Quaternaire
Revue de l'Association française pour l'étude du Quaternaire

vol. 20/1 | 2009
Volume 20 Numéro 1

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Édition électronique
URL : http://journals.openedition.org/quaternaire/5008
DOI : 10.4000/quaternaire.5008
ISSN : 1965-0795

Éditeur
Association française pour l'étude du quaternaire

Édition imprimée
Date de publication : 1 mars 2009
Pagination : 25-24
ISSN : 1142-2904

Référence électronique
Jörg Lämmermann-Barthel, Inge Neeb, Matthias Hinderer et Manfred Frechen, « Last glacial to Holocene fluvial aggradation and incision in the southern Upper Rhine graben: climatic and neotectonic controls. Dépôt et incision fluviatiles dans le sud du fossé du Rhin supérieur du dernier glaciaire à l´Holocène : contrôles climatiques et néotectoniques », *Quaternaire* [En ligne], vol. 20/1 | 2009, mis en ligne le 01 mars 2012, consulté le 10 octobre 2019. URL : http://journals.openedition.org/quaternaire/5008 ; DOI : 10.4000/quaternaire.5008

Quaternaire, **20**, (1), *2009*, p. 25-34

LAST GLACIAL TO HOLOCENE FLUVIAL AGGRADATION AND INCISION IN THE SOUTHERN UPPER RHINE GRABEN: CLIMATIC AND NEOTECTONIC CONTROLS

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Jörg LÄMMERMANN-BARTHEL [1], Inge NEEB [1], Matthias HINDERER [1]
& Manfred FRECHEN [2]

ABSTRACT

We present a new model of landscape evolution for the southern Upper Rhine Graben based on analysis of Digital Elevation Models, new OSL and ^{14}C dating, and a sediment budget. According to these data a three step scenario was developed (i) between ca. 60 to 16 ka BP accumulation of an alluvial fan in the southern Upper Rhine Graben, here called Upper Rhine Fan, downstream of the mouth of the Hochrhein valley. This fan is mostly composed of coarse-grained meltwater deposits. (ii) 16 to 10 ka BP incision of the Upper Rhine Fan and accumulation of a successive fan further downstream by redepositing the eroded sediments (iii) 10 ka BP to present incision of the Rhine river into the younger fan leading to the present situation. Only phase (i) has experienced a significant sediment supply from the Alps and/or Alpine foreland. During the middle Würmian, fluvial aggradation is proved by several ages from sand lenses between ca. 60 and 27.5 ka BP. The period between ca. 27.5 and 16 ka BP is represented by a single or few layers of coarse-grained cobble and boulder-rich gravels and blocks. Because sand lenses are lacking they cannot be dated directly, but most presumably their deposition was related to the Late glacial meltdown. The repeated incision of the two fan surfaces after the Last Glacial Maximum and the Younger Dryas may be caused by high inputs of sediment-poor meltwater at this time. Weak Holocene aggradations may be linked with periods of climatic deterioration, tectonic pulses, and direct human impacts.

Key-words: Upper Rhine Graben, alluvial fan, neotectonic, Late Quaternary, sediment budget.

RÉSUMÉ

DÉPÔT ET INCISION FLUVIATILES DANS LE SUD DU FOSSÉ DU RHIN SUPÉRIEUR DU DERNIER GLACIAIRE À L´HOLOCÈNE : CONTRÔLES CLIMATIQUES ET NÉOTECTONIQUES

Le nouveau modèle évolutif présenté pour le Sud du fossé du Rhin supérieur a été obtenu à partir de l´analyse des isohypses, des nouvelles datations OSL et ^{14}C et du budget sédimentaire.

Cette évolution s'est déroulée en trois phases : (i) de 60 à 30 ka B.P., un cône alluvial, appelé ici « Cône du Rhin supérieur » s'est constitué dans le Sud du fossé du Rhin supérieur, immédiatement en aval de la vallée du Haut-Rhin ; ce cône est constitué essentiellement de dépôts grossiers mis en place par des eaux de fonte ; (ii) de 16 à 10 ka B.P., l'incision du « Cône du Rhin supérieur » a pour conséquence, plus loin en aval, la construction d'un second cône à partir des sédiments érodés et (iii) de 10 ka B.P. à l`actuel, l'incision du Rhin dans le cône le plus récent est responsable de la morphologie actuelle.

Les volumes considérables de sédiments provenant des Alpes ou de leur Avant-pays ont été transportés uniquement pendant la phase (i). L'aggradation fluviatile du milieu du Würm est démontrée par les datations obtenues sur les lentilles de sable qui ont livré des âges de 60 à 27,5 ka B.P. La période comprise entre 27,5 et 16 ka B.P. est représentée par une simple ou plusieurs séquences de gravières grossiers. En l'absence de datations absolues, on suppose que ces derniers sont corrélés à la fonte des glaciers à la fin du Würm. Les incisions des deux cônes après le dernier maximum glaciaire et le Dryas récent seraient à mettre en relation avec l'apport de grandes quantités d`eaux froides pauvre en sédiments. Les dépôts peu volumineux de l'Holocène peuvent être reliés aux périodes de détérioration climatique, aux mouvements tectoniques ou aux impacts dus à l'Homme.

Mots-clés: fossé du Rhin supérieur, cônes alluviales, Quaternaire supérieur, néotectonique, budget sédimentaire.

1 - INTRODUCTION

The Upper Rhine Graben (URG) is part of the European Cenozoic rift system that developed in the northwestern foreland of the Alps between Basel (Switzerland) and Frankfurt (Germany). It has a length of about 300 km, trending north-northeast, and an average width of 35-45 km (fig. 1). According to Behrmann *et al.* (2003), the southern Upper Rhine Graben is still seismically active. Earthquakes with magnitudes up to 5 (Richter scale) occur approximately on a 30 years cycle. Modern uplift rates are up to 1 mm/a on the eastern graben shoulder south and east of Freiburg (Demoulin *et al.*, 1998).

During the Pleistocene, the sedimentary graben infill was primarily controlled by climate fluctuations. Multiple glaciations led to strong erosion and partly

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[1] Institute of Applied Geosciences, Technische Universität Darmstadt, Schnittspahnstr. 9, 64287 Darmstadt/Germany

[2] Leibniz Institute for Applied Geosciences, Section Geochronology and Isotope Hydrology, Stilleweg 2, 30655 Hannover, Germany

