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On the pre-history of the turbidite concept: an Alpine perspective on occasion of the 70th anniversary of Kuenen's 1948 landmark talk

Dominik Letsch[1]

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Abstract

The recognition of turbidity currents as an important geological agent of sediment transport, sedimentation, and erosion 70 years ago, initiated a bonanza in clastic sedimentology and led to new interpretations of both recent marine sediments and ancient sedimentary rocks. Only scarce attention had been paid to graded bedding, a hallmark of turbidites, before ca. 1930 and almost nobody had linked it to episodic mass flow sedimentation. This article is an addition to the pre-history of the turbidite revolution from an Alpine, and more specifically, a Swiss perspective. It focuses on two time periods, the early and middle part of the eighteenth century and the turn from the nineteenth to the twentieth century. In the former period, Swiss naturalists such as Scheuchzer and Gruner had not only recognized the ubiquity of graded bedding in some Alpine flysch successions, but also proposed hypotheses as to its likely origin. In doing so, Gruner invoked in 1773 periodic sediment mobilization due to bottom currents on the floor of an ante-diluvian sea, resulting in distinct episodes of sediment settling giving rise to normally graded layers. Gruner's model was inspired by several contemporaneous pioneers of experimental clastic sedimentology. This interest in physical sedimentology declined during the nineteenth century and it was only with the start of the second period discussed herein that geologists began to re-appreciate the importance of sediment movement at the bottom of the oceans. This time, inspiration came from the practical experience of Swiss geologists with shore collapse events and subsequent sedimentary mass flows in lakes. Building on that, they were able to better interpret parts of the Alpine sedimentary record, especially flysch successions. However, it was only with Bailey, Migliorini, Kuenen and others during the 1930s and 1940s that the link between mass flows and graded bedding was finally established.

Keywords Flysch · Wildflysch · Mass flow sedimentation · Eighteenth century geology · Turbidites · Limnogeology · History of sedimentology · Shore collapse · Applied geology

1 Introduction

70 years ago, on occasion of the 18th International Geological Congress held in Great Britain in summer 1948, a talk by the Dutch geologist Philip Henry Kuenen on *Turbidity currents of high density* (Kuenen 1950) initiated a fundamental change of thought in sedimentology, which has later been considered "[…] *the only true revolution in thought in this century about clastic rocks.*" (Walker 1973). Although other developments in sedimentary geology during later decades of the century may have proved the latter statement somewhat premature, the recognition that turbidity currents and related subaqueous sedimentary density, or mass flows (cf. Mulder and Alexander 2001 for general discussions on physical and terminological aspects) are important depositional agents, has changed the way geologists look at marine and lacustrine clastic rocks ever since (the "turbidite revolution"). From an Alpine perspective, the explanation of immature marine sandstones exhibiting graded bedding (so abundant in sedimentary successions traditionally referred to as flysch, Tercier 1947; Hsü 1970) as the products of turbidity currents (Kuenen

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✉ Dominik Letsch
dominikletsch@hotmail.com

[1] Guggerstrasse 39, 8702 Zollikon, Switzerland

and Migliorini 1950) had a profound impact on palaeogeographic and palaeotectonic interpretations (e.g. Trümpy 1983, 2003; Mutti et al. 2009). As shall be discussed later in more detail, the turbidite concept did not come out of a complete vacuum. A couple of late nineteenth and early twentieth century geologists had thought about graded sandstones and coarser grained mass flow deposits and their work is well-documented in several summary papers (e.g. Walker 1973; Mutti et al. 2009).

All these nineteenth and early twentieth century contributions have been formulated within the language of modern geology (see below for a discussion of this term) and may thus be viewed as the more recent pre-history of the turbidite concept. On the other hand, only scant information is available on even earlier attempts to explain graded bedding, except for Trümpy's (2003) remarks on Johann Jakob Scheuchzer's early mention of Alpine flysch deposits (see below). It is a primary goal of this article to present and discuss the ideas of the eighteenth century Swiss naturalist and lawyer Gottlieb Sigmund Gruner, who formulated a concise interpretation of an Alpine flysch succession in the Glarus Alps of Switzerland. Though rooted within a completely different tradition to see and interpret the physical world, Gruner's interpretation shows surprising similarities with the modern concept of sedimentation by means of turbidity currents. By placing Gruner's ideas into their mid-eighteenth century historic framework, it will emerge that his recognition of graded bedding and its interpretation were not due to an isolated stroke of genius but fitted well into an early eighteenth century research tradition embracing a kind of clastic proto-sedimentology. The interest in these matters got lost over the decades following the end of the *ancien régime*, to re-appear only towards the end of the nineteenth century, when Swiss geologists realized the importance of sub-lacustrine mass flow sedimentation in several Swiss lakes. It is a further goal of this article to document this second phase of research which, being initially driven by problems of applied geology, provided substantial inspiration for interpretation of Alpine flysch deposits. Interestingly, although these limnogeology pioneers clearly recognized turbidity currents *avant la lettre* as an important sediment dispersal mechanism, they failed to make the link to sandstones with graded bedding in the geological record. The last part of this article will therefore try to explain the extraordinary fact, that more than 150 years had elapsed between Gruner's early appreciation and interpretation of graded bedding and the turbidite revolution.

Before proceeding to Gruner and his eighteenth century geological background, we shall start with a short review of the few decades preceding the turbidite revolution. This will demonstrate that the formulation of the turbidite model demanded a substantial mental step, bridging the gap between field observations and an understanding of physical processes of mass flow sedimentation.

2 Observations on graded bedding before 1950: the long way to the turbidite model

Before the advent of the Kuenen-Migliorini hypothesis linking normally graded sandstone units with submarine turbidity flows (Kuenen and Migliorini 1950), only few geologists paid attention to graded bedding. Trümpy (1983), e.g., reported that prior to ca. 1950 almost no Swiss geologist knew how to tell sedimentary polarity within a flysch succession. However, this neglect was not an altogether complete one and the pre-1950 geological literature contains several "random" (Walker 1973) reports on graded bedding. The term itself had been introduced by Bailey (1930) and an even earlier American textbook on structural geology already mentioned the "[the] *common diminution in coarseness of beds from bottom toward the top* […] (Leith 1913, 132) without much further ado. According to his own testimony, Bailey had already realized the use of graded bedding as a way-up criterion in 1906 while doing fieldwork in western Scotland. While this may be the case, it still needed the input of a young American geologist (Thomas L. Tanton) some 20 years later on occasion of two Princeton-University fieldtrips (one across Canada and another to Bailey's beloved Scotland), to convince him of the use of truncated cross-bedding and even graded bedding as viable geopetal indicators (see Dott 2001). Be that as it may, Bailey's conversion and his subsequent praise of the new method in two widely read and cited publications (Bailey 1930, 1936) led to an increased awareness of graded bedding, at least in North America (Shrock 1948).

