https://doi.org/10.5194/egusphere-2024-683
Preprint. Discussion started: 14 May 2024

Overdeepening or tunnel valley of the Aare glacier on the northern margin of the European Alps: Basins, riegels, and slot canyons

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Abstract

This work summarizes the results of an interdisciplinary project where we aimed to explore the origin of overdeepenings or tunnel valleys through a combination of a gravimetry survey, drillings, dating and a synthesis of previously published work. To this end, we focused on the Bern area, Switzerland, situated on the northern margin of the European Alps. In this region, multiple advances of piedmont glaciers during the Quaternary glaciations resulted in the carving of the main overdeepening of the Aare River valley (referred to as Aare main overdeepening). This bedrock depression is tens of km long and up to several hundreds of meters to a few kilometers wide. We found that in the Bern area, this main overdeepening is made up of two >200 m-deep troughs that are separated by a c. 5 km-long and up to 150 m-high transverse rocky ridge, interpreted as a riegel. The basins and the riegel are overlain by a >200 m- and 100 m-thick succession of Quaternary sediments, respectively. The bedrock itself is made up of a Late Oligocene to Early Miocene suite of consolidated clastic deposits, which are part of the Molasse foreland basin, whereas the Quaternary suite comprises a middle Pleistocene to Holocene succession of glacio-lacustrine gravel, sand and mud. A synthesis of published gravimetry data revealed that the upstream stoss side of the bedrock riegel is c. 50% flatter than the downstream lee side. In addition, information from >100 deep drillings reaching depths >50 m suggests that the bedrock riegel is dissected by an anastomosing network of slot canyons. We propose that these canyons established the hydrological connection between the upstream and downstream basins during their formation. Based on published modelling results, we interpret that the riegels and canyons were formed through

incision of subglacial meltwater during a glacier's decay state, when large volumes of meltwater were released. Such a situation has repeatedly occurred since the Middle Pleistocene Transition approximately 800 ka ago, when large and erosive piedmont glaciers began to advance far into the foreland. This resulted in the deep carving of the inner-Alpine valleys, and additionally in the formation of overdeepenings on the plateau on the northern margin of the Alps.

1 Introduction

Overdeepenings, or tunnel valleys (e.g., Jørgensen and Sandersen, 2006; Dürst Stucki et al., 2010), are bedrock depressions below the current fluvial base-level (Fischer and Häberli, 2012). The downstream closures of these basins have adverse slopes that generally dip in the upstream direction (Häberli et al., 2016). Because bedrock depressions with such characteristics are commonly found in previously glaciated areas (Figure 1), their formation has been interpreted as resulting from the erosional work of glaciers with support by subglacial meltwater (Wrigth, 1973; Herman and Braun, 2008; Egholm et al., 2009; Kehew et al., 2012; Patton et al., 2016; Liebl et al., 2023; and many others). Overdeepenings have been reported for the Quaternary from beneath the Greenland and Antarctic glaciers (Ross et al., 2011; Patton et al., 2016), the North Sea (Moreau et al., 2012, Lohrberg et al., 2022), North America (Wright, 1973; Lloyd et al., 2023) and northern Europe including Scandinavia (Clark and Walder, 1994; Piotrowski, 1997; Kron et al., 2009). In addition, numerous Paleozoic successions entailing glaciogenic paleovalleys were also described (e.g. Douillet et al., 2012; Dietrich et al., 2021). Such erosional troughs have particularly been identified in the European Alps (Preusser et al., 2010), where >200 m-deep and several km-long bedrock depressions beneath the modern base-level occur in the Alpine valleys as well as on foreland plateaus on either side of this mountain belt (Preusser et al., 2010; Dürst Stucki and Schlunegger, 2013; Magrani et al., 2020). Geophysical surveys (e.g., Rosselli and Raymond, 2003; Reitner et al., 2010; Stewart and Lonergan, 2011; Stewart et al., 2013; Perrouty et al., 2015; Burschil et al., 2018; 2019; Ottesen et al., 2020) in combination with drillings (Jordan, 2010; Dürst Stucki et al., 2010; Büchi et al., 2017; 2018; Gegg et al., 2021; Bandou et al., 2022; 2023; Anselmetti et al., 2022; Schwenk et al., 2022a, b; Gegg and Preusser, 2023; Schaller et al., 2023) disclosed that such overdeepenings can be several kilometers wide and tens of kilometers long and that they are generally made up of individual sub-basins separated by bedrock swells, or riegels (Cook and Swift, 2012). Bedrock swells or riegels that separate bedrock depressions have also been reported from modern landscapes. In this context, a riegel is a rock wall, which is oriented across a previous glacier's flow direction.

An ensemble consisting of a riegel separating upstream and downstream basins has been considered as a classical feature of a landscape, which was repeatedly sculpted by glaciers during the past glaciations (Brocklehurst and Whipple, 2002; Brocklehurst et al., 2008; Cook and Swift, 2012; Steinemann et al., 2021). Observations from modern landscapes (see Figure 2 for examples in the Swiss Alps) have

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additionally shown that such bedrock swells or riegels may be cut by slot canyons or inner gorges (Montgomery and Korup, 2011; Steinemann et al., 2021), establishing a hydrological link between the upstream and downstream basins. These features were used as key information for invoking dissection by meltwater as an important erosional mechanism (Carter and Anderson, 2006; Steinemann et al., 2021). Although bedrock swells or riegels were reported as common features in overdeepenings (Gegg and Preusser, 2023), the occurrence of inner gorges or slot canyons (Figure 1) have only recently been disclosed (Bandou et al., 2023). It is the scope of this work to document such structures in an overdeepening and to discuss their importance for our understanding of how such depressions were formed.

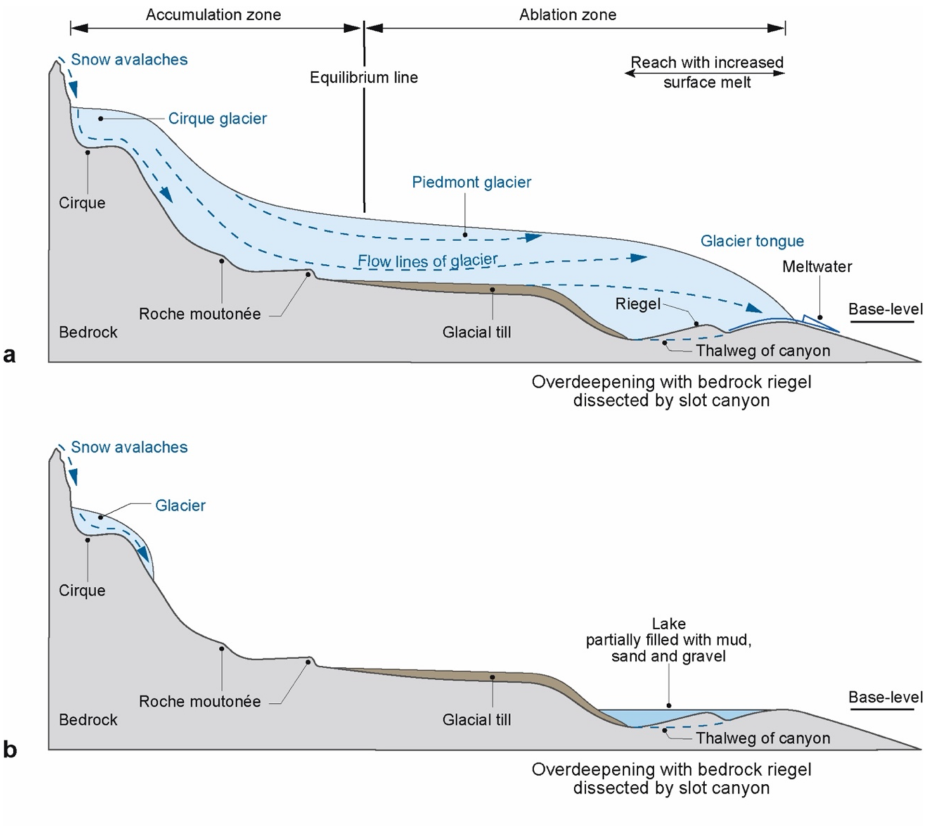

Figure 1

Figure 1: Architecture of a landscape sculpted by piedmont glaciers during glaciations. a) Situation immediately following a full glacial period during which a piedmont glacier, which extended far into the foreland, started to melt. As a result, large volumes of meltwater are produced in the ablation zone close to the glacier's tongue. This meltwater has the potential to contribute to the erosional downwearing of the bedrock, and it can cause the incision of canyons into bedrock riegels, which separate two overdeepened basins. b) During interglacial time periods, the piedmont glaciers disappear, and small ice caps may be preserved in the higher parts of a mountain belt. During this time, the overdeepened basin will be filled by lacustrine sediments and will eventually host a lake. Modified after Schlunegger and Garefalakis (2023).

