3D morphology of a glacially overdeepened trough controlled by underlying bedrock geology

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Abstract

Subglacial overdeepenings are common elements of mountain forelands and have considerable implications for human infrastructure. Yet, the processes of overdeepening by subglacial erosion and especially the role of bedrock geology are poorly understood. We present a case study of the Gebenstorf–Stilli Trough in northern Switzerland, a foreland overdeepening with a regionally unique, complex underlying bedrock geology: in contrast to other Swiss foreland overdeepenings, it is incised not only into Cenozoic Molasse deposits, but also into the underlying Mesozoic bedrock. In order to constrain the trough morphology in 3D, it was targeted with scientific boreholes as well as with seismic measurements acquired through analysis of surface waves. Our results reveal an unexpectedly complex trough morphology that appears to be closely related to the bedrock geology. Two sub-basins are incised into calcareous marls and Molasse deposits, and are separated by a distinct ridge of Jurassic limestones, indicating strong lithological control on erosional efficiency. We infer generally relatively low glacial erosion efficiency sensu stricto (i.e. quarrying and abrasion) and suggest that the glacier’s basal drainage system may have been the main driver of subglacial erosion of the Gebenstorf–Stilli Trough.

1. Introduction

Subglacial overdeepenings, i.e. closed troughs eroded below the fluvial base level, are common elements of formerly glaciated mountain forelands (Cook and Swift, 2012). In the northern European Alpine example, they underlie ~10% of the land surface (Dürst Stucki and Schlunegger, 2013). Despite their significance for, among others, construction projects, groundwater and radioactive waste disposal (Preusser et al., 2010; Stumm, 2010), the understanding of overdeepenings in terms of formation processes and controlling factors is limited and subject to debate (Cook and Swift, 2012; Alley et al., 2019). This applies especially to the influence of bedrock geology on the efficiency of subglacial erosion (Goudie, 2016).

Several authors (e.g. Augustinus, 1992; Brook et al., 2004) have reported a correlation of rock mass strength and glacial trough cross section, with steep and narrow troughs developing in resistant bedrock, and wide and shallow troughs in weak lithologies. However, effects of more complex patterns of bedrock lithology have hardly been studied. As an exception, Pomper et al. (2017) reported deeper-reaching subglacial erosion where the Lower Salzach Valley (Austria) is underlain by soft Cretaceous marls as opposed to lime- and dolostones. Further, Harbor (1995) modelled glacial erosion into bedrock with a weak zone in the trough centre, and observed increased downcutting, narrowing and steepening initiating in but, not restricted to, the weak zone. On a smaller scale, Glasser et al. (1998) showed by detailed field mapping that discontinuities from bedrock foliation parallel to the ice flow enhance erosion through quarrying, whereas discontinuities orthogonal to ice flow rather increase abrasion. Similarly, the orientation of sedimentary bedding has a discernible influence on basal ice velocity and thus on subglacial landform morphology (Phillips et al., 2010). Quarrying is frequently considered the more efficient glacial erosion process (e.g. Cohen et al., 2006; Zoet et al., 2013; Alley et al., 2019), but in weak and poorly jointed rocks, abrasion might outweigh quarrying (Krabbendam and Glasser, 2011). The importance of jointing and joint space has been further highlighted by Dürnfelth et al. (2010), who found a strong correlation of glacial erosion rates and fracture density (see also Hooey et al., 2012; Becker et al., 2014). Most of these investigations specifically focused on glacial erosion in non-overdeepened settings.

In overdeepenings, characterized by an adverse slope at the distal end, the subglacial hydrological conditions are very different (Cook and Swift, 2012). In order to maintain erosion, sediment has to be evacuated from the glacier base against this adverse slope, whereby...
Pressurized melt water plays an important role (Alley et al., 1997, 2019; Cook and Swift, 2012; Buechi et al., 2017). The abundance of subglacial water steadily increases towards the glacier snout, where it facilitates the erosion of large terminal overdeepenings even under diffusive ice (Herman et al., 2011). There, subglacial water has been suggested to be the main driver of subglacial erosion, analogous to tunnel valleys (Cofaigh, 1996; Dürst Stucki et al., 2010; Fiore et al., 2011; Dürst Stucki and Schlunegger, 2013). It is therefore questionable to what extent the findings of subglacial erosion in non-overdeepened settings can be applied to the formation and evolution of overdeepened glacial troughs.

This study sheds light on the morphology of a subglacial overdeepening in the northern Alpine foreland of Switzerland, based on borehole and seismic data. The selected overdeepening is of special interest and relevance due to its unique, complex bedrock geology. The connection of the trough morphology with bedrock architecture and the area’s tectonic setting allow inferences about the geological controls and the processes of overdeepening erosion.

