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Fluvial, glacial, or tectonic origin of Lake Zurich basin – changing views during the last 200 years: a historical sketch and some conclusions for modern discussions

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Abstract

The deeply excavated rock troughs which are occupied by lakes, huge masses of Quaternary sediments and major rivers in the Swiss plain have attracted the attention of geologists for a long time. Today the question of how and how fast these features were formed is of importance in view of the long term storage of radioactive waste beneath the Swiss plain. The present article is intended to provide a historical basis for this ongoing discussion as exemplified by the Lake Zurich basin. It summarizes the changing views during the last 200 years on the three possible processes of valley formation, namely fluvial erosion, glacial erosion and tectonics. After a first phase of mainly tectonic (*gaping fractures*) and fluvial explanations in the wider sense (also including *diluvial* i.e. non-actualistic processes), the debate shifted in the second half of the 19th century to the question of the relative importance of fluvial and glacial processes. This debate continued well into the 20th century and was vigorously fought between A. Heim and A. Penck and their pupils. To account for overdeepened troughs without invoking glacial erosion Heim postulated neotectonic movements. His once very popular theory of an alpine back-sinking in Quaternary times could however finally be disproved in the second half of the 20th century by combining a better knowledge of the tectonic structure of the basement of Lake Zurich with the now possible measurements of recent movements of the Earth's crust.

Zusammenfassung

Die tief ausgehobelten Felströge im Schweizer Mittelland, die heute von quartären Sedimentmassen, Seen und Flüssen eingenommen werden, erregten schon lange das Interesse der Geologen. Heute ist die Frage, wie und wie schnell diese Felströge sich gebildet haben von grosser Bedeutung für die mögliche Endlagerung radioaktiver Abfälle unter dem Schweizer Mittelland. Der vorliegende Artikel soll eine historische Grundlage für die laufenden Diskussionen bieten und konzentriert sich auf das Beispiel des Zürichseetales. Er fasst die wandelnden Ideen der letzten 200 Jahre zusammen zur Frage der drei möglichen Prozesse der Talbildung d. h. fluvialer Erosion, glazialer Erosion und tektonischer Vorgänge. Nach einer ersten Phase hauptsächlich tektonischer (*klaffende Spalten*) und im weitesten Sinne fluvialer (darunter auch *diluviale* und somit nicht-aktualistische) Erklärungen fokussierte sich die Diskussion während der zweiten Hälfte des 19. Jahrhunderts auf die Frage der relativen Bedeutung der glazialen gegenüber der fluvialen Erosion. Diese Debatte dauerte bis ins 20. Jahrhundert an und wurde leidenschaftlich zwischen A. Heim und A. Penck sowie ihren Schülern geführt. Um übertiefte Felstäler ohne Gletschererosion zu erklären, postulierte Heim neotektonische Bewegungen. Seine einst populäre Theorie der alpinen Rücksenkung konnte schliesslich jedoch widerlegt werden, durch bessere Kenntnis der regionalen Tektonik sowie durch die heute möglichen direkten Messungen rezenter Erdkrustenbewegungen.

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1 Introduction

Ever since the beginning of modern geological research in the area around Zurich in the early decades of the 19th century, the question of how and when the Lake Zurich and the valley or basin it occupies formed, attracted great interest and was thoroughly discussed (Fig. 1). The same question of course applies to other lakes and valleys as well. To make one point clear right at the beginning: the present paper is not so much concerned with the question of the origin of the lake i. e. the water mass itself (e. g. Staub 1938, Schlüchter 1979: 102) but rather with the valley or the basin it occupies. Today this topic has acquired considerable practical importance in view of the long-term storage of radioactive waste in deep geological repositories (e. g. Talbot 1999, Fischer & Häberli 2012). Important questions concern the capability of glaciers during future glaciations to carve new valleys in the Swiss midlands and thus to remove the protective rock cover over such waste repositories. Additionally the neotectonic activity of Northern Switzerland has moved into the focus of research (Pavoni 1987, Müller et al. 2002).

The present article is intended to provide a historical basis for the ongoing discussions and thus highlights the evolution of thought on these topics during the last two hundred years, and focuses especially on a geological controversy which concerned precisely these two issues (i. e. glaciers as a valley-forming geological agent and neotectonics) and which was vigorously disputed by the

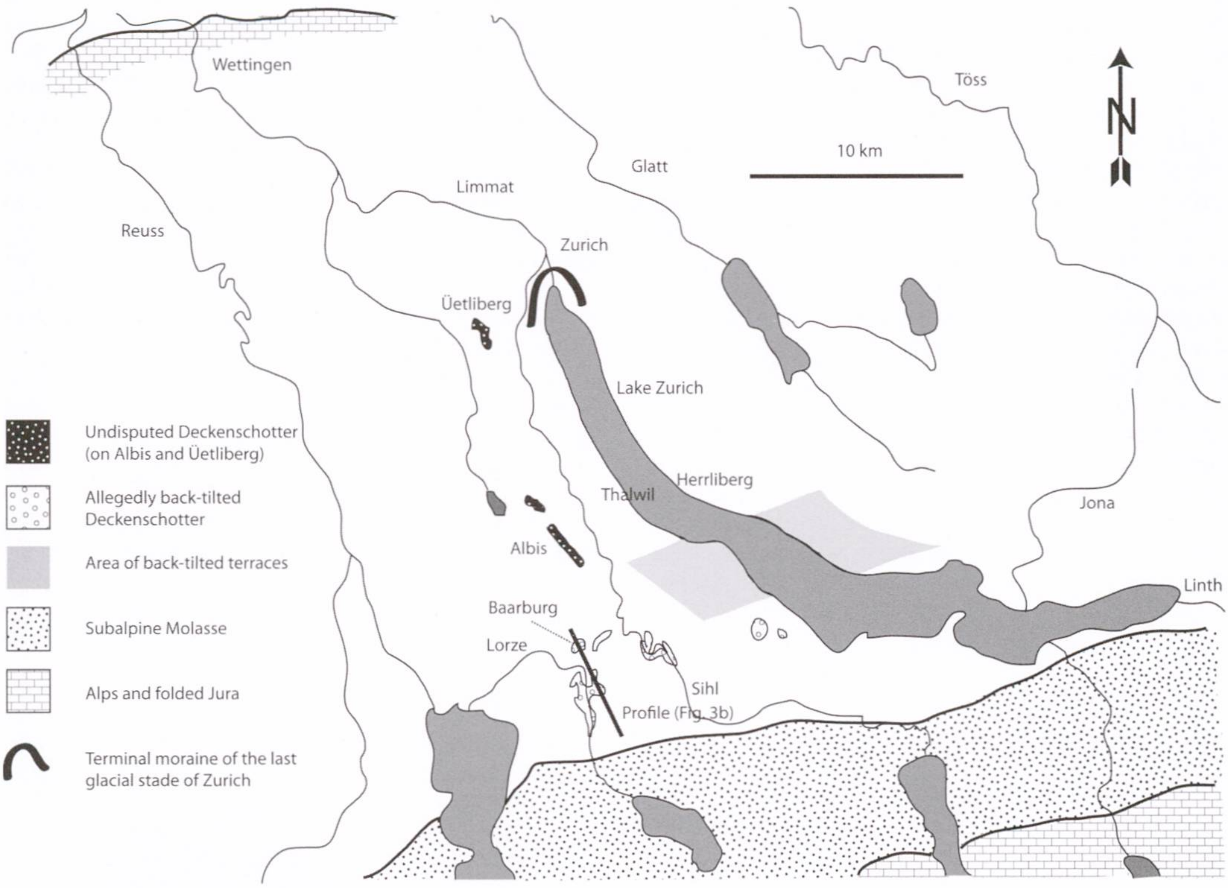


Fig. 1: Geological and geographical sketch map of the area treated in this article. The geology follows Suter (1939). The aerial extent of the back-tilted terraces is copied from Pavoni (1953). The trace of the profile in Fig. 3b is indicated. For further explanations see text.

