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Catastrophic lake level drop due to moraine dam failure: did it happen to Lake Zurich in the late Pleistocene?

Dedicated to Matthias Freimoser (1939-2018) in deepest gratitude

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Abstract

Moraine-dammed lakes are a common element of formerly glaciated landscapes, especially in mountainous areas and their emptying due to failures of their natural dams is a serious natural hazard, whose risk assessment is far from trivial. While Lake Zurich may seem quite different from these ephemeral and often much smaller lakes, it still shares some characteristics with them. Different authors have proposed a once higher lake level which then supposedly suddenly dropped due to destabilization of the skirting terminal moraine complex in the present-day city of Zurich. Potential triggers for this event, which is assumed to have taken place in the late Pleistocene, may have been a strong earthquake or a flood wave issuing from the Alps (due to a landslide or the outbreak of a glacier-dammed lake), both eventually causing tsunamis to overtop and erode the skirting moraine ridge. Seductive as it is, this hypothesis is struggling with serious problems and evidence for higher lake levels is still sparse. The present paper reviews existing problems and offers new evidence from a hitherto neglected field (the geomorphology of tributary valleys) in support of the hypothesis. One of these valleys exhibits signs of a sudden drop in base level leading to the formation of an upriver-wandering knickpoint, and relics of a former riverbed preserved as isolated strath terraces way above the present-day river course. Accepting age models proposed by earlier authors (implying several thousands of years of a stable higher lake level), the Lake Zurich case is a drastic example of the difficult predictability of this kind of natural catastrophe. Finally, some thoughts are given on the tremendous impact single flood events can have on regional geomorphology.

Zusammenfassung

Durch Moränenwälle gestaute Seen sind ein typisches Element vormals vergletscherter Gebiete. Die Entleerung solcher Seen aufgrund plötzlichen Kollabierens ihrer Dämme stellt eine ernsthafte Naturgefahr dar, deren Risikobeurteilung ein oftmals schwieriges Problem darstellt. Während sich der Zürichsee in vielerlei Hinsicht von solchen oftmals kurzlebigen und viel kleineren Seen unterscheidet, gibt es doch Gemeinsamkeiten. Aufgrund dieser wurde verschiedentlich die These aufgestellt, er sei während des Spätglazials höher gestaut gewesen und wäre dann abrupt abgesunken aufgrund einer Destabilisierung des stauenden Moränendamms im heutigen Gebiete der Stadt Zürich. Auslöser dafür könnte ein Erdbeben oder eine Flutwelle aus den Alpen (ausgelöst durch einen Bergsturz oder den Ausbruch gletschergestauter Seen) gewesen sein und einen dadurch verursachten Tsunami. Obwohl die Hypothese attraktiv ist, stösst sie doch auf Einwände und die Evidenz für einstmals höhere Seespiegel ist bislang dürftig. Dieser Artikel bietet eine Besprechung der Beweislage und damit verbundener Probleme. Zudem liefert er neue Indizien für einen einst höheren Spiegel des Zürichsees aus einem bislang nicht bearbeiteten Gebiet, der Geomorphologie der seitlichen Zuflüsse des Sees. Einer dieser weist einen Knick im Längsprofil auf, welcher zusammen mit Flussterrassen auf einen einstigen raschen Abfall des Vorfluters hindeutet. Der Zürichsee stellt somit ein drastisches Beispiel für die äusserst schwierige Beurteilung solcher Naturgefahren dar, da früher publizierte Datierungen eine über mehrere Tausend Jahre sich erstreckende Phase der Stabilität eines einst höher gestauten Sees anzeigen. Schliesslich wird die Bedeutsamkeit einzelner katastrophaler Flutereignisse für die regionale Geomorphologie ausgedehnter Gebiete diskutiert.

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1 Catastrophic drainage of moraine-dammed lakes: a serious natural hazard

The sudden drainage of moraine-dammed lakes is a common phenomenon in mountainous regions, especially in the aftermath of deglaciations. Whereas many of these catastrophic outbursts and associated floods happen in remote areas without causing any loss of human life (such as e.g. in British Columbia, Clague & Evans 2000, or the Alps, Blass et al. 2003), some devastating events in more densely populated regions are recorded from the Peruvian Andes. Emptying of the moraine-dammed Lake Cohup caused the death of some 6000 people and destroyed major parts of the city of Huaraz in 1941 (Heim 1948). Irrespective of whether or not human life is in danger, moraine-dammed lakes are a serious threat for any kind of infrastructure in partially glaciated mountain areas and ongoing glacier retreat will likely augment this natural hazard in the near future. Risk assessments, depending mainly on geotechnical properties of the moraine dams and the potential of possible triggers promoting lake emptying, are difficult and fraught with unknowns and therefore mostly qualitative (e.g. O'Conner and Beebee 2009).

