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ORIGINAL PAPER

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A multi-scale approach to study the lithospheric structure of the southern Upper Rhine Graben: from seismic tomography through reflection seismics to surface geology

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Abstract This paper integrates the results of different techniques—local and regional travel time tomography, reflection seismics, and surface geology. With this integration of different techniques, working on different scales, it is possible to derive a comprehensive picture of the present-day structures in the lithosphere of the Upper Rhine Graben. It is shown that the stucture of the lithosphere is dominated by structures related to the Variscan orogeny. Late stage strike-slip reactivation of the internal faults of the Rhine Graben is observed in the field. This reactivation is of dominant influence on the geomorphology in the southern end of the Upper Rhine Graben.

Keywords Upper Rhine Graben · Seismology · Reflection seismics · Tectonics

Introduction

Ziegler (1992) described the Rhine Graben as the most prominent segment of the European Cenozoic Rift System. This system of rifts and basins of Oligocene age extends from the North Sea through Germany and France to the Valencia Trough on the Mediterranean coast (Fig. 1).

This study is focused on the Upper Rhine Graben (URG) which extends over approximately 300 km along the German-French border (Fig. 2). The graben is flanked by the crystalline massifs of the Vosges (France) and the Black Forest (Germany). Schumacher (2002) describes the development of the URG as a series of tectonic phases that is closely related to the Alpine orogeny. Behrmann et al. (2003) have retrodeformed the oblique opening of the graben. The development of the URG is largely dominated by the presence of an inherited system of Variscan faults (Ziegler 1992; Edel and Weber 1995; Schumacher 2002). Extensive field study has been conducted by Bergerat (1987) to study the paleo stress development of the URG. Field work in structural geology is mostly concentrated on the boundary faults of the graben, due to a lack of outcrops in the graben itself.

The URG was thought to have hydrocarbon potential, and therefore high quality industry seismic lines are available in the region, which image the upper 3 km of the earth. The available seismic lines for the southern part of the graben are interpreted and presented by Rotstein and Schaming (2004) and Rostein et al. (2004). Two deep reflection seismic lines were shot in the framework of the DECORP-ECORS program. The interpretation of the northern line was presented by Wenzel et al. (1991), and the southern line by Brun et al. (1992). The graben is proven to have developed as an asymmetrical half graben, with a wedge-shaped sedimentary infill. The main boundary fault is situated on the eastern side of the graben in the north, and on the western side in the southern part of the graben. The deep seismic lines further show evidence for a partly laminated and intensely deformed lower crust. Studies on the seismicity of the URG are mainly focused on the eastern boundary faults. Focal mechanisms show that the boundary faults are activated in a sinistral transpressive setting (Plenefisch and Bonjer 1997).

Panza et al. (1980) were the first to present a European scale model of the lithosphere–asthenosphere system based on seismic surface and body waves, and showed a significantly thinned lithosphere underneath the Rhine Graben. Later tomographic studies studies were based on a network that was specially designed to verify the distinct long wavelength uplift of the lithosphere-asthenosphere system (Granet 1986; Glahn and Granet 1992; Glahn et al. 1993; Achauer 2002). These

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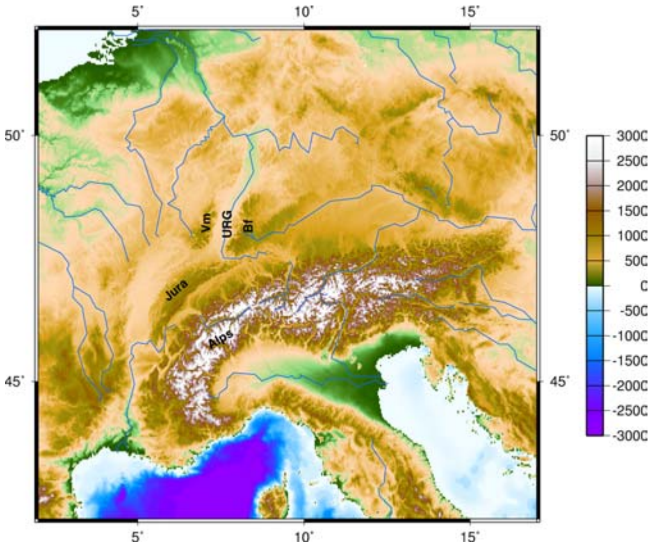