geological establishment some hundred years ago (chap. 4). As the present article is of mainly historical character, the youngest developments in this field of research will not be discussed in great detail. The interested reader is instead referred to volume Nr. 103/3 of the Swiss Journal of Geosciences which encompasses several articles dealing with the problem of overdeepened valleys in the alpine foreland.

2 Thoughts on valley formation and erratic blocks from 1800 to 1870: diluvial floods, tectonic fractures and increasing recognition of glaciers as a geological agent

Attempts around 1800 to explain Alpine valleys and their continuations into the Swiss midland were mostly based on the assumption of terrible catastrophes in Earth's history (*catastrophism*). Horace Bénédict de Saussure – the great physicist, geologist and alpine explorer from Geneva – spoke of a last great revolution (*la grande debâcle*) that affected Earth's crust of the Alps and its neighbourhood. This revolution thus not only folded and faulted parts of the Alps but also caused a withdrawal of the Sea which finally led to the carving of valleys and the distribution of erratic blocks over the Swiss midlands and even parts of the Jura mountains (de Saussure 1786: 340). Johann Gottfried Ebel expressed similar views (Ebel 1808: 82–84; see also Franks et al. 2000: 37–38): a great marine flood approaching Switzerland from the SE carved out the Alpine valleys and threw erratic boulders into the Swiss Plateau. Hans-Conrad Escher von der Linth – even though much more cautious and better informed about the actual geological constitution of the Alps than most of his contemporaries – also found great floods the most plausible mechanism to distribute erratic boulders over the lowlands of Switzerland (see e. g. the useful summary Escher's son Arnold has given [Escher 1852: 389–392]). Contrary to de Saussure and Ebel he did however not invoke a global cause but rather a regional explanation (Escher 1820: 126). According to him the big Alpine longitudinal valleys (e. g. the part of the Rhône valley upstream of Martigny) were originally closed longitudinal troughs and accordingly filled with water masses. On the other hand, the valleys which run today at right angles to the former valleys are of more recent origin: they formed catastrophically when the longitudinal water masses emptied due to a sudden failure of their natural dams. The resulting flood carved the oblique valleys and brought a huge amount of alpine debris into the Swiss midland (cf. also Studer 1863: 602). The increasing awareness in the years between 1820 and 1840 of a much enlarged extension of Alpine glaciers in former times (the *Ice age* of Karl Schimper 1837; cf. Jopling 1975 for an exhaustive review of the early literature on this topic) gave a new and convincing explanation for the widespread occurrence of erratic blocks (see especially the important book by Charpentier 1841). However it was not until 1862 that the possibility of a glacial origin of Swiss valleys was taken into account (see below). Arnold Escher (1844: 168) still favored a «fluvial» origin of most foreland valleys due to a sort of *diluvial* flood which may have been triggered by the impulsive upheaval of part of the Alps, whereas his friend Studer (1864) invoked huge tectonic «gaping fractures» (*klaffende Spalten*), assisted by some sort of fluvial erosion (see below), as the main cause for valley formation – a view also partly shared by his friend Escher in his later years (e. g. Escher & Bürkli 1871: 2). The assumption of open fractures was quite feasible at a time when the Swiss geological establishment still adhered to a tectonic model of the Alps which was dominated by vertical movements and not by horizontal contraction (Letsch 2011).

A totally different way of thinking was chosen by those geologists who explained the formation of valleys as basically a process of fluvial erosion, as it can be observed in modern river beds. The most prominent representatives of this *uniformitarian* school of thought were James Hutton and Charles Lyell (1830, 1833 and 1863). Even though the fluvial theory of valley formation was quite popular in Britain during the first half of the nineteenth century, it was not all generally accepted in Switzerland. Of course smaller valleys and creeks were accepted as products of fluvial erosion (Studer 1844: 345–359) and even some bigger valleys might have been formed by currents. However, it was repeatedly stressed (e. g. Studer 1844: 360) that bigger water masses than those observed today would have been necessary to account for big valleys. Thus as far as the bigger valleys were concerned the possibility of a purely fluvial origin by means of modern fluvial processes and discharges was not considered (see e. g. the discussion in Studer 1864: 488–489) until Rütimeyer (1869) published his influential though somewhat turgid treatise «*Über Thal- und See-Bildung*» and Heim (1878) published his results from the Alpine Reuss valley (see below).

3 The erosive role of glaciers: Ramsay's hypothesis (1862) and its reception by Swiss and British geologists

The idea that mountain glaciers and also their lowlands continuations during ice ages could act as effective agents of valley formation was first rigorously proposed by the influential Scottish geologist Sir Andrew Crombie Ramsay (1862), then president of the Geological Society of London. His hypothesis was based on several different lines of evidence: he firstly denied the then popular assumption that the course of Swiss valleys and lakes was determined by gaping fractures (see chap. 2) and generally questioned the then popular tectonic model of vertical forces being responsible for the structure and elevation of the Alps. He insisted instead on the importance of horizontal contraction as the main force in orogeny (Ramsay 1862: 190) – a view which became popular only 10 to 15 years later in Switzerland due to the work of Eduard Suess and Albert Heim (Letsch 2011, 2014). However gaping fractures giving rise to lake basins were no more feasible in such a scenario. Furthermore Ramsay pointed out that many Swiss lakes (including Lake Zurich, Ramsay 1862: 197) are situated in *profound hollows* which were bordered by *rocky barriers* at their downstream continuations (e.g. Ramsay 1862: 189). Finally Ramsay based his thoughts on his personal field experience in Scotland where he observed numerous small rock basins (so called *tarns*) which were often filled by lakes and which he attributed to the grinding action of glaciers.
The reactions to Ramsay's provoking ideas were mostly negative, be it in Switzerland (e.g. Studer 1864: 487, Favre 1865, Rütimeyer 1869: 60, Escher & Bürkli 1871: 3 ff., Escher 1878: 65, Heim 1875) or in Britain (e.g. Ball 1863, Lyell 1863: 311–319). However, vigorous support came from the eminent physicist John Tyndall (1864). Furthermore, one of the probably most rigorous Swiss field geologists of his days – Franz Josef Kaufmann (1872: 451) – accepted glacial erosion as one of several possible agents of valley building. A strong argument against Ramsay's hypothesis however was the generally agreed upon assumption of Swiss geologists that the deep and broad Alpine and foreland valleys must be older than the Ice Age(s), as diluvial (i.e. glacier-transported) and prediluvial deposits were frequently found deep inside these valleys (e.g. Lyell 1863: 314, Mayer 1875: 468, Heer 1879: 550). Obviously, this evidence loses its strength as soon as one admits numerous different glacier advances and retreats, but it retains its validity at least for the last glaciation(s) as will be shown in chapter 5.4.
During the two decades succeeding Ramsay's 1862 paper Swiss geologists remained

generally skeptical or even sometimes hostile towards the theory of glacial erosion of valleys even though they fully admitted the Ice Age theory in general. This was mainly due to the increasing influence which Albert Heim (from 1872 onwards Professor for Geology in Zurich; Fig. 4a) exerted on the geological establishment. The lasting impression of his beloved and admired teacher Arnold Escher (passed away in 1872) and especially his extensive fieldwork in Central Switzerland (Heim 1878) strengthened his belief that glaciers rather preserve than create valleys which he ascribed to the effect of fluvial erosion.