Apart from its practical use for defining polarity in strongly deformed Precambrian rock successions, Bailey (1930) also pointed out that current (i.e. cross) and graded bedding are attributes of two mutually exclusive sandstone facies, and he suggested the latter to be typical for sedimentary processes in deeper marine environments. Realizing that graded bedding demanded some sort of settling of sedimentary particles within the water column following an initial disturbance, he proposed earthquake-induced destabilization and submarine landslides of previously deposited sediment on coastal fringes. Daly (1936), being less concerned with sedimentary rocks in the field, postulated submarine muddy "density currents" (giving ample credit to earlier ideas based on observations in Lake Léman in Switzerland by Forel 1888) to account for submarine canyons offshore North America and Africa, but did not comment on the likely sedimentary deposits resulting from such currents. Bramlette and Bradley (1940) were the first to describe graded sand layers from Quaternary deep-marine sediment cores recovered from the floor of the North Atlantic. Seemingly independently of both Bailey and Daly, but citing Heim' (1908) fossil and recent Swiss examples of subaqueous slumps (see discussion in chapter 4 of this paper) as supporting evidence, they interpreted one of their turbidite samples as: "[…] *material thrown into suspension by a submarine slump, carried beyond the slide itself, and deposited rapidly. Material thus thrown into suspension would be expected to settle according to the respective settling velocities of the various constituents*." (Bramlette and Bradley 1940, 16). Three years later, while war between Allied and Axis forces raging on the Italian peninsula, the Italian mining engineer Carlo I. Migliorini published a very short but quite concise note (Migliorini 1943), wherein he suggested a new depositional process for the formation of marly and sandy formations of the Apennines. Since he assumed them to have been deposited far offshore, he was forced to offer a viable mechanism to transport coarser grained detritus into these otherwise supposedly rather muddy realms of the seafloor. Like Bailey (1930) or Bramlette and Bradley (1940), he linked them to initial slump or submarine sliding movements developing into a turbid plume: "*In submarine conditions, however, such a sliding cannot occur in the same manner as in dry conditions, because the mobilized material will mix with water and form a heavily loaded turbid plume. This flow will behave like a liquid denser than the ambient water and will proceed along the bottom up to where its slope will permit or the sediment load will be deposited along the way*." (Migliorini 1943, 49, using the translation by Ricci-Lucchi 2003). Remarkably, Migliorini did not refer to Bailey's pre-war publications and he also did not explicitly make the link from this depositional process to graded bedding.

Shortly after the war, Kuenen really boosted the turbidite revolution with his talk at the International Geological Congress in London in 1948 (Kuenen 1950). While his talk and the later paper were mostly concerned with questions of the physical character of density currents (for which he used for the first time the new term turbidity currents introduced by the US oceanographer D. Johnson in 1938, cited in Walker 1973) based on his experimental studies and citing Heim's examples from Swiss lakes (see below), he only shortly suggested a link to graded bedding: "*Many occurrences of graded bedding may be due to deposition from turbidity currents of high density when these have spread out to rest on basin floors, each bed resulting from a separate flow*." (Kuenen 1950, 52). A lucky by-product of Kuenen's 1948 talk was his acquaintance with Migliorini which brought together the experimental and physical expertise of the former with the latter's field experience. This ultimately resulted in their landmark joint publication *Turbidity currents as a cause of graded bedding* (Kuenen and Migliorini 1950) which laid the foundation for future articulations of the turbidite concept (Walker 1973).

What can be learnt from this short historical sketch of observations and explanations of graded bedding during the first half of the twentieth century is the fact, that there had been only very few people who really took an interest in or even remarked graded bedding before ca. 1950. This may seem astonishing to present-day geologists, being acquainted with the concept of turbidity currents from their early undergraduate days on. Obviously, it was only with a theory and a catchy name at hand that a larger group of geologists started observing the phenomenon (Trümpy 1983). The following presentation of Gottlieb Sigmund Gruner's observations and thoughts on an Alpine flysch succession in the Glarus Alps is intended to show that (likely theory-driven) observations of graded bedding were also made in the eighteenth century, although much fewer people were involved and the theoretical mindset of these researchers has been a completely different one.

3 Gottlieb Sigmund Gruner: marine bottom currents of the ante-diluvian Swiss Sea

Before discussing Gruner's remarkable thoughts on the origin of graded bedding in Alpine flysch successions of central Switzerland, it seems appropriate to put him and his ideas into the background of mid-eighteenth century naturalist research in central and western Europe.

3.1 Historical background

There is perhaps no better way to describe the fundamental change that thinking and writing about the Earth underwent during the last decades of the eighteenth and the first decades of the nineteenth century than Ellenberger's (1994, 318) observation, that a contemporary geologist without much historical knowledge, who attempts to read early to mid-eighteenth century texts on the Earth shall find himself lost in a foreign universe. Texts dating from let's say 1820 onwards, on the other hand, will generally be understood much more readily, despite the fact that geology has also made tremendous progress since that latter date. What makes the big difference between these two periods, which (perhaps not entirely by accident) are separated by the French Revolution and the two following decades of war in Europe, is not at all the formulation of a new overarching theory of the Earth, but rather the development of geology in the modern sense of the term. Apart from institutional and organizational aspects (such as the foundation of new universities, specialized societies, or specific scientific periodicals), it was the formulation of a common scientific language and nomenclature and the development of new techniques (especially geological mapping and biostratigraphy), that led to the consolidation of the science of modern geology (e.g. Studer 1863; Zittel 1899; Laudan 1987; Ellenberger 1994).

In the years between 1760 and 1773, when Gruner published his relevant contributions to the origin of Alpine flysch successions, these developments were still in the, albeit not so distant, future. With few and rather restricted exceptions (encompassing especially the central European mining industry with its rather practical outlook), there was neither an institutional framework nor the mental apparatus (including a generally agreed-upon nomenclature) available to pursue anything like the modern term geology would imply. On the other hand, there existed a widespread and vivid interest in questions concerning the structure and composition of the Earth's crust and ultimately also its history within circles of both theoretically and more practically interested naturalists and mining practitioners (with the two circles often overlapping in the German-speaking cultural sphere). Thus, while it would be anachronistically inappropriate to refer to these persons as geologists, their interests can arguably be described as geological from the present-day point of view. We shall hence use the latter term in the following in order to avoid tedious circumscriptions such as science of the Earth etc. (see e.g. Eyles 1969; Rappaport 1969, 1997; Fischer 1973; or Laudan 1987 for general discussions of geological knowledge and thought during different parts of the eighteenth century).

As it is beyond the scope of this article to give a detailed account of eighteenth century geological research, we shall only briefly mention some key concepts and ideas, and the men who formulated them, which were relevant for Gruner. One of the most prominent ideas of his time undoubtedly was the Great Flood or Deluge, which was generally regarded (at least during the first half of the century) as a historical fact and as a kind of an anchor point for further geological and also historical studies (Rappaport 1978; Ellenberger 1994). Opinion was divided on the question of how exactly to interpret the Biblical record (global versus local flooding) and how to explain the Deluge within the framework of Newtonian physics (strictly physical approaches versus the intervention of miracles). Two of the most prominent European diluvialists, John Woodward (1723, first published 1695) and Johann Jakob Scheuchzer (e.g. 1716), argued for a global devastating event, being responsible not only for the deposition of almost all rocks of the Earth's outer crust, but also for the formation of valleys and mountains (Fischer 1973). These extreme approaches temporarily found many adherents but perhaps even more critics, and gradually the inferred importance of the Deluge as a geological agent has been diminished or even questioned during the first half of the century. The deposition of large stacks of finely bedded sediments, often containing well-preserved traces of ancient marine and terrestrial life, demanded a long-standing and generally quiet body of water; an inference which did not fit well with a turbulent global flood. This long-standing body of water was either envisaged as an "ante-diluvian" sea of restricted extent, or as a once global but since then gradually diminishing ocean. The latter group of theories, which later became to be called neptunic, were made popular by two famous and equally contentious books, de Buffon's 1749 *Théorie de la terre* (see e.g. Roger 1995) and de Maillet's notorious 1748 *Telliamed* (Carozzi 1969). Both these grand theories actually ignored the Deluge as a geologically effective agent.