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Here, we summarize the results of an interdisciplinary project where we aimed at exploring the origin of tunnel valleys or overdeepenings using a combination of data collected through a gravimetry survey (Bandou et al., 2022, 2023), drillings (Reber and Schlunegger, 2016; Schwenk et al., 2022a, b) and dating (Schläfli et al., 2021; Schwenk et al., 2022a). We focus our study on the Bern area situated on the northern margin of the European Alps (Figure 3a). For this region, we draw a map of the bedrock structure combining the results of a gravimetry survey in the region (Bandou et al., 2023) with information obtained through drilling. This map shows that an overdeepened trough or a tunnel valley system, referred to as the Aare main overdeepening (Schwenk et al., 2022), is made up of two basins separated by a bedrock riegel, which itself is cut by one or multiple slot canyons. This structure has a similar geometry as the examples reported from the Alpine valleys, which points to similar processes resulting in their formation.

2 Riegels and slot canyons in the Alpine valleys, and overdeepenings in the Bern area

Bedrock swells between neighboring basins are common features in previously glaciated landscapes and have been reported from various regions around the globe (Anderson et al., 2006; Alley, 2019). They are particularly found in the European Alps (see Figure 2, for a few examples), and they have also been detected underneath active glaciers (Feigel et al., 2018; Nishiyama et al., 2019). In the Alps, most of the bedrock swells occur at the base of valleys (Figure 2) and are dissected by inner gorges or slot canyons that connect the upstream with the downstream basin (Hantke and Scheidegger, 1973; Valla et al., 2009; Montgomery and Korup, 2011). In addition, the Alpine bedrock riegels have a geometry where the upstream stoss side is flatter and has thus a lower dip angle than the downstream lee side. This is particularly the case for the swell in (Figure 2): the Aare valley (Figure 2a; dip of stoss side and lee sides <5° and >6°, respectively; Hantke and Scheidegger, 1973), the Trift valley (Figure 2b; c. 30° versus 40°; Steinemann et al., 2021), the Maggia valley (Figure 2e; 6° versus 40°), and the downstream end of the Urbach valley (Figure 2f; c. 20° versus 6°). In this work, we will document that the overdeepening beneath the city of Bern shares the same geometric properties as the ensemble of bedrock riegels and slot canyons in the Alpine valleys.

The target overdeepening near Bern was sculpted by the Aare piedmont glacier with sources in the Central European Alps. From there, the Aare glacier flowed onto the Swiss Plateau over a distance of >20 km, and it merged with the Valais glacier north of Bern, at least during the Last Glacial Maximum (LGM) c. 20 ka ago (Figure 3b). Upstream of the city area of Bern, two bedrock depressions, referred to as the Gürbe tributary channel and the Aare main overdeepening (Figure 3c), form prominent basins that are between c. 150 (Gürbe trough; Geotest, 1995) and >250 m deep (Aare main trough, Kellerhals and Häfeli, 1984) and several kilometers wide (Bandou et al., 2022). Downstream of the city of Bern, the Aare main overdeepening splits into several distributary branches. Among these, the Bümpliz channel ('Bü' in Figure 3c) is the most prominent one with a depth >200 m (Schwenk et al., 2022a, b).

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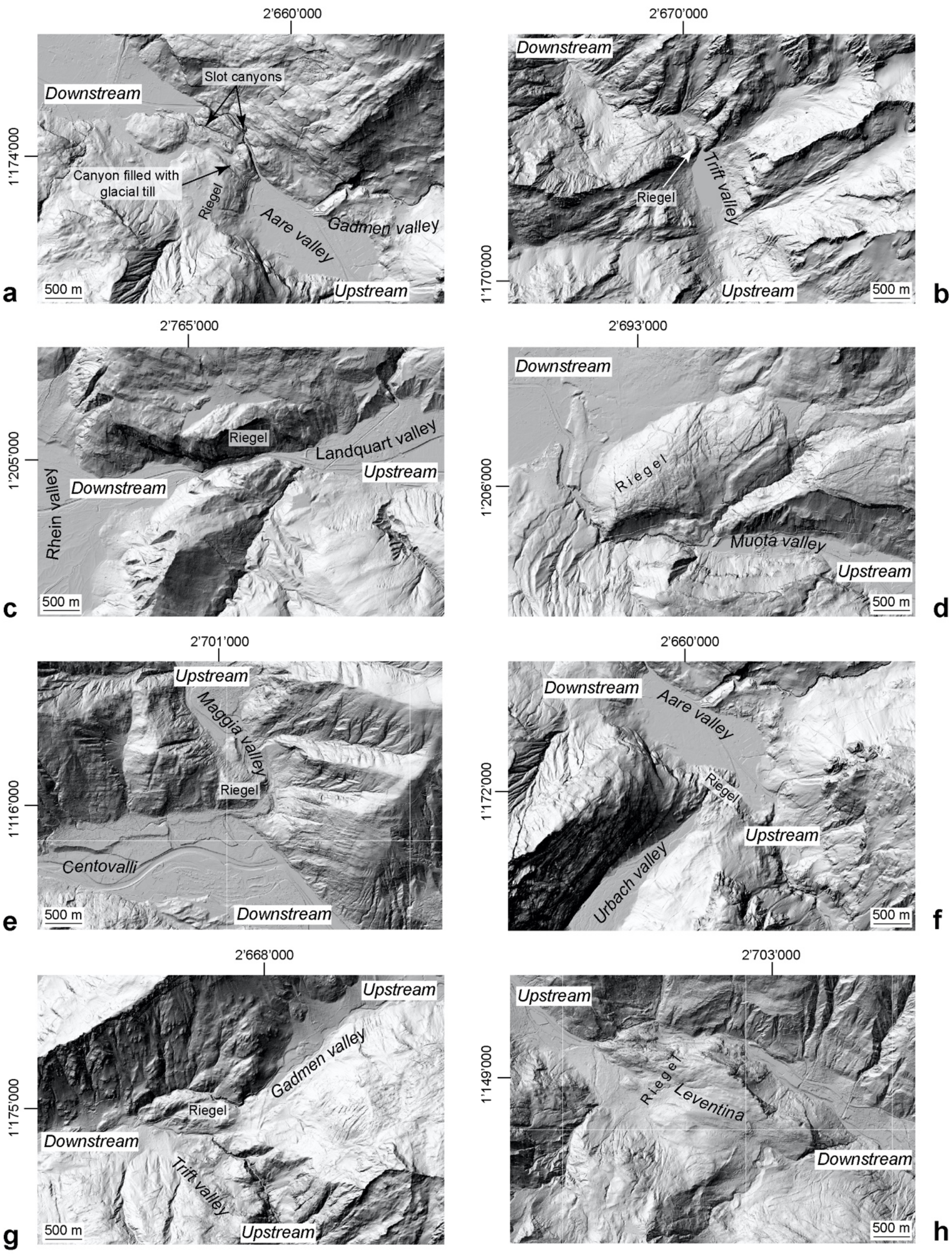

Figure 2

Figure 2: Hillshade 2 m-SwissAlti3D DEM (© swisstopo) illustrating examples in the Alpine valleys where bedrock riegels separate overdeepened basins situated farther upstream and downstream. The coordinates refer to the Swiss coordinate system.

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The other depressions such as the Zollikofen trough are shallower and reach a depth of <150 m (Reber and Schlunegger, 2016). The study region also hosts the Meikirch overdeepening (labelled as 'Me' on Figure 3c), a nearly 200 m-deep trough (Dürst Stucki et al., 2010; Dürst Stucki and Schlunegger, 2003), which appears to be isolated from the rest of the overdeepening system (Reber and Schlunegger, 2016).

