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Plio-Pleistocene folding in the southern Rhinegraben recorded by the evolution of the drainage network (Sundgau area; northwestern Switzerland and France)

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Key words: Southern Rhinegraben, Burgundy Transform Zone, neotectonics, fault reactivation, tectonic geomorphology, river terraces, drainage evolution

ABSTRACT

The southern Rhinegraben represents a key area to unravel the Neogene paleohydrographic history of the northern Alpine foreland. At least, three successive main drainage systems are documented by the youngest sediments of the graben fill. They are respectively pre-, syn- and post-dating the folding of the Jura Mountains (about 10-5 Ma ago).

Pliocene to recent uplift and shortening of the Pliocene fluvial gravel ("Sundgauschotter"), which accumulated on a nearly plain surface, and the progressive deflection and capture of rivers resulted from reactivation of pre-existing Paleogene faults. The alluvial terraces along the major rivers of the Sundgau area show upward warping near the uplift areas. Furthermore, river beds responded to uplift by lateral shift.

During the Pliocene-Pleistocene, fluvial drainage diverted stepwise from the initial, westwards directed course (towards the Bressegraben) to the N (into the Rhinegraben): Firstly, uplift in the south at the boundary between the Rhinegraben and the Jura Mountains induced a northwards directed migration of the middle Pliocene, E-W flowing paleo-drainage system. Successively, a late Pliocene/early Pleistocene lowering of the base level in the Rhinegraben north of Mulhouse resulted in the capture by southwards directed backward erosion of this system into the Rhinegraben, as likewise documented by the reconstitution of the paleo-drainage patterns in the Sundgau area. In addition, a gradually capture moving from NE to SW has been identified for the Sundgau catchment area.

ZUSAMMENFASSUNG

Die Morphogenese des südlichen Rheingrabens hängt stark mit der hydrographischen Entwicklung des zentralen Alpinen Vorlandes zusammen. In den jüngsten Ablagerungen der Grabenfüllung sind nämlich mindestens drei Hauptentwässerungssysteme dokumentiert. Die fluviatilen Sedimente vom mittleren Miozän bis zum Quartär wurden vor, während und nach der Hauptphase der Jurafaltung abgelagert (ca. 10-5 Ma).

Eine Reaktivierung von paläogenen Brüchen während des Plio-Pleistozäns ist sowohl durch die Auffaltung der pliozänen Sundgauschotter als auch durch die fortschreitende Ablenkung und Anzapfung von Flüssen im südlichen Elsass (Sundgau) belegt. Alluviale Terrassen entlang der Hauptflüsse im Sundgau wurden in der Nähe von Antiklinalen gehoben und verstellt. Das weist darauf hin, dass die tektonische Aktivität zumindest bis in das Pleistozän anhielt.

Die Rekonstruktion des Paläoentwässerungssystems zeigt, dass die Umlenkung des gesamten Flussnetzes im Sundgau, das während des Pliozäns nach Westen in den Bressegraben gerichtet war und sich dann nach Norden in den Rheingraben reorientierte, schrittweise stattfand: Infolge von Hebungen im Süden entlang der Rheingraben/Jura-Grenze migrierte der mittelpliozäne Hauptfluss nordwärts und die Absenkung im Rheingraben nördlich von Mulhouse während des Spätpliozäns und des Pleistozäns führte dann zur allmählichen Anzapfung des Entwässerungssystems von Norden.

Introduction

The southern Rhinegraben consists structurally of a mosaic of blocks, which are frequently delimited by predominant, more or less N-S trending faults (Fig. 1). The bounding faults have been active in response to stress regimes that varied with time (e.g. Ziegler 1992). In particular, reactivation of pre-existing Palaeozoic faults determined the configuration and large-scale orientation of the Cenozoic rift system (Schumacher 2002). In the south, both Palaeozoic and Cenozoic tectonic structures influenced the evolution of the adjoining Jura Mountains, when these were folded and thrusted since the Miocene (Laubscher 1978, 1986, 1992, 2001; Ziegler 1994; Ustaszewski et al. 2001). The changing morphology of the southern Rhinegraben and the surrounding areas affected the paleo-hydrography of the northern Alpine foreland. In particular, local and temporal changes of the base level in the wider southern Rhinegraben area led to river deflections and drainage reversals (Liniger 1966; Petit et al. 1996; Villinger 1998). The best example is the

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Plio-Pleistocene evolution of the main drainage system in the study area. During the Pliocene, paleoflow was directed to the west into the Bressegraben, whereas during the early Pleistocene it changed towards the north into the Rhinegraben (Fig. 2). Consequently, the southern Rhinegraben is a key area in which all these major hydrographic changes of the northern Alpine foreland occurred. This rises the obvious question which processes actually controlled the hydrographic evolution of the area. This paper will pay attention to the diverse factors which affected the evolution of the drainage network in an area of moderate humid climate and slow tectonic deformation.

In comparison to geophysical and geodetic investigations, geological and geomorphologic studies in the Rhinegraben area have been subordinate during the last 20 years. Particularly, geomorphologic analyses dealing with the topographic evolution of the last few million years are wanting, despite some notable recent studies by Vogt (1989, 1992) and Nivière & Marquis (2000).

The principal purpose of this paper is, therefore, to evaluate the effects of local and regional tectonic movements on the Plio-Pleistocene evolution of the southernmost drainage network of the Rhinegraben, and to assess the formative role of climatic change.

Geological Setting

The study area covers the southernmost part of the Rhinegraben. In the south it is bounded by the Jura Mountains, and to the west and east, respectively, by the Vosges and the Black Forest, while it is bounded by the Alsacian plane in the north (Fig. 1). This area is known as the Sundgau. Geomorphologically, it is characterized by the occurrence of a hilly landscape with altitudes decreasing from south to north. The relief flattens rather abruptly at the latitude of Mulhouse, i.e., north and west of a NE-SW trending scarp between Dannemarie and Mulhouse (Fig. 1). The Rhine valley represents the eastern boundary of the Sundgau (Fig. 1).

The NNE trending Rhinegraben forms the central segment of the European Cenozoic rift system, which extends from the North Sea to the Mediterranean (e.g. Ziegler 1990). The Rhinegraben is bounded in the north by the Rhenish Massif, whereas in the south it is bounded by the Jura Mountains (Illies & Fuchs 1974; Ziegler 1992, 1994). In adjacent northern France, the rift system continues to the south within the Bressegraben. The two grabens are linked by the so-called Burgundy Transfer Zone, a transtensional, sinistral structure (Laubscher 1970; Rat 1978; Bergerat & Chorowicz 1981) that follows pre-existing Permo-Carboniferous faults bounding the ENE-WSW trending Late Paleozoic Burgundy trough (Boigk & Schöneich 1970; Allenbach 2004). These faults became reactivated when the Rhinegraben and the Bressegraben formed (Laubscher 1986, 2001; Ziegler 1990; Schumacher 2002). The investigated area is located near the eastern end of the Burgundy Transfer Zone (Fig. 1). Within the context of this paper, additional Palaeozoic faults, which have been described by Edel & Fluck (1989) and Lutz (1999) are important. These include a WSW-ENE striking fault at the latitude of Mulhouse that pre-conditioned the northern border fault of the horst of Mulhouse (Fig. 1), a fault crossing the area between Altkirch and the northern Ajoie that represents an ancestor of the Illfurth fault and W-E trending faults near the boundary between the Rhinegraben and the Tabular Jura (Giamboni et al. 2004).

The Bressegraben and the Rhinegraben subsided since the late Eocene and continental as well as shallow-marine clastics and carbonates accumulated (e.g. Pflug 1982). Coarse material dominates at the margins of the rift becoming finer-grained to the centre (see review by Duringer 1988). During initial rifting in Priabonian times left lateral shear along pre-existing Permo-Carboniferous structures led to the development of a pull-apart basin in the western part of the southern Rhinegraben, the so-called Dannemarie basin (Fig. 1). It represents an asymmetric depocenter containing about 1000 m sediments (Doebl 1970). To the west, the basin is bounded by the Illfurth fault (Fig. 1). To the south, it is delimited by the flexure zone of northern Ajoie (Liniger 1964, 1967). Palaeozoic structures in the basement pre-conditioned the development of these (and other) faults in the sedimentary cover (Schumacher 2002).

During the early and middle Miocene a new tectono-sedimentary system was established. The southern Rhinegraben underwent uplift and erosion. As a result, Late Chattian to Middle Miocene deposits are missing (Fischer 1965; Villemin et al. 1986). Uplift started south of the Rhinegraben in the area of Delémont (Fig. 1) and propagated northward to the Kaiserstuhl area as inferred from Tertiary fluvial sediments in the Jura Mountains (Berger 1996; Kälin 1997; Laubscher 2001). Alternatively, localized uplift of the southern margin of the Rhinegraben may have resulted from transpressional reactivation of the Burgundy Transform Zone in reaction to the establishment of a local stress field that was induced by NW-SE oriented compression (Laubscher 2001; Schumacher 2002; Giamboni et al. 2004).