Generally speaking, moraine-dammed lakes are short-lived (often only a few years to several decades) water bodies that form in mountainous areas between terminal moraines, deposited during glacier advances, and the retreating glacier snout or steeply sloping bedrock representing former glacier beds. Due to the often poorly sorted, coarse grained and not so well consolidated nature of the till, sand, and gravel deposits constituting the lake-damming terminal moraines, the latter are unstable and labile features. Their failure, caused by rapid incision triggered by overtopping waves due to, e.g., icefalls, landslides, or other massive water fluxes into the dammed lake, can give rise to devastating outburst floods and related mass flows (such as debris flows) which can reach downvalley for dozens of km (Clague and Evans 2000). The aim of the present paper is to review and to test an attractive hypothesis put forth by Schindler (1971, 2004) and Strasser et al. (2008), proposing that Lake Zurich also experienced a dramatic moraine-dam failure induced lake level drop in the late Pleistocene. By doing so, emphasis will be laid on a hitherto neglected aspect: the

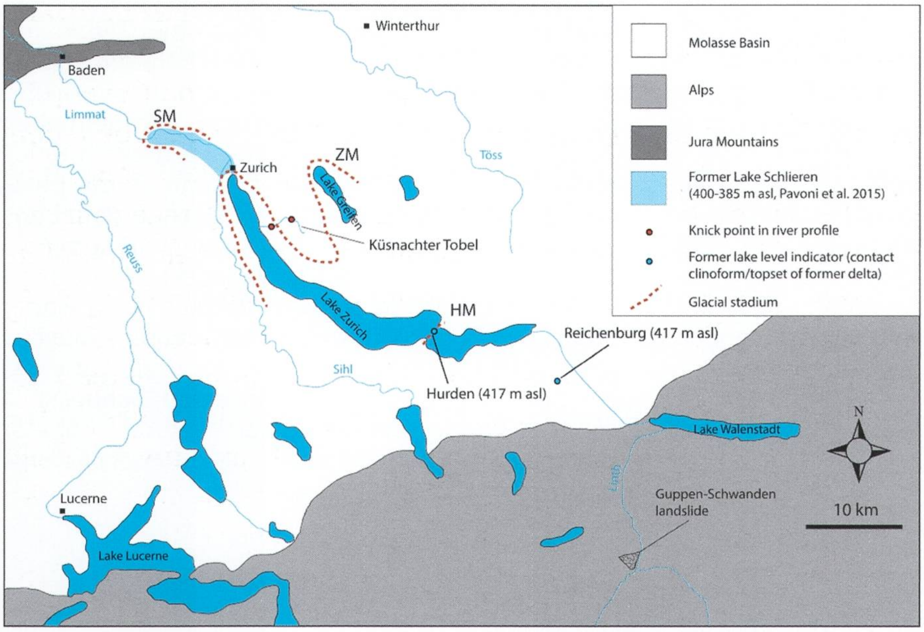

Fig. 1: Geographical and geomorphological map displaying Lake Zurich and its surroundings (based on Geologische Karte der Schweiz, 1: 500'000, 2005). Glacial retreat stadiums of the last glaciation are indicated by dotted red lines (HM: Hurden Moraine, SM: Schlieren Moraine, ZM: Zurich Moraine). Former lake level indicators refer to the contacts between clinoforms and topsets of ancient gravel delta deposits, which are robust proxies for former lake levels (von Moos 1943, Schindler 1971, 2004). See text for further explanations.

potential impact such an instantaneous drop in base level must have had on local geomorphology.

