Zeitschrift: Bulletin für angewandte Geologie

Herausgeber: Schweizerische Vereinigung der Petroleum-Geologen und –Ingenieure; Schweizerische Fachgruppe für Ingenieur-Geologie

Band: 12 (2007)

Heft: 1

Artikel: Neotectonic activity in the Upper Rhine Graben : Jura Mountains junction (North-Western Switzerland and adjacent France)

Autor: Ustaszewski, Kamil / Schmid, Stefan M.

DOI: https://doi.org/10.5169/seals-226364

Bull. angew. Geol. Vol. 12/1 Juli 2007 S. 3-19

Neotectonic activity in the Upper Rhine Graben - Jura Mountains junction (North-Western Switzerland and adjacent France)

Kamil Ustaszewski[1], Stefan M. Schmid[1]

Keywords: Neotectonics, Upper Rhine Graben, Jura Mountains, reflection seismics, Permo-Carboniferous trough, 1356 Basel earthquake, Northern Switzerland

Abstract

This contribution provides evidence for latest Pliocene to recent basement-rooted shortening in the southernmost Upper Rhine Graben and adjacent Jura. NE to ENE trending folds affecting the base of the Pliocene Sundgau gravels are interpreted to have formed by NW-SE shortening. This is in agreement with the NW-SE-orientation of maximum horizontal stresses inferred from seismotectonic studies. The spatial coincidence of the most prominent of these folds with the position of major basement-rooted faults suggests that they formed by thick-skinned reactivation of WSW-ENE and NNE-SSW-striking faults in dextral and sinistral mode, respectively. Dextral transpressive reactivation of the WSW-ENE-striking fault system (Rhine-Bresse transfer zone) dominates.

Deflections of recent river courses around the crests of topographically clearly discernible anticlines suggest that this deformation is still ongoing at present. A change from thin-skinned tectonics, which prevailed during the main phase of Jura folding, to very probably still ongoing thick-skinned tectonics is inferred to have occurred in the Late Pliocene. This change might be linked to the incipient inversion of Permo-Carboniferous troughs within the Alpine foreland in general. In particular, such inversion in a dextral transpressive mode along a basement fault, which is part of the Rhine-Bresse transfer zone, might be held responsible to have triggered the 1356 Basel earthquake.

Zusammenfassung

Dieser Beitrag liefert Hinweise auf im Sockel einwurzelnde Verkürzungen im südlichen Oberrheingraben und angrenzenden Jura. NE bis ENE streichende Falten, welche die Basis der pliozänen Sundgauschotter erfassen, werden als Resultat einer NW-SE Verkürzung interpretiert. Dies steht im Einklang mit seismotektonisch abgeleiteten, NW-SE-gerichteten maximalen horizontalen Spannungen. Die räumliche Übereinstimmung der prominentesten dieser Sundgauschotter-Falten mit dem Verlauf grösserer, im Sockel einwurzelnder Verwerfungen legt deren Reaktivierung nahe. WSW-ENE streichende Verwerfungen wurden dabei dextral reaktiviert, wohingegen NNE-SSW streichende Verwerfungen eine sinistrale Reaktivierung erfahren haben. Dextral transpressive Reaktivierung WSW-ENE streichender Verwerfungen der Rhein-Bresse Transferzone dominiert.

Die Ablenkung von Flussläufen, welche die Scheitel topographisch deutlich erkennbarer Falten queren, weisen auf rezent andauernde Deformation hin. Es wird daher angenommen, dass im späten Pliozän eine Umstellung von Abscherungstektonik, die während der Hauptphase der Jurafaltung wirksam war, zu im Sockel einwurzelnder Verkürzung erfolgt sein muss, welche vermutlich bis heute wirksam ist. Diese Umstellung könnte generell mit einer beginnenden Inversion permokarboner Tröge im Alpenvorland verbunden sein. Im Speziellen könnte eine derartige dextral transpressive Reaktivierung einer Verwerfung innerhalb der Rhein-Bresse Transferzone als Ursache der Basler Erdbebens von 1356 angesehen werden.

[1] Geologisch-Paläontologisches Institut, Universität Basel, Bernoullistrasse 32, CH-4056 Basel, Switzerland, Kamil.Ustaszewski@unibas.ch

1. Introduction

1.1 Research objectives

The present day architecture of the northwestern Alpine foreland largely resulted from the interplay between extensional and collisional tectonics that took place since Early Cenozoic times. The resulting interference is particularly complex, where the southern Upper Rhine Graben (URG), formed during Eo- to Oligocene extension, abuts the northern margin of the Jura Mountains fold and thrust belt. The latter formed as a consequence of Alpine subduction and collision from the Late Miocene onwards.
According to the widely accepted concept of thin-skinned Jura folding, that postulates décollement via complete decoupling between basement and cover along Triassic evaporite horizons (e.g. Buxtorf 1907, Laubscher 1961, Burkhard 1990, Jordan 1992), the role of pre-existing basement faults linked to the formation of the URG would only be a passive one during later compressive events. Such pre-existing faults would merely act as nuclei during the formation of Jura-type folds, thrusts and transverse strike-slip structures such as oblique ramps. However, a minority of authors prefers a thick-skinned origin of all, or at least of parts, of the shortening in the Jura Mountains and adjacent areas. Thereby pre-existing basement faults would play an active role, be it by their reactivation in terms of strike slip faulting that occurs within a basement, which is decoupled from the folding of the sedimentary cover above the Triassic detachment horizon (Pavoni 1961), or, as was more recently proposed, by the inversion of faults delimiting the Permo-Carboniferous troughs of the northwestern foreland of the Alps (e.g. Pfiffner et al. 1997 and references therein).
Unfortunately, controversies addressing the thick-skinned vs. thin-skinned dilemma often overlooked the evolution in time and space of the post-Oligocene shortening of the northwestern Alpine foreland. It is perfectly feasible to accept a thin-skinned origin of the main structural features within the Jura fold-and-thrust belt that essentially formed within a relatively short time span between the Late Miocene and Early Pliocene (the authors believe that the evidence for this is overwhelming, e.g. Ustaszewski & Schmid 2006), and to reconcile this view with recent discoveries regarding a thick-skinned reactivation of pre-existing basement faults in latest Pliocene to recent times (e.g. Giamboni et al. 2004a,b; Ustaszewski et al. 2005a).
At present, the southern end of the URG is characterised by increased seismicity, as seen in the clustering of seismic events in both the historical and the instrumental earthquake catalogues of Switzerland (Swiss Seismological Service 2003). Earthquakes, for instance, have repeatedly harmed the city of Basel in medieval times. The most severe earthquake occurred in 1356 with an estimated epicentral intensity between IX and X (Mayer-Rosa & Cadiot 1979). The inferred focal depths of this, as well as those of most of the other earthquakes in the NW foreland of the Alps, reaching the base of the crust (Deichmann et al. 2000a), suggest basement reactivation and hence a thick-skinned neotectonic scenario at least for the seismogenic components of neotectonic activity.
However, despite dedicated research (Meyer et al. 1994; Nivière et al. 2000; Meghraoui et al. 2001; Lambert et al. 2005) neither source nor mechanism of the 1356 Basel earthquake (strike slip, thrust or normal fault?) have yet been unambiguously identified. There is also no general agreement yet, whether the currently ongoing deformation in the «northwestern» Alpine foreland still predominantly affects the sedimentary cover (ongoing thin-skinned tectonics, deep-seated seismogenic activity being of minor importance) or whether basement and cover currently deform by the same amounts (thick-skinned tectonics). Solving such questions is of key importance for seismic hazard assessment studies or for the choice of suitable repository sites for the storage of

high-active nuclear waste, issues that require a detailed knowledge of fault kinematics and accurate estimates of present-day deformation rates.

This contribution presents an overview of recently identified neotectonic features at the Jura Mountains - Upper Rhine Graben junction in northwestern Switzerland and adjacent France. The presented features combine geomorphologic observations and evidence from reflection seismic lines. The observations favour the interpretation that basement-rooted («thick-skinned») tectonics are dominant since the latest Pliocene, whereas Jura-type décollement tectonics ceased at about that time.

1.2 Geological setting, seismicity and recent displacement rates

The study area (Fig. 1) is located in northwestern Switzerland and adjacent France, at the junction of the southernmost URG and the northern Jura fold and thrust belt. Some recent and exhaustive descriptions of the regional geology are found in Becker (2000), Giamboni et al. (2004a), Dèzes et al. (2004) and Ustaszewski & Schmid (2006).