Present day drainage pattern

The southern Upper Rhinegraben includes two main drainage basins separated by a NNW-SSE trending first-order watershed. In the west, a small area drains to the southwest via the Doubs valley into the Bressegraben and, hence, belongs to the Mediterranean catchment. In the east, including the Sundgau, drainage is directed towards the Rhine river that is part of the North Sea drainage.

The western area is drained in the south by the Allaine, Coeuvatte and Vendline rivers, which are sourced in the Tabular Jura (Ajoie). Its northern part is drained by the Bourbeuse and the Savoureuse rivers. In both areas the upper courses of the rivers are approximately parallel to each other and turn to the west towards the Doubs river near Montbéliard (Fig. 1).

The eastern area is drained in the south by the Ill river, in-

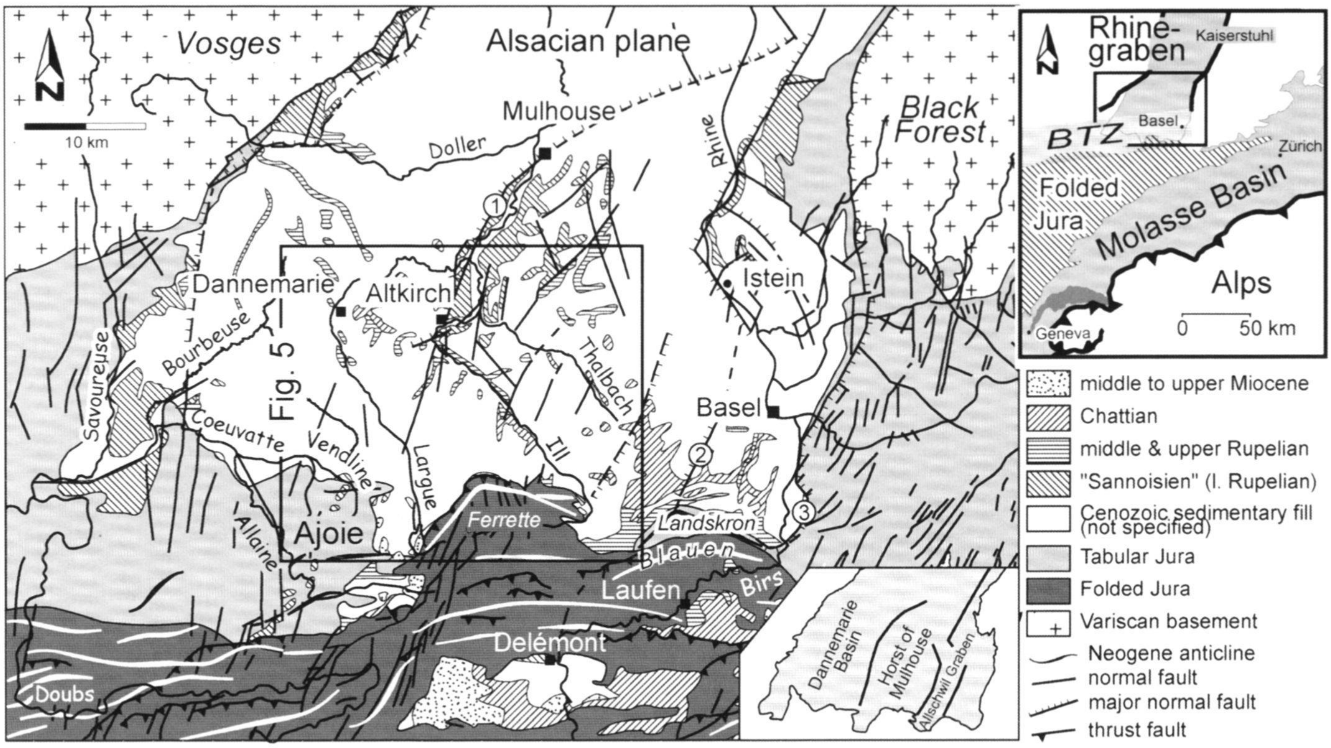


Fig. 1. Geological map of the southern Upper Rhinegraben and its surrounding area. Inset shows the main features of the Alpine foreland north of the Central Alps. The Vosges and Black Forest are pronounced shoulders of the graben. The regional main rivers are the Rhine, Rhône, Aare and Doubs. BTZ = Burgundy Transform Zone; numbered faults: 1) Illfurth Fault, 2) Allschwil-Istein Fault, 3) Rhine Valley Flexure.

cluding the reaches Largue and Thalbach, and in the north by the Doller. All are entering into the Rhine valley.

The Ill river originates in the Ferrette anticline where it flows eastwards. After turning around the eastwards plunging anticline it is directed to the NW transecting Pliocene Sundgau gravel and Oligocene deposits. Close to Altkirch its course changes sharply to the NE, where it incises the Early Rupelian ("Sannoisian") marls. Near Mulhouse the river enters the Alsacian plane and flows to the north parallel to the Rhine river, joining it near Strasbourg.

The Largue river shows a similar pattern of flow, but in contrast to the Ill river, its northwards directed upper course is not incised into Oligocene sediments. Near Dannemarie the river sharply turns to the NE, incising Late Rupelian marls. It joins the Ill river near Illfurth.

The Thalbach river, a main tributary of the Ill has its source in the eastern part of the Sundgau and flows to the NW, incising Sundgau gravel and Oligocene deposits. It reaches the Ill river east of Altkirch, downstream of a gorge cut into Early Rupelian sediments.

In the north, the Doller river was cut into the Permo-Carboniferous rocks of the southern Vosges. Within the Vosges mountains it flows to the SE and then to the E, when it reaches the Alsacian plane. The confluence with the Ill river is north of Mulhouse (Fig. 1).

History of the southern Rhinegraben drainage

In the early Pliocene, the northern Alpine drainage was directed eastward across the Swiss Molasse plain to the paleo-Danube river (Fig. 2 a). The upper reaches corresponded approximately to the present Aare river. It has been termed the Aare-Danube System (Liniger 1966). A first capture of this system to the north into the Rhinegraben was postulated to have occurred between 4.9 Ma and 4.18 Ma (Petit et al. 1996) as evidenced by an episode to protogyne cobbles and alpine minerals identified in the Alsatian plain (Lauterbourg section) by Geissert et al. (1976) and Boenigk (1987). It should be noted that the chronometric ages are based on rodent biochronology and the values originally given by Petit et al. (1996) have been updated after Fejfar et al. (1998). In our opinion this very short episode is questionable, because the North European Grabens, the Central Graben of Netherlands and the Bressegraben are devoid of alpine material. Alternatively, the observed alpine material could have been provided by local reworking of Oligocene and/or Miocene Molasse sediments of northern Jura and southern Upper Rhinegraben and has not to be attributed to a northward flowing paleo-Aare.

Strong subsidence in the Bressegraben during early to middle Pliocene caused headward erosion from the west, which resulted in the capture of the paleo-Aare river by the "paleo-

