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ORIGINAL PAPER

The Variscan tectonic inheritance of the Upper Rhine Graben: evidence of reactivations in the Lias, Late Eocene–Oligocene up to the recent

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Abstract Processing of gravity and magnetic maps shows that the basement of the Upper Rhine Graben area is characterized by a series of NE–SW trending discontinuities and elongated structures, identified in outcrops in the Vosges, Black Forest, and the Odenwald Mountains. They form a 40 km wide, N30–40° striking, sinistral wrench-zone that, in the Visean, shifted the Variscan and pre-Variscan structures by at least 43 km to the NE. Wrenching was associated with emplacement of several generations of plutonic bodies emplaced in the time range 340–325 Ma. The subvertical, NE–SW trending discontinuities in the basement acted as zones of weakness, susceptible to reactivation by subsequent tectonism. The first reactivation, marked by mineralizations and palaeomagnetic overprinting along NE–SW faults of the Vosges Mountains, results from the Liassic NW–SE extension contemporaneous with the break-up of Pangea. The major reactivation occurred during the Late Eocene N–S compression and the Early-Middle Oligocene E–W extension. The NE–SW striking basement discontinuities were successively reactivated as sinistral strike-slip faults, and as oblique normal faults. Elongated depocenters appear to form in association with reactivated Variscan wrench faults. Some of the recent earthquakes are located on NE–SW striking Variscan fault zones, and show sinistral strike-slip focal mechanisms with the same direction, suggesting also present reactivation.

Keywords Rhine Graben · Vosges · Black Forest · Odenwald · Variscan · Lias · Tertiary · Wrench fault · Reactivation

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Introduction

Reactivation in continental crust depends on the thermal and rheological state of the lithosphere, the existence of mechanical anisotropy inherited from previous tectonic events, and the orientation and nature of superimposed stress regimes (Vauchez et al. 1998; Holdsworth et al. 2001a, b). These authors suggested that if pre-existing structures are large enough to form significant areas of mechanical anisotropy in the continental lithosphere, then they are likely to suffer subsequent deformation. This is particularly true when the pre-existing structures occur in mechanically strong load-bearing upper crust or upper mantle. Reactivation of pre-existing surface is possible when the degree of mechanical anisotropy is high, heat flow is low, and when the surface is suitably oriented with respect to the direction of a superimposed stress regime. Providing these conditions are met, a high resolved shear stress occurs on pre-existing surfaces, leading to their reactivation (Jezek et al. 2002). Crustal scale mechanical anisotropy can be observed in crustal sections that are well-exposed on the surface, but it is hidden in basins or intracontinental rift domains, which are covered by sediments. Therefore, geophysical methods are required to depict the existence of orogenic fabric beneath sedimentary basins, in particular, modeling and processing of gravity and magnetic data.

In this study we determine the orientation and composition of the Variscan basement structures in the Upper Rhine Graben (URG), and assess the role of reactivated Variscan structures during subsequent tectonic phases. For this purpose, we use previous magnetic data, and a recently compiled comprehensive gravity dataset from the URG (Y. Rotstein et al., submitted for publication; Gabriel et al. 2004). This new dataset includes data acquired by the Mines Domaniales des Potasses d'Alsace, the German National Data Center (Institut für Geowissenschafliche Gemeinschaftsaufgaben), and the Bureau de Recherches Géologiques et Minières in France. Finally, we develop a model of successive reactivation of a large-scale Variscan shear zone, which has been preserved in the URG.

The Upper Rhine Graben

The URG constitutes the central segment of the Tertiary rift system that crosses Western Europe from the North Sea to the Mediterranean (Illies 1967, 1974; Ziegler 1994; Fig. 1). The tectonics of the URG were discussed by Illies (1967, 1974, 1977, 1978), Bergerat (1985), and Villemin and Bergerat (1987), and the sedimentary sequences were described by Doebl (1967, 1970), Bartz (1974), Ziegler (1994), and Schumacher (2002). Illies (1978) was the first to suggest that the Rhine Graben is the result of ''mutual mechanical interactions of pre-existing basement features, mantle diapirism and varying stress conditions.''

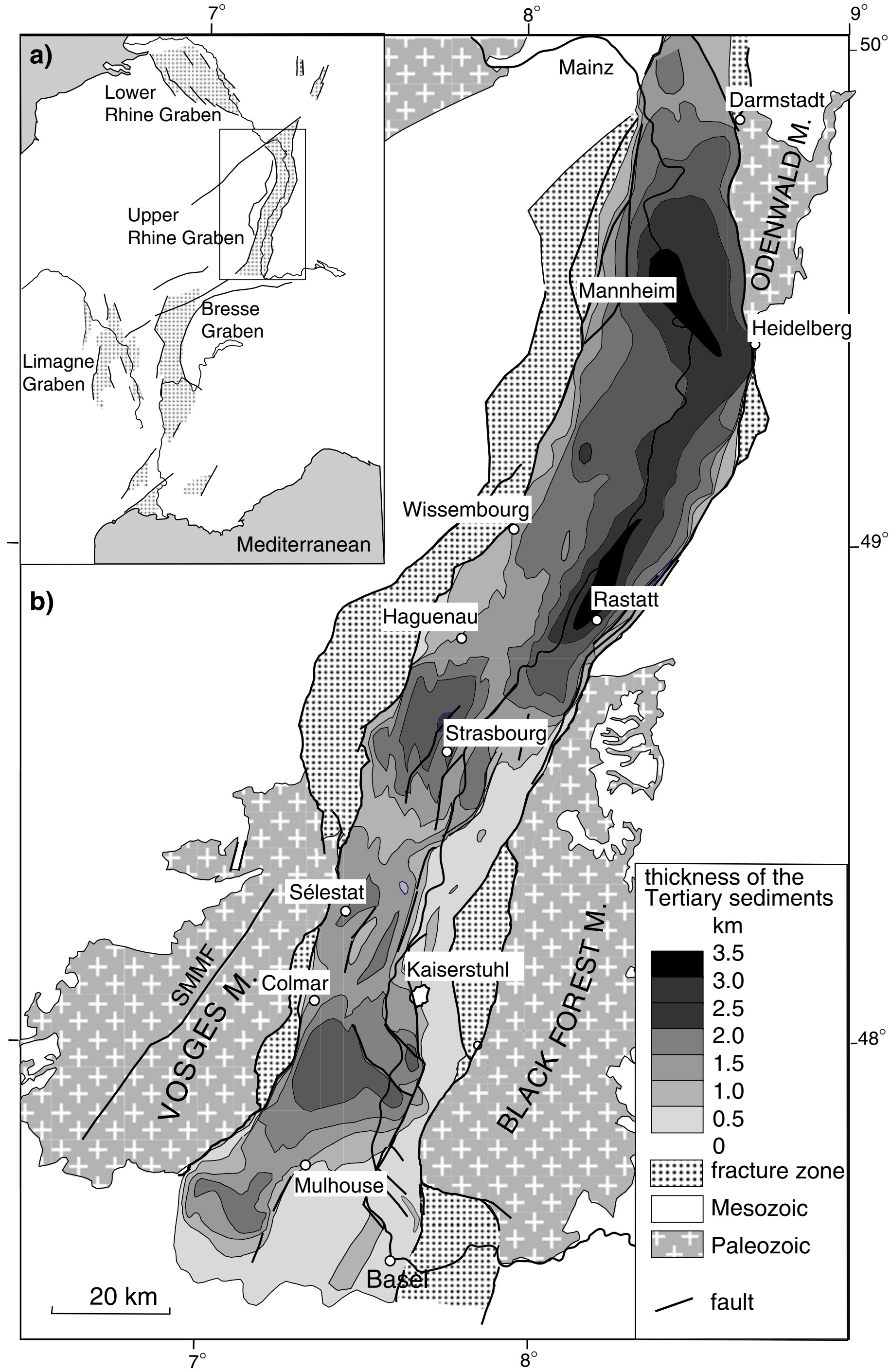
Tertiary—recent tectonic evolution of the URG

The Tertiary evolution of the URG included a number of stress regimes from the Late Eocene rifting episodes, up to the Late Miocene, when the present stress regime was established. The URG was subjected to compression with N–S oriented σ_1 stress axis in the Late Eocene, extension with an E–W oriented σ_3 stress axis in the Oligocene, and renewed compression with a NNE–SSW oriented σ_1 axis in the Late Oligocene–Early Miocene (Bergerat 1985; Villemin and Bergerat 1987). The existence of the latter phase was contested recently (Rotstein et al. 2005a). It is the east–west oriented Oligocene extension, which is coeval with maximum rifting episode and development of thick sedimentary sequences in the URG (Doebl 1967, 1970). Since the Late Miocene the URG is characterized by a NW–SE striking σ_1 axis, resulting in a left lateral transcurrent motion (Illies 1977; Bergerat 1985; Schumacher 2002; Rotstein et al. 2005b), as confirmed by focal mechanisms of the recent earthquakes (Ahorner 1975; Bonjer et al. 1984; Bonjer 1997; Plenefisch and Bonjer 1997). Locally, a steep σ_1 stress axis associated with horizontal NE–SW oriented σ_3 axis, also indicates extension (Plenefisch and Bonjer 1997). The Early Miocene stress regime resulted in thick sedimentation in the Heidelberg Basin, and possibly also in basins located farther south in the URG. However, these sediments were eroded in the southern URG during the Miocene (e.g., Schumacher 2002; Rotstein et al. 2005b). The onset of the Miocene–Recent stress regime was associated with an anticlockwise rotation of the stress field by about 60°, in the Early Miocene (Illies 1974, 1978). The timing of this rotation coincides with the anticlockwise rotations that affected the western Mediterranean and Alpine microblocks (Lowrie and Alvarez 1975; Van den Berg 1979; Montigny et al. 1981; Edel et al. 2001). Sedimentation during the Pliocene–Pleistocene was mostly concentrated in two small, NW–SE trending basins, near Freiburg and Heidelberg (Bartz 1974).