The orientation of maximum horizontal stresses (SH_{max}) in the north-western Alpine foreland, inferred from fault plane solutions for seismic events and the inversion of focal mechanisms, is consistently NW-oriented (Plenefisch & Bonjer 1997; Deichmann et al. 2000a; Reinecker et al. 2003; Kastrup et al. 2004). Down to a depth of about 15 km, there is a predominance of fault plane solutions indicating strike-slip; from 15 km down to the MOHO normal faulting events prevail (Plenefisch & Bonjer 1997; Deichmann et al. 2000a). The extension axes show a very stable NE-SW-orientation throughout. On the other hand, the SH_{max}-orientations in the sedimentary cover, decoupled from the basement (comprising crystalline basement, Permo-Carboniferous troughs and Lower Triassic) along rheologically weak Middle and Upper Triassic evaporite layers, scatter from NNW over N to NNE, as is primarily deduced from in-situ stress measurements (Baumann 1981; Müller et al. 1987; Becker 1999, 2000; Reinecker et al. 2003) and fault-slip data (Philippe 1994; Ustaszewski & Schmid 2006). The depth-dependent change in the orientation of SH_{max} is particularly well documented in boreholes along the easternmost Folded Jura (Müller et al. 1987) and has been used as an argument for still ongoing décollement tectonics (Müller et al. 1987, 2002). However, this contrasts with recent work providing arguments for currently ongoing thick-skinned reactivation of basement faults (Meyer et al. 1994; Lopes Cardozo et al. 2003; Giamboni et al. 2004a; Ustaszewski et al. 2005a).

A recent compilation of GPS-data from 53 permanent stations from 4 different networks in Western Europe, with observation periods of up to 7 years between 1996 and 2003, allowed a determination of horizontal displacement rates relative to Eurasia. Stations located between 4 and 16° E, comprising the domain of the Alps and the northern Alpine foreland, show horizontal displacement rates between 0.1 and 2.9 mm/a relative to Eurasia (Tesauro et al. 2005, their Fig. 2). Convergence rates regarding the Swiss part of the northwestern Alpine foreland only are in the order of less than 1 mm/a (Müller et al. 2002). It is uncertain, however, as to how much of the present-day convergence deduced for the earth's surface by such studies is accommodated by seismogenic activity within the directly underlying basement as long as the thick-skinned vs. thin-skinned controversy regarding the neotectonic scenario remains unsolved.

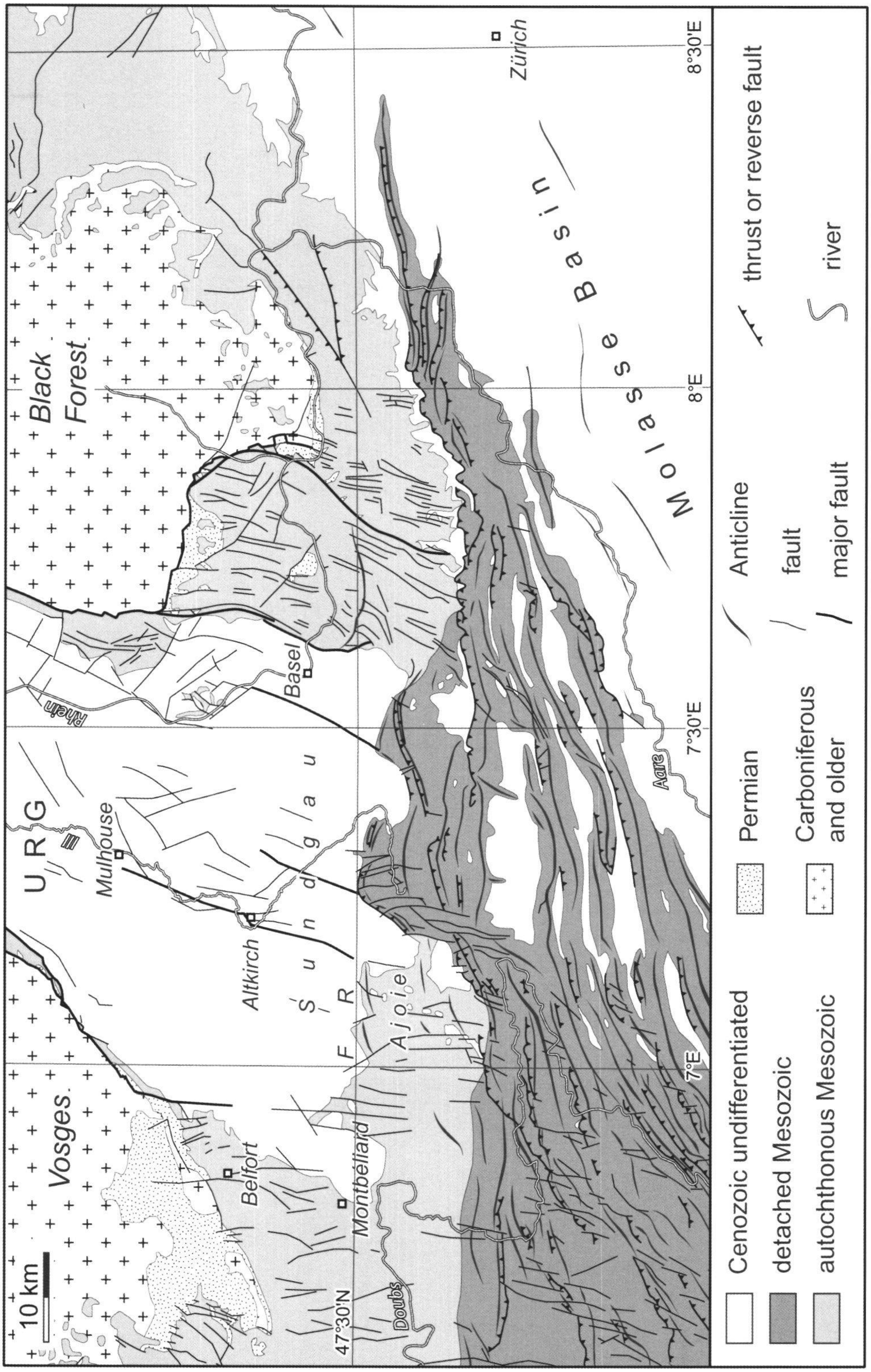

Fig. 1: Tectonic map of the larger study area. Geographic names are in italics. F = Florimont anticline, R = Réchésy anticline.

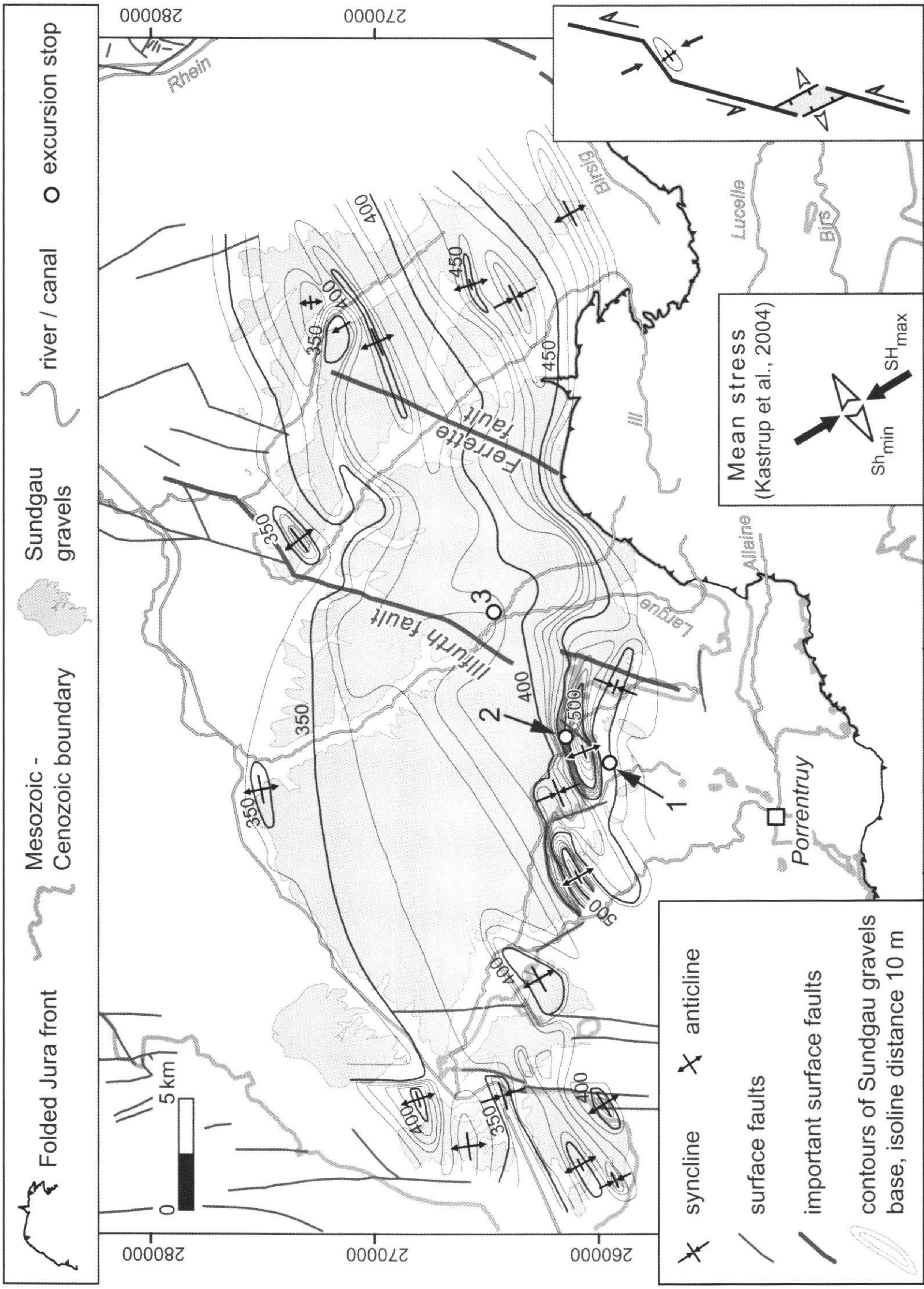

Fig. 2: Contour map of the base of the Pliocene Sundgau gravels in metres above sea level (after Giamboni et al. 2004a). Bottom right inset: kinematic sketch of the Illfurth fault explaining the occurrence of restraining and releasing bends. VSP-ASP convention 2006 excursion stops are indicated.

