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Kinematic analysis of the Upper Rhine Graben boundary fault system

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Abstract

This paper presents a new set of kinematic data for the central part of the Upper Rhine Graben. Fault slip measurements were gathered covering the near field of a 200-km-long segment of the graben boundary faults, on both sides. The resulting kinematic analysis shows a strong predominance of strike-slip faulting and some oblique-slip and pure normal faulting. Overall, there is a regional coherence in the orientations of the extensional and shortening axes associated with both types of faulting throughout the entire study area. The data set is best interpreted as the result of more or less continuous, sinistrally transtensive kinematics with a NW–SE to NNW–SSE oriented, or subvertical shortening, and a NE–SW to E–W oriented extensional direction. Local transpressive overprints are not reflected in the pattern of brittle deformation in the near field of the boundary fault system. We conclude that the opening history of the Rhine Graben may be less complex than hitherto assumed.

Keywords: Upper Rhine Graben; rift; Kinematics; Deformation; Tertiary

1. Introduction

The Upper Rhine Graben is an approximately 300-km-long continental rift situated in the central European Alpine foreland (Fig. 1) and its development is closely linked in space and time with the development of the European Cenozoic Rift System and Alpine orogeny (e.g. Ziegler, 1992; Michon et al., 2003; Dèzes et al., 2004). The graben is the result of continental extension beginning in the Late Eocene. The climax of the rifting process was reached in the Early Oligocene (e.g. Illies and Greiner, 1978; Schumacher, 2002), but major subsidence and filling of the rift basin continued through the Neogene and into the Quaternary in the northern half of the graben. Subsidence in the southern half of the Upper Rhine Graben ceased in the Neogene and was followed by widespread uplift and erosional truncation of its syn-rift fill. Locally, however, up to 250 m of sediments were deposited in tectonically controlled basins in the southern Upper Rhine Graben in the Quaternary. Today the Upper Rhine Graben boundary faults are thought to operate in a left lateral strike slip sense under NW–SE oriented compression (e.g. Illies and Greiner, 1979; Plenefisch and Bonjer, 1997). The possible influence of Variscan structural inheritance on the opening of the rift is discussed by Schumacher (2002).

From fault slip analysis and direct inversion of data from the wider area of the European continental platform on both sides of the Upper Rhine Graben, Bergerat (1985, 1987) and Villemin and Bergerat (1987) inferred a complex four-stage development for the graben, with N–S compression in the Late Eocene, E–W extension in the Oligocene, NE–SW compression in the Early Miocene and NW–SE compression from the end of the Miocene until today. This interpretation was largely based on the integration of the Rhine Graben data with other data for the European Platform and the dating of the separate phases is mainly based on observations outside the graben. In contrast, fault slip analysis at the southern termination of the Rhine Graben (Larroque and Laurent, 1987) showed evidence for a more stable stress field, active from Eocene to Miocene times, with N–S compression and E–W extension. An earlier study of stylolites and joints on the eastern side of the graben reflects only one kinematic phase with a dominant N–S to NW–SE compression (Buchner, 1981). More recently Schumacher (2002) integrated the paleo-stress interpretation from Bergerat (1985) with isopach maps of sedimentary deposits in the Upper Rhine Graben, essentially reproducing the complex, multi-stage opening history of the graben discussed above. On the other hand, the results of recent retro-deformation studies of the southern Upper Rhine Graben (Behrmann et al., 2003; Bertrand et al., 2005; Cornu and Bertrand, 2005) showed that deformation there cannot be adequately restored unless

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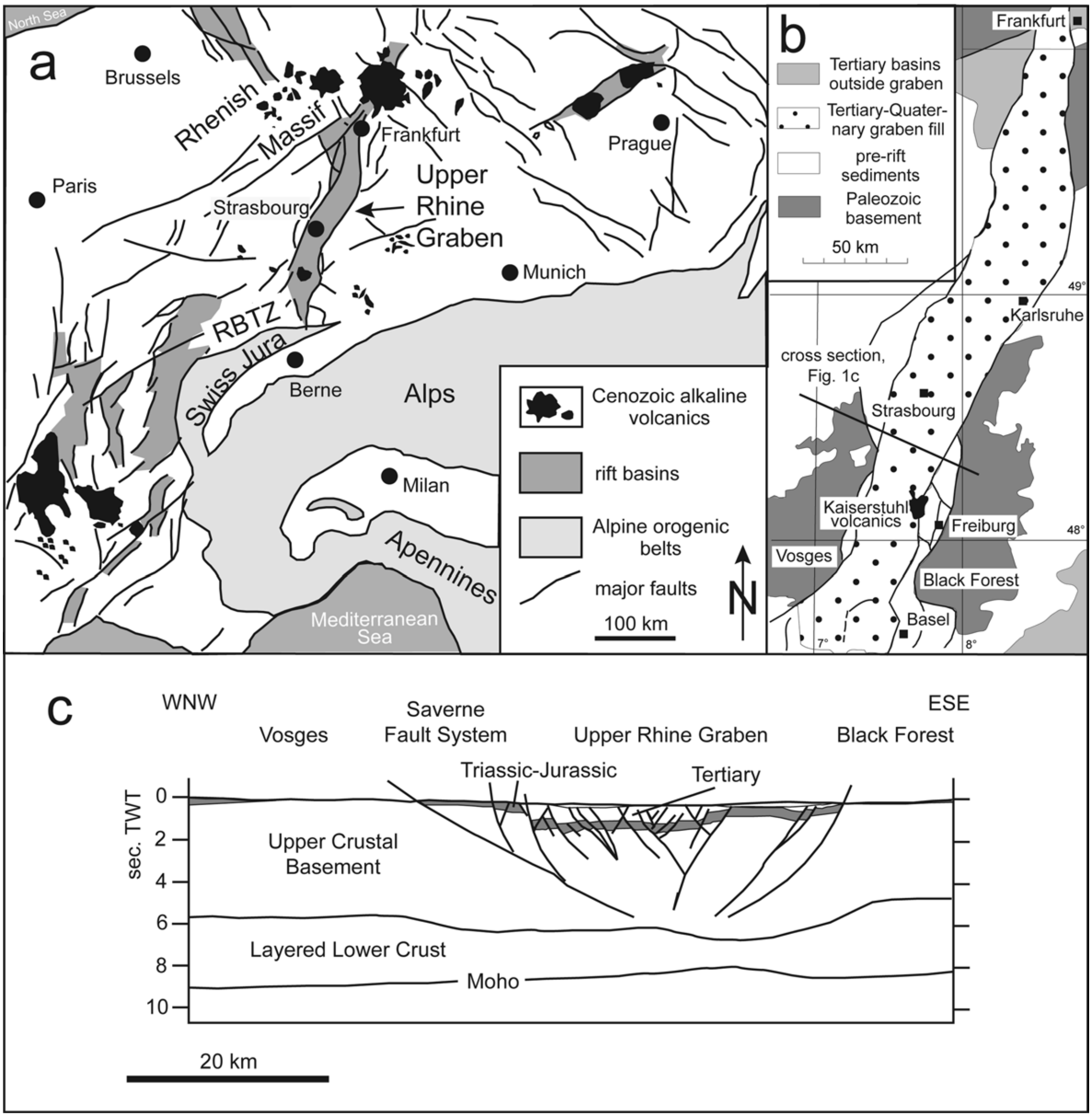