2. Study area

The study area is located in northern Switzerland, close to the eastern termination of the WSW-ENE trending Jura Mountains (Fig. 1). The local bedrock stratigraphy comprises Triassic and Jurassic sediments deposited on an epicontinental platform and unconformably overlain by Cenozoic clastics of the northern Alpine Molasse Basin (Bitterli-Dreher et al., 2007; Jordan et al., 2008).

The oldest rocks exposed at the surface of the study area are shallow marine limestones and dolomites of the Schinznach Formation (Fm.; late Middle Triassic; Figs. 2A, A.1). They are overlain by the Middle to Late Triassic Bänkerjoch Fm., an alternation of gypsum/anhydrite with claystone and dolomite, and Klettgau Fm., a heterogeneous unit comprising mostly marl, silt- and sandstone. The following Early Jurassic Staffelegg Fm. as well as the Opalinus Clay of the early Middle Jurassic consist of marine claystones, siltstones and marls. During the later Middle Jurassic, marls and limestones (PKI: Passwang Fm., Klingnau...

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Fig. 1. Overview map of central and eastern northern Switzerland with major tectonic units and surface geology (A: IGME 2005: Commission for the Geological Map of the World et al., 2005; LGM: Last Glacial Maximum; MEG: Most Extensive Glaciation). The cross-section on B (from Jordan et al., 2015, altered) illustrates the tectonic architecture of the study area (purple box in A). Note that foreland overdeepenings (SV: Seetal Valley, RV: Reuss Valley, LV: Limmat Valley, GV: Glatt Valley, TV: Thur Valley) generally only occur within the Molasse basin, with the exception of the Gebenstorf-Stilli Trough (Fig. 2).
Fms., Ifenthal Fm.; Fig. A.1) were deposited in a shallow sea that deepened towards the early Late Jurassic, when the predominantly calcareous marls of the Wildegg Fm. formed (Gygi, 2000; Deplazes et al., 2013). These marls transition gradually over few meters to decameters into bedded and massive marine limestones of the Villigen and Burghorn Fms. (in the following referred to as “Malmkalk”; Fig. A.1; Gygi, 2000; Bitterli-Dreher et al., 2007; Jordan et al., 2008).

In the Paleogene, the Mesozoic strata of the Jura Mountains were uplifted on the forebulge of the Alpine orogeny and began being eroded and karstified, while further south/southeast the Molasse Basin subsided (Fig. 1; Pflüffner, 1986; Berger et al., 2005). In Oligocene-Miocene times heterogeneous sandstones, siltstones, and marls of the Lower Freshwater, Upper Marine, and Upper Freshwater Molasse were deposited in the study area, and generally remained rather poorly lithified (Fig. A.1; Bitterli-Dreher et al., 2007; Jordan et al., 2008).

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During the Pleistocene, multiple advances of Alpine glaciers reached far into the foreland and considerably reshaped the landscape (Graf, 2009; Keller and Krayss, 2010; Preusser et al., 2011). This includes the subglacial erosion of overdeepenings, most of which are carved exclusively into Molasse deposits (Fig. 1; Graf, 2009; Preusser et al., 2010). An exception is the Gebenstorf-Stilli Trough (GST), which cuts through the FJ and into the TJ (Fig. 2; Jordan, 2010). It extends ~9 km northward from the Birrfeld Basin (Nitsche et al., 2001) into the present-day confluence area of the rivers Aare, Reuss and Limmat and has a distinctly elongated shape with a maximum width of ~1 km (enclosed by the 300 m a.s.l. isoline; Bitterli-Dreher et al., 2007; Pietsch and Jordan, 2014). The maximum trough depth exceeds 110 m below surface and 75 m below the lowest known Pleistocene base level (PBL, 300 m a.s.l.; Graf, 2009; Gegg et al., 2020). Situated entirely outside the LGM (Bini et al., 2009), the GST was presumably incised during the late Middle Pleistocene (Bitterli-Dreher et al., 2007; Pietsch and Jordan, 2014). The maximum trough depth exceeds 110 m below surface and 75 m below the lowest known Pleistocene base level (PBL, 300 m a.s.l.; Graf, 2009; Gegg et al., 2020). Situated entirely outside the LGM (Bini et al., 2009), the GST was presumably incised during the late Middle Pleistocene (Bitterli-Dreher et al., 2007; Pietsch and Jordan, 2014). The significant narrowing from the wide Birrfeld basin towards the GST coincides with a change in trough morphology from U-shaped to V-shaped (Jordan, 2010; Dürst Stucki and Schlunegger, 2013). It has been hypothesized that the narrowing and change in shape are a result of the dominant bedrock lithology changing from rather soft, poorly lithified Molasse sandstones, siltstones and marls in the south towards the more resistant limestones and marls of the Jura Mountains in the north (Bitterli-Dreher et al., 2007; Jordan, 2010).