A prominent Swiss critic of diluvianism à la Woodward and Scheuchzer was Johann Georg Sulzer (Carozzi and Carozzi 1987), who reedited Scheuchzer's *Naturgeschichte des Schweizerlandes* (Scheuchzer 1716–1718) in 1746. Therein and in later articles and books he rejected the notion of one great flood and instead inferred numerous and more local inundations to account for layered sedimentary rocks. He also developed the theory that the catastrophic emptying of hanging lakes in high mountainous areas (such as the Alps) could account for major floods and deposition of great quantities of debris in the lowlands (Carozzi and Carozzi 1987; Ellenberger 1994). This highly original and fruitful conjecture has been re-discovered by later generations of geologists in Switzerland and elsewhere and lake-outburst floods, being either deduced from the geological/geomorphological record or actually observed, have become recognized as an important geological agent (e.g. Escher 1822; Bretz 1923; Wegmann 1935; Baker 1978; Bürgisser et al. 1982; Clague and Evans 2000; Letsch 2018). Sulzer, while denying the catastrophe of a global Deluge, hence provided an elegant kind of small-scale catastrophism to account for deposition of poorly sorted surficial debris. With this remark we shall close this short *tour d'horizon* of mid-eighteenth century geological research and turn to the person and ideas of Gottlieb Sigmund Gruner.

3.2 Gottlieb Sigmund Gruner: life and work

Gottlieb Sigmund Gruner (1717–1778) was born near Burgdorf, a small town some 15 km NE of Bern, as the son of the local protestant dean. After visiting Latin school in his native Burgdorf and law studies in Bern he was promoted a notary in 1739. The following decade he spent at several central German courts, taking different positions such as actuary of the count of Hessen-Homburg, and thereby got firsthand knowledge of major parts of Prussia and Silesia on extended trips (Studer 1863; Heitzmann

2008). From 1749 onwards, he again lived in the Canton of Bern and earned his living as a law clerk and lawyer in the wider Burgdorf area. According to Studer's judicious judgement in his almost encyclopedic *Geschichte der physischen Geographie der Schweiz bis 1815* (Studer 1863), Gruner, even though predominantly relying on second-hand information gathered through extensive correspondence with local clergymen and other savants, made important, carefully weighted, and often quite detailed contributions to the general knowledge of Switzerland's natural history. This latter term is used here in its old sense and encompasses a multitude of mostly descriptive knowledge on topics as varied as topography, hydrology (especially mineral springs), glaciers, or the occurrence of "fossils" (used in the broad old sense of the term including remains of ancient organisms, minerals, or rocks).

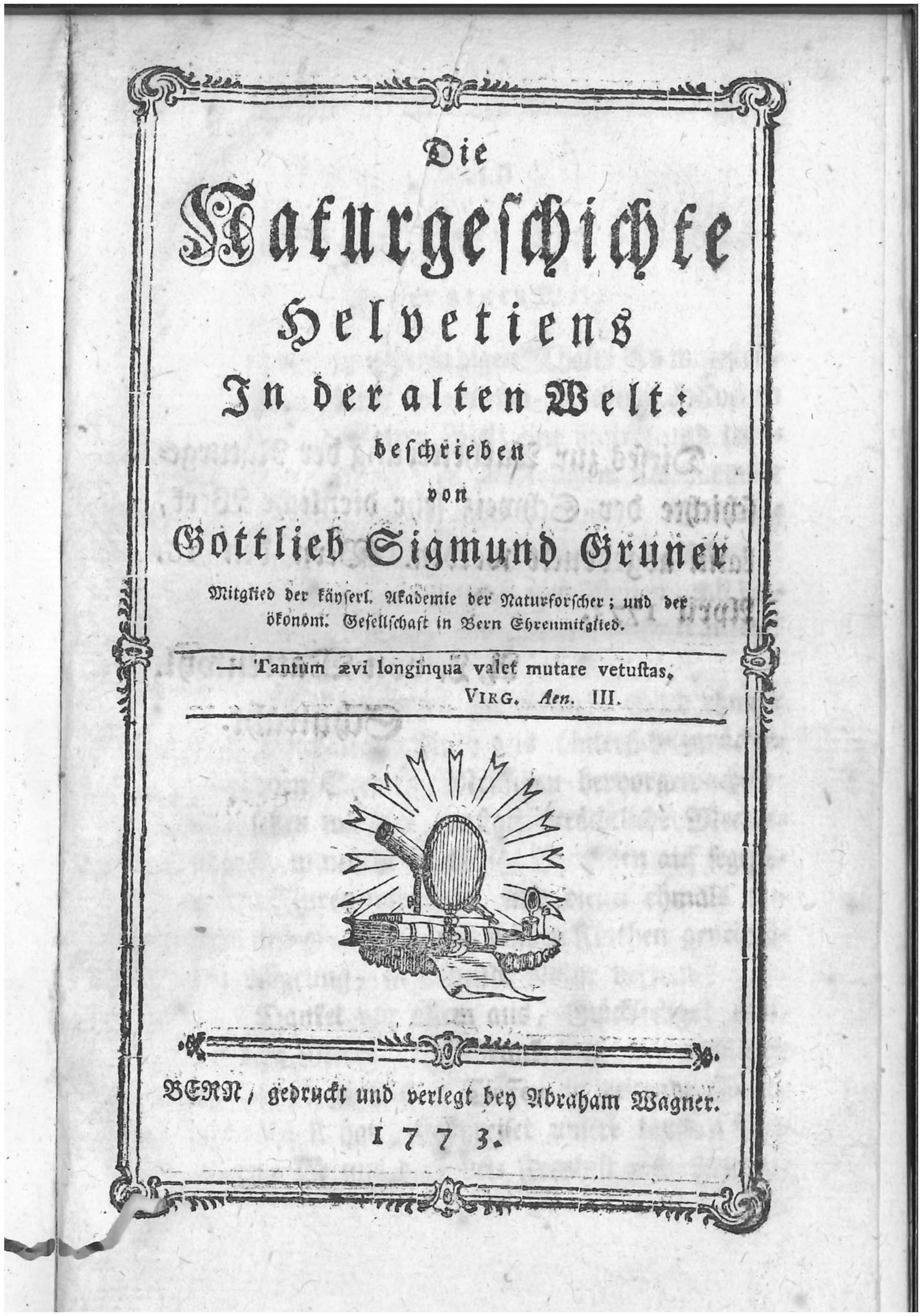
Gruner's magnum opus, *Die Eisgebirge des Schweizerlandes* (*The ice-covered mountains of Switzerland*, Gruner Gruner 1760a, b) in three volumes, is mainly a topographic description of major parts of the then only rudimentary mapped Swiss Alps and surrounding areas. It is accompanied by numerous beautiful, though heavily exaggerated and schematic, woodcuts depicting Alpine sceneries and several maps indicating the occurrences of different rock types and minerals (see especially Heitzmann 2008 for a more detailed discussion on this aspect of Gruner's oeuvre). In the third volume, Gruner also touched the more speculative question of the age and origin of the rocks (and the fossils contained therein) constituting the Swiss Alps. He enlarged this interesting discussion in a later book, *Die Naturgeschichte Helvetiens in der alten Welt* (*Natural history of Switzerland during the old world*, Gruner 1773, Fig. 1), which contains original new thoughts on the origin of what is known today as Alpine flysch successions. Based on his meticulous description of fossils (in its modern sense), which he interpreted as the relics of marine animals (especially ammonites and oysters) and his belief that almost all rock types originated within or through the action of water (Gruner 1760b, 103; a view quite common in those days, see e.g. Laudan 1987), Gruner postulated that the whole of Switzerland once must have been covered by a salty sea over a prolonged (*"many centuries"*, Gruner 1760b, 98) period of time. In accord with many other mid-eighteenth century naturalists, Gruner made it clear that he did not believe the Deluge capable of depositing the huge successions of sedimentary rocks outcropping in parts of the Alps, the Swiss lowlands, and the Jura mountains. Hence, he assumed the salty Swiss sea to have existed in ante-diluvian times, which he referred to as the old world. Bottom currents on the floor of this ante-diluvian sea (an idea most likely influenced by de Maillet's *Telliamed* and Buffon's *Théorie de la terre*, see e.g. Rappaport 1997) he held responsible for the transport of erratic blocks strewn all over the Swiss lowlands and the Jura Mountains (Gruner 1773, 28). It was only with the Deluge that the isolated Swiss sea emptied and that its waters spread towards the lower, and formerly dry, areas surrounding Switzerland, thereby carving out most present-day valleys. The trigger for this event (note the similarity to Sulzer's hanging lakes outburst theory sketched by Carozzi and Carozzi 1987) Gruner found in the general water flood of the Deluge and accompanying earthquakes (Gruner 1773, 90). With this sketch of Gruner's regional geological history of Switzerland, the stage is now set to discuss his views on the explanation of Alpine flysch successions.