Fig. 1 The position of the Upper Rhine Graben (*URG*) in Europe. The Rhine Graben is situated in the foreland of the Alpine chain, and terminates in the south on the Jura Mountains. *Vm* = Vosges Mountains, *Bf* = Black Forest

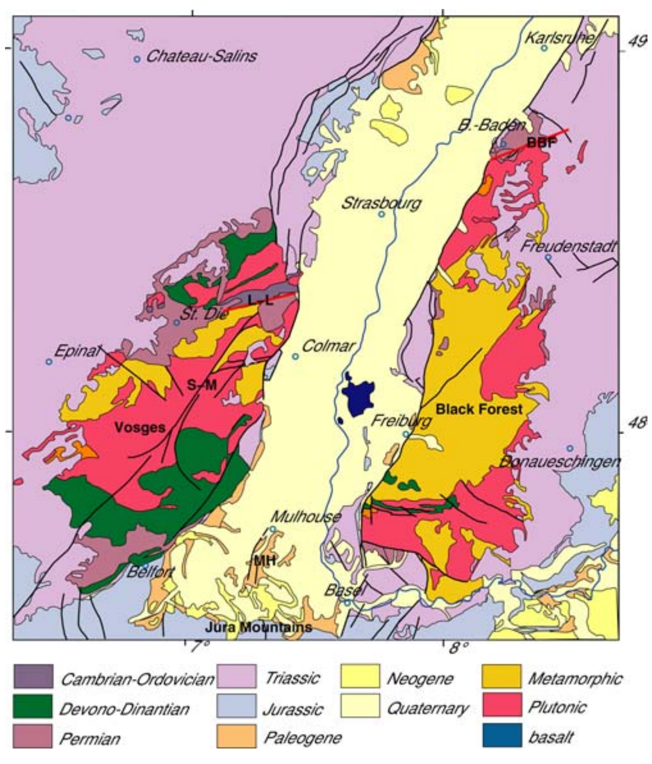

Fig. 2 Geological map of the URG. The Quaternary sediments of the graben are in contrast with the crystalline VM and Bf. In the southern part of the graben, Paleogene, and Neogene sediments outcrop in the Mulhouse Horst (*MH*). In the southern end of the study area, the Jurassic outcrops on the Jura Mountains. *DB* = Dannemarie basin. *AB* = Allschwil basin. BBF and L–L are the Baden Baden, and Lalaye Lubine faults that are part of the separation between the Saxothuringian (to the NW), and the Moldanubian zones (to the SE). *S–M* = Ste. Marie-aux-Mines fault, which is described as a Late Variscan shear zone by Edel and Wenzel (1995)

studies showed that the the influence of the graben is limited to the crust and that the presence of a mantle diapir can be excluded. A local earthquake tomography (LET) presented by Lopes Cardozo and Granet (2003) confirms the dominance of Late Variscan wrench faults in the southern end of the graben region, and provides crucial data from the seismogenic part of the crust between 2 km and 10 km. A teleseismic tomography presented by Lopes Cardozo and Granet (2004) shows that structures in the lithospheric mantle down to 100 km are orientated obliquely to the axis of the graben, and have presumably a Late Variscan origin.

The aim of this study is to show how the results from different techniques, with different scales can be combined to come to a coherent image of the entire lithosphere of the URG, from the base of the lithosphere to the surface. For this purpose, the findings from earthquake tomography, seismic lines, and surface geology are combined.