Evolution of Moho topography in the URG

The thermal structure and rheology of the lithosphere beneath the URG are likely to be strongly influenced by mantle uplift, which was observed in seismic refraction surveys (Meissner and Vetter 1974; Edel et al. 1975; Mueller et al. 1980; Gajewski et al. 1987), and deep seismic reflection lines (Wenzel and Brun 1991; Brun et al. 1991). The depth to the Moho oscillates around 24–25 km beneath the southern URG, 30–32 km in the Paris Basin, and about 55 km in the Alps. Nevertheless, the age of the mantle uplift is still being discussed, and it is likely to have been the result of more than one mechanism. A part of the elevated Moho in the URG is attributed to the Alpine flexural bulge (Gutscher 1995; Bourgeois et al. 2004). Its age is post-Early Miocene, because the Alps have reached their present configuration only after the block rotations that affected the Southern Alps and the Mediterranean microblocks, in the range 21.5–18 Ma (Lowrie and Alvarez 1975; Van den Berg 1979; Montigny et al. 1981). Part of Moho topography observed in the Ecors-Dekorp profiles (Brun et al. 1991) is believed to have taken place already during the Late Variscan extension. The almost constant thickness of about 25 km of the pre-Westphalian crust indicates

Fig. 1 **a** The Tertiary rift system of western Europe, **b** isobath map of the pre-Tertiary basement, after Doebl and Olbrecht (1974), and unpublished data



that the north-westward plunge of the Moho in the URG region is mostly due to the increasing thickness of the Permian-Late Carboniferous cover in that direction. The Late Oligocene–Miocene uplift associated with erosion in the southern URG, and northward migration of the depocenter, could have been a result of additional Moho uplift. The high Moho topography, and the occurrence of the 17–18 Ma old Kaiserstuhl volcano (Wimmenauer 1966; F. Keller and R. Montigny, personal communication) above the Moho dome, led Illies (1978) to suggest that the mantle diapirism in the URG was one of the main factors controlling the rifting.

The inherited pre-Mesozoic crustal fabric in the URG

Edel and Fluck (1989) used the gravity and magnetic data to propose the existence of a NNE–SSW striking, sinistral fault system of Carboniferous age in the URG basement. The existence of this fault system was later confirmed by Rousset et al. (1993), who used residual gravity maps, after removal of the effects of the sediments and of the Moho topography from the Bouguer gravity maps. Boigk and Schöneich (1970) reported WSW–ENE trending Permian troughs and ridges in the entire URG. Schumacher (2002) suggested that these Permian structures controlled the early stages of the Tertiary graben formation. In contrast, Edel et al. (2002) suggested that NE–SW trending Variscan fabric is the major feature controlling the graben formation. The object of the present paper is to confirm and develop this hypothesis.

Gravity and magnetic data

Gravity and magnetic anomalies depend on the thickness and density of sediments, and on the density and magnetic susceptibility of the underlying basement. The processing of gravity and magnetic maps (derivatives, downward continuation, analytical signals, filtering) is commonly used to establish lithological boundaries within the basement and discuss their tectonic significance. The first and second vertical derivatives of gravity data depict the graben borders, and enhance lateral changes in basement structure and composition, which are associated with density variations. On the first vertical derivative of the gravity map, the borders of the graben, mostly striking N15–20°, are characterized by steep slopes (Fig. 2). In the central part of the URG, where the graben trend changes, the strike of the gravity gradient along the borders is N30E° to N35E°. This trend prevails not only within the graben itself but can also be observed in the eastern part of the crystalline complex of the Vosges Mountains (VM), in the Black Forest Mountains (BFM), and the southern Odenwald Mountains (OM). Gradients in the first vertical derivative map, after removal of the gravity effect of the sedimentary infill, enhance the effects of basement geology and locate sub-vertical discontinuities (Fig. 3a). The map indicates density discontinuities that correspond to lithological changes, often associated with faulting. This is shown in more detail by two examples from the central part (Fig. 3b), and the southern termination of the graben (Fig. 3c; Lutz 1999; Edel et al. 2002), which show that the basement bodies and associated faults mostly strike NE–SW. This means that the elongated NE–SW striking, short wavelength anomalies in the map that was not corrected for the effect of the sediments (Fig. 2), mainly reflect basement structures. The gravity effect of the sedimentary cover is characterized by wavelengths significantly higher. In addition to the dominant NE–SW trends, N–S and N50° striking lineaments with a smaller lateral extent than the NE–SW lineaments, can also be observed (Fig. 3), and are likely to be associated with changes in basement lithology.

Similar observations can be made using the aeromagnetic maps of Germany (Bundesanstallt für Bodenforschung) and France (Bureau de Recherches Géologiques et Minières), and the ground magnetic map of the central URG (Edel et al. 1982). The anomalies that, in NE France and SW Germany mostly strike E–W to ENE–WSW, have a NNE–SSW to NE–SW trend in the URG (Edel and Weber 1995). Magnetic field reduced to the pole, and its first vertical derivative in the central URG, delineate pre-Permian basement bodies with different magnetic susceptibilities (Fig. 4; Lauer and Taktak 1971; Edel et al. 1986; Edel and Fluck 1989). Their dominant strike is about N35°, with occasional N70° and N–S trends, similarly to the pattern that is observed in the gravity maps.

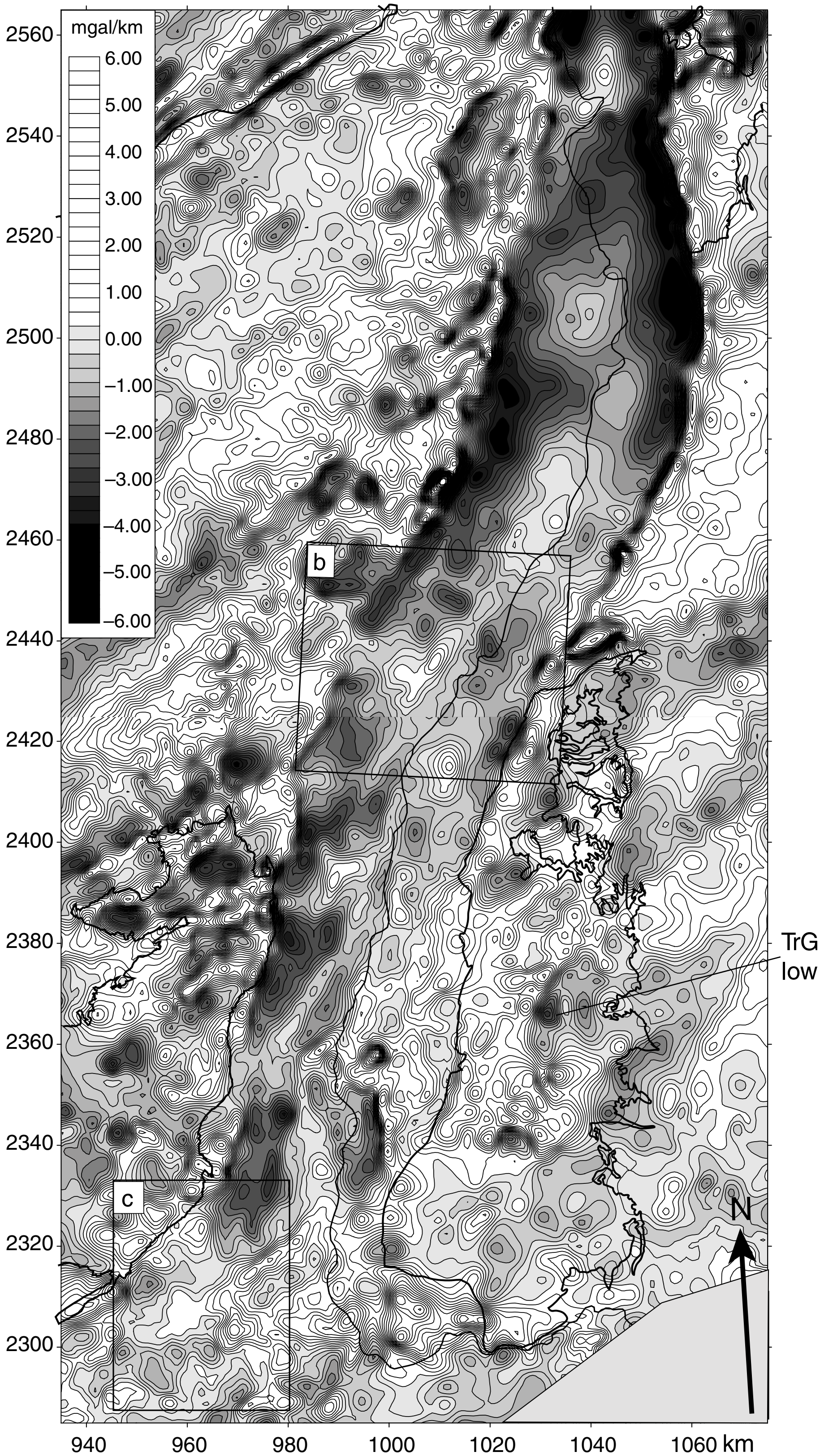
Previous gravity studies and density measurements in the VM, BFM and OM (Plaumann 1988; Edel and Weber 1995) have shown that the negative gravity anomalies in these areas are, generally, correlated with Carboniferous granites. The magnetic data, and rock susceptibility measurements from the same areas show that the magnetic bodies mostly correspond to Carboniferous gabbros, diorites and granodiorites, and their volcanic equivalents (Lauer and Taktak 1971; Edel et al. 1986; Edel and Fluck 1989). The main results of the present analysis of the gravity and magnetic data are summarized in Fig. 5. They show the basement discontinuities and the axes of the elongated gravity and magnetic anomalies, which are interpreted to correspond to granitic and mafic magmatic and volcanic bodies, respectively. The majority of these basement structures in the graben have a N30–35° strike. Such structures with the same orientation can also be seen in Paleozoic VM, BFM, and OM, where they are identified in outcrops. The major tectonic feature of this map is the shift by 40–45 km along a major sinistral strike-slip zone, striking N30–40° and located underneath the URG sediments, of the Early Paleozoic of the northern Vosges and Baden-Baden areas (Edel and Fluck 1989; Rousset et al. 1993).