2. Evidence for latest Pliocene to recent tectonics

2.1 Evidence recorded by the deformation of the Pliocene Sundgau gravel sheet

Pliocene fluvial gravels, cropping out in the southernmost URG and the southerly adjacent Jura Mountains, play a key role in deciphering the tectonics post-dating the main phase of Jura folding. These so-called Sundgau gravels unconformably overlie both the Paleogene syn-rift sediments in the URG and the autochthonous Mesozoic in the Tabular Jura of the Ajoie (Fig. 2). The Sundgau gravels were deposited by a braided river that drained westward through southernmost Alsace («Sundgau») towards the Bresse Graben, and eventually into the Mediterranean Sea. The biostratigraphically determined age of the Sundgau gravels ranges from 4.2 to 2.9 million years (Petit et al. 1996; Fejfar et al. 1998). During this time interval the drainage divide between the North Sea and the Mediterranean Sea was located around the Kaiserstuhl volcano, approximately 60 km north of the area investigated (e.g. Fig. 4b in Giamboni et al. 2004a). This riverbed was abandoned 2.9 million years ago, associated with a southward shift of the drainage divide into the western Sundgau. Subsequently, the contiguous gravel cover was dissected by four N- to NW-wards draining tributaries of the Doubs (the Allaine) and Rhine river (from W to E: Largue, Ill and Thalbach) systems, which have eroded down into the Paleogene syn-rift fill of the URG, thus exposing the base of the gravel sheet along their valley flanks (Fig. 2). The eastern end of the Sundgau gravel sheet, west of Basel, is also clearly erosional. According to the literature the southward migration of the water divide could be due to a slow-down (or the end) of the up warping of the Vosges-Black Forest arch (Dèzes et al. 2004), or alternatively, the accelerated subsidence in the northern URG, which is concomitant with a drop of the local base level and subsequent regressive erosion (Doebl 1970; Schumacher 2002; Giamboni et al. 2004b).

The thickness of the Sundgau gravels varies between 5 and 20 m (Théobald et al. 1958; Liniger 1970a, 1970b; Ruhland et al. 1973). They consist of predominantly clast-supported, crudely bedded gravel beds with a shifting network of shallow channels. Intercalations of sand lenses are very rare. These sedimentological criteria suggest that deposition occurred on a nearly planar and horizontal surface; hence this surface can be used as a reference plane for deciphering vertical tectonic movements that postdate the deposition of the gravels. Contouring the base of the Sundgau gravels revealed an array of syn- and anticlines with average amplitudes of 30-50 m and maximum amplitudes of up to 150 m regarding two en-échelon anticlines in the southwest (Florimont and Réchésy anticlines), testifying to post-2.9 million years horizontal shortening and vertical uplift in the area of the southernmost URG (Giamboni et al. 2004a). Since the fold amplitudes exceed the average gravel thickness by up to an order of magnitude, it can be excluded that these contours merely result from the infilling of a pre-existing topography. Fig. 2 also compares the contours of the base of the Sundgau gravels with the mean stress regime, which reveals strike-slip characteristics and a maximum horizontal stress (SH_{max}) oriented at around azimuth 330° (bottom centre inset, after Kastrup et al. 2004). Evidently, the folds in the Sundgau gravels trend largely perpendicular to the orientation of present-day SH_{max}.

An isolated anticline with an amplitude of approximately 20 m, affecting the base of the Sundgau gravels, is located at a kink of the NNE-trending Illfurth normal fault that formed during the opening of the URG (Fig. 2). Within the current stress field, the Illfurth Fault is favourably oriented for accommodating sinistral strike-slip motion. This isolated anticline thus formed most likely at a restraining band of the Illfurth fault (far right inset in Fig. 2).

Further to the south, near Seppois le Haut in the Largue valley, conjugate normal faults are directly seen to affect the Sundgau gravel cover in a gravel pit (Fig. 3). This outcrop is located near the southernmost tip of the Illfurth Fault (Fig. 2). The normal faults affecting the Late Pliocene gravel cover are traceable by intercalated sand lenses in the grain-supported gravels (Fig. 3a and b). Small-scale normal faults with displaced markers allowed estimating the extension direction, which is NE-SW (Fig. 3c). Further

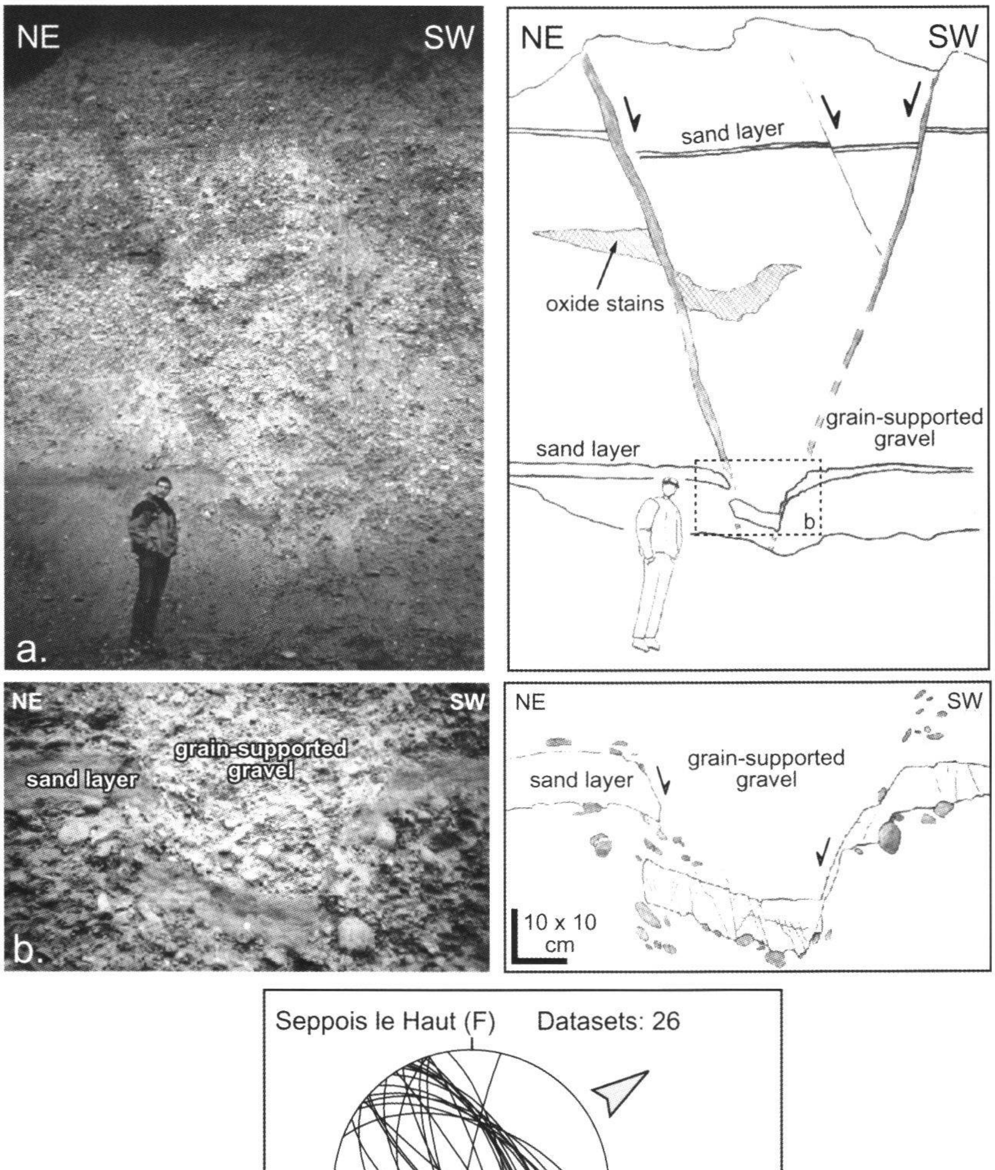

Fig. 3: Deformation features in the Sundgau gravels related to local extension near a releasing bend of strike slip faulting. (a) Conjugate normal faults affecting the Late Pliocene Sundgau gravels in an abandoned gravel pit in the Largue valley at Seppois le Haut, France (excursion stop no. 3; Swiss coordinates: 581'600/264'400; see figs. 2 and 4 for location). Intercalated sand lenses in the grain-supported gravels and oxide stains serve as markers. (b) Sand layer affected by cm- to dm-scale conjugate normal faults. Outside the faulted sand layer the shear zone is traceable by rotated and broken pebbles. (c) Representation of fault-orientations and of the shortening and extension axes in a lower hemisphere equal area projection.

south, in the Tabular Jura, a similarly oriented fault is found, but offset to the east with respect to the Illfurth Fault. The formation of the conjugate normal faults is therefore interpreted to have occurred most likely at a releasing bend between two left stepping NNE-trending faults (bottom right inset in Fig. 2). The existence of both restraining and releasing bends along the Illfurth Fault hints at left-lateral strike-slip reactivation of the «Rhenish» fault system after the deposition of the Sundgau gravels, concomitant with dextral reactivation of the Rhine-Bresse transfer system.