3. Methodology

The Gebenstorf-Stilli Trough was investigated with three scientific boreholes along its trough axis (Fig. 2B). These are, from south to
north, QGBR (47°29′00″ N, 8°14′11″ E; Gegg et al., 2019b), QGVO (47°29′43″ N, 8°14′18″ E; Gegg et al., 2019c), and QUST (47°30′46″ N, 8°14′3″ E; Gegg et al., 2019a). All three boreholes terminated at least 10 m into the bedrock to allow for a confident bedrock identification. Recovery and core quality were maximized by combined application of pneumatic hammering (‘Düsterloh Hammer’) and wire-line drilling with a triple-tube core barrel. After detailed stratigraphic logging of the drill cores, selected 1-m-intervals were sampled for petrographic analysis of coarse-grained sediments (>100 clasts >15 mm in diameter, if not indicated otherwise). To further constrain the morphology of the Gebenstorf-Stilli Trough, we recorded ambient noise on ~230 seismic 3-component stations that were distributed along eight acquisition lines (Fig. 2B; Nagra, 2021). The data processing workflow is sketched on Fig. 3 and involved computation of the horizontal-to-vertical spectral ratio (HVSR) for each of the 10–30 min long recordings and picking of the respective fundamental frequency $f_0$ (Fig. 3A; SESAME European Research Project, 2004). The frequency of the pulse maximum $f_0$ depends on the depth of the shear wave (S-wave) velocity contrast indicative for the bedrock below unconsolidated sediments. In case of ambiguity in the spectral information, $f_0$ was selected conservatively, with regard to the bedrock model of Pietsch and Jordan (2014).

Conversion of $f_0$ to bedrock depth $z$ is possible if the average S-wave velocity of the Quaternary strata $v_{s, E}$ is known (Eq. (i); see Nakamura,

![Diagram](image_url)

**Legend**

- A: Fundamental frequency profile
- B: Shear wave velocities
- C: Depth model of trough base
- D: Interpreted cross section

Fig. 3. Workflow applied for the construction of the cross sections from the geophysical data exemplified by a clip of acquisition line D. The fundamental frequency profile (A) is, with help of the shear wave velocity profile (B), converted into a depth model of the trough base (C), and complemented with borehole and surface data to a finalized geological cross section (D).
4. Results

4.1. Planform morphology

In terms of bedrock geology, the GST can be subdivided into three sections of approximately equal length. The southern section is embedded in the folded Jura (fJ), whereas the middle section is mostly incised into Molasse deposits, and the northern section into the Mesozoic of the Tabular Jura (TJ, Fig. 2A). These three sections show striking differences in planform morphology (Pietsch and Jordan, 2014): both the TJ and FJ sections are narrow (300–400 m at 300 m a.s.l.) and either straight in their entirety or composed of straight segments, respectively. In contrast, in the Molasse section the trough takes a sinuous course towards north while widening gradually (up to ~800 m at 300 m a.s.l.) until a sudden constriction at the transition to the TJ. The sinuosity index S of the Molasse section, defined as the ratio between total length of the trough axis between two selected points and the shortest connection of said points, is 1.06 (Fig. C.1). Our boreholes and seismic acquisition lines cover the central (QGGR, QGVO, lines A–E) and northern (QUST, lines F–H) sections of the GST (Fig. 2B).

4.2. Boreholes

QGGR and QGVO recovered Late Pleistocene Niederterrasse gravels overlying a thick unit of lacustrine/deltaic sand and several meters of basal coarse-grained sediment, while the trough infill in QUST almost exclusively comprises gravels (Fig. 4; see Fig. 2B for locations). The coarse-grained deposits consist largely of far-travelled, i.e. Alpine or Molasse-derived, clast lithologies dominated by grey limestones, diverse sandstones, and quartzites (Fig. 4). Lithologies of the local Jura Mountains play a subordinate role: light beige limestone clasts that can be attributed to the Villigen Fm. («Malmkalk») make up no more than 18% (usually below 10%), and calcareous marl clasts attributed to the Wildegg Fm. were not encountered in the chosen intervals. Only the lowermost ~0.3 m of the Quaternary infill at QGGR consists predominantly of light limestone fragments, and the lowermost ~0.4 m of QUST contains individual soft marly clumps identified as Wildegg Fm. (Gegg et al., 2019a, 2019b).

