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Tectonic Units of Central Switzerland: Their interpretation from A.D. 1708 to the present day

with 4 figures

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Abstract

A short review on the development of ideas concerning the structure of the mountains around Lake Lucerne, especially from the beginnings of alpine geology (1708) to the breakthrough of the nappe theory (1902).

Zusammenfassung

In diesem Artikel wird die Entwicklung der tektonischen Deutung der Berge um den Vierwaldstättersee behandelt. Das Hauptgewicht liegt auf den ersten zwei Jahrhunderten (1708 -1902) der alpinen Geologie; neuere Ergebnisse werden nur kurz erwähnt. Auch die Probleme der Zentralmassive werden nur angedeutet (Johann Gottfried Ebel, Albert Heim).

Für das Verständnis der Helvetischen Decken war das Profil am Urnersee wichtig (Figuren 1 - 3). Die grossartigen Zeichnungen von Johannes Scheuchzer und Luigi Ferdinando Marsigli, zu Beginn des 18. Jahrhunderts, stehen am Beginn der Forschung in den Alpen. Horace-Bénédict de Saussure sprach hier, wohl erstmals, vom seitlichen Zusammenschub als Ursache der Faltungen. Erst die biostratigraphische Datierung der Formationen, durch Bernhard Studer, Arnold Escher und andere, erlaubte eine erste Deutung der Zusammenhänge. Marcel Bertrand postulierte 1884 die Überschiebung der Axen-Decke, nicht aber der Drusberg-Decke. Albert Heim gab 1891 eine hervorragende Schilderung, ignorierte aber Bertrand's These und beharrte auf der, im Hinblick auf den Urnersee besonders abstrusen, Theorie der Doppelfalte. Erst Maurice Lugeon's Synthese von 1902 erklärte den Deckenbau der helvetischen Kalkalpen.

Die innerschweizerischen Klippen wurden namentlich durch Franz Josef Kaufmann (ab 1875) erkannt. Er betrachtete sie als Überreste einer jurassischen Gebirgskette. M. Bertrand deutete 1884 ihren exotischen Charakter an, und Hans Schardt brachte 1893 den Beweis für diese These.

Der Kontakt zwischen Molasse und Alpen führte anfangs des 19. Jahrhunderts zu einer Kontroverse zwischen J. G. Ebel und Hans Conrad Escher. B. Studer stellte 1853 eine recht merkwürdige Hypothese auf, um die Herkunft der Molasse-Gerölle zu erklären (Figur 4).

1. Major tectonic complexes

This paper gives a brief outline of the interpretation of the main tectonic units in Central Switzerland (The Four Forest Cantons and parts of Lucerne) during the last three centuries. Developments up to 1902 are mainly taken from an unpublished guidebook, «A Cruise on Lake Lucerne: geology, history of geology, local history», written for an excursion of the International Commission on the History of Geology (INHIGEO), in September 1998.

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Four major tectonic units form these mountains:

A. The *Aar Massif*, a bulge or upthrust of European Upper Crust, constitutes the backbone of the high Alps of Uri and of the Bernese Oberland. Its rocks, which include fairly large granite bodies, were affected by Variscan (mid-Devonian to Late Carboniferous) as well as by Alpine deformation. The *Mesozoic cover* (mainly Upper Jurassic limestones) was folded together with the gneisses, whereas the *North-Helvetic Flysch* (Upper Eocene and Lower Oligocene) has been more or less detached from its substratum.

B. The *Helvetic nappes* are derived from a scar S of the Aar Massif; their Jurassic and Cretaceous sediments stem from the proximal European passive margin of the Alpine seas.

The *Axen nappe* contains large volumes of Jurassic rocks. Cretaceous and Eocene formations occur only in the frontal part of the nappe, where they form two spectacular plunging lobes. Whether the small Gitschen unit, which underlies the Axen nappe on the left side of the Reuss valley, and the analogous Weissberg slices of the Engelberg valley constitute a separate nappe or not may be disputed.

The *Border Chain*, at the northern margin of the Alps, is formed by south-dipping, imbricated and locally folded slabs of Cretaceous and Eocene rocks.

The highest Helvetic unit, the *Drusberg nappe*, consists mainly of rather thick Cretaceous formations, apart from a few slivers of Upper Jurassic limestones at its proximal edge. It is laid into several recumbent folds. During an early stage of the structuring, part of the Upper Cretaceous and Eocene sediments have become detached and were transported to the front of the Alps, where they were overridden by the later thrust of the Border Chain and form the cushion of the so-called Subalpine Flysch (most of which is not a flysch by sedimentological standards).

C. The Penninic (quite exceptionally Austroalpine) *Flysch* and *Klippen nappes* are outliers, resting on top and in front of the Helvetic nappes. At least two nappes of Upper Cretaceous to Middle Eocene flysch are frequently underlain by wildflyschs, tectonic mélanges comprising also olistostromes with «exotic» boulders. The Triassic, Jurassic and Cretaceous rocks of the famous klippen are preserved in three mountain groups, in Obwalden, Nidwalden and Schwyz. They are derived from the Middle Penninic, Briançonnais s.l. belt and correspond to the Médianes nappe of the Prealps.