2.2 Geomorphologic evidence for presently ongoing deformation

The Florimont and Réchésy anticlines are clearly discernible on a shaded relief map, constructed using the Swiss 25 m digital elevation model (Figs. 4b and c). The topography of the anticlines has resulted from the folding of Late Jurassic to Paleogene sediments. This is discernible from the close correlation between the strike of the hill slopes and the strike and dip measured in the folded Late Jurassic and Paleogene sediments around the two anticlines (Fig. 4c). The contours of the base of the Sundgau gravels (Fig. 4d) also correlate very closely with topography. This proofs that the topography formed after deposition of the Sundgau gravels, i.e. after 2.9 million years ago. Moreover, the Allaine and Cœuvatte rivers are deflected away from the fold crests (Fig. 4b). Because the geomorphologic features described above appear to be very young, the growth of the anticlines and the lateral propagation of their doubly plunging crests to either side very probably continued up to the present.

2.3 Subsurface evidence for reactivated basement faults

A reflection seismic line across the Réchésy anticline (Fig. 5) documents that it formed right above an extensional flexure. The age of the extensional flexure is evident from the S-ward tapering and onlap of Paleogene synrift sediments. From the topography and the height of the base of the Sundgau gravels (from Giamboni et al. 2004, superimposed in Fig 5b), it is seen that the topographic crest of the Réchésy anticline, the crest in the Sundgau gravel fold and the position of a basement fault zone (or high) underlying the Mesozoic succession all spatially coincide. This suggests an essentially post-2.9 million years age of the anticline by compressive or (more likely) transpressive reactivation of the extensional flexure above an underlying ENE-trending basement fault (Giamboni et al. 2004; Ustaszewski et al. 2005a; Ustaszewski & Schmid, in press).

3. Discussion

3.1 The kinematic framework of neotectonic activity in the southern URG

The deformation recorded by the Sundgau gravels provides evidence for latest Pliocene to recent tectonics in the area investigated. Deformation of their stratigraphic base reveals an array of NE-SW- to ENE-WSW-oriented syn- and anticlines with amplitudes up to 150 m, which very probably formed above transpressively reactivated pre-existing basement faults that are part of the Rhine-Bresse transfer zone (Giamboni et al. 2004; Ustaszewski et al. 2005a). The spatial coincidence between folds mapped in the base of the Sundgau gravels and reactivated basement faults, recognised in reflection seismic lines, points towards a thick-skinned origin of this shortening (Fig. 4 and 5).

The observation of anticlines located at restraining bends and normal faults located at releasing bends of NNE-trending faults in the URG (Figs. 2 and 3) supports the idea that some of the folds traceable in the Sundgau gravels also formed above sinistral-

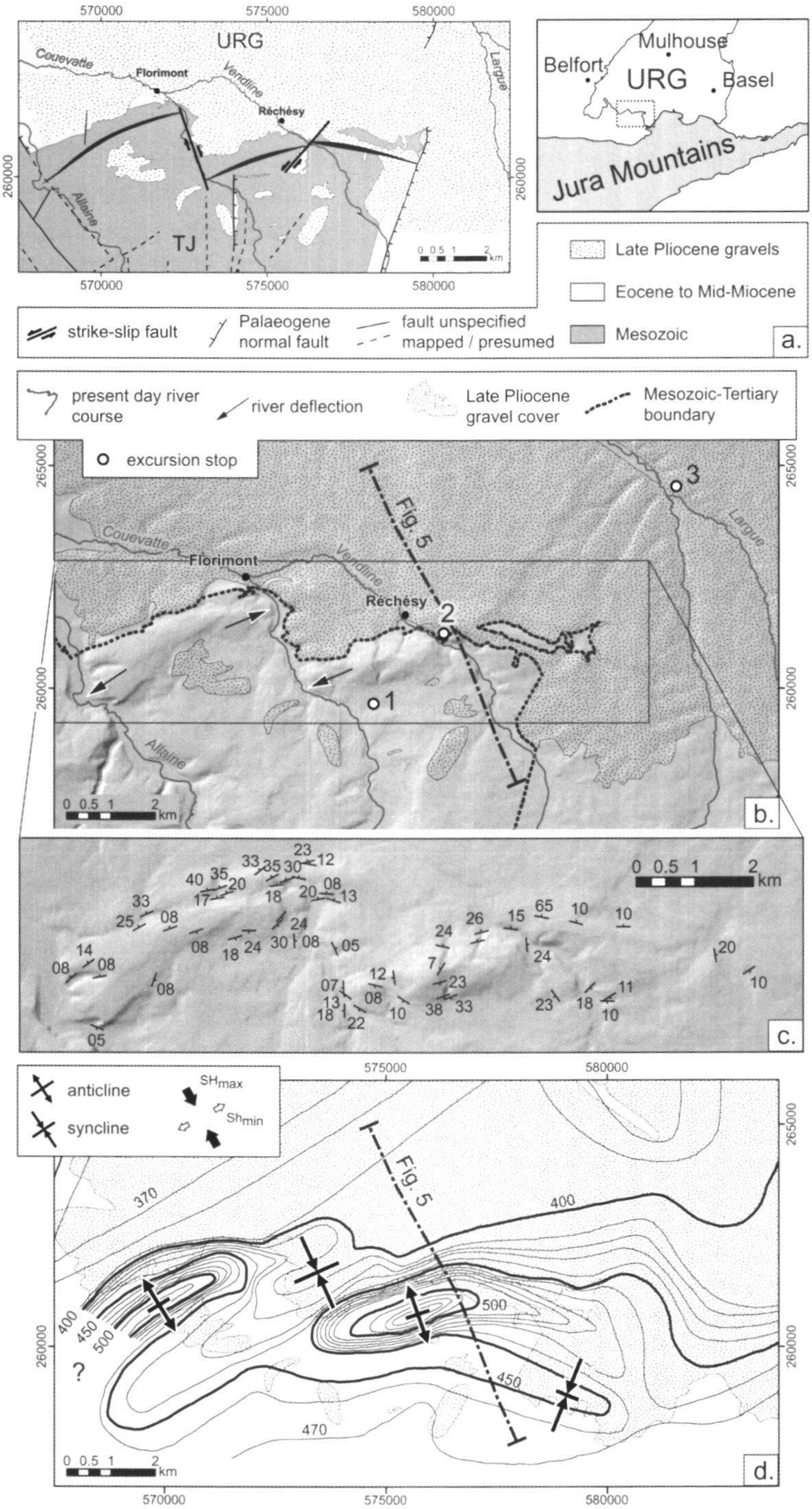

Fig. 4: (a) Simplified geological map of the area around the en-échelon aligned Florimont and Réchésy anticlines at the Tabular Jura - URG boundary. (b) Shaded relief map illustrating the juvenile morphology of the two anticlines. Note the deflection of the Allaine and Coeuvatte rivers around the fold hinges. (c) Strike and dip of bedding planes measured in Mesozoic and Palaeogene sediments around the anticlines. (d) Contoured base of the Sundgau gravels (from Giamboni et al. 2004). Top left inset: recent stress field from a seismotectonic study of Kastrup et al. (2004). Figure modified after Ustaszewski & Schmid (in press). VSP-ASP convention 2006 excursion stops are indicated.

ly reactivated NNE-trending (Rhenish) faults. Left-lateral strike-slip faulting along NNE-trending Rhenish faults is indeed in good agreement with seismotectonic evidence (Plenefisch & Bonjer 1997; Deichmann et al. 2000a).

