

Analysis of overdeepened valleys using the digital elevation model of the bedrock surface of Northern Switzerland

Peter Jordan

Received: 6 March 2008 / Accepted: 7 June 2010 / Published online: 30 November 2010
© Swiss Geological Society 2010

Abstract Based on surface and borehole information, together with pre-existing regional and local interpretations, a 7,150 square kilometre Raster Digital Elevation Model (DEM) of the bedrock surface of northern Switzerland was constructed using a 25 m cell size. This model represents a further important step in the understanding of Quaternary sediment distribution and is open to a broad field of application and analysis, including hydrogeological, geotechnical and geophysical studies as well as research in the field of Pleistocene landscape evolution. An analysis of the overdeepened valleys in the whole model area and, more specifically in the Reuss area, shows that, in most cases, overdeepening is restricted to the areas covered by the Last Glaciation Maximum (LGM). However, at various locations relatively narrow overdeepened valleys outreach the tongue basins and the LGM ice shield limits. Therefore, an earlier and further-reaching glacial event has probably contributed significantly to the overdeepening of these valleys. No significant overdeepening has been identified downstream of Böttstein (Aare) and Kaiserstuhl (Rhine), although the ice extended considerably further downstream, at least during the most extensive glaciation. Except for the bedrock between Brugg and Böttstein, no overdeepened valleys are found significantly north of the outcrop of Mesozoic limestone of the Folded and Tabular Jura. A detailed analysis of the Reuss area shows that the Lake and Suhre valleys are separated from the Emmen—Gisikon Reuss valley basin by a significant bedrock barrier. The individual bedrock valleys

are divided into several sub-basins, indicating a multiphase evolution of the valleys. Some of the swells or barriers separating the sub-basins coincide with known late LGM retreat stages. In the Suhre valley, an old fluvial valley floor with restricted overdeepened sections is documented.

Keywords Quaternary cover · Bedrock surface · Overdeepened valleys · DEM · GIS

Introduction

Motivation

A well established knowledge of the bedrock surface geometry and the thickness and spatial distribution of unconsolidated rock is of fundamental interest for a wide range of scientific and applied applications. It is a prerequisite for investigating the Quaternary landscape evolution and the processes involved therein. Quaternary valley fills can form important aquifers and this aspect is important for hydrogeological studies and for various issues relating to geothermal heat pumps. In addition, the distribution of buried Quaternary valleys influences seismic wave propagation and, as a result, the earthquake hazard and the static corrections required in reflection seismic data processing. Finally, the effects of future glaciations have to be considered for evaluating the long-term safety of deep geological repositories for radioactive waste.

Geological setting

The study area is located in the peri-alpine Molasse basin and adjacent areas of the Tabular and Folded Jura (Fig. 1). The bedrock consists of poorly consolidated shales to

Editorial handling: Markus Fiebig.

P. Jordan (✉)
Böhringer AG, Mühlegasse 10, 4104 Oberwil, Switzerland
e-mail: peter.jordan@boe-ag.ch

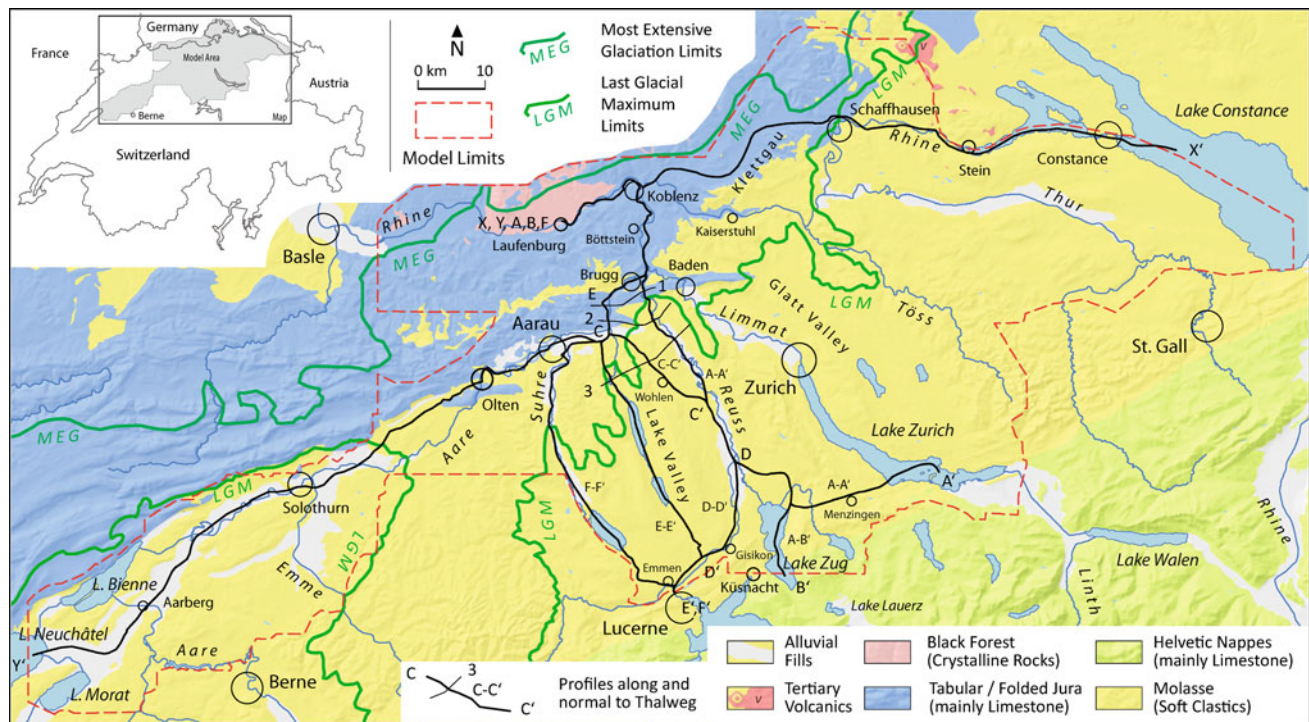


Fig. 1 Extent of bedrock surface model area in northern Switzerland showing major geological-tectonic units and the extent of the Middle Pleistocene Most Extensive Glaciation (MEG) and Late Pleistocene

Last Glacial Maximum (LGM, according to Bini et al. (2009). Profile traces refer to thalweg sections in Figs. 4 and 5

conglomerates and well consolidated Mesozoic limestone with marl intercalations, respectively.

This region was subject to several glacial advances (e.g. Graf 2010). Here, during the Middle Pleistocene Most Extensive Glaciation (MEG, e.g. Schlüchter and Kelly 2000), most of the area was covered by the alpine ice shield (Fig. 1). Later, during the Late Pleistocene Last Glaciation Maximum (LGM, e.g. Bini et al. 2009), glaciation was restricted mainly to the Molasse basin; advancing along the southern foot of the Folded Jura, the eastern mega-branch of the Rhone glacier reached the Solothurn area (Fig. 1). Near Bern it was joined by the Aare glacier. The Reuss glacier covered most of the central part of the model area, advancing along the south–north trending Suhre, Lake and Reuss valleys. A western branch of the Rhine glacier flowed through the Lake Walen depression, where it converged with the Linth and, later, the Reuss glacier. The north-eastern part of the area shown in Fig. 1 was covered by the main (Lake Constance) branch of the Rhine glacier.