4 The glacial erosion controversy revived: Heim's «Alpine Rücksenkung»

4.1 Early developments: From Escher (1870) to Wettstein (1885) and Heim (1894)

As pointed out above Heim came in the 1870s to the conviction that Alpine valleys and accordingly also their lowlands continuations were solely the product of fluvial erosion (e.g. Heim 1878). The lake-filled troughs that skirt the Alps, however, challenged this view considerably: how could a river erode such spoon-shaped hollows or «overdeepened basins» – with an «inverse» gradient – into bedrock and how could they subsequently be occupied by lakes?

For Lake Zurich this problem had already been addressed by Heim's much admired teacher Arnold Escher in one of his last publications (Escher & Bürkli 1871). The deepest part of this Lake is situated between Thalwil and Herrliberg (266 m above sea level [this and all following numbers quoted from old papers are the original numbers and may differ by a couple of meters to the modern values due to newer altitude determinations]). At the northern end of the lake around Zurich the outflowing river Limmat does not touch bedrock until Wettingen, where the bedrock surface lies 365 m above sea level. Escher thus concluded that a possible explanation for this could be a tectonic tilt between Herrliberg and Wettingen, whereby either the former place subsided by at least 99 m or the latter place rose by the same amount or a combination of both (Escher & Bürkli 1871: 3). The direct cause of the lake itself was found by Escher in the dam made up of glacial debris and moraines in the city of Zurich. However, Escher remained very cautious and pointed out that so far any evidence in favor of this tectonic tilt was lacking (see also the negative remarks which he made already a quarter of a century before [Escher 1847: 110] or the ones by Gutzwiller [1880: 23]). Thus, Escher presented a partly tectonic explanation for the origin of Lake Zurich and analogous lake basins. Similar models had also been proposed by Eduard Desor (cited in Lyell 1863: 310; cf. also Studer 1864), Lyell (1863), Rütimeyer (1869), Rothpletz (1882: 19–20).

A comprehensive theory of the origin of Lake Zurich was given by Heim's scholar Alexander Wettstein (1885). His account seems to be the first rigorous (i.e. based on a thorough knowledge of the local geology) attempt to explain the lake by means of either a tectonic uplift of the eastern Folded Jura in the area around Baden and Wettingen or, alternatively, a tectonic sinking of the future area of Lake Zurich before the last glaciation (of the two then known to Wettstein) which rendered a fluvial valley with normal gradient into an overdeepened trough with an inverted gradient of its bedrock bottom (Wettstein 1885: 57 f., Fig. 2 is a summary of his findings). This trough was subsequently filled during the last glaciation with gravel and moraines (between Baden and Zurich) and water masses now forming the lake (between Zurich and Hurden).

It took three further years that Albert Heim for the first time spoke to a public audience about the «lake-problem» (public lecture in 1888, see Heim 1890). Undoubtedly did he exert considerable influence on his scholar Wettstein but it nevertheless seems that he worked out his theory about Lake Zurich after Wettstein finished his studies (even though Heim [1885: 398] identified dislocations earlier as a possible mechanism to account for lakes, a view also shared by Rütimeyer [1869]).

Heim (1890, 1891: 477-479,1894) brought a new element into the discussion: the prominent natural terraces (Fig. 5) which accompany the shores of Lake Zurich and which he thought to represent former levels of the fluvial Linth valley before the Ice Age(s) and the development of Lake Zurich. Continued and intermittent uplift of the Alpine orogen forced the Linth river repeatedly to incise his bed and thus to create terraces. After the final completion of crustal shortening across the Alps the whole mountain chain supposedly sank back some 300 m (*alpine Rücksenkung*: «Alpine back-sinking»; Heim 1919: 189 ff for a discussion of the nomenclature) and thus produced a flexure that skirts the mountains (*alpine Randflexur:* «Alpine marginal flexure»). As a direct consequence of this back-sinking the fluvial terraces which formerly dipped gently away from the Alps changed their gradients and are now dipping towards the Alps in the zone of the marginal flexure (*Gebiet der rückläufigen Terrassen:* «area of back-tilted terraces» in Fig. 1). Supposedly old (i.e. dating back to the first of the three then accepted Ice Ages) gravels lying today mostly on top of the Molasse mountains, so called Deckenschotter («cover gravels»), were also affected by this flexural movement and thus sank back by the same amount as the terraces (gravel masses around Wädenswil, Sihl- and Lorzetobel, Baarburg etc., cf. Fig. 1, 3).