Tomography studies

A combined interpretation of the regional teleseismic travel time tomography (Lopes Cardozo and Granet 2004), and the LET (Lopes Cardozo and Granet 2003) provides the crucial link between the structure of the entire lithosphere and the structures in the upper crust (Fig. 3).

Teleseismic travel time tomography yields relative P-wave velocity images for certain depth intervals; the interpretation of these images for depths from 25 km to 100 km shows a dominance of 30°N–35°N striking structures. This dominant structural trend is oblique to the axis of the Rhine Graben, but parallel to known faults in the Vosges that have a Late Variscan origin (Edel and Weber 1995). The first layer of the teleseismic tomography (10–25 km) is largely influenced by the low velocity sedimentary infill of the graben.

The LET gives access to absolute P-wave velocity images, but these are expressed in relative velocity with regard to the model of Mayer et al. (1997) to make comparison between different layers easier. The LET images show the internal structure of the southernmost end of the Upper Rhine Graben. Especially the structure of the region south of Mulhouse is illuminated. In the 2 km layer, an elevated crustal block, known as the Mulhouse Horst is shown as a high velocity anomaly. Two adjacent basins are shown as low velocity anomalies. These basins are the Dannemarie basin and the Allschwil basin on the western and eastern side of the horst respectively. The 25°N–30°N trending faults associated with this structure can be continued into the 6 km layer. In this layer an interesting body of low velocities is seen underneath the Jura fold-and-thrust belt in the southern end of the model. The northern limitation of this body coincides with the rim of a Late Paleozoic trough system underlying the Jura.