In addition to the MEG, various Middle to Late Pleistocene ice advances are postulated to have outreached the LGM limits but are not yet well documented (e.g. Schlüchter and Kelly 2000; Graf 2003, 2009, 2010; Graf et al. 2007; Isler 2005; Preusser 2010).

Overdeepened valleys

Local reports on overdeepened valleys in northern Switzerland can be traced back to Werner + Partner AG and Petraqua (1975) and Schlüchter (1979). A first attempt to compile the available information on bedrock surface into a regional map was made by Wildi (1984) and Pugin (1988). During subsequent years, knowledge of bedrock geometry was continuously improved in various regions and some additional important overdeepened valleys were detected (see chapter 2.2). However, these findings have not yet been compiled in a regional model.

The term “overdeepened valley” is used in different ways. In a relative sense, it includes bedrock structures that are significantly deeper than the actual surface. In an absolute sense, it denotes depressions deeper than a downstream swell. Wildi (1984) suggests using the 300 m a.s.l. isoline as a reference as it corresponds to the important bedrock swells at Böttstein and Kaiserstuhl in the Aare and Rhine valleys, respectively (Fig. 1).

The age and origin of overdeepened valleys in northern Switzerland are still under discussion. This ranges from speculation on being the result of a singular early Middle Pleistocene (pre- or early MEG; e.g. Haldimann 2007, 2009) erosion valley event to concepts of successive formation

and enhancement over the whole Middle to Late Pleistocene period (e.g. Schindler 1982; Graf 1993; Müller et al. 2002). Most authors agree on the importance of sub-glacial fluvial erosion of temperate glaciers for the formation of overdeepened valleys (Benn and Evans 1998; Hinderer 2001; Haldimann 2009).

Digital database and elevation model of the bedrock of northern Switzerland

Aim

To provide the information on bedrock geometry and unconsolidated rock thickness needed for the geological repository siting process, it was originally decided to update the Wildi (1984) and Pugin (1988) isoline maps based on new borehole and seismic data and recent monographs. Starting this inventory in a classical style by compiling borehole information and various isoline interpretations of different authors into a draft, it was soon realised that the enormous volume of often incomplete and contradictory geodata requires a Geographical Information System (GIS), which also provides better access to seismic data and allows basal operations such as assigning elevations to outcrop lines. Following a pilot study (Jordan 2004), the idea was formulated to integrate the borehole and isoline information into a continuous digital elevation model (DEM). Such a model is open to easy quality control and improvement when new information becomes available. It also allows cross-sections to be produced and unconsolidated rock thickness to be calculated. To facilitate such computations, the model was constructed in the same 25 m × 25 m raster as the Swiss regional land surface elevation model provided by the Federal Office of Topography (swisstopo).

Database

The most important raw information on bedrock geometry in deeper domains is derived from borehole data. For the present model, more than 15,000 logs provided by cantonal authorities and private consultants were incorporated (Table 1). After eliminating all double entries and dubious or inconsistent information, there were still 12,500 datasets left for further modelling. This number also includes deep boreholes not reaching the bedrock surface and thus giving a minimum depth.

In the shallow domain, the outcrop of the interface between bedrock and unconsolidated rock provides additional information on bedrock geometry. To obtain this information, outcrop areas have been digitised from geological maps (if available from the Geological Atlas 1:25,000), or from other regional maps on smaller scales (e.g. Hantke 1967; Isler et al. 1984; Schläfli 1999).

Where available, local and regional concepts, maps and sketches of the bedrock surface geometry have been collected, scanned and georeferenced (Table 2). Valuable information about the position of the bedrock surface was also found in regional hydrogeological studies, in particular in the Hydrogeological Atlas of Switzerland (scale 1:100,000), which covers the entire area of interest. Concepts on Pleistocene landscape development are, for example, given by Hantke (Hantke 1978–1983); Schlüchter (1987); Villinger (1998); Graf (1993, 2003, 2010).

Modelling technique

In a first approach, geostatistical methods such as kriging or inverse distance weighted method (IDW) were discussed and tested for bedrock surface modelling. However, these methods did not provide satisfactory results. This may be due to the low and patchy density of the borehole data,

Table 1 Most important borehole databases used

Source	Extent
Dr. H. Jäckli AG, consultants, Zurich	Emmental to Lake Constance
Dr. H. Naef, consultant, St. Gallen	Fricktal, Zurich lowlands (Weinland), Canton Thurgau
Dr. von Moos AG, consultants, Zurich	Northern part of Canton Zurich
Energy and Water Authority, Canton Bern	Wohlensee to Burgdorf
Environmental Authority, Canton Solothurn	Canton Solothurn
Federal Office of Water Management and Geology	Entire Area
Geoform, consultants, Minusio	Entire Area
Geothermal borehole database, Canton Aargau	Canton Aargau
Geothermal borehole database, Schärli and Kohl (2002)	Entire Area
Mengis & Lorenz, consultants, Lucerne	Reuss, Rotach, Suhre and Lake Valleys (Canton Lucerne)

In addition to these digital databases, all borehole indications from the Geological Atlas of Switzerland were digitised (map numbers: 22 Burgdorf, 28 Luzern, 60 Bielersee, 63 Murten, 67 Neuchâtel, 72 Solothurn, 76 Lyss, 84 Sursee, 89 Zug, 100 Bern, 102 Zurzach, 109 Büren a. A., 110 Frick, 116 Rigi, 120 Baden and 125 Romanshorn)

Table 2 Published bedrock isoline maps taken into account for the present model

Publication	Scale	Extent (for location see Fig. 1)
Werner + Partner AG and Petraqua (1975), Werner + Partner AG and Petraqua (1976), Werner + Partner AG and Wanner (1981)	Local	Three successive sections of the Emme valley
Schindler (1982)	Local	City of Schaffhausen and adjacent area
Wyssling AG (1983)	Local	Urdorf, Reppisch valley (south-east of Zurich)
Wildi (1984)	Regional	North-eastern Switzerland
Haldimann et al. (1984)	Local	Lower Aare valley (Brugg—Koblentz)
Pugin (1988)	Regional	Western Switzerland
Pasquier (1986)	Sub-regional	Gäu valley (south-west of Olten)
(Geologisches Institut der Universität Bern 1996)	Sub-regional	Suhre, Lake and Reuss valleys and adjacent area
Wyssling AG (1996)	Local	Hausen—Windisch area (south of Brugg)
Keller and Krayss (1999)	Sub-regional	Thurgau (Thur valley and adjacent area)
Matousek et al. (2000)	Sub-regional	Geol. Atlas, sheet Zurzach
Wagner et al. (2001)	Sub-regional	High Rhine valley from Koblenz to Basle
Hantke et al. (2003)	Local	Thur valley
Frank (2005)	Sub-regional	Weinland area (south of Schaffhausen)
Zaugg and Vogel (2005)	Sub-regional	Swiss shore of Lake Constance and adjacent area
Graf et al. (2006)	Sub-regional	Geol. Atlas, sheet Baden (east of Brugg)
AfU Zug (2007)	Sub-regional	Canton of Zug (east of Lake Zug)
Wyssling (2007)	Sub-regional	Geol. Atlas, sheet Uster (southern Glatt valley)

which ranges from one borehole per two to three square kilometres up to several boreholes per square kilometre. A recent study by Dürst Stucki (2009) showed that, even in regions with a much higher information density, the kriging and IDW methods did not result in a geomorphologically plausible elevation model. Dürst Stucki et al. (this volume) concluded that the method used here is time-consuming but provides by far the best results.