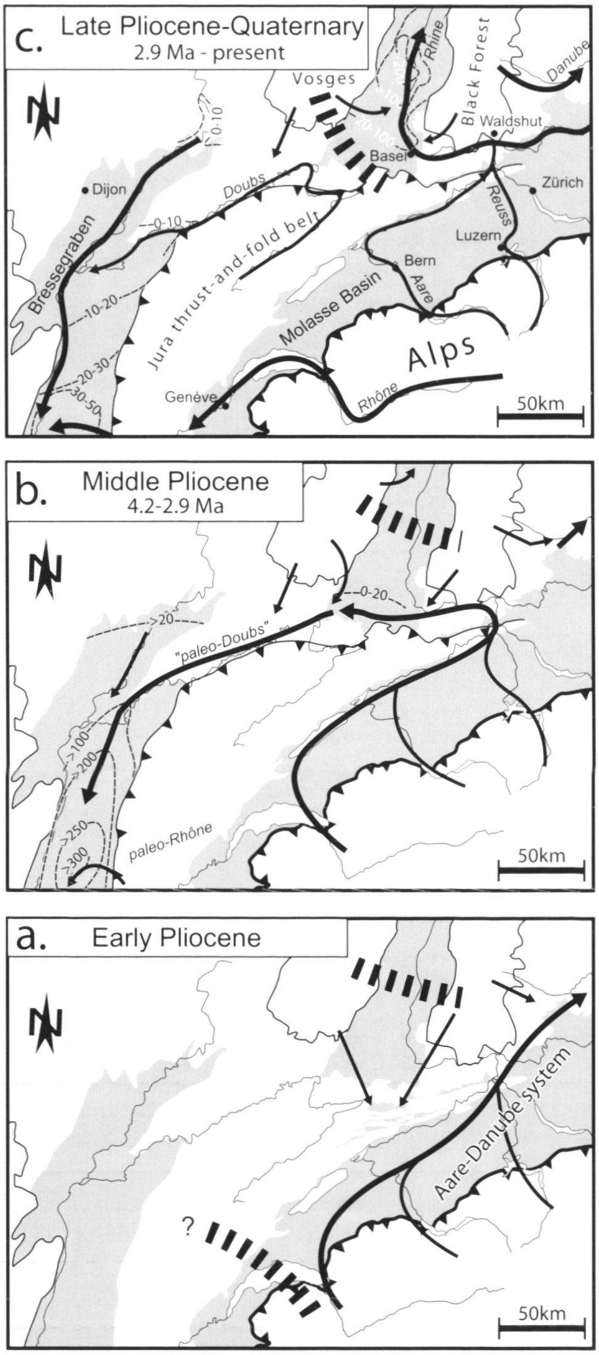


Fig. 2. Main paleohydrographic changes in the Alpine foreland during the Neogene. Thick arrowed lines represent main rivers, thin arrowed lines tributary reaches (after Liniger 1966; Villinger 1998; Petit et. al. 1996). Dashed lines correspond to isopachs of the Pliocene (Fig. 2b) and Quaternary (Fig. 2c) sedimentary cover (after Doebl, 1970; Debrand-Passard, 1984).

Doubs river" (Fig. 2 b) in late Zanclean time (around 4.2 Ma according to new calibration by Fejfar et al. 1998, Petit et al. 1996). At the same time, uplift of the southeastern Black Forest decoupled the paleo-Aare from the paleo-Danube and a new episode of fluvial deposition in the southern Rhinegraben and northern Tabular Jura (Ajoie) started: the paleo-Aare river flowed along the northern side of the Jura Mountains, crossed the southern Rhinegraben to the west and continued via the Doubs valley to the Bressegraben (Fig. 2 b), depositing the so-called Sundgau gravel. It consists of up to 70% material originating in the Alps and the Molasse basin. Analyses of the gravel composition by Bonvalot (1974) postulated that the Sundgau gravel and its equivalents in the northern Bressegraben ("Cailloutis de Desnes" and "Sables de Neublans") were deposited by one and the same river during the middle Pliocene (late Zanclean to early Piacenzian, 4.2-2.9 Ma; Petit et al. 1996).

During late Pliocene and early Quaternary, the Bressegraben was uplifted. Simultaneously, the southern Rhinegraben subsided (Doebl 1970). As a consequence, the paleo-Aare river was once again captured and forced to flow northward through the Rhinegraben (Fig. 2 c; Liniger 1966; Petit et al. 1996), depositing up to 200m of Alpine gravel in the Rhine Valley north of Basel.

Finally, during the Pleistocene the Alpine Rhine river, sourcing in the eastern Swiss Alps, joined the Paleo-Aare near Waldshut (Fig. 2) forming the present Rhine river system (e.g. Villinger 1998).

This main paleohydrographic change is also recorded in the northeastern Bressegraben: the supply of Alpine material into the graben during the late Zanclean and early Piacenzian abruptly ceased when the paleo-Aare was captured near Basel to the north (Fig. 2 b, c; at 2.9 Ma). However, a small amount of weathered Alpine material still reached the northeastern Bressegraben during the Pleistocene (Bonvalot et al. 1984; Petit et al. 1996) due to some westward draining rivers that locally reworked Pliocene gravel in the Sundgau.

Tectonism post-dating the Jura folding

The Pliocene "Sundgau gravel" (4.2-2.9 Ma) was deposited by a shallow braided river, having a shifting network of unstable, low-sinuosity channels. Depth of the channels was of the order of 1m. The deposits are dominated by clast-supported, crudely bedded longitudinal bedforms and lag deposits, as well as transverse bedforms with planar cross-beds. Thin sandy, bar-top sheets are formed at bar margins by surface runoff. According to Schumm (1985), the slope of such low sinuosity braided rivers is in the order of 1.5 to 2.0‰.

These sedimentological characteristics strongly support the assumption that the base of the "Sundgau gravel" formed on a nearly planar and horizontal surface. Therefore, this planar surface represents an ideal marker horizon to record post Middle Pliocene differential vertical displacements due to folding and/or faulting.

The gravel's base map (Fig. 3) reveals a system of narrow folds with predominantly SW-NE trending and laterally plunging fold axes. The syn- and anticlines largely correspond to

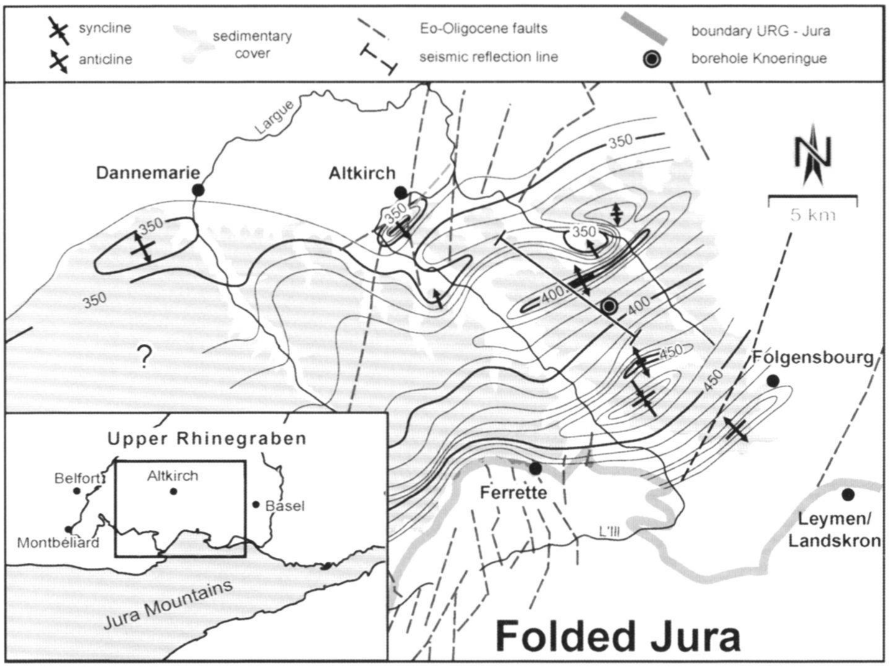


Fig. 3. Isohypse map of the base of the Pliocene Sundgau gravel (after Giamboni et al., 2004).

topographic depressions and highs, respectively, except at places where they are eroded by antecedent rivers. Even the different fold amplitudes exhibit a general conformability with the topographic structures. The area with the highest relief (up to 550m), i.e. the northern Ajoie, exhibits the most accentuated anticlines with the largest amplitudes (90 and 120m; Giamboni et al. 2004). In contrast, folds with small amplitudes (10-20m), such as those west and northwest of Folgensbourg, or south of Dannemarie (Fig. 3) correspond to a gentle, slightly undulating relief. A further significant feature visible on the map is the general rise of the "Sundgau gravel" base from north to south (Fig. 3). This, and the accentuated rise at the northern rim of the Ferrette anticline, conforms to the geometry of the folded Jura front at this place.

Some of the minor undulations in the gravel's base (e.g. in the area W of Folgensbourg or S of Dannemarie) might correspond to the progressive filling of a not exactly planar surface. However, the alignment of folds observed in the gravel's base is highly systematic throughout the contoured area. This strongly suggests that their origin is indeed related to tectonic processes

In fact, the upfolding of the Sundgau gravel is spatially related to late Palaeozoic structures of the basement which have been transpressively reactivated (Ustaszewski et al. 2001; Giamboni et al. 2004).

Methods and Strategy

To evaluate how moderate tectonic movements affect the geomorphology and, hence, the drainage system in the study area, we apply a step-by-step approach, each successive step being based on another method. For each step the results and interpretations are given below.

To relate folding and uplift of the Pliocene marker horizon to movements along faults in the basement seismic sections were investigated.

To reconstitute the paleo-drainage systems fluvial geomorphologic relics were mapped. Some of the relics, such as fill terraces, alluvial fans and cones, are obviously associated with accumulation, while others, such as cut terraces, dry valleys, wind and water gaps and paleo-meanders, are related to erosion. In conjunction with their stratigraphic record, these features form the base for the reconstruction of previous river courses.