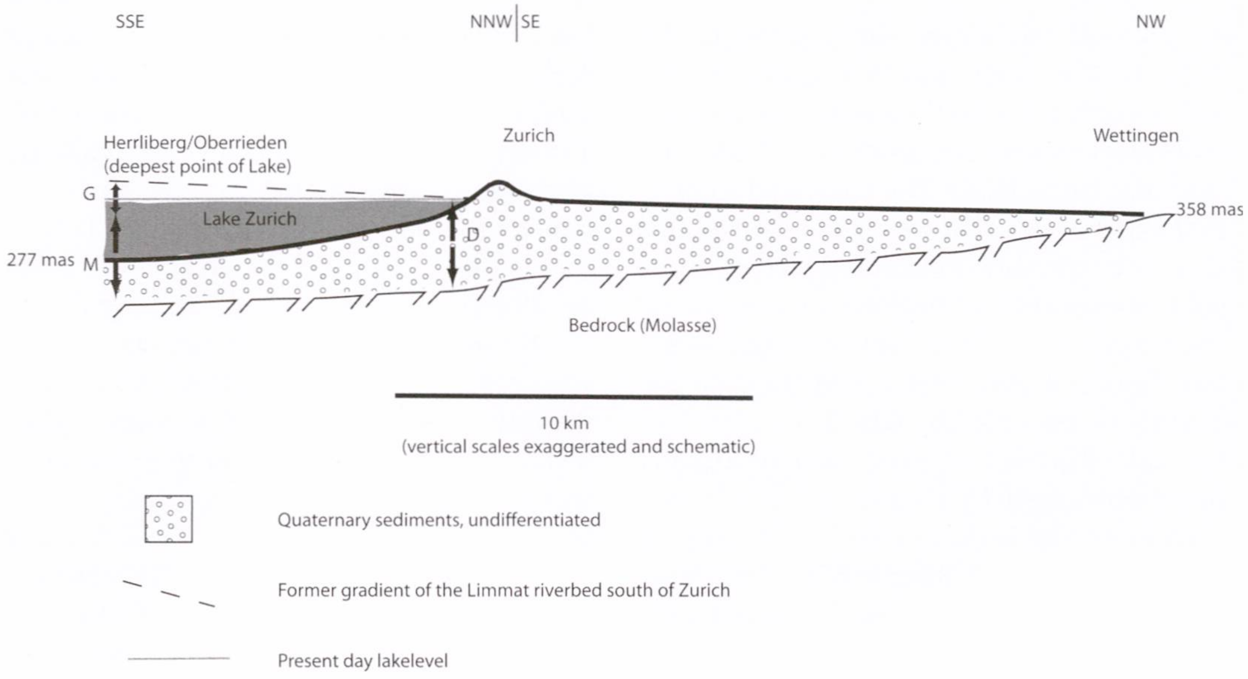


Fig. 2: Summary of Wettstein's (1885: 57 f) knowledge of the overdeepening of Lake Zurich basin. G: the necessary original slope of the Limmat riverbed between Herrliberg und Baden (Wettingen) which amounts to at least 50 m according to Wettstein; M: rise of the Molasse bedrock surface between the deepest point of the lake and Wettingen (= 92 m [358 masl-266 masl] + thickness of Quaternary sediments; 99 m + thickness of Quaternary sediments according to Escher's earlier estimate; see text); D: thickness of Quaternary sediments at the Lake outlet near Zurich (at least 40 m according to Wettstein; according to a drill in 1970 [Schindler 1971: 286] more than 210 m). The whole amount of tectonic tilt between Herrliberg and Wettingen is thus G + M.

4.2 Culmination of the controversy (1894 to 1912): the alleged back-tilted «Deckenschotter» between Lake Zurich and Lake Zug

Heim's student August Aeppli (1894) was sent out to substantiate his teacher's speculations concerning the huge gravel and moraine masses between Lake Zurich and Lake Zug through rigorous mapping. Aeppli's findings indeed confirmed Heim's model: most of the well cemented gravel masses cropping out along the courses of the rivers Sihl and Lorze in the area under consideration were considered to be of high age and to once have belonged to an extensive and tabular gravel layer that continued into the Deckenschotter on the Albis mountain (cf. the tables in Aeppli 1894 and our Fig. 1, 3). After deposition of this Deckenschotter sheet during the first glaciation but before the last and probably also before the penultimate glaciation this gravel sheet was deformed due to the Alpine marginal flexure: the proximal parts of it sank back by some 300 m and form now the gravel covers of e.g. the Baarburg near Sihlbrugg and the gravel outcrops along the Lorze river (Fig. 3b).
The supposedly high age of these gravels and the assumption of basically one extensive gravel sheet were heavily criticized by Brückner during the first decade of the 20th century (Penck & Brückner 1909), then Professor at Bern University. Penck and Brückner (Fig. 4) undoubtedly rank among the most influential German Quaternary geologists and physical geographers of the late 19th and early 20th centuries. They defined the classic tetra-partition of Alpine Ice Ages (Günz, Mindel, Riss and Würm) and were

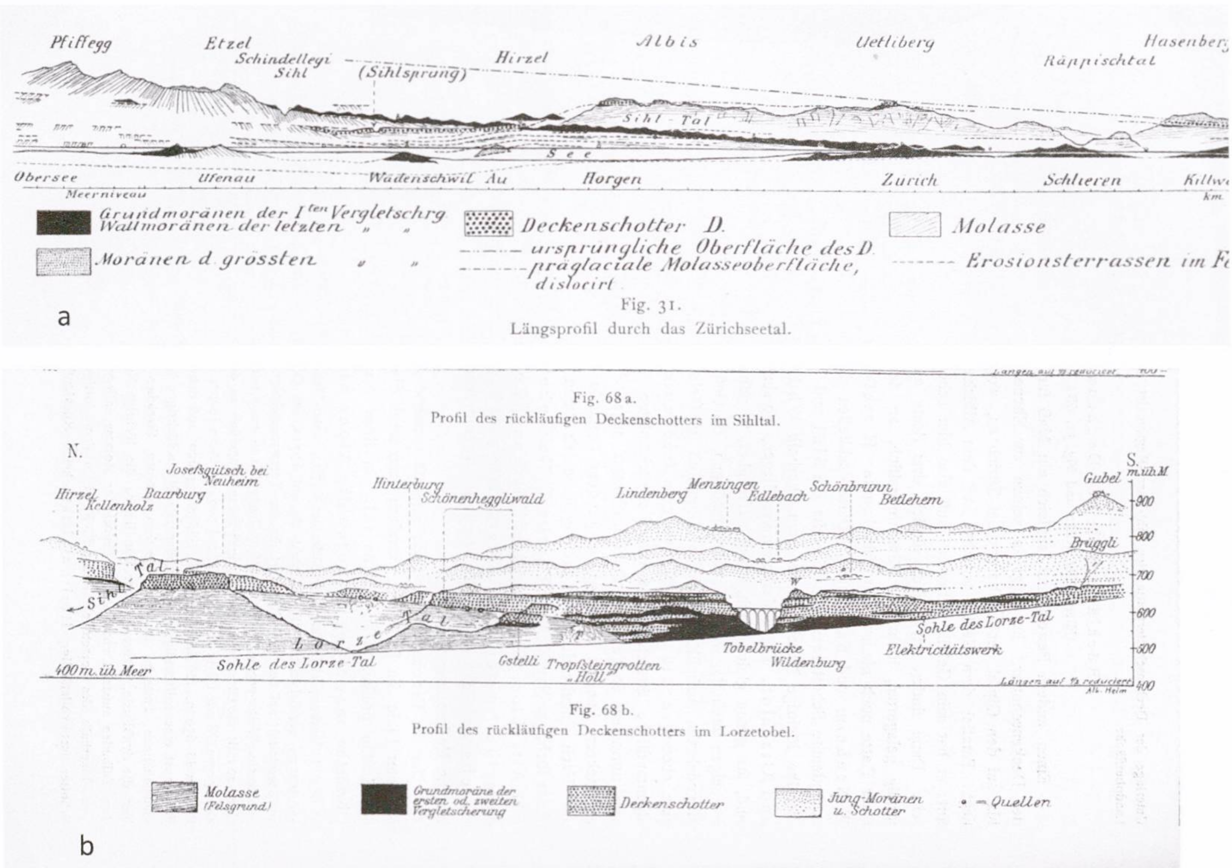
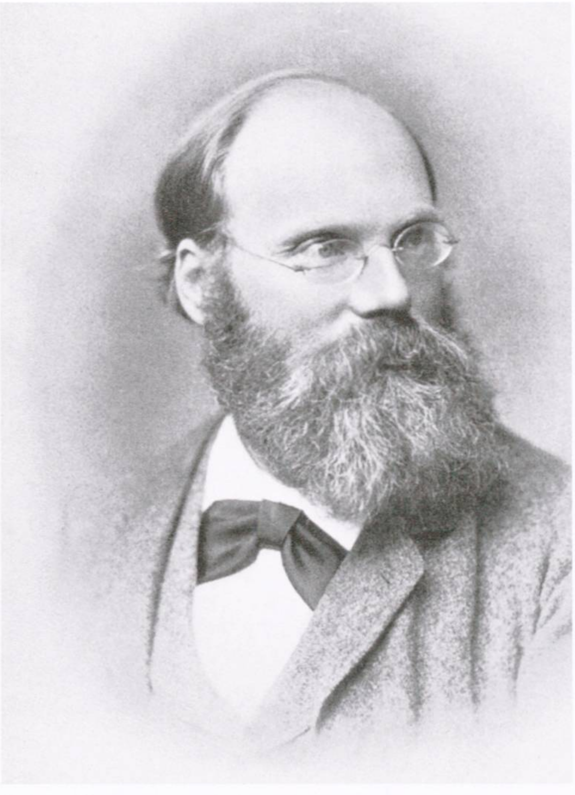