NE–SW trending basement structures in outcrops and boreholes

Carboniferous faulting and magmatism in the Vosges

In the VM, two major N30–35° trending faults, Sainte-Marie-aux-Mines and Hunsruck-Kohlschlag Faults

Fig. 2 First vertical derivation of the Bouguer gravity anomaly map of the Upper Rhine Graben. The gravity map is based on data provided by the German Institut für Geowissenschaftliche Gemeinschaftsaufgaben, the French Mines de Potasse d'Alsace, and the Bureau de Recherches Geologiques et Minières, and calculated using correction density of 2.67 (adapted from Gabriel et al. 2004; Rotstein et al. submitted for publication). Geographic coordinates: Lambert II extended. *TrG* Triberg granite. Insets (*b*) and (*c*) are used in Fig. 3



(SMMF and HKF; Fig. 6), were active as sinistral wrench-fault zones during the Visean (Fluck 1980; Fluck et al. 1991). Two generations of elongated granitic bodies intruded parallel to these faults, the 340 Ma old I-type granite des Crêtes (Schaltegger et al. 1996), and leucogranite bodies dated 330–325 Ma

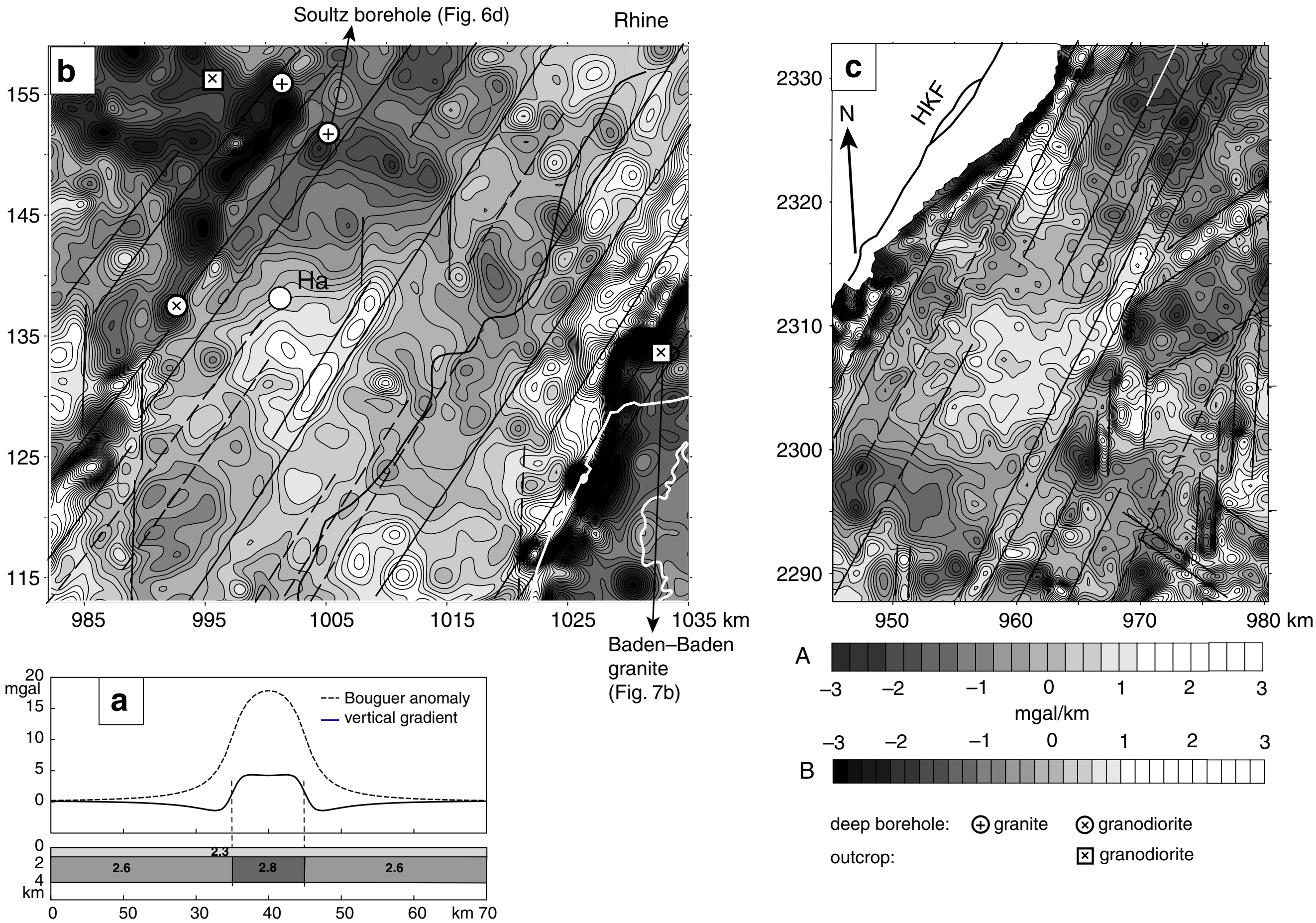


Fig. 3 **a** Calculated 2D Bouguer gravity anomaly and vertical gradient of prismatic structure with vertical boundaries. The maximum slopes of the first derivative are located above the boundaries; **b**, **c** first vertical gradient of the Bouguer map after removal of gravimetric effect of the sedimentary cover, processed after **b** Papillon (1995) in Lambert I coordinates and **c** Edel et al. (2002) in Lambert II coordinates. See location of (**b**) and (**c**) in Fig. 2. The *lines* represent gravimetric discontinuities, i.e., faults or boundaries between units with contrasting densities

(Boutin et al. 1995; VaG, and TuG in Fig. 6a). In the southeastern part of the VM, in the eastern part of the Devonian–Dinantian basin (Fig. 6b), the HKF shifts the WNW–ESE trending belt of the Late Visean volcanites and sediments dated 345–340 Ma (Schaltegger et al. 1996), by about 4 km toward the NE (Coulon et al. 1979). The NW–SE striking klippen belt of gneisses and peridotites (Fig. 6b) changes its trend, and becomes sub-parallel to the HKF, and farther to the north, it is shifted by about 6 km toward the NE. The age of the HKF was derived from Late Visean andesitic volcanics that were emplaced in a NE–SW trending zone, parallel to the HKF (Fig. 6b; Coulon et al. 1979).

The E–W to ENE–WSW striking Vittel-Lalaye-Lubine Zone (VLLF; Fig. 6a) borders the high-grade internal orogenic zone of the central VM, and the low-grade rocks in the northern VM. North of this fault zone, the calc-alkaline, I-type magmatic suite of the Champ du Feu massif intruded the Early Palaeozoic sediments and volcanites in the time range 340–330 Ma (Von Eller 1964; Boutin et al. 1995; Altherr et al. 2000). These rocks are characterized by intermediate to high magnetic susceptibility (Lauer and Taktak 1971; Edel et al. 1986), and show magnetic anomalies that can be traced toward the west underneath the Triassic series, and also eastward underneath the sedimentary cover of the URG (Fig. 5). West of the northern VM, these granitoids show elongated shapes trending ENE–WSW. The anisotropy of magnetic susceptibility (AMS) measurements displays magnetic lineations, and foliations, parallel to this direction (Fig. 6c). Farther eastward, close to the border with the URG, a diorite dyke (Mod, Fig. 6c) trending N30° shows steep magnetic foliation, and sub-horizontal lineations parallel to the strike of the foliation. The dyke is cut by a younger granite (Andlau granite), which was emplaced at a higher structural level than the previous intrusions (Altherr et al. 2000). The

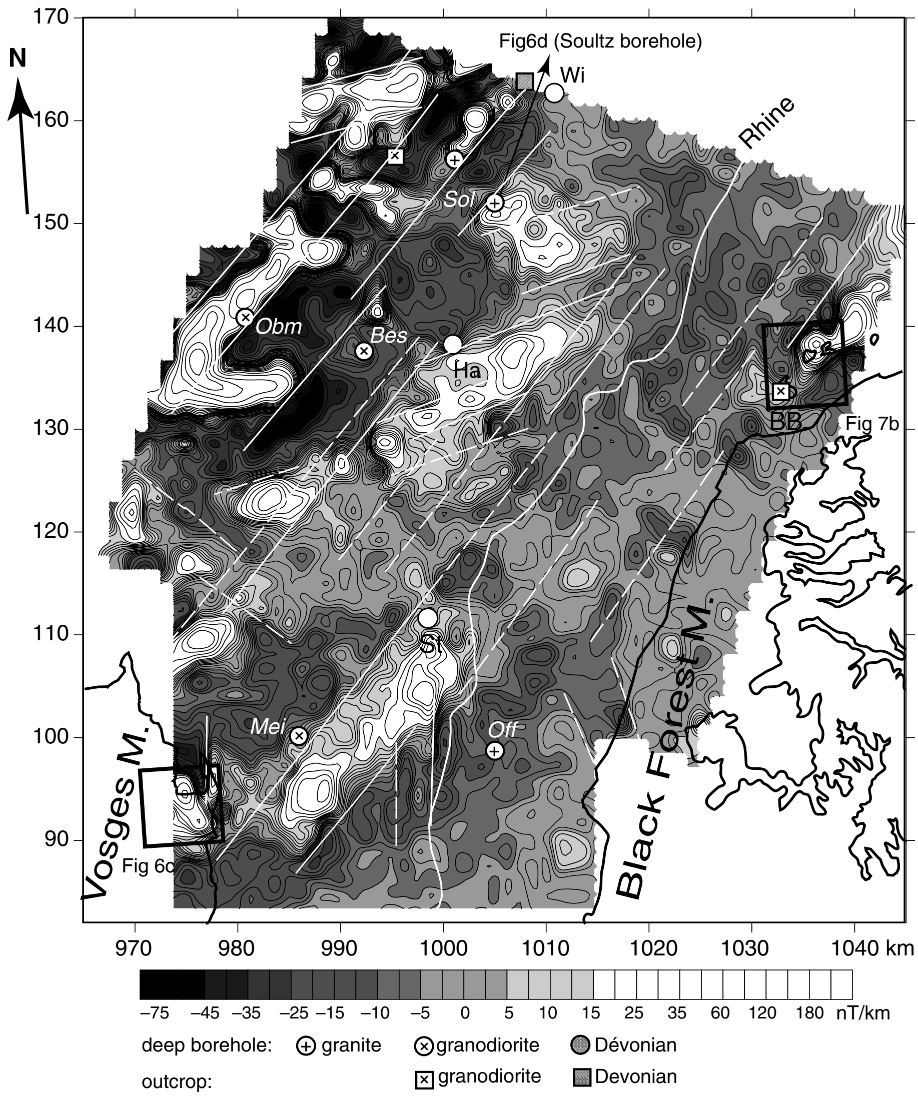


Fig. 4 First vertical derivation of the magnetic anomaly at ground level, reduced to the pole, reprocessed after Papillon (1995). Lambert I coordinates. *Bold lines* show contours of the Paleozoic Vosges Mountains and Black Forest Mountains. The *straight lines* represent magnetic discontinuities, i.e., faults or boundaries of magnetic bodies. *Dashed lines* were drawn on a map with smaller intervals of isolines, which better show lineations. *St* Strasbourg, *Ha* Haguenau, *BB* Baden-Baden. Boreholes—*Sol* Soultz, *Bes* Berstheim, *Obm* Obermodern, *Mei* Meistratzheim, *Off* Offenbourg

granite is characterized by high magnetic susceptibility, particularly along its borders (Lauer and Taktak 1971; Edel et al. 1986). The magnetic foliations of this granite strike N30–40° and dip toward the NW, parallel to the older diorite dyke. The magnetic lineations strike parallel to the foliation in the east, where the granite body can be considered as a large dyke, and turn ENE–WSW to E–W in the west. The results of AMS studies are geometrically consistent with the mesoscopic fabric of numerous metasediment xenoliths and diorite enclaves measured by de Waard (1952). The pattern of AMS fabrics, as well as the shape and orientation of the enclaves, indicate that their origin is related to the magma emplacement during regional tectonic activity (Paterson et al. 1998). In the adjacent graben, NE of the Andlau granite, the borehole located at the edge of a prominent N40° striking magnetic anomaly (*Mei* in Fig. 4) penetrated a granite of the same type. This indicates the continuity of the high magnetic granite exposed in the VM, underneath the sedimentary cover of the graben. The magnetic map shows that the structure has a NE–SW strike parallel to the magnetic and magmatic lineations of the Andlau granite.