The applied modelling procedure is based on isolines constructed by hand in a GIS (Jordan 2007, 2008a, b). GIS tools such as georeferencing, query, selection, overlay, computing, calculating, labelling and suitable symbolising facilitated the work. The standard equidistance of the isolines is 25 m. Equidistances of 12.5, 10 and 5 m and, in places, even 1 m isolines have been constructed in areas with a high information density and nearly horizontal or strongly structured bedrock.

For the calculation of the 25 m × 25 m Digital Elevation Model (DEM), the ANUDEM code (Hutchinson 1988, 2000) was used (termed “topo-to-raster” in ESRI ArcGIS). Initial models calculated only on an isoline basis could be improved significantly by introducing a line representing the assumed thalweg (see Jordan 2008b for further explanation). Borehole data were not directly used for DEM generation. The introduction of disperse point information in the modelling process results in a high conformity of the DEM with raw data at a specific position but in very poor

results in the near field, with the point data forming pimples or pores (Jordan 2008b). Hence, the borehole data could be used to control the quality of the model by calculating the difference between model elevation and borehole value (Jordan 2008a, b; Dürst Stucki 2009).

The DEM was improved iteratively following specified quality targets:

- Difference between DEM and borehole bedrock elevation value <5 m
- DEM should not be higher than the bottom of boreholes not reaching the bedrock
- In areas with mapped bedrock exposures, the DEM should not be lower than 2 m below surface (criterion used to distinguish between unconsolidated rock domain and bedrock outcrop in Swiss Geological Atlas)
- In areas mapped as unconsolidated rock domains, the DEM should not be above surface.

Extent of the resulting DEM

The current Digital Elevation Model (Fig. 2) is the first regional compilation of knowledge on the bedrock surface in northern Switzerland for more than 25 years; it covers most of the Wildi (1984) and the north-western part of the Pugin (1988) isoline maps. The model reaches from Lake Neuchâtel in the west to Lake Constance in the east and

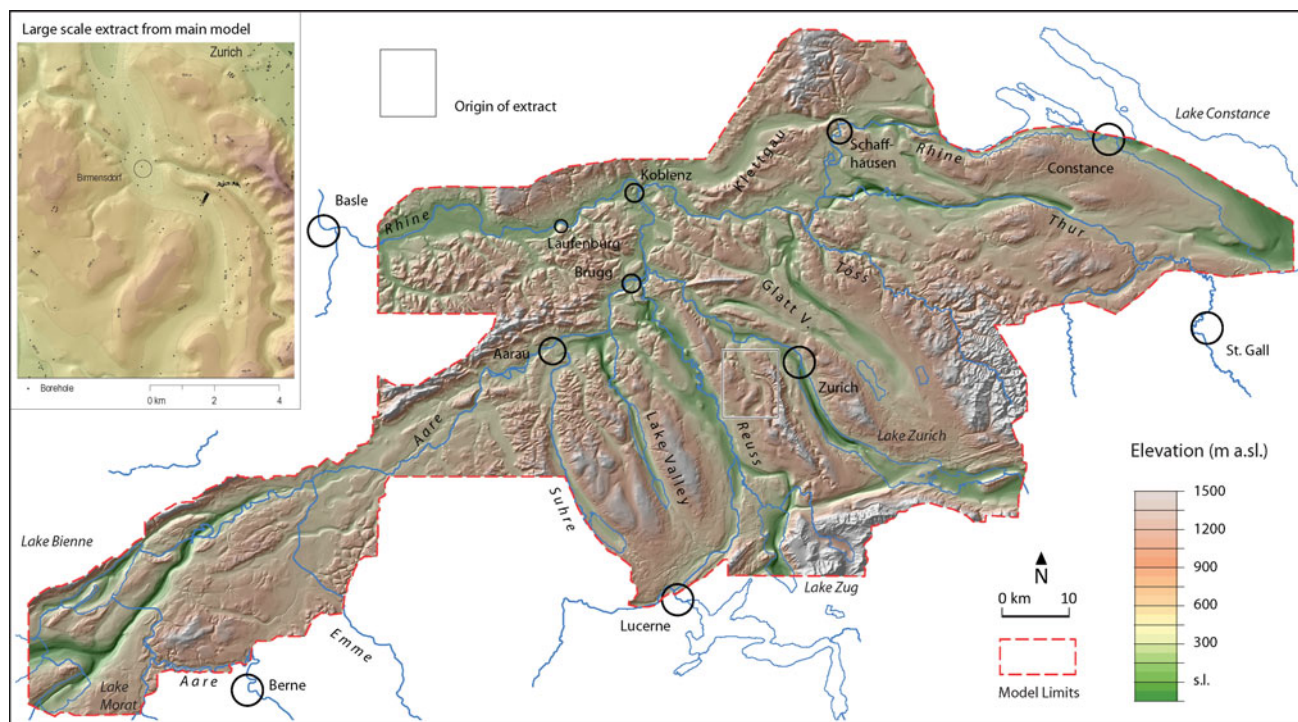


Fig. 2 Northern Switzerland without unconsolidated rock cover: Hillshade view of current continuous Digital Elevation Model (DEM) of the bedrock surface. *Inset top left:* Extract showing details of model

from the Rhine river in the north to the Alpine Front in the south, covering 7,150 square kilometres. Excluded are the hilly regions to the north-west (Jura) and the south and south-east (Molasse highlands). Within its limits the model is continuous. Thanks to recent modelling work at the University of Bern (Dürst Stucki et al., this volume), the area covered by a model with a 25 m grid cell was extended southwards into the Bern region (not yet realised in Fig. 2).

Analyses of the DEM top bedrock with the focus on the geometry of sediment-filled Quaternary valleys

Overall DEM-based analysis of sediment-filled Quaternary valleys in northern Switzerland

The GIS-based analyses of the bedrock DEM allow better characterisation of the Quaternary-filled valleys both on map view (Fig. 3) and on sections (Figs. 4, 5).