To elucidate the effects of external environmental forces, the principle of a steadily decreasing gradient was applied, as may be expected for rivers that reached the equilibrium stage, by no longer being affected by tectonic movements, climate fluctuations, base level changes etc. (Schumm 1986, 1993; McKeown et al. 1988). With respect to tectonic folds, two types of river courses are distinguished: (1) longitudinal rivers flowing parallel to a fold or to a fold-and-thrust belt and (2) transverse rivers flowing almost perpendicular to tectonic structures (e.g. Burbank et al. 1996). The latter kind of rivers is antecedent, if it was established prior to the growth of a structure and if it maintained their original course across the zone of uplift. In addition, however, uplift of folds may lead to the deflection of a single reach or to the merging of several tributaries.

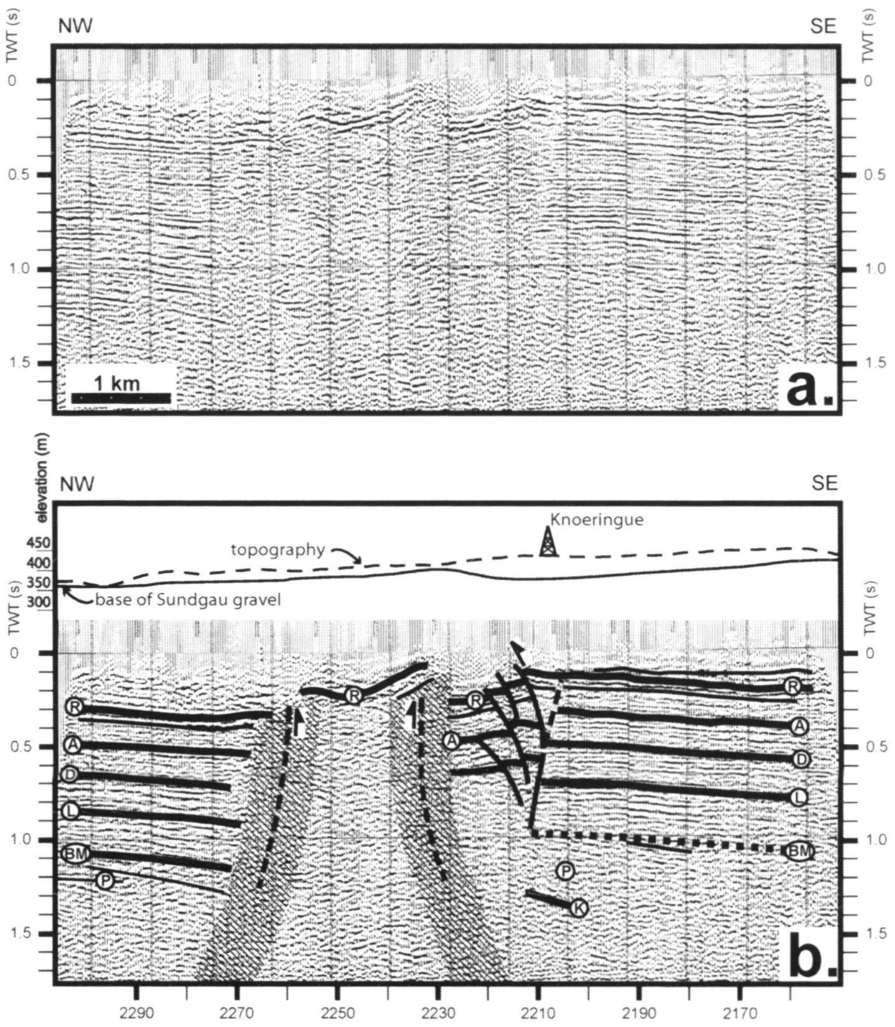


Fig. 4. Seismic profile through the Sundgau (section of Shell France). a: non-interpreted and non-migrated section. b: interpreted section. R = Upper Rupelian basal marine sands; A = unconformity at the base of the Tertiary; D = top of Dogger; L = top of Liassic; BM = unconformity at the base of the Mesozoic; P = reflectors within the Permian; K = top of the crystalline basement; cross-hatched = diffuse fault zone. The base of the Pliocene Sundgau gravels, as derived from the isohypse map (Fig. 3), as well as the surface topography are shown in the upper part of the figure. Their vertical scale is exaggerated by a factor of 3. For location see Fig. 3.

Results and their Interpretation

Post-Pliocene folding

Data

A reflection seismic section shot between Altkirch and Folgensbourg (Fig. 3) allowed to compare the surface topography, undulation of the base of the Sundgau gravel and other subsurface structures. On this section (Fig. 4) two well imaged segments are characterized by a sequence of rather parallel, SE-dipping reflection bands. Inbetween a 3 km wide domain displays low reflection quality. Across this domain the correlative reflection bands of the two segments are vertically displaced in the order of 0.2 s TWT (400-500 m). The subsurface structures, surface topography and base of the Sundgau gravel reveal some common features. The upwarped base of the Sundgau gravel (around registration point 2230) coincides with the highest position of the up-thrust reflection band R (Fig. 4).

Interpretation

The stratigraphic position of the reflectors has been calibrated by means of the well Knoeringue (Fig. 4). The virtually parallel reflection bands represent Early Triassic to Late Jurassic sediments (about 1.0 to 0.5 s TWT) covered by Paleogene deposits. Obviously, a zone of normal faults has been formed during early Oligocene times within the intermediate domain. It links-up with the lower part of the Mulhouse horst to the NW. The two flanking sequences represent blocks whose tilting is related to the Paleogene rifting of the Rhinegraben and to sinistral transtension within the Burgundy Transfer Zone. However, these upper parts (above 0.3 s TWT) show clear evidence for post-Rupelian compressional or transpressional deformation. The pronounced reflection horizon R, which represents basal marine sands of late Rupelian age, is folded and up-thrusted towards SE (between registration points 2260 and 2230). Transpressional deformation is also indicated by a flower-structure like pattern of steep reverse faults near well Knoe-

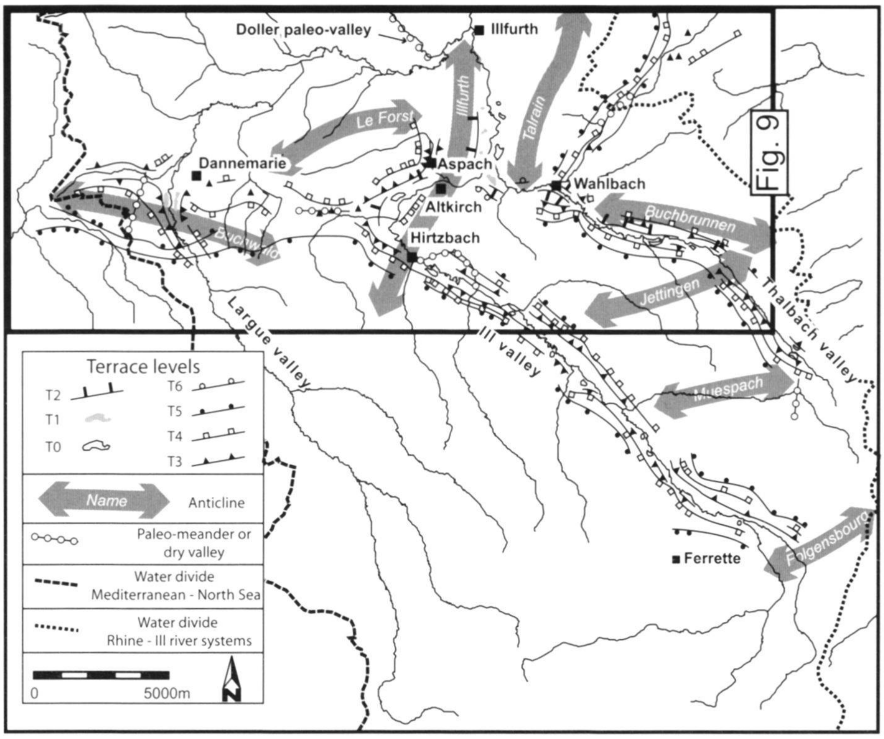


Fig. 5. Map of terrace remnants (T5-T0), paleomeanders and deformed dry valleys plotted on a present-day hydrographical map. Anticlines are inferred from the base map of the Sundgau gravel (Fig. 3) as well as from DEM analysis and field data.

ringue (registration point 2210). This configuration suggests a basement-rooted, transpressional deformation of a pre-existing normal fault zone. Therefore, it appears that the Burgundy Transfer Zone, which follows a Late Paleozoic fracture systems, might have been reactivated by Neogene and Quaternary compression resulting in a dextral transpression (Schumacher 2002; Giamboni et al. 2004).

