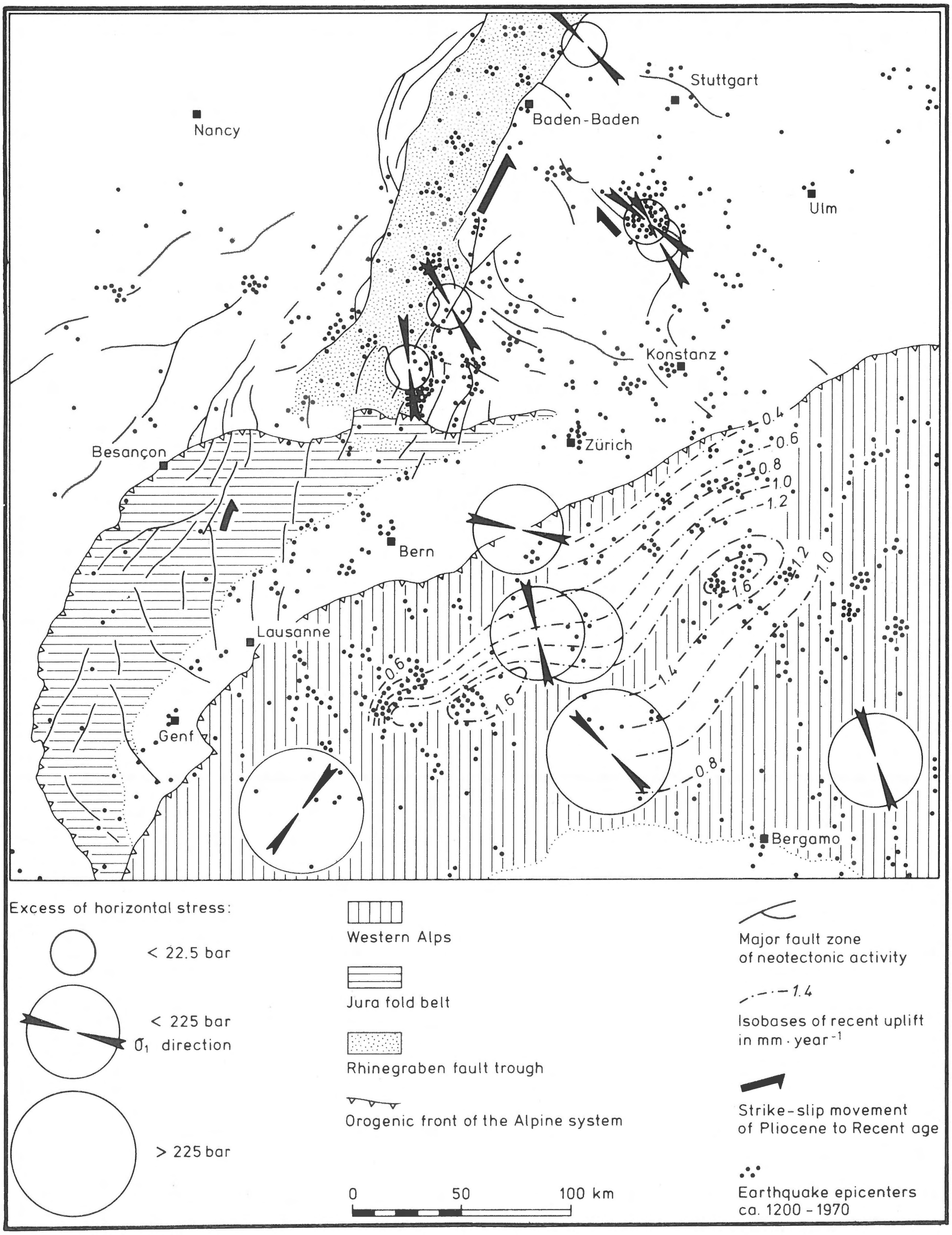

Fig. 15

Stress pattern and strain release

Structural map of the Central Alps and the southern Rhinegraben with measured stress directions and magnitudes. The regional stress behavior consists of active stress generation in the Central Alps and strain release by Recent crustal movements and seismicity in the foreland. The Rhinegraben, being roughly parallel to the sinistral shear component of the regional stress field, undergoes a corresponding strike-slip reaction. A pattern of approximately SSW-NNE trending sinistral strike-slip faults and conjugate shear elements of NW-SE orientation, is present between the southern end of the graben and the Alpine fold belt. Stress flux and mass transport from the Alps towards the Rhinegraben are illustrated by the distribution of seismic epicentres and the contour lines of Recent uplift in the Alps.
From: Illies & Greiner (1976).

graphic features of the mid-oceanic ridges.