Figure 3 shows areas with (1) top bedrock lying below 300 m a.s.l., (2) unconsolidated sediment thicknesses exceeding 80 m and (3) bedrock overdeepenings (undrained depressions). The elevation of 300 m a.s.l. corresponds to the swells at Kaiserstuhl (Rhine) and Böttstein (Aare), downstream of which Wildi (1984) identified no more large-scale overdeepening. The thickness of 80 m corresponds to the unconsolidated rock cover of the central

and location of borehole information. Visible are the remains of different fluvial and glacial valleys carved into the bedrock close to the location of Birmensdorf (south-west of Zurich)

Klettgau valley, a well known abandoned Rhine channel (e.g. Hofmann 1977; Schindler 1982) with considerable relative (but not absolute) overdeepening. The extent of undrained depressions (absolute overdeepening) has been calculated by comparing the top bedrock elevation with successive swell levels along the thalweg (see inset in Fig. 3).

Downstream of Böttstein and Kaiserstuhl (300 m a.s.l.), the analysis of the DEM is in agreement with the results of Wildi (1984) and shows only scarce, small depressions with unconsolidated sediment thicknesses >80 m and local kolk-like drainless structures.

In the north-eastern part of the model area, undrained depressions are mostly restricted to the LGM extent (Fig. 3). Typically, the overdeepened valleys end in distinct tongue depressions. Within the southern Thur and northern Glatt branches, narrow deep channels radiating from the tongue basins penetrate the known LGM limits. These channels are continued by some small undrained but shallow basins. Although covered by some 80 m of unconsolidated sediments, the Klettgau valley is neither undrained nor does it reach below 300 m a.s.l.

Figure 4a shows a section along the Rhine river branch bedrock thalweg, i.e. the interconnection of the deepest points of the rock surface in every section normal to the bedrock depression axis. For a better comparison, all thalweg sections of Fig. 4 and 5 starts at Laufenburg (km 0) and the measure increases upstream. The cross-section

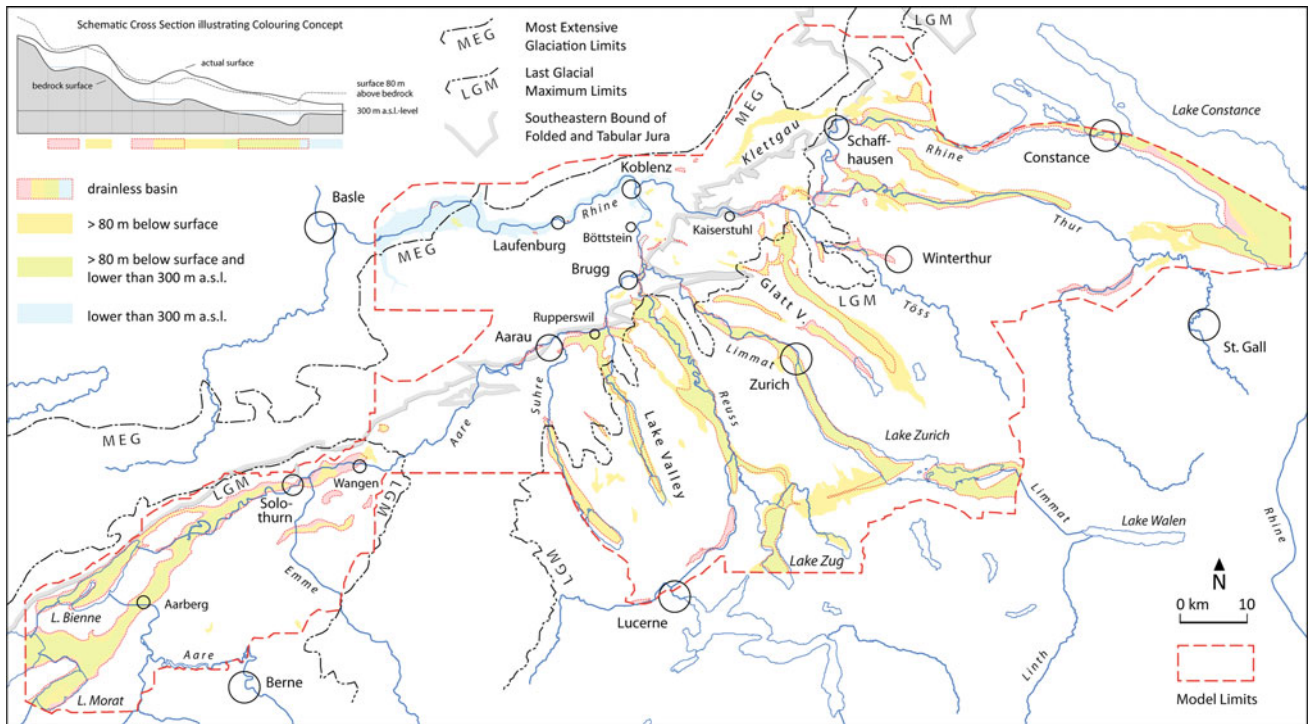
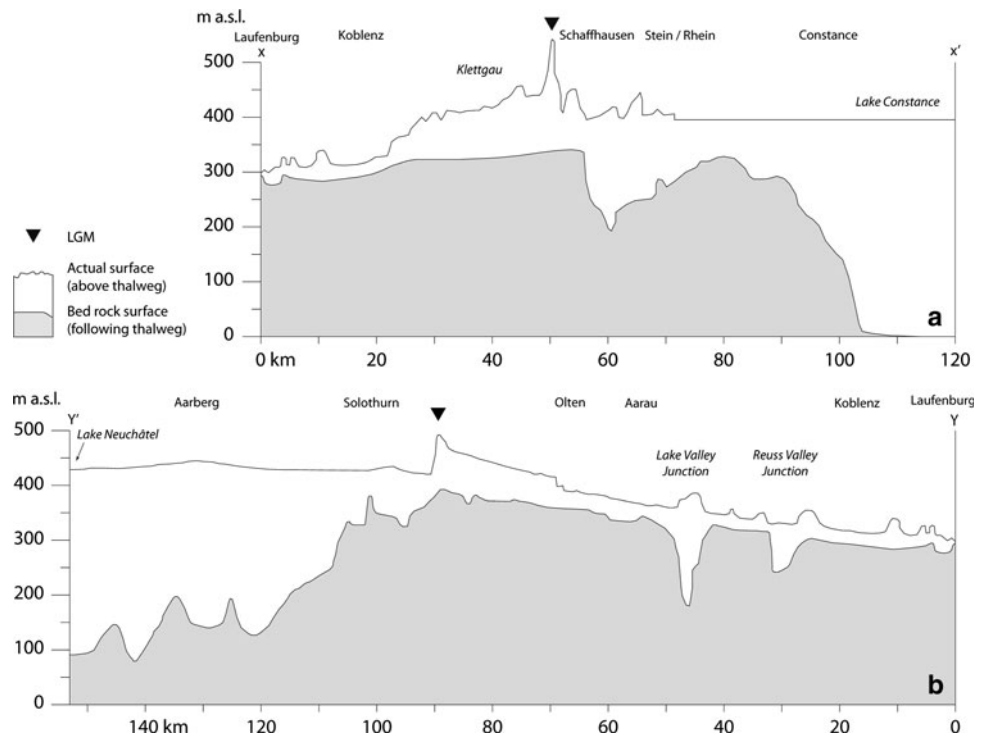