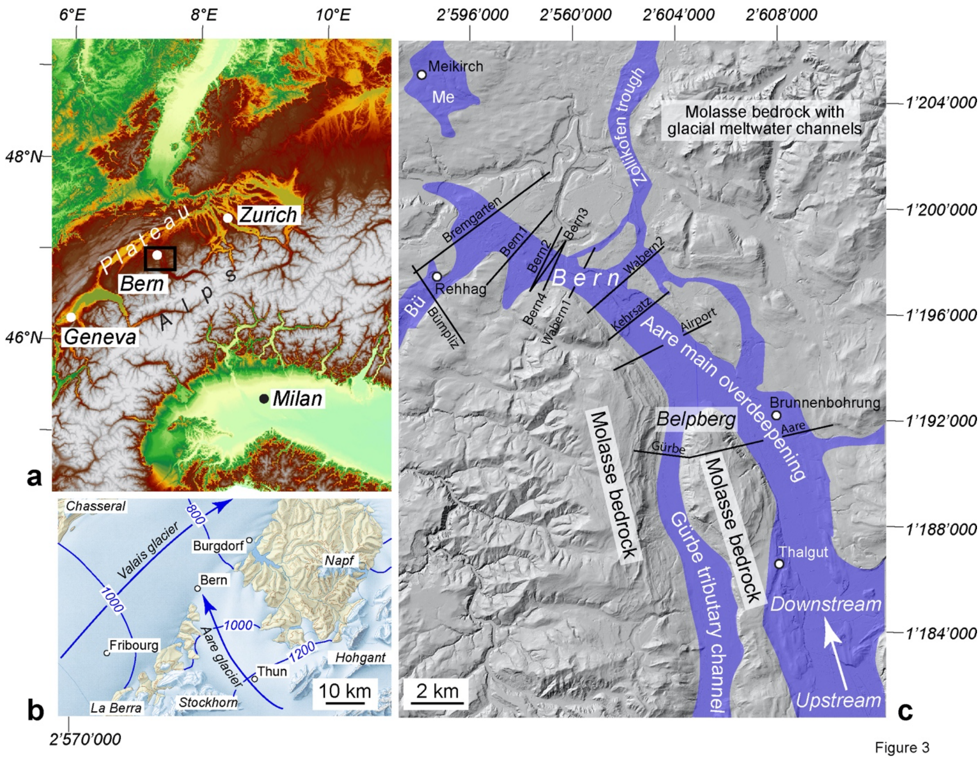

Figure 3: Local setting illustrating the a) Alpine arc (modified from Bandou et al., 2023) with latitudes and longitudes, b) the study area during the Last Glacial Maximum (LGM; map with isohypses of the glacier's surfaces taken from Bini et al., 2009), and c) the surface geomorphology (2 m-SwissAlti3D DEM © swisstopo) together with the orientation of the Aare main overdeepening, taken from Reber and Schlunegger (2016). The figure c) shows (i) the sections along which gravity data was collected (black lines; Bandou et al., 2022; 2023), and (ii) the sites (white circles) where sediments in drillings (Rehhag: Schwenk et al., 2022a, b; Meikirch: Welten, 1982; Preusser et al., 2005; Schläfli et al., 2021: Brunnenbohrung: Kellerhals and Häfeli, 1984; Zwahlen et al., 2021) and exposures (Thalgut: Welten, 1982; 1988; Schlüchter, 1989; Preusser and Schlüchter, 2004) were either dated with various techniques, or where existing ages were reconfirmed by a subsequent analysis. Me=Meikirch overdeepening; Bü=Bümpliz trough. The numbers along the figure margin refer to the Swiss coordinate system (CH1903+).

Because the area between the northern termination of the Aare main overdeepening and the Meikirch trough is made up of exposed bedrock (Gerber, 1927), a connection between both depressions was ruled out (Reber and Schlunegger, 2016). The Aare main overdeepening itself is the most prominent trough in the city area of Bern and has a maximum depth of nearly 250 m (Reber and Schlunegger, 2016). The bedrock in the region comprises an amalgamated suite of Early Miocene Upper Marine Molasse (UMM) sandstone beds south of Bern. Sedimentological analyses showed that these sediments were

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deposited in a shallow marine, mostly coastal environment (Garefalakis and Schlunegger, 2019). In the region north of Bern, the bedrock is made up of a Late Oligocene to Early Miocene suite of Lower Freshwater Molasse (LFM) sandstones and mudstones (Isenschmid, 2019). These sediments were originally deposited in a fluvial environment (Platt and Keller, 1992; Isenschmid, 2019). The contact between the UMM and the LFM gently dips towards the south (Isenschmid, 2019), with the consequence that south of Bern, the base of the Aare main overdeepening might consist of LFM deposits, while most of the upper part of the overdeepening is laterally bordered by bedrock of the UMM.

3 Dataset and Methods

3.1 Compilation of gravity data

The bedrock topography underneath the city area of Bern was already reconstructed in 2010 and then updated in 2016 based on information retrieved from thousands of drillings that is available from the Geoportal of the Canton Bern (Dürst Stucki et al., 2010; Reber and Schlunegger, 2016). Whereas such information yielded highly resolved spatial information on the bedrock geometry, particularly on its shallower <50 m-deep part (Reber and Schlunegger, 2016), reconstructions of the details for the deeper and thus central part of the Aare main overdeepening have been thwarted because of a lack of drilling information at that time. Here, we benefit from the results of a recent gravity survey conducted in the city area of Bern and information of new drillings >50 m deep (Bandou et al., 2023; Figure 3c). In particular, Bandou et al. (2023) measured the Bouguer gravity anomalies along 10 sections (black lines in Figure 3c). The obtained values were then subtracted from the regional gravity field yielding a residual gravity anomaly value at each site where gravity data was collected. Note that the Quaternary deposits and thus the overdeepening fill has a lower bulk density than the Oligo-Miocene sediments forming the bedrock in the region (Schwenk et al., 2022a; Bandou et al., 2022). Therefore, the occurrence of Quaternary sediments overlying an overdeepened trough result in a negative residual gravity anomaly (Kissling and Schwendener, 1990). Accordingly, a larger bulk mass of Quaternary sediments yields a stronger (and thus a more negative residual anomaly) signal than a fill with less Quaternary material (Kissling and Schwendener, 1990; Bandou et al., 2022). Following this concept, we compiled the residual anomaly data from Bandou et al. (2023) for each gravity profile and drafted a contour map where each line displays the same residual anomaly value. This map (Figure 4a) was drawn by hand, thereby considering the a-priori information about the orientation of the Aare main overdeepening (Reber and Schlunegger, 2016).

3.2 Estimating the general shape of the bedrock topography

For a selection of 6 cross-sections along which the residual gravity anomalies were well constrained, Bandou et al. (2023) reconstructed the cross-sectional shape of the overdeepenings using a 3D gravity

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software referred to as PRISMA (Bandou, 2023). This program uses multiple right-handed prisms to predict the gravity effect of a given structure underneath a point of interest. It bases on an analytical solution by Nagy (1966) and Banerjee and DasGupta (1977) and was conceptualized (Bandou, 2023) to model the general shape of an overdeepening fill. Upon applying this model, Bandou et al. (2023) particularly considered geophysical and geological a-priori information such as the residual gravity anomalies, the density contrasts between the bedrock and the Quaternary fill, the depth of bedrock encountered in drillings, and the already existing bedrock topography model by Reber and Schlunegger (2016). Here, we used the depth of the bedrock as unraveled upon applying the PRISMA routine (Bandou, 2023) to reconstruct the general course of the isohypses (i.e. the lines of constant elevation) of the bedrock underneath the city area of Bern (Figure 4b). Upon drawing this map, we considered that a trend towards less negative residual anomalies points towards a shallowing of the bedrock (Kissling and Schwendener, 1990; Bandou et al., 2023).

3.3 Combining the results of the gravity survey with drilling data to reconstruct the details of the bedrock topography

We used the existing bedrock topography map of Reber and Schlunegger (2016) as a basis where the isohypses were originally drawn every 10 meters, thereby using the information of thousands of drillings in the region. Because these drillings mainly penetrated the entire Quaternary sequence at the lateral margins of the Aare main overdeepening, the reconstruction of the shallower parts of the bedrock trough is precise. We updated this existing map with information about the general shape of the overdeepening retrieved through the gravity data by Bandou et al. (2023) (Figure 4), and we additionally considered the information of >100 drillings that were sunk >50 m deeply into the subsurface during the past years (Figure 5). Similar to Reber and Schlunegger (2016), we draw the isohypses by hand thereby inferring that changes in the direction of the contour lines and the depths of the bedrock were gradual. We finally combined the map displaying the geometry of the bedrock underneath the overdeepening with the elevation data offered by the 2 m-SwissAlti3D DEM (based on LIDAR data of swisstopo) to present the shape of the bedrock topography as shaded relief. We finally used this map as a basis to draw the cross-sections displayed in Figures 6 and 7.