Manuscrit reçu le 13/12/2007, accepté le 09/01/2009

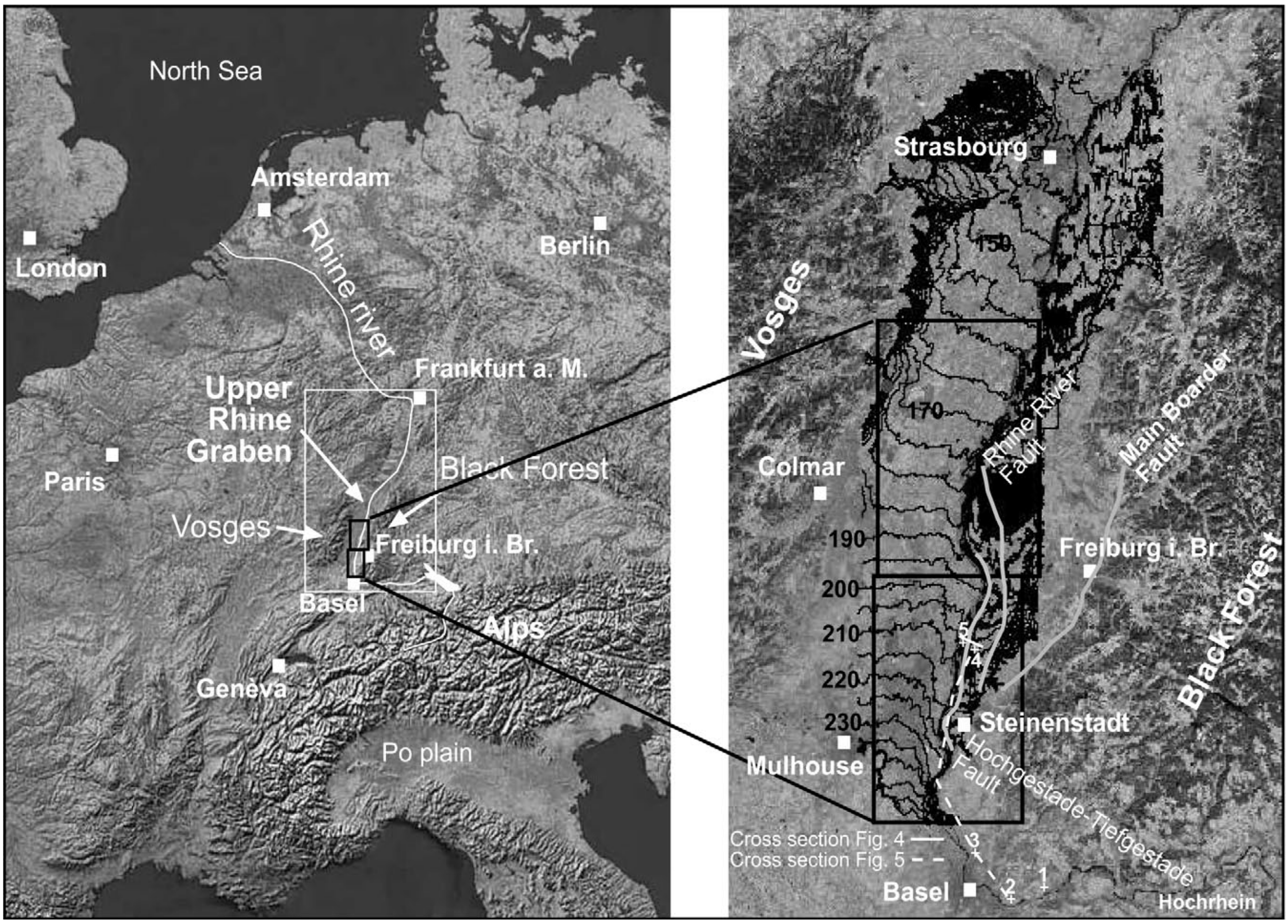


Fig. 1: The Upper Rhine Graben (URG) in Europe (left) and present contour lines of the southern URG (right).
Lower rectangle indicates the denudation area, upper rectangle the accumulation area. Numbers indicate position of investigated gravel pits: 1) Herten 2) Wyhlen 3) Haltingen/Hupfer 4) Hartheim/Knobel 5) Bremgarten Source of satellite image: NASA MrSID, contour lines derived from NASA SRTM data.

Fig. 1 : Le fossé du Rhin supérieur en Europe (à gauche) et les courbes de niveau actuel du sud du Fossé du Rhin supérieur (à droite).
Le rectangle du bas indique la zone de dénudation, le rectangle du haut la zone d`accumulation. Les numéros indiquent les gravières ayant fait l'objet de recherches : 1) Herten, 2) Wyhlen, 3) Haltingen/Hupfer, 4) Hartheim/Knobel, 5) Bremgarten Source du satellite NASA MrSID, les courbes de niveau actuel sont dérivés de NASA SRTM data.

overdeepening of Alpine valleys and peri-Alpine basins (Ellwanger *et al.*, 2003). The Upper Rhine Graben (URG) received a vast amount of glacial debris from the Rhineglacier area and the Swiss Midlands via meltwater transport through the Hochrhein valley. In the region of Basel the meltwaters entered the Upper Rhine Graben (URG) accumulating an extensive, gravel-rich alluvial fan further called Upper Rhine Fan. This fan correlates to the "Niederterrassenschotter" of the Hochrhein area (gravels of lower terrace). The subsequent fluvial reworking and neotectonic movements altered the fan surface. At present, two distinct terrace levels can be observed east of the Rhine River with a difference from 4 m in the north close to Hartheim and up to 15 m in the south at Steinenstadt: the higher terrace called Hochgestade and the lower terrace called Tiefgestade (Elsass *et al.*, 1999). On the western side of the Rhine River only a smooth undulating surface exists.

Until now, the timing of fan accumulation and subsequent erosion in the southern URG is unclear and a process-oriented model is completely lacking. In this study we provide new sedimentological and geochronological data, which are analysed in the frame of a stepwise reconstruction of different palaeosurfaces from Digital Elevation Models (DEMs) and a sediment budget approach. A synthesis of these different data sets allows us to set up a new landscape evolution model for the southern URG from Late Pleistocene to Holocene. The model is interpreted in the context of external controls (mostly from Alpine glaciations) and internal controls, e.g. neotectonic movements.

2 - METHODS

Different palaeosurfaces of the Upper Rhine Fan are reconstructed by a geomorphological analysis of the modern DEM. We use the NASA SRTM data in a 90*90m resolution which is accurate enough for the purpose of this study. From the raster data contour lines in 10 m steps were calculated and visualized. First, isolines were assigned to different geomorphological levels of the fan. Those are: A1: the topmost accumulation surface, representing the oldest level of the fan"; E1: the erosion surface of incised valleys into this surface and corresponding to the Hochgestade; A2: a lower accumulation surface, which was formed at the outlets of the incised valleys further downstream; E2: a modern erosion surface which shows a dissection of the younger surface. As shown in figure 2, the accumulation surfaces A1 and A2 were reconstructed by interpolating the isolines across the erosion levels E1 and E2, respectively. In terms of regional geomorphology, A1 was reconstructed by connecting the eastern and western fan surface and thus levelling out the incision into the Hochgestade (E1). North of the line Colmar to Kaiserstuhl, the original surface A2 was reconstructed by compensating the incision of E2.

Although geomorphological analysis yields a clear, relative stratigraphical order of repeated accumulation and dissection stages a process-oriented interpretation of the fan evolution is only possible in the frame of reliable geochronological dating. In order to do this, we investigated active gravel pits on the eastern side of the Rhine and in the Hochrhein valley. Figure 3 shows the map with investigated gravel pits and outcrop photos.