The boreholes reached the base of the overdeepening in depths of 111.5 m (225.8 m a.s.l.), 64.9 m (266.1 m a.s.l.), and 76.0 m (255.2 m a.s.l.), respectively (Fig. 4). Light beige limestones of the «Malmkalk» were encountered below the overdeepening in QGGR and QGVO, and grey calcareous marls of the Effingen Member, Wildegg Fm., in QUST. We combined these findings with the logs of >450 existing boreholes in the perimeter as well as a 1:25’000 scale geological map (Graf et al., 2006) to a base Quaternary subcrop map (see Section 5.2). The generally massive «Malmkalk» is characterized by frequent stylolites in varying orientations including horizontal and vertical, as well as shallow (<40°), southeast–dipping fractures with an average spacing of ~0.6 m in QGGR, and ~1.4 m in QGVO (corrected after Terzaghi, 1965). Deep-reaching, sediment-filled paleokarst predating the Quaternary and exhibiting presumed subglacial hydrofractures was encountered in QGGR (Gegg et al., 2020). The calcareous marls of the Wildegg Fm. have a similar fracture spacing of ~1.1 m in QUST, and contain intervals where the rock is softened or granular-disintegrating. The bedrock surface is truncated by a karst cavity in QGGR, but developed as a sharp, horizontal boundary in QGVO and QUST with minor drilling-induced disturbance by fresh fracturing and/or grinding.

4.3. Surface-seismic sections

The interpreted cross sections are plotted on Figs. 5, and B.1–B.8 show the individual cross sections together with the respective raw data. The uncertainty of the applied method is difficult to quantify as it depends on multiple factors, such as the heterogeneity of the trough infill, the local inclination of the base of Quaternary, the impedance contrast to the bedrock, the presence of other geological boundaries (e.g. Molasse-Mesozoic) in close proximity, and the amplitude and frequency of industrial noise. Empirically, the seismic measurements are in good accordance with boreholes in the vicinity (max. Distance 170 m). Average differences amount to ~7±10 m, with maximum values of ~21±22 m (over- and underestimation, respectively; see Table B.1).

An exception is the site of borehole QGGR, where the trough depth is underestimated by ~30 m, however this borehole is located close to the trough wall that has likely affected the respective measurements (Table B.1, Fig. 5). The intra-Quaternary shear wave velocities show an increasing trend towards the north (~500 m/s at 50 m depth for lines A and B, ~550 m/s for lines C and D; ~600 m/s for line G). Although these differences are smaller than the variations along a given line, they correlate with a trough infill that becomes increasingly more coarse-grained and higher in density towards the north (Fig. 4; Gegg et al., 2019a, 2019b, 2019c).

The cross sections show a trough composed of two sub-basins (Gebenstorf Basin in the central and Stilli Basin in the northern trough section; ‘nested basins’ after Patton et al., 2016) separated by a distinct bedrock ridge (Lauflohr Ridge, Figs. 5, 6). The GST gradually widens from ~350 to ~800 m at 300 m a.s.l. (i.e. at PBL; Graf, 2009) between lines A and D while transitioning from a V- to a more U-shaped cross section (VI increases from 0.2 to 0.4). This widening coincides with a shallowing of the overdeepened centre from its maximum depth at ~225 to ~265 m a.s.l., following the trend of the «Malmkalk» surface that rises towards the TJ (Fig. 6), and as a result, the overdeepened cross sectional area remains approximately constant (Fig. 5). North of line D, the trough narrows abruptly and further shallows to ~295 m a.s.l. at line E, where the bedrock geology changes gradually from «Malmkalk» to the underlying marl (Wildegg Fm.; Fig. 5). Further north (lines F–H), seismic data are affected by greater uncertainties than in the south. The trough deepens to at least 255 m a.s.l. at QUST, and the distinct trough shoulder east of QUST (constrained by a second borehole on line G, Figs. 5, B.7) suggests a rather U-shaped cross section.
The overdeepening terminates close to line H, with an average adverse slope of ~1.6° between lines G and H (Fig. 6).

5. Discussion

5.1. Planform morphology

5.1.1. Paleo-ice flow and erosion

Dürst Stucki and Schlunegger (2013) distinguish two general types of overdeepenings in the vicinity of the Alps, i) proximal Alpine-type overdeepenings composed of straight segments, and ii) distal, anastomosing foreland-type overdeepenings (see also Magrani et al., 2020). These morphologies are interpreted as a result of geological as well as paleo-glaciological differences: while Alpine-type overdeepenings are carved into zones of weakness (i.e. fault zones) by thick ice streams in the mountain valleys, foreland-type overdeepenings occur in the generally rather poorly lithified Molasse deposits independently from structural weak zones (Preusser et al., 2010; Dürst Stucki and Schlunegger, 2013). Pressurized subglacial melt water plays an important role especially in the erosion of foreland overdeepenings near the glacier termini (Herman et al., 2011; Alley et al., 2019), and could possibly be its main driver (Dürst Stucki et al., 2010; Dürst Stucki and Schlunegger, 2013). Pressurized subglacial melt water plays an important role especially in the erosion of foreland overdeepenings near the glacier termini (Herman et al., 2011; Alley et al., 2019), and could possibly be its main driver (Dürst Stucki et al., 2010; Dürst Stucki and Schlunegger, 2013). Morphologically, the central section of the GST resembles a typical foreland overdeepening, whereas the southern (FJ) and northern (TJ) sections have more similarities with inner-Alpine overdeepenings. This morphological variability occurs despite the common distal position, similar melt water availability (periodically high) and ice thickness (low), suggesting the same prevailing erosional mechanisms (see Section 5.2.2; Herman et al., 2011; Cook and Swift, 2012). We infer that in the case of the GST, the morphological differences are controlled predominantly by the bedrock geology and resulting pre-glacial topography.