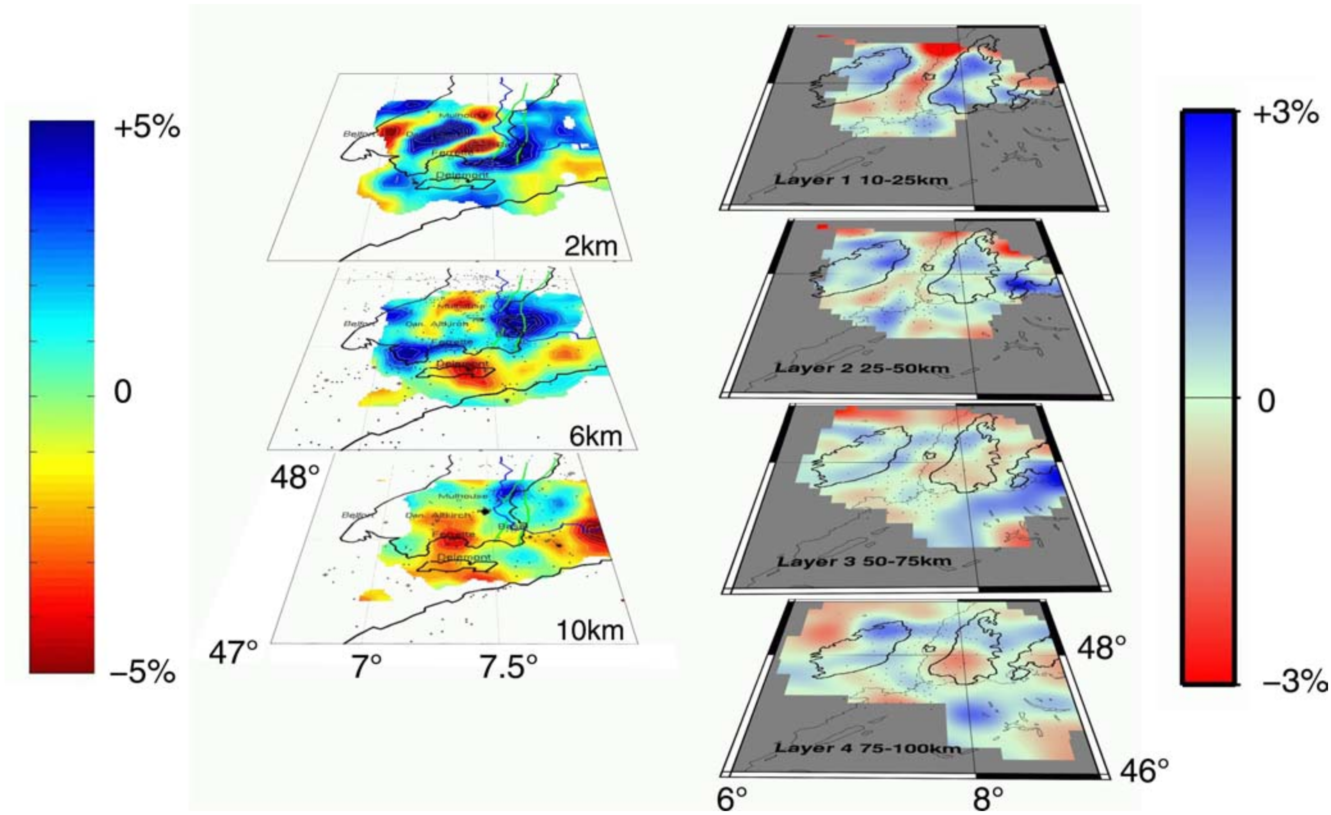

Fig. 3 The results of the teleseismic tomography (*right*) and local earthquake tomography (*LET*). The velocities in the LET are relative to the model of Mayer et al. (1997). Note the presence of non graben parallel structures in the two velocity models

The total absence of structures with the 10°N trend of the Rhine Graben in the interpretations of the two seismic velocity models shows the limited influence of the rifting. On the other hand, the dominance of Late Paleozoic structures shows the importance of inherited structures on the present-day crustal and lithosphere tectonics.

Reflection seismic studies

A comparison of reflection seismics with LET can be helpful to extrapolate the structures seen in the LET towards the surface, and to constrain independently the position of faults in the LET. Reflection seismics have the advantage of great detail and precision on the geometry and location of the large-scale structures. A disadvantage is that the profiles are only 2-D, and it is therefore difficult to draw conclusions on the orientations of structures.

A deep reflection seismic profile that crosses the southern part of the URG was presented and interpreted by Brun et al. (1992). A comparison between the deep reflection seismics and a profile through the LET is given in Fig. 4. The image shows an overall good agreement between the results of the two methods. The asymmetry of the Rhine Graben, as observed in the seismic line, is reflected in the low P-wave velocities, associated with the sedimentary infill of the graben, in the tomography.

Other reflection seismic profiles were shot to obtain insight into the potential hydrocarbon play of the URG. These profiles give independent constraints on the position of faults in the LET. Figure 5 shows a comparison between a profile through the LET and two seismic lines that cross the western and eastern limitations of the Mulhouse Horst.

The profile through the LET runs from the foothills of the Vosges, through the Dannemarie basin, the Mulhouse Horst, and the Allschwil basin into the Black

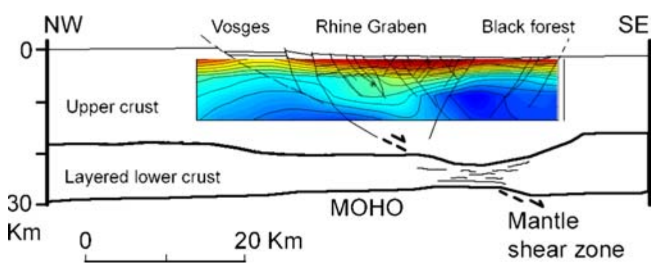

Fig. 4 A compilation of two profiles cross cutting the Rhine Graben. The profile through the LET (*in colour*) is compared with the interpretation a of deep reflection seismic profile (Brun et al. 1992) at the same place. Note the coincidence of low velocities in the LET, with the position of Rhine Graben, and the coincidence of high velocities in the LET, with the Vm and Bf massifs. The asymmetrical structure of the graben as it is interpreted in the seismic profile is clearly reflected in the velocity model