The style of the Upper Pliocene to Recent graben tectonics is totally different from the structures formed during earlier graben development. As first mentioned by Müllerried in 1921, former dip-slip fault planes of the graben had in many places been overprinted by horizontal slickensides of a left-lateral sense. In general, the amounts of horizontal displacement are relatively small. Buchner (1977) investigated a zone of intense shearing in a quarrying area in Triassic sandstones west of Strasbourg where he calculates a total sinistral displacement of 3 meters only. Nearly all the earthquakes in the Rhinegraben are caused by strike-slip motions. Ahorner (1975) evaluated a number of fault-plane solutions and calculated the annual seismic slip rate of the graben to be about 0.05 mm; this is equivalent to a sinistral strike-slip displacement parallel to the graben axis of about 50 m per million years. A compatible behaviour of the regional stress field was confirmed by Illies & Greiner (1976) who showed, by means of in-situ stress measurements, that the graben axis follows reasonably well the sinistral shear component of the regional strain ellipse (Fig. 7).

In order to gain a better understanding of the mechanical interrelations between plate and intraplate tectonics in the system of the Alps and their foreland, a program of in-situ stress determinations has been started. It was established that there is a decreasing gradient of active tectonic stresses from the Central Alps, where the excess of horizontal stress culminates, down to the northern foreland – similar to the morphological slope of the mountain range. The amounts of horizontal stresses in the foreland appear comparatively low (Fig. 15).

As proven by geodetic observations, wide parts of the Alpine mountain belt are actually under regional uplift of up to about 1.7 mm per year (Eidg. Landestopographie, 1976). In eastern Switzerland the isobase of recent updoming trend roughly normal to the directions of the greatest principal stress (Fig. 15). Most of the measured σ_1 directions follow the NW-SE trend, calculated also from fault-plane solutions of earthquakes (Ahorner, 1975). In the area south of the Rhinegraben, this general trend is superimposed upon by a more radial pattern of σ_1 directions, converging on the south end of the graben. The crustal unit north of the Alps has a strongly consolidated Hercynian basement and appears to have acted as a rigid block adjacent to the zone of Alpine orogeny. Within this rigid abutment the Rhinegraben forms a weak zone, appropriately predestined for strain relief of Alpine stresses. Within the mountain body, it is undeterminable even now if the substantially high amounts of horizontal stresses (Greiner & Illies, 1977) and the measured rates of regional uplift are effecting a more elastic horizontal strain or irreversible tectonic deformations. Regardless of the tectonic style of Recent crustal movements in the Alps, the stresses accumulated in the mountain body, are released prevalently in the foreland by block motions and seismic activity.

The youngest Alpine compressional deformations in the subalpine molasse and the Jura fold belt ended in Pliocene times. Following the cessation of this orogenic activity, the mountain body underwent a mainly epeirogenic, rapid regional uplift. The measured excess stress may be partially explained by the topographic effects of the high mountain ranges. Another contributing factor causing excess horizontal stress comes from rapid unloading by erosion resulting in mineral phase transformation at depth causing a regional extension. In the foreland, the weak zone represented by the Rhinegraben fitted the sinistral component of the post-orogenic regional stress field. Consequently, graben tectonics were reactivated with shear movements (Illies & Greiner, 1976). An Upper Pliocene to Recent fault pattern associated with this sinistral shear and sets of conjugate dextral strike-slip faults form the transition between the southern segment of the Rhinegraben and the adjacent part of the Alps in Switzerland. This local yielding of the foreland north of the Alps is illustrated also by the distribution of earthquake epicentres. Dense clusters of historic seismic events accentuate the crustal mobility at the Baden-Baden – Lausanne – Konstanz triangle (Fig. 15). The most catastrophic earthquake in Europe north of the Alps was that of Basel in 1356, located in the very centre of this unit.