3.3 Gruner's interpretation of the Glarus slates

Gruner attached special importance to slate and shale formations in the Alps, as he saw in them unambiguous proofs for prolonged and episodic sedimentation at the bottom of a standing body of water (e.g. Gruner 1760b, 103). Already Johann Jakob Scheuchzer (Fischer 1973) had been impressed by the lower Oligocene Engi slates, and especially their rich fossil content, outcropping in the footwall of the famous Glarus thrust in the Glarus Alps (Furrer and Leu 1998). As documented by Trümpy (2003), he recognized the graded bedding within these economically important slate layers and speculated about its origin (Scheuchzer 1718). Probably under the influence of Woodward's (1723, first edition 1695) idea that global sedimentation following the general turmoil of the Deluge should have resulted in a kind of "mega-grading" according to weight of all sedimentary particles and fossils whirled around with the diluvial muddy waters, Scheuchzer invoked a post-depositional explanation for the graded bedding of the single layers of the slate. He wrote: "*However, from the given facts it has to be assumed that the principle layer* [i.e. the whole slate formation] *has formed by means of a general settling of material and that each particular layer* [i.e. a graded slate layer] *has not immediately acquired its highest degree of solidity, but has stayed in the state of a fluid such as water mixed with clay. Hence, in each particular layer heavier particles have settled over a prolonged period of time to the bottom and have thus separated from the lighter particles.*" (Scheuchzer 1718, 111, see also Scheuchzer 1716, 114).[1]

Gruner, undoubtedly building upon Scheuchzer's descriptions and interpretations, now took a remarkable mental step and transformed Scheuchzer's diluvial explanation (including the ad-hoc post-depositional-grading hypothesis) into a more timely (i.e. mid-eighteenth

[1] All original German or French text passages quoted in this article have been translated by the author. Original texts can be found in the Electronic Supplementary Material.


Die

Naturgeschichte

Helvetiens

In der alten Welt:

beschrieben

von

Gottlieb Sigmund Gruner

Mitglied der käyserl. Akademie der Naturforscher; und der ökonom. Gesellschaft in Bern Ehrenmitglied.

— Tantum ævi longinqua valet mutare vetuſtas.
Virg. *Aen.* III.

BERN, gedruckt und verlegt bey Abraham Wagner.
1773.

Fig. 1 Cover page of Gruner's 1773 *Natural history of Switzerland during the old world*. The old world refers to the situation before the Deluge (i.e. ante-diluvian times)

century) hypothesis invoking a long-standing ante-diluvian sea (Fig. 2): "*The substance constituting the roof slates, whose individual particles are invisible for the eye and can hardly be felt with the fingers, consists, following the judgement of every naturalist, of fine-grained muddy and marly earth, which can only be found on the floor of lakes and the sea. Thus, an extended body of water must have existed for a prolonged period of time within our* [i.e. Switzerland's] *borders, whose internal movements periodically liquified the muddy matter covering its floor. The quiescence following these disturbances let these mud particles fall down again, such that as a consequence of the alternation of movement and calmness during a very long span of time, thin layers were stacked on top of each other bit by bit, eventually forming whole mountain masses. Two main arguments render this inference not only probable but rather beyond question. 1. Because these slaty layers almost always contain creatures living in the sea such as*

Der Stoff der Tach- und Tafelschiefer, deren Bestandtheile dem Auge nicht sichtbar, und der Hand kaum fühlbar sind, bestehen, nach dem Geständniß aller Naturforscher, aus einer feinen Schlamm- und Mergelerde, dergleichen sich nur auf dem Grunde der Seen und des Meers befindet. Ein grosses Gewässer muß also eine lange Zeit hindurch seinen Sitz in unsern Gränzen gehabt haben, deßen Bewegung die Schlammtheile auf dem Grunde rege gemacht, und deßen darauf gefolgte Ruhe dieselben

dieselben wiedrum sich niederstürzen laßen, so daß durch die abwechslende Bewegung und Ruhe, in einem sehr langen Zeitlauffe, sich nach und nach dünne Schichten aufhäuffen, und zu ganzen Gebirgen anwachsen können. Zween Hauptgründe machen dieses nicht nur wahrscheinlich, sondern beynahe unzweifelhaft. 1. Weil diese Schieferlagen meistens Seegeschöpfe, als Fische, Muscheln und Seepflanzen in sich schließen: Wie Z. E. in dem Glarnischen Tafelschiefer und in der Schiefergrube bey Meyringen. Diese zwey Schieferberge aber sind die einzigen, die noch in der Schweiz angestochen und benutzt worden: Folglich ist gläublich, daß man in den meisten dieser Gebirge dergleichen fremde Körper eingeschloßen finden würde. 2. Weil sie allezeit aus sehr dünnen Lagen zusammengesetzt sind, die fast allemal regelmäßig mit einer Blatte von feinerm, und einer von gröberm Korne, miteinander abwechseln, von denen die gröbere allezeit unten, die fremden Körper aber immer zwischen beyden sich befinden. Anders wird sich also die Anlag dieser Felsen kaumm begreifen laßen; als daß sie nach und nach im Lauf einer langen Zeit, wechselweise von einer Schichte zu der andern, durch eine ordentliche Abwechslung von Bewegung und Ruhe, eines darauf gestandenen Wassers müßen angelegt worden seyn; Da immer bey einer jeden Bewegung die gröbern Theile, als die schwersten zuerst, und hernach die feinern und leichtern, sich niedergestürzt, und wechselweise Schichten von feinerm und gröberm Korne angelegt haben.