Data on granite fabric in drill cores from the URG

Farther to the north, within the URG and close to its western margin, the Soultz-sous-Forêt boreholes (Figs. 3b, 4) penetrated a monzogranite emplaced at 331 ± 9 My, and buried under 3,000 m of sediments (Alexandrov et al. 2001). The boreholes are located at the intersection of N40° and N130° trending gravity lows, which are both apparent also after stripping the gravity effect of the sediments (Fig. 3b). The N40° trending gravity low coincides with a magnetic low that

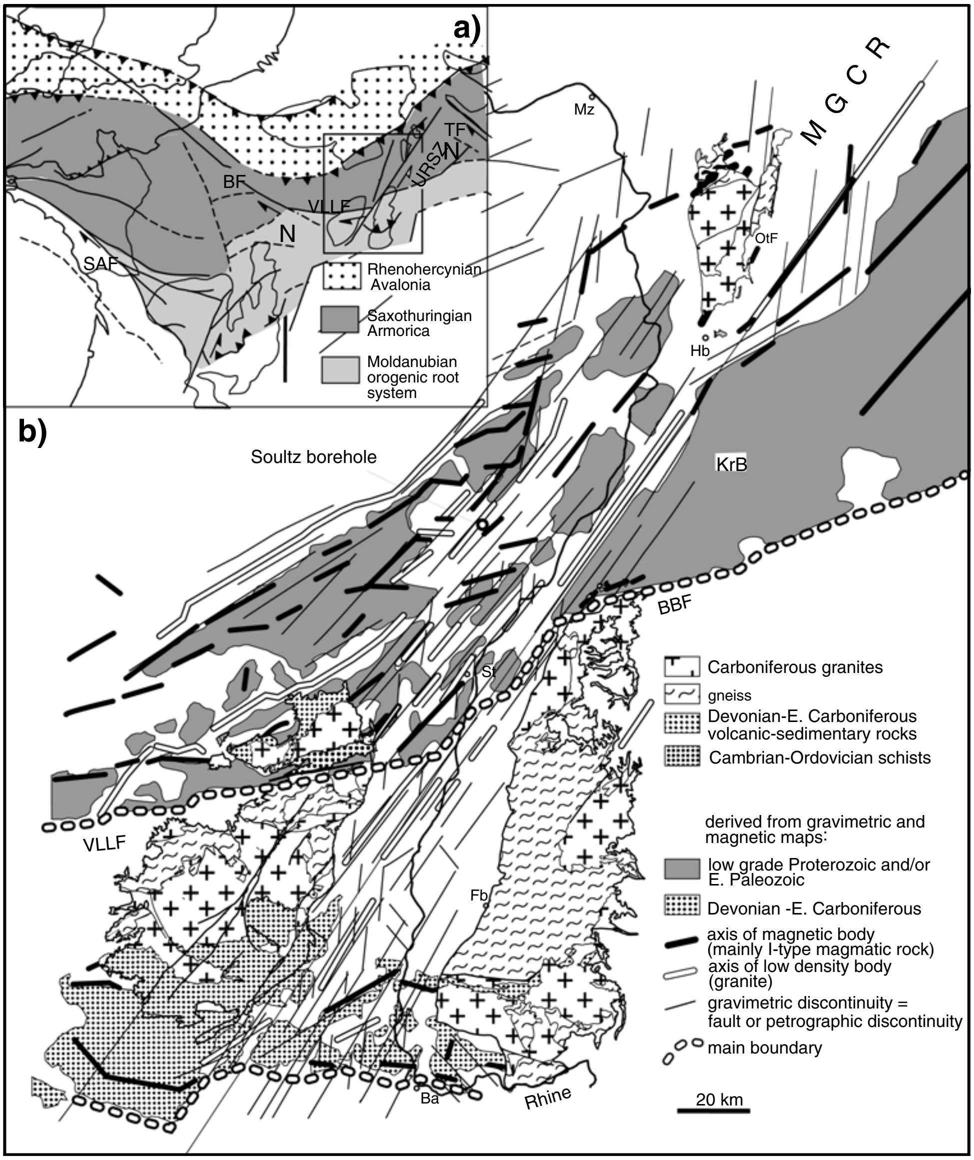


Fig. 5 **a** Geological sketch map of the western Variscides, after Edel and Weber (1995). **b** Geological map of Vosges Mountains, Black Forest Mountains, and Odenwald Mountains, and extension of the Paleozoic and/or Proterozoic rocks, derived from the processed gravity maps. The axes of gravimetric lows correspond to elongated granitic bodies. The axes of positive magnetic anomalies represent elongated magmatic bodies, mostly of Visean age. The map illustrates the sinistral strike-slip motions along NE–SW faults. *TF* Thuringian Fault, *BF* Bray Fault, *SAF* South Armorican Fault, *VLLF* Vittel-Lalaye-Lubine Fault, *BBF* Baden-Baden Fault, *MGCR* Mid-German Crystalline Ridge, *KrB* Kraichgau heavy body of probable Proterozoic to Paleozoic age, *URSZ* Upper Rhine Shear Zone

has the same strike, while the N130° trending gravity low coincides with a magnetic high of trapezoidal shape (Fig. 4). The western and northern borders of the latter magnetic anomaly strike N40° and N130°, respectively. Mostly high susceptibilities of about 13×10^{-3} SI were measured in the porphyric granite observed in cores from the Soultz wells (Rummel 1991). These results indicate that the borehole is located on the western margin of the high susceptibility monzogranite. The orientations of biotite (001) planes, and feldspars (010 and 100) cleavages were measured in cores from the Soultz boreholes, using optical goniometer (Schulmann et al. 1997). The biotite shows mostly sub-horizontal NE–SW trending zone axes, and the feldspar planes show preferred orientation along a NE–SW direction (see rose diagram in Fig. 6d). Schulmann et al. (1997) interpreted the preferred orientation of the biotite and feldspar crystals as resulting from magma deformation in sub-solidus state due to NE–SW oriented flow. The rather horizontal fabric in the granite cores is also evidenced by AMS measurements, but no preferred direction of K1 could be observed (Just et al. 2003).

Carboniferous structures of the Black Forest

The northern and eastern parts of the central BFM gneiss complex show dominant NNE striking foliations (Flöttmann and Gallus 1986; Fig. 7). In addition, the NW boundary of the Triberg granite, which intruded this metamorphic complex, is parallel to the fabric strike of the adjacent gneisses (TrG, Fig. 7a). This

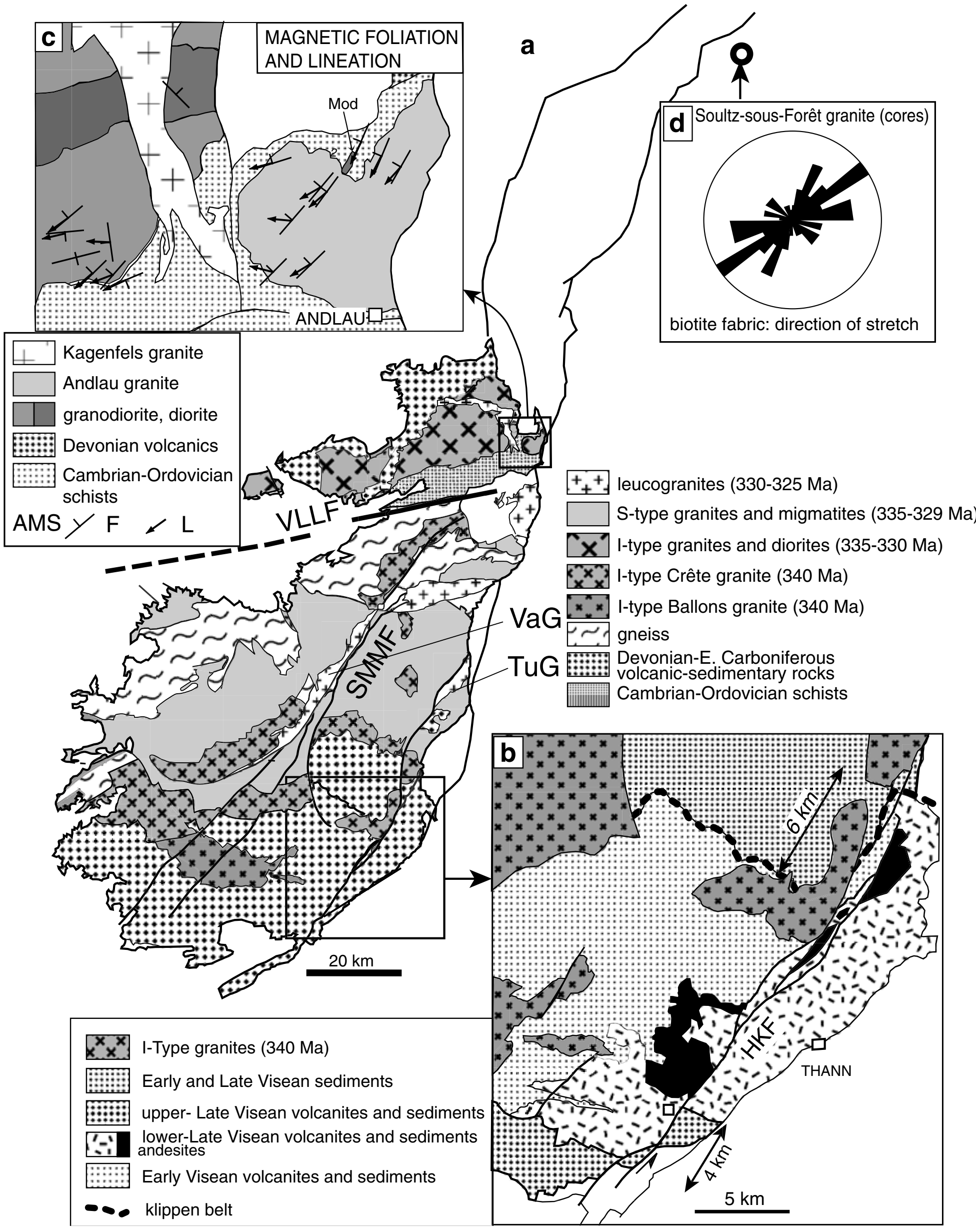


Fig. 6 **a** Geological map of the Vosges Mountains (VM) (Fluck et al. 1989). *VaG* Valtin leucogranite, *TuG* Turckheim leucogranite, *SMMF* Sainte-Marie-aux-Mines Fault. **b** Geological map of the south-eastern VM (after Coulon et al. 1979), *HKF* Hunsruck-Kohlschlag Fault. **c** Geological map of the north-eastern Vosges (after Von Eller 1964; Von Eller et al. 1970), and magnetic foliations and lineations obtained from measurements of the anisotropy of magnetic susceptibility. **d** Biotite fabric of granite cores from the Soultz borehole (after Schulmann et al. 1997)

relationship can also be seen on the vertical derivative gravity map (Fig. 2). There, the NW boundary of the negative anomaly has a steep gradient, which coincides with the NW margin of the granite body.