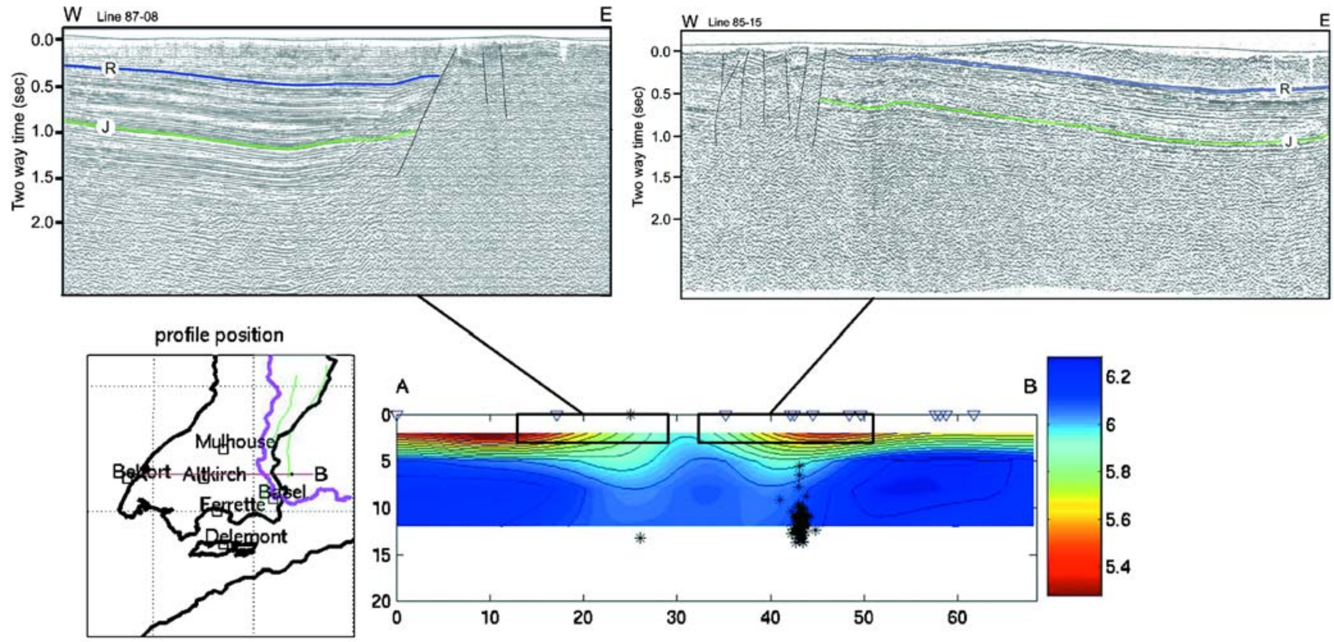

Fig. 5 A compilation of a profile through the LET crossing from the Dannemarie basin (west), over the Mulhouse Horst, into the Allschwil basin (east), and two industrial reflection seismic sections. Clear faulting is seen in the seismic sections at the position of the large velocity contrast between the crystalline Mulhouse Horst and the sedimentary infill of the two adjacent basins. The seismic sections show folding of the sediments in the basins, which is seen as proof for later stage compression

Forest. Again, the Mulhouse Horst is characterized by high P-wave velocities, and the adjacent basins by low P-wave velocities.

The faulting that is shown in the western seismic profile forms the separation between the Mulhouse Horst and the Dannemarie basin. This fault zone, known as the Illfurth fault, is known from previous studies (Niviere and Winter 2000) and is thought to have been reactivated recently. The Dannemarie basin is observed on the western side of the line and the Mulhouse Horst on the eastern side. A steep westward dipping normal fault is observed.