Assuming an initially plane base of the Sundgau gravel sequence, the warping would point to a Pliocene to Quaternary activity of the subjacent reverse faults. However, it cannot be excluded that Neogene up-thrusts formed local swells and depressions prior to the deposition of the Sundgau gravel. When compared to the surface topography, however, the up-warped base of the Sundgau gravel appears to coincide locally with a topographic depression (registration point 2230). Such a relief inversion resulted from enhanced erosion of an elevated area. A different situation occurs in the area around registration point 2210. There, a local gentle hill spatially coincides with a depression at the base of the Sundgau gravel. At this flower structure at Knoeringue tectonic movements occurred probably during the Miocene, i.e. before the deposition of the Sundgau gravel and, therefore, the topographic hill is the result of enhanced fluvial erosion controlled by the uplift in the southeast at point 2230 (see below).

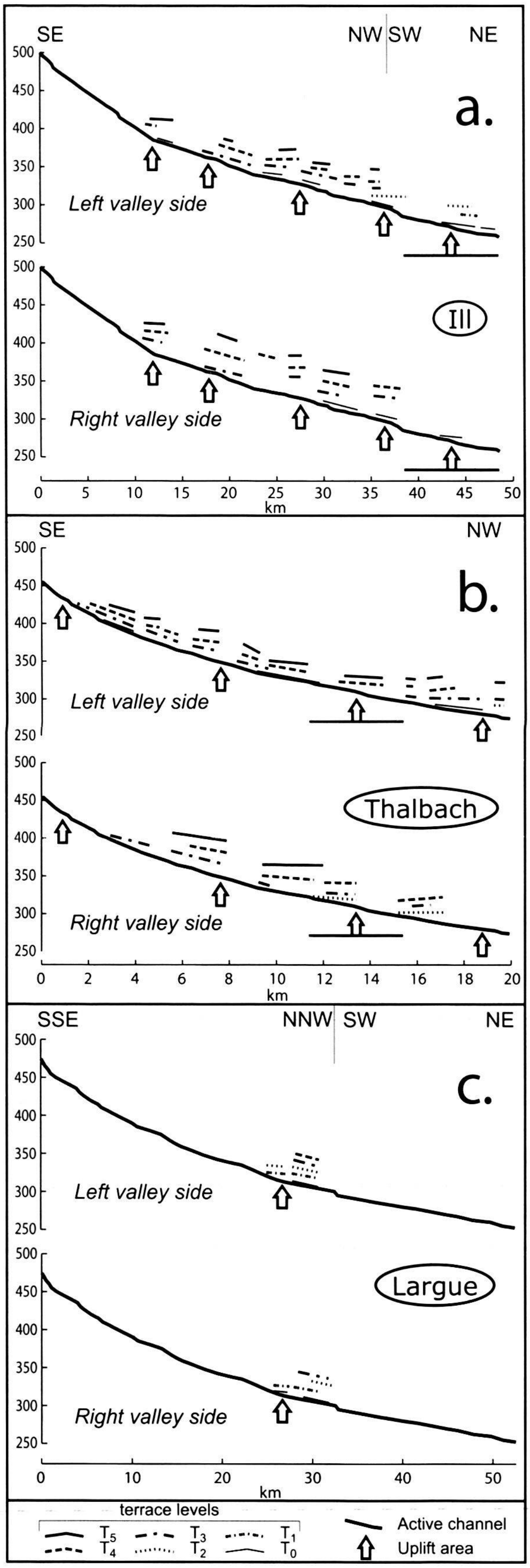
In addition, Plio-Pleistocene tectonic structures north to the area covered by the Sundgau gravel were interpreted by Nivière & Winter (2000) to indicate compressive or transpressive reactivation of the Oligocene Illfurth fault in the northwest and the fault bounding the horst of Mulhouse in the north. All these structures are stated to root in the basement (Edel & Fluck 1989).

Paleo-river systems

Methods

River terraces are remnants of old river beds. Using their relative altitude above the present valley floor and their position on the valley slope, remnants can be correlated and different paleo-river systems can be differentiated (e.g. Haldimann et al. 1984). However, deposition, erosion and dissection by alluvial fans and cones can perturb the results and need therefore to be taken into account.

As a first step of analysis, all horizontal (0-1°) or subhorizontal (1-2°) surfaces along the three main rivers draining the Sundgau, i.e. the Thalbach, Ill and Largue (Figs. 1, 4) were considered for potential terrace remnants. Their exact geometry and topographic position were determined using aerial photographs (Fig. 5). In addition, a Digital Elevation Model (DEM) was employed to identify dry valleys, paleo-meanders, and water and wind gaps. In a second step, alluvial terraces and other planar features were differentiated, especially the multi-generation loess layers (Khodary-Eissa 1968; Bibus 1990), which cover discordantly large parts of the Sundgau. Under a thin loess cover (<3 m) proper flat and semi-planar terrace remnants are still recognisable as slightly inclined,



convex surfaces. A thick loess cover, however, obliterates the remnants. The thickness of the loess cover was estimated by the amount of gravel on a remnant plane. Only gravel-rich surfaces were analysed. For the correlation of the terrace remnants, thin loess cover and relative elevation above the present-day river channel, as well as their proximity to known uplift areas, were considered. To avoid miscorrelation due to the interfingering of terraces and alluvial fans formed by tributaries (fans and cones cause a dissection of the terrace and their flat edge can be confused with the edge of a terrace), such alluvial features were excluded from further analysis.

Assuming a longitudinal slope decrease of the paleo-river similar to that of the present river, the geomorphologic remnants were correlated (Figs. 6, 7). Because of dissection, right and left valley side were studied separately. Where laterally plunging folds are crossed by rivers (Fig. 3), a different uplift intensity between the left and the right valley side may have occurred.

As a proxy for the magnitude of river incision, the following ratio of valley floor width vs. valley height (V_f) was used (after Bull & McFadden 1980):

$$V_f = V_{fw} / [(E_{ld} - E_{sc}) + (E_{rd} - E_{sc})] / 2$$

where V_{fw} is the width of the valley floor and E_{ld}, E_{rd}, E_{sc} are the altitudes of the left and right divides and of the present stream respectively (see below).

Additional information about the source area of the paleodrainage systems was derived from the lithology of pebbles composing the terraces.

In the absence of more precise dating, the relative age of the mapped surfaces was deduced by means of their relative elevation and position relative to the Pleistocene terraces of the Rhine river north of Basel. The Rhine terraces are stated to be formed during the Late Pliocene to Quaternary main glacial stages of the Alps and their northern foreland (e.g. Gutzwiller 1908; Penck & Brückner 1909; Wittmann 1961; Hantke 1978; Haldimann et al. 1984; Verderber 1992); the more elevated the alluvial terraces are, the older they are.

The classical ice age chronological system (Penck & Brückner 1909) can be and is still used as a chronostratigraphic frame related to morphostratigraphy. Recent studies of circum-Alpine Quaternary deposits show, however, that this scheme is not suitable for areas far from the study area of Penck and Brückner (e.g. Schlüchter 1989; Bini 1997). Nonetheless, the scheme provides a useful chronology for southern Germany and surrounding areas, also because alternative chronostratigraphic time scale is not available at this moment. However, investigations in the area between Basel

Fig. 6. Longitudinal profile of the Ill (a), Thalbach (b) and Largue (c) rivers from the headwaters of the main branch to the mouth, showing the location and elevation of fluvial terrace segments. Uplift areas are marked by vertical arrows. Note the kink in profile direction marked by a vertical line in the Figures 6a and 6c.

and Lake Constance have newly led to some refinement of the scheme by the introduction of the Haslach as a new glacial period between the Günz and the Mindel (Verderber 1992; Schreiner 1996).

Traditionally, the alluvial terraces along the Rhine valley from Basel to Mulhouse are related to Penck and Brückner's system (e.g. Gutzwiller 1912; Fischer et al. 1971; Bitterli-Brunner et al. 1984; Verderber 1992). However, the Pleistocene alluvial processes were also affected by tectonic movements (e.g. Théobald 1948; Verderber 1992; Nivière & Marquis 2000;). In the Sundgau, therefore, the landscape probably documents the response to both climate change leading to the aggradation of the Sundgau gravel and the Pleistocene sedimentary infilling of the Rhinegraben and to tectonic activity that induced, amongst others, the development of strath terraces cut into the bedrock (Bull 1990).

Results

The formation of the terraces along the Rhine river was hitherto mainly explained by terrace aggradation during glacial periods and by incision and formation of fill-cut terraces during interglacial intervals. The terraces within the Sundgau, however, differ locally from this scheme, mostly because: (1) there is a maximum of 6 terrace levels, but only along the Ill valley (Fig. 6 a); (2) the Largue valley depicts terraces only near the uplift area (Fig. 6c) and (3) the terraces along the Ill, Thalbach and Largue consist of material very similar to the Sundgau gravel with only small amounts of Jurassic material. Furthermore, the paleo-Ill and paleo-Largue were affected by the advance and retreat of glaciers during the Riss glacial maximum only, when the northern Folded Jura was covered by ice (Hantke 1978).