Farther to the south, a narrow belt of Devonian–Early Carboniferous volcano-sedimentary rocks, the Badenweiler-Lenzkirch Zone (BLZ in Fig. 7a), separates the high-grade gneiss mass of the central BFM from the granites and gneisses in the southern parts of these mountains. To the east, the BLZ is trending NE–SW, parallel to the main fabric orientation in the gneisses. Toward the west, the trend of the BLZ becomes E–W, and is associated with dextral strike-slip movements (Sittig 1981). Deep seismic reflection data show that the BLZ dips toward the NW underneath the gneiss mass, to a depth of at least 12 km (Lüschen et al. 1987). Geochronological studies show that the exhumation of the high-grade gneisses along the northern part of the BLZ occurred in the time-range of 335–332 Ma (Schaltegger 2000). Consequently, the eastern ramp of the thrust belongs to the series of N30–35° trending structures that is apparent in the gravity maps.

North of the BFM, the Baden-Baden Fault (BBF) forms the eastern extension of the VLLF, shifted by about 43 km to the NE (Edel and Fluck 1989; Figs. 5, 7a). North of it, low-grade metasediments and metabasites exhibit mylonitic foliation, either parallel

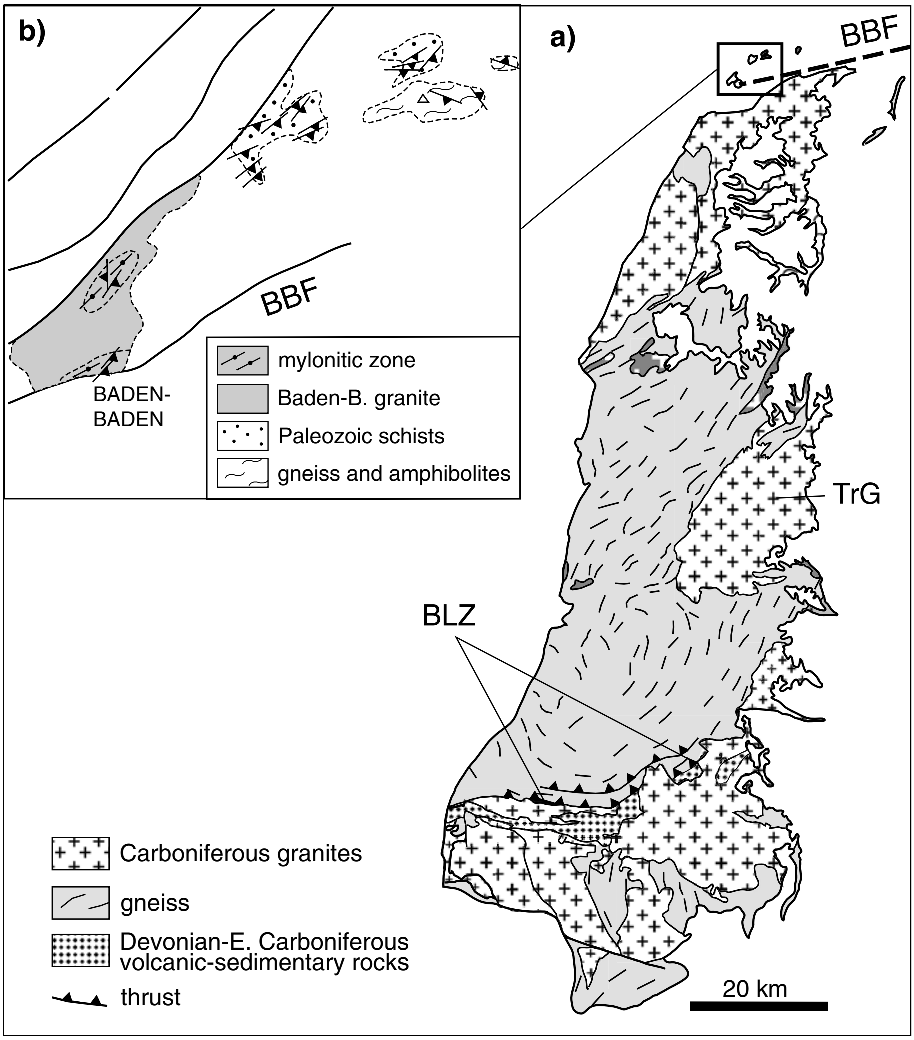


Fig. 7 **a** Geological map of the Black Forest Mountains, including foliations after Flöttmann and Gallus (1986); **b** geological map and structural features of the Baden-Baden area after Wickert et al. (1990). *TrG* Triberg granite, *BLZ* Badenweiler-Lenzkirch Zone, *BBF* Baden-Baden Fault

to the N70° trending BBF, or to the N40° trending eastern boundary fault of the URG (Fig. 7b; Wickert et al. 1990). In the late Early Carboniferous, this unit was intruded by the Baden-Baden I-type granite that is equivalent to the younger granites in the northern VM that, geochemically, resembles the Andlau granite (Altherr et al. 2000). The Baden-Baden granite was later affected by ductile, left-lateral strike-slip faults trending N40°, or N70° (Wickert et al. 1990).

Granitoid fabrics in the OM and Mid-German Crystalline Ridge

The mafic and felsic plutonic rocks of the OM crop out in the northern extension of the N30–40° trending belt of elongated magnetic and gravity anomalies (Figs. 5, 8; Krohe 1992; Altherr et al. 1999). These 340–330 Ma old (Kreuzer and Harre 1975) plutonic rocks experienced deformation during the emplacement, and subsequent cooling that resulted from the NE–SW-oriented transtension in the E–W extensional stress regime (Krohe 1992; Fig. 8b). Granodiorite–granite intrusions of the southern OM show magnetic foliations and lineations trending WSW–ENE that are the product of syn-emplacement deformation (Greiling and Verma 2001; Fig. 8c). The metamorphic complex of eastern OM is separated from the calc-alkaline plutonic units of western OM by the NNE–SSW trending Otzberg Fault Zone (OtF, Fig. 8b). This fault is a sinistral transcurrent fault, which gradually developed toward the NE into a thrust zone, exhuming the crustal nappe of the Spessart metamorphic complex (Weber 1995; Edel and Weber 1995). The K–Ar and Ar^{40}–Ar^{39} ages of about 329 Ma, in a lamprophyre dyke that transects the cataclasites and mylonites of the OtF, postdate the sinistral strike-slip motion along this zone (Hess and Schmidt 1989).

East of the OM, the NE trending magmatic belt observed in the eastern VM, BFM, and southern OM, disappears underneath the Triassic sediments (Fig. 5).

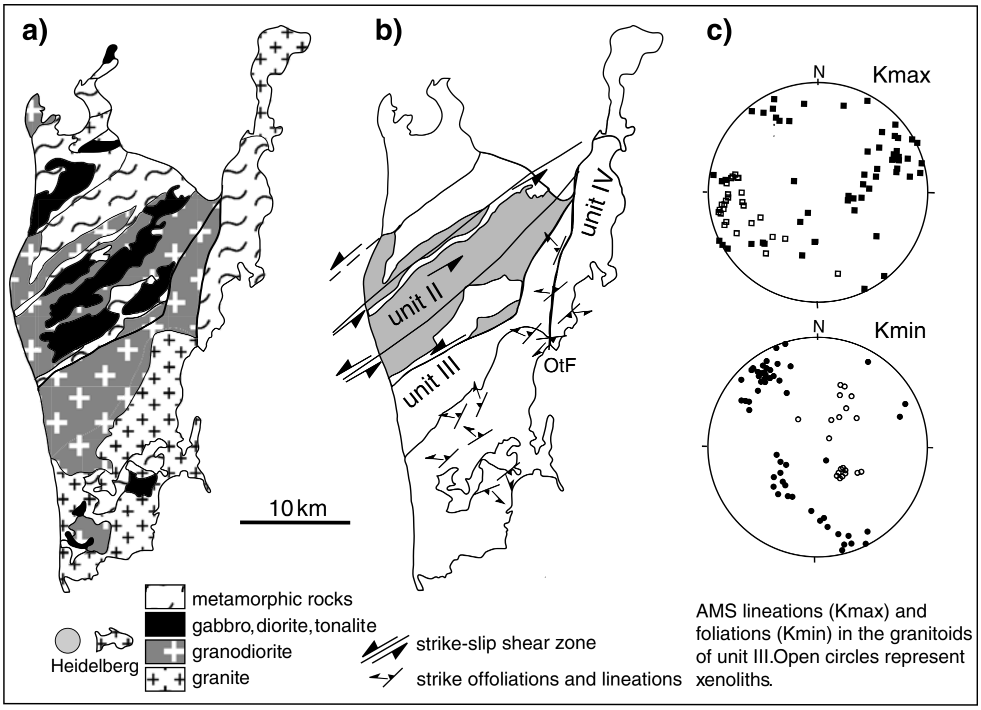


Fig. 8 **a** Geological map of the Odenwald M. **b** Structural map of the Odenwald Mountains (after Krohe 1992). *OtF* Otzberg Fault. **c** Anisotropy of magnetic susceptibility lineations (K_{max}) and foliations (K_{min}) in the southern Odenwald (after Greiling and Verma 2001)

Here, a 35–40 km wide, 160 km long gravity low has been observed, which indicates the occurrence of Early Paleozoic metagranites and Variscan plutonic rocks (Edel and Weber 1995). These magmatic bodies correspond to the southern margin of the Mid-German-Crystalline-Ridge (MGCR in Fig. 5; Weber 1995; Oncken 1997) and represent the NW limit of the heavy Kraichgau body (KrB). The axis of the gravity low coincides with the northern extension of the major sinistral NE striking, strike-slip fault zone, which shifts the KrB 43 km toward the NE (Fig. 5). A part of these inferred magmatic rocks appears to be magnetic and, therefore, in analogy to the URG, they are believed to correspond to diorite, or to granodiorite intrusions.