Fig. 1. (a) The position of the Upper Rhine Graben in the European Cenozoic Rift System as described by Ziegler (1992). RBTZ denotes the location of the Rhine–Bresse Transform Zone. (b) Geological sketch of the Upper Rhine Graben and the flanking Vosges and Black Forest mountains. (c) Interpretation of DEKORP-ECORS deep reflection seismic profile (cf. Brun et al., 1992). Figure modified after Behrmann et al. (2003).

a sequence of movement vectors on faults oriented N 80°E to N60°E is applied.

Therefore, there is an active debate on the opening history of the Upper Rhine Graben. Discrepancy exists between the results of kinematic and sequential retro-deformation modelling of the pre-rift series, which show a relatively stable orientation of the extensional axes, and the published paleostress and basin configuration-based interpretations, which indicate a more complex development. A comprehensive analysis of brittle deformation data from the near field of the principal boundary faults of the Upper Rhine Graben has not yet been attempted. Such data have the potential to contribute valuable information on the kinematics of these structures that locate most of the strain associated with the rifting. Therefore, the study reported here was undertaken with the aim to collect all available mesoscopic fault-slip data in order to test the different hypotheses regarding kinematics of faulting and stress field evolution of the rifting. We suppose that in contrast to a simple, continuous kinematic evolution, a complex multistage history should have left a complex overprint and find its expression in corresponding mesoscopic fault patterns and overprinting structures.

2. Methodology

We have concentrated on the kinematics of the boundary faults of the Upper Rhine Graben, where structures are spatially continuous and their geometry is clearly defined. We decided not to include the areas near the northern and southern terminations (Fig. 1) where the fault system abuts against the Rhenish Massif and the Swiss Jura, both areas of young and active deformation themselves. At least for the southern end of the Upper Rhine Graben, the eastern termination of the Rhine–Bresse Transfer Zone (RBTZ; Fig. 1a) and the Swiss Jura thrust front a very complex kinematic interaction in time and space was recently documented by Giamboni et al. (2004), Ustaszewski (2004) and Ustaszewski et al. (2005). The bearing of these data on the understanding of the kinematics of the Upper Rhine Graben will be briefly discussed at the end of our contribution.

We have targeted 14 large quarries in the area between Heidelberg and Freiburg on both the eastern and the western sides of the Upper Rhine Graben (Fig. 2). In this way we covered the 200-km-long central part of the graben with spacing in the order of 20–50 km. Most of the quarries examined are situated on or near the two graben boundary faults (eastern boundary fault (EBF) and western boundary fault (WBF) in Fig. 2), near the fault delimiting the Saverne Depression north of the Vosges Mountains and in the piedmont (Vorbergzone) of the Black Forest. Two locations (Merdingen, Badloch) are close to the surface trace of the Rhine River Fault (RRF in Fig. 2), an important structure delimiting the piedmont from the internal part of the graben (cf. Behrmann et al., 2003). Most of the measurements were done in Lower Triassic Buntsandstein outcrops. Some data were collected in Triassic and Jurassic limestones (Wolxheim, Merdingen). The fault slip data from the Kaiserstuhl volcanics (Badloch) document deformation of Mid-Miocene or younger age (e.g. Baranyi et al., 1976; Kraml et al., 1999). To explain the relatively small number of observations we have collected, it needs to be emphasized that the fault slip data from the quarries examined in this study constitute the only coherent data sets to be found in the Mesozoic pre-rift and Tertiary syn-rift sediments in the area investigated by us. Unlike convergent or collisional mountain belts, rifts like the Upper Rhine Graben are areas of subsidence and sedimentation and rocks containing an unambiguous syn-rift deformation record in proximity to the fault system are, therefore, poorly exposed. Moreover, in the case of the Upper Rhine Graben the uplifted rift shoulders mostly consist of Permian sediments and/or yet older basement rocks with a record of intensive brittle deformation of pre-Mesozoic age (e.g. Wickert et al., 1990; Krecher and Behrmann, in press), making it impossible to derive kinematic or paleo-stress interpretations for Tertiary or younger deformation from fault slip data.

All data collected for this study consist of measurements of fault plane–striation pairs. The sense of movement on the plane was defined by shear sense indicators, mainly striations and fibres on fault planes, which were found to be especially well developed in the Buntsandstein. The background of kinematic analysis of faults and shear fractures is extensively discussed in the literature and here we refer the reader to the review of Petit (1987). We collected only one measurement per fault plane–striation pair and only included fault planes with clear shear indicators in the kinematic evaluation, so as to avoid corruption of the data set. However, this means that we may have collected less data per outcrop than other authors. Measurements on faults that did not allow unequivocal derivation of the sense of movement are plotted in Fig. 3, but were not included in the kinematic evaluation presented in Figs. 4 and 5.