Fig. 3 Overdeepened structures in northern Switzerland revealed by analysis of the present bedrock surface DEM. Three approaches are shown: (1) areas below 300 m a.s.l. (Wildi 1984 criterion, blue and green); (2) areas with more than 80 m unconsolidated rock cover

(yellow and green); (3) undrained basins (framed by red dots and filled red if no other colour applies). See schematic cross-section top left for additional explanation concerning the colouring concept

Fig. 4 Thalweg sections along **a** Lake Constance—Hegau branch of the Rhine glacier and **b** Lake Neuchâtel—Solothurn—Aarau (main) branch of the eastern Rhone glacier (profile traces in Fig. 1). The vertically strongly exaggerated sections start at Laufenburg and follow the bedrock thalweg upstream (for further explanation and discussion see text)



presented in Fig. 4a shows the relatively shoal and gently inclined Klettgau channel carved in the Mesozoic limestone of the Tabular Jura, the smaller Schaffhausen—Stein

am Rhein depression terminated approximately at the outcrop limits of Mesozoic limestone, and the very deep main Lake Constance basin. Both overdeepened structures

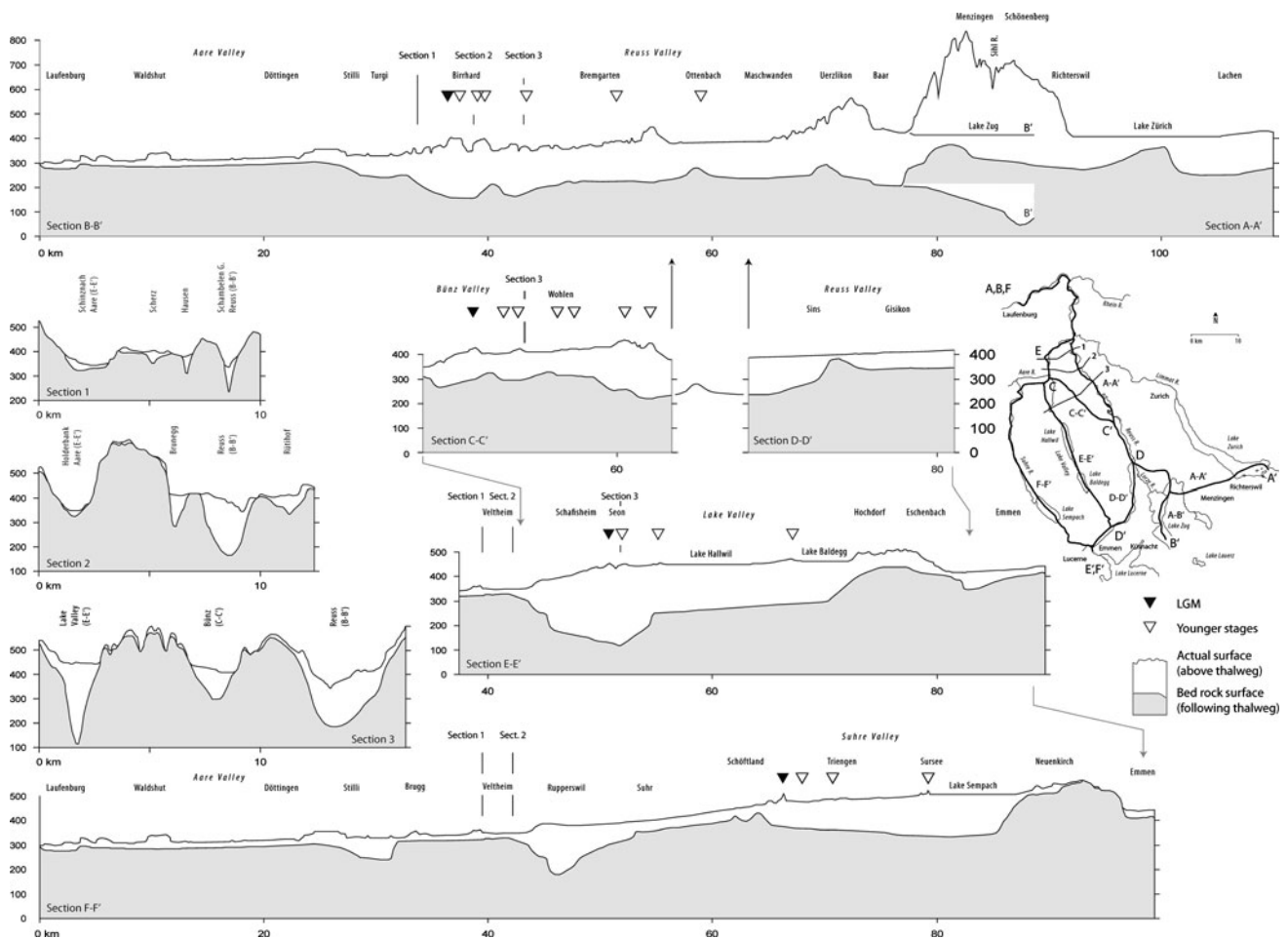


Fig. 5 Thalweg sections (A–A' to F–F'; vertically strongly exaggerated) along the different axes of the Reuss glacier domain including the Linth-Rhine to Reuss conjunction passing the now completely hidden Richterswil—Messingen valley (Section A'–A). All sections start at Laufenburg (for profile traces see inset and Fig. 1). Segments

with identical courses of interlacing sections are partly omitted for better visibility. *Arrows* indicate connectivity between different profiles. Cross-sections 1–3 are oriented normal to the thalweg. The LGM and younger melting stages are shown by *arrow heads*. For further discussion see text

show a distinct steep frontal end and several substructures indicating a multistage origin.

The Limmat valley depression (which is believed to have been formed by a branch of the Rhine-Linth glacier) shows no tongue basin and clearly penetrates the known LGM limits. It ends at the limestone ridge of the Folded Jura.

The branches of the Reuss glacier, following the current Reuss valley and Lake valley (“Seetal”), again show distinct frontal tongue basins. Along all branches in the Reuss glacier system, the overdeepened and undrained basins outreach the known LGM limits. In the case of the Reuss river branch, several anticlines of the Folded Jura are penetrated by a rather narrow appendix reaching the Böttstein swell. This appendix seems to be shallower than the strongly overdeepened basin south of the Folded Jura. The steeply inclined limestone of the Jura anticlines are cut by gorge-like features. (See following chapter for further discussion of Reuss area structures.)