The Upper Rhine Shear Zone

The gravity and magnetic surveys carried out in the URG area showed the existence of a large zone of NE–SW trending magnetic and gravity anomalies of elliptical shape. The vertical derivatives of the magnetic and gravity anomalies indicate that these anomalies represent geological bodies with steep NE–SW trending margins. This is confirmed by 2D modeling along profiles crossing the URG (Gabriel et al. 2004; Y. Rotstein et al., submitted for publication). Boreholes penetrating these anomalies in the northern (Saxothuringian) part of the studied area confirm that these are magmatic rocks. We note that the light and weakly magnetic bodies generally consist of felsic granitoids, whereas heavier and magnetic structures are mostly identified as granodiorite or diorite intrusions (Edel and Weber 1995). In places, where such bodies are exposed on the surface, the magmatic bodies show magnetic or deformational fabrics, sub-parallel to the NE–SW trend seen on the gravity and magnetic maps. These observations are consistent with the magmatic fabrics determined from the oriented granitoid cores of the Soultz boreholes. They suggest the existence of a magmatic belt, formed by strongly elongated plutonic bodies, which show magmatic planar and linear fabrics, parallel to their long axes. This is in agreement with magma batches emplaced during a regional tectonic event with dominant wrench component.

The entire magmatic belt coincides geometrically with the left-lateral shift of the heavy Kraichgau ''Saxothuringian'' block, which consists of Early Paleozoic series and probable Late Proterozoic basement (e.g., Edel and Weber 1995). Similar sinistral displacement of Devonian and Lower Carboniferous units is suggested by the gravity data in the southern ''Moldanubian'' part of the URG (Fig. 5), but with significantly lower magnitude by comparison with the northern part. This large-scale kinematic pattern is, possibly, the result of crustal scale sinistral wrenching affecting pre-Variscan and early Variscan basement of the URG. Geological observations in the southern Variscan outcrops show the existence of sinistral NE–SW trending faults, accompanied by magmatic activity in the central and southern VM. In addition, boundaries of large magmatic intrusions in the southeastern BFM show a similar trend. These data imply only limited sinistral wrenching in the southern part of the investigated area. We suggest that it indicates that the major tectonic and magmatic activity associated with sinistral wrenching is developed in the northern "Saxothuringian" domain, and is progressively decreasing southward. The importance of the syn-wrenching magmatism in the north is supported by coherent magmatic fabrics of the granitoids in OM, northern VM, and in the northern BFM.

The age of this important wrench-dominated magmatism, determined by isotopic dating of numerous granitic bodies, ranges from 342 to 330–325 Ma. The wrench faulting at around 340 Ma is believed to have been associated with early arc magmatism in the southern VM. Later (335–330 Ma), it was associated with the thrusting of deep crustal units in the central VM (Rey et al. 1989) and BFM (Schaltegger 2000). The wrench faulting was also associated with the emplacement of crustally derived granites, spatially related to large NNE–SSW trending sinistral faults and thrusts (Schulmann et al. 2002). Plutonic bodies trending NE–SW, in the northern VM, northernmost BFM and OM, were emplaced during the same period (335–330 Ma).

The Carboniferous crustal-scale strike-slip faults, associated with NE–SW trending plutons, form a 40 km wide, 400 km long zone, named here the Upper Rhine Shear Zone (URSZ, Fig. 5a). Its trend changes from N30° in the south-west to N40° in the north-east. This sinistral wrenching is associated with large-scale dextral displacements along NW–SE striking Thuringian, Bray, and South Armorican fault zones (TF, BF, SAF in Fig. 5a), which caused Early Carboniferous reworking of assumed Neo-Proterozoic and Early Palaeozoic crust (Edel and Weber 1995). The URSZ is characterized by steeply inclined, NE–SW trending faults, shear zones, and contacts between plutons and host rocks that are susceptible to reactivation by late tectonics.

Reactivations of the URSZ

Lias reactivation

Palaeomagnetic investigations carried out in the Visean basin of the southern VM show that a large part of the volcanic and volcano-sedimentary rocks underwent several remagnetization stages (e.g., Edel 1997). Although most of the overprints may have occurred in the Late Carboniferous, several post-Carboniferous overprint stages have also been detected showing clusters of poles, which are located along the apparent polar wander path (APWP) of Europe (Fig. 9a). One group of poles fits into the Late Triassic–Lias segment of the APWP. The second group of poles is consistent with the Late Jurassic–Cretaceous part, and the third group that overlaps partly the second one is scattered around the Tertiary–Recent poles. The K–Ar dating of diagenetic illites from cores of Triassic sandstone from the URG, yielded an age of 188 Ma, also indicating an Early Jurassic hydrothermal activity (Liewig et al. 1987; Liewig 1993). Similar ages of 195–210 and 160–170 Ma were established in diagenetic illites from Triassic sandstones in the northern VM, which were remagnetized in Triassic and Jurassic times (Tournier et al. 1999).

In the southern VM, a post-Triassic low temperature mineralization consists of numerous polymetallic veins containing lead, zinc, copper, quartz, barite and fluorite mineralizations. They are of unclear age, being irregularly distributed along NE–SW oriented faults (Fluck 1992). A map depicting hydrothermal veins (Edel 1997) in the southern VM shows the majority of the sub-vertical veins to be parallel to the NE–SW faults, which belong to the URSZ (Fig. 9b). The orientation and distribution of veins in this area clearly indicate NW–SE oriented tensional stress, associated with high to intermediate differential stress values (Price and Cosgrove 1990).

It is not clear whether the mineralization in the southern Vosges can be temporally correlated with the Early Jurassic hydrothermal activity in the Triassic sandstones, and with the Late Triassic–Lias magnetic overprints in the Carboniferous volcanites. However, the NW–SE Jurassic extension is known to have affected the NE–SW trending faults in southeastern France, and in the external Alps (Lemoigne et al. 2000; Fig. 9c). This tectonic phase, characterized by high fluid pressure, may have also reactivated the Carboniferous NE–SW faults in the area of the future URG, which are ideally oriented with respect to the Jurassic tensional stress. Our palaeomagnetic data (Fig. 9a), and the orientation of inferred tensional stress directions in the URG, are consistent with Late Triassic–Early Jurassic break-up of Pangea. These observations are also consistent with rifting in the Atlantic Ocean and in the Alpine–western Tethys domain. Therefore, they can be considered to represent the first reactivation of the Variscan fabrics of the URSZ.

Tertiary rifting

The distribution of the Tertiary sediments in the URG (Doebl 1967, 1970; Schumacher 2002) suggests that the

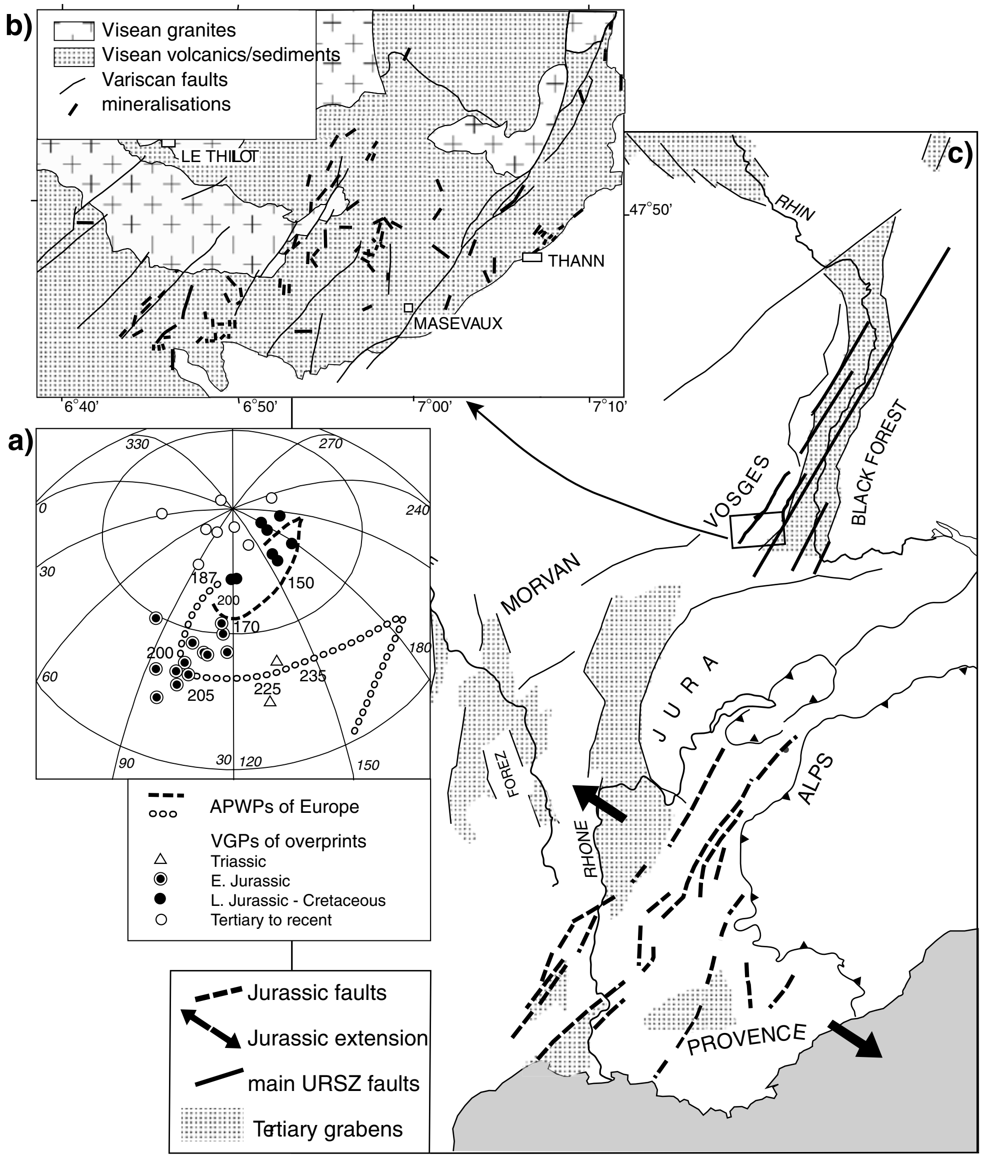


Fig. 9 **a** Virtual geomagnetic poles of overprints recorded in Visean volcano-sedimentary rocks of the southern Vosges basin (after Edel et al. 1997 and unpublished poles). Ages of poles are in Ma. **b** Distribution of post-Triassic polymetallic veins in the southern Vosges Mountains (after Edel et al. 1997). **c** The main faults of the Upper Rhine Shear Zone and the normal faults active during the Jurassic NW–SE extension (after Lemoigne et al. 2000)

pre-existing structures controlled the rifting, particularly in the Late Eocene and Early Oligocene (Fig. 10). The Late Eocene sediments were deposited in three elongated basins, the Mulhouse, Strasbourg, and Rastatt basins that occupy three parallel Variscan strike-slip zones (Fig. 10a). The succession of major N30° trending faults, i.e., the Kreuzweg Fault, the SMMF, and the Ognon Fault, within the Variscan basement of the VM, appear to represent a southern extension of the NE trending Strasbourg Basin (Fig. 10a). This relation is also represented by a narrow Tertiary graben, which extends along the northern SMMF zone (P. Fluck, oral communication).