The fractured basement, overlain by thick, poorly consolidated sediments, enabled the Rhinegraben to attract strain relief of Alpine stresses. In detail the Rhinegraben shows two sharp knickpoints altering its axial trend, the first about 30 km south of Karlsruhe and the second near Heidelberg; this results in three differently trending segments. Due to the graben geometry, the angle between the local graben axis and the direction of maximum horizontal compressive stress, as known from the adjacent South German Block, varies considerably for the three segments. Although the graben as a whole acts as a sinistral shear element, the respective tectonic reactions of the individual segments are of different character (Fig. 14).

Towards the southern mouth of the rift valley the anticlines of the Pliocene-folded Jura mountains intruded the graben like breaking waves. In the adjacent segment to the north, active graben tectonics will be controlled by the 175° direction of σ_1, which forms an acute angle with the approximate 015° trend of the local graben axis. Consequently, both sinistral shear and tensional vertical movements evolved. South of the Kaiserstuhl volcano, antithetic tilt blocks, horsts and local graben features illustrate physiographically the neotectonic behaviour of this part of the graben (Illies & Greiner, 1976).

The central segment of the Rhinegraben trends about 030°. The σ_1 direction, as measured in the block unit to the east of it, is about 130°, that is nearly normal to the local graben axis. Consequently, compressive forces control the neotectonic deformations along the eastern rim of this segment. Additional compression arises from the sinistral shear motion, which in this segment operated against the grain of the graben feature. At several places the eastern master fault, although initially a dip-slip element, has been overprinted by a second generation of reverse or thrust faults (Illies & Greiner, 1976). Fault-plane solutions of earthquakes showed a coupled mechanism of sinistral shearing with overthrusting (Ahorner, 1975). The sediment fill of this segment is under fluvial erosion over wide areas and the geodetic height anomalies are positive, indicating regional uplift of the graben floor (Mälzer & Schlemmer, 1975). Furthermore, perhaps associated with the above features, hydrocarbons as well as thermal ground waters of deep aquifers are often overpressured. Moreover, the extraordinarily high heat flow values observed in this segment might be enhanced by ascending pore water migration. A series of hot brines, like that of Baden-Baden, rises along those fault zones which reopened under the Recent stress conditions; most of these zones follow the trend of σ_1, sometimes the thermal fissures are conditioned by the activity of "dog-legged" strike-slip faults.

The northern segment of the graben reacted differently again. Sinistral shear and its almost exactly N-S trend favoured further crustal extension, giving rise to subsiding basins in which sediments were accumulated. Consequently, this segment is characterized by the maximum thickness of Pleistocene sediments (about 380 m; Bartz, 1974), by a dense pattern of growth faults active during this period (Schneider & Schneider, 1975) and by high rates of geodetically-established current subsidence (Schwarz, 1976).

The two localities along the western rim of the Rhinegraben where in-situ stress measurements have been performed, indicated totally different directions and amounts of horizontal stresses (Greiner & Illies, 1977). The regional stress field generated by Alpine plate tectonics, in the upper crust of the South German Block east of the graben, appears to have been almost entirely absorbed by the Recent tectonic activity and seismicity of the Rhinegraben. Consequently, as shown by the distribution of Recent crustal