Fig. 2 The relevant text passage wherein Gruner describes graded bedding in the Engi slates (Northhelvetic flysch of early Oligocene age) from the Glarus Alps and interprets it by episodic movements and subsequent sediment settling on the floor of the ante-diluvian Swiss sea. See text for a translation and the Electronic Supplementary Material for a transcription of the German original (from Gruner 1773, 31–32)

fish, clams and sea weeds: so e.g. in the roof slates of the Glarus area or in the slate pit near Meyringen [Meiringen in the Bernese Oberland]. *But these two slate mountains are the only ones which so far have been cut through and exploited in Switzerland: hence it seems likely to find similar foreign bodies* [fossils] *in others as well. 2. Because these slate formations are always composed of very thin layers, which in turn consist almost always of a coarser and a finer grained sheet, regularly alternating, with the coarser sheet always below, the foreign bodies always between the two. Thus, it seems difficult to account for the origin of these rocks in another way as follows: they have been formed during a long period of time by means of the regular change of movement and quiescence of an overlying body of water. After each episode of movement, the coarser parts, being the heavier ones, settled first, the finer and lighter ones afterwards and so alternating layers of finer and coarser grains have been laid down.*" (Gruner 1773, 31–32, see also Gruner 1760a, 145 for a shorter and less explicit remark on the same topic). The last sentence, admittedly if taken out of historic context, is essentially compatible with an explanation of graded bedding by means of turbidity currents. However, it would of course be an anachronistic distortion of the evidence to ascribe to Gruner the anticipation of this concept some 170 years before the turbidite revolution. Put into its proper historical context, it seems more reasonable to assume that Gruner was thinking about submarine bottom currents (a veritable kind of submarine rivers, Gruner 1773, 34; an idea made popular by Buffon in his 1749 *Théorie de la terre*) as a cause for the periodic disturbances resulting in graded bedding in the Engi slates.

Summing up it can be inferred that graded bedding in some Alpine flysch successions has been observed or at least was appreciated by several naturalists such as Scheuchzer (1718), Sulzer (who had re-edited and commented Scheuchzer's *Naturgeschichte des Schweizerlandes*, Carozzi and Carozzi 1987), or Gruner (1773). Gruner's conjecture that only alternating episodes of disturbance and calmness could have caused the graded bedding of the Engi slates, was in line with results of an early eighteenth century research tradition of "sedimentological experiments" started by the Swedish polymath Emanuel Swedenborg (Swedberg). In his *Miscellanea observata* from 1722, Swedenborg ([1722] 1847, 18–20) described how he could reproduce a crude kind of graded bedding by agitating water in a glass vessel mixed with sand, fine scrapings of granite, and wood shavings and subsequently letting them settle according to weight. By periodically recharging the water with his sand-granite-wood mixture, he succeeded in producing clearly defined superimposed layers. Although Swedenborg's experiments attracted only limited attention outside the Swedish and German-speaking areas, which (according to Rappaport 1997, 179) may have been caused by his obscure style of writing and his rationalist presentation, he seems to have inspired Sulzer (1746, 23) to conduct similar experiments (Carozzi and Carozzi 1987). Gruner, citing both the names (but no specific articles or books) of Swedenborg and Sulzer, almost certainly based his bold conjecture about graded bedding in the Engi slates on this experimental work.

4 Modern pioneers during and shortly after the nappe tectonics revolution

The recognition that large parts of the Alps are not an assemblage of autochthonous uplifts due to large-scale folding of the Earth's crust, but rather the product of thrusting and stacking of horizontally displaced giant rock slabs (Bertrand 1884; Quereau 1893; Schardt 1894, 1898; Lugeon 1901), led to a completely new view on Alpine tectonics at the *fin de siècle* (the nappe tectonics revolution, Letsch 2016). Concomitant with its major tectonic implications, nappe tectonics also opened new ways to interpret Alpine sedimentary successions, although sedimentology was still an area of rather minor interest for most contemporary geologists working in the Alps (e.g. Trümpy 2003, but see Bernoulli and Jenkyns 2009 for some outstanding late nineteenth century pioneers). In this chapter, I will argue that by means of actualistic reasoning (fed by practical experience of sub-lacustrine and subaerial sedimentary slide, fall and slump movements), some of the key protagonists of the nappe tectonics revolution made outstanding contributions to a better understanding of the sedimentology of Alpine flysch deposits. In doing so, they provided inspiration and supportive evidence for the pioneers of the early phases of the later turbidite revolution between ca. 1930 and 1950.

4.1 Lakes as natural analogues

Rapid urbanization during the second half of the nineteenth century led to the widespread construction of artificial terraces (*quais*) along the shores of Switzerland's many lakes, in order to render hitherto "useless" shore areas into precious building land, railway tracks, or public promenades (Schardt 1892). These activities triggered several smaller and larger catastrophes (see e.g. Huber 1982), which not only increased the risk consciousness of the overly optimist Swiss society of the economic boom years in the aftermath of the 1848 foundation of the Federal State, but also led several geologists to better appreciate the importance of sub-aqueous sedimentary mass transport. In the following, some instructive examples shall be presented which later on will be put into the wider context of early Alpine and later marine sedimentology.

Following heavy rain on September 21. 1875, parts of the foundation of the newly built railway track on Lake Zurich's western shore collapsed during 22–24 September and sank, together with the train station of the village of Horgen, into the nearby lake. A commission of experts consisting of engineers and geologists (among them the renowned Zurich geology professor Albert Heim, see Trümpy and Westermann 2008 for further information on Heim) found the likely reason for the shore collapse: landfill for the new railway line onto unconsolidated gravel, sand and silt, underlain by weak lacustrine marls ("*weicher Schlammboden*") resulted in an overload and in oversteepened sub-lacustrine slopes (Moser et al. 1876). A bathymetric campaign in the immediate aftermath of the catastrophe revealed the astonishing fact that large parts of the natural lakebed offshore Horgen had changed due to the shore collapse: "[…] *the old sublacustrine slope had changed completely, the whole slope had slumped. Since this slump movement had affected the whole slope down to the very bottom of the lake, i.e. 450 m away from the axe of the railway line, we have to ask ourselves with some astonishment where all the slump mass went? Far offshore, in the area of the flat lakebed, the latter seems to have experienced a vertical aggradation of some 1 to 3 m. There, the slumped sediment has evenly covered the ground, mixed with water, and partially suspended with the surrounding water,* […]. *Thus, a new sedimentary layer has formed, whose thickness is within the error of bathymetric soundings, and which is hence difficult to survey*." (Moser et al. 1876, 9).