2 Late last-glacial Lake Zurich: was it substantially higher than today?

Lake Zurich may at first sight not look like a potential candidate for any late- to post-glacial moraine-dam failures and connected outburst floods, given both its size and location within a lowland setting. However, as early as at the beginning 1970s, field evidence had been described in favor of the assumption of a once considerably higher lake level of lake Zurich during the late last glacial (Schindler 1971). Apart from the fact that four breaches eroded the damming terminal moraine wall in today's city of Zurich (Fig. 1; ZM: Zurich Moraine of the Last Glacial Maximum) down to a constant level of 403-405 m asl, direct evidence for a higher ancient lake level is documented by ancient delta deposits. Clinoform/topset contacts, being a robust proxy for lake level, on the Hurden peninsula and in gravel bodies supposedly deposited in the former southern prolongation of Lake Zurich at Reichenburg indicate an old lake level of 417 m asl (Fig. 1, von Moos 1943, Schindler 1971, 2004). Impressed by the supposedly simultaneous downcutting of four massive breaches in the Zurich area, Schindler (1971, 2004) has postulated a catastrophic dam failure and concomitant lake level drop from 417-418 m to 403.5-404.5 m asl initiated by a flood wave. As a potential trigger for the latter he hypothesized a substantial earthquake, outbreak of an early Lake Walenstadt due to a collapse of the Linth glacier's snout (an idea already envisaged by Wegmann 1935); or a massive landslide/rockfall event into the southern continuation of Lake Zurich in the Glarus area (e.g. the Guppen-Schwanden landslide, Fig. 1). More recently, Schindler's hypothesis has received considerable support from seismic and drilling investigations in the Lake Zurich Basin. This new data suggests a strong alpine earthquake (with magnitude stronger than 6.5) some 13'760 calibrated years BP which may have caused dam failure of the Zurich Moraine either directly through ground shaking or indirectly through a tsunami wave overtopping the dam (Strasser et al. 2008).

Seductive as it is, the hypothesis of a catastrophic, earthquake-induced, dam collapse, lake level drop, and a severe but short-lived flood downstream of the Zurich Moraine faces considerable obstacles. Among others, three lines of evidence seem especially unfavorable (for more detailed criticisms see Pavoni et al. 2015). First, assuming a ca. 19.5 ka age for the Zurich Moraine (Keller & Krayss 2005), Strasser et al.'s (2008) dating of the strong alpine earthquake, supposedly triggering dam failure, would imply a ca. 5 to 6 ka phase of moraine stability ponding lake Zurich at least 17 m higher than the immediately adjacent former Lake Schlieren (Fig. 1). Even when assuming a gravel-armoured outflow channel (a well-known stabilizing factor in stable moraine-dammed lake systems, O'Conner and Beebee 2009) connecting these two lakes across the Zurich Moraine, such a situation seems very unlikely to have prevailed for a prolonged period of time. Second, the existence of alleged moraine dam failure and flood related reworked moraine deposits just north of the Zurich Moraine (as depicted by Strasser et al. 2008), cannot be reconciled with the results of detailed geotechnical investigations such as e.g. recent underground excavations for urban tunneling projects (described in detail in Pavoni et al. 2015). These have not revealed any coarse grained chaotic sediments but instead fluvio-lacustrine delta gravel deposited in the former Lake Schlieren. Third, any wave-cut benches or terraces (representing former lacustrine shorelines) above the present-day lake level are completely lacking in the Lake Zurich Basin (Gubler 2009, Pavoni et al.

2015), whereas such features have been described from the much smaller Lake Greifen (Jung 1969, Wyssling 2008). Furthermore, a thorough survey of geotechnical reports from most major Lake Zurich tributary delta complexes has not yielded any evidence in favor of former lake levels (easily discernible from dynamic probing [Rammsondierung] test diagrams) higher than 409-410 m asl (Pavoni et al. 2015, M. Freimoser † & D. Letsch, unpublished work).

3 A geomorphological test: river incision due to sudden base level fall

Wrapping up the above discussion, it seems fair to state that, despite its attractiveness, the hypothesis of a dam-collapse induced catastrophic drop of Lake Zurich's ancient lake level meets many difficulties. A major weakness is the sparseness of direct evidence for a long-lived higher former lake level. Turning attention thus towards more indirect evidence, geomorphology could possibly offer pertinent information on that problem. Assuming Lake Zurich's former lake level to have stayed for a prolonged period of time higher than today, one could expect local tributaries (the abundant ravines and creeks incised into the lake's surrounding slopes composed of Neogene Molasse bedrock) to have adjusted their longitudinal profiles accordingly. As it is well known from rivers in equilibrium (i.e. those reaching a balance between erosion and deposition) to have concave longitudinal profiles adjusted to base level (e.g. Leopold et al. 1964), sudden drops in the latter lead to predictable consequences. Starting with the more or less instantaneous drop in base level, a zone of enhanced erosion and fluvial incision (a knickpoint) comes into being at the downstream end of the river. The latter then propagates upstream and thus forms the steeper junction between two different river profile segments (Fig. 2, see also, e.g., Burbank & Anderson 2011, Finnegan 2013).