The pairs of measurements were then used to construct Angelier plots (Fig. 3). The common extension, intermediate and shortening axes of a population of fault slip data were calculated using the Right Dihedra method (see e.g. Angelier and Mechler, 1977; Pfiffner and Burkhard, 1987). In the Upper Rhine Graben, where the deformation is dominated by pre-existing structures, the Right Dihedra method is considered more appropriate than paleo-stress inversion. Our approach was similar to that chosen by Ustaszewski (2004) and Ustaszewski et al. (2005) and the axes obtained for shortening and extension were checked for coherency with the results obtained with the P–T axes method (Marrett and Allmendinger, 1990). The Right Dihedra method was not used in the evaluation of one outcrop (Neustadt; see Figs. 2 and 3), as there was only one set of normal faults present. For Right Dihedra method calculations, we used a demonstration version of the TectonicsFP program (Reiter and Acs, 2004).

3. Observations

A total of 313 fault plane-striation pairs were measured. For 261 of these, we could derive a reliable sense of shear (Fig. 3). Generally the most comprehensive data sets come from the Lower Triassic Buntsandstein and from the intrusive carbonatites at the centre of the Kaiserstuhl volcano. In most of the outcrops, two or three sets of faults were found. A noteable exception is the Neustadt quarry, where only one NNE–SSW-trending fault set with dominantly normal sense of slip is observed. The Malsch and the Wolxheim data sets are combinations of measurements taken at smaller outcrops situated close to each other.

A dominant sinistral fault set, with a N–S or NNE–SSW trend, is observed in all the outcrops. The normal conjugate situation with a 60° angle between the dextral and sinistral fault sets, where the dextral faults have a NW–SE trend, is observed in the Malsch, the Gueberschwihr and the Koenigsbourg outcrops (Fig. 3). Other dextral fault sets are the ENE–WSW-trending planes found in the Kuhbach and Rothenbach quarries (Fig. 3). Although at an angle higher than 60° with the sinistral set present at the same locations, we suppose that both are cogenetic. Probably the simplest explanation for presence of these unusual dextral fault orientations is that the ENE–WSW orientation corresponds to the structural grain of the Variscan units in the basement underlying the Mesozoic sediments (e.g. Edel and Weber, 1995). Thus, fault reactivation or simply the presence of a strong strength anisotropy provided by the fabric in the basement may be prima causa for the generation of the dextral fault sets.

Approximate dip-slip normal faulting might be overlooked in most of the diagrams in Fig. 3, but plays a significant role in the definition of overall faulting kinematics at the following locations. Some normal faulting on steeply dipping ENE–WSW planes is recorded at Malsch. More abundant normal faulting on E–W- and N–S-trending faults planes is present at Badloch, Merdingen and Wolxheim, and N–S-trending normal

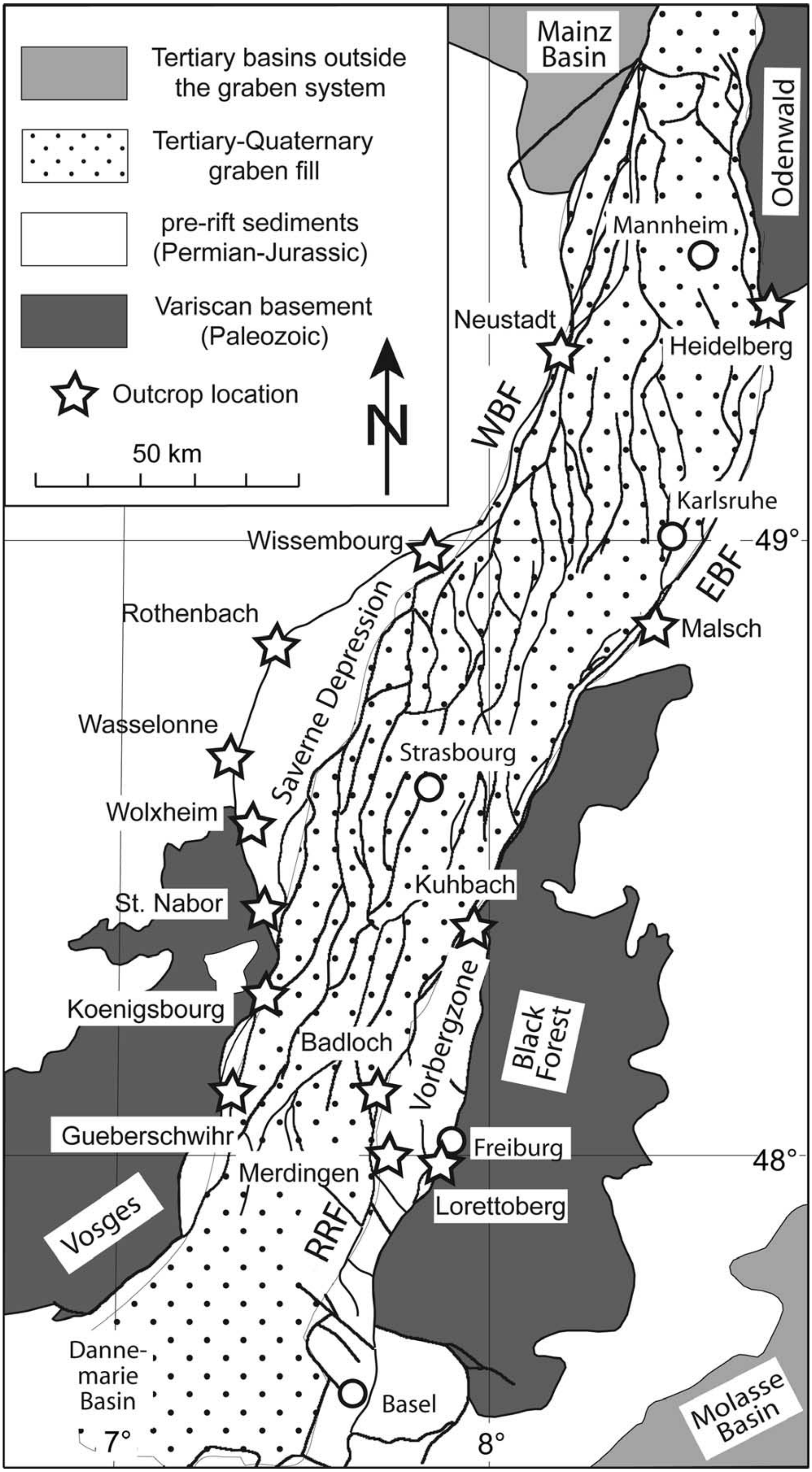

Fig. 2. Geological sketch map of the Upper Rhine Graben showing the fault system and locations (stars) of the outcrops analysed in this study.