The Mesozoic strata outcropping in the FJ and TJ have a higher bulk erosional resistance than the Molasse deposits (Kühni and Pfiffner, 2001) despite strong internal variations (Yanites et al., 2017) and it has been shown before that glacial troughs tend to be narrower in more resilient rocks (Augustinus, 1992; Brook et al., 2004). In addition, the erosional resistance of the Mesozoic has facilitated the Jura Mountains to persist as a low mountain range for several millions of years, whereas the Molasse Basin topography is comparatively levelled off. As a consequence, while Pleistocene ice flow over Molasse deposits could diverge to the sides, the FJ and TJ sections of the GST lie within distinct, likely pre-existing valleys (Ziegler and Fraefel, 2009). These valleys constrained the ice and basal water flow, which is often accompanied by an increase in velocity and erosional activity (Hallet, 1979; Herman et al., 2015; Patton et al., 2016). Given the similar trough widths in FJ and TJ, it appears that the different tectonic histories of both units are not expressed through significantly different erosional susceptibilities, which could be due to the structural strike of the FJ being orthogonal to paleo-ice flow (Glasser et al., 1998).

Although comparatively poorly constrained, the width of the overdeepened (below 300 m a.s.l.) GST appears to remain largely constant across the FJ (Fig. 1; Bitterli-Dreher et al., 2007; Pietsch and Jordan, 2014) where bedrock properties change drastically over short distances (Yanites et al., 2017). In contrast to the modern valley, the shape of the buried overdeepening is seemingly little affected by short-scale variations in erosional resistance, which applies also to the Hausen Trough further west (Fig. 2B; Graf, 2009; Pietsch and Jordan, 2014). This suggests that there is a certain inertia in trough morphology,
which can adjust only gradually to bedrock changes. This hypothesis is supported by the slow and gentle widening of the GST after the transition from the FJ into the northward adjacent Molasse. As a result, the GST remains comparatively narrow even in its central section, with a maximum width that is more typical of inner-Alpine than for foreland overdeepenings (Table 1).
5.1.2. The role of structural preconditioning

The Gebenstorf-Stilli Trough is the only known overdeepening of the northern Alpine foreland that extends significantly (i.e. kilometers) beyond the Molasse Basin (Fig. 1; Jordan, 2010), raising the question why such localized incision into the Mesozoic strata was possible at this specific position. Previously, structural geological control enabling the breach of the (fluvial) Aare Valley into the exposed TJ (approx. at line F) has been suggested (Haldimann et al., 1984). The straight and/or kinked morphology of those GST sections incised into Mesozoic bedrock support the idea that the overdeepening, and the likely preceding fluvial valley system (Ziegler and Fraefel, 2009), could follow discrete fault zones in the bedrock (similar to e.g. the inner-Alpine valleys of the rivers Rhone and Adda). This hypothesis is in the following reviewed based on our investigations.

At the outcrop-scale, N-S fractures, mostly with strike-slip kinematics, are a typical characteristic of Upper Jurassic limestones across the study area and beyond (Figs. 7, D.1; Madritsch, 2015). Minor N-S striking faults have been recognized in elongation of the GST (Matousek et al., 2000) and along strike of the FJ to the east (Diebold et al., 2006; Jordan et al., 2011). However, a densification of this kind of structures around the breach of the GST, especially in the TJ, is not discernable. In addition, individual strike-slip faults do not appear to have a strong structural imprint on the immediately surrounding Mesozoic bedrock (e.g. increase of fracture density, cataclasis development) according to field observations in the vicinity of the GST (Fig. D.1). No evidence for a major fault zone underneath the overdeepened trough has been observed in two regional seismic campaigns (Sprecher and Müller, 1986; Madritsch et al., 2013). However, the presence of a strike-slip fault zone with minor vertical throw hindering its seismic detection (Nagra, 2019) in the subsurface of the GST cannot be excluded. Despite the lack of evidence for a distinct fault zone, we can therefore not rule out structural control for the breach of FJ and TJ and/or glacial erosion thereafter.

In contrast to the southern and northern GST sections, the central section is characterized by a gently sinuous planform morphology. Its sinuosity (S = 1.06) is similar to other distal Molasse-hosted overdeepenings in the northern Alpine foreland (Pietsch and Jordan, 2014; Fig. C.1), e.g. Seetal Valley (S = 1.07), middle Reuss Valley (S = 1.05), Limmat Valley (S = 1.07), Glatt Valley (S = 1.12) and Thur Valley (S = 1.05), and generally similar to tunnel valleys (Cofaigh, 1996; van der Vegt et al., 2012). This morphology has previously been interpreted as indicative for erosion of the poorly lithified Molasse independent from structural control (i.e. not along straight fault segments; Preusser et al., 2010; Dürst Stucki and Schlunegger, 2013).