It has to be noted that latest Pliocene to recent dextral transpressive reactivation of ENE-trending faults, which are part of the Rhine-Bresse transfer zone, is hitherto supported almost exclusively by geological evidence (Meyer et al. 1994; Giamboni et al. 2004a; Ustaszewski et al. 2005a), whereas seismotectonic evidence supporting the reactivation of such ENE-trending faults is scarce. However, the 23 February 2004 earthquake in the Rhine-Bresse transfer zone near Rigney (France), with a moment magnitude M_w = 4.5 and a focal depth of 15 km, yielded a focal mechanism that indicates reverse faulting (Swiss Seismological Service 2004; Baer et al. 2005). This focal mechanism is regarded as seismotectonic evidence for the compressive inversion of Permo-Carboniferous troughs in the northwestern Alpine foreland (Fig. 6). This is com-

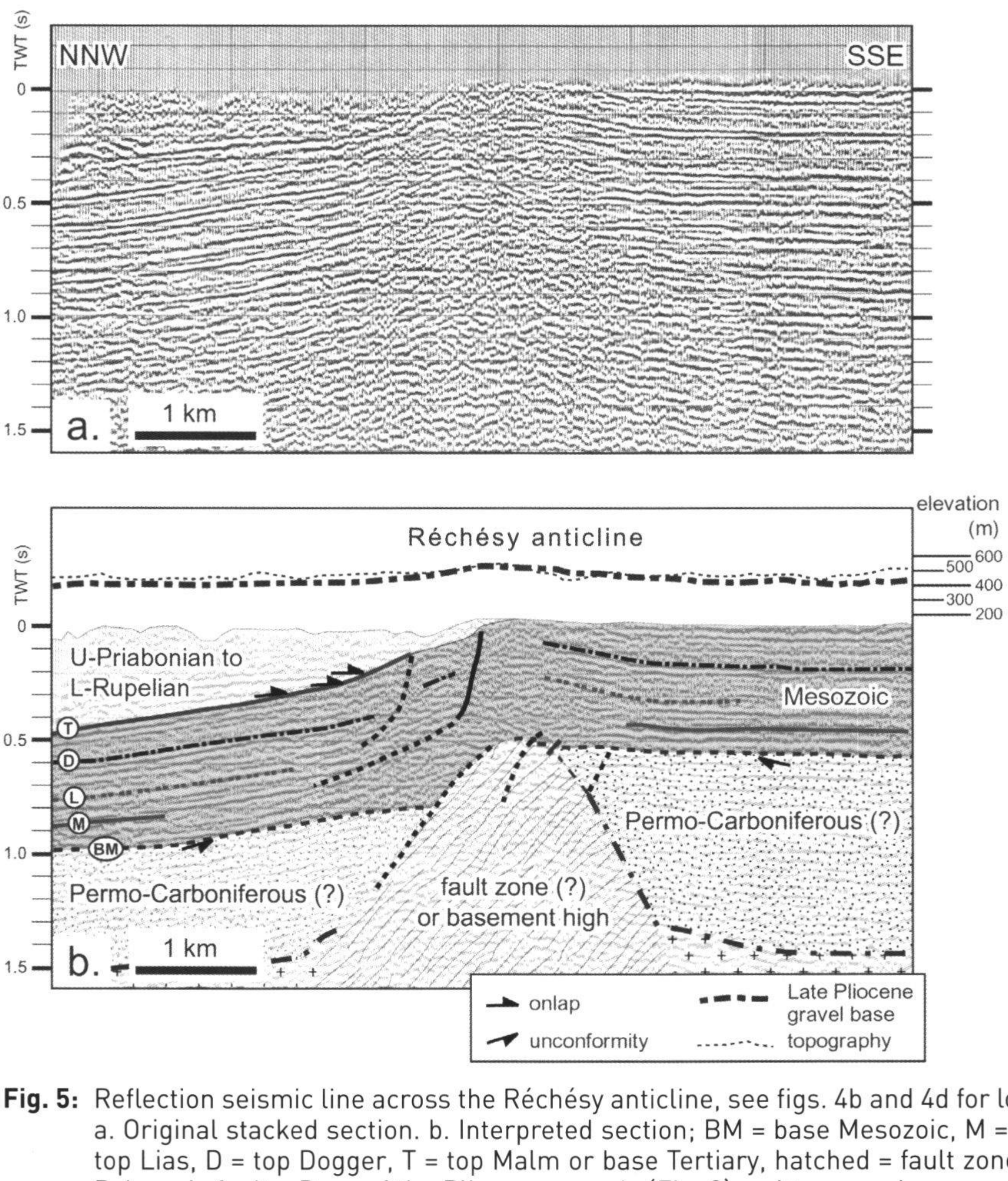

Fig. 5: Reflection seismic line across the Réchésy anticline, see figs. 4b and 4d for location of the section. a. Original stacked section. b. Interpreted section; BM = base Mesozoic, M = top Muschelkalk, L = top Lias, D = top Dogger, T = top Malm or base Tertiary, hatched = fault zone associated with late Paleozoic faults. Base of the Pliocene gravels (Fig. 2) and topography are superimposed. The vertical scale is exaggerated by a factor of 1.2 to coincide with the depth in s TWT (calculated using seismic velocities from boreholes nearby). Note the correlation between the angle of dip of Mesozoic reflectors and that of the base of the gravels. Fold crests in both gravels and Mesozoic sediments coincide and are located precisely above the basement fault zone; this suggests a thick-skinned origin of the Post-Late Pliocene folds.

patible with dextral transpression along the Rhine-Bresse transfer zone as deduced from our data (Fig. 7). It is also compatible with ideas proposed by Ziegler (1990), Philippe (1994) and Pfiffner et al. (1997) for other parts of the northwestern foreland of the Alps in terms of a kinematic framework. Note, however, that these authors proposed such a thick-skinned reactivation for the main phase of Jura folding, which we consider

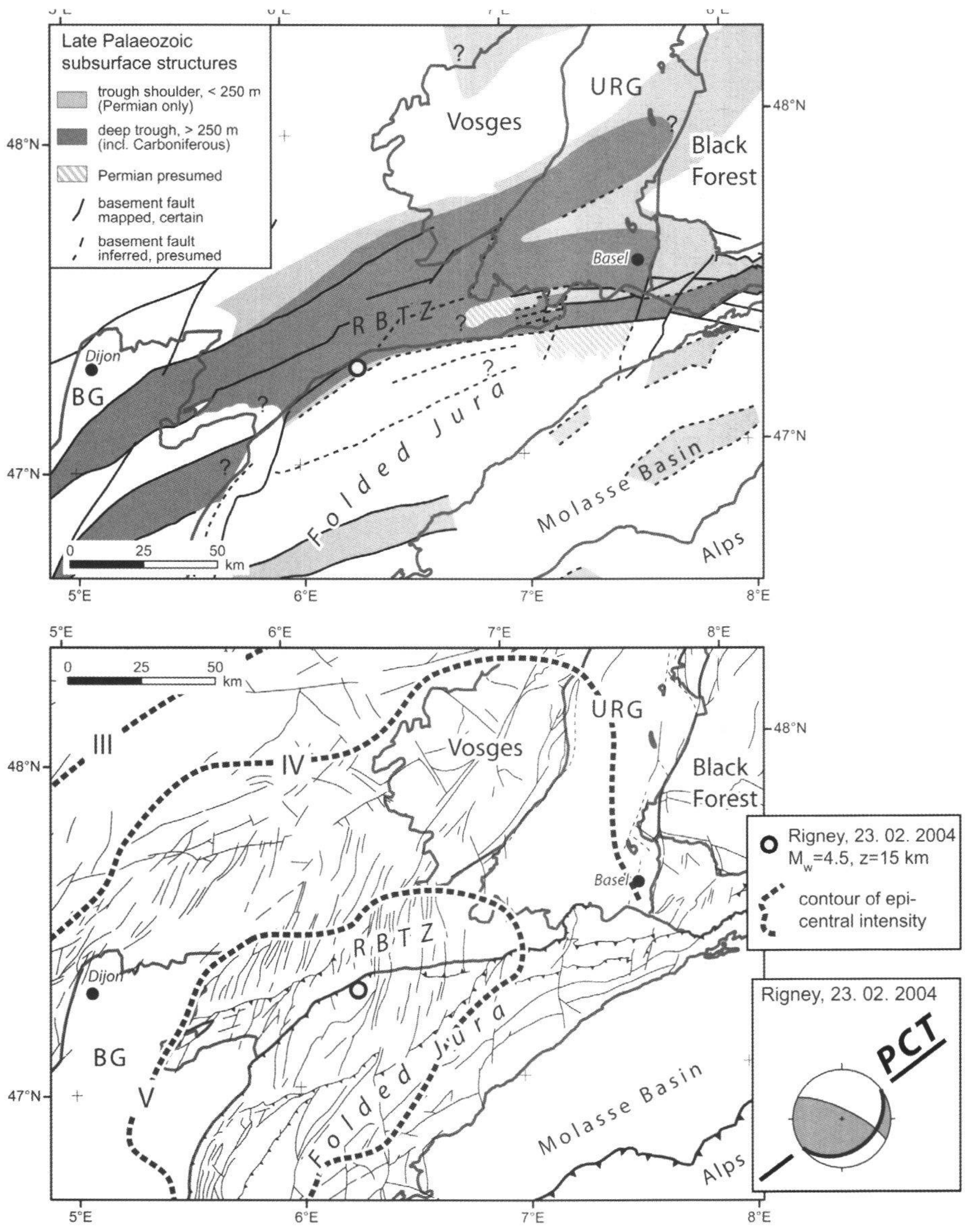

Fig. 6: Late Paleozoic structures in the Rhine-Bresse transfer zone (RBTZ), with the outlines of the major tectonic elements superimposed. BG = Bresse Graben, URG = Upper Rhine Graben. Bottom: location of the epicentre of the Rigney earthquake (Swiss Seismological Service 2004; Baer et al. 2005) and contours of epicentral intensity on the French territory (RéNaSS 2004), which are ellipsoidal with the long axis paralleling ENE-oriented subsurface faults. Map traces of faults reaching the surface (see top figure for subsurface faults) are shown in black. The focal mechanism (Baer et al. 2005; bottom right inset) is reverse faulting. Note that the ENE-trending, SE-dipping nodal plane (labelled «PCT» for Permo-Carboniferous trough) is again parallel to major subsurface basement faults in the epicentral area.

as purely thin-skinned. Hence we consider this thick-skinned kinematic framework to be valid for latest Pliocene to recent deformation only, with a weak precursor in the Early Miocene, i.e. before the main phase of the formation of the purely thin-skinned Jura fold-and-thrust belt.