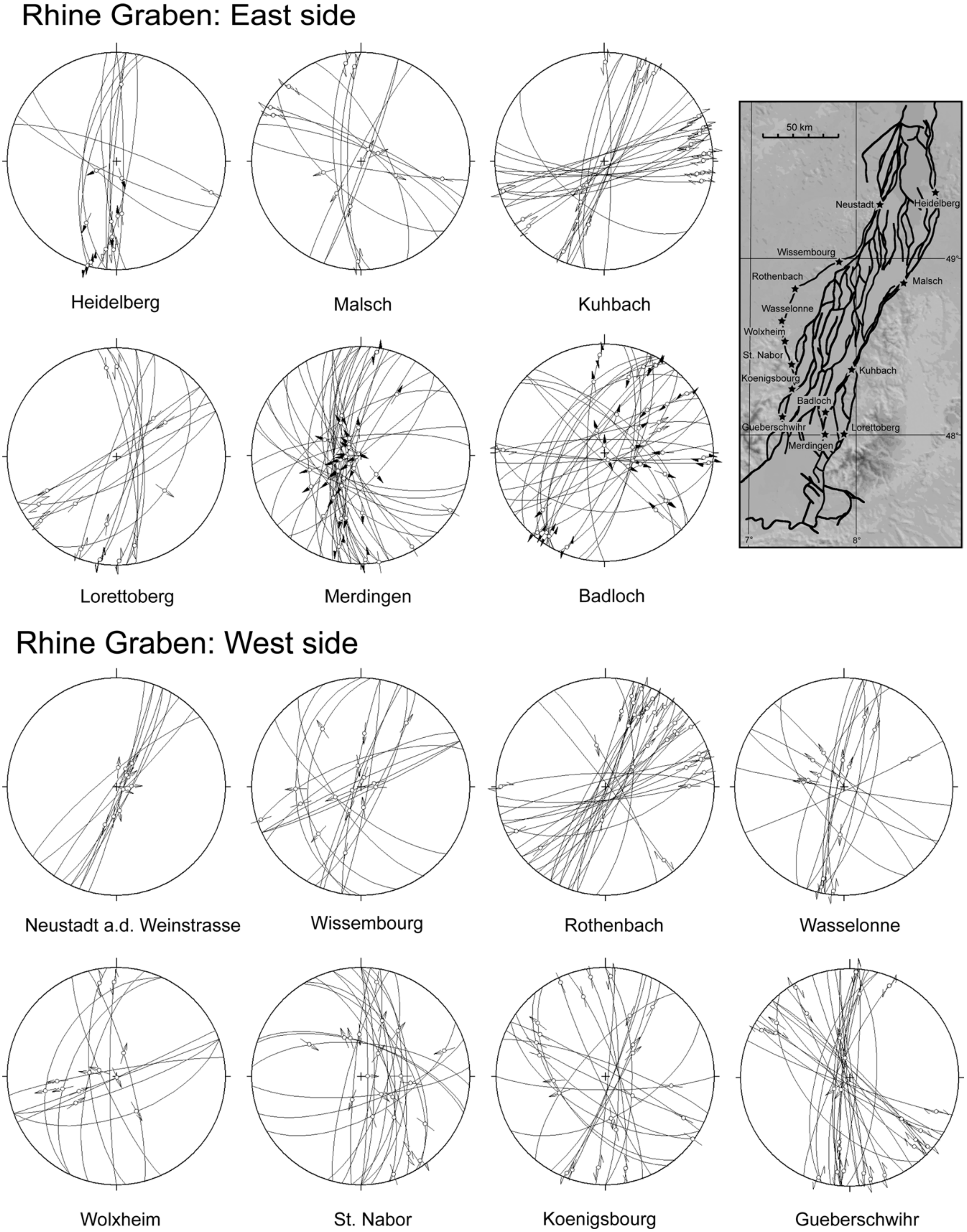

Fig. 3. Angelier plots (lower hemisphere projections) showing the measured fault plane-striation pairs for each outcrop. Arrowheads on striation plunge symbols indicate senses of displacement of hanging wall blocks, pairs of half arrows indicate sense of displacement on strike slip faults, striation plunge symbols without arrows indicate faults on which the sense of displacement could not be determined unequivocally. Number of data at each location is given in Table 1. A dominant NNE–SSW-trending sinistral fault set is observed in most of the outcrops. Note presence of ENE–WSW-trending dextral faults, best observed in the Kuhbach and Rothenbach outcrops. See text for discussion.