A couple of years later, a far more disastrous, though geologically quite similar event happened in the city of Zug in central Switzerland in the night of July 4/5 1887. Enhanced by an exceptionally high groundwater level, construction works for a new quai fringing the lake shore involving pile foundations (the ramming of which caused strong vibrations), and new landfill led to the collapse of unconsolidated sandy silt mixed with lacustrine chalk. As a result, 35 buildings slid into the lake, 11 persons lost their lives, and 650 inhabitants their shelter (Heim et al. 1888; Ammann 1987). Bathymetric soundings carried out shortly after the catastrophe revealed a sub-lacustrine mudslide, that had moved for some 1020 m over the rather flat (ca. 1.7°) lake bottom, and gave rise to a deposit of some 1–4 m thickness (Heim et al. 1888). Less dramatic instances of quai collapses also occurred along the shores of Lac Léman (Lake Geneva) in 1877 (Vevey), 1883 (Clarens), and 1891 (Montreux). The latter event has been analyzed in great detail by Schardt (1892) and added further illustrations for both sub-lacustrine mass transport and sedimentation. Also based on bathymetric soundings in the aftermath of the catastrophe, Schardt concluded: "*Hence, the drowning of the quai and the adjacent shores corresponds to a veritable sub-lacustrine land-slide of much greater importance than just the slide of disappeared on-shore material.*" (Schardt 1892, 252). Schardt's publication on the Montreux 1891 shore collapse was supplemented with a general discussion of processes shaping natural lake shores, and Schardt paid special attention to alluvial fans (*cônes de dejection*) prograding into Lac Léman. Among the latter, the Montreux fan (on which the central part of the eponymous town is built) is fed by the steep mountain gorge carved out by the Baye de Montreux and hence consists of predominantly coarse detritus. The Montreux area thus supplied Schardt with an instructive recent example of blocks, gravel, and sand being directly transported from a mountainous hinterland into a nearby standing body of water.

From a modern perspective, it seems fair to conclude that the acquaintance with artificially induced sub-lacustrine sedimentary mass transport events gave the geologists involved (mainly Albert Heim and Hans Schardt) a quite privileged position, from which they could better appreciate the geological importance of such processes than most of their colleagues. Heim's (in Moser et al. 1876) interpretation of the deeper sub-lacustrine aspects of the Horgen 1875 catastrophe as a slump-induced turbidity current in all but name has been fully confirmed by later sedimentological investigations based on piston cores (Kelts and Hsü 1980, see also Strasser et al. 2013 and Strupler et al. 2015 for modern seismic reflection and high-resolution bathymetric data). In the following, it will be explored how exactly Heim, Schardt and other geologists used this actualistic first-hand knowledge of subaquatic sedimentary processes to explain the Alpine sedimentary record, especially one of its perhaps most exotic facets—the mysterious flysch and wildflysch successions.

4.2 Genetic explanations of flysch and wildflysch

Before the 1950s, questions concerning the depositional mechanisms, the palaeogeographic setting, and the original bathymetry of Alpine flysch successions was a topic rather rarely touched upon. Although flysch as a supposedly synorogenic facies had been incorporated into various paleotectonic models (e.g. Argand 1916; Arbenz 1919), there was no consensus, if it should be considered rather a shallow (e.g. Schardt 1897; Boussac 1912; Beck 1912) or deep (e.g. Fuchs 1883; and partly Tercier 1939) marine deposit, albeit the majority of workers certainly declined towards the fist possibility (see e.g. the short historical discussion in Trümpy 1960). The main reason for this ambiguous situation was certainly, apart from the lack of diagnostic depth-indicator fossils, the still rather poor knowledge of submarine mass flow sedimentation.

Hans Schardt, the geologist who more than anybody else had triggered the hot phase of the nappe tectonics revolution (Schardt 1894), proposed during the 1890s a new look on the origin of the thick cushion of flysch lying underneath, in front, and on top of the allochthonous stack of rocks constituting the *Préalpes romandes*. Freed from the constraints of autochthonous tectonic interpretations, Schardt could better account for the ubiquitous occurrence of giant blocks and breccias consisting of sedimentary rocks of alien (exotic) facies and granitoid rocks (Fig. 3) in areas with no basement outcropping wide and far. Schardt proposed flysch to constitute a syn-orogenic facies i.e. debris deposited in front of moving nappes (see also Şengör 2003). He stressed the importance of coarse-grained breccias for a true understanding of flysch: *"In order to account for the origin of flysch, it is of prime importance to find an explanation for the breccias composed of large components."* (Schardt 1898, 201). Given Schardt's experience with recent terrestrial and sub-lacustrine landslides and related mass transport phenomena, and his intimate knowledge of the steep ravines around Montreux, periodically spilling coarse-grained detritus into Lac Léman (Schardt 1892), it may come as no surprise that he

Fig. 3 Flysch breccia consisting of exotic crystalline blocks and pebbles embedded in a fine-grained dark clay-silt matrix: supposedly the product of submarine mass flow processes (Iberg-Mélange, Isentobel, Canton of Schwyz, Swiss coordinate grid: 2,699,720/ 1,208,065, see Letsch 2017 for more information on the geologically interesting Isentobel). Such deposits inspired Hans Schardt during the early 1890s to think of submarine landslides. For detailed descriptions of this breccia see Quereau (1893, 24), Bayer (1982, appendix, 309–311), and Trümpy (2006, 87–88)

invoked landslides as an important agent of flysch and wildflysch deposition: "*Taking everything into consideration, one is rather inclined to view these* [flysch] *breccias as the products of landslides dumped directly into the flysch sea.*" (Schardt 1898, 202). However, perhaps misled by his otherwise quite fruitful recent Lac Léman analogue, he generally considered flysch to have been deposited in shallow water (see especially Schardt 1897, 236).

The use of modern sub-lacustrine mass movements as analogues for fossil marine Alpine sedimentary succession was made even more explicit a few years later. Inspired by the late nineteenth century Swiss lacustrine research discussed in the preceding chapter, Arnold Heim (Albert Heim's geologist son) published a paper on fossil and recent sub-aqueous landslides (Heim 1908). Therein, he described a great variety of different phenomena ranging from folded slump structures in Micoene freshwater limestone, over similar structures in hemipelagic Createaceous marls, to the famous exotic blocks in the Alpine wildflysch. Paying due credit to the variability of the phenomenon, he distinguished different degrees of disruption during transport of sub-aqueous mass movements. In the case of complete disruption, he gave a concise description of what, according to modern terminology, might best be classified as a turbidity current: "*A not yet consolidated mass of lose sand or mud is able to flow without being wrinkled into* [slump] *folds. While sliding, this mass dissolves into a mash or even a suspension (general turbidity of water) and its re-deposition results in a fine-grained layer of wide lateral extent and without any folds as if it were only the sequel of the earlier deposition. The difference to normal sedimentation is simply the fact, that the new deposit consists of re-worked older sediment of a more near-shore facies character.*" (Heim 1908, 153). In his later and more frequently cited publication on submarine denudation and chemical sediments, Heim (1924) repeated several main points of his 1908 publication and added further instances of neritic and even littoral sediment being transported into deeper water. In this context, he also mentioned the pioneering work of the Zurich pharmacist and biologist Friedrich Nipkow who, being primarily interested in recent lake diatoms, took sediment samples from the deeper part of Lake Zurich using an early version of a piston coring device (Nipkow 1920). In doing this, he could not only prove the presence of littoral sediment and gastropod shells in Lake Zurich deepest part (138 m water depth), but he also encountered and illustrated (to our knowledge for the first time ever) turbidites *avant la lettre* (he referred to them as "*allochthonous layers*") in a sediment core (Fig. 4, Nipkow 1927). Even though he did not comment on the graded bedding of these layers (see Hsü 2004, 45 for a modern core photograph documenting the same turbidites), he correctly linked them to lakeshore-collapse induced slumps. Heim's father Albert took up his son's chain of reasoning and suggested in his last great treatise (a thorough study of landslides and related phenomena written at the age of 83!) that many flysch breccias might be the products of sub-aqueous slides and shore collapses (Heim 1932, 43).