3.2 Which fault produced the Basel 1356 earthquake?

The NW-SE-orientation of present-day SH_{max} within the basement appears well documented by seismotectonic evidence compiled by Kastrup et al. (2004). Together with our present knowledge regarding the orientation of pre-existing faults, this puts certain constraints as to which pre-existing fault might have been reactivated in which mode during the 1356 Basel earthquake. In view of the crucial importance of the high-magnitude Basel earthquake for seismic hazard evaluations, the quality of such evaluations critically depends on solving this difficult question. Three sets of faults are prone to reactivation in the Basel area. We argued that the NNE-striking Rhenish faults and the ENE-striking faults of the Rhine-Bresse transfer zone, which continue west of Basel into the «Constance-Frick» trough (e.g. Diebold & Noack 1997; see also Ustaszewski et al 2005b, their Fig. 2), are presently active in terms of sinistral strike slip and dextrally transpressive movements, respectively. A third family of NW-SE-striking faults is found around Basel and east of this town only (see Fig. 6 top). It appears to be presently active there. This is for example suggested by fault plane solutions regarding the 1999 Pratteln and 2003 Zeiningen events (Deichmann et al. 2000b, 2004), which are indicative for dextral strike-slip reactivation. Note also that the foci of the recently triggered earthquakes in connection with the Basel Deep Heat Mining Project (Geothermal Explorers Ltd. 2007; Swiss Seismological Service 2007) group along such a NW-SE-oriented fault, indicating enhanced permeability within this (still active?) fault zone. Although these NW-SE-striking faults seem to be active, their limited length on a geological map (< 40 km) appears to be insufficient for creating the surface rupture length necessary for an earthquake with magnitude 6.5 or higher (Wells & Coppersmith 1994).

The data available so far do not allow for clearly deciding between faults related to the ENE striking Rhine-Bresse transfer zone (including the Constance-Frick trough as its eastern continuation) on the one hand, and NNE-striking Rhenish faults on the other hand. Conspicuously, the epicentre of the 1356 Basel earthquake immediately south of Basel is located near the intersection of the two fault sets, suggesting mutual interactions between those two simultaneously active fault systems.

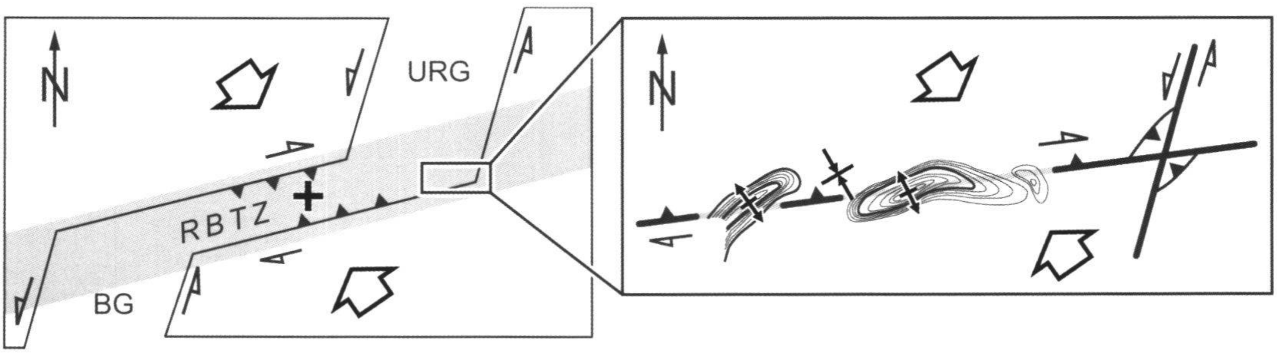

Fig. 7: Proposed kinematic sketch for neotectonic activity in the study area. The Rhine-Bresse transfer zone (RBTZ) is under dextral transpression, causing subsequent uplift («+») due to the presumed inversion of ENE-trending Permo-Carboniferous troughs. En-échelon surface folds develop above ENE-trending basement faults. Simultaneously, NNE-trending faults of the URG-system are active as sinistral strike-slip faults. Transpressive fault splays or pop-ups develop at the intersection of the two differently oriented fault systems.

Both fault systems have been proposed as likely candidates for having provoked the 1356 Basel earthquake. Meyer et al. (1994) and Laubscher (2006) favour the Rhine-Bresse transfer zone, mainly based on the E-W elongated shape of the zones of equal damage (Mayer-Rosa & Cadiot 1979), and they left it open as to whether this fault system was reactivated in dextral strike slip or thrust mode. Answering this question would demand knowledge of the ratio and orientation of the principal stresses such as can be obtained through inversion of fault plane solutions for seismic events. Such data (Kastrup et al. 2004) are only available for the areas north of Basel (strike slip mode) and south of Basel (combination of strike slip and normal faulting). Our evidence for dextral transpression along the Rhine Bresse transfer zone west and southwest of Basel, together with the fault plane solution of the Rigney 2004 earthquake, rather suggests a combination of strike slip and thrusting for the present-day stress field in the area west of Basel, a stress field that might also have triggered the 1356 Basel earthquake. In view of the relatively larger strain accumulation we detected above faults related to the Rhine Bresse transfer system regarding latest Pliocene to recent deformations (Réchésy and Florimont anticlines) we favour the hypothesis that this is the fault system, which was activated, in agreement with ideas proposed by Meyer et al. (1994) and Laubscher (2006). The most probable mode of reactivation is dextral transpression (Fig. 7).

However, we cannot completely exclude sinistral reactivation of one of the NNE-striking Rhenish faults during the 1356 Basel event. But we agree with Laubscher (2006) that the evidence for a reactivation of a Rhenish fault during the Basel earthquake in extensional mode (the so-called «Reinach fault») provided by Meghraoui et al. (2001) is incompatible with our knowledge about the present-day stress field. Also the geological evidence provided in our contribution would rather point to a reactivation of Rhenish faults in sinistral strike slip mode. Furthermore, we agree with Laubscher (2006) that the geomorphologic evidence provided by Meghraoui et al. (2001) for the «Reinach fault» being an active seismogenic fault is far from convincing, and that gravitational sliding is very probably responsible for the «faults» documented by the trenching.

In conclusion, a dextral transpressive reactivation of a fault that is part of the ENE-striking Rhine-Bresse transfer zone is the most likely candidate for having caused the 1356 Basel earthquake (Fig. 7). Reactivation of an ENE-striking Rhenish fault cannot be excluded. However, such a reactivation would be expected to have occurred in sinistral strike slip mode rather than in normal fault mode.

3.3 What induced the change from thin-skinned to thick-skinned deformation in the Late Pliocene?

In the following, we speculate on the geodynamic causes that might have led to the above described transition from thin-skinned tectonics to basement-rooted deformation. Two possibilities are briefly outlined: (1) deactivation of intra-crystalline glide along the basal décollement, and (2) ongoing tectonic underplating in the foreland of the northwestern Alps (Mosar 1999).

(1) The theory that décollement in the Jura fold- and thrust belt occurred by viscous flow, i.e. processes such as intra-crystalline glide within the Mid- and Upper Triassic halite and anhydrite layers, is rheologically viable and widely accepted nowadays (Laubscher 1961; Müller et al. 1980; Jordan 1987). Intra-crystalline glide processes in some of the evaporites may be activated at very low temperatures that are equivalent to an overburden column in the order of 1 km. Based on apatite fission track data, 1-3 km of uplift and erosion of the entire Swiss Molasse Basin after 5 million years BP were recently documented (Cederbom et al. 2004). According to these authors, the uplift

was triggered by accelerated erosion in the Swiss Alps in response to increased precipitation rates, leading to the isostatic rebound of the Alps together with the northerly adjacent foreland basin. It is believed that such an amount of erosion in the northern Molasse Basin may have caused the sedimentary overburden (and, hence, temperature) to fall beneath the critical threshold necessary to keep intra-crystalline glide systems in the basal Jura décollement active. The inferred timing of the uplift slightly predates the onset of sedimentation of the Pliocene Sundgau gravels at 4.2 million years ago, which, in turn, is thought to be the latest possible time at which thin-skinned folding in the Northern Jura Mountains has come to a halt (Becker, 2000; Ustaszewski & Schmid 2006). This suggests a causal relationship between the timing of rebound-triggered exhumation in the Molasse Basin and the cessation of thin-skinned Jura folding.

(2) A crustal-scale transect across the northwestern Alps, including the Molasse Basin and the Jura fold and thrust belt, exhibits a steep basal frontal thrust below the external massifs and a very narrow frontal portion (Mosar 1999), an overall geometry that is believed to be unstable when analyzed in terms of the critical taper theory (Chappel 1978; Davis et al. 1983; Dahlen et al. 1988). By integrating geodetically determined uplift rates and the seismicity distribution, Mosar (1999) proposed that the Alpine orogenic wedge is currently in the process of accreting new basement nappes from the European crust at its base (below the Jura-Molasse transition) in an attempt to regain stability. If true, the propagation of such incipient thrust faults towards the foreland has conceivably already reached the area of the external Jura fold-and-thrust belt, as revealed by the reverse faulting mechanism of the M_W = 4.5 earthquake in the Rhine-Bresse transfer zone on 23 February 2004 with a focal depth of 15 km (Baer et al. 2005).