Since the terrace material is lithologically very similar to the Pliocene Sundgau gravel and contains only locally components originating from the Jura Mountains, most terraces appear to be strath terraces incising the Pliocene and Oligocene substratum. Local accumulation, lateral erosion (valley asymmetry) as well as terrace formation within uplifted areas (Largue valley) resulted from climate-induced increase on water discharge and a tectonically controlled incision, similarly concluded for the Rhine river in the Sierentz depression (Nivière & Marquis 2000).

South of Hirtzbach, remnants occur in the Thalbach and Ill valleys. North of Hirtzbach, they are dispersed within a E-W trending zone. The terraces in these areas are situated mainly transverse to the present day drainage (Fig. 5). The Ill valley displays six different terraces (Fig. 6a): 3 high (T_5-T_3) and 3 lower levels (T_2-T_0). Upstream Hirtzbach, only the three high terraces (T_5-T_3) and a lower one (T_0) were identified. T_0 is well recognisable all along the river, whereas T_5-T_3 have no correlatives downstream of Hirtzbach. However, remnants west of Hirtzbach are fitting well to T_5-T_3 (Figs. 6, 7), implying a westward continuation of the terrace system. T_2 and T_1 are present only in the lower, SW-NE directed valley segment.

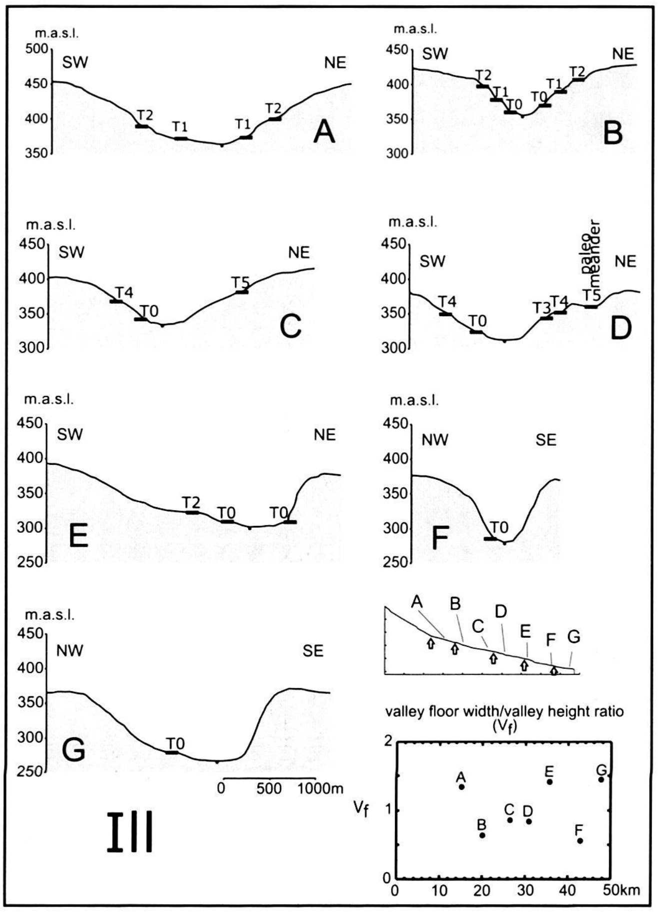


Fig. 7a. Valley cross-sections of the Ill valley. Position of the cross sections is shown on the longitudinal river profile. Areas of uplift are marked by vertical arrows. Valley floor width/valley height ratios are plotted on a scatter graph.

In the Thalbach valley, the T_5 terrace has no correlatives to the west. However, remnants of a terrace higher than T_5 occur to the west and document an ancestor river (Fig. 5). The remnants of T_5 and T_4 along the Thalbach valley end at kilometre mark 18, west of Wahlbach. They continue to the NNE into the tributary valley north of Wahlbach (Fig. 5) and cross the present-day water divide (Figs. 3, 6), displaying a decreasing gradient to the NNE. Pebbles of Middle Jurassic carbonates within the T_3 level along the Thalbach river indicate that the previous catchment area extended into the northern Jura Mountains. In fact, such material is not known from the Pliocene Sundgau gravel (Liniger 1967) and hence, a reworking of the gravel deposits can be excluded.

During the latest Pliocene and the early Pleistocene, the paleo-Doller flowed to the SSE, as documented by continuous terraces beginning at the foothills of the Vosges and ending few kilometres north of Aspach (Briquet 1930; Ménillet et al. 1989). T_4 relics near Aspach (Fig. 5) are situated along the axis of this paleo-stream and contain material eroded from the Vosges. Therefore, these terrace relics represent the southern

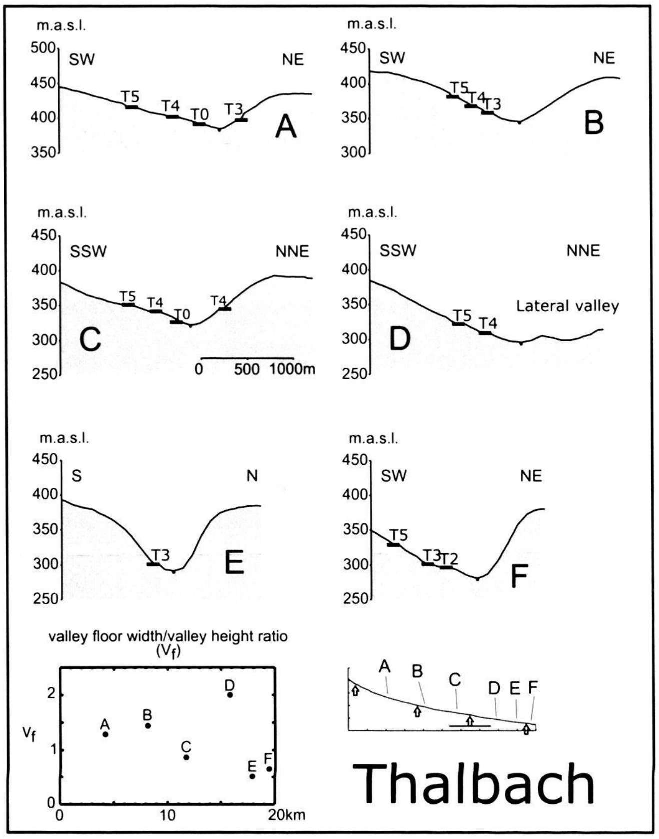


Fig. 7b. Valley cross-sections of the Thalbach valley. Position of the cross sections is shown on the longitudinal river profile. Areas of uplift are marked by vertical arrows. Valley floor width/valley height ratios are plotted on a scatter graph.

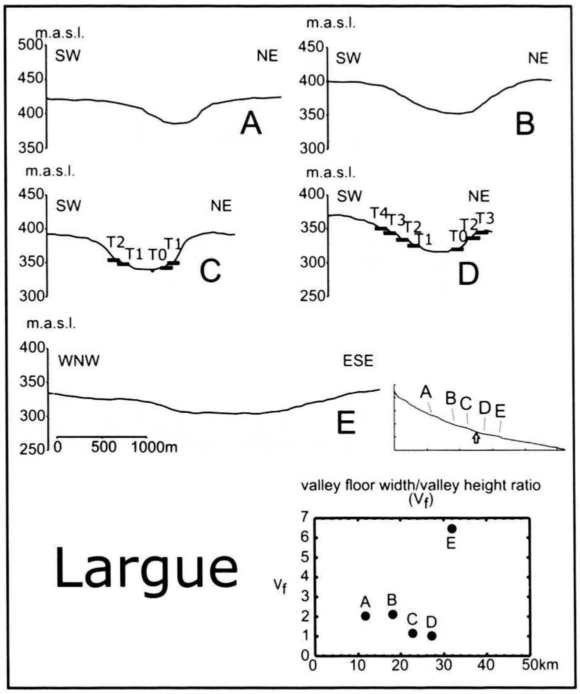


Fig. 7c. Valley cross-sections of the Largue valley. Position of the cross sections is shown on the longitudinal river profile. Areas of uplift are marked by vertical arrows. Valley floor width/valley height ratios are plotted on a scatter graph.

continuation of the paleo-Doller river into the Sundgau, as already postulated by (Briquet 1930).

To the west, T_5 remnants occur across the present Largue valley and continue south of the Buchwald hill. North of the Buchwald hill only T_4 and T_3 relics are present (Fig. 5). Furthermore, the Largue valley exhibits only terraces lower than the T_5 level, i.e. T_4-T_2. No terraces were found neither on its upper valley, nor north of Dannemarie (Fig. 6 c).