5.2. Trough morphology in 3D

5.2.1. Lithological control on subglacial erosion

The maximum depth of the GST of ≥112 m below surface (~225 m a.s.l.) is typical for Swiss foreland overdeepenings (Table 1; Magrani et al., 2020). It is reached just beyond the FJ in the southern sub-basin (Gebenstorf Basin, GB) that shallows considerably further north. The shallowing of the GB occurs entirely within the narrow band of the «Malmkalk» that emerges at angle of ~4° towards the northwest, where it is exposed and referred to as TJ (Figs. 5, 6). This suggests strong lithological control for the depth of the basin: it appears that the subglacial erosional efficiency decreased significantly upon reaching the Jurassic limestones. A similar erosion pattern was observed in a seismic study of Lake Neuchâtel (NW Switzerland; Ndiaye et al., 2014), whose overdeepened floor reaches down to, but is not significantly incised into, the Mesozoic strata under ~200 m of Molasse cover. In QGBR, deep-reaching sediment-filled paleokarst was encountered in the limestone (Gegg et al., 2020). The fact that even karstified and presumably weakened «Malmkalk» was preserved and not completely eroded by the overdeepening glacier emphasizes its erosional resistance (see also Ndiaye et al., 2014). Moreover, the paleokarst walls throughout the bedrock interval of QGBR show abundant, randomly oriented surficial fractures, some of which are filled with intruded sediment (Gegg et al., 2020). The authors conclude that subglacial hydrofracturing is the most plausible explanation for the origin of these fractures, and that their abundance could point towards a multitude of subglacial water pressure events. Such a record would require erosion rates low enough to allow for prolonged direct contact of the karstified limestone with the glacier’s basal drainage system. However, we consider possible

Table 1
Quantitative comparison of the Gebenstorf-Stilli Trough (GST) with other overdeepenings in Switzerland.
(Based on Magrani et al., 2020).

|                     | Max depth [m] below surface | Max width [m] 20 m below surf.* | Terminal adverse slope [°] |
|---------------------|-----------------------------|---------------------------------|---------------------------|
| Alpine overdeepenings | Average 337                 | 1453                            | 2.7                       |
|                     | Median 288                  | 962                             | 1.7                       |
| Foreland overdeepenings | Average 180                | 2024                            | 1.0                       |
|                     | Median 115                  | 1298                            | 0.6                       |
| Gebenstorf-Stilli Trough | ≥112                      | 920                             | 1.6                       |

* The approach by Magrani et al. (2020) uses a minimum sediment thickness or water column of 20 m to define overdeepening extent, thus maximum width is given 20 m below present-day ground surface.
that the limited downcutting over the «Malmkalk» may have led to increased lateral erosion within the overlying Molasse, as the shallowing of the GB coincides with a doubling in trough width, so that the overdeepened cross sectional area remains nearly constant (see Fig. 5, sections A–D).

The shallowest depth of the GST is reached at the crest of the Laufohl Ridge, where the base of the southward-dipping Jurassic limestone is breached (Figs. 6, 7). There, the GST is barely overdeepened as its base is close to PBL at 300 m a.s.l. (Graf, 2009). In the underlying calcareous marls of the Wildegg Fm. erosional efficiency was again...
increased and culminated in the Stilli Basin (SB). We hypothesize that the enhanced erosion rates are the result of an interplay of several paleogeological as well as geological factors. Firstly, an abrupt increase in ice and melt water flux have likely increased subglacial erosion at the confluence of the catchments of Aare, Reuss, and Limmat (cf. MacGregor et al., 2000; Pomper et al., 2017). According to Ziegler and Fraefel (2009), this confluence had been established before, and remained largely fixed throughout, the Pleistocene. The deepening of the GST into the SB initiates where the three present-day valleys merge (Fig. 7), and it is not unlikely that a major ice confluence occurred at the same position during excavation of the GST. This position lies along the escarpment of the JF (Figs. 6, 7), an area of increased topography, where ice flow was again focused into a morphologically defined valley, which may have further accelerated flow velocity (see Section 5.1.1; Hallet, 1979; Herman et al., 2015; Patton et al., 2016). An increase in erosion rate towards the SB could thus be achieved through increased ice flow and velocity alone. In addition to that, Yanites et al. (2017) attributed generally lower erosional resistance (to fluvial downcutting) to the Wildegg Fm. when compared to the «Malmkalk» (see also Pomper et al., 2017). This is supported not only by their slope-forming and cliff-forming nature (see Fig. 7), respectively, but also by our drill cores: in contrast to the «Malmkalk», the Wildegg Fm. is occasionally soft or disintegrating (see also Laws et al., 2007), and in the GST infill its clasts are not preserved, except for individual soft fragments in the lowestest ~0.4 m of QUSB. Finally, additional structural weakening of the bedrock below the SB can again not be excluded (see e.g. Haldimann et al., 1984, and faults mapped by Matousek et al., 2000).