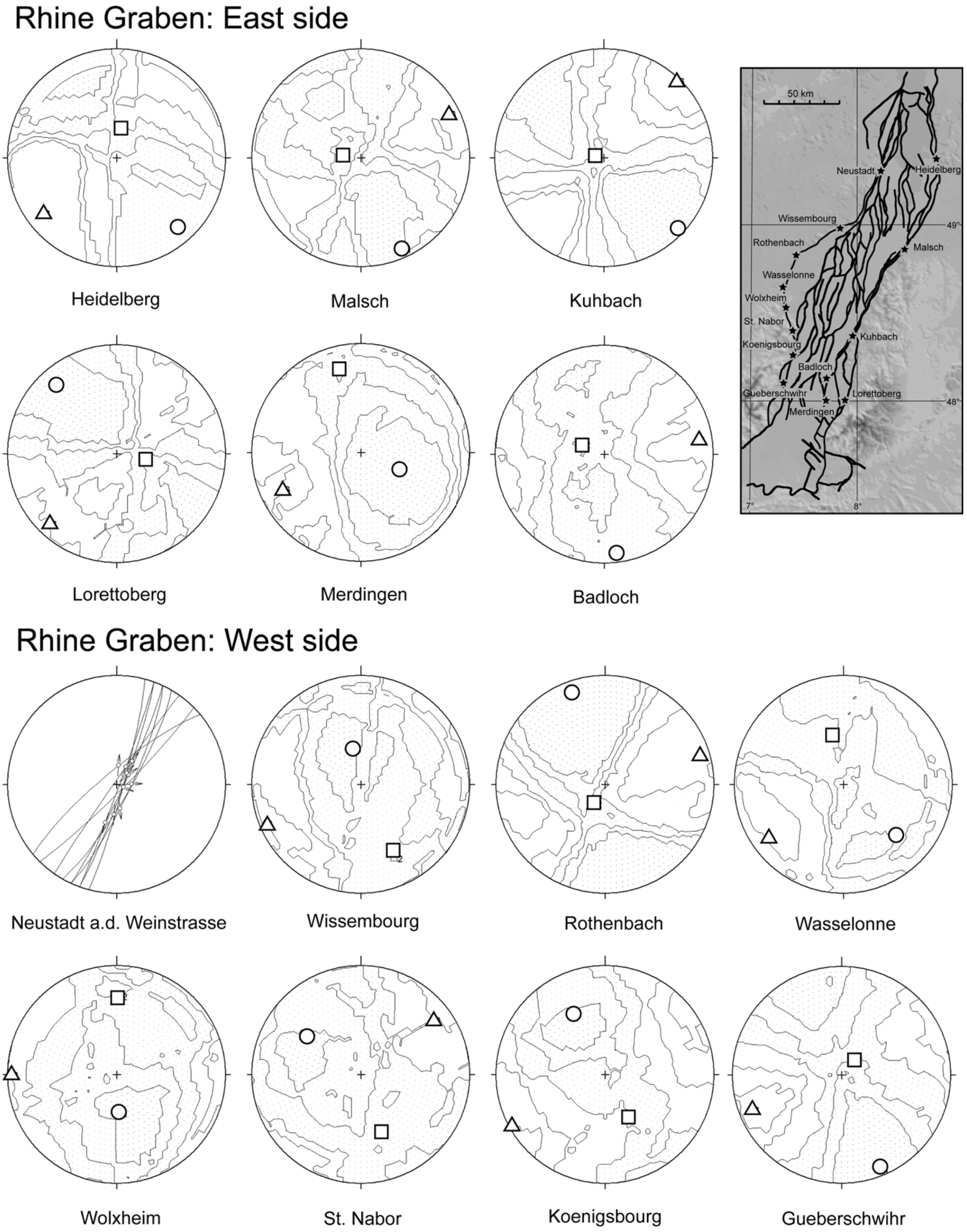

Fig. 4. Right Dihedra method plots (lower hemisphere projections) calculated on the base of the data shown in Fig. 3 (see also Table 1). Note the stable NE–SW to E–W orientations of the stretching axes (triangles). The near horizontal position of the shortening (circles) and stretching axes, observed in most outcrops, shows that strike-slip kinematics prevails. Normal faulting kinematic solutions were calculated for the Merdingen, Wissembourg and Wolxheim locations. For the Neustadt location only one set of faults is observed and no reliable Right Dihedra method calculation could be undertaken. Squares indicate the positions of the intermediate kinematic axes. Contouring according to Reiter and Acs (2004), following the method explained in Angelier and Mechler (1977). Stippled areas denote minima for overlap of tensile quadrants derived from the individual pairs of measurements.

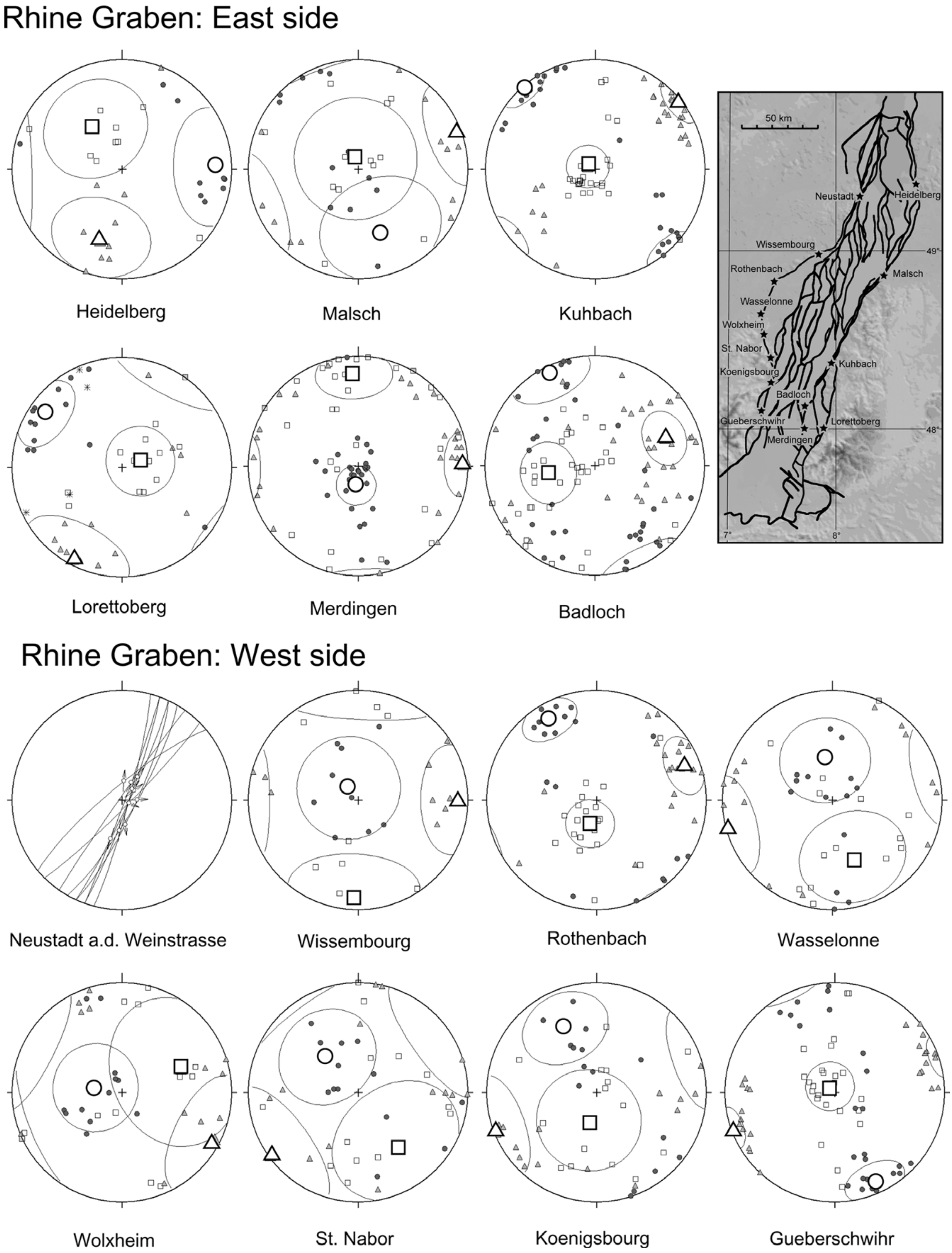

Fig. 5. P–T axes for the measured faults, calculated using the method of Marrett and Allmendinger (1990). Small circles around the mean kinematic vectors P, T and B show the confidence cones of 99% significance. Note the coherence for most of the outcrops between the mean orientations for the P (circles), T (triangles) and B (squares) axes and the positions of the shortening, intermediate and extensional axes resulting from Right Dihedra method (Fig. 4).

faults occur at Wasselonne. An exception is formed by the normal faulting observed in the Wissembourg outcrop, with fault dips of some 40°.