Fig. 3: [a] Length profile of Lake Zurich valley illustrating Heim's theory of alpine back-sinking. The supposedly old *Deckenschotter* were thus moved vertically downwards by some 300 m in the area between Hirzel and Schindellegi. [b] geological profile through the area of allegedly back-tilted *Deckenschotter* (profile trace see Fig. 1). Both figures are from Heim (1919: 408).

strong supporters of an important role played by the glaciers in valley building. As far as the latter point is concerned, the two stood in great opposition to almost the whole Swiss geologist establishment of that time (chap. 3). Heim's theory of a Quaternary alpine back-sinking had been clearly established to account for deep and inverted valleys without invoking glacial erosion. His two main field arguments to support this mechanically very unsound hypothesis were the inverted terraces (chap. 4.1, 4.3) and the back-tilted Deckenschotter just mentioned. Thus it seemed necessary to Brückner to study them. According to him the main masses of these gravels along the Lorze and the Sihl were of young age and were deposited between the Linth glacier in the east and the Reuss glacier in the west during a temporary glacier retreat phase of the last glaciation (*Laufen-Schwankung* of the Würm Ice Age; cf. Penck & Brückner 1909: 505-514). Some of the slightly higher lying gravels of the area (mainly the Baarburg gravel) were probably deposited by a similar mechanism during the penultimate (the Riss) glaciation. Brückner's views were again criticized by yet another pupil of Heim's, Gogarten (1910: 25-27). The tone in this dispute had by then become very polemic; however one very important point was made by Gogarten (1910: 26): the ages assigned to certain gravel bodies are very subjective and hardly possess any credibility. Nevertheless, close mapping of the geometry of individual gravel bodies, its gravel composition, the state of weathering of its crystalline pebbles and the geometric rela-



a

b

Fig. 4: The three main protagonists of the glacial erosion controversy around the turn of the century: [a] Albert Heim (photography made during the 1880s; from Brockmann-Jerosch 1952: plate 6); [b] Albrecht Penck (right) and Eduard Brückner while doing fieldwork in Flims in 1893 (picture is reproduced from Büdel 1977).

tionships among them and to interbedded till layers can provide hints to their relative ages. Exactly this procedure was followed by Roman Frei in his monumental and excellent PhD-thesis (Frei 1912) on the Swiss *Deckenschotter*. As he also was a student of Heim's, he was of course obliged also to study the supposed *Deckenschotter* between Lake Zurich and Lake Zug. Astonishingly, he came to views which differed from his teacher's model: he denied a connection between the high lying old gravels on the Albis (which undoubtedly are *Deckenschotter*) and the gravel masses along the Sihl and Lorze. Additionally he split the latter gravels into two systems – as Brückner had done. However he assigned slightly different ages to these two systems: the older and higher system (to which the Baarburg gravel belongs) was deposited during a glaciation before the penultimate, and the younger system cropping out along the Sihl and Lorze during the penultimate (Riss).

Despite Frei's (1912) impressive and very rigorous piece of work, his teacher Heim adhered to his original age designations after he had repeatedly visited the area under consideration in 1913 (e.g. Heim in Frei 1914: 6, Heim 1919: 191, 410). In March 1914 Frei died of typhus at the age of 26 while working as a petroleum geologist in Borneo. With this young and very productive man – who was also heavily appreciated by Heim despite their scientific differences – Penck and Brückner lost their strongest Swiss supporter of their criticism of Heim's *Rücksenkungstheorie* and the associated age model for the gravel masses between the Lakes of Zurich and Zug.

To close this discussion on the ages of these gravels it should be added that more recent workers were inclined to follow Brückner and Frei, and not Heim and his scholars in their age designations. Ottiger et al. (1990) adduced an Early Last-glacial age to the gravels along the Sihl and the Lorze and a Penultimate-glacial («Riss») age to the topographically higher gravels of the Baarburg. Wyssling (2002) and Gubler (2009) identified a Middle Pleistocene age for both of these gravel complexes.

4.3 River terraces or forms of glacial erosion?

The characteristic terraces that shape and structure the slopes of Lake Zurich have already been mentioned above. Today they have mostly lost their sharp contours due to the intense urbanization in the suburbs of Zurich, but still some hundred years ago these terraces determined the regional topography and also structured and controlled settlements and agriculture. Settlements were thus built on the flat parts of the terraces (the treads) and the steep slopes connecting one tread with the next (the risers) were used as vineyards (Fig. 5), according to the old saying: «*Wo der Pflug kann gahn, soll die Rebe nicht stahn*» (Where the plough can go, the wine shall not stay).

Albert Heim and his followers (Wettstein 1885, Aeppli 1894, Gogarten 1910) regarded basically all these terraces as remnants of ancient valley floors: the terraces were supposedly shaped by rivers which alternately widened their bed or entrenched their bed as a function of intermittent uplift of the bedrock (chap. 4.1). Penck & Brückner (1909) questioned this model and instead argued that (most of) these terraces merely follow more resistive layers in the bedrock (i.e. the Molasse which is mainly composed of mudstones, sandstones and subordinate conglomerates) which were shaped by the glaciers during the four glaciations. A sharp, very polemic and often somewhat tedious counterattack to this inference came from Gogarten (1910) and Heim (1919). Without going too much into the details of this debate on the origin of the terraces of Lake Zurich, it shall suffice to point out that a clear decision between these two competing theories would only have been possible with a better knowledge of the geology of the underlying Molasse and especially its structure. As this knowledge only became available some 40 years later (chap. 4.4), it was easy for both sides of this debate to strain the scant field evidence in order to fit it into their preferred model. This was even easier for Heim and his followers as the alleged relations between the bedding planes of the Molasse and the surfaces of the terraces (according to Penck and Brückner there should be no difference between these two kind of planes) were assumed to be quite complicated and to depend on two poorly known factors: the original inclinations of the terrace surfaces and the Molasse layers (Fig. 6). The final decision in this debate was only to come in the 1950s and 1960s as shall be shown in the following.