It should be noted that a potential narrow and steep-walled inner gorge (Dürst Stucki et al., 2010; Jansen et al., 2014; Montgomery and Korup, 2011) inside the GST could possibly not be imaged by our chosen methodology. This is due to the spacing of acquisition points, and due to the spacing of acquisition points, and due to Korup, 2011) inside the GST could possibly not be imaged by our chosen methodology. This is due to the spacing of acquisition points, and due to the spacing of acquisition points, and due to the spacing of acquisition points, and due to...
approach of active and passive measurements succeeded at imaging the trough base and, calibrated and complemented with borehole data, allowed us to develop a well-constrained model of the GST (Fig. 7) that is currently being incorporated into an updated version of the Base of Quaternary model of Northern Switzerland by Nagra (Loepfe et al., 2021). The chosen methodology is therefore a well-suited and cost-effective approach for mapping overdeepened basins.

Our results suggest that the trough morphology is considerably controlled by the underlying bedrock geoide. Due to relatively high erosional resistance, resulting high relief and constrained ice flow conditions, the overdeepening is inner-Alpine-like and narrow across the Folded Jura. In contrast, where it transitions into the weaker Molasse deposits further north, the GST becomes wider and more sinuous, similar to other foreland overdeepenings. The trough widening in the Molasse is interpreted as a consequence of less constrained ice flow but likely also of the underlying, more resilient «Malmkalk» (Jurassic limestone) rising towards the north. The trough shallowing culminates in a bedrock ridge whose top lies close to the lowest known Pleistocene base level (i.e. in non-overdeepened position). Further north, erosion depth increased again resulting in a second sub-basin. This is due to weaker marls underlaying the trough, aided by ice flow being again topographically constrained and possibly increased due to glacier confinement. Thus, we propose that bedrock geoide and ensuing topography exert substantial control on subglacial overdeepening erosion. In addition, we suspect that based on borehole data, the morphological complexity of overdeepenings may generally be underestimated.

The different resistances to subglacial erosion together with a lack of evidence of glaciectonism as well as the composition of the basal coarse-grained trough infill, which is poor in locally derived material, suggest that both glacial coupling and therefore glacial erosion sensu stricto, especially through plucking, was relatively inefficient in the GST. In contrast, the scarcity of well-preserved basal diamict, signs of subglacial hydrofracturing, as well as the paleoglaciological setting in general indicate that availability and pressure of basal water must have been periodically very high. This basal water played a significant role in overdeepening erosion, and we consider possible that it may have been its main driver. This would render the GST and other Alpine foreland overdeepenings analogs of tunnel valleys, as has previously been suggested.

However, it would probably be an oversimplification to attribute any given overdeepening to exclusively glacial or melt water erosion. The subglacial incision process is likely more complex, and the dominant mechanisms time-dependant (e.g. glacial erosion during peak glacial conditions, and enlargement by melt water during deglaciation). It should be noted that studies investigating erosion by melt water and its geological controls are restricted to the subaerial environment. The erosive impact of subglacial water on the overdeepened glacier bed is poorly understood, and should be targeted by future work.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2021.107950.

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3D morphology of a glacially overdeepened trough controlled by underlying bedrock geology

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Supplementary material

Supp. A: Summary scheme of the pre-Quaternary stratigraphy of the study area (Fig. A.1).

Supp. B: Cross sections A to H, input data and interpretations (Fig. B.1-B.8).

Differences between seismic and drilled trough depth (Table B.1).

Supp. C: Sinuosities of distal foreland overdeepenings of Switzerland (Fig. C.1).

Supp. D: Structural survey of a major strike-slip fault in a «Malmkalk» outcrop (Fig. D.1).
Fig. A.1: Summary scheme of the pre-Quaternary stratigraphy of the study area.

Molasse
- OSM - Upper Freshw. M.
- OMM - Upper Marine M.
- USM - Lower Freshw. M.

«Malmkalk»:
- Villigen and Burghorn Fm.
  locally with paleokarst and siderolithic fill

Wildegg Fm.
- PKI
  - Ifenthal Fm.
  - Klingnau Fm.
  - Passwang Fm.

Opalinus Clay

Staffelegg Fm.

Klettgau Fm. and Bänkerjoch Fm.

Schinznach Fm.