In contrast, within the western branch of Rhone glacier overdeepened and undrained basins are clearly restricted to the known LGM limits. The very deep sub-branches distinguishable in the south-west of the model area coalesce in the downstream direction. In the frontal part, depressions are mostly shoal. The thalweg section (Fig. 4b) shows a deep, internally structured depression which is terminated by a steep end upstream (west) of Solothurn. The shoal depression downstream of Solothurn marks the LGM limits. It is followed by a gently descending valley floor which is only interrupted by two Reuss glacier intruders (see following chapter).

Detailed analysis of the Reuss area

As noted above, most glaciers advanced along different axes. To understand the process of overdeepening, a comparison between the different branches is crucial. This is done here, by way of an example, for the Reuss area.

Downstream of Lake Lucerne, the Reuss river crosses a ridge of inclined Molasse sediments in a SE–NW direction, turns northeast at Emmen and follows along the northern foot of a Molasse ridge until Gisikon, where it turns northwards into the lower Reuss valley (Fig. 1). North and north-east of Emmen there are two other important north-trending valleys, the Suhre valley and Lake valley (“Seetal”), which were also formed by the Reuss glacier. They are separated from the current lower Reuss valley by a hilly landscape. As will be shown, this separation also exists at bedrock level. Alternative connections from the alpine to lower Reuss valley follow the line Schwyz–Lake Lauerz–Lake Zug, with a branch connecting Lake Lucerne with Lake Zug via Küssnacht. Finally, there is the now completely buried Menzingen valley running parallel to the alpine strike between Lake Zurich (Richterswil) and Lake Zug (Wyssling 2002; Blüm and Wyssling 2007).

For the analysis of the Reuss area, different thalweg sections have been extracted from the DEM (Fig. 5). At places without prominent bedrock depression, i.e. between the Reuss and the Suhre and Lake valleys, the line of least elevation difference was selected.

Section A–A' following the current Reuss river to Maschwanden and then propagating through the old Lorze–Reuss valley of Baar and the Menzingen valley to upper Lake Zurich shows six overdeepened basins, each culminating (in the flow direction) in a steep end and an arc-shaped swell. In the upper part including most of the current Reuss valley, the structure carved in the bedrock is U-shaped (sections 2, 3). North of the Birrhard swell, the bedrock valley broadens to the Birrfeld basin, which connects with the Rapperswil basin (see below) via the Brunegg pass. Towards the north, at the intersection with the limestone rocks of an anticline of the Folded Jura, there are three V-shaped openings to the lower Aare valley, which are (from W to E) the Scherz, Hausen and Schambelen gorges. Of these three openings, the depths are greater and the degree of V-shape higher from W to E. North of the Schambelen gorge, where the current Reuss river meets the Aare and Limmat rivers, the small Turgi basin opens. From there, the bedrock thalweg rises continuously to the swell of Böttstein, where the absolute overdeepening ends. Over the last 24 km, from Döttingen to Laufenburg, the bedrock decreases continuously with the already mentioned small rises and two kolk-like depressions close to Laufenburg.

In the case of the Reuss valley, the broad U-shape bedrock valley is restricted to the LGM domain. However, the shape and the existence of a bedrock swell also roughly coincide with a lithological change from Molasse sediments to limestone of the Jura Mountains. A direct relationship between the LGM limit and the northern end of the U-shape bedrock valley therefore seems rather unlikely. This is supported by the fact that the overdeepening of the Reuss-

Aare system extends approximately 10 km to the north of both the LGM limit and the southernmost outcrop of the limestone, mostly in the form of relatively narrow V-shaped valleys.

The current upper Reuss valley, beginning at Emmen and meeting the section A–A' at Maschwanden (section D–D'), shows a swell south of Sins which corresponds in orographic position (about 70 km from Laufenburg) to the Uerzlikon swell of section A–A' but at a significantly higher level.

The Bünz valley, interconnecting the Reuss with the Aare valley via Wohlen (section C–C'), is characterised at the surface by terminal moraines of the LGM and succeeding stages. The bedrock topography shows the step-like marginal boundary of the Bremgarten basin in the south-east and two additional basins towards the north-west. The first is a local U-shaped basin (section 3) and the second, north-western one is the Rapperswil basin discussed below. As in the Reuss valley, some of the bedrock surface steps and swells below the terminal moraines of the LGM and succeeding stages, but there is no clear match between the position of moraines and bedrock structures.

Section E–E' shows that, also at bedrock level, the Lake valley is clearly separated from the Emmen–Gisikon Reuss valley. Branches of the Reuss glacier have obviously overridden the obstacle between Eschenbach and Hochdorf. There is no evidence for an internal subdivision of the upper Lake valley. This may be due to lack of information as borehole data are scarce in this area. Downstream, south of the terminal moraines of the LGM close to Seon, there is a clear increase in overdeepening and a narrowing of the valley before it opens again to the Rapperswil basin, which includes areas lying considerably north of the LGM extent.

The Suhre valley (section F–F') is also clearly separated from the Emmen–Gisikon Reuss bedrock valley by a huge bedrock swell. Below Lake Sempach there is a basin with maximum depth in the south and continuously shoaling northwards. At Schöffland, there is a double swell which is again outside the known LGM limits. The bedrock surface then gently sinks until, at Suhr, it reaches a level some 50 m above the bedrock level at Laufenburg. The thalweg segments of section F–F' from Schöffland to Suhr, from Veltheim to Brugg and from Döttingen to Waldshut seem to be relicts of an old fluvial continuous valley floor below the recent Suhre and Aare valley with a successively decreasing slope from 5‰ at Schöffland to 1‰ at Waldshut. The prominent Rapperswil basin is carved into this former valley floor. The deepest point of the depression is, however, not in the 10 km long, east–west trending basin, but further south in the relatively narrow northernmost part of the Lake valley (sections E–E' and 3). The Rapperswil basin is limited by the Holderbank swell below the current Aare valley (section 2) and the Brunegg swell (shown in

section 2 but not at culmination) leading to the Birrfeld basin.

Conclusions

The continuous DEM of the bedrock surface is a powerful tool for the discussion of hydrological and geomorphological concepts and a good basis for deciphering the Pleistocene landscape evolution of northern Switzerland.

As already recognised by Wildi (1984), no overdeepenings occur downstream of Kaiserstuhl (Rhine) and Böttstein (Aare) corresponding to areas below 300 m a.s.l., despite the fact that at least during the MEG the glaciers reached about 40 km further downstream.

An overall analysis shows that overdeepened undrained valleys are mostly restricted to areas with a Molasse substratum and to areas within LGM limits, but there are important exceptions in both cases.

Only in the Rhone glacier domain (current subjurassic Aare valley), overdeepening is strictly restricted to LGM limits (Wangen), even though there is undoubted evidence that the Rhone glacier advanced much further during the MEG via Aarau to the current Rhine valley.

In most of the Reuss and Rhine glacier branches, narrow V-shaped overdeepened valleys radiating from the frontal tongue basins penetrate the known LGM limits. And the prominent Rupperswil tongue basin of the Reuss glacier lies completely outside. Obviously, these structures must have formed prior to LGM times.