The identification of knickpoints in longitudinal profiles of Lake Zurich tributaries could thus help to reconstruct ancient lake levels as upper reaches («old river profile» in Fig. 2) may still exhibit profiles adjusted to a former lake level. Based on a survey of 6 tributary profiles (using the excellent 19th century 1:25'000 topographic map of the Canton of Zurich by Johannes Wild, which documents the original state of these creeks before any flood-preventing construction works), we tried to identify knickpoints and potential old river profile relics. A constant feature of all these river profiles (taken from the following creeks/ravines: Aabach, Erlenbacher Tobel, Heslibach, Kusenbach, Küs-

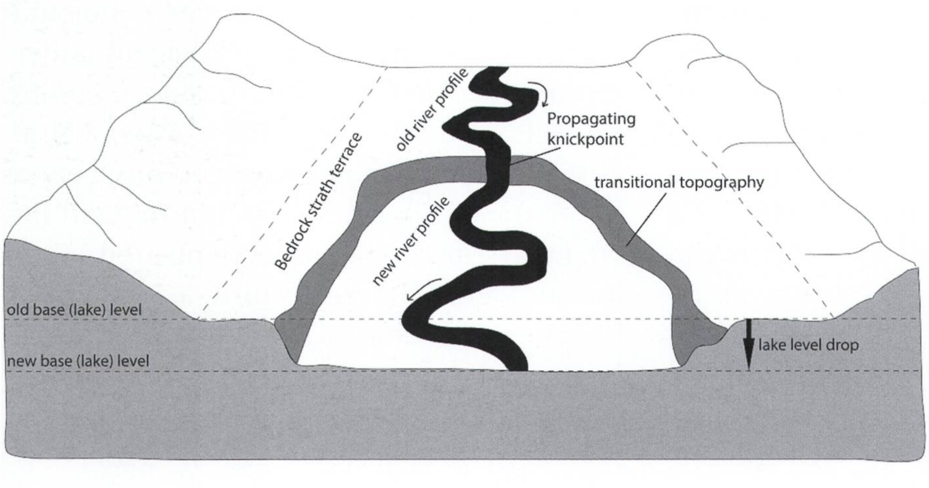

Fig. 2: Schematic sketch explaining the geomorphic consequences of a sudden base level drop on a river profile (redrawn after Finnegan 2013). For further explanation see text.

nachter Tobel, Werenbach) is a well-developed lower reach approximating an exponential curve (see Fig. 3 for the example of the Küsnachter Tobel which will exclusively be dealt with in this paper). The zero intercepts of these 6 curves cluster closely around the long-term postglacial lake level of Lake Zurich (403.5 to 404.5 m asl, Schindler 1971): 403.15, 405.52, 402.97, 406.61, 403.85, 403.75, respectively. Their arithmetic mean of 404.31 m asl ($\sigma^2 = 2.08$) is thus an excellent proxy for the long-term base level to which all these small rivers adjusted their lowest reaches. The upper reaches of these river profiles exhibit more complicated patterns and not all of them can be interpreted in a straightforward manner. However, in the case of the biggest and deepest of all these ravines, the Küsnachter Tobel, the lowermost reach (adjusted to a 403.85 base level) develops up-river via a steeper transitional zone (a knickpoint, Fig. 3, for geographic location of this knickpoint see Fig. 1) into a long and smooth profile adjusted to a theoretical base level (zero intercept) of 419.62 m asl.

Recalling the above discussion of migrating knickpoints due to sudden base level drops (Finnegan 2013), we suggest this upper reach of the Küsnachter Tobel to represent a relic profile adjusted to a formerly higher base i.e. lake level at ca. 419.6 m asl. In fact, assuming our reasoning is correct, the actu-