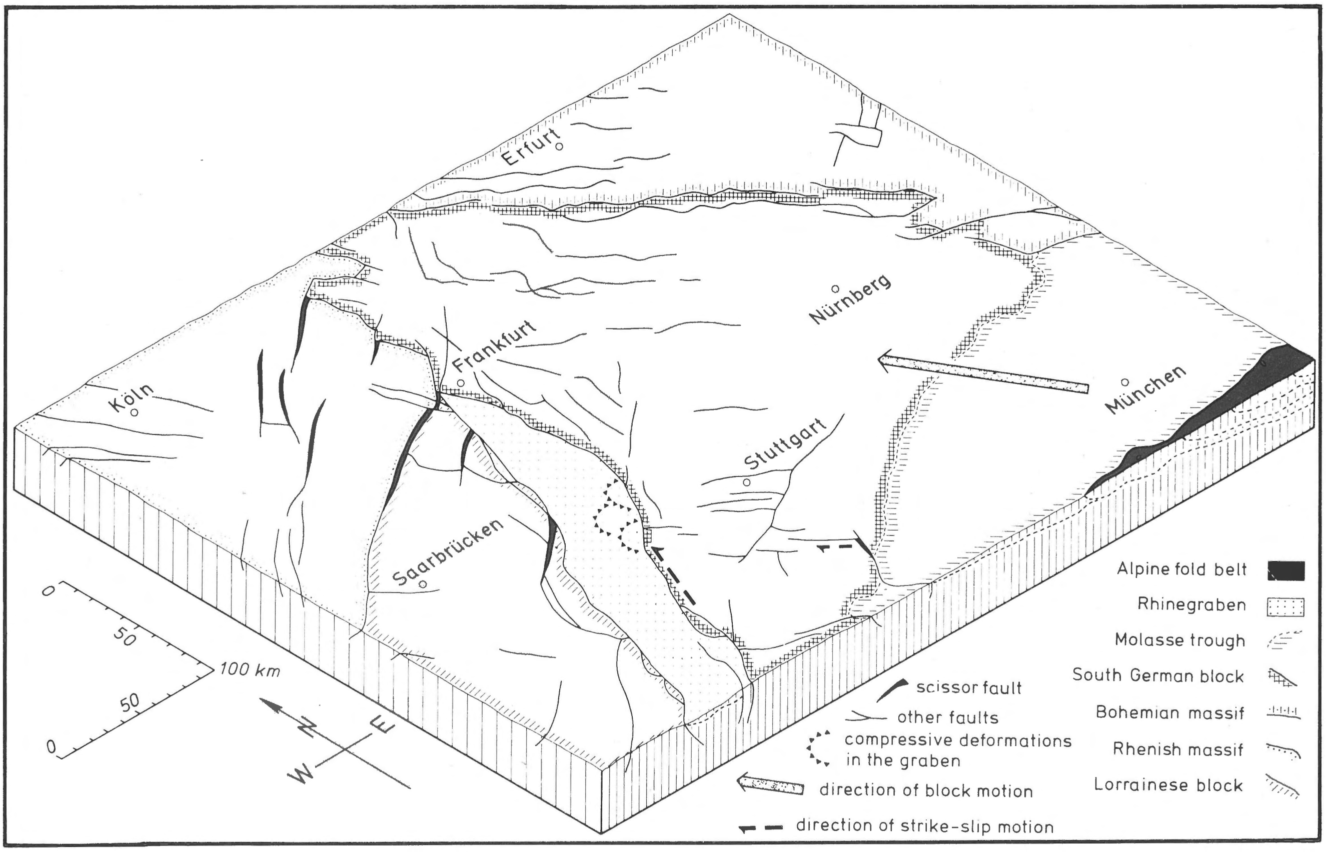

Fig. 16
Recent block movements in the Alpine foreland
Block diagram to illustrate some features of neotectonic block motions north of the Alps. The triangular South German Foreland Block is being pushed northwestward by recent Alpine tectonics. The Rhinegraben reacts with left-lateral shear movements. Due to the different general trend of the central part, compressional deformations are observed along the eastern rim of this segment. Beyond the northern end of the graben, the block motion is transmitted immediately to the southeastern edge of the adjacent Rhenish Massif. Due to the resulting yielding of the massif, basement controlled fracture zones were re-activated to form scissor faults.
From: Illies & Greiner (1976).