Dominant lithofacies
- lime- / dolostone
- claystone
- marl
- sandstone
Fig. B.1: Cross section A, input data and interpretation.
Fig. B.2: Cross section B, input data and interpretation.
Fig. B.3: Cross section C, input data and interpretation.
Fig. B.4: Cross section D, input data and interpretation.
Fig. B.5: Cross section E, input data and interpretation.
Fig. B.6: Cross section F, input data and interpretation.
Fig. B.7: Cross section G, input data and interpretation.
Fig. B.8: Cross section H, input data and interpretation.
Table B.1: Differences between seismic and drilled base of Quaternary (BQu) along the Gebenstorf-Stilli Trough based on drill logs from the borehole database of Nagra. Drilled values are marked with (?) if they are taken from logs that do not specifically identify the underlying bedrock, but the described lithology suggests its interpretation.

| Sect. | Type                        | Distance [m] | BQu [m a.s.l.]       | Difference [m] |
|-------|-----------------------------|--------------|----------------------|----------------|
|       |                             |              | seismic   | borehole | seismic   | borehole |
| A     | Exploration borehole        | 170          | 325.9     | 316.0    | 9.9       |          |
| A     | Geothermal probe            | 0            | 322.3     | 322.8    | -0.5      |          |
| A     | Geothermal probe            | 65           | 246.0     | 244.0 (?)| 2.0       |          |
| A     | Geothermal probe            | 0            | 373.3     | 377.0    | -3.7      |          |
| A     | Geothermal probe            | 0            | 393.3     | 377.0    | 16.3      |          |
| B     | Exploration borehole        | 20           | 392.5     | 398.0    | -5.5      |          |
| B     | Geothermal probe            | 35           | 326.3     | 313.2    | 13.1      |          |
| B     | Exploration borehole        | 0            | 326.5     | 311.8    | 14.7      |          |
| B     | Exploration borehole        | 55           | 324.7     | 316.4    | 8.3       |          |
| B     | Scientific borehole QGBR    | 0            | 257.4     | 225.8    | 31.6      |          |
| B     | Exploration borehole        | 90           | 301.9     | 323.5    | -21.6     |          |
| B     | Geothermal probe            | 55           | 335.1     | 349.0    | -13.9     |          |
| C     | Exploration borehole        | 40           | 311.3     | 315.2    | -3.9      |          |
| C     | Exploration borehole        | 85           | 307.1     | 312.7 (?)| -5.6      |          |
| C     | Geothermal probe            | 20           | 369.1     | 362.0    | 7.1       |          |
| D     | Scientific borehole QGVO    | 30           | 264.1     | 266.1    | -2.0      |          |
| D     | Exploration borehole        | 0            | 324.0     | 317.7    | 6.3       |          |
| E     | Exploration borehole        | 50           | 311.9     | 319.9    | -8.0      |          |
| F     | Geothermal probe            | 30           | 332.1     | 331.0    | 1.1       |          |
| F     | Geothermal probe            | 70           | 331.2     | 326.0    | 5.2       |          |
| F     | Geothermal probe            | 90           | 327.0     | 314.0    | 13.0      |          |
| F     | Exploration borehole        | 30           | 345.4     | 338.6    | 6.8       |          |
| F     | Geothermal probe            | 70           | 344.7     | 336.0    | 8.7       |          |
| F     | Exploration borehole        | 25           | 345.4     | 342.5    | 2.9       |          |
| G     | Exploration borehole        | 35           | 341.0     | 330.1    | 10.9      |          |
| G     | Exploration borehole        | 160          | 326.6     | 310.7 (?)| 15.9      |          |
| G     | Exploration borehole        | 25           | 323.2     | 305.1 (?)| 18.1      |          |
| G     | Scientific borehole QUST    | 0            | 276.0     | 255.2    | 20.8      |          |
| G     | Scientific boreh. (seismic survey) | 155       | 296.4     | 291.0    | 3.4       |          |
| G     | Exploration borehole        | 140          | 321.6     | 312.2    | 9.4       |          |
| H     | Scientific boreh. (seismic survey) | 25       | 321.0     | 315.3    | 5.7       |          |
| H     | Exploration borehole        | 175          | 320.4     | 324.0 (?)| 3.6       |          |
| H     | Exploration borehole        | 0            | 326.6     | 318.2 (?)| 8.4       |          |

average: -7.2 / +9.8
Fig. C.1: Sinuosities of major distal foreland overdeepenings of Switzerland. Note that the sinuosity of the central GST segment (zoom-in; S = 1.06) is similar to other Molasse-hosted overdeepenings.
Fig. D.1: Structural survey of a «Malmkalk» outcrop (northeastern slope of Scherzberg; 47°26′43″ N, 8°10′40″ E) exposing a major strike-slip fault (red line on D.1A; panoramic photograph not to scale with D.1B). We observe no increased frequency of (striated) fractures in vicinity of the fault at 19 m along the outcrop wall (D.1B). Two groups of fractures occur, one with orientations similar to the major fault (10/85E, red line), one with a strike of ~140 (D.1C). D.1D: Zoom-in on the core of the fault. D.1E: Zoom-in on striated fracture plane (ruler is in centimeters).