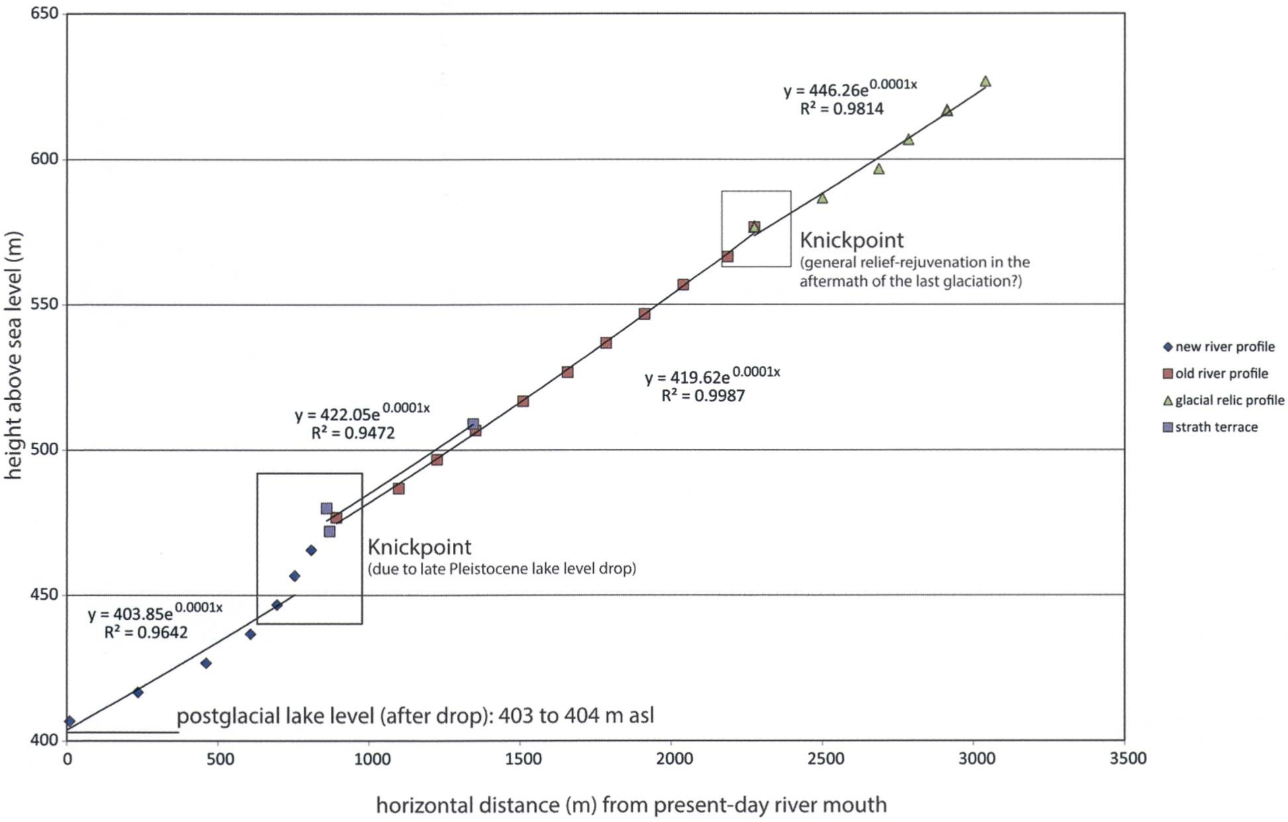

Fig. 3: Longitudinal profile of the Küsnachter Tobel. The profile has been obtained using the 19th century 1:25'000 topographic map of the Canton of Zurich by Johannes Wild. Original topographic heights have been corrected to modern values by subtracting 3.26 m (taking into account the modern and more precise height determination of the base point of Swiss topographic maps, the Repère Pierre du Niton in Lake Léman). The knickpoint separating the lower reach of the Tobel from an older river profile is a strong indication for a once sudden drop in regional erosional base level. Interpretation of the upper knickpoint and river section upstream of it is not so straightforward. Perhaps, following a suggestion of Schlunegger & Schneider (2005) for other pre-Alpine catchments, it is a relic of a late-glacial landscape which, following a general base level drop following deglaciation, is continuously being destroyed by a process of regional relief-rejuvenation. «e» is the base of natural logarithm, and R^2 is a correlation coefficient describing the robustness of the applied trend-line. See text for further explanations.

al zero intercept could be expected to have been even slightly higher due to the slight horizontal shift (to the right on Fig. 3) of the former higher lake level. Be that as it may, there is indeed even more evidence in the Küsnachter Tobel for a once higher base level. Both abundant field evidence and numerical modeling studies (Leopold et al. 1964, Burbank & Anderson 2011, Finnegan 2013) suggest that former river levels are still preserved even after base level drops in the form of bedrock strath terraces (Fig. 2) which may or may not be covered by ancient river alluvium. Such strath terraces can in fact be observed in the Küsnachter Tobel at various places and on different levels (Fig. 4) and some have even been mapped by Gubler (2009). With their discrete spatial distribution following present-day bedrock topography, and the moderately to well-rounded and sorted appearance of their gravel cover, they can easily be distinguished from glacially influenced gravel, such as the glacial «Wulp-Schotter» cropping out further up-stream in the Küsnachter Tobel (Letsch 2012). Three better developed strath terrace relics have been indicated on Figure 3 and they fit nicely into an exponential curve with zero intercept at 422 m asl i.e. slightly higher than the base level indicated by the rivers reach upstream of the knickpoint.