The eastern seismic profile shows faulting that is located on the sharp velocity contrast between the Mulhouse Horst and the Allschwil basin, as observed in tomography. The steep faults form the eastern boundary of the horst, and do not show a large normal offset as observed on the Illfurth fault.

Surface geology

An interesting outcrop was found in an abandoned gravel quarry south of Seppois Le Haut. The gravels in the quarry belong to the ‘‘Sundgau gravel’’ formation of Pliocene age. The quarry is situated at the border of the Grumbach river, at the point where this river meets the Largue river (Fig. 6a). In the gravels, clear faulting is seen (Fig. 6b). Two maxima are seen in the trend of the faults in the quarry, one around 120°N, and a second around 160°N. The faults have a large normal component but differential offset of small-scale faulting implies some strike-slip component. There is a striking coherence between the trends of the observed faults and the orientations of the Grumbach and Largue valleys (Fig. 6a, c).

From the structures observed in Seppois Le Haut, it can be concluded that extension took place after the rifting phase of the URG. If the Grumbach and Largue valleys are indeed fault controlled, the length of the fault could at least be as long as the part of the valley that is parallel to the observed faulting, which is 12 km. A 15 km long part of the valley of the Ill river, south of Altkirch, also runs parallel to the observed 120°N striking faults. However, a lack of outcrops means that there is no further proof of the link between tectonics and geomorphology.

The observed 120°N striking faults could either be interpreted as the dextral conjugate of the 25°N–30°N striking faults observed in the velocity structure at 2-km depth and in the seismic lines, or as relay ramps in the system of basement strike-slip faults. It is quite probable that the fault is activated under the active left-lateral strike-slip of the basement. The faulting seems to have affected the geomorphology of a region where the ‘‘Sundgau gravels’’ outcrop. These partially unconsolidated gravels are thought to be easily erodible, therefore it seems that the motion on the faults is dominant over the erosion rate.

Discussion

This integration of the presented data is not straightforward. In the tomography, it is observed that at large