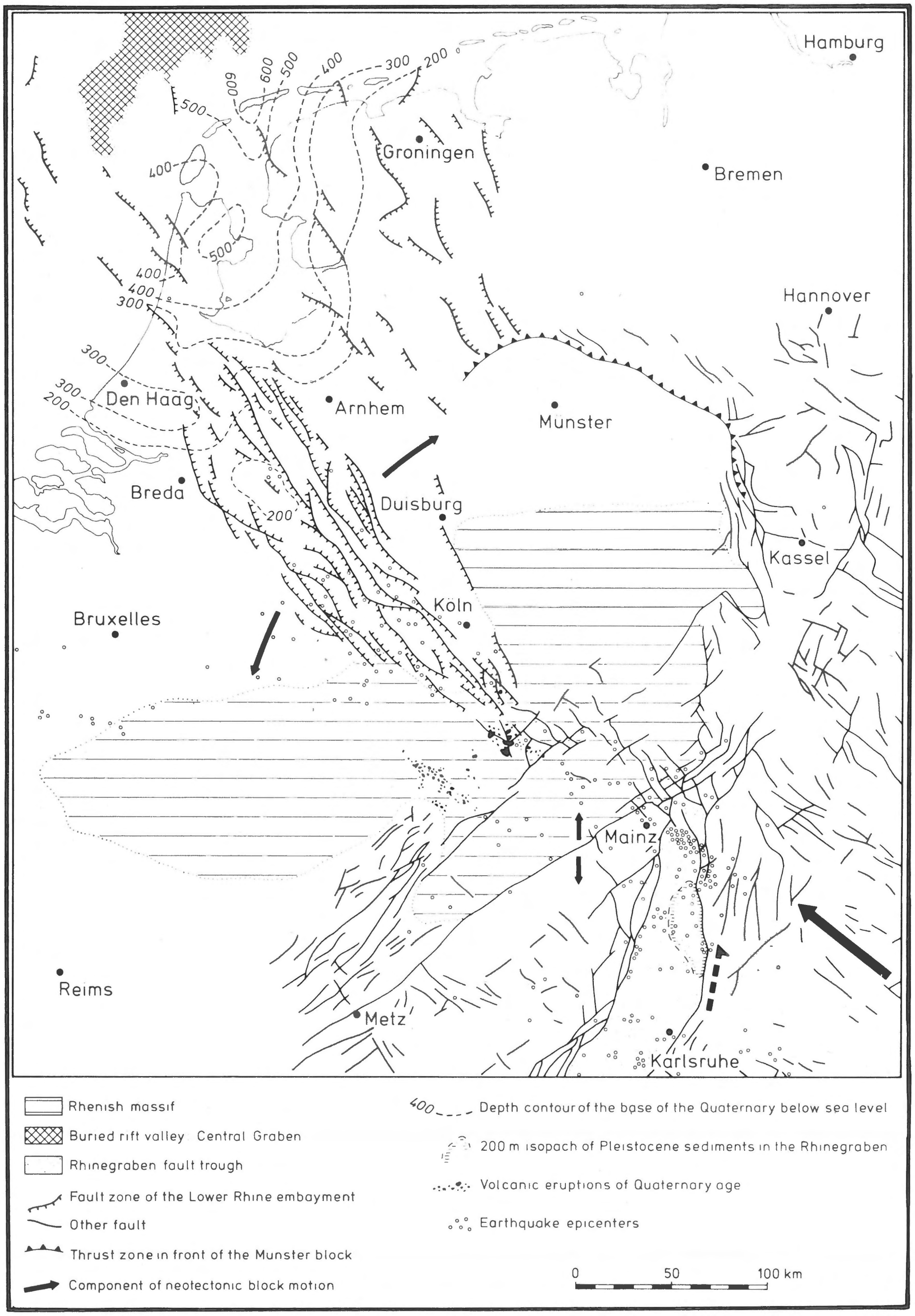

Fig. 17
Relation to Lower Rhine Embayment
Neotectonic map of the northern part of the Rhinegraben, the Lower Rhine Embayment, and the southern end of the Central Graben of the North Sea Basin. The sinistral shear motion of active Rhinegraben tectonics is interrupted near Mainz, since the southern border of the Rhenish Massif appears to cause a lateral offset of the originally tensional rift valley. A system of seismically active fractures traverses the massif between Mainz and Köln. The rift of the Lower Rhine Embayment, being parallel to σ_1 of the regional stress field, is under active crustal extension. The contours of base Quaternary indicate, that the southern end of the Central Graben – an extinct rift valley since end-Mesozoic times – became incorporated in the neotectonic rift valley progression.
From: Illies & Greiner (1976).

movements, earthquake epicentres and focal depths, the neotectonic role of the Rhinegraben is characterized by E-W asymmetry (**Mueller & Rybach**, 1974). The western flank of the northern part of the graben is found to be shaded from Alpine stresses. Only weak and indistinct tectonic stresses could be observed in this area. Farther westwards, between Saarbrücken and Luxemburg, a stress field again appears, with the same northwestward trend of maximum compression as found east of the graben (**Greiner & Illies**, 1977).