None of the investigated terrace systems (Fig. 6) show a steadily decreasing gradient. The analysed remnants of terraces reveal either an upwarping or a distinct increase in gradient in downhill direction. Low gradients generally occur within the uphill parts of anticlines, while downhill the gradient strongly increase (Fig. 6a-c). In addition, the remnants on the right side of the Ill valley are more elevated than on the left (difference of 6-20m), except for the T_0 relics. When the river flowed parallel to the fold axis terrace remains developed at the same altitude (Fig. 6 a, km 35; Fig. 6b, km 11-16). Similarly, valley cross-sections and V_f-ratios (Fig. 7) show an increase of valley incision and minimum V_f-values in uplifted areas. Especially along the Ill river, a valley narrowing, steeply indented valley slopes, and low V_f-values occur downhill of the downcutted anticlines (Fig. 7a, sections B, D, F). In contrast, where a river is deflected (Fig. 7a, section E; Fig. 7b, section F) or flowed parallel to a rising anticline (Fig. 7b, section C) the valley became asymmetric and oversteepened near the uplift.

Interpretation

Applying the expanded chronology of Penck (Schreiner 1996), the incision of T_5 terraces corresponds to the Günz/Haslach interglacial, incision of T_4 to the Haslach/Mindel interglacial and incision of T_3 to the Mindel/Riss interglacial. The Riss stadium is subdivided into at least three periods by two erosional interglacials (Schreiner 1996). The talus of the T_2 and T_1 can be related to these two erosional events. The lowest terrace T_0 would then correspond to the Riss/Würm interglacial.

The oldest paleo-drainage pattern left only vaguely traceable terrace remnants (T_6) in the lower Thalbach valley. They are topographically higher than the T_5 system and, consequently, are considered to be older as T_5. The T_6 relics occur W of the most westward T_5 remnants of the Thalbach valley (Fig. 5). Therefore, we argue for an older westward draining paleo-Thalbach river (Fig. 8). However, because of the sparse T_6, relics it remains unclear if the T_6 level represented a Pliocene tributary of the westwards flowing paleo-Aare (Fig. 2b) or an Early Pleistocene local drainage decoupled from the already northwards draining paleo-Aare/Rhine system (Fig. 2c).

Chronologically, the capture of the paleo-Thalbach river documented by T_5 remnants would have taken place before the Haslach period (> 1 Ma, Verderber 1992).

The T_5-T_3 remnants clearly show, that the water divide between the Pleistocene northward draining paleo-Aare/Rhine river system and the westward draining Doubs system was situated a few kilometres east of Altkirch (Figs. 4, 9). At that time, the Thalbach river was already captured by the Aare/Rhine system and flowed to the NE (Fig. 8). In contrast, the Ill and Doller systems represented the easternmost branches of the paleo-Doubs and, therefore, belonged to the Mediterranean drainage.

During T_2 times the regional base level lowered due to persistent subsidence in the Rhinegraben during the Quaternary (Illies & Greiner 1978, 1979). This led to the piracy of the Sundgau drainage system to the north. As a result, the tributaries started to incise backward, beginning in the Rhine valley and continuing southward. Firstly it diverted the paleo-Ill river together with the paleo-Doller river (Fig. 8, see also Briquet 1930). The piracy occurred in the area NE of Altkirch and integrated the paleo-Thalbach to the Ill river system (Fig. 8). The paleo-Ill capture occurred between the Mindel/Riss interglacial and the first Riss erosional event (around 500 ka, Verderber 1992).

The general change in the drainage from towards the Mediterranean to towards the North Sea is related to the overall base level change. The local drainage pattern, however, reflects the effects of growing anticlines and neotectonic movements in the Sundgau. Small rivers responded to the tectonic movements by parallel/longitudinal flow, deflection or merging or – if erosional power is sufficient – antecedent river cut down.

The T_6 – T_3 relics along the Thalbach provide evidence for a change of the river's course in response to the development of the Talrain and the Buchbrunnen anticlines northwest and east of Wahlbach (Fig. 5). The NNW flowing paleo-Thalbach became deflected to the W by the Buchbrunnen anticline. At T_5 to T_3 times the river turned around the western end of this anticline and became pinned between the Buchbrunnen and Talrain anticlines, the latter acting as a topographic barrier. Subsequently, the tributary creek southeast of Altkirch (Fig. 8) was deflected by the growing Talrain anticline and its course changed from the SE-NW, a direction attributed to the paleodrainage trend during T_6 times (Fig. 8, dashed arrow), to the NE.

During T_2 times, the Thalbach was captured by the paleo-Ill and began to cross the Talrain anticline (Fig. 8). Contemporaneously, under influence of the rising Buchbrunnen anticline, T_5, T_4 and T_3 remnants were uplifted along the river's right valley side. The corresponding levels on the left valley side were not affected by this initial uplift (Fig. 6 b, km 11-15). Consequently, the uplift post-dates the T_5 to T_3 stages. The minor difference in relative position between the left and the right valley side along the fold further to the south implies an essentially antecedent river course across the growing structure (Fig. 6 b, km 7-8).

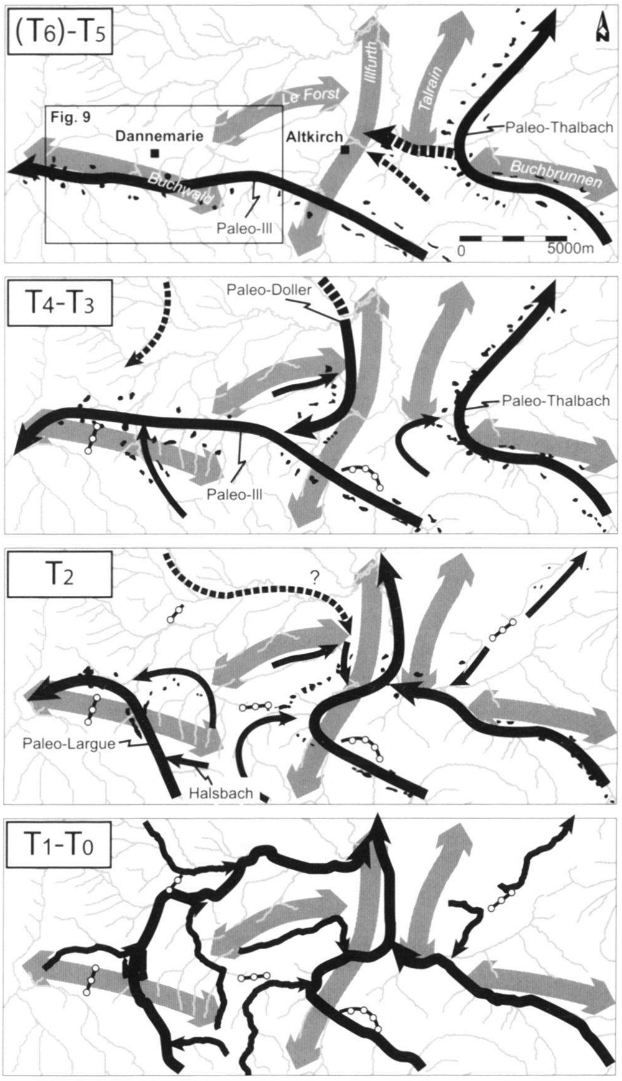


Fig. 8. Sketch maps illustrating the major paleohydrographic changes and captures of the Sundgau drainage system. Drainage patterns are shown on a present-day map. Grey bands = anticline axes; thick lines = major rivers; thin lines = tributary streams; dashed lines = assumed streams; lines with white circles = wind gaps and paleo-meanders. T6-T0 = strath terrace levels. For position see Fig. 5.

Until now, the Ill river maintained its antecedent course across the anticlines south of Altkirch (Fig. 8). The difference in elevation of the correlative levels at both valley sides reflects differentiated surface uplift. The Ill valley appears to be squeezed between the WSW plunging Folgensbourg, Muespach, Jettingen and Illfurth anticlines in the east and an area of diffuse uplift in front of the Ferrette anticline in the west (Figs. 3, 6). Downstream Altkirch, the depression between the Illfurth anticline and the Talrain anticline controlled the backwards incision that led to the piracy of the paleo-Ill system during T_3 time (Fig. 8).