One important observation is the almost complete absence of clear overprinting relationships between fault sets of apparently different kinematics. Even though we were aware that other authors did distinguish up to four different phases of faulting and related them to changing paleo-stress conditions (Bergerat, 1985, 1987); this is something we are unable to reproduce in our field observations. Overprinting of normal faulting on strike-slip faulting was only observed in the Badloch and Merdingen quarries, the two locations near the Rhine River Fault (RRF; Fig. 2) in the interior of the graben. In the case of Badloch the faulting must be of Miocene or younger age, constraining a maximum age for the overprinting sequence here. Badloch has a small subset of dip-slip faults and at Merdingen there are only few strike slip faults (Fig. 3). In the kinematic analysis (see below) we chose not to separate the fault populations for this reason, but note that a normal-slip after strike-slip sequence may be something diagnostic for the Rhine River Fault. Care has to be taken, however, as the constraints on timing of the faulting at Badloch do not apply to the Merdingen data.

4. Results of kinematic analysis

The Right Dehedra method could be applied to 13 of the 14 locations. Results are documented in Table 1 and shown in Fig. 4. The best-defined solutions were obtained for those sites where the measurements clearly divide into fault sets. Examples for this are the Kuhbach, Rothenbach and Gueberschwihr locations. However some sites with less data (i.e. Malsch, Wissembourg) and sites with a large range of azimuthal distribution of fault orientations (Badloch, Merdingen) also give interpretable results.

Clear strike-slip solutions with axes of compression in a NNW–SSE to NW–SE orientation are evident in the majority of the sites. On the eastern side of the Upper Rhine Graben these are Heidelberg, Malsch, Kuhbach, Badloch and Lorettoberg and on the western side Rothenbach and Gueberschwihr. Deviations from kinematic solutions showing Andersonian-type faulting are shown by the oblique-slip solutions at Wasselonne, Koenigsbourg and St. Nabor and the normal faulting on a set of very steep planes at Neustadt. From the Neustadt data, a roughly ESE–WNW extension direction can be derived qualitatively. Bedding is not strongly tilted in the area, thus secondary rotation of the faults is not very likely. Approximate normal-faulting solutions were obtained for Merdingen, Wissembourg and Wolxheim.

A second set of results (Fig. 5) was obtained using the P–T axes method (Marrett and Allmendinger, 1990). The obtained axes for shortening and extension are mostly coherent with the results obtained from the Right Dihedra method and are shown in Fig. 5. Very good coherency between the two methods exists in the Kuhbach, Badloch, Lorettoberg, Rothenbach, Koenigsbourg and Gueberschwihr outcrops. Only in the Heidelberg and Wasselonne outcrops are solutions somewhat different. Not surprisingly, these are the outcrops where the data sets are small. At Wolxheim, with the smallest dataset, no coherent kinematic solution was found with the P–T axes method.

A rather constant pattern of NE–SW to E–W orientations of the extensional axis can be derived over the entire area from our data and evaluations (Fig. 6). The positions of the interpreted shortening axis are mostly close to horizontal, with a general NW–SE to NNW–SSE orientation. Three locations show overall normal faulting kinematics with a sub-vertical shortening axis (Merdingen, Wolxheim and Wissembourg). Interestingly, this is in those areas where the boundary fault systems of the graben show partitioning of displacement into several major structures, i.e. the Saverne Depression and the piedmont zone (Vorbergzone) delimited by the Rhine River Fa near Freiburg (see Fig. 2).

5. Discussion

We have focused on the planes with reliable shear indicators and thus obtained a relatively small but robust data set. The measurements were taken in quarries close to the two Rhine

Table 1
Results of kinematic analysis for each outcrop. Axis 1–3 = principal axes of finite strain, obtained from Right Dihedra method calculations. *N* = number of measured fault plane-striation pairs, *n* = number of faults with unknown sense, n.c. = not computed. See text

Outcrop	Axis 1 (shortening)	Axis 2 (intermediate)	Axis 3 (stretching)	*N*	*n*
Heidelberg	139/17	006/66	234/17	13	4
Malsch	155/09	283/75	063/12	33	1
Kuhbach	133/07	290/82	043/03	27	1
Badloch	173/10	295/72	081/15	33	0
Lorettoberg	318/17	101/69	224/12	15	0
Merdingen	113/61	347/18	249/22	33	5
Neustadt	n.c	n.c	n.c	10	2
Wissembourg	349/62	156/27	248/06	18	9
Rothenbach	334/14	200/70	068/14	32	11
Wasselonne	134/33	346/52	235/15	15	1
Wolxheim	175/61	002/28	270/03	12	0
St. Nabor	306/40	161/44	052/18	21	8
Koenigsbourg	335/34	135/55	238/09	24	9
Gueberschwihr	157/08	037/75	249/13	27	1