RECENT RIFT VALLEY PROPAGATION

North of Frankfurt the slide-bar mechanism of the Rhinegraben is interrupted, since the Hercynian block of the Rhenish Massif had caused an eastward offset of the rift system from the Rhinegraben to the Hessen depression. Along this offset the South German Crustal Block borders directly the adjacent Rhenish Massif. The northwestward shift of the former will be transmitted immediately to the latter, but only along a relatively short segment of the block border in the eastern part of the Taunus mountain range (NW of Frankfurt). An increase towards this contact area of the excess of horizontal stress was observed. At this point the Rhenish Massif is being pushed forward asymmetrically on its southeastern edge in the same predetermined northwestward direction. Consequently, the southern border of the Rhenish Massif west of this point broke up along the Taunus-Hunsrück lineament (Fig. 16). The well-exposed fault breccia of this element was already observed by Goethe in 1817 and he termed it "Urbreccie", which means "primeval breccia". The reactivation of the Palaeozoic block boundary by hinge or scissor faulting was confirmed by fault plane solutions of local earthquakes (**Ahorner & Murawski**, 1975), as well as by vertical dislocations of Pleistocene river terraces. Parallel to this roughly SW-NE feature, two other neotectonic fracture zones split the western frame of the northern Rhinegraben; the first SW of Frankfurt and the second west of Karlsruhe. At both fracture zones, Quaternary tensional faulting is observed to produce intersection of faults with the graben rim (**Illies & Greiner**, 1976). This yielding of the western abutment of the northern graben segment, indicated by the activity of cross-faults, has provided additional lateral space for Quaternary rifting and fault trough subsidence.

Further north, a continuous belt of seismic epicentres traverses the Rhenish Massif between Mainz and Köln and connects the Rhinegraben and the fault trough of the Lower Rhine Embayment (Fig. 17). An average trend of σ_1 of about 135° has been calculated by fault plane solutions of earthquakes (**Ahorner**, 1975). In contrast to other parts of the Hercynian fold belt, the Rhenish unit is prevalently composed of strongly folded shales and slates. Under the neotectonic stress conditions this particular lithology reacted by a more heterogeneous yielding using a dense pattern of