4 Results

4.1 Patterns of residual gravity anomalies

Based on the results of a gravity survey, Bandou et al. (2022; 2023) showed that the Quaternary fill of the Aare main overdeepening results in a residual gravity anomaly signal that ranges between c. -4.0 and -0.5 mGal. In addition, they showed that the gravity signal of the Quaternary fill has a pattern with a distinct change from upstream to downstream. In particular, along the Gürbe-Aare transect (Figure 3c), which also crosses a mountain ridge (Belpberg) made up of Molasse bedrock, the corresponding

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maximum residual anomalies signal ranges from c. -2.9 mGal in the Gürbe valley to c. -4.1 mGal in the Aare valley (Bandou et al., 2022). Farther downstream, the signals of the overdeepening fill decreases,

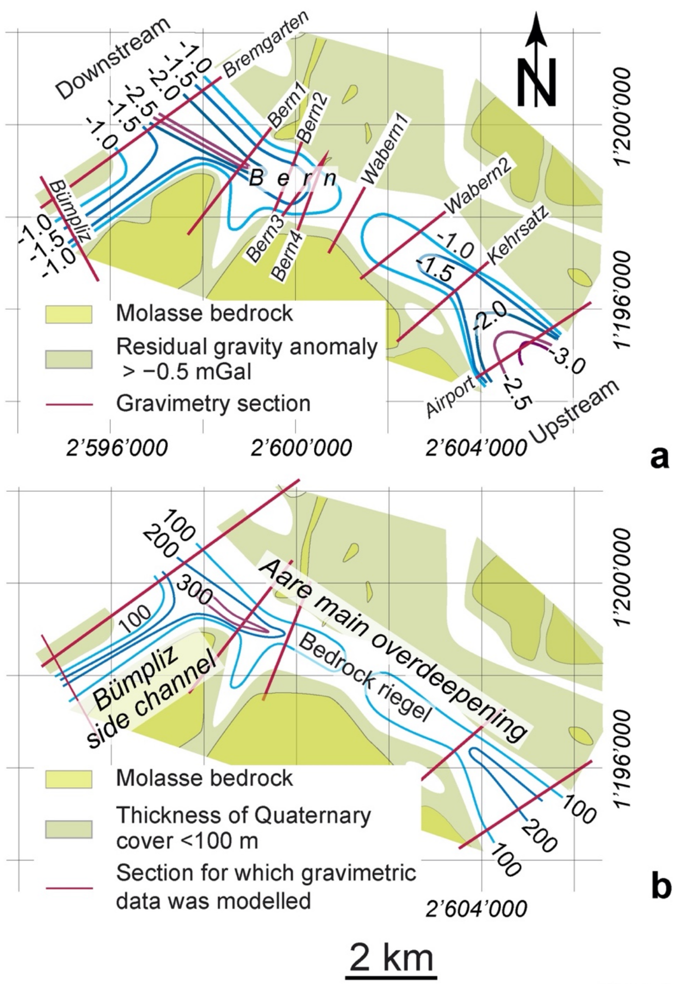

Figure 4

Figure 4: Residual gravity anomalies and inferred thicknesses of Quaternary sediments. a) The contour lines of the residual gravity signals (mGal) caused by the Quaternary fill of the Aare main overdeepening are mainly based on gravity surveys along 10 sections (red lines; Bandou et al., 2023). Here, more negative values imply a greater gravity signal and thus a larger bulk mass of Quaternary sediments overlying the overdeepened trough (Kissling and Schwendener, 1990; Bandou et al., 2022). b) Spatial distribution of Quaternary sediments, here expressed by the related thickness pattern. These are mainly based on the results of gravity modelling, where Quaternary mass and its spatial distribution was forward modelled until a best-fit between the modelled and observed gravity signals of the Quaternary mass overlying the overdeepened trough was reached (Bandou, 2023; Bandou et al., 2023). Note that only the residual gravity anomalies of the Airport, Kehrsatz, Bern4, Bern2, Bremgarten and Bümpliz sections were modelled by Bandou et al. (2023). The grid refers to the Swiss coordinate system (CH1903+).

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and the corresponding values change from c. -3.0 mGal (Airport profile) to approximately -1.5 and finally c. -1.0 mGal along the Kehrsatz and Wabern2 profiles, respectively (Figure 4a). The lowest residual anomaly signal with values between c. -0.5 mGal and -1 mGal were reported for the Wabern1 profile (Bandou et al., 2023; Figure 3a). Farther downstream, the gravity signal related to the Quaternary fill increases again and reaches values between c. -1.0 and c. -2.0 mGal along the Bern sections, and then approximately -2.5 mGal along the Bremgarten section c. 2 km farther downstream. The residual anomaly data collected along the aforementioned gravity sections thus clearly depict the course of the Aare main overdeepening, which strikes SE-NW in the city area of Bern (Figures 3c, 4a). Towards the NW margin of the study area, a second overdeepening referred to as the Bümpliz side channel (Schwenk et al., 2022b) strikes SW-NE and converges with the Aare main overdeepening NW of Bern. The gravity signal of the Bümpliz sedimentary fill is less and reaches a value of c. -1.5 mGal (Figure 4a; Bandou et al., 2023).

4.2 The thickness pattern of Quaternary sediments

The thickest Quaternary suite can be found upstream and downstream of Bern (Figure 4b), where the Aare main overdeepening is between 4 and 5 km wide and > 200 m deep, consistent with drilling information (Bandou et al., 2023). In the city area of Bern, however, the main trough tends to become shallower. This is indicated by the thickness of the Quaternary sediments which becomes 100 m and possibly less (Figure 4b). We acknowledge that further 3D-gravity modelling would be needed to definitely verify such a claim. Although the data cover is low in this zone, the depth versus residual anomaly conversion could be constrained from nearby tie points. Accordingly, the resulting map displaying the thickness pattern of the Quaternary sediments suggests that the bedrock is situated at deeper levels forming a basin on either side of Bern, and that both depressions are separated by a bedrock swell or a riegel that is c. 150 m high but still buried by >100 m of Quaternary sediments (Figure 4b). Finally, the upstream side of the bedrock riegel dips gentler than the downstream side, which is twice as steep: on the stoss side, the residual gravity anomalies change from <-2.5 mGal to >-1.0 mGal over a downstream distance of c. 4 km whereas on the lee side, the same change in the gravity signal occurs over only 2 km. Given that the residual gravity signal is a direct response of the bulk mass of Quaternary sediments overlying the Molasse bedrock, and thus their volume supposing a lower density than the Molasse bedrock (Bandou et al., 2022; 2023), the differences in the upstream and downstream gradients of the residual gravity anomaly values disclose the contrasts in the dip angles of the bedrock topography.

4.3 The consideration of deep drillings discloses the occurrence of slot canyons

The reconstructed bedrock topography of the target region reveals a complex pattern (Figure 5), which can be described as a bedrock riegel that is dissected by multiple, partly anastomosing slot canyons or