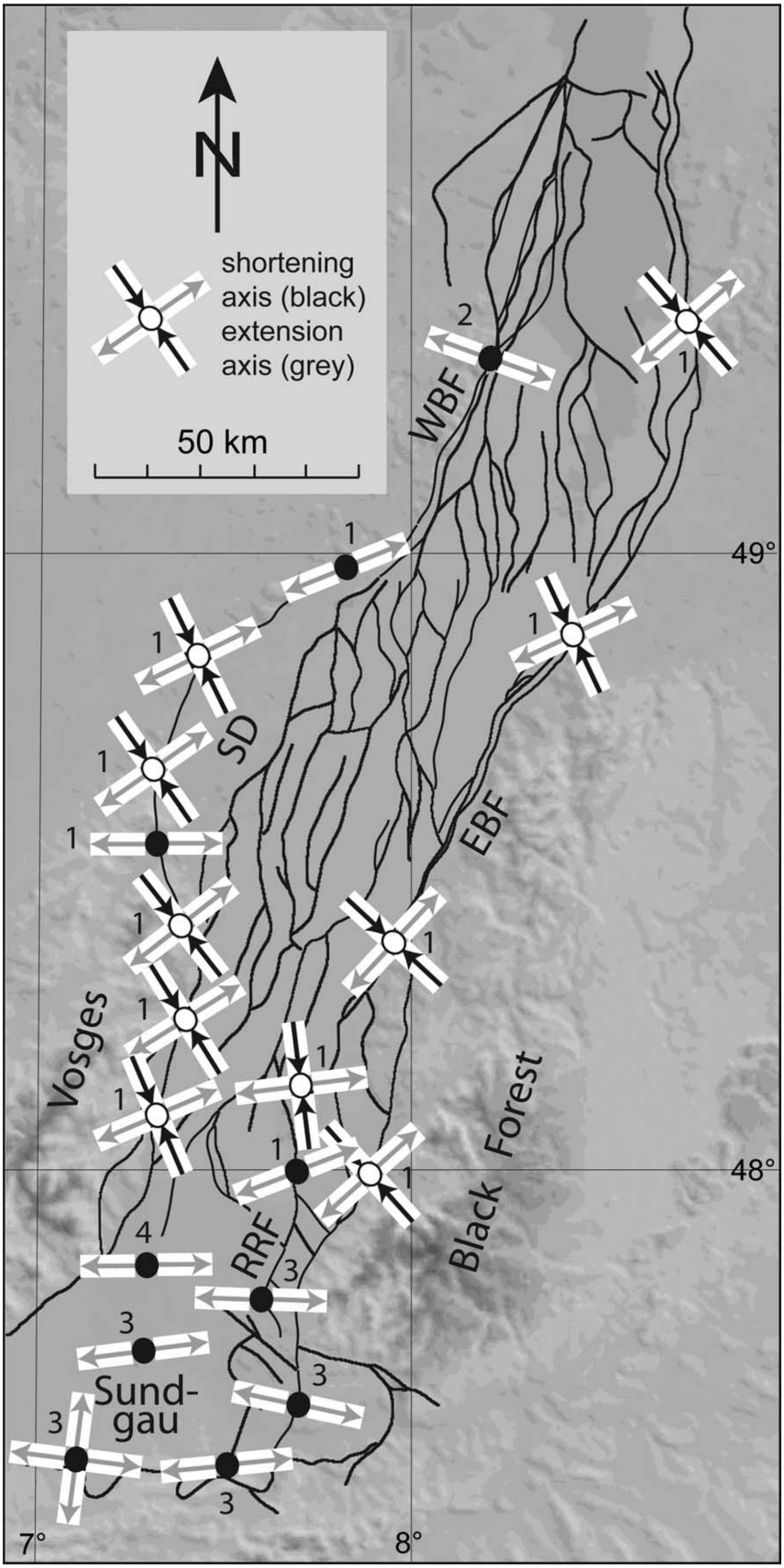

Fig. 6. Geological sketch map of the Upper Rhine Graben showing (1) the results of the Right Dihedra method calculations (Fig. 4 and Table 1). Stretching and shortening axes represent the barycenters of the shortening and extension sectors derived from the Right Dihedra method. Open circle symbols show sub-vertical

Graben boundary fault zones and the important Rhine River Fault in the graben interior. By documented offset of strata at depth, movement on all these faults is known to have large normal components (in most parts much larger than 1 km; see e.g. Behrmann et al., 2003; Bertrand et al., 2005). It is therefore striking to see that in our observations the kinematic signature of strike-slip faulting prevails. In addition most of the observed normal movement seems to have been accommodated on very steeply dipping planes, giving some hint as to an a priori strike-slip or oblique-slip nature of these structures. If the assumption often made is correct that fault patterns have self-similar geometries (e.g. Hirata, 1989; Barton and Zoback, 1992), then the geometrical properties of smaller-scale fault systems in the near field of larger-scale structures should indeed be a reflection of their orientation and kinematics. If so, we have to propose that the fault pattern defining the Upper Rhine Graben must have originated as fractures with a significant strike-slip component and essentially operated in this mode since their formation. As the Upper Rhine Graben can be considered as a low-strain, low displacement rift (e.g. Groshong, 1996) with a ductile master décollement zone within the lower crust or near the crust-mantle boundary (see Behrmann et al., 2003), rotation of faults and faulted blocks are very minor, if any. This feature is well seen in the cross-section in Fig. 1c, where the orientations of pre- (Triassic–Jurassic) and syn-rift (Tertiary) sediments are more or less horizontal everywhere.

The homogeneity in structural trends throughout the central part of the Upper Rhine Graben underlines the importance of the observed structures in the structural setting of the graben (Fig. 3). The homogeneity in observed fault slip sense indicates that the observed phase of deformation affected the entire central part of the Upper Rhine Graben, over a length of 200 km. The NNE–SSW-trending (oblique) sinistral faults correspond to the Rhine Graben boundary faults. The sinistral activity of these faults is ongoing today, as is shown by earthquake focal mechanisms (e.g. Plenefisch and Bonjer, 1997; Lopes Cardozo and Granet, 2003). Dextral movement is on conjugate faults, but in some cases is also accommodated on planes with an ENE–WSW orientation. The existence of these latter fault trends in our observations indicates, at least on a local scale, the importance of structural inheritance for fault formation in the Upper Rhine Graben.