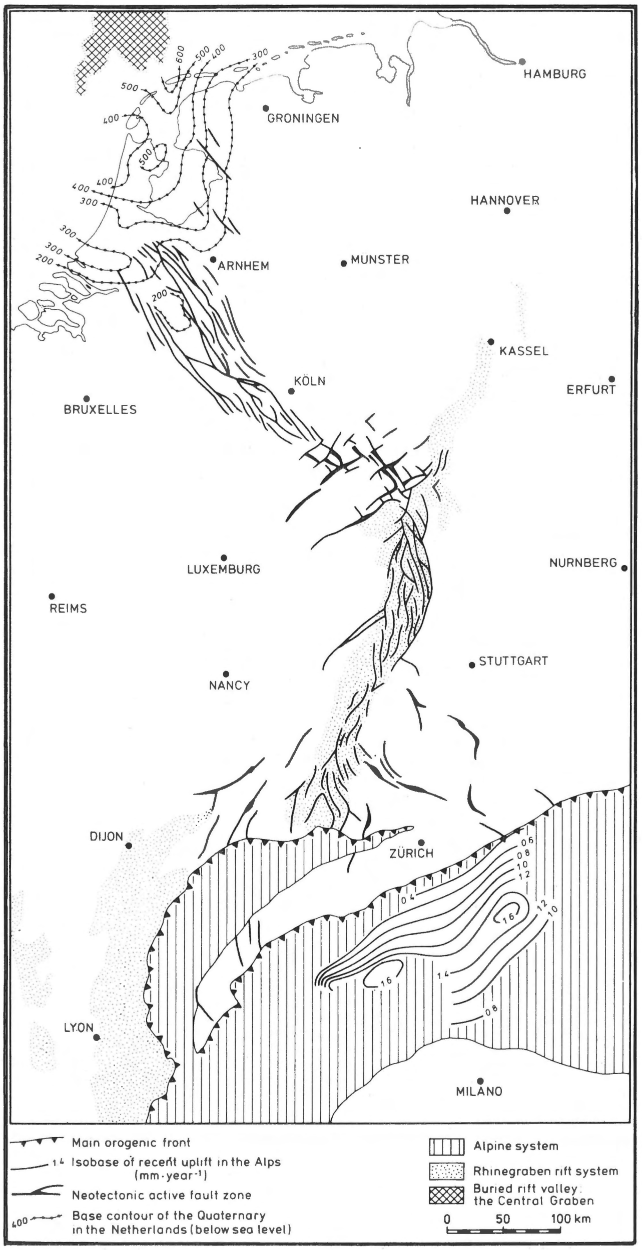

Fig. 18
Quaternary rift belt
A bundle of seismotectonically active faults traverses Western Europe to link the Western Alps with the buried rift of the North Sea Basin. Pre-existent grabens and fault zones guided the mobile subplate boundary. In accordance with the regional stress conditions, the Recent Rhinegraben acts as a sinistral shear zone, but the Lower Rhine Embayment as a tensional rift valley. In the Rhenish Massif between them, a dense pattern of normal faults absorbs rift valley propagation. High rates of uplift reveal the Western Alps to be under isostatic readjustment. Contemporaneous intraplate rifting in the foreland is controlled by a sideward extension of the mountain body. The aseismic furrow of the Zuider Sea depression acts as the northernmost segment of this mobile belt.
From: Illies & Greiner (1976).

pre-existent joint, cleavage and bedding planes. As a result only short and irregular normal faults of varying sense of displacement were produced (Stengel-Rutkowski, 1976). Continuous graben features are absent. Volcanic eruptions in the Eifel and the Neuwied area appear to be concentrated on NW-SE lines. Although the young volcanism thus conformed to the dominant σ_1 trend, no surface faults also corresponding to such a stress can be found. Apparently the fracturing which allowed the magma to penetrate the crust was caused by a mechanism similar to that of hydraulic fracturing in well-stimulation practice.

The axis of Pleistocene to Recent rifting of the Lower Rhine Embayment, cutting the northern part of the massif, is in accordance with the regional stress regime. This rift segment exhibits a fan-shaped widening with spreading rates that increase towards the NW (Ahorner, 1962). It implies a divergent yielding of the framing parts of the massif (Fig. 17).

The described Quaternary rift tectonics and the Recent seismicity of the Lower Rhine Embayment disappear west of about Nijmegen. At the same latitude, but with a 60 km eastward offset, the Zuider Sea depression sets in; the base of the Quaternary is depressed to a maximum depth, below the island of Terschelling, of about 600 m (Atlas van Nederland, 1975). This neotectonic depression forms a southern attachment to the Central Graben of the North Sea Basin (Fig. 17). The Central Graben remained an extinct rift valley since end-Mesozoic times, and no original interconnection can be recognized between this rift belt and the Lower Rhine Embayment. But the pattern of neotectonic deformations does indicate in more recent times a rift-to-rift propagation as observed similarly at several places in the East African rift system. Perhaps it was the weakened basement and the poorly consolidated state of the sediment fill, that attracted subsequent rift valley progression when block motions and regional stress field were suitable to trigger it off.

Because the trend of the Lower Rhine Embayment corresponds with the direction of maximum horizontal compression, in the same way that the Rhinegraben fits the sinistral shear component of the present-day regional stress field, an active subplate boundary has been formed joining the Western Alps to the southern end of the Central Graben of the North Sea Basin (Fig. 18). This boundary thus connects rift segments of different age, trend and structure.

ACKNOWLEDGEMENTS

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