4.4 Decline and death of a hypothesis: from 1912 to 1964

In the three decades following Heim's last and rigorous statement of his theories concerning the origin of Lake Zurich, the backsinking of the Alps and the origin of the terraces fringing Lake Zurich (Heim 1919), Swiss geologists were divided into those adhering to Heim's ideas – some strictly, others rather reluctantly – (e.g. Weber 1934, Staub 1938, Suter 1939, von Moos 1946, Stein

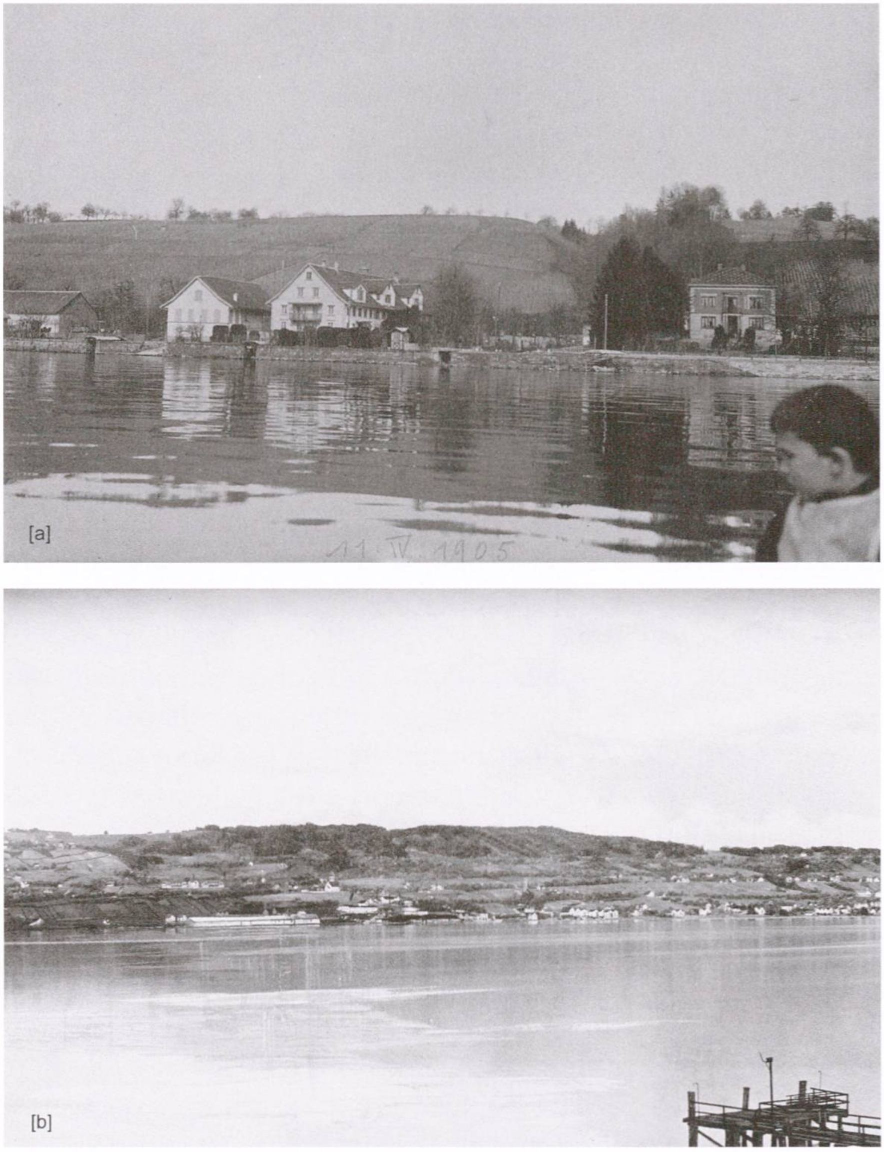


Fig. 5: Early 20th century illustrations of the natural terraces sculpturing the slopes of Lake Zurich basin. [a] moraine covered bedrock terrace between Zollikon and Küsnacht. Photograph made by the geologist Emil Letsch in 1905. The boy in the right corner is the present author's grandfather. [b] bedrock terraces with almost no Quaternary cover between Meilen and Männedorf (from Penck & Brückner 1909: 518–519).

1948) and those rejecting them right away or at least seriously questioning some of them (e.g. Früh 1919, Beck 1933, Zingg 1934, Renz 1937, Speck 1946). A major advance in this controversy was only achieved when Nazario Pavoni carried out meticulous stratigraphic studies in the Molasse around Lake Zurich (Pavoni 1952, 1957). Mapping out marker beds in the bedrock (mainly freshwater limestone layers, some bentonites and peculiar conglomerate and sandstone layers) he could determine the internal tectonic structure of the bedrock. Thus he could convincingly demonstrate (Pavoni 1953, 1956) that Heim's «river terraces» indeed follow exactly the structures of the Molasse and hence can only be considered as true layer terraces (*Schichtterrassen*) as already suspected by Penck & Brückner (1909). Ringger (1964) gave additional evi-