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inner gorges (Bandou et al., 2023). At this stage, we cannot precisely reconstruct the number of the inferred canyons because we lack a high-resolution database of deep drillings (Figure 5). Yet, the discrepancy (Figure 6) between (i) a relatively low gravity signal particularly between the Wabern2 and the Bern sections (Figure 4a) and (ii) several drillings that reached the bedrock at much deeper levels that are >200 m below the surface (Figures 5, 6) can only be resolved by invoking the occurrence of a plateau at shallow elevations that is dissected by one or multiple slot canyons. These gorges are up to 150 m deep and appear to connect the overdeepened basins upstream and downstream of the city area of Bern. In particular, south of Bern along the Aare profile (Figures 3b and 7a), the Aare main overdeepening is U-shaped in cross-section and displays two levels, each of which with steep lateral flanks and a flat base. While the upper flat base occurs at an elevation of c. 450 m a.s.l., the lower flat contact to the bedrock is situated at c. 250 m a.s.l. and thus approximately 200 m deeper than the upper level (Bandou et al., 2022). Approximately 5 km farther downstream along the Airport section (Figures 3b, 7b), the cross-sectional geometry of the Aare main overdeepening maintains its generally U-shaped geometry with a base at an elevation between 200 and 250 m a.s.l. There, the base of the overdeepening appears less flat than farther upstream, but we acknowledge that the density of drillings in the region (Figure 5) and the resolution of the gravity data (Figure 4a, Bandou et al., 2023) is not high enough to fully support this comparison. Upon approaching the city area of Bern, the base of the bedrock becomes shallower and appears to evolve towards a plateau particularly between the Kehrsatz and Bern2 sections (Figures 5, 6, 7c, d and e). This plateau is situated at an elevation of c. 400 m a.s.l. (dashed lines on Figure 7) and dissected by multiple slot-canyons, some of which are up to 150 m deep and too narrow to be detected by the gravity survey (Bandou al., 2023). Farther to the Northwest reaching the terminal part of the Aare main overdeepening (Figure 3b), the trough widens again and gives way to a relatively deep basin where the deepest part occurs at an elevation of 300 m a.s.l. and possibly even deeper (Figures 5, 7f). This terminal basin appears to be connected with the Bümpliz side channel farther to the SW. Yet the density of drillings is too low (Figure 5) to determine whether a possible bedrock swell separates the Aare main overdeepening from the Bümpliz tributary channel (Figure 3b).

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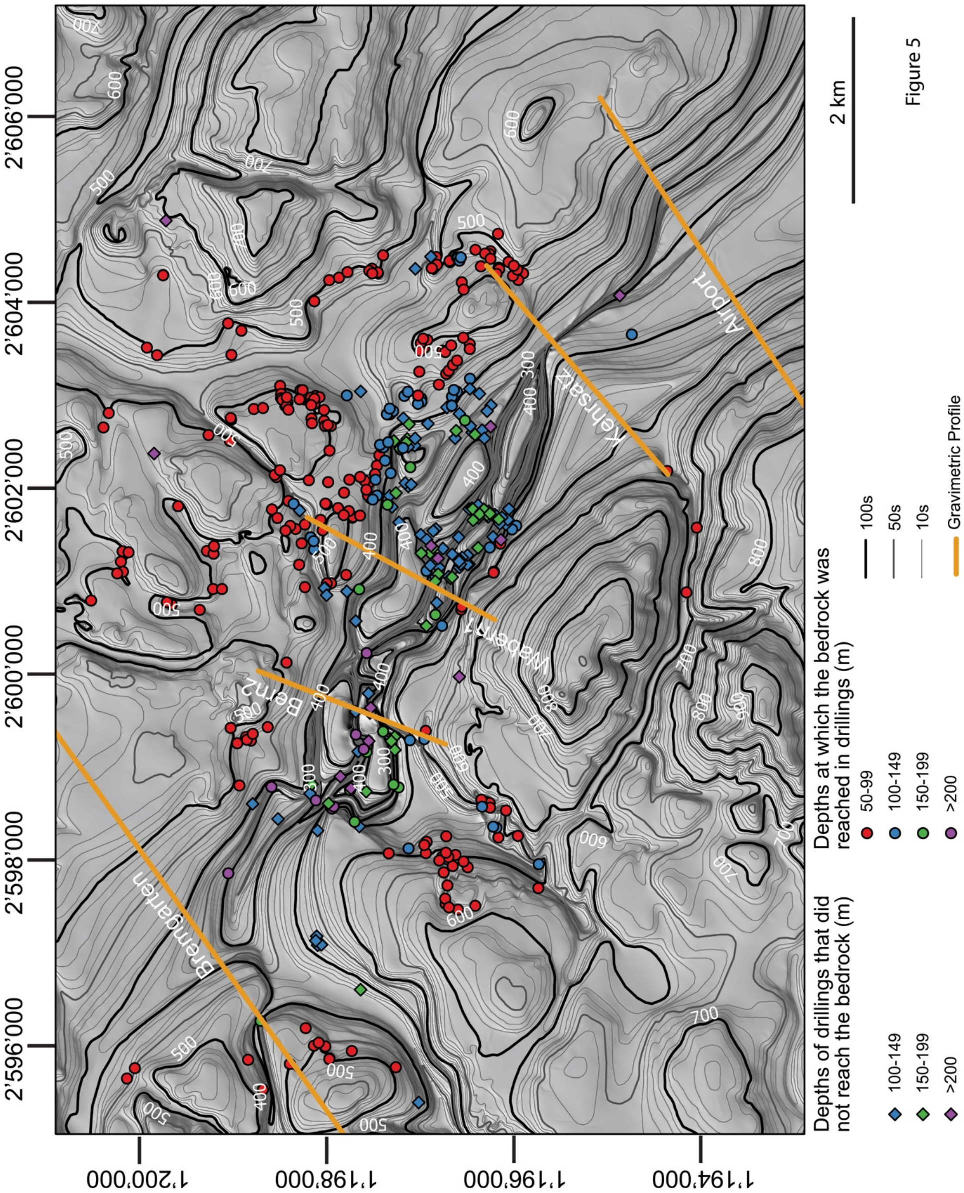

Figure 5: Hillshade DEM, illustrating the bedrock topography of the Bern area, together with deep drillings that either reached the bedrock (circles) or that ended in Quaternary sediments (diamonds). The shallow drillings (<50 m) are not displayed on this map since the number is too large (more than 1000, please see Reber and Schlunegger, 2016). The isohypses were drawn for every 10 meters. The coordinates along the figure margin refer to the Swiss coordinate system (CH1903+). The sections shown on this map are used to illustrate the cross-sectional geometry of the overdeepening beneath Bern (see next figures).

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5 Discussion

5.1 Subglacial origin and the role of subglacial meltwater

It is agreed upon in the literature that the formation of overdeepened basins can be understood as the response of erosion by glaciers. As summarized in Figure 1, the main arguments that have been put forward are (i) the depth of the base of these depressions, which are generally located below the current fluvial base-level, and (ii) the occurrence of adverse slopes in the downstream direction of these basins (Preusser et al., 2010; Patton et al., 2016; Alley et al., 2019; Magrani et al., 2022; Gegg and Preusser, 2023). As outlined in the previous sections, such geometric features are also encountered for the Aare main overdeepening beneath the city of Bern. Therefore, it is not surprising that the origin of this depression has repeatedly been interpreted as the response of the erosional processes of a glacier with a source in the Central Alps of Switzerland (Dürst Stucki et al., 2010; Preusser et al., 2010; Reber and Schlunegger, 2016; Magrani et al., 2022; Bandou et al., 2023). Furthermore, as already outlined by Bandou et al. (2023) and further detailed in this work, the overdeepening underneath Bern can additionally be subdivided into a southeastern and a northwestern sub-basin. These depressions are separated from each other by a bedrock riegel or swell, which itself is dissected by one or multiple slot canyons establishing a hydrological link between the upstream and downstream basins (Figures 1, 5 and 7).

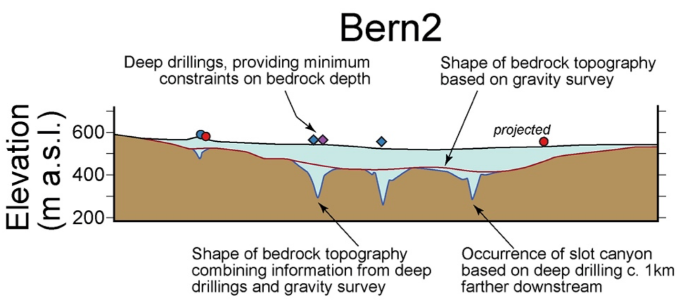

Figure 6

Figure 6: Example that illustrates of how we proceeded upon reconstructing the bedrock topography beneath Bern. We started with the general shape of the bedrock topography using the gravity signal of the bulk Quaternary mass as a basis (red line, and Figure 4b). Information from drillings >50 m deep (circles and diamonds: see Figure 5 for explanation of colors) allowed then to reconstruct the course and geometry of the slot canyons (blue line). The mass of their Quaternary fill is too low to be identified by the gravity survey. This is the case because the strength of a gravity signal decays exponentially with depth (see also Bandou et al., 2023, for further

Using geomorphic evidence in combination with information about rates of rock uplift and fluvial incision into bedrock, Montgomery and Korup (2011) argued that an ensemble of bedrock riegels and slot canyons were shaped over several glacial/interglacial periods, and that they were most likely formed by subglacial meltwater during the decay of the glaciers and ice caps, when large volumes of meltwater were released. Such processes were particularly invoked to explain the history of inner gorge formation

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in the Landquart and the Trift valleys (Figures 6b, 6c) situated in the Swiss Alps (Montgomery and Korup, 2011; Steinemann et al., 2021).