4 Consequences for the catastrophic base level drop hypothesis

We thus suggest that both the relic river profile and several strath terraces (representing

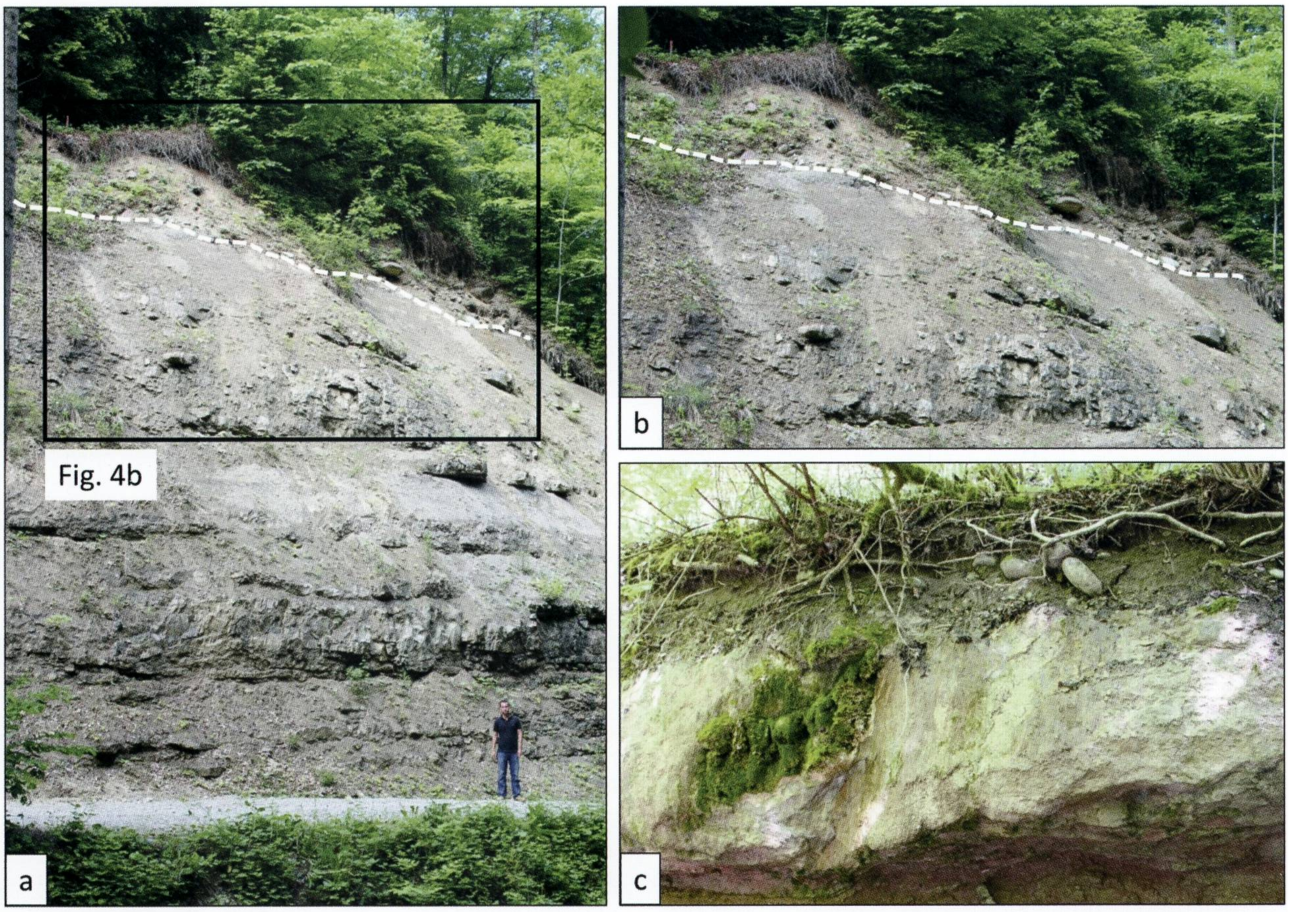

Fig. 4: Field pictures from the Küsnachter Tobel (for location see Fig. 1). a: Ancient riverbed preserved as an alluvium-covered bedrock (strath) terrace many meters above the present-day riverbed. Base of terrace fill (highlighted by a dotted white line) is at ca. 480 m asl. b: detailed view of the coarse-grained river alluvium overlying sandstones and siltstones of the Molasse bedrock. C: Close-up of another strath terrace with the latter's alluvial cover giving rise to a small spring (highlighted by partly green calcareous tufa).