In order to set up a more reliable chronological frame for the last glacial fluvial sediments, optically stimulated luminescence dating on quartz- and feldspar grains was applied. In one case a trunk could be dated using ^{14}C (gravel pit Bremgarten). Fluvial sediments are particularly suitable for the application of optically stimulated luminescence dating techniques, which measure the time elapsed since the last exposure to sunlight (e.g., Frechen, 1995; Jain *et al.*, 2003; Murray *et al.*, 1995; Preusser, 1999; Wallinga *et al.*, 2001). Our specific methodological approach with an extensive discussion of dating results is going to be published by Frechen *et al.* (submitted). All measurements were carried out at the Leibniz Institute for Applied Geosciences (Hannover, Germany). Here only a short overview will be given as far as necessary for the chronological frame of the Upper Rhine Fan.

OSL-dating requires fine to medium-sized sand. The sediments of the A1 stage of the Upper Rhine Fan consist mainly of gravel-rich deposits which are part of the so called Neuenburg Formation (RPF/LGRB 2005). The upper part of the Neuenburg Formation contains a prominent coarse layer, called “Obere Groblage”, which forms a marker horizon and is an important aquifer (RPF/LGRB 2007). This ca. 5 m thick layer contains coarse-grained and poorly sorted imbricated gravels with some blocks and only weak stratification indicating a very dynamic sedimentation process (Heinz, 2001) The “Obere Groblage” can be observed in gravel pits of the lower terrace along the Hochrhein valley, i. g. Wyhlen

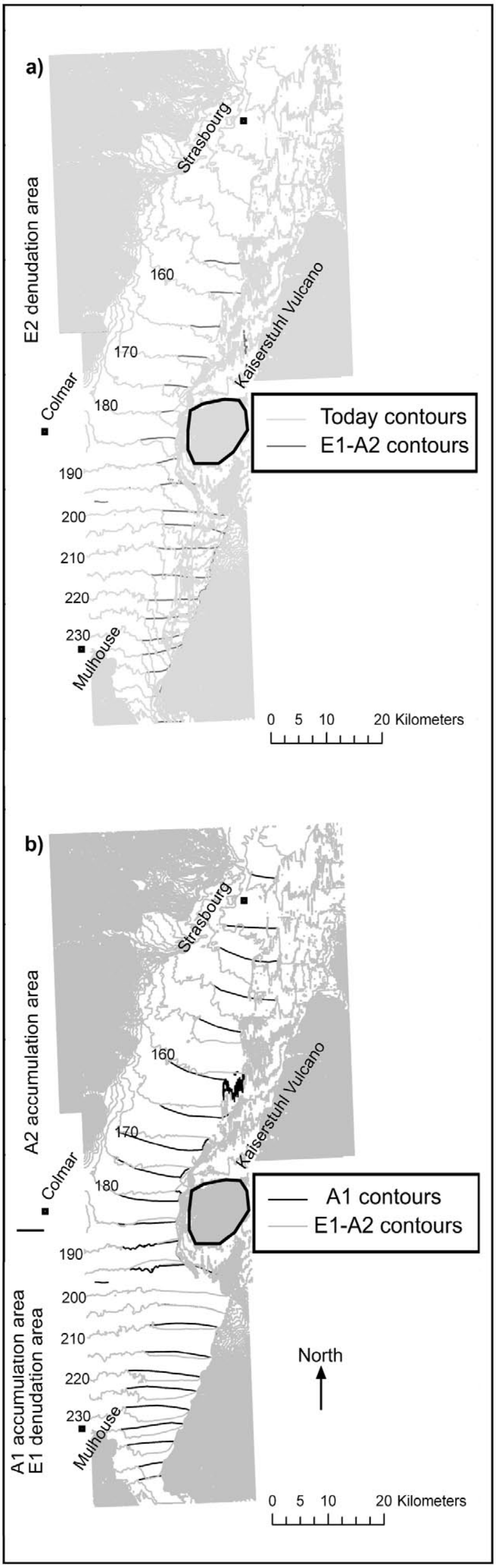


Fig. 2: Reconstruction of palaeo-landscapes for different stages and volumetric estimations.

a) Reconstruction of accumulation surface A1. The incision of E1 within the surface A1 is compensated. b) Reconstruction of accumulation surface A2. In the north modern contour lines were levelled out for incision of E2. In the south, A2 corresponds to E1 when the tectonic offset between Hochgestade and Tiefgestade is removed.

Fig. 2 : Reconstitution des paléo-paysages du Sud du fossé du Rhin supérieur à différentes époques.

a) Reconstitution de la surface d`accumulation A1; b) Reconstitution de la surface A2.

(fig. 3a & b) and can be easily identified in wells of the southern Upper Rhine Graben. All sedimentological criteria point to relatively short period of strongly enhanced discharge and must be correlated to the Alpine glacier meltdown period after the LGM (Ellwanger *et al.*, 2003). Thus, the lithostratigraphic correlation of this layer has an important chronostratigraphic value (event stratigraphy in the sense of Whittaker *et al.*, 1991). Because the layer contains no sand lenses suitable for direct dating, samples from sandy horizons or lenses below and/or above in the upstream part of the fan were taken Such kind of "sandwich ages", defining a time frame of a minimum and maximum age, could be obtained from the gravel pit of Wyhlen, (fig. 3a & b, tab. 1). At the same time the upper age represents a minimum age for the A1 surface. Gravel pits further downstream could not be sampled in this "sandwich" mode, because the "Obere Groblage" is below the excavation level at Bremgarten and at Knobel (fig. 4). There we got important information about minimum ages of the terrace levels Hochgestade and Tiefgestade. The E1 sediments at the outcrop level at both gravel pits consist of fluvial gravels and sands of Alpine origin.

Repeated accumulation and dissection of the Upper Rhine Fan makes it suitable to apply a sediment budget approach and independently prove the evolutionary model derived from geomorphology, sedimentology and OSL dating. According to Einsele & Hinderer (1998) and Hinderer (2003), a sediment budget employs conservation of mass to quantify sediment sources, sinks, and pathways in a closed geosystem. Moreover, a sediment budget can be used to quantify the effects of changing sediment supply on the system and to understand the large-scale morphological responses. Estimations of accumulated sediment volumes are compared with volumes of material removed from source areas since the disturbance took place. In the case of the Upper Rhine Fan, the accumulated sediment volume should be less