Most of the overdeepened undrained structures end at least when the outcrop of the Mesozoic limestone of the Tabular or Folded Jura are reached. Minor and mayor penetrations of deep undrained valleys into limestone ridges are only observed in the Lake and current Reuss valley branches, respectively, of Reuss glacier. In the latter case, the southern Mesozoic outcrop limits are outreached by approximately 10 km. In general, the valley shape changes from U to V and narrows considerably at the limestone outcrop.

The specific analysis of the Reuss area reveals that the overdeepened valleys are internally structured into swells and sub-basins. In some few cases, these structures are related to the lithology of the bedrock, i.e. to ridges of inclined conglomerate (e.g. near Lucerne) or limestone strata (Folded Jura). Some other swells are in the vicinity of terminal moraines of the LGM and subsequent stages suggesting a synchronous formation during. In the Birrfeld basin, subsequent stages of overdeepening are clearly documented. In the Suhre valley, an older valley floor was affected by more recent overdeepening. All these observations point towards a multiphase evolution of the bedrock valleys. And in their external parts, most of the

valleys seem to be the result of older glaciation events with similar or larger extents compared to the LGM.

Acknowledgments We would like to thank all the individuals and institutions who made the large volume of data available and helped to bring this project to its present stage. In particular, we are very grateful to Nagra (Swiss National Cooperative for the Disposal of Radioactive Waste) for initiating and funding the project; special thanks go to Hanspeter Weber, Michael Schnellmann and Wilfried Albert. We would like to thank all colleagues who have been involved in the drafting and modelling work, particularly Balthasar Blülle, Maya Schniepper, Thomas Schuler and Marco Schwab. Finally, thanks go to Hansruedi Graf, Dietrich Ellwanger, Markus Fiebig, Heinz Schneider, André Lambert and Linda McKinley for reviews of an earlier draft and editorial assistance.

References

- AfU (Amt für Umweltschutz des Kantons) Zug. (2007). Geologie und Grundwasservorkommen im Kanton Zug. Erläuterungen zur Grundwasserkarte 1:25,000. 156 Seiten, 3 Planbeilagen (u.a. Geologische Karte der Felsoberfläche des Kantons Zug 1:50,000). Büro Dr. Lorenz Wyssling AG, Pfaffhausen.
- Benn, D. I., & Evans, J. A. (1998). *Glaciers and Glaciations* (p 734). London: Arnold.
- Bini, A., Buoncristiani, J.-F., Couterrand, S., Ellwanger, D., Felber, M., Florineth, D., Graf, H. R., Keller, O., Kelly, M., Schlüchter, C., & Schoeneich, P. (2009). Die Schweiz während des letzteiszeitlichen Maximums (LGM) 1:500,000. *Bundesamt für Landestopografie*.
- Blüm, W., & Wyssling, G. (2007). *Ur-Sihl und Richterswiler Gletschertal*. Zurich: Zürcher Umweltpraxis.
- Dürst Stucki, M. (2009). Modellierung der Felsoberfläche in der Region Bern (Kartenblatt 498 1166, Bern 1:25,000). Unpublished Master's thesis, University of Bern, Switzerland.
- Dürst Stucki, M., Reber, R. & Schlunegger, F. (this volume): Subglacial tunnel valleys in the Alpine foreland—an example from Bern, Switzerland. *Swiss Journal Geosciences*.
- Frank, S. (2005). Entsorgungsnachweis Quartär—Aquifere Zürcher Weinland—Beurteilung der geologisch-hydrogeologischen Verhältnisse. Bericht 7609 der Dr. von Moos AG für die HSK, NAHYD 55.
- Geologisches Institut der Universität Bern. (1996). Felsrelief der zentralen und südlichen Aargauer Täler. Unpublizierte Karte in Zusammenarbeit mit der Abteilung Umweltschutz des Kantons Aargau (Plot der GIS-Datensätze).
- Graf, H. R. (1993). Die Deckenschotter der zentralen Nordschweiz. Dissertation Nr. 10205, ETH Zurich.
- Graf, H. R. (2003). Geschichte des unteren Thurtals. *Mitteilungen der Deutschen Gesellschaft für Allgemeine und Angewandte Entomologie*, 59, 7–29.
- Graf, H. R. (2009). Stratigraphie und Morphogenese von frühpleistozänen Ablagerungen zwischen Bodensee und Klettgau. *Eiszeitalter und Gegenwart—Quaternary Science Journal*, 58–I, 12–53.
- Graf, H. R. (2010). Stratigraphie von Mittel- und Spätpleistozän in der Nordschweiz. Beiträge zur Geologischen Karte der Schweiz 168.
- Graf, H. R., Bitterli-Dreher, P., Burger, H., Bitterli, T., Diebold, P. & Naef, H. (2006). Geologischer Atlas der Schweiz 1:25,000, Blatt 120 Baden (LK 1070). Bundesamt für Landestopografie.
- Graf, A., Strasky, S., Ivy-Ochs, S., Akcar, N., Kubik, P. W., Burkhard, M., et al. (2007). First results of cosmogenic dated