The link between flysch sedimentation and deep marine subaqueous mass transport was made even more explicit by the German geologist Erich Horn. As a participant of a German bathymetric survey of the deep-sea trenches east of Taiwan and the Philippines in 1912, he got acquainted with both extreme submarine topography and active tectonics and volcanism. In a thought-provoking and highly original paper on the geological significance of deep-sea trenches (Horn 1914), he gave a schematic cross-section of an ideal island arc and its foredeep (Fig. 5), which was influenced by Suess' discussion on foredeeps (Suess 1909) but contained interesting new elements. Citing the Swiss examples of sub-lacustrine mass transport phenomena described by Heim (1908), Horn postulated the importance of submarine slides: "*Since subaqueous slides of young deposits could be inferred on slopes with inclinations as low as 4° in Swiss lakes*[1]) [with the superscript referring to a footnote citing Heim 1908 and Hahn 1913], *it seems of course natural to assume subaqueous slides of sediment on the slopes of deep-sea trenches*." (Horn 1914, 434). He also pointed out that shallow-marine terrigenous clastic sediments will be transferred to abyssal realms of the sea and he explicitly linked it to flysch sedimentation (Fig. 5), which hence was recognized as a deep-marine mass flow deposit. To our knowledge, this is the first time that a connection between fossil flysch sedimentation in the Alps and recent deposition in deep-sea trenches has been proposed in the literature. Argand's (1916) proposal to use the Banda Sea of Indonesia as a present-day analogue for the former Alpine ocean(s) may well have been inspired by Horn's paper, since, although Argand himself failed to cite his 1914 paper, his close friend Arbenz (1919) counted Horn as a precursor of Argand's embryotectonics (see Trümpy 2003 for a discussion of this concept).

5 Discussion and conclusions

The historical material presented in this paper highlights in some detail observations and thoughts during two periods of Alpine geological research (the mid-eighteenth century and the turn from the nineteenth to the twentieth century) on what is known today as the product of sedimentary density or mass flows in general and turbidity currents in particular. It does not seem feasible to relate the scientific achievements of these two separate periods within a continuous chain of progress. Quite on the contrary, it is

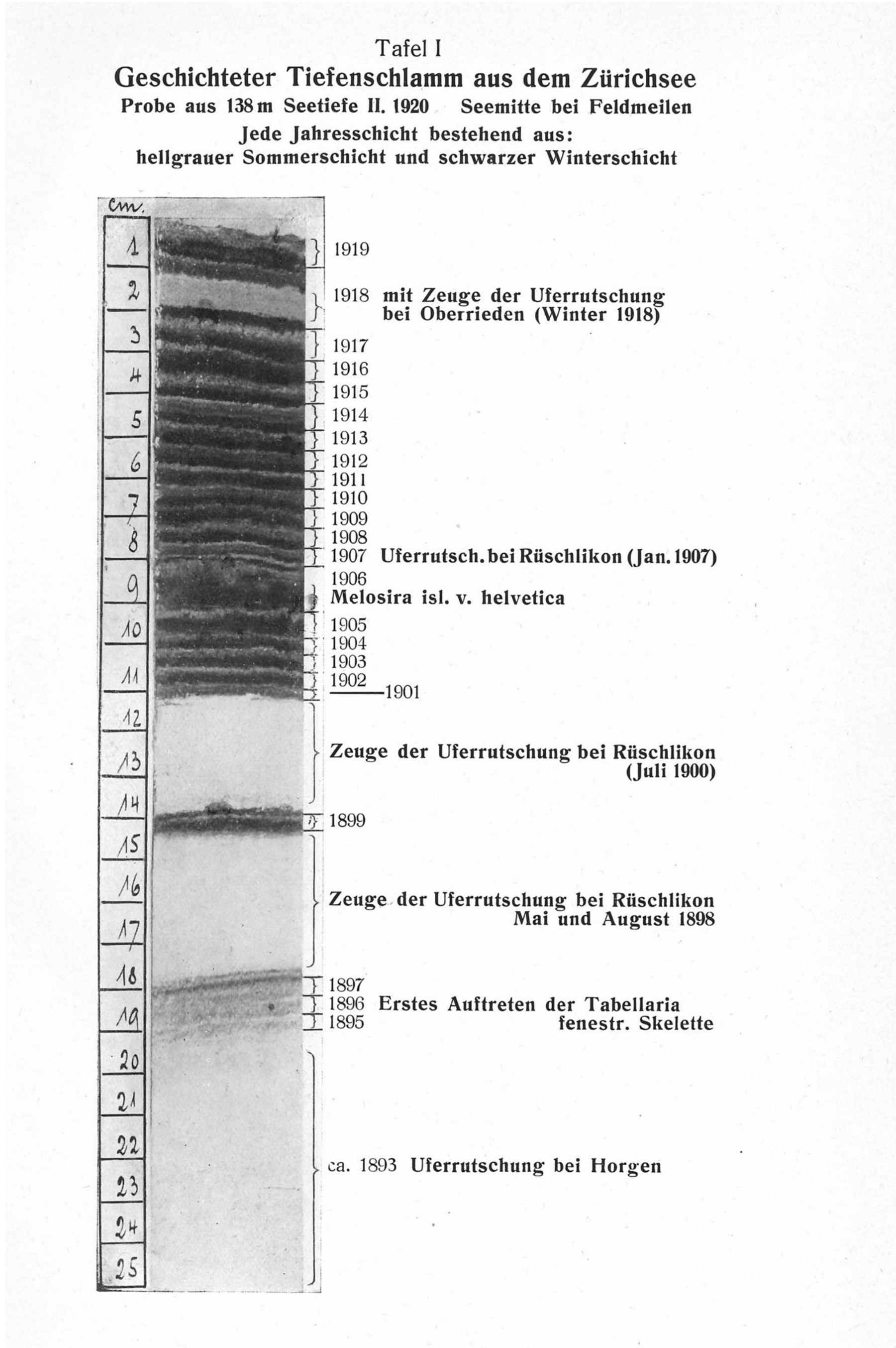


Fig. 4 Sediment core taken from the floor of Lake Zurich between Feldmeilen and Oberrieden (Nipkow 1927, between pages 4 and 5). Thicker and pale layers between dark background sedimentation are turbidites related to littoral slide and slump movements

astonishing to observe that graded bedding (clearly recognized and genetically discussed by Scheuchzer and Gruner) did not play any role at all for lake-research pioneers such as Albert and Arnold Heim, Hans Schardt or Friedrich Nipkow. This is strikingly demonstrated by Heim's (1924, 18) failure to interpret the graded bedding within the Engi slates as the product of mass flow sedimentation (contrary to Gruner 1773), although he was acquainted with recent examples (Heim 1908; Nipkow 1927) and even discussed the importance of turbidity currents for deeper marine sedimentation in the very same paper. Bailey's (1930) recognition of its abundance and his speculations on its likely origin can thus be regarded as a further case of a completely independent re-discovery of an important geological concept (see Menard 1986; Şengör 2003; Letsch 2015; or Blattmann et al. 2018 for other examples). On the other hand, Bailey (1930) and other harbingers of the turbidite revolution (Daly 1936; Bramlette and Bradley 1940; Kuenen 1950; Kuenen and Migliorini 1950) explicitly referred to Swiss geologists and