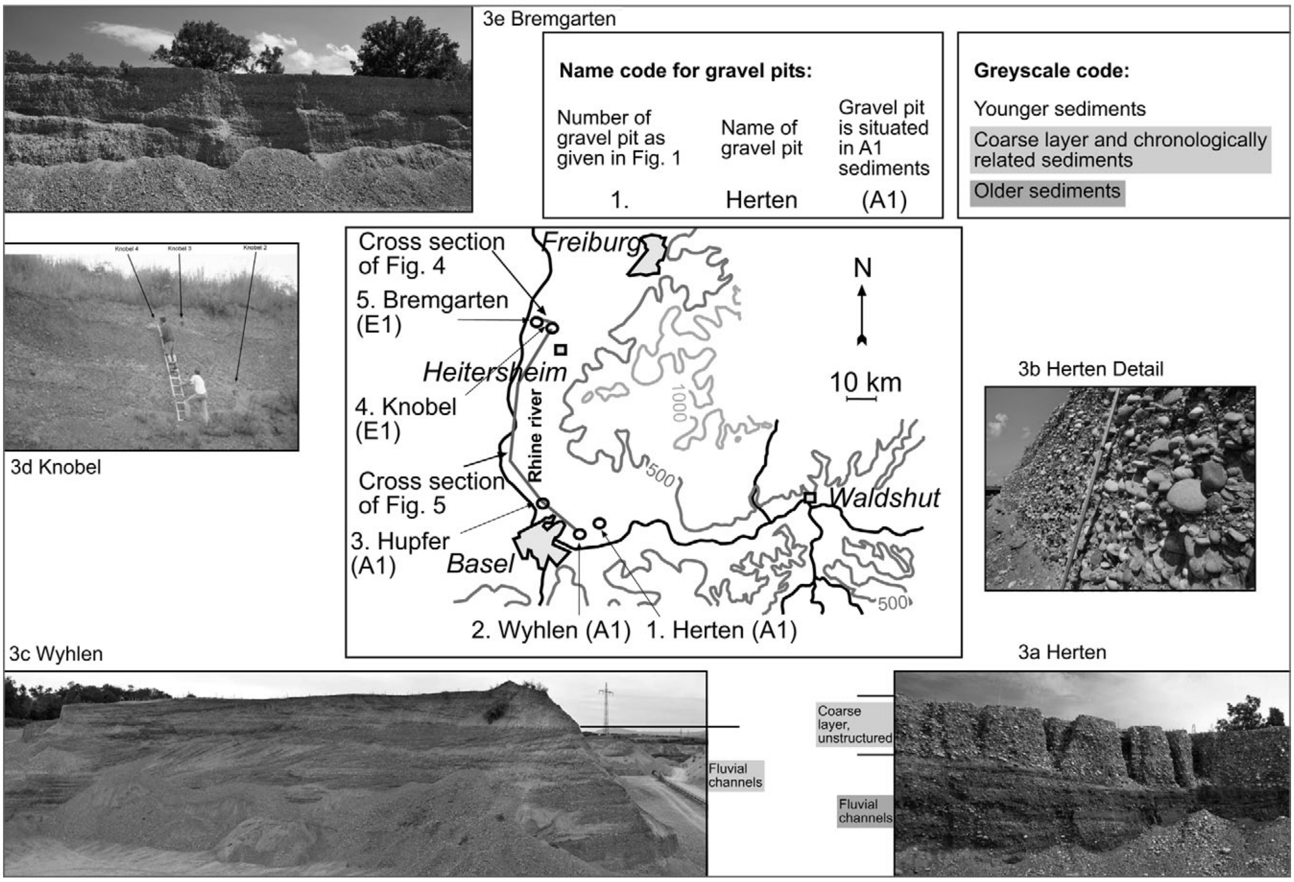


Fig. 3: Map with investigated gravel pits and drill sites.
The morphological surface to which the locations belong is indicated in brackets. For explanation of these surfaces see text. Course of sections in fig. 4 & 5 are shown.
a. Panorama of gravel pit Wyhlen. **b**. The photo shows an outcrop from gravel pit Wyhlen. The coarse layer is clearly visible in the upper part. This coarse layer marks the base of the A1 fan. Detailed sedimentological section of a 5 m thick layer of coarse-grained and poorly sorted imbricated gravels with some blocks and only weak stratification indicating a very dynamic sedimentation process. **c**. Panorama of Hupfer pit in Haltingen with thick and extensive cut and fill elements, interpreted as scour pool fills of a braided river system. **d**. Outcrop at gravel pit Knobel, arrows show position of samples KNO 2-4 for OSL Dating. **e**. Photo of gravel pit Bremgarten. The trunk was found 2 m below topographic surface.
Fig. 3 : Localisation des gravières et des sondages étudiés.
L`unité morphologique de chaque site est indiquée en italiques. Concernant l`explication de ces unités, voir le texte. Les intersections des fig. 4 & 5 sont indiquées.
***a**. Vue de la gravière de Wyhlen. **b**. Gravière de Wyhlen, coupe sédimentologique détaillée, d'une épaisseur de 5 m, de graviers grossiers, imbriqués et peu triés, avec quelques blocs et une faible stratification, indiquant des processus sédimentologiques très dynamiques. **c**. Vue de la gravière Hupfer à Haltingen, avec d'épaisses et nombreuses figures d'ablation et de dépôt, interprétées comme des remplissages de mouilles d'un système à chenaux tressés. **d**. Gravière de Knobel, les échantillons pour les datations OSL sont designés KNO2-4. **e**. Photographie de la gravière Bremgarten. Le tronc a été trouvé à 2 m sous la surface topographique.*

than the eroded volume, as a result of open system conditions. The difference mostly correlates to the loss of fines out of the system due to suspended load and/or wind deflation.

3 - RESULTS

3.1 - MORPHOLOGY

South of a line Colmar to Kaiserstuhl modern contour lines show a slightly convex form in the central part of the URG, interrupted to the east by an incised valley (fig. 1 & 2a, b). East of the valley, the contour line pattern is complicated owing to alluvial fans, entering the URG from the Black Forest. North of the line Colmar to Kaiserstuhl, the contour line pattern changes and shows an overall concave trend but has a convex section in the central graben area. On the eastern graben margin, the incised channel of the southern part proceeds up to the north. The deepest incision during the E1-erosion occurred in the south and formed the Hochgestade terrace which becomes shallower towards the north (fig. 2a). Near to Kaiserstuhl volcano, the landscape changes from incision to accumulation.