- pre-Last Glaciation erratics from the Montoz area, Jura Mountains, Switzerland. *Quaternary International*, 164–165, 43–52.
- Haldimann, P. (2007). Deep valleys in the Swiss Molasse Unit—10 million years of erosion and sediment accumulation. *Geophysical Research Abstracts*, 9, 11542.
- Haldimann, P. (2009). Zur Entstehungsgeschichte übertiefer Felsrinnen im Alpenvorland: Fakten, Interpretation und Thesen. Kolloquium zum Thema glaziale Tiefenerosion, 21. January 2009: <http://www.kne-schweiz.ch/index.php?id=198>.
- Haldimann, P., Naef, H., Schmassmann, H. (1984). Fluviale Erosions- und Akkumulationsformen als Indizien jungpleistozäner und holozäner Bewegungen in der Nordschweiz und angrenzenden Gebieten, Nagra Technischer Bericht NTB 84-16.
- Hantke, R. (1967). Geologische Karte des Kantons Zürich und seiner Nachbargebiete. *Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich*, 112(2).
- Hantke, R. (1978–1983). Eiszeitalter (3 volumes). Ott Verlag, Thun, 1901.
- Hantke, R., Müller, E., Scheidegger, A. E., & Wiesmann, A. (2003). Der Molasse-Schuttfächer des Ottenberg und der Lauf der Thur seit dem jüngeren Tertiär. *Mitteilungen der Deutschen Gesellschaft für Allgemeine und Angewandte Entomologie*, 59, 85–111.
- Hinderer, M. (2001). Late Quaternary denudation of the Alps, valley and lake fillings and modern river loads. *Geodinamica Acta*, 14, 231–263.
- Hofmann, F. (1977). Neue Befunde zum Ablauf der pleistozänen Landschafts- und Flussgeschichte im Gebiet Schaffhausen-Klettgau-Rafzerfeld. *Eclogae Geologicae Helvetiae*, 70, 105–127.
- Hutchinson, M. F. (1988). Calculation of hydrologically sound digital elevation models. In: Proceedings of the Third International Symposium on Spatial Data Handling (pp. 117–133), August 17–19, Sydney. International Geographical Union, Ohio: Columbus.
- Hutchinson, M. F. (2000). ANUDEM Software. Centre for Resource and Environmental Studies, Australian National University, Canberra. <http://cres.anu.edu.au/outputs/software.php>.
- Isler, A. (2005). Erläuterungen zum geologischen Atlas der Schweiz 1:25,000, Blatt 100 Bern (LK 1166). Bundesamt für Wasser und Geologie.
- Isler, A., Pasquier, F. & Huber M. (1984). Geologische Karte der zentralen Nordschweiz 1:100,000. Geologische Spezialkarte 121.
- Jordan, P. (2004). Felsisohypsenkarte am Jurasüdfuss zwischen Oberbuchstien SO und Lenzburg AG. Report Imper Geologie, Heiligkreuz.
- Jordan, P. (2007). Digitales Höhenmodell der Basis des Quartärs (DHM_B_QU, „Felsmodell“). Nagra Arbeitsbericht NAB 07-12.
- Jordan, P. (2008a). Digitales Höhenmodell. Am Beispiel der Felsoberfläche der Nordschweiz. *Gas-Wasser-Abwasser*, 6(2008), 443–449.
- Jordan, P. (2008b). Designing the DEM of the Base of the Swiss Plateau Quaternary Sediments. Extended Abstract, In: Proceedings of the 6th ICA Mountain Cartography Workshop, 11–15 February 2008, Lenk, Switzerland, http://www.mountaincartography.org/publications/papers/papers_lenk_08/jordan.pdf.
- Keller, O., & Krayss, E. (1999). Quartär und Landschaftsgeschichte. In: Schläfli, A. (ed.): Erläuterungen zur Geologischen Übersichtskarte des Kantons Thurgau 1:50,000 (pp. 39–67), *Mitteilungen der Thurgauischen Naturforschenden Gesellschaft*, 39–67.
- Matousek, F., Wanner, M., Baumann, A., Graf H. R., Nüesch, R. & Bitterli, Th. (2000). Geologischer Atlas der Schweiz 1:25,000. Blatt 102 Zurzach (LK 1050). Mit Erläuterungen. Landesgeologie, Bundesamt für Landestopografie, Bern.
- Müller, W. H., Naef, H. & Graf, H. R. (2002). Geologische Entwicklung der Nordschweiz, Neotektonik und Langzeitzzenarien Zürcher Weinland. Nagra Technischer Bericht NTB 99-08.
- Wagner, B., Huggenberger, P., Schaub, D., Thater, M. (2001). Erkundung der Grundwasserleiter und Böden im Hochrheintal. Abschlussbericht. Landratsamt Waldshut.
- Pasquier, F. (1986). Hydrodynamique de la nappe du Gäu (cantons de Soleure et Berne). Thèse Univ. Neuchâtel. (p. 111) (http://doc.rero.ch/Im.php?url=1000,40,4,20050413125353-R/2_these_PasquierF.pdf).
- Preusser, F. (2010). Stratigraphische Gliederung des Eiszeitalters in der Schweiz. *Jb. Mitt. Oberrhein. Geol. Verein, Neue Folge*, 92, 83–97.
- Pugin, A. (1988). Carte des isohypses de la base des sédiments du Quaternaire en Suisse occidentale, avec quelques commentaires”. Landeshydrologie und –geologie Bern, Geologische Berichte Nr. 3.
- Schärli, U., & Kohl, T. (2002). Archivierung und Kompilation geothermischer daten der Schweiz und angrenzender Gebiete. Beitr. geol. Schweiz. Geophysik 36. *Schweizerische Geotechnische Kommission*.
- Schindler, C. (1982). Baugrunderkennung Schaffhausen 1:10'000. Beiträge zur Geologie der Schweiz, geotechnische Serie, kleinere Mitteilungen, 73.
- Schläfli, H. (ed.) (1999). Erläuterungen zur geologischen Übersichtskarte des Kantons Thurgau. - Mitt. Naturforsch Ges. Thurgau 55.
- Schlüchter, C. (1979): Übertiefe Talabschnitte in Berner Mittelland zwischen Alpen und Jura (Schweiz) *Eiszeitalter und Gegenwart* 29, 101–113.
- Schlüchter, C. (1987). Talgenese im Quartär—eine Standortbestimmung. *Geographica Helvetica*, 2, 109–115.
- Schlüchter, C., & Kelly, M. A. (2000). Das Eiszeitalter in der Schweiz. Eine schematische Zusammenfassung, Überarbeiteter Neudruck. Stiftung Landschaft und Kies, 605 Uttigen.
- Villinger, E. (1998). Zur Flußgeschichte von Rhein? und Donau in Südwestdeutschland. *Jb. Mitt. Oberrhein. Geol. Verein, Neue Folge*, 80, 361–398.
- Zaugg A., Vogel, G. (2005). EP-05 Fallstudien zur sedimentologischen und hydrogeologischen Charakterisierung der Oberen Süsswassermolasse zwischen Zürichsee und Bodensee. Nagra Arbeitsbericht NAB 05-022.
- Werner + Partner AG, Wanner, J. (1981). Grundlagen für die siedlungswirtschaftliche Planung des Kantons Bern. Hydrogeologie Emmental, Teil III: Unteres Emmental.
- Werner + Partner AG, Petraqua. (1975). Grundlagen für die siedlungswirtschaftliche Planung des Kantons Bern. Hydrogeologie Emmental, Teil I: Oberes Emmental.
- Werner + Partner AG, Petraqua. (1976). Grundlagen für die siedlungswirtschaftliche Planung des Kantons Bern. Hydrogeologie Emmental, Teil II: Mittleres Emmental.
- Wildi, W. (1984). Isohypsenkarte der quartären Felstäler in der Nord- und Ostschweiz mit kurzen Erläuterungen. *Eclogae Geologicae Helvetiae*, 77(3), 541–551.
- Wyssling, G. (2002). Die Ur-Sihl floss einst ins Reusstal. *Jahreshefte Vereinigung Pro Sihltal*, 52, 1–14.
- Wyssling AGL. (1983). Karte der Felsoberfläche, Abschnitt Urdorf—Birmensdorf. In: L. Wyssling AG, (ed.) Die Grundwasserverhältnisse im Gebiet Reppisch—Urdorf, Amt für Gewässerschutz und Wasserbau des Kantons Zürich.
- Wyssling AGL. (1996). Karte der Felsoberfläche 1:5,000. In: L. Wyssling AG, (ed.) Geologische Datensynthese Hausertal/AG zwischen Birrfeld und Brugg. Baudepartement des Kantons Aargau, Abteilung Tiefbau.
- Wyssling, G. (2007). Geologischer Atlas der Schweiz 1:25,000. Blatt 128 Uster (LK 1092). Mit Erläuterungen. Landesgeologie, Bundesamt für Landestopografie, Bern.