relics of the ancient river course) of the Küsnachter Tobel document a former level of Lake Zurich around 420 m asl. This is, to our knowledge, the first indirect geomorphic evidence in support of a former higher lake level. What are now the consequences for the hypothesis of a catastrophic base level drop of Lake Zurich during the late Pleistocene championed by Schindler (1971, 2004) and Strasser et al. (2008)? First, the relic river profile upriver of the knickpoint (adjusted to a base level of 419 m asl) and the slightly higher level of strath terraces (adjusted to a base level of 422 m asl) both demand a more or less constant or gradually slowly falling lake level around 420 m asl over a certain period of time. The sharp knickpoint connecting this reach to the lowermost reach (adjusted to the Holocene long-term lake level) furthermore suggest a fast base level drop. So far, the evidence seems completely in agreement with the general idea of a moraine-dam failure induced drastic drop of Lake Zurich's level. However, given the lack of any age indications on the strath terraces in the Küsnachter Tobel, the timing proposed by Strasser et al. (2008) and consequently also the proposed earthquake trigger some 13760 calibrated years BP cannot be evaluated directly by this new geomorphic evidence. On the other hand, assuming Strasser et al.'s (2008) timing to be correct, the long period since 13760 calibrated years BP would only have caused the knickpoint wandering upstream for less than a km, whereas the relatively short time span between the terminal retreat of the Linth glacier from Lake Zurich basin and the supposed earthquake and moraine dam failure (some 5 to 6 ka) was sufficient time for the river to erode a major ravine adjusted to a ca. 420 m asl base level. While this may seem at first sight rather implausible, it is in general accord with many other observations from formerly glaciated areas in general, and the Lake Zurich basin in particular. Church & Ryder (1972) have coined the useful term paraglacial for the increased scales and rates of geological/geomorphological processes taking place in the aftermath of glacial climates. Apart from the lack of vegetation and the availability of fresh rocky detritus, it is especially the presence of «unstable landforms» such as e.g. steep slopes carved by glaciers or abundant moraines (and moraine dammed lakes) that contribute to the enhanced dynamics of landscapes immediately after deglaciation. To put it in another way, there is simply a lot of potential for landscape change around in such settings and this may even be true for areas only marginally influenced directly by glacial activity (see e.g. Schlunegger & Schneider 2005). An instructive example from the wider Zurich area is the fluvial incision of the Sihl valley. According to circumstantial evidence presented by Gubler (2009), the river Sihl must have eroded its 70 to 100 m deep and 250 m wide valley south of Langnau within an astonishingly short time span of several hundred years. Less dramatic but nevertheless instructive examples are provided by many other creeks and ravines in the vicinity of Zurich whose incision cannot be explained under present-day conditions (e.g. Pavoni et al. 2015).

Summing up the consequences of the geomorphological evidence presented so far for the hypothesis of a catastrophic lake level drop due to an earthquake-induced moraine dam failure, it seems fair to state that the evidence generally supports such a hypothesis. However, concerning timing and the exact mechanism of dam failure, we cannot add much more to the discussion. An interesting task for future research would be to try to date the gravel-covered strath terraces in the Küsnachter Tobel (Fig. 4b). This might help bracketing the timing of base level drop and could hence help testing the 13760 BP earthquake trigger hypothesis.

5 Flood catastrophes and their impact on landscapes

Having assessed the likelihood of a sudden partial emptying of Lake Zurich during the late Pleistocene, we shall complement this short contribution to local geology by broadening somewhat our perspective. Historically, supposed ancient flood catastrophes have often been invoked to explain certain features of the landscape, in Switzerland and elsewhere (see e.g. Rudwick 2008). The incision of major valleys in the Swiss Molasse Basin and the transport of erratic boulders from the Alps to the lowlands had generally been interpreted as the products of giant floods and streams as late as until the mid-nineteenth century (see Letsch 2014 for a historical exposé of these ideas). The growing awareness of glacial ice as a potent agent of both erosion and transport gradually displaced the idea of giant flood catastrophes from the late nineteenth and early twentieth century geological repertoire.