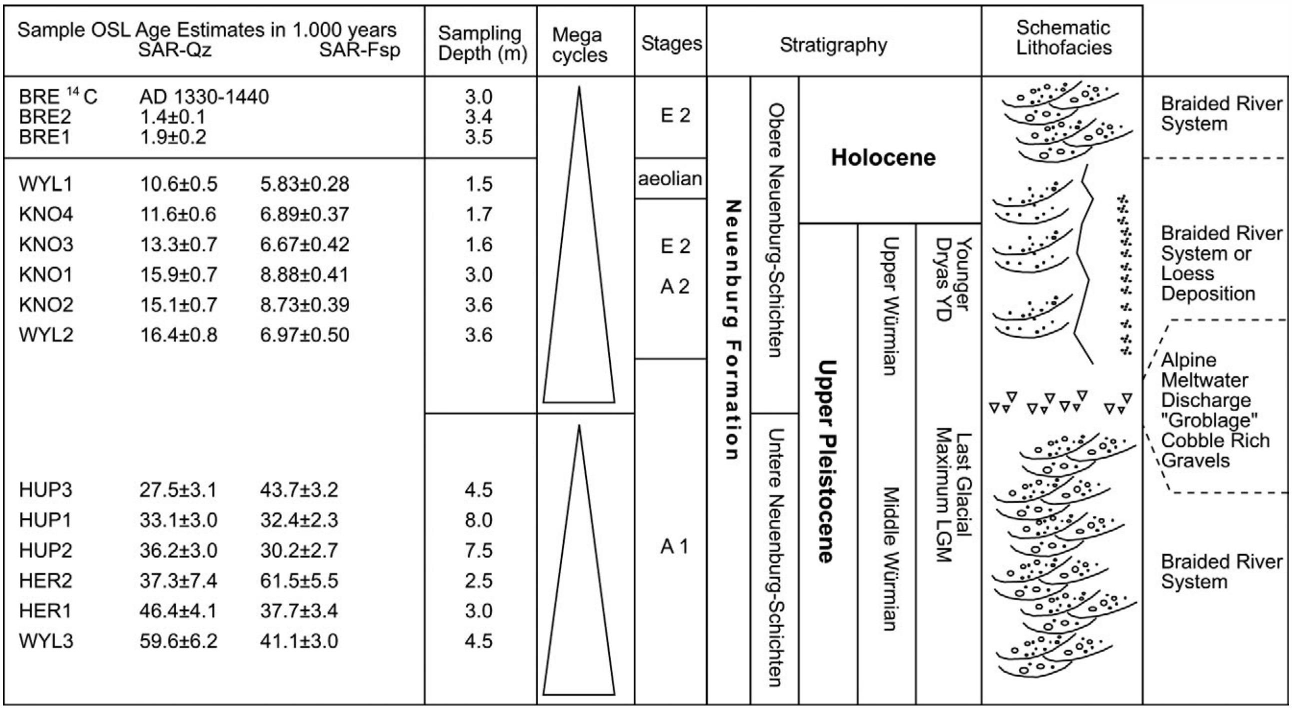
The results of palaeo-surface reconstruction are two stacked convex shaped alluvial fans (fig. 2). The fan with palaeosurface A1 has a length of about 33 km and a ground level elevation of 195 to 250 m asl. Fan A2 has a comparable volume but is flatter with a maximal length of 71 km, a width of 17 km and a ground level elevation of 135m to 195 m asl. The incised valleys within the fan bodies (E1 and E2) are very similar in size and both are cone shaped with an upstream width of 4 and 3.5 km, and a downstream width of 12 km.

3.2 - AGES

The age of the different morphological stages can be framed from OSL and ^{14}C datings in five gravel pits. The used data are documented in detail by Frechen *et al.* (submitted). Because the aim of this paper is to establish a chronostratigraphic frame for the Upper Rhine Fan we use approximate ages which are based on the most likely ages as extracted from variations of IRSL feldspar and OSL quartz ages and error ranges (see Frechen *et al.*, submitted).

OSL datings (tab. 1) from the lowermost Hochrhein valley of sediments just below the "Obere Groblage" in the gravel pits of Wyhlen and Herten yielded OSL ages of ca. 60 to 37 ka BP. At Hupfer pit the "Obere Groblage" was not deposited, presumably because of the elevated and marginal setting in the valley. OSL ages of sand layers in coarse-grained fluvial deposits of these gravel pits below the "Obere Groblage" show similar ages between ca. 62 and 28 ka BP.

The minimum age of the "Obere Groblage" and the A1 surface can best be estimated from datings of overlying thin aeolian and fluvial deposits at the gravel pits of Wyhlen and Knobel (fig. 3 and tab. 1). At Wyhlen, overlying fluvial and loess deposits show most reliable OSL quartz ages between 16.4 ± 0.8 and 10.5 ± 0.5 ka BP, at



Sample	OSL Age Estimates in 1.000 years SAR-Qz	SAR-Fsp	Sampling Depth (m)	Stages
BRE ^{14}C	AD 1330-1440		3.0	E 2
BRE2	1.4±0.1		3.4	
BRE1	1.9±0.2		3.5	
WYL1	10.6±0.5	5.83±0.28	1.5	aeolian
KNO4	11.6±0.6	6.89±0.37	1.7	E 2 A 2
KNO3	13.3±0.7	6.67±0.42	1.6	
KNO1	15.9±0.7	8.88±0.41	3.0	
KNO2	15.1±0.7	8.73±0.39	3.6	
WYL2	16.4±0.8	6.97±0.50	3.6	
HUP3	27.5±3.1	43.7±3.2	4.5	A 1
HUP1	33.1±3.0	32.4±2.3	8.0	
HUP2	36.2±3.0	30.2±2.7	7.5	
HER2	37.3±7.4	61.5±5.5	2.5	
HER1	46.4±4.1	37.7±3.4	3.0	
WYL3	59.6±6.2	41.1±3.0	4.5	

Tab. 1: OSL Age estimate in 1.000 years for 5 gravel pits Wyhlen, Herten, Hupfer, Knobel und Bremgarten, for details see Frechen *et al.*, submitted.
Schematic stratigraphical correlation between A1, E1, A2, E2, together with a simplified lithofacies. White triangles represent cobble and boulder rich gravel. These sediments are not suitable for OSL Dating.
Tab. 1 : Liste des datations OSL estimées de 1000 ans, les échantillons se situent aux gravières de Wyhlen, Herten, Hupfer, Knobel et Bremgarten. Pour plus de détails, voir Frechen et al., soumis.
Corrélation stratigraphique schématique entre A1, E1, A2, E2, et un lithofaciès simplifié. Les triangles blancs représentent du gravier riche en galets et blocs.

Knobel similar ages of 15.9 ± 0.7 to 11.6 ± 0.6 ka BP. These fluvial sediments represent reworked sediments of erosion level E1, thus postdating A1 level.

At Bremgarten gravel pit, (fig. 3e) in the Tiefgestade, samples from a sand layer about 3.5 meters below surface gave OSL age estimates ranging from 1.9 ± 0.2 to 1.4 ± 0.1 ka BP. A trunk covering this sand layer shows a radiocarbon age of 510 ± 45 a BP. Thus, all fluvial sediment covers in the area of the E1 palaeolandscape show clear postglacial ages.

3.3 - SEDIMENT BUDGET

Whereas the whole fan volume is mainly a result of glacial denudation of the Alps which can only be quantified in the context of an overall sediment budget of the Rhine-glacier area, the Swiss midlands and the Upper Rhine Graben (Neeb *et al*., 2004), the removed volume of sediments by the E1 incision can be directly linked to the formation of the younger A2 fan north of the Kaiserstuhl - Colmar line. Because almost completely coarse-grained material is eroded and re-deposited, one can assume closed conditions for this short-term denudation-accumulation system. Volume estimations on the denudation area and the accumulation area were carried out for the A1 DEM as well as for the A2 DEM. Subtracting the E1 DEM from the A1 DEM gives negative volumes for the dissection area (erosive volume) and positive values for the accumulation area (accumulative volume) which both have been quantified. The results indicate an erosive performance of 0.35 km³ during E1 incision into A1 and an accumulative performance in the northern area of 0.39 km³, forming the A2 (fig. 2). The numerical estimates of the volumes are in excellent agreement considering an error range of about 20%. Uncertainties are mostly related to unclear morphological structures at the southern fan margin. It might be that the A1 surface reaches further south than the study area. Thus, part of the erosive volume was possibly not taken into account. On the other hand, the slightly larger volume of the fan could be also caused by lateral sediment supply to the A2 fan from the Black Forest.