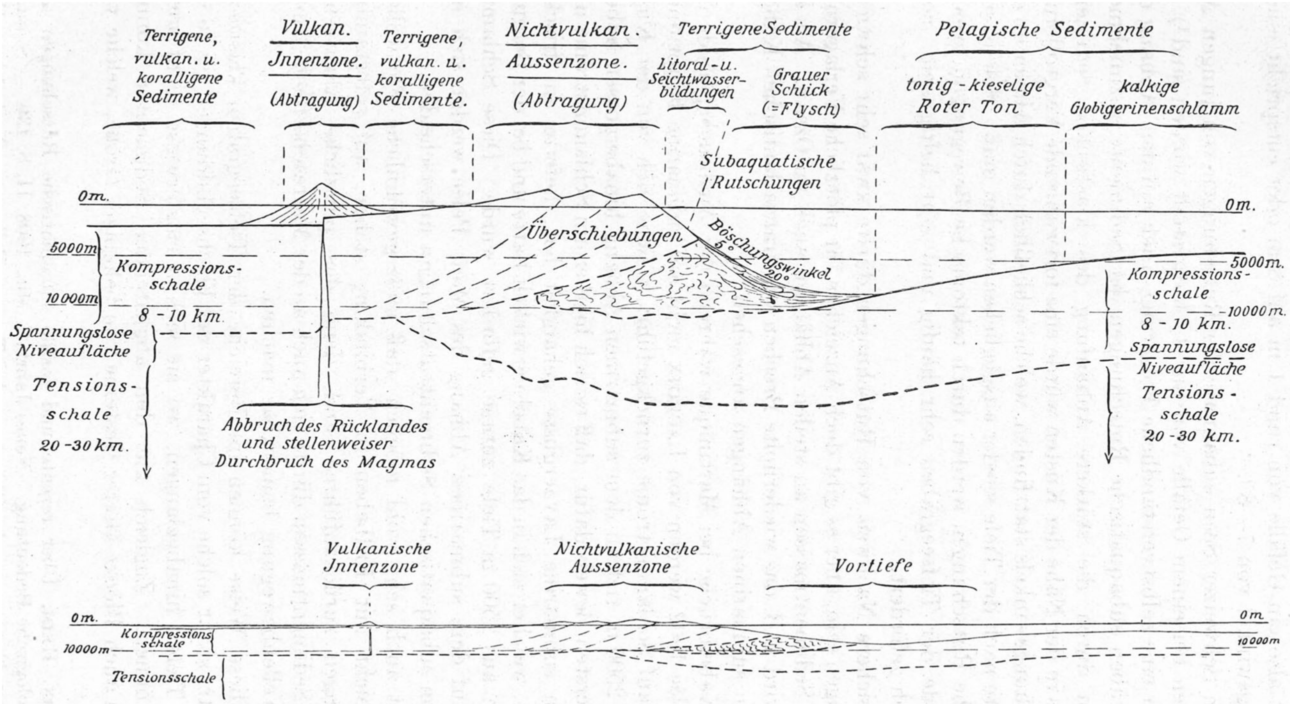


Fig. 1. Facielles und tektonisches Profilschema eines Inselbogens mit Vortiefe. Oben 5mal überhöht, darunter dasselbe Profil in gleichem Maßstab für Höhe und Länge.

Fig. 5 Ideal sections (both with and without vertical exaggeration) of an island arc and the corresponding foredeep (Horn 1914, 433). Note that Horn explicitly interpreted flysch ("*Grauer Schlick (= Flysch)*") as a deepwater sediment formed by means of subaquatic slide and slump movements

lake research pioneers (namely Hans Schardt, François-Alphonse Forel, Arnold and Albert Heim, and Friedrich Nipkow) as sources of inspiration. Hence, Swiss lakes already functioned as small-scale analogues for oceans or as natural laboratories many decades before the rapid evolution of limnogeology during the 1970s and 1980s (Hsü and Kelts 1985). Ironically, the latter development had itself been inspired by the fabulous rise of marine geology during the 1960s.

The fact that generations of expert Alpine (and extra-Alpine) geologists, most of them excellent observers, failed to take notice of a sedimentary feature as ubiquitous as graded bedding, whereas Scheuchzer and Gruner in the eighteenth century not only recognized but also theoretically explained it, is in want of an explanation. The proliferation of history and philosophy of science studies during the post-war era has resulted in a remarkable plethora of often contradictory accounts on how science actually works or should be supposed to work. However, there seems to be at least one crucial point on which many philosophers of science (otherwise upholding quite divergent views) seem to agree and this is the denial of the classical empiricist claim that science proceeds from observation to theory (e.g. Popper 1969; Feyerabend 1975; Kuhn 2000; see also Wegmann 1967 and Şengör 2001 for specifically geological perspectives on this aspect of science). Or, to put it another way, theories and hypotheses are necessary starting conditions to observe or measure anything at all. Applied to the case of graded bedding and its origin, one might argue that it has indeed been the lack of a genetic theory which prevented nineteenth century Alpine geologists to notice graded bedding. Scheuchzer, on the other hand, was clearly influenced very strongly by Woodward's idea of mega-grading in the aftermath of the Deluge. It is suggested here that only Woodward's bold conjecture gave him an ideological background, so to speak, against which the countless repetition of graded beds in the Engi slates must have appeared as an anomaly. His notice of graded bedding can thus be considered an excellent example of a theory-driven observation, and he invented the ad-hoc hypothesis of post-depositional particle settling to account for an anomalous observation within the Woodwardian Deluge theory.

It was in opposition to the Woodward-Scheuchzer Deluge theory that Swedenborg ([1722] 1847) and Sulzer (1746) carried out their sedimentological settling experiments, and that Gruner (1773) proposed his astonishingly modern explanation of the graded bedding in the Engi slates. With the bold theorizing on the evolution of the Earth typical for the late 17th and eighteenth centuries falling out of vogue during the "*heroic age of geology*" (Zittel 1899) following the end of the *ancien régime*, interest in graded bedding and the origin of flysch successions seems to have faded away in Alpine geology. It took more than a hundred years until the combination of new conjectures on Alpine tectonics (made possible by the nappe tectonics revolution) and inspiration from process-oriented research on sub-lacustrine mass flow sedimentation (Moser et al. 1876; Heim et al. 1888; Schardt 1892) provided a new fertile mental template to organize field observations on Alpine flysch into a more coherent scheme (Schardt 1898; Heim 1908, 1924; Horn 1914). And it even took some more decades for geologists to re-discover graded bedding and to link it to turbidity currents (Kuenen 1950; Kuenen and Migliorini 1950). A lesson to be learnt from the part of the prolonged pre-history of the turbidite concept reconstructed in this article might be, that, perhaps, there are no such things as "pure observations" in geology (see Pettijohn 1957, 230 for an early criticism of that term). It is always a previously held mental prejudice, be it a mythic belief or a scientific theory, which enables man to observe, to classify, and eventually to explain the complex and often chaotic world surrounding him. Or, to use a saying ascribed to Louis Pasteur (quoted by Wegmann 1963, 7): "*Only a prepared man can discover what he sees*."

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