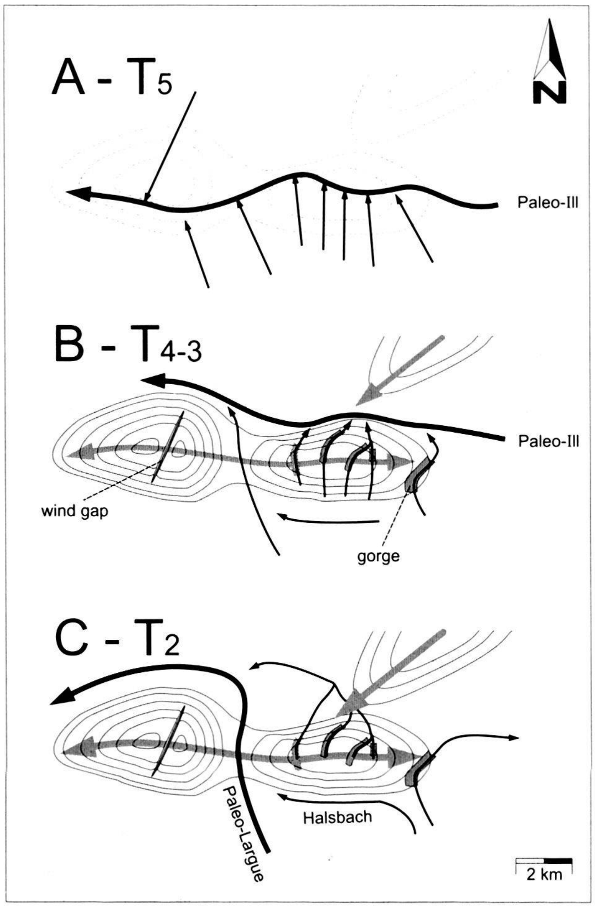


Fig. 9. Sketch map showing the evolution of the Buchwald anticline in relation to changes of the local drainage pattern. For position see Fig. 8.

The paleo-Largue river was the last major stream of the Ill catchment area to be captured by the Rhine river system. T_5 remnants on top of the anticline southwest of Dannemarie substantiate a nearly flat paleo-topography until the Haslach glacial stage. Subsequent uplift of this anticline and the region northwest of Dannemarie is a noteworthy example for local diversion of a drainage pattern. The uplift caused the migration of the paleo-Ill from south of the future Buchwald hill to the north (Fig. 9 b). Furthermore, the small creek that drained this area before could not compensate the uplift by erosion and abandoned its channel bed as a result. Consequently, a wind gap developed on the top of the Buchwald hill. The reaches SSE of Dannemarie were subsequently segmented in a northern system that entrenched a steep narrow valley and a southern longitudinal reach (Halsbach) parallel to the anticline (Fig. 9 b, c). Only the paleo-Largue river had sufficient stream power to incise the growing anticline (Figs. 8, 9). Uplift and lateral growth of the anticline ENE of Dannemarie formed a topographic barrier and caused the adjacent drainage basin to merge to a larger with one single outlet (Fig. 9 c).

Discussion

The capture of the Pliocene paleo-Aare to the north into the Rhinegraben was explained previously by Plio-Pleistocene tectonic extensions in the Sundgau area, which led to a renewed subsidence of the Dannemarie and the Sierentz grabens (e.g. van Wervecke 1913; Liniger 1967; Reymond & Théobald 1975; Théobald et al. 1977). In contrast to this interpretation, this major change in paleo-hydrography at the Pliocene-Pleistocene boundary is now thought to be related to tectonic movements north of the study area that induced altogether a drastic lowering of the regional base level. This is evidenced by up to 200 m thick Quaternary deposits in the southern Rhinegraben between Mulhouse and Strasbourg (Fig. 2). In fact, the Rhinegraben, acting tectonically in the Quaternary as a large sinistral strike-slip system (Illies & Greiner 1978, 1979), was an area of major subsidence encompassing essentially two pull apart basins, one in the north and one in the south, which was separated by a central graben sector that experienced syn-sedimentary compression (restraining bend).

Alternatively, under influence of the Miocene to Recent regional stress field with greatest principal stress (s1) oriented NNW-SSE to NW-SE (Larroque et al. 1987; Larroque & Laurent 1988; Plenefisch & Bonjer 1997), the WSW-ENE trending Burgundy Transfer Zone (inset of Fig. 1) was reactivated in a dextral transpressive manner. Under the influence of this right lateral shear regime, NNE to NE orientated and deep-rooted faults produced at the surface upfolding of anticlines, as shown along the Burgundy Transfer Zone in northern Ajoie (Ustaszewski et al. 2001; Giamboni et al. 2004), and in the Sundgau area by the differential uplift of the Sundgau gravel (Fig. 3).

Post-depositional uplift of the Sundgau gravel is documented by the river terraces and the concomitant drainage pattern. In contrast to the alluvial terraces along the Rhine river between Schaffhausen and Mulhouse, which are considered to reflect the interplay of accumulation during glacial stages and erosion during interglacial periods (Verderber 1992), the terraces in the Sundgau area were formed by relatively small rivers with low stream power, showing only restricted accumulation features. However, the terrace levels in the Sundgau correlate with those along the Rhine valley, and hence, indicate, that erosion in the Sundgau area was likewise affected by a climatically induced lowering of the base level during the Quaternary (e. g., Müller et al. 2002). As shown by other studies (e.g. Verderber 1992; Müller et al. 2002), responses of dynamic rivers to such cutting events include continuous adjustments of the river floor by vertical erosion. This process typically produces terrace levels, i.e. paleo-river floors, nearly parallel to the present river bed (Gregory & Walling 1973). In the Sundgau area, such congruent terrace levels were encountered at reaches undisturbed by folding (Fig. 6). On the other hand, increases in the number of terrace levels and strong left-right side asymmetry of the terrace levels point to enhanced erosion near the growing anticlines. Correspondently, the older terraces (Günz/Haslach interglacial) proximal to the uplift area are offset in the order of up to 30-40m and those in a distal position in the order of 10m. The maximum offset is estimated to have been 50m ±10m. This estimate corresponds to an approximate uplift rate of 0.05mm/a, which is comparable with the rates inferred from geomorphological and structural studies along the eastern Jura front (0.05 to 0.1mm/a, Müller et al. 2002; Ustaszewski 2003, pers. comm.).

A comparative evaluation of the factors that affected the drainage system in the Sundgau indicates that compared with the moderate uplift, the subsidence of the southern Rhinegraben north of the study area was evidently the most important formation agent.

Nonetheless, the effect of transpressive deformation in the Sundgau area, as recorded by the evolution of the drainage system, is astonishing. Up to now topographic relief was used for the identification of localized active tectonic deformations when relatively great tectonic activity (and seismicity) occurred in the area (e.g. Merritts et al. 1994 [California]; Li et al. 1998 [northern China]; Lavé & Avouac 2000 [Himalayas]). The results presented in this paper now clearly demonstrate, that alluvial systems are also highly responsive to tectonic regimes that induce deformation at relatively low rates. In other words, landscapes also record precisely this kind of long-term tectonic activity.

However, the piracy of Sundgau rivers was not only affected by the subsidence of the Rhinegraben and by the transpressive tectonics in the Sundgau area, but also by the extrusion of salt diapirs in the Mulhouse Salt Basin. The thick evaporites at the base of the graben fill formed salt ridges and domes during the Tertiary and Pleistocene (Lutz & Cleintuar 1999). They are still active today (Liaghat et al. 1998) and responsible for the parallel drainage axis in the graben: the Ill river flows parallel to the Rhine river up to Sélestat, near Strasbourg, separated by a few kilometres wide zone which corresponds exactly to a N-S oriented salt ridge in the subsurface (Lutz & Cleintuar 1999). This halokinesis-related relief probably existed during the entire Quaternary. The base of the alluvial infill of this age indicates the existence of two channels (Théobald 1976). The course of the Ill is prolonged by this divide and, hence, the Ill responded in the Sundgau area with a time lag on base level changes in the Rhine valley. This delayed response may explain the time difference between the first capture of the paleo-Thalbach river, which was probably produced by slight local subsidence E/NE of Mulhouse and uplift along the Illfurth fault, and the capture of the Ill river system. Its direct access to the Rhine river in the area of Mulhouse, actually, was hindered by diapirism.

Summary

Landscape analysis in the Sundgau area proved to be suitable to determine the existence of local uplift and the effects of regional subsidence in an area where outcrops are rare and tectonic activity is moderate (<0.1mm/a). For this study, the reconstruction of the base of the Sundgau gravel as well as the interpretation of seismic reflection data were indispensable for the understanding of the style and timing of tectonic deformation. At least six Plio-Pleistocene terrace levels in the Sundgau area are correlative with the alluvial terrace systems of the Rhine river. Altogether, they demonstrate, that stream power and erosional events were coupled with the climatic changes during the Quaternary. In addition, the spatial distribution and up-warping of the terraces indicate that fluvial incision was enhanced by tectonic uplift. Differential uplift motions led to the deflection and merging of several streams. In contrast, the youngest major paleohydrographic change in the northern Alpine foreland, which encompasses the capture of the paleo-Rhine river from its Pliocene course towards the Bressegraben to the north into the Rhinegraben, was most of all governed by regional subsidence in the Rhinegraben to the north of the study area and not by local uplift in the Sundgau area.

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