4. Conclusions

(1) The southern URG experienced thick-skinned reactivation of WSW-ENE and NNE-SSW-striking faults in dextral and sinistral mode, respectively, since the Late Pliocene. Dextral transpressive reactivation of the WSW-ENE-striking system (Rhine-Bresse transfer zone) dominates, as evidenced by the spatial coincidence between NE- to ENE-trending syn- and anticlines with amplitudes up to 150 m in the base of Pliocene fluvial gravels and ENE-trending basement faults bordering an extensive Permo-Carboniferous trough system, hinting at its incipient inversion. Geomorphologic evidence strongly suggests that deformation is still ongoing at present.

(2) Dextral transpressive reactivation of a fault that is part of the ENE-striking Rhine-Bresse transfer zone is the most likely candidate for having caused the 1356 Basel earthquake, but reactivation of a NNE-striking Rhenish fault cannot be excluded.

(3) A geodynamic reorganization took place during the Late Pliocene. This reorganization apparently led to the deactivation of the Triassic basal décollement and (subsequently or simultaneously) to the compressive inversion of formerly extensional basement faults in the Alpine foreland. It is speculated that one or a combination of the following factors might have induced this change:

- Post-5 million years uplift of the Molasse Basin and concomitant erosion of 1-3 km of its Tertiary infill (Cederbom et al. 2004), eventually leading to a temperature decrease within the viscously deforming basal décollement horizon and consequently a rise of basal shear stress above a critical threshold.
- Ongoing tectonic underplating of European crust in the foreland of the northwestern Alps (Mosar 1999).

References

Baer, M., Deichmann, N., Braunmiller, J., Husen, S., Fäh, D., Giardini, D., Kästli, P., Kradolfer, U. & Wiemer, S. 2005: Earthquakes in Switzerland and surrounding regions during 2004. Eclogae Geol. Helv., 98, 407-418.

Baumann, H. 1981: Regional Stress Field and Rifting in Western Europe. Tectonophysics 73, 105-111.

Becker, A. 1999: In Situ Stress data from the Jura Mountains - new results and interpretation. Terra Nova 11, 9-15.

Becker, A. 2000: The Jura Mountains - an active foreland fold-and-thrust belt? Tectonophysics 321, 381-406.

Burkhard M. 1990: Aspects of the large-scale Miocene deformation in the most external part of the Swiss Alps (Subalpine Molasse to Jura fold belt). Eclogae Geol. Helv. 83, 559-583.

Buxtorf, A. 1907: Geologische Beschreibung des Weissenstein-Tunnels und seiner Umgebung. Beitr. Geol. Karte Schweiz, NF 21.

Cederbom, C. E., Sinclair, H. D., Schlunegger, F. & Rahn, M. 2004: Climate-induced rebound and exhumation of the European Alps. Geology 32, 709-712, doi: 10.1130/G20491.1.

Chappel, W. M. 1978: Mechanics of thin-skinned fold-and-thrust belts. Geological Society of America Bulletin, 89, 1189-1198.

Dahlen, F. A. & Suppe, J. 1988: Mechanics, growth and erosion of mountain belts. In Clark, S. P., Burchfiel, B. C. & Suppe, J. (Eds.), Processes in continental lithospheric deformation, Volume 218: Geological Society of America Special Paper, Geological Society of America, 161-178.

Davis, D., Suppe, J. & Dahlen, F.A. 1983: Mechanics of fold-and-thrust belts and accretionary wedges. Journal of Geophysical Research, 88, 1153-1172.

Deichmann, N., Ballarin Dolfin, D. & Kastrup, U. 2000a: Seismizität der Nord- und Zentralschweiz. NAGRA Technischer Bericht, 00-05. NAGRA, Wettingen, 94 S.

Deichmann, N., & 17 co-authors 2000b: Earthquakes in Switzerland and surrounding regions during 1999. Eclogae Geol. Helv. 93, 395-406.

Deichmann, N. & 18 co-authors 2004: Earthquakes in Switzerland and surrounding regions during 2003. Eclogae Geol. Helv. 97, 447-458.

Dèzes, P., Schmid, S. M. & Ziegler, P. A. 2004: Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. Tectonophysics 389, 1-33.

Diebold, P. & Noack, T. 1997: Late Paleozoic troughs and Tertiary structures in the Eastern Folded Jura. In: Pfiffner, O. A., Lehner, P., Heitzmann, P., Mueller, S. & STECK, A. (Eds), Deep structure of the Swiss Alps. Results of NRP 20. Birkhäuser, pp. 59-63.

Doebl, F. 1970: Die tertiären und quartären Sedimente des südlichen Rheingrabens. In: Illies, J. H. & Mueller, S. (Eds), Graben Problems. Proceedings of an International Rift Symposium held in Karlsruhe October, 10-12, 1968. E. Schweizerbart'sche, Stuttgart, pp. 56-66.

Fejfar, O., Heinrich, W.-D., & Lindsay, E. H. 1998: Updating the Neogene rodent biochronology in Europe. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen 60, 533-554.

Geothermal Explorers Ltd., 2007, Projekt Deep Heat Mining Basel. Beantwortung der Fragen der Behörden des Kantons Basel-Stadt vom 15. Dezember 2006 zum induzierten Erdstoss vom 8. Dezember 2006 in Basel, Geopower Basel AG, p. 43, with 65 p. Appendix, http://www.geopowerbasel.ch/html/Bericht.html.

Giamboni, M., Ustaszewski, K., Schmid, S. M., Schumacher, M. E. & Wetzel, A. 2004a: Plio-Pleistocene Transpressional Reactivation of Paleozoic and Paleogene Structures in the Rhine-Bresse transform Zone (northern Switzerland and eastern France). International Journal of Earth Sciences 93, 207-223, doi: 10.1007/s00531-003-0375-2.

Giamboni, M., Wetzel, A., Nivière, B. & Schumacher, M. E. 2004b: Plio-Pleistocene folding in the southern Rhinegraben recorded by the evolution of the drainage network (Sundgau area; Northwestern Switzerland and France). Eclogae Geol. Helv. 97, 17-31, doi: 10.1007/s00015-004-1112-4.

Jordan, P. 1987: Eine Methode zur Abschätzung tektonischer Scherraten aufgrund mikrostruktureller Beobachtungen. Eclogae Geol. Helv. 80, 491-508.

Jordan, P. 1992: Evidence for large-scale decoupling in the Triassic evaporites of Northern Switzerland: An overview. Eclogae Geol. Helv. 85, 677-693.

Kastrup, U., Zoback, M. L., Deichmann, N., Evans, K. F., Giardini, D., & Michael, A. J. 2004: Stress field variations in the Swiss Alps and the northern Alpine foreland derived from inversion of fault plane solutions. J. Geophys. Res. 109(B01402), doi:10.1029/2003JB002550.

Lambert, J., Winter, T., Dewez, T. & Sabourault, P. 2005: New hypotheses on the maximum damage area of the 1356 Basel earthquake (Switzerland). Quaternary Science Reviews 24, 381-299.

Laubscher, H. 1961: Die Fernschubhypothese der Jurafaltung. Eclogae Geol. Helv. 54, 222-282.

Laubscher, H. 1986: The eastern Jura: Relations between thin-skinned and basement tectonics, local and regional. Geologische Rundschau 75, 535-553.

Laubscher, H. 2001: Plate interactions at the southern end of the Rhine graben. Tectonophysics 343, 1-19.

Laubscher, H. 2006: Zur Geologie des Erdbebens von Basel. In: Meier W.: Da verfiele Basel überall. 184. Neujahrsblatt der GGG Basel. Schwabe Verlag Basel, 207-230.

Liniger, H. 1970a: Bemerkungen zur Tektonik am Südende des Rheingrabens. In: Illies, J. H. & Mueller, S. (Eds), Graben Problems. Proceedings of an International Rift Symposium held in Karlsruhe 1968, International Upper Mantle Project. Scientific Report. E. Schweitzerbart'sche, Stuttgart, pp. 103-106.

Liniger, H. 1970b: Geologischer Atlas der Schweiz 1:25 000, Atlasblatt 55: Bonfol, mit Erläuterungen. Kümmerly & Frey, Bern.

Lopes Cardozo, G. G. O. & Granet, M. 2003: New insight in the tectonics of the southern Rhine Graben-Jura region using local earthquake seismology. Tectonics 22, 1078, doi:10.1029/2002TC001442.

Mayer-Rosa, D. & Cadiot, B. 1979: Review of the 1356 Basel earthquake: basic data. Tectonophysics 53, 325-333.

Meghraoui, M., Delouis, B., Ferry, M., Giardini, D., Huggenberger, P. & Spottke, I. 2001: Active normal faulting in the Upper Rhine Graben and paleoseismic identification of the 1356 Basel earthquake. Science 293, 2070-2073.