The N–S regional compression during the Eocene was expressed by NE–SW sinistral, and NW–SE dextral strike-slip displacements, observed along the borders of the graben (Bergerat 1985; Villemin and Bergerat 1987). The N–S orientation of the principal stress axis σ_1 is favorably oriented to reactivate the NE–SW trending Variscan strike-slip faults in a sinistral mode. Association of these NE–SW wrench faults with N–S faults, which can also be observed in the gravity and magnetic maps (Figs. 2, 3, 4), resulted in the formation of pull-apart basins. The Strasbourg and Rastatt basins in particular, resemble pull-apart basins associated with a releasing bend along a sinistral strike-slip fault (Fig. 10a; Price and Cosgrove 1990). Schumacher (2002) also suggested that during the Late Eocene rifting phase, pull-apart basins originated in the URG. He proposed that the formation of these basins was controlled by ENE–WSW trending Permian-Carboniferous structures. However, we note that this hypothesis requires

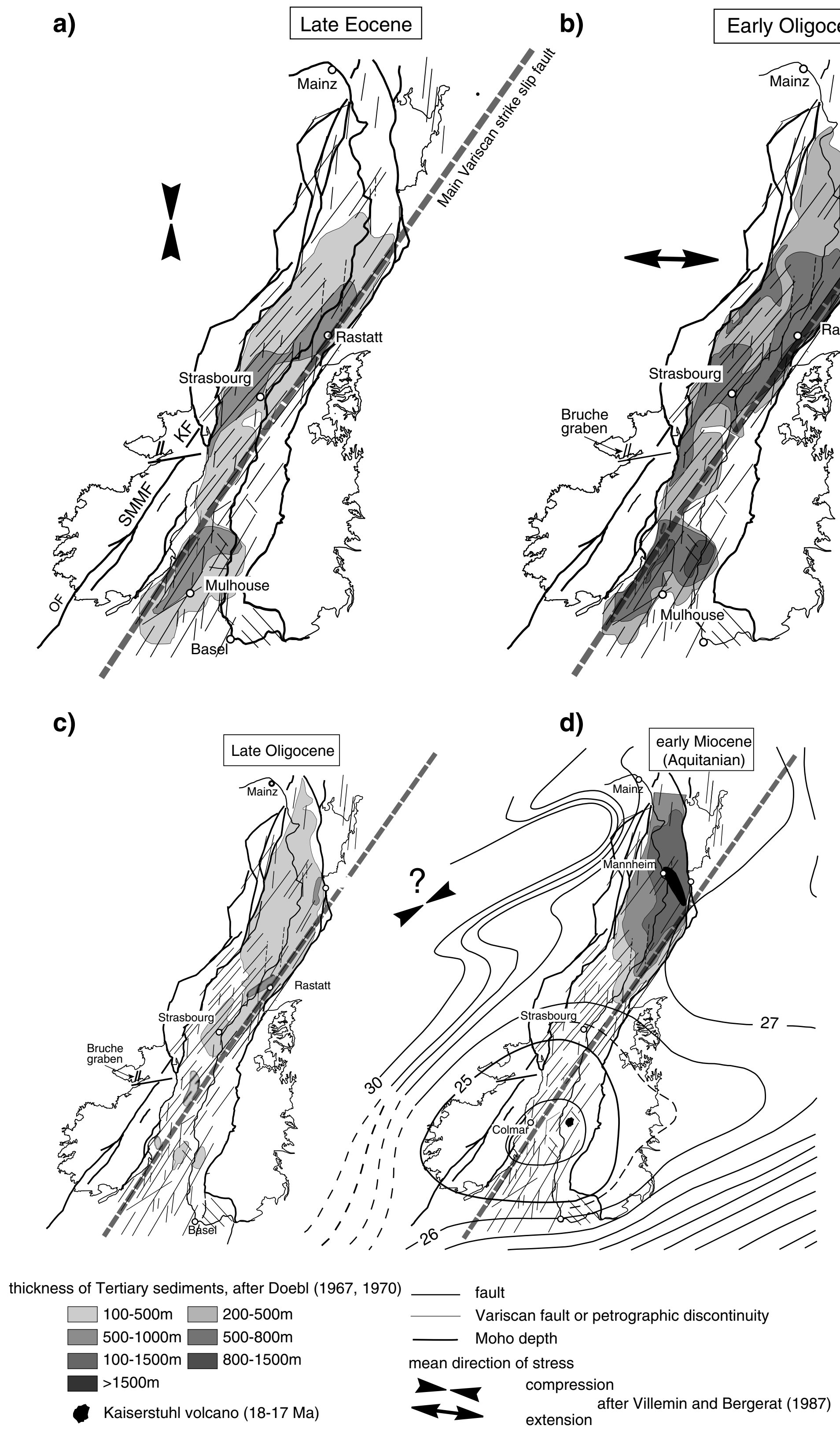


Fig. 10 Isopach maps of the **a** Late Eocene, **b** Early Oligocene, **c** Late Oligocene, and **d** Early Miocene, after Doebl (1967, 1970), with the basement discontinuities derived from gravimetric and magnetic maps. The mean direction of stress is taken from Bergerat (1985) and Villemin and Bergerat (1987). The isobaths of the crust–mantle boundary are after Edel et al. (1975), modified using the results of deep seismic reflection studies (Lüschen et al. 1987; Brun et al. 1991; Wenzel and Brun 1991)

a NNE–SSW oriented σ_1 stress axis during the Late Eocene, which is not consistent with the results of the paleostress analysis by Bergerat (1985).

During the Oligocene extension, characterized by E–W oriented σ_3 axis (Bergerat 1985; Schumacher 2002), N–S striking normal faults developed in the URG. However, the N30–35° trending Variscan faults could have also been reactivated as oblique faults with normal and sinistral strike-slip components (Fig. 10b). The Early Oligocene isopach map shows that the thickest sediments are along the N35° striking Rastatt trough and the western potash basin, the axes of which coincides with the major Variscan strike-slip fault (Figs. 1, 9b). It demonstrates the likelihood of Oligocene reactivation of major NE–SW trending Variscan discontinuities.

The Early Miocene is marked by important changes of the tectonic regime in western Europe and the western Mediterranean, including the URG area. The convergence of the Africa and Europe plates led to the anticlockwise rotations of the Southern Alps, Corsica-Sardinia, the Apennines and the Transdanubian microblock, and to the associated anticlockwise rotation of the principal direction of stress observed on the European platform (Illies 1978; Lowrie and Alvarez 1975; Van den Berg 1979; Marton 1987; Montigny et al. 1981). This rotation was quite rapid, and was achieved, most probably, at 18–17.5 Ma (Edel et al. 2001). The pole of rotation was located north of Corsica, in the Ligurian Sea, resulting in a westward motion of the southern and western Alps. The formation of arc shaped western Alps, and the newly established compressional stress recorded in the southern URG (Laubscher 2001; Giamboni et al. 2004; Rotstein et al. 2005a, b), appear to be the results of rotations and westward movements of these blocks. We note that the Kaiserstuhl volcano was likely emplaced over the crest of the upper mantle high during the rotation. During the same period, and possibly also more recently, the southern URG was uplifted, resulting in widespread erosion and migration of the depocenter to the north (Illies 1967; Sittler 1969; Schumacher 2002).

Illies (1974) suggested that both the reactivation of pre-existing basement features, and the Eocene–Oligocene URG rifting, were associated with the uplift of the crust and the upper mantle. This is supported by the elevated Moho topography (Fig. 10d), which is greater than the 1–1.5 km lithospheric doming that was attributed to the Alpine flexural bulge (Gutscher 1995). Nevertheless, the remaining Moho topography seems to reflect two distinct contributions. First, it is likely the large-scale NNE–SSW striking Moho ridge illustrated by the 27 km isobath, which is associated with Eocene–Oligocene rifting. Only the part of the URSZ that coincides with this area of elevated Moho exhibits features related to reactivation of NE–SW oriented Variscan fabric during Eocene–Oligocene. The northeastward continuation of the URSZ beyond the OM, which is not located on the Moho ridge, was not reactivated. Second, the additional dome which culminates beneath the southern URG at about 24 km depth is, probably, not associated with the Eocene–Oligocene rifting, but rather with the post-Oligocene uplift as suggested in Fig. 10d. The spatial correlation between the Moho dome, the erosion in the southern URG, and the migration of the depocenter northward, indicates that all these events might have been related to each other.

Late Miocene–Recent reactivations

In the Late Miocene, the continuing Africa–Europe convergence caused another phase of compression in the URG, affecting mainly the Jura fold belt, with a NW–SE oriented stress axis σ_1 (Bergerat 1985; Villemin and Bergerat 1987; Laubscher 2001; Schumacher 2002; Giamboni et al. 2004). This stress regime lasted up to the Recent and is constrained by focal mechanisms of earthquakes (Ahorner 1975; Bonjer et al. 1984; Bonjer 1997; Plenefisch and Bonjer 1997), and by in situ stress measurements (Illies and Greiner 1979). Maximum seismic activity occurred in the southeast URG, mainly along N10° trends (Fig. 10a, b). In the same area, the focal mechanisms indicate predominant sinistral strike-slip motions along N–S to NNE–SSW striking alignments of epicenters (Fig. 11b). Focal mechanisms west of Freiburg show extension associated with N130–150° trending faults. Farther north, in the Heidelberg–Mannheim Basin, the normal faulting is also indicated by the earthquake source mechanisms (Fig. 11b). Both areas correspond to Pliocene–Quaternary basins (Bartz 1974), exhibiting a NNW–SSE trend, compatible with faulting planes of the focal mechanisms. In addition, a few focal mechanisms suggest that reversed faulting with a NE–SW trend occurs in the southernmost part of the URG. All of these observations are consistent with a NW–SE direction of σ_1 stress axis (occasionally with steep inclination), and with a NE–SW direction of σ_3.

However, several focal mechanisms show N–S to NNW–SSE directions of the σ_1 axis, which deviate from the general trend. The most important are the Sierentz earthquake swarm (Rouland et al. 1980; Event no. 1 in Fig. 11c), an earthquake on the SMM Fault (Plenefisch and Bonjer 1997; Event no. 2 in Fig. 11c), and the Rastatt earthquake (Ahorner 1975; Event no. 3

in Fig. 11c). These have a strike-slip mechanism, but with a N30–35° strike, parallel to the pre-existing Variscan faults. All three foci appear, therefore, to be located on N30–35° trending Variscan structures. With the exception of the Sierentz main shock, these events also have a component of reverse faulting that suggests transpression. Pure strike-slip movement in the Sierentz earthquake is possible, provided the Variscan fault was vertical, while the σ_1 stress axis was horizontal. In general, the Variscan structures in the URG basement seem to still play an important role in the present day tectonics.