Recently, possible effects of transpression, modifying the Upper Rhine Graben basin structure to a minor degree, have been detected near the SW termination around the Dannemarie Basin (Fig. 2) and NW of the central segment of the Eastern Boundary Fault (EBF; Fig. 2). In the former area transpressive structures are probably related to Plio-Quaternary Vosges uplift (Rotstein et al., 2005a) and thick-skinned compressive movements (Giamboni et al., 2004) of the same age in the foreland of the Swiss Jura thrust front and at the NE termination of the Rhine–Bresse Transfer Zone (RBTZ; Fig. 1a). In the latter, a Miocene age of synclines in syn-rift sediments (Rotstein et al., 2005b) is documented from truncation of structures by unconformities in reflection seismic sections. Whatever the cause for these transpressive structures, they produce very small horizontal NW–SE to N–S shortening strains (Giamboni et al., 2004; Rotstein et al., 2005b), or seem to be local effects in response to permutation of principal stresses (Larroque et al., 1987) at restraining bends (Rotstein et al., 2005a) of the large Eastern Boundary Fault system operated in dominant sinistral strike-slip mode. What makes these effects more or less invisible in brittle faulting, we suspect, is that the structures produced are very gentle folds or flexures, i.e. zones of very low-strain distributed over a wide area.

The Right Dihedra method was used to derive the axes of shortening and extension. In our view this method is to be preferred over classical paleo-stress inversion, because of the known importance of pre-existing structures in the region (e.g. Edel and Weber, 1995; Ustaszewski, 2004). Faults, shear zones and other large-scale mechanical anisotropies can play a role in modifying the orientations of principal stress axes over large areas (e.g. Zoback, 1992). Therefore, derivation of principal stress orientations from fault populations of known kinematics must be considered as hazardous, unless the elastic and frictional parameters of the studied objects are known well. Our Right Dihedra method kinematic plots show overall NW–SE shortening and NE–SW extension, with some local deviations (Fig. 4). Most of the observed shear indicators fit to this kinematics and, given the absence of convincing overprinting relationships, we have no reason to separate the faults into subsets. Dating of the faulting is the obvious problem, since most of the outcrops investigated are in Mesozoic rocks, leaving open the question when in the Tertiary–Quaternary the individual mesoscopic faults formed. The major part of the movements, however, must have occurred in the Eocene and Oligocene, when the bulk of the syn-rift sediments formed (e.g. Doebl and Obrecht, 1974; Behrmann et al., 2003). The close spatial interaction of strike-slip, oblique-slip and normal faulting in many of the locations studied and the absence of obvious overprinting leads us to propose that the Upper Rhine Graben probably operated as a sinistrally oblique rift for most of its history. The kinematic signature of faulting in the Miocene carbonatites exposed at the Badloch quarry gives evidence for continuation of this picture into the Plio-Quaternary. Comparing the results of seismotectonic studies (Bonjer et al., 1984; Kastrup et al., 2004), focusing on the recent field of deformation with the kinematic data from our study, it seems clear that sinistral transtension has been the mode of deformation in the North Alpine foreland and the wider Upper Rhine Graben area for most of its Tertiary–Quaternary history.

orientation of intermediate kinematic axis, closed circle symbols show sub-vertical shortening axis. (2) Extension direction qualitatively inferred from the Neustadt fault slip data (Fig. 3). (3) Pattern of Paleogene extension directions at the southern termination of the graben, simplified from Ustaszewski et al. (2005), and (4) extension direction from outcrop reported in the study of Larroque and Laurent (1987). Shaded relief background derived from SRTM data available at http://comp1.geol.unibas.ch/. See text for discussion.

Our findings are in line with the observations on horizontal stylolites (Buchner, 1981) to the east of the Upper Rhine Graben and results of an earlier fault kinematics study south of the main body of the Upper Rhine Graben (Larroque and Laurent, 1987). The pattern consisting of tortuous fault traces forming a coalescent, segmented fault system, mainly seen in the northern and central parts of the Upper Rhine Graben (see Fig. 2) provides additional support for the idea of sinistrally transtensive opening (cf. Keep and McClay, 1997; Clifton et al., 2000; Mart and Dauteuil, 2000), where faults with different orientations and kinematics may move simultaneously. Most of the faults shown in Fig. 2 have formed early in the rifting history, documented by differences in thickness of the Paleogene basin fill (e.g. Doebl and Obrecht, 1974). Transtensive kinematics also supported the results of 3D retro-deformation studies (Behrmann et al., 2003; Bertrand et al., 2005; Cornu and Bertrand, 2005).

Our results are at variance with studies advocating a complex, multi-stage kinematic history (e.g. Schumacher, 2002) for the Upper Rhine Graben, derived from interpretation of basin geometries and the evolution of the large-scale paleostress field. However, they show interesting similarities with the results of a detailed investigation of Paleogene brittle deformation at the southern termination of the Upper Rhine Graben. There, Ustaszewski et al. (2005) documented E–W to ESE–WNW extension and/or more complex radial extension patterns. The principal results of this study are integrated in Fig. 6. Evidently the southern termination has a rift-related strain field indeed somewhat different from that of the rest of the graben, in that strain is dissipated over a much wider area and less homogeneous in orientation.

In summary, we show that results of plate-scale, or platform-scale, investigations of paleo-stress (Bergerat, 1985, 1987), as derived from small-scale fault populations, should be applied with due care in the attempt to understand the kinematic history of large extensional structures. The notion in the early literature that kinematics of the Upper Rhine Graben was two-stage, comprising earlier orthogonal rifting and later sinistral strike-slip (e.g. Illies, 1977; see also discussion in Schwarz and Henk, 2005), or multi-stage (Schumacher, 2002) needs to be proven and substantiated, but at this stage is not supported by the fault-slip data available from the vicinity of the largest faults of the Upper Rhine Graben system.

6. Conclusions

A small but robust set of fault slip data has been gathered for the central part of the Upper Rhine Graben boundary fault system. Almost all data can be explained as reflecting sinistral transtension. Pure or oblique strike slip faulting prevails in most of the investigated sites close to the graben boundary faults, but normal faulting is important in areas where movement is partitioned into more complex arrays of large-displacement faults and at the southern termination of the graben. There is a remarkable consistency in orientation of NE–SW to E–W extension over the studied strike length of the graben (200 km), with the notable exception of the northeastern and southern terminations, where extension may locally be radial, or in the WNW–ESE direction. Calculated shortening axes mostly have subhorizontal NW–SE to NNW–SSE or subvertical orientations. Our data suggest that with the exception of phases of short-lived transpression in parts of the structure, the Upper Rhine Graben opened in more or less continuous, sinistrally transtensional kinematics in space and time. This is the signature dominating recent deformation in the Upper Rhine Graben and the Northern Alpine foreland.

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