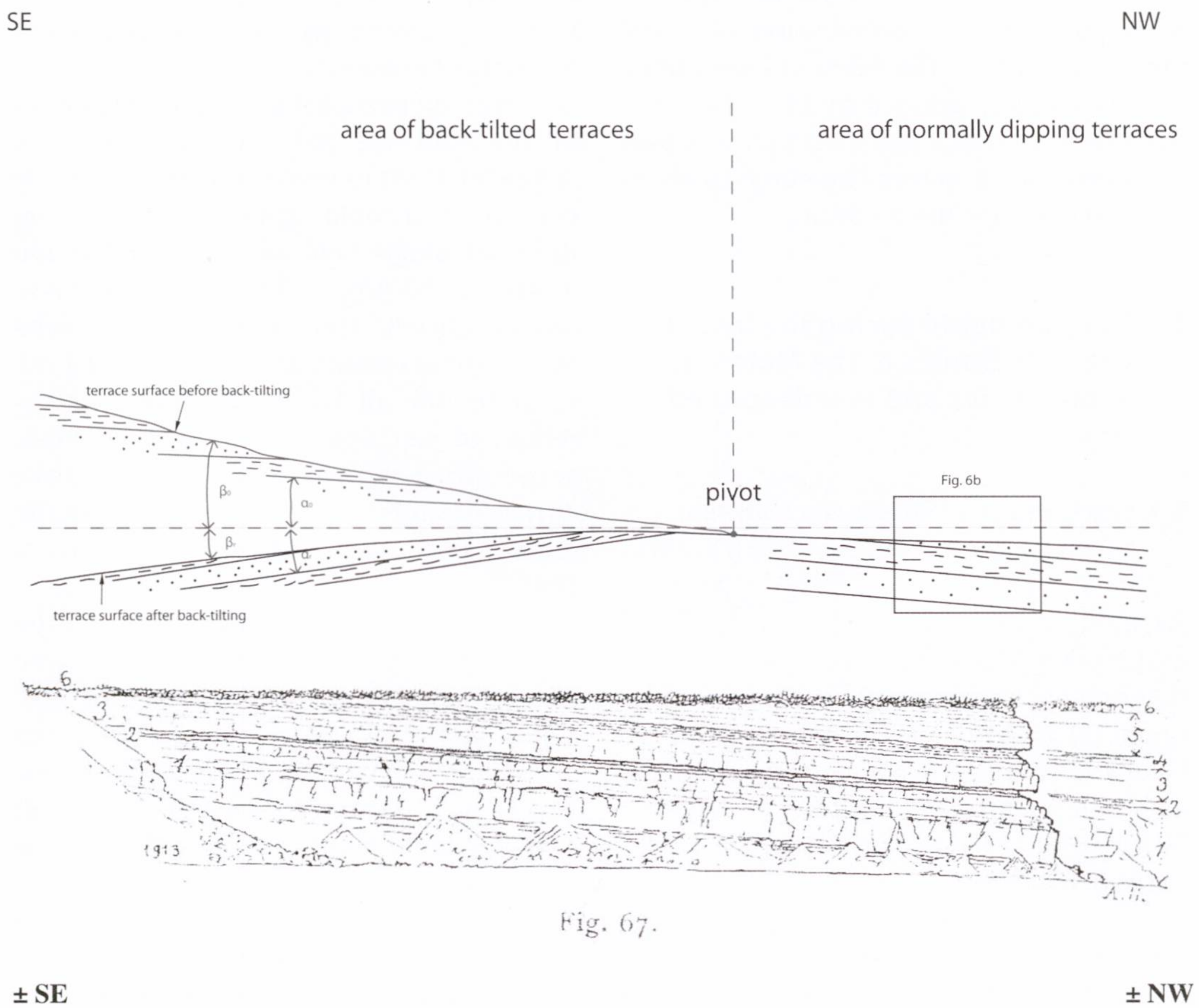


Fig. 6: [a] Theoretical geometrical relations (not absolutely to scale) between the layers of the Molasse and the terrace surfaces in the area of the back-tilted terraces according to Heim's descriptions (1919: 191). α_0: original slope (i.e. before Alpine back-sinking) of the Molasse layers towards the NW (3° to 4°); α_r: recent slope of the Molasse layers towards the SE (5° to 8°); β_0: original slope of the terrace surfaces towards the NW; β_r: recent slope of the terrace surfaces towards the SE. [b] Sketch of a famous outcrop (Horgen Allmend; from Heim 1919: Fig. 67) which shows a terrace surface (Nr. 6) crosscutting different Molasse layers (Nr. 1–5) in the area to the NW of the back tilted terraces (area in the box in Fig. 6a). Heim used this outcrop as an argument to disprove Brückner's conjecture that the terraces follow Molasse layers. And indeed have later workers confirmed this particular example (e.g. Ringger 1964: 63–65) even though Ringger generally disagreed with Heim. This outcrop, situated outside the area of the allegedly back-tilted terraces, can be considered as an example for the layer-terrace relationships before the Alpine back-sinking.

dence to this conjecture in his geomorphological study of the Lake Zurich terraces. His study also showed that some quite prominent terraces – as e.g. the one from Zollikon shown in Fig. 5 – are not at all pure and sharp-edged bedrock terraces but merely somewhat flatter parts of the bedrock relief with a terrace-shaped moraine cover on top. All this can be considered as the final piece of evidence against Heim's theory of an Alpine back-sinking in Quaternary times. However, neotectonic movements and a possibly considerable contribution of fluvial erosion in shaping the valley of Lake Zurich were not at all excluded by these findings, even though little if any attention was paid to neotectonics before the early 1970s as shall be shown in the following.

5 Developments during the last 50 years: tectonics of the Molasse, neotectonics and overdeepened troughs

5.1 Fractures and faults in the Molasse: a tectonic control of Lake Zurich basin?

As already pointed out (chap. 2, 3) the assumption of important tectonic fractures determining location and probably also the depth (in a sort of a tectonic graben) of the Lake Zurich basin (and many other basins and valleys as well) was quite common in Switzerland around 1850. In the years after 1870 such alleged (and in fact never directly observed) fractures became very unpopular due to the increasing influence of Albert Heim who generally downplayed the importance of brittle deformation (e.g. Heim 1878). With the notable exception of Rothpletz (e.g. 1894: 8–23; cf. also the remarks in Gogarten 1910: 16) the influence of brittle tectonics on location and development of the Lake Zurich basin was not seriously considered until the early 1930s (Staub 1934: 86 and 1951: plate 4) despite the cautious hint by the most influential geologist of the nineteenth century, Sir Charles Lyell (1863: 317). Following conspicuous marker horizons in the Molasse (chap. 4.4) Staub's pupils Pavoni (1952, 1957) and Büchi (1958) postulated a multitude of normal faults (with vertical slip amounts of up to 150 m [Pavoni 1957: 278]) which seemed to determine the general course of the Lake Zurich basin. These findings were enthusiastically taken up by René Hantke (e.g. Suter & Hantke 1962, Hantke et al. 1967, Hantke 1991, Hantke & Scheidegger 1997) in order to account for valley formation without invoking great amounts of erosion.

However, more recent stratigraphic studies in the Molasse led Pavoni (Pavoni & Schindler 1981) to revise his earlier tectonic conception. It could e.g. be shown that more than one single bentonite marker horizon exists in the Upper Freshwater Molasse around Zurich. Thus, many normal faults became unnecessary as it was no longer difficult to link all known bentonite occurrences to just one horizon. Nevertheless, active strike-slip folding beneath the Lake Zurich basin is indeed taking place as the recent seismicity suggests (e.g. Pavoni 1987).

To sum up, a direct tectonic control of the Lake Zurich basin in form of a tectonic graben is definitely not supported by geological and geophysical evidence. However it seems reasonable to assume that minor strike-slip faults (e.g. Hsü & Kelts 1970: 528) helped to determine the position of the present day lake basin.

5.2 Recent crustal movements: earthquakes, precise leveling and deformed gravel terraces confirm active neotectonics but disprove Heim's «Alpine backsinking theory»

In the late 1940s and 1950s the awareness of Quaternary and even of recent movements of the Earth's crust in Switzerland was rather limited, at least at the Geological Institute in Zurich (Pavoni, personal communication 2012 [However, it should be mentioned that Rudolf Staub, then Professor of Geology in Zurich and Director of the Institute, was of the opinion, that recent tectonic (i.e. not only isostatic) movements still continued in the Alps (e.g. Staub 1934: 177). Faults of Late Quaternary age were then indeed found and studied by Jäckli (1951) and Eckardt (1957) in the external crystalline massifs (i.e. Aar, Gotthard and Tavetsch massifs). However, as suspected already by Eckardt (1957: 87) and later supported by finite-element modeling (Ustaszewski et al. 2008), movement along these faults may be due to the last deglaciation, i.e. at least some of these movements are glacio-isostatic (see also Hantke 1978: 394]). The Alps were basically considered as a finished tectonic edifice which merely experienced some isostatic uplift. The reasons for this attitude are not totally clear. Maybe it was the still to be felt influence of Albert Heim (passed away in 1937) who considered the horizontal contraction that built the Alps to have ceased already in pre-Quaternary times. Additionally the then still very popular concept of the highly influential German geologist Hans Stille (1924), that orogenic movements occur in supposedly short-lived and globally synchronous phases which were interrupted by longer lasting periods of tectonic quiescence (with the Holocene being such an «un-orogenic» episode; Stille 1924: 22) may have attributed to this neglect of recent movements even though Stille's scheme was not taken equally serious in Western Europe as e.g. in Eastern Europe (Trümpy 1973: 229 and personal communication 2008). Apart from these more theoretical and even to some extent ideological reasons (see also Bourcart 1955: 35, Wegmann 1955: 7) it was merely the lack of technical devices to measure horizontal movements as accurate as today by means of GPS that may have caused this disinterest. However, contrary to horizontal movements, vertical movements could be measured quite well by that time by means of repeated precision leveling campaigns which had been carried out in Switzerland as early as in 1893–1903 (e.g. Schaer & Jeanrichard 1974, Jeanrichard 1975, Gubler 1976). Despite this excellent and growing data set it took until 1971 that the geological significance of these measurements began to be appreciated and studied by the newly founded working group «Rezente Krustenbewegungen» under the leadership of Nazario Pavoni (cf. Eckardt 1974, Pavoni 1979). Robust features of these measurements were the recognition that the Alps are still uplifted by the order of magnitude of 1 mm per year compared to the foreland (zero point of the Swiss leveling grid in Aarburg) and that the uplift pattern is displaced relative to the present day topography with the zone of maximum uplift lying some 50 km to the south of the crest of the Alps (Gubler et al. 1981, Gansser 1982). Even though a glacio-isostatic contribution to this recent uplift could not be totally excluded, theoretical considerations, good agreement between the geodetically and geothermochronologically determined (i.e. long term) uplift rates and the correspondence between uplift patterns, gravity anomalies and the recent crustal stress field as determined by earthquakes, led Schaer & Jeanrichard (1974), Schaer et al. (1975), and Pavoni (1979) to attribute the recent uplift to ongoing horizontal contraction orthogonal to the Eastern and Central Swiss Alps in a NNW-SSE direction.