Discussion and conclusions

In order to discuss the processes of tectonic reactivation, it is important to consider the geometry of pre-existing structures, and the mechanical properties of the deformed crust. These can be depicted from the style of tectonic rejuvenation, which is represented either by zone of reactivation, or by zone of complete reworking of pre-existing fabrics (Holdsworth et al. 2001a). The reactivation is manifested by the development of breccias and cataclasites, or by localized shear zones represented by zones of mylonites (Schmid and Handy 1991). On the other hand, the crustal reworking is related to complete obliteration of pre-existing fabrics.

The URSZ as a lithosphere scale discontinuity

It appears that the first major event that shaped the tectonic fabric of the URG was the Variscan deformation. During the Visean, a major part of the future URG was part of a 40 km wide and 400 km long transcurrent zone, which had a N30–40° trend, and shifted the pre-Variscan and early Variscan structures in a left lateral sense. We suggest that this zone of heterogeneous deformation created a crustal-scale discontinuity along which all previous fabrics were reworked. The alternations and spacing of magnetic and gravity anomalies indicate steeply inclined boundaries of the lithological units. This pattern is confirmed by field observations in the northern VM, OM and BFM.

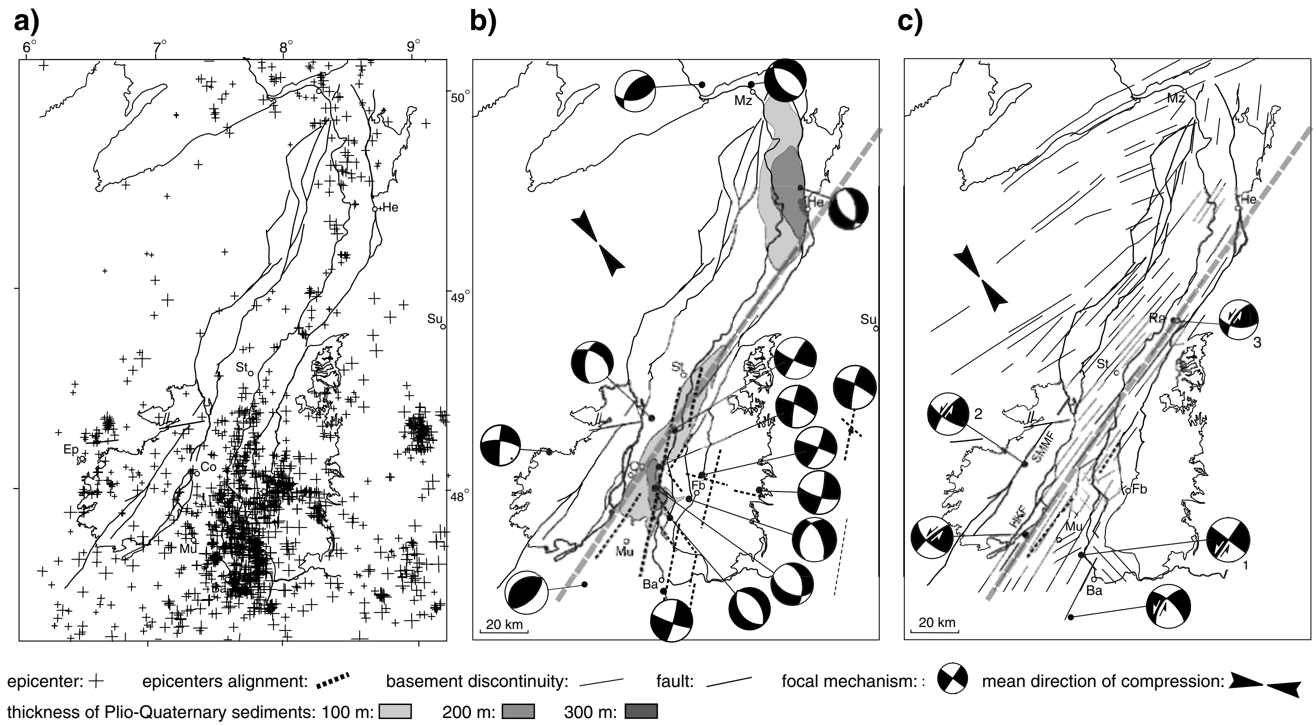


Fig. 11 Seismicity of the Upper Rhine Graben: **a** map of epicenters from Réseau National de Surveillance Seismique and from Bonjer et al. (1984). **b** Thickness of Pliocene–Pleistocene sediments (after Bartz 1974), alignment of epicenters, and selected focal mechanisms reflecting the present tectonic activity (taken from Ahorner 1975; Bonjer et al. 1984; Bonjer 1997; Plenefisch and Bonjer 1997). **c** Focal mechanisms of reactivated Variscan faults and of faults constrained by Variscan anisotropy of the crust. The mean direction of stress is derived from in situ measurements of stress (adapted from Illies and Greiner 1979), and microtectonic analysis (adapted from Villemin and Bergerat 1987). *Ba* Basel, *Mu* Mulhouse, *Co* Colmar, *St* Strasbourg, *Fb* Freiburg, *Ra* Rastatt, *He* Heidelberg, *Ma* Mainz, *Su* Stuttgart

Large-scale faults (SMMF; HKF) appear to be the surface brittle–ductile products of deeply rooted zones of continental reworking. The Late Visean granitoids used these zones of weakness during their emplacement, and contributed to thermal rejuvenation of the existing crust (Handy et al. 2001). Therefore, we interpret the Visean wrenching period as a tectonic event of primary importance, responsible for significant thermal and mechanical reworking of the URG domain. The orogenic fabrics in the studied area satisfy the criteria of continental reworking as defined by Holdsworth et al. (2001a, b) and we suggest that this event is likely to have led to the development of subvertical mechanical anisotropy at crustal scale.

The seismic tomography studies in the investigated area (Glahn and Granet 1993; Lopez Cardozo 2003; Lopez Cardozo and Granet 2003) showed the existence of NE–SW trending structures at a depth range of 25–50 km, roughly parallel to the URSZ. The orientation of these structures reflects the anisotropy of the Moho refracted Pn (Bamford 1977), and suggests that this fabric corresponds to the localized deformation in the mantle that took place during the Variscan orogeny. Hence, the sub-crustal, upper lithospheric mantle fabrics in the URG are geometrically consistent with those in the crust, as shown in this study. This indicates the existence of a shear zone of lithospheric magnitude, as described and documented in other areas (e.g., Vauchez and Nicolas 1991).

Temperature, rheology, and mechanical anisotropy as principals controls of reactivation

It is also important to consider the thermal state of the crust and burial depth of Variscan rocks during the subsequent stages of reactivation. The crust of the URG and the VM, OM, and BFM were covered by Permian sediments, indicating that all of this area was close to the surface shortly after the end of the Variscan orogeny. In addition, the period of cooling between Visean tectonism and magmatism, to the onset of Tertiary extension, is quite long (ca 300 Ma). This suggests that the crust must have cooled down prior to the beginning of tensional stress, even for a very high post-orogenic geotherm (e.g., Cloetingh and Burov 1996). Based on these considerations, we suggest that the URG crust was rigid and brittle during all of the subsequent stages of Mesozoic and Tertiary deformations. This conclusion is also consistent with the exclusively brittle deformations in the URG, which result in the development of faults, slicken side surfaces, and zones of cataclasites (e.g., Bergerat 1985).

A cold geotherm favors the high necking depth, and the control of the rifting process by deep mantle rheology (Cloetingh et al. 1995). The rifting in the URG was most likely controlled by brittle Byerlee type behavior, exploiting both crustal and mantle mechanical anisotropy parallel to the URSZ. This mechanism is mostly similar to the models proposed for the development of other Cenozoic basins in central and western Europe, namely the Eger Basin in the western part of the Bohemian Massif (Babuska and Plomerova 2000), and the Limagne Graben in the eastern French Massif Central (Babuska et al. 2002). These works demonstrated that the sub-crustal structure of the lithosphere gave rise to a zone of mechanical predisposition for the formation of Tertiary grabens. The present study suggests that the mechanical anisotropy at crustal level plays a similar, or even a more important role in the mechanical predisposition for future rifting, than the structural anomaly in mantle lithosphere.

It is also likely that the Tertiary–Recent elevation of the mantle has been associated with a substantial increase in heat flow in the URG (Kahle and Werner 1980), but did not substantially modify the rheological behavior of the Variscan upper crustal fabric. Therefore, the mechanical properties, and geometry of steep pre-existing structures, controlled the frictional mode of deformation in the studied zone of reactivation during the Late Tertiary and up to Recent.

Role of fabric geometry in the Tertiary–Recent reactivations

As shown by Vauchez et al. (1997, 1998), the mechanical anisotropy is the source of the so-called tectonic inheritance manifested by systematic reactivation of ancient tectonic directions. These authors also discussed the issue of tectonic inheritance, which may explain preferential rift propagation in the interior of continental plates. There exists a remarkable difference between the magnetic and gravity patterns inside and outside the URSZ (Fig. 2; Edel and Weber 1995). The majority of the gravity and magnetic anomalies in the southern and central VM and BFM, generally show E–W to ESE–WNW trends, in contrast to the NNE–SSW trends of magnetic and gravity anomalies inside the URG. The field observations of structures and orogenic fabrics in the southern part of the Variscan crystalline complex, also show roughly E–W trends. Such orientation of crustal fabrics is not favorable for reactivation during the compressive, N–S trending, Late Eocene or E–W trending Oligocene tensional stresses, because of no, or very low resolved shear stress on these surfaces. However, as discussed here, the fabric trends of the URSZ are appropriate for reactivation, because of their high resolved shear stress, which could have been building up on these planes during the Eocene and Oligocene compressional and tensional loads (Fig. 9a, b). Therefore, we assume that arc shaped, NE–SW trending URG in the studied area is most likely a product of the mechanical predisposition. In contrast, the N–S trends in the southern part of the graben, most likely reflect tensional failure mode, without reactivation of pre-existing anisotropy (Fig. 1). Progressive deposition of sediments from the Late Eocene to the Early Oligocene is compatible with wrench-dominated reactivations of pre-existing mechanical anisotropy only in the URG. However, since the Late Oligocene, the reactivation is less significant, due to the fact that compressive stress becomes oriented at a very high angle (Miocene to present, Fig. 10) to the URSZ fabrics.

It is important to consider the existence of inherited mantle anisotropy underneath the URG (Lopez Cardozo 2003), which may potentially correspond to strong olivine fabric in the direction of the URSZ. However, data on mantle tomography are not yet sufficiently detailed, and further research is needed to confirm the close relationship, and possible coupling between the mantle and the crustal fabrics in the URG.

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