However, the recognition of giant flood catastrophes during the late Pleistocene in the United States' Pacific Northwest (Columbia River Plateau, Washington State, Oregon) led to a partial re-assessment of the traditional uniformitarian dogma that only constant dripping wears the rock away (see also Wegmann 1935). First proposed by J Harlen Bretz in the early 1920s (Bretz 1923), the hypothesis of cataclysmic and devastating floods due to the sudden emptying of the formerly glacier-dammed Lake Missoula in mountainous western Montana has met very stiff resistance from the geological establishment over decades (see e.g. Baker 1978 and Allen et al. 2009 for well-told historical accounts). New research has, however, completely confirmed the Lake Missoula Flood story. It is now part of conventional geological wisdom that some 15000 to 18000 years ago, 40 to as many as 90 giant floods of truly

Fig. 5: Two examples illustrating the enormous impact giant floods caused by the emptying of ice-dammed lakes can have on landscapes. a: completely dry canyon («coulee») some 400 to 500 m wide incised into Miocene Columbia River Basalt (Frenchman Coulee next to Frenchman Springs, ca. 20 km south of Quincy, Washington State). The tremendous amount of erosion of this and many other coulees in the area was due to several cataclysmic floods coming from the late-glacial Lake Missoula. b: giant current ripples (for better visibility, three of them are outlined by a white dashed line) composed of sand and gravel with maximum individual ripple heights of as much as 15 m! Paleoflow of Lake Missoula floodwater (producing the giant ripples) was from the right to the left (West Bar of Columbia River, near to Crescent Bar, Washington State).

apocalyptic or delugal dimensions (reaching peak discharges 10 to 20 times global average discharge or 60 times the discharge of the Amazon River) originated from Lake Missoula. Rushing down over the Columbia River Plateau, these floods tremendously changed the geomorphology of vast tracts of land and produced landforms almost unique on Earth – the «Channeled Scablands». Conspicuous elements of this strange landscape are huge river-less canyons (locally referred to as coulees, dry waterfalls of Niagara dimensions, and giant gravel/sand bars and ripples (Fig. 5), all witnesses of these cataclysmic flood events. Comparative sedimentological studies have shown that megafloods of Missoula and even larger dimensions have also occurred in other parts of the world (e.g. in the Altai Mountains in Siberia, Carling et al. 2009), and supposedly even on Mars (e.g. Coleman and Baker 2009, or Irwin and Grant 2009).

Closing the circle, we eventually come back to the wider Lake Zurich area. Keeping in mind the lessons learnt from the Lake Missoula Floods, we are better prepared to appreciate the fact that very few dramatic events (especially in a paraglacial setting following the last glaciation) can cause tremendous changes in the landscape such as the ultra-rapid incision of the Sihl valley proposed by Gubler (2015). The present paper has contributed new evidence in favor of a once substantially higher Lake Zurich and hence lends further credibility to the hypothesis of a dramatic partial emptying due to moraine-dam failure in the area of the present-day city of Zurich (Schindler 1971, 2004). Even though the supposed flood resulting from this event can in no way be compared with something so gigantic as the Missoula Floods, it nevertheless may have left traces in the geological and geomorphological record of the Limmat valley between Zurich and Baden (Fig. 1). Whereas the proposed substantial «reworked moraine» deposits (interpreted as proximal dam breach deposits by Strasser et al. 2008) do not seem to exist (Pavoni et al. 2015), fine-grained overbank deposits on top of the Limmattal and Sihltal gravel deposits downstream of Zurich (Pavoni et al. 1992, 2015) are viable potential archives which may have recorded the exceptional flood rushing down the Limmat valley when the moraine dam skirting a 14 m higher Lake Zurich burst during the late Pleistocene. The last and perhaps most intriguing lesson to be learnt from the Lake Zurich case is the appreciable potential longevity (several thousand years) of large moraine-dammed lakes even within lowland settings. Their sudden emptying, whatever the ultimate trigger may have been, is a potential source for major flood catastrophes downstream and it is the challenge of the geologist to try to decipher the relics of such ancient floods within the Quaternary geological record.

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Several persons have helped and motivated me to write this paper. First and foremost to mention are the numerous inspiring discussions on Lake Zurich geology with the late Conrad Schindler and Matthias Freimoser that led me think about the problem of formerly higher lake levels. Thomas Bolliger first pointed out to me the existence of strath terraces in the Küsnachter Tobel on the occasion of a joint excursion together with Beat Rick in 2007. Last but not least, I would like to acknowledge Alan Busaca and Kevin Pogue for introducing me to the spectacular Lake Missoula Flood story during a memorable field trip of the Geological Society of America through eastern Washington State and northern Oregon in autumn 2017. It has been my appreciation of the gigantic impacts floods can have on geomorphology that finally triggered the writing of this paper.

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