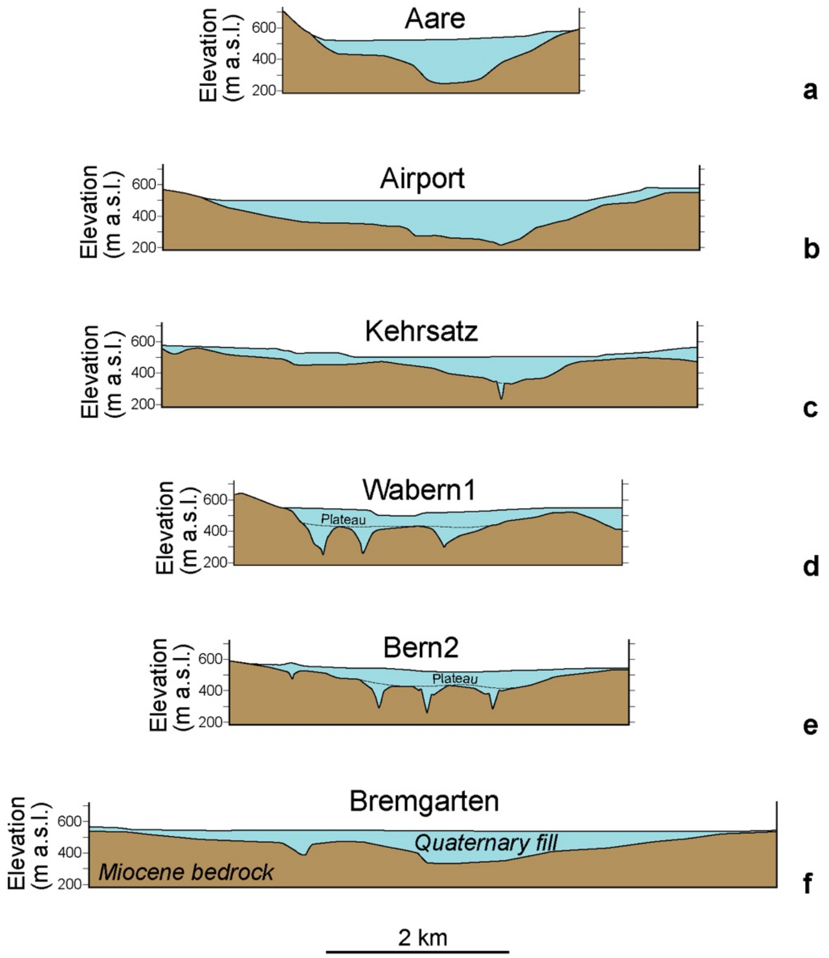

Figure 7

Figure 7: Sections through the Bern area, where the geometry of the bedrock is taken from the DEM illustrated in Figure 5. The Aare section is taken from Bandou et al. (2022). See Figures 3 and 5 for location and orientation of sections.

As further examples, erosion by subglacial meltwater was put forward to explain the occurrence of inner gorges at the margin of the Fennoscandian ice sheet (based on the pattern of surface exposure ages; Jansen et al., 2014) and such a mechanism was used to explain (i) the origin of the deep channels on the floor of the eastern English Channel, and (ii) the breaching of the bedrock swell at the Dover strait during the aftermath of the Marine Isotope Stage (MIS) 12 or a later glaciation (Gupta et al., 2007; Cohen et al., 2014; Gupta et al., 2017). In this context, Jansen et al. (2014) noted that a typical field evidence for inferring a subglacial meltwater control includes (i) the occurrence of anastomosing

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channels, (ii) undulating valley long profiles, and (iii) a topography that apparently amplifies the hydraulic potential. The resolution of our data is at a larger scale than the thalweg irregularities, but sufficient to display the anastomosing patterns of the slot canyons, with channels meandering, splitting and merging again (Figure 5).

5.2 Formation through erosion by subglacial meltwater inferred from theory and modelling

A subglacial meltwater contribution to the controls on the formation of overdeepenings was inferred based on theoretical relationships between meltwater runoff and the sediment transport capacity of proglacial and subglacial streams (e.g., Boultoon and Hindmarsch, 1987; Alley et al., 1997; Herman et al., 2011, Beaud et al., 2016). Because sediment transport increases exponentially with both the amount and seasonality of meltwater runoff, Alley et al. (1997) interpreted that subglacial and proglacial streams are among the most efficient sediment-transport mechanisms on Earth. This process peaks in the ablation zone of a glacier, where surface melt reaches the bed and significantly contributes to the generation of subglacial runoff. Yet, subglacial meltwater appears to play a minor role in contributing to a sedimentary budget if the subglacial runoff has a negligible contribution from surface melt (Alley et al., 1997). Finally, Cohen et al. (2023) showed that subglacial water is able to remove the sediment from the base of a glacier and to further incise into bedrock provided that the pressure of the subglacial meltwater and that of the ice overburden is at least the same, as also put forward by Boulton and Hindmarsch (1987). The results from the model of Cohen et al. (2023), tailored to determine the location of the subglacial drainage pathways, further suggest that such conditions most likely prevailed at the front of piedmont glaciers and particularly during the decay when large volumes of meltwater were available. In addition, the model predicts that under such circumstances, the locations of subglacial meltwater pathways are likely to coincide with segments where high rates of glacial erosion occur (Cohen et al., 2023). Therefore, it is not surprising that reaches with evidence for intense erosion by both water and ice occur in the same area and are hydrologically connected with each other, as is the case for the ensemble of overdeepened basins and slot canyons beneath Bern. Yet besides hydrological conditions, the erosional resistance of bedrock plays an important role where a bedrock swell could potentially form. This aspect is elaborated in the following paragraph.

5.3 The role of bedrock strength

The formation of riegels and basins is consensually understood as conditioned by differences in bedrock strengths. This also concerns the controls on the size of a basin itself where bedrock with a low erosional resistance tends to host a larger basin than lithologies where the erosional resistance is high (e.g., Magrani et al.., 2020; Gegg and Preusser, 2023). Following this logic, swells preferentially form in locations where the bedrock has a lower erodibility than the rock units farther upstream and downstream. This has been documented for the riegel in the Trift valley (Figure 2a), which separates

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an overdeepened basin upstream from a wide valley farther downstream (Steinemann et al., 2021). There, the bedrock forming the ridge is made up of a banded, biotite-rich gneiss (Erstfeld gneiss), whereas the bedrock upstream and downstream of the swell is cut by multiple faults and fractures, thus offering a lower resistance to erosion. As another example, the bedrock riegel downstream of the confluence between the Aare and Gadmen valleys (Figure 2a) is made up of the Quinten Formation (Stäger et al., 2020). These limestones tend to have a higher mechanical strength (Kühni and Piffner, 2001) than the sandstones-marl alternations (North Helvetic Flysch; Stäger et al., 2020) downstream of the bedrock swell, and the suite of sandstones, marls and dolomite beds upstream of it (Mels- and Quarten Formations; Stäger et al., 2020). In the Bern area, the inferred riegel is underlain by Late Miocene shallow marine sandstone (i.e. UMM), whereas the bedrock farther downstream comprises a suite of Late Oligocene fluvial sandstones (i.e. LFM) and marl interbeds (Isenschmid, 2019). It is postulated that the UMM sediments have a higher erosional resistance than the underlying LFM unit, based on the observation that the UMM forms a cap rock in the region (Isenschmid, 2019). Accordingly, the bedrock architecture in the Bern area is comparable to the examples explained above where the UMM bedrock forming the swell has a larger erosional resistance than the LFM units at least downstream of the riegel (Isenschmid, 2019). It is possible that Lower Freshwater Molasse (LFM) deposits with a low erosional resistance also occur at the base of the overdeepening farther upstream of the swell. We infer this from the Gurten drilling on the SW margin of the Wabern1 profile (Figure 4) where the LFM bedrock was encountered at a depth of >300 m a.s.l. (Garefalakis and Schlunegger, 2019). This is indeed shallower than the basal part of the Aare main overdeepening along e.g., the Airport profile (Figure 6b).