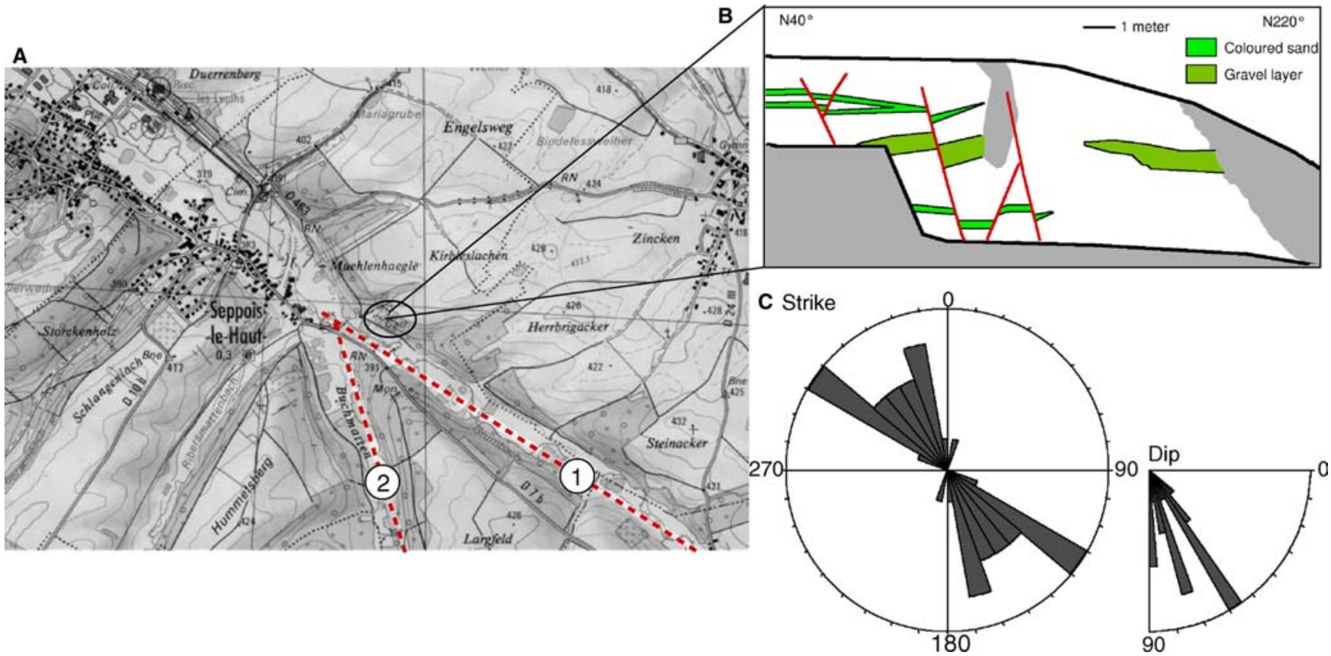

Fig. 6 **a** Map of the region around Seppois Le Haut, centered at coordinates 47°30′N, 7°12′E. *Black circle* indicates the location of the studied quarry. *Dashed lines 1* and *2* indicate the orientations of the Grumbach and Largue valleys respectively. **b** A sketch of the SE quarry wall. *Red lines* indicate faults, *grey areas* are not visible because of debris. **c** Rose diagrams of the 21 measured faults. Note the coherence in the strike of the faults and the orientations of the Largue and Grumbach valleys

depth, the dominant structure is not directly associated with the Rhine Graben. Instead the structures oblique to the graben are thought to be the signature of the Variscan structural grain of central Europe in the velocity images.

Closer to the surface, Rhine Graben related structure becomes increasingly dominant. The upper layer of the teleseismic tomography (Fig. 3) clearly reflects the surface geology in the region (Fig. 2).

The local earthquake tomography gives a more detailed image of the velocity structure in the southern end of the graben. It can be seen that the internal faults of the graben are not parallel to the graben axis.

The seismic data clearly prove that some of the velocity contrasts in the upper layers of the local earthquake tomography are related to faulting (Figs. 4, 5). They show that this faulting is continuous to shallow depth. They also show that the low velocity bodies in the upper part of the local earthquake tomography are associated with sedimentary basins, and the high velocity bodies with uplifted crystalline basement rocks. The structure of the Mulhouse Horst becomes clear from an integration of the 2-D seismic lines that give the detail, and the LET that gives the 3-D continuity of the structures.

The field data (Fig. 6) show clearly that some amount of deformation took place since the Late Pliocene. The observed faults are interpreted to be the conjugates of the large faults associated with the Rhine Graben, as they are observed in tomography and on the seismic lines. The faults are presumably active today. The conjugate faults, and their geomorphological reflection, are observed only in the region where the Pliocene Sundgau gravels outcrop. This supports the idea that these conjugate sets were formed during the late stage strike-slip reactivation of the Rhine Graben faults.

Conclusions

With an integration of different techniques—local and regional travel time tomography, reflection seismics, and surface geology—it is possible to derive a comprehensive picture of the present-day structures in the lithosphere of the URG.

The lithospheric mantle velocity in the region shows structures that are not directly related to the Rhine Graben. These structures are interpreted to be related to the Variscan orogeny, and its subsequent collapse.

Closer to the surface, the structure of the Rhine Graben is clearly retrieved in the velocity model. It is seen that the structure of the graben is dominated by faults that have a trend oblique to the graben axis.

The structure of the Mulhouse Horst is clearly shown to be dominated by faults at both sides of the horst. Late stage strike-slip reactivation of the internal faults of the Rhine Graben is clearly reflected in one outcrop in the field, and in the geomorphology of the southern end of the URG. This phase of strike-slip reactivation is thought to be active until recently based on the reflection in the geomorphology of the faults.

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