3.4 - NEOTECTONIC MOVEMENTS

Another outcome of DEM and sedimentological studies are strong indications that the distinct morphological step from the Hochgestade to Tiefgestade, which only occurs east of the Rhine River, is basically of tectonic nature and reflects very recent neotectonic movements in the southern Upper Rhine Graben. It strikes SSW-NNE. This is in agreement with findings of Behrmann *et al.* (2003), at faults southwest of Freiburg. Here in recent times seismically active faults show similar orientations as the Hochgestade-Tiefgestade fault (fig. 1). Embayments of the cliff point to a morphological overprint by repeated undercutting of the Rhine River due to river course changes since the formation of the fault.

New well sections from the Tiefgestade and the Hochgestade were compared (fig. 4). Both sedimentary logs show similar sequences, except for the youngest sediments, making it very likely that the eastern side has been uplifted with respect to the western side indicating a very young age of this fault. Fluvial activity terminated on the Hochgestade latest at around 11 ka BP (Gravel pit Knobel) whereas it continued on the Tiefgestade until historical time (Gravel pit Bremgarten). In addition, the sedimentary sequence above the "Obere Groblage" of the A1 depositional period seems to be condensed, i.e. it shows reduced thicknesses and extended depositional gaps. In the well at Bremgarten gravel pit, two fluvial fining upward cycles are developed which are absent at

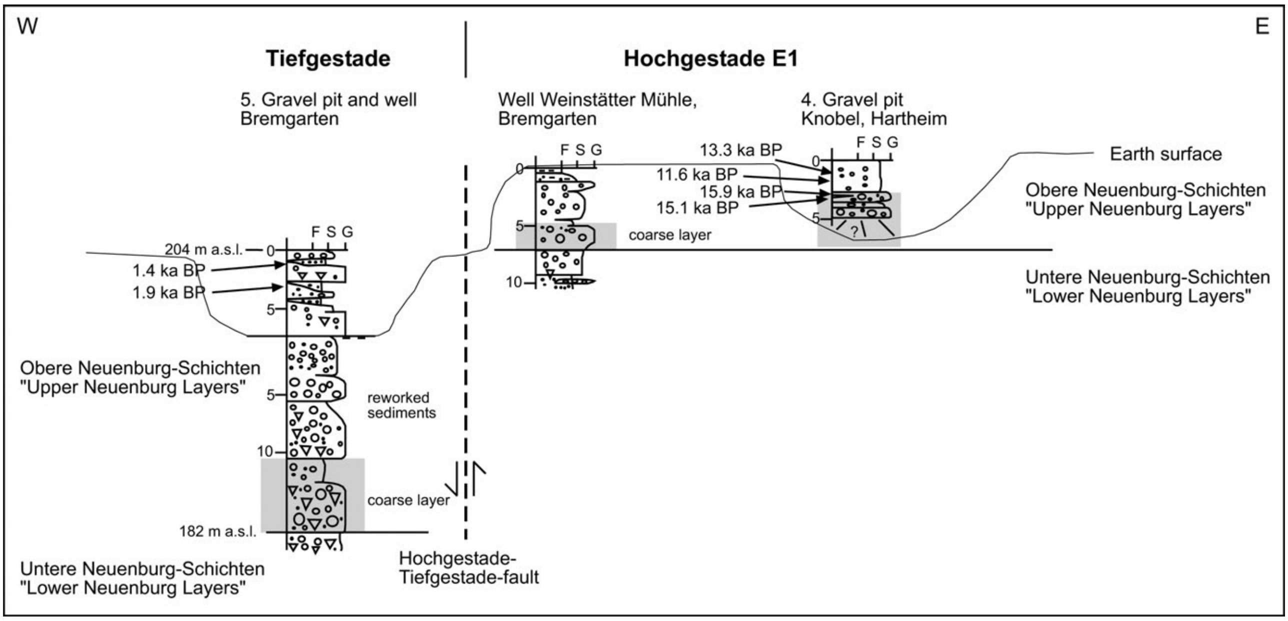


Fig. 4: Correlation of sedimentary successions of Hochgestade and Tiefgestade between Knobel and Bremgarten from outcrops in gravel pits and well logs. OSL datings are indicated.

Fig. 4 : Corrélations entre les unités sédimentaires de Hochgestade et de Tiefgestade entre les gravières Knobel et Bremgarten.

Knobel and at Weinstätter Mühle drilling (fig. 4), (the complete litholog of this drilling is given by Hagedorn 2004, the drilling in the gravel pit Bremgarten has the number (8011/1022) RP Freiburg LGRB the litholog is documented there).

The cross section in figure 5 (course of the section and outcrop photos see fig. 3) shows a very low incline of the topography from Wyhlen to Hupfer, The OSL ages in the braided river deposits yield ages of 59.6 ka in Wyhlen and 43.7 to 36.2 ka in a distance of 15 km in Hupfer / Haltingen. In the higher eastward situated section of Hupfer there is no deposition of the coarse layer similar to Wyhlen. Tectonic uplift at Hupfer is presumed, the elevated area might have been disconnected from fluvial activity before 20 ka. The incline 30 km towards north (gravel pit Knobel on the Hochgestade, c.f. fig 4) is steep. The coarse layer is not exposed. The OSL datings yield 15.9 -11.6 ka (tab1).

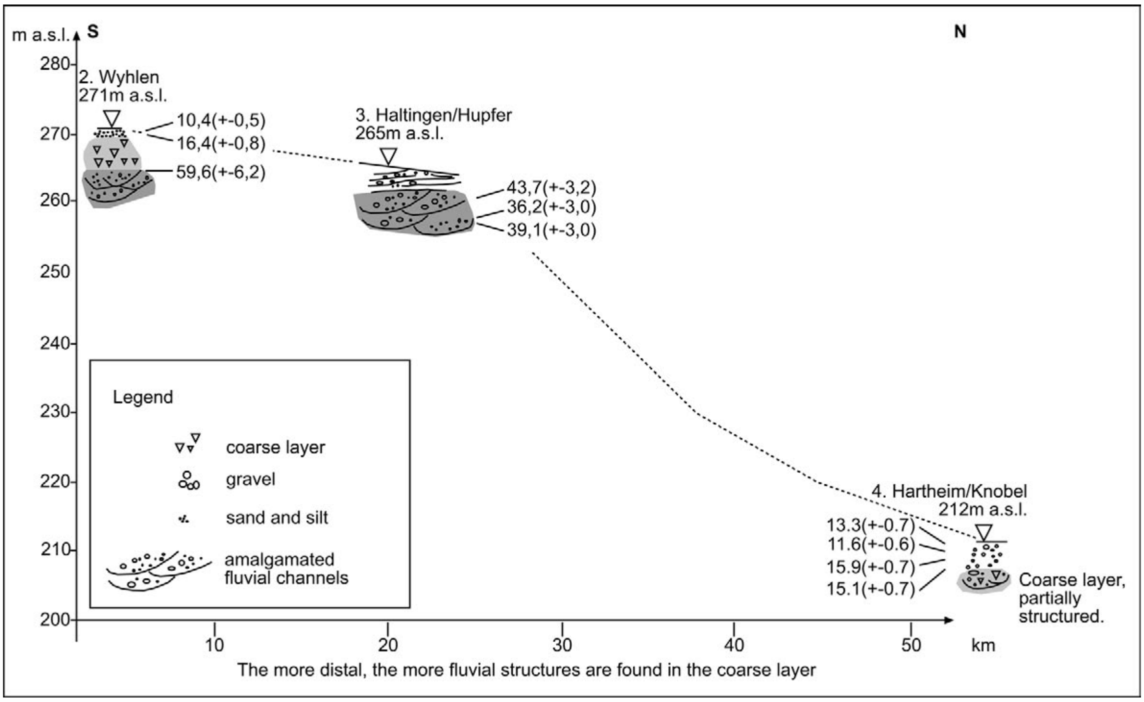


Fig. 5: Cross section from south to north.
See also fig. 3 a b, c, d & e. The coarse layer is clearly visible in the upper part at Wyhlen. This coarse layer marks the base of the A1 fan.
Fig. 5 : Coupe géologique du sud au nord.
Voir aussi fig. 3a, b, c, d & e. Des sédiments du "coarse layer" sont bien visibles dans la gravière de Wyhlen.