Presumably more important than the contrasts in bedrock erodibility: the bedrock swell underneath Bern is situated just upstream of the confluence area between the Valais and Aare glaciers (Figure 3b). As such, this situation shares many similarities with the examples in the Alpine valleys where the bedrock swells are situated directly upstream (Figures 2c, 2d, 2e and 2f), directly downstream (Figures 2a, b) or at the confluence (Figures 2g, h) between a tributary and a trunk valley. In the same sense, Lloyd et al. (2023) found that overdeepened basins and, as a consequence, the occurrence of bedrock swells farther downstream, are mainly situated in the confluence area of glacial valleys. In this case, the deep carving into the bedrock would be the result of an acceleration of the ice flow in response to the increase in the ice flux downstream of the confluence region (Herman et al., 2015). Alternatively, a bedrock riegel could also form upstream of the confluence of two glaciers as is the case in the Maggia and Urbach valleys (Figure 2e, f). Such a situation most likely also prevailed in the Bern area, at least during LGM times. There, the damming of the Aare glacier by the much larger Valais glacier could have caused a reduction of the flow velocity of the Aare glacier (Figure 3b). Consequently, the shear velocity and thus the bedrock abrasion rates would decrease, thereby facilitating the preservation of a bedrock swell.

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5.4 Differences in the geometries between the exposed riegels and basins in the Alpine valleys, and the overdeepening beneath Bern

Despite obvious similarities, there are also major differences between the geometric properties of the overdeepening system beneath Bern and the currently exposed riegels and slot canyons in the Alpine valleys (Figure 2 versus Figures 5 and 7). The most striking one is the occurrence of the riegel and inner gorges approximately 50-100 m below the current base-level, and the absence of an obvious continuation of the thalweg NW of Bern (Figure 3c). It is indeed very unlikely that the Aare main overdeepening was linked with the Meikirch depression farther to the north (Figure 3c). We base this interpretation on available geological maps (Gerber, 1927) and drillings (Reber and Schlunegger, 2016), showing that the northern edge of the Aare main overdeepening and the Meikirch trough are separated by Molasse bedrock with no evidence for connecting channels. Accordingly, the inferred interpretation where the slot canyons beneath Bern were formed by subglacial meltwater requires a mechanism where the meltwater is not only capable to incise into bedrock beneath a glacier, but also to escape the depression by ascending nearly 200 m from the base of the overdeepening to the surface near the glacier's snout. Using Bernoulli's principle as a basis (e.g., Batchelor, 1967), it was proposed that such an ascent of subglacial meltwater was driven by the translation of large hydrostatic pressures into hydrodynamic pressures at the downstream margin of a glacier (Dürst Stucki and Schlunegger, 2013). In addition, such a mechanism is most effective at work where the surface slope of a glacier is steeper than the adverse slope of an overdeepening (Hooke and Pohjola, 1994), as is commonly found in the frontal part of a glacier (Figure 1a). Since the ratio between the densities of ice and water is >0.9 (Harvey, 2007), the inferred 200 m-rise of the meltwater requires a minimum hydrostatic pressure corresponding to >250 m-thick ice to allow an upward water flow, and it conditions the occurrence of a hydrologically closed subglacial channel network. Such a scenario is realistic, as in the Bern area the Aare glacier was several hundred m thick during the past glaciations (Bini et al., 2009; Preusser et al., 2011; Figure 3b). If this hypothesis is valid, then the thickness of the piedmont glaciers sets an uppermost limit to the depth at which overdeepenings can be carved into the bedrock, mainly because sufficient pressures are required for the subglacial meltwater to ascend to the surface from deeper levels. Yet it is possible that the large porosities of nearly 20% in the Molasse sandstones (Keller et al., 1990) could have facilitated the escape of subglacial meltwater to the groundwater. This could have caused a reduction in static pressures, violating the inference of a closed system. However, we consider the permeabilities of the Molasse sandstone beds (<1000 md, Keller et al., 1990) as low enough to consider depressurization through meltwater runoff to the groundwater as negligible.

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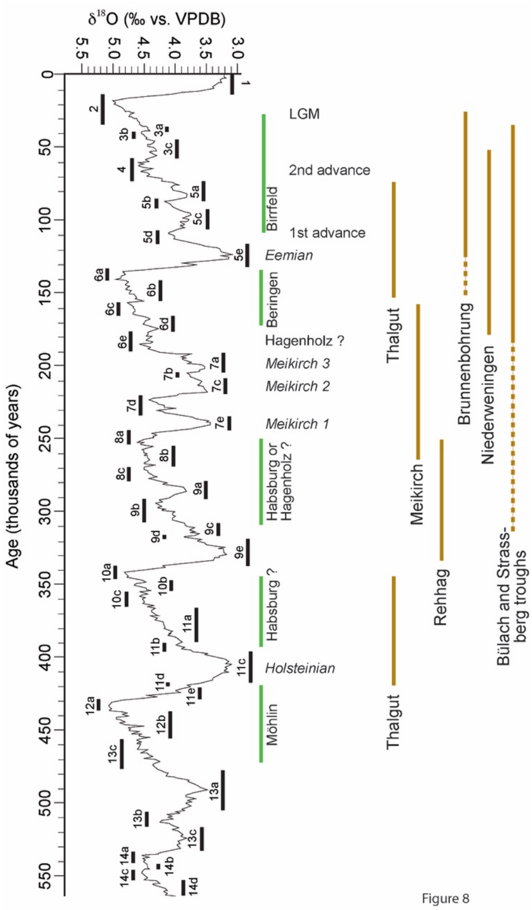

Figure 8: Development of stable isotopes and Marine Isotope Stages (MIS) within a chronological framework (Lisiecki and Raymo, 2005; Railsback et al., 2015) and glacial periods recorded in the Plateau of the Swiss Alps (modified after Preusser et al., 2011; 2021). The age of the Möhlin glaciation is taken from Dieleman et al. (2022). The age of the Thalgut section is based on pollen records (Welten, 1982; 1984) and was subsequently described by Schlüchter (1989), yielding a Holsteinian age for the basal part of the section. The chronological framework for the upper part of this section was then updated by Preusser and Schlüchter (2004). The Holsteinian could either correspond to MIS 9 (according to U/Th ages established for peat layers in the type section of the Holsteinian at Bossel, Germany; Geyh and Müller, 2005) or to MIS 11 based on $^{40}Ar/^{39}Ar$ ages of tephra (Roger et al., 1999). Following Koutsodendris et al. (2012) we preferentially use an age assignment to MIS 11. Ages for the Meikirch section are based on pollen assemblages (Welten, 1982) and optically stimulated luminescence (OSL) ages by Preusser et al. (2005). The pollen assemblages of Welten (1982) were subsequently reinterpreted by Schläfli et al. (2021). The ages of the deposits encountered in the Brunnenbohrung are based on concentrations of ^{14}C measured in organic material at nearly the base of the drilling (Kellerhals and Häfeli, 1984; Zwahlen et al., 2021). The chronological framework of the Rehhag drilling was established by Schwenk et al. (2022a) using the results of feldspar luminescence dating conducted on two samples at the top of a section, which is exposed in a quarry next to the Rehhag drilling. Finally, the chronology of the Niederweningen drilling and sediments encountered in the Bülach and Strassberg troughs are based on OSL signals measured in quartz minerals (Niederweningen: Dehnert et al., 2012; Bülach and Strassberg troughs: Büchi et al., 2018).