These geodetic efforts starting during the 1970s did not confirm Heim's theory of a Quaternary back-sinking of the Alps but, on the contrary, gave support to Penck and Brückner's conjectures (1909: 463) that uplift rates steadily increase when approaching the Alps from their northern foreland (see also Hantke 1959: 19). However, at that time Heim's theory had been become obsolete anyway (chap. 4.4). On the other hand some interesting inferences can be drawn from the recent crustal uplift rates which bear also to the origin of Lake Zurich.

It could be shown e.g. that the eastern Folded Jura is still uplifting relative to the northernmost part of the Molasse basin, as it has been hypothesized by Escher (Escher & Bürkli 1871) and suggested by Wettstein (1885), to account for the inverse gradient of the bedrock of the Limmat valley between Zurich and Baden (chap. 4.1, Fig. 2). The same uplift pattern could also be deduced from the study of gravel terraces and the regional pattern of fluviatile bed-rock erosion (Haldimann et al. 1984, Haldimann 1987), yielding uplift rates astonishingly similar to the geodetically determined ones (Müller et al. 2002: 70). Another very interesting observation is the congruence between the regional tectonic structure of the Molasse surrounding Lake Zurich with its very gentle folds (Pavoni 1957) and the recent uplift rates (Müller et al. 2002: 90–91). Thus these fold structures seem indeed to be actively growing as it has been hypothesized already by Hsü & Kelts (1970: 531) based on their seismic investigation of Lake Zurich.

5.3 The detection of sediment filled overdeepened troughs and seismic investigations of Lake Zurich

Apart from the tectonic structure of the Molasse and neotectonics, two other fields of research have produced evidence which has proved highly relevant also for the question of the origin of Lake Zurich. Firstly, increasing commercial drilling activities (mostly for engineering and hydrogeological purposes) in the Alpine foreland have demonstrated the existence of deep and also overdeepened (i.e. with an inverse gradient of the bedrock) troughs and basins incising into the Molasse which have been subsequently refilled by mainly glaciolacustrine sediments (e.g. Wyssling & Wyssling 1978, Haldimann 1978, Schlüchter 1979, Freimoser & Locher 1980, Wildi 1984, Pugin 1988 and Jordan 2010). These troughs do not only occur in Heim's zone of alleged back-sinking but also far away from the Alps; thus they lend additional support to the improbability that tectonics (at least as the only agent) play a direct role in the formation of overdeepened valleys. Secondly, close study of the subsurface of Lake Zurich and the Limmat valley by seismic methods and direct drilling (e.g. Hsü & Kelts 1970, Schindler 1968, 1974, 1976, Finck et al. 1984, Hsü & Kelts 1984) has revealed a much bigger and aerially more expanded overdeepening as the one accepted and explained by Heim's theory of alpine back-sinking. Indeed, there is basically one big overdeepened trough in the Linth-Lake Zurich-Limmat valley extending from the Linth plain, where this river leaves the Alps, to the first bedrock contact of the river bed at Wettingen (Fig. 1).

5.4 Some final remarks on changing theories, enduring hard facts, and one robust concept in Swiss Quaternary geology

As pointed out at the beginning of this historical survey we do not enter the ongoing discussions on valley building during the Quaternary (e.g. Herman et al. 2011 for a recent approach to model glacial erosion). However it is tempting to look into the history of science in general and in the history of geology in particular for enduring hard facts and robust concepts, i.e. observations and mental conceptions which remain somehow fixed even though measuring techniques, theoretical assumptions, models, and even paradigms and methodologies may change. If we do this for the particular case of the origin of Lake Zurich basin and other valleys of the alpine foreland we find indeed some interesting features. One of these shall finally be described in the following.
There is remarkable agreement that the last glaciations(s) were not of an erosive but rather an accumulative nature. This inference can already be seen when reading Arnold Escher's works around the centre of

the 19th century: he made his point quite clear that the lake basin of Lake Zurich existed before the (one and only then known or accepted) glaciation (Escher 1844: 168). The basin owed its existence according to Escher due to one or more enormous floods in pre-glacial times. During the glaciations the same basin was partly re-filled by glacial debris including the famous erratic boulders. Thus he distinguished an earlier erosive and a later accumulative «event». Quite a similar pattern – even though in a different overall concept – was assumed by Heim (e.g. 1919: 277–279). According to him the main episode of valley building in the Swiss plain occurred in the penultimate interglacial (*die grosse Interglacialzeit* which corresponds to the *Mindel-Riss-Interglacial* of Penck and Brückner 1909) by means of fluvial erosion. Also during this interglacial the main part of the alleged back-sinking of the Alps (chap. 4.1) took place (e.g. Heim 1919: 405). Later glaciations were instead merely assumed to be of an accumulative nature. Surprisingly this division between an older, mostly erosive and a younger, mostly accumulative period during the Quaternary is also found in the more recent literature. Schlüchter (e.g. 1975: 80, 1981, 1987, Schlüchter & Kelly 2000) repeatedly pointed out his belief that at some time in the Middle Pleistocene a morphological or maybe also a tectonic «event» (*Morphologisches oder tektonisches Ereignis, mittelpleistozäne Wende*) took place which changed the overall geological setting from a mainly erosive to a dominantly depositing one (see also Haldimann 2007).

We could add and discuss some other such robust concepts which withstood the change of time (as e.g. the existence of overdeepened valleys as already described by Wettstein 1885, or the assumption of pre-Quaternary fluvial precursors of our modern valleys), however it seems a good opportunity to close this historical enterprise with a famous sentence made by Albert Heim some 130 years ago which seems to have proved correct even though not in the sense as Heim anticipated it: «*denn einen langen Athem hat die Wahrheit.*» (as the truth has a long breath).

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