Meyer, B., Lacassin, R., Brulhet, J. & Mouroux, B. 1994: The Basel 1356 earthquake: which fault produced it? Terra Nova 6, 54-63.

Mosar, J. 1999: Present-day and future tectonic underplating in the western Swiss Alps: reconciliation of basement/wrench-faulting and décollement folding of the Jura and Molasse basin in the Alpine foreland. Earth and Planetary Science Letters 173, 143-155.

Müller, W. H. & Briegel, U. 1980: Mechanical aspects of the Jura overthrust. Eclogae Geol. Helv. 73, 239-250.

Müller, W. H., Blümling, P., Becker, A. & Clauss, B. 1987: Die Entkoppelung des tektonischen Spannungsfeldes an der Jura-Überschiebung. Eclogae Geol. Helv. 80, 473-489.

Müller, W. H., Naef, H. & Graf, H. R. 2002: Geologische Entwicklung der Nordschweiz, Neotektonik und Langzeitszenarien, Zürcher Weinland. NAGRA Technischer Bericht, 99-08. NAGRA, Wettingen, 226 S.

Nivière, B. & Winter, T. 2000: Pleistocene northwards fold propagation of the Jura within the southern Upper Rhine Graben: seismotectonic implications. Global and Planetary Change 27, 263-288.

Pavoni, N. 1961: Faltung durch Horizontalverschiebung. Eclogae Geol. Helv. 54, 515-534.

Petit, C., Campy, M., Chaline, J. & Bonvalot, J. 1996: Major palaeohydrographic changes in Alpine foreland during the Pliocene-Pleistocene. Boreas 25, 131-143.

Pfiffner, O. A., Erard, P. & Stäuble, M. 1997: Two cross sections through the Swiss Molasse Basin (lines E4-E6, W1, W7-W10). In: Pfiffner, O. A., Lehner, P., Heitzmann, P., Mueller, S. & Steck, A. (Eds), Deep structure of the Swiss Alps. Results of NRP 20. Birkhäuser, pp. 64-72.

Philippe, Y. 1994: Transfer Zone in the Southern Jura Thrust Belt (Eastern France): Geometry, Development and Comparison with Analogue Modelling Experiments. In Mascle, A. (Ed.), Hydrocarbon and Petroleum Geology of France, Volume 4: Special Publication of the European Association of Petroleum Geologists, A. Springer, 327-346.

Philippe, Y., Colletta, B., Deville, E. & Mascle, A. 1996: The Jura fold-and-thrust belt: a kinematic model based on map-balancing. In Ziegler, P. & Horvath, F. (Eds.), Peri-Tethys Memoir 2: Structure and prospects of Alpine Basins and Forelands., Volume 170: Paris, Mem. Mus. natn. Hist. nat., 235-261.

Plenefisch, T. & Bonjer, K. 1997: The stress field in the Rhine Graben area inferred from earthquake focal mechanisms and estimation of frictional parameters. Tectonophysics 275, 71-97.

Reinecker, J., Heidbach, O. & Mueller, B. 2003: The 2003 release of the World Stress Map (available online at www.world-stress-map.org).

RéNaSS 2004: Réseau National de Surveillance Sismique, Ecole et Observatoire des Sciences de la Terre de Strasbourg, http://renass.u-strasbg.fr/, accessed on 04-04-2004.

Ruhland, M., Blanalt, J. G. & Bômont, M. 1973: Carte Géologique detaillée de la France à 1/50 000, Ferrette, feuille XXXVII-22. Ministère du développement industriel et scientifique, Bureau de recherches géologiques et minières, Service Géologique National, Orléans.

Schumacher, M. E. 2002: Upper Rhine Graben: Role of preexisting structures during rift evolution. Tectonics 21(1): 1006, doi:10.1029/2001TC900022.

Swiss Seismological Service, ETH Zürich 2003: ECOS - Earthquake Catalog of Switzerland, http://www.seismo.ethz.ch/.

Swiss Seismological Service, ETH Zürich 2004: Regional Moment Tensor Catalog, http://www.seismo.ethz.ch/moment_tensor/2004/homepage.html.

Swiss Seismological Service, ETH Zürich, 2007, Das Deep-Heat-Mining-Projekt in Basel, http://www.seismo.ethz.ch/basel/.

Tesauro, M., Hollenstein, C., Egli, R., Geiger, A. & Kahle, H.-G. 2005: Continuous GPS and broadscale deformation across the Rhine Graben and the Alps. International Journal of Earth Sciences 94, 525-537, doi: 10.1007/s00531-004-0453-0.

Ustaszewski, K., Schumacher, M. E., Schmid, S. M. & Nieuwland, D. 2005a: Fault reactivation in brittle-viscous wrench systems - dynamically scaled analogue models and application to the Rhine-Bresse Transfer Zone. Quaternary Science Reviews 24, 363-380, doi:10.1016/j.quascirev.2004.03.015.

Ustaszewski, K., Schumacher, M. E. & Schmid, S. M. 2005b: Simultaneous normal faulting and extensional flexuring during rifting: an example from the southernmost Upper Rhine Graben. International Journal of Earth Sciences, 94, 680-696, doi: 10.1007/s00531-004-0454-z.

Ustaszewski, K. & Schmid, S. M. 2006: Control of pre-existing faults on geometry and kinematics in the northernmost part of the Jura fold and thrust belt. Tectonics 25, TC 5003, doi 10.1029/2005TC001915.

Ustaszewski, K. & Schmid, S. M. in press: Latest Pliocene to recent thick-skinned tectonics at the Upper Rhine Graben - Jura Mountains junction. Swiss Journal of Geosciences.

Wells, D. L. & Coppersmith, K. J. 1994: New empirical relationship among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bull. Seismol. Soc. America 84, 974-1002.

Ziegler, P. A. 1990: Collision related intra-plate compression deformations in Western and Central Europe. Journal of Geodynamics, 11, 357-388.

Ziegler, P. A., Schumacher, M. E., Dèzes, P., Van Wees, J.-D. & Cloetingh, S. 2004: Post-Variscan evolution of the lithosphere in the Rhine Graben area: constraints from subsidence modelling. In Wilson, M. (Ed.), Permo-Carboniferous magmatism and rifting in Europe, Volume 223: Geological Society of London Special Publications, Geological Society, 289-317.

Appendix

Description of stops visited during the excursion at the annual convention of the Swiss Association of Petroleum Geologists and Engineers, Sunday, June 18th 2006: «Neotectonics in the border zone between Tabular Jura and southernmost Upper Rhine Graben». Excursion leaders: Kamil Ustaszewski and Stefan M. Schmid. Coordinates are Swiss National coordinates, system CH1903 (see Fig. 2, 3).

1. Panoramic stop at the football field in Lugnez (JU)

Swiss coordinates: 574'500/259'500, elevation: 415 m a.s.l.

Panoramic view of the southern limb of an anticline at the Tabular Jura-Upper Rhine Graben border towards north. The gentle, forested hill in view constitutes the southern limb of an E-W-trending anticline, whose vertical growth had disrupted the formerly contiguous Sundgau gravel sheet (Fig. 3). The gravel sheet at the top of the anticlines is at present completely eroded except for few (mostly siliceous) pebbles, which are occasionally found in tree roots in the forest between the villages of Courcelles and Pfetterhouse, up to an elevation of approx. 550 m a.s.l., i.e. some 130 m higher than the observation point. The maximum thickness of the gravel sheet itself, on the other hand, is between 5 and 20 m. The fold amplitude thus exceeds the gravel thickness by up to an order of magnitude. Consequently, it is concluded that the growth of the anticline and the concomitant formation of topography must postdate the deposition of the Pliocene Sundgau gravels with a reported biostratigraphic minimum age of 2.9 million years.

2. South of Réchésy (F), abandoned quarry

Swiss coordinates: 575'950/261'350

Quarry in Late Eocene-Lower Oligocene («Sannoisian») border conglomerates of the Upper Rhine Graben, which were deposited during an incipient phase of rifting along the N-limb of an E-W-trending extensional flexure. The conglomerates are almost purely monomict: components of reworked Upper Jurassic limestones predominate by far. Subordinately, ferric pisolithes of the «Sidérolithikum» are found. Pressure solution pits and stylolithes are very common. Intercalation of cm- to dm-thick calcarenite layers occur. Dip of strata is gently towards N. The conglomerates show that the post-2.9 million years anticlines had a precursor as extensional flexures during the opening of the Upper Rhine Graben (see Fig. 5).

3. Seppois-le-Haut (F), abandoned gravel pit

Swiss coordinates: 581'600/264'400

Gravel pit offering an exposure of the Pliocene Sundgau gravels in the Largue valley, just upstream of the village of Seppois-le-Haut. The crudely bedded gravels are grain-supported and reveal two up to dm-thick sand layers that pinch out laterally. Both the upper and lower sand layers are visibly affected by NW-SE-trending conjugate normal faults that accommodated NE-SW-extension (Fig. 3). The occurrence of normal faults at this locality is kinematically explained as a local accommodation feature in a releasing bend of a NNE-trending, left-lateral strike-slip fault (see bottom right inset in Fig. 2).