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5.5 Chronological framework

A high-resolution chronological framework (e.g., Reber et al., 2014; Kamleitner et al., 2023a) has been established from deposits of the LGM that occurred c. 20 ka ago (Ivy-Ochs et al., 2008; Kamleitner et al., 2023b) (Figure 7). A relatively detailed chronology is also available for the first and second glacial advances during the Birrfeld glaciation (Ivy-Ochs et al., 2008; Preusser, 2004; Preusser et al., 2007; 2011; Pfander et al., 2022). For previous glaciations, the chronological framework is less clear. Yet, Preusser et al. (2011) summarized multiple evidence for proposing that the piedmont glaciers did advance into the Alpine foreland between 185 and 130 ka, i.e. the Beringen glaciation (MIS 6, Figure 8), and that this advance into the foreland was larger than during the LGM. The age assignments to the glaciations preceding MIS 6 are still debated. While the largest extent of the north Alpine glaciers (Most Extensive Glaciation of the Swiss Foreland cf. Schlüchter, 1988) was assigned to the Möhlin glaciation (Preusser et al., 2011) and recently dated to 500±100 ka and thus to MIS 12 through burial dating with cosmogenic ^{26}Al and ^{10}Be (Dieleman et al., 2022), a re-evaluation of the reported concentrations of the cosmogenic nuclides yielded an age that is more consistent with MIS 6 (Nørgaard et al., 2023). Yet we favour the chronology by Dieleman et al. (2022) and the assignment to a MIS 12 age because it is better supported by a-priori field-based information such as the results of detailed mapping. The ages of the Habsburg and Hagenholz glaciations, which occurred between the Beringen and Möhlin glaciations, are the least constrained. Whereas Preusser et al. (2011) considered the Hagenholz ice advance to postdate MIS 7 (Figure 8), Büchi et al. (2018) and subsequently Preusser et al. al. (2021) rather considered the Hagenholz glaciation to predate MIS 7 thereby following Keller and Kryass (2010).

The Quaternary fill of overdeepenings can now be placed into the aforementioned chronological framework of glacial advances onto the Swiss plateau during the past glaciations (Figure 8). The database is sparse, but the available ages imply that the oldest backfills that have been dated so far postdate the Most Extensive Glaciation (or the Möhlin glaciation), dated to MIS 12 (Figure 8). This is the case for the sedimentary fill of the Are main overdeepening where the occurrence of a Holsteinian interglacial lacustrine sequence (Figure 8) was reported for the basal marls of the Thalgut section, which could either correspond to MIS 9 (Roger et al., 1999) or MIS 11 (see discussion in Preusser et al., 2011; Koutsodendris et al., 2012; and Schwenk et al., 2022a for discussion of ages). In addition, c. 6 km farther downstream from the Thalgut section, nearly the entire sedimentary sequence of the Aare main overdeeepening was encountered in the Brunnenbohrung drilling (Figure 3c) and was constrained to an age postdating MIS 6 (Kellerhals and Häfeli, 1984; Zwahlen et al., 2021). The related sedimentary suite could thus span the entire time interval between the Beringen and Birrfeld glaciations including the Holocene (Bandou et al., 2022). Farther north of Bern, the Quaternary succession overlying the bedrock has an age that is MIS 8 and older (Schwenk et al., 2022a), thus corresponding to the Habsburg glaciation or any other glacial period pre-dating Habsburg (Figure 8). These ages are not precise enough to reconstruct in detail the history of how and particularly when the overdeepenings were formed, but

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they are consistent with the chronologies established for other overdeepening fills (Figure 8). In particular, most published ages do support an interpretation where the deep troughs were originally formed after the Middle Pleistocene Transition (Schlüchter, 2004) and thus during the same period when the U-shaped Alpine valleys were carved (Häuselmann et al., 2007; Valla et al., 2011). This was also the same time when the base-level in the northern margin of the Swiss Plateau lowered at the highest rates (Claude et al., 2019). Apparently, the change in the frequency of glacial-interglacial cycles from a 40 ka- to a 100 ka-periodicity, which occurred c. 800 ka ago, not only resulted in rapid glacial erosion (Pedersen and Egholm, 2013) and in the deep glacial carving of U-shaped valleys in the Alps (Häuselmann et al., 2007, Valla et al., 2011), but also in the formation of overdeepenings with complex geometries including basins, riegels and slot canyons in the foreland.

6 Conclusions

Bedrock riegels separating upstream and downstream basins are common features in modern Alpine valleys, and they are likely to be encountered in overdeepenings. In addition, we propose that these riegels occur as ensembles together with slot canyons that cut through the swells and establish a hydrological link between the upstream and downstream basins. We suggest this based on our reconstruction of the bedrock topography of the Aare main overdeepening in the Bern area, and we propose that such ensembles of basins, riegels and slot canyons also occur in other Alpine overdeepenings such as the Rhone, Rhine and Inn valleys (Figure 9). We suggest that these slot canyons were formed through incision by glacial meltwater during the decaying state of a glacier when large volumes of meltwater were available. For the bedrock swell underneath Bern, the resolution of the dataset presented in this work does not allow to locate and reconstruct the precise course of the inferred slot canyons. Yet the presented reconstruction of the bedrock topography does reconcile (i) the occurrence of a low residual gravity anomalies in the Bern area (Figure 4a), which implies a relatively low bulk mass of Quaternary sediments, and (ii) the depth at which Quaternary sediments were encountered in drillings (Figures 5, 6). In addition, in many Alpine valleys, such structures appear to be preferentially formed in the confluence area between two glacial valleys and where the bedrock has a relatively low erodibility. We posit this hypothesis for the overdeepening below the Bern area, where such a bedrock swell appears to be situated just upstream of the confluence between the Aare and Valais glaciers, at least during LGM times and possibly during previous glaciations. In addition, the inferred bedrock riegel beneath Bern is located where the bedrock has a lower erodibility than downstream and possibly upstream, at least in the basal part of the trough. Yet, we acknowledge that an improved understanding about the origin of such structures requires more information particularly on the chronology of glacial advances and the overdeepening fills.

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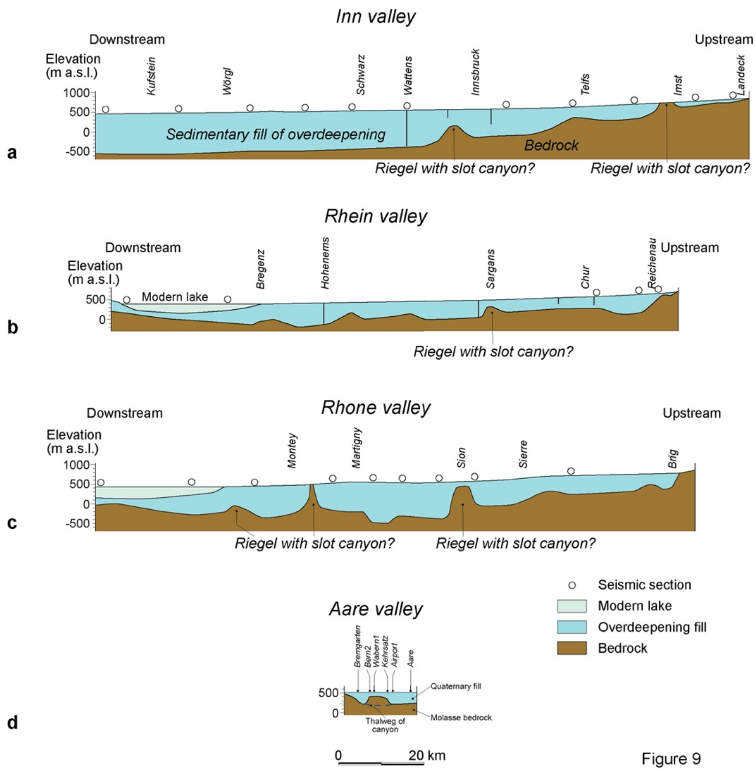

Figure 9: Sections showing the patterns of overdeepenings from upstream to downstream for a) the Inn valley, b) the Rhine valley, c) the Rhone valley and d) the Aare valley in Bern area. The examples of the Inn, the Rhine and the Rhone valleys are taken from Hinderer (2001), whereas the section along the Aare valley is a modified version of Bandou et al. (2023) and bases on the data presented in Figure 5. The data from the Aare valley covers a short distance only, but it shows a striking similarity to the riegels in the large Alpine valleys. Therefore, it is quite likely that the other riegels are also dissected by narrow channels and that all settings share a similar origin.

Acknowledgement

This work was financially supported by the Swiss National Science Foundation (project No. 200021_175555) with contributions from the Stiftung Landschaft und Kies, swisstopo and the Gebäudeversicherung Bern GVB.

Data availability

All data used in this paper can be ordered by the Authorities of the Canton Bern and by the authors on request.

Autor contributions

EK designed the study, together with FS and DB. DB collected the gravity data and processed them, with support by UM and EK. FS wrote the paper and conducted the analyses and interpretation of the

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data. RB drafted the bedrock topography map. PS, MS, DM and GD contributed to the discussion. All authors approved the article.

Competing interests

The authors declare that they have no conflict of interest.

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