4 - LANDSCAPE EVOLUTION

Geomorphological reconstructions of palaeosurfaces show three distinct stages of the evolution of the Upper Rhine Fan which could be clearly put into a relative time order. Together with new geochronological data and sedimentological observations at gravel pits and wells a more reliable time frame was set up:

– A1: most rapid aggradation of the oldest morphologically visible stage of the Upper Rhine Fan with coarse-grained deposits has taken place between ca. 60 and 16 ka BP (maximum ages). Between ca. 60 and 28 ka BP frequent OSL ages have been determined for various sand layers and sand lenses which point to a relatively continuous fluvial aggradation within this period. Main aggradation and forming of the A1 surface terminates shortly after the deposition of the prominent "Obere Groblage" which can be traced from the western Hochrhein valley to the southern Upper Rhine Graben. The termination of this period can be derived from OSL datings at Wyhlen and Knobel between 16.4 ± 0.8 and 15.1 ± 0.7 ka of thin aeolian and fluvial deposits respectively. Loess deposits at about 10.6 ± 0.5 ka at Wyhlen show a complete deactivation of the fan during the Younger Dryas (tab. 1).

– E1 (Hochgestade) and A2: the age of this erosion-accumulation phase can be framed by the last fluvial deposits on the A1 fan surface 16.4 ± 0.8 ka (Wyhlen pit) and reworked fluvial deposits at the Hochgestade with 11.6 ± 0.6 ka (Knobel pit), respectively. Morphological analysis and sediment budget proves a direct link of the erosion period E1 and the accumulation period A2 forming the new fan further downstream.

– E2: corresponds to the incision of the A2 fan and represents the modern alluvial plain of the Rhine River. Representative ages could be found in the Bremgarten pit on the Tiefgestade (fig. 4). Fluvial deposits about 3.5 m below surface yielded OSL age estimates of 1.9 ± 0.2 and 1.4 ± 0.1 ka BP. A trunk covering the sand layer of Bremgarten gave a radiocarbon age of 510 ± 45 BP showing very recent sedimentation, although the gravel pit does not belong to the present flood plain of the Rhine River. Decoupling of the Bremgarten site from river floods might be as young as river training started in the

19th century. Such ages have not been found at the Knobel pit, which is situated just a few hundred meters further to the east on the Hochgestade. These findings indicate that the Tiefgestade was already formed at this time and fluvial activities of the Rhine River could not reach the Hochgestade any more.

5 - ORIGIN OF MORPHOLOGICAL STAGES

5.1 - ALPINE FORELAND GLACIATIONS AND CLIMATE CONTROL

In the regional context repeated accumulation and incision of the Upper Rhine Fan can be interpreted in terms of foreland glaciations of the northwestern Alps, regional climate, and neotectonic movements. An important early-Würmian glaciation in the Swiss Alps is proved by luminescence dates of about 103 ± 18 ka BP at the Thalgut site (Preusser & Schlüchter, 2004). The foreland lobes subsequently decayed at the transition to the Middle Würmian interstade, e.g. the Rhine glacier terminated up valley of Sargans in the Swiss Alpine Rhine valley (Fliri, 1989). Luminescence datings of proglacial outwash fan deposits at Lake Neuchâtel and glacio-fluvial sands at Mülligen in the Reuss valley (both Switzerland) point to a meltdown of these early Würmian Alpine foreland glaciers at around 60 to 70 ka BP (Preusser & Graf, 2002; Preusser *et al.*, 2007). This melt-down was followed by a Middle Würmian interstadial-complex with wetter climatic conditions and three drier and colder episodes between 50 to 30 ka BP (Preusser, 2004). This interstade-complex with ice-free conditions in the Alpine foreland has been proved at the Gossau gravel pit (Swiss Midlands, 60 to 28 ka BP ^{14}C, Schlüchter & Röthlisberger, 1995; Preusser *et al.*, 2003; Frechen *et al.*, 2007). In the western Vosges Mountains, however, Seret *et al.* (1990, 1992a) conclude from cores of bogs at Grande Pile, that a large ice advance must have happened between 50 ka and 30 ka which possibly was larger than that during the Last Glacial Maximum. In the southern Vosges a large piedmont ice existed at the same period.

The lower part of the first aggradation phase of the Upper Rhine Fan with OSL ages between ca. 60 and 28 ka BP corresponds well to the timing of melt-down of early Würmian foreland glaciers and climate fluctuations with local glacier advances during the Middle Würmian. The higher production rate and supply rate of sediments at that time can be well explained by the melting and thus a mobilisation of glacial debris and, in contrast to interglacial conditions like today, a lack of lacustrine sediment traps. During the middle Würmian Alpine glaciers seem having produced considerable amounts of debris maybe due to warm-based conditions and favourable sediment transport due to a more humid climate. In addition, a stabilizing vegetation cover was repeatedly destroyed during this period, due to climatic perturbations (Preusser, 2004) which could have also contributed to increased mid-Würmian sediment fluxes.

After the Middle Würmian a second major advance of Alpine glaciers took place from 25 to 15 ka BP in the Late Würmian with its maximum extension between 24 and 21.5 ka BP (Preusser, 2004). The rapid collapse of these foreland glaciers of the last glacial maximum at around 17.5 ka BP (Preusser, 2004) is most likely represented by the prominent “Obere Groblage” for which a sandwich age of ca. 28 to 16 ka BP was determined. Apart from this coarse layer, the Late Würmian period is weakly recorded in the southern URG. OSL ages between ca. 16 and 10 ka BP come from relatively thin fluvial deposits of a braided river type which could be just reworked older sediments. Higher thicknesses at Bremgarten are most likely due to local sediment trapping by neotectonic subsidence.

This cut-off from major sediment supply of the URG latest around 16 ka BP was most probably caused by the formation of perialpine lakes (Hinderer, 2001). Undersupply of sediments, in particular of bed load, in combination with high discharge rates owing to continued glacier melting and increasingly humid climate conditions led to a turn from accumulation and/or transfer to erosion and degradation of the fan (formation of surfaces E1 and A2). These eroded sediments were quickly re-deposited when the river gradient decreased significantly in front of the A1 fan, where the Rhine River reached the almost flat river plain. Here a new fan was deposited by downstream progradation of coarse grained sediments. Due to the low resistance of the eroded unconsolidated meltwater deposits, the Rhine River reached rapidly a new, smoother gradient which has been in equilibrium with postglacial conditions, i.e. high discharge but low sediment load. The continuous headward erosion of the Rhine led to a cone-shaped terrace landscape. Within the older fan this surface corresponds to an erosive surface (E1). This type of terrace is referred to as a fill and cut terrace (Bull, 1991). The younger fan corresponds to an accumulation surface (A2).

As the youngest sediments have an age of about 11.6 ± 0.6 ka (Knobel pit) on the Hochgestade, we assume that the meltdown of the last glacier advance at the end of the Younger Dryas led again to a significant increase of sediment-poor meltwater discharge and initiated a second phase of incision of the Rhine river forming the modern surface E2, which dissected the surface of the A2 fan. Bourlès *et al.* (2006) report from the Vosges Mountains that during climate draw-back of the Younger Dryas again glacier expansions took place followed by a rapid retreat. In contrast, Mercier (2002) supposes that local glaciers existed in the Vosges until 7.2 ka BP.

5.2 - TECTONIC MOVEMENTS

Another driving force could be the onset of neotectonic activity separating the Hochgestade from the Tiefgestade terrace, termed Hochgestade-Tiefgestade-fault in figure 1. Continuous subsidence within the A1 fan might have caused antecedent incision of the A2 fan further downstream which may have taken place in several steps presumably according to Holocene climatic fluctuations, tectonic activity, and human impact. Datings from the Bremgarten gravel pit show temporal fluvial accumulation at around 1.9 to 1.4 ka BP and at around 500 a BP. Definitely, at this time the morphological step between the Hochgestade and Tiefgestade must have existed already, because the Knobel pit on the Hochgestade shows no sediments younger than 11.6 ± 0.6 ka BP. The river could not surmount this step and the Hochgestade was no more influenced by fluvial processes. The interpretation of the Hochgestade terrace as a fault is also supported by a seismic reflection transect at Bremgarten (Bram *et al.*, 2005). At Bremgarten a prominent horizontal reflector is observed at 130 ms which continues at 120 ms when crossing from Tiefgestade to Hochgestade.

The ages of 1.9 to 1.4 ka BP might be linked with climatic detoriations during the invasion of the Barbarians and the break down of the Roman Empire. The last fluvial alteration of the landscape, as evidenced by radiocarbon dating of a trunk, was about 500 years ago by aggradations of sand and gravel on the Tiefgestade (tab. 1). It is not clear whether this age is representative for the entire Tiefgestade and reflects an allocyclic, external control. Possible reasons for changing fluvial dynamics are:

– The Basel earthquake of 1356 with an estimated magnitude of 6.0 to 6.5 and a radius of 200 km (Meghraoui *et al.*, 2001), which could have activated slopes and supplied sediment to the river.

– A more or less contemporaneous rupture event along the Hochgestade-Tiefgestade-fault may have caused increased fluvial dynamics resulting in rapid accumulation of sediments. Today, the Bremgarten pit is outside the active river flood plain.

– Climatic deterioration caused by the Little Ice Age.

– Human impact by increased deforestation which leads to more sediment load of the rivers.

The activation of the Hochgestade-Tiefgestade-fault led to increased sedimentation of the Rhine River on the “Tiefgestade” due to subsidence presumably already starting in the Late Würmian. As the highest offset rates are observed in the south and the fault runs out at the Kaiserstuhl, the response of this neotectonic displacement in the south might be an incision in the north forming the present-day E2 surface. While A1, E1 and A2 are climate induced surfaces, the “Tiefgestade” and E2 seem to be a direct response to neotectonics. Taking OSL dating and sediment logs, the maximum displacement of about 15 m happened after the built-up of the A1 fan, thus after about 16 ka BP. This would indicate a mean displacement rate of ca. 1 mm/a. Neotectonic displacement rates from terrace studies in the northern URG are more than one magnitude lower (Peters, 2007). Nivière *et al.* (2008) estimate long term slip rates on faults in the Freiburg area of 0.04 and 0.1mm/a. They do agree that in the short term faults (in their work the Rhine River fault) could have moved faster considering the offset of the late Pleistocene deposits.

6 - CONCLUSIONS

In this paper we present a new model of landscape evolution in the southern Upper Rhine Graben based on DEM analysis including OSL and ^{14}C datings, and a sediment budget. According to these data a three step scenario was developed: (i) 60 to 16 ka BP accumulation of an alluvial fan in the southern URG here called Upper Rhine Fan at the outlet of the Hochrhein (Higher Rhine) valley close to Basel; this fan is mostly composed of coarse-grained fluvial deposits of Alpine origin; (ii) 16 to 10 ka BP incision of the Upper Rhine Fan and accumulation of a new fan further downstream from the eroded sediments, and (iii) 10 ka BP to present incision of the Rhine river into the younger fan leading to the present situation.

Most striking is that only phase (i) seems to have experienced a significant sediment supply from Alpine regions which ended with event-like meltwater deposits (deposited in short time in a very dynamic environment) during the initial melt-down period after the Late Glacial Maximum. During the late stage of melt-down perialpine lakes formed at all major Alpine tributaries of the Rhine River which can well explain the cut-off of the southern Upper Rhine Graben from the Alpine sediment supply latest after 16 ka BP owing to their high trap efficiency. Thus, after ca. 16 ka BP only sediment-poor meltwaters were discharged to the southern Upper Rhine Graben, which caused incision instead of accumulation (ii). A second phase of incision seems to have started at the end of the Younger Dryas when again a pulse of sediment-poor meltwater discharge reached the URG. An alternative or additional explanation is an increasing subsidence in the southern part due to neotectonic movements along the Hochgestade-Tiefgestade-fault. Few datings from Holocene fluvial deposits may be linked with climatic deterioration (e.g. Little Ice Age), tectonic pulses (Basel earthquake 1356 AD), and/or direct human impact during the last 200 years.

Our example demonstrates that the classical para glacial cycle according to Church & Ryder (1972) might be strongly altered in complex geosystems where intermittent sinks become temporarily active. As is the case in our example, a subsystem may give exactly the opposite response, i.e. instead of increased sediment accumulation during glacial meltdown, erosion, reworking and degradation takes place. Thus, general conclusions have to be given very carefully always taking into account the position and downstream coupling of a subsystem within a complete routing system.

ACKNOWLEDGEMENT

We thank the Deutsche Forschungsgemeinschaft (German Research Foundation) for funding the project Hi 643/2-3 “Sediment budget of Pliocene and Quaternary unconsolidated deposits of the Rhineglacier area, Swiss Midlands and the Upper Rhine Graben”. We also thank P. Elsass/BRGM Strasbourg for cheerful collaboration and J. Heinz (Hydroisotop) for introducing us to the sedimentology of the different gravel pits. J. Vandenberghe and D. Harmand remarkably increased the quality of this paper with their constructive suggestions. Special thanks to D. Harmand for the translation into proper French.

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