D. Only a very small part of the *Molasse Basin* is here discussed. The usually flat-lying Miocene beds of the *Plateau Molasse* are upturned sharply near Lucerne. SE of the city, the Lower Freshwater Molasse (Upper Oligocene and lowest Miocene) is laid into sharp, steep folds. These structures are truncated by the thrust of the great slab of *Subalpine Molasse*, expelled from more proximal parts of the Foreland Basin on the arrival of the Helvetic nappes. On the Rigi mountain, it consists of Middle Oligocene shales followed by several km of conglomerates. They dip at about 30° to the S, where they are overridden by the much steeper thrust of the Helvetic Border Chain.

2. The Aar Massif and its cover

The central belt of the Alps [basement massifs, Penninic and Austroalpine basement and metasediments] was long considered as the Primitive core of the chain. The early travellers were specially interested in the mineralogy of these rocks. HORACE-BÉNÉDICT DE SAUSSURE (1740-1799) was probably the first geologist to recognize (1786) the presence of Secondary rocks within the central belt, notably to the E of the Montblanc Massif.

JOHANN GOTTFRIED EBEL (1764-1830) was born in Prussia and obtained an M. D. degree at Frankfurt on the Oder. In 1796, he was suspected of sympathies for the French Revolution, having translated Siéyès' pamphlet «Le Tiers Etat». He emigrated first to Paris, then to Switzerland, where he became a citizen in 1801. In 1793, he published a travel guide of Switzerland, which went through several editions. It contains many geological informations.

Ebel's most important geological work is «Ueber den Bau der Erde in dem Alpengebirge» of 1808. His outlook is marked by German natural philosophy and by Werner's system. He was the first and, for a long time, the last scientist to attempt a coherent synthesis of the Alps. Their core is made up by Primitive Rocks, «as old as the Earth itself». Their bedding is invariably steep and strikes WSW - ENE. «In consequence of this, the primitive rock edifice was from its origin a single body ... in the structure of which reigns the highest and most solid order, the great Law of Parallelism» (p. 202). Ebel also attributes all zones of gypsum and of limestone in the central part of the chain to the primitive rocks, thus contradicting de Saussure. In order to prove his laws, Ebel is obliged to stretch the evidence outrageously. Apparent deviations from the strict parallelism of the strata are imputed to defective topographic base maps. In the Ticino valley below Biasca, through which Ebel must have travelled several times, by foot or on horseback, he notes that «the dense forest cover makes it impossible to recognize the dip of the strata» (p. 94). The present-day observer, in a train or even in a motor-car, cannot fail to see that the gneiss layers are perfectly horizontal.

In spite of these shortcomings, Ebel's work marks a progress of Alpine geology. In his quality of guidebook author and professional traveller, he acquired a broad knowledge of the Alps. Some of his rock descriptions are excellent.

During the second quarter of the 19th century, the Mesozoic age of the sediments overlying the massif became established. In the thin «Zwischenbildungen», Middle Jurassic fossils were found, and the thick limestones («Hochgebirgskalk») were shown to be of Late Jurassic age. Mesozoic rocks were also recognized within the central part of the chain, thus confirming de Saussure's views. Instead of Ebel's single basement core, several «massifs», separated by younger rocks, were now distinguished, the Aar Massif being the most external, northerly one.

A discussion arose about the role of the crystalline rocks, especially the [late Variscan] granites and volcanics. Did they exert an active force, in accordance with Leopold von Buch's theory of elevation craters, or were they deformed passively, together with the surrounding sediments? The two great mid-century Swiss geologists were divided; BERNHARD STUDER (1794-1887) hesitated, while ARNOLD ESCHER (1807-1872) upheld the second view, which finally prevailed.

In his great work of 1878, ALBERT HEIM (1849-1937) provided the definite proof for the passive role of the volcanics. E of the Reuss valley, a northerly branch of the Aar Massif, the Erstfeld dome, is partly overridden by the central part of the Massif, which forms a large frontal fold, with a core of Late Paleozoic rhyolites, on the Windgälle mountain. Heim found rhyolite pebbles in Middle Jurassic sediments, thus showing that the Windgälle porphyries could not be held responsible for the folding of the sediments. In the upper Aare valley, Armin Baltzer (1880) demonstrated that the contact between gneisses and limestones, which there show spectacular imbrications, was of tectonic nature.

Heim's 1878 work also marked a great step forward in the interpretation of small-to medium-scale structures (Milnes, 1979). Most early geologists had assumed that the folding of rocks was only possible while these were still in an unconsolidated state. Heim and others demonstrated the deformation of solid rocks. Heim provided excellent figures showing the ductile behaviour of limestones and metapelites. The semi-ductile folding of basement rocks, with a pronounced ante-Alpine fabric standing almost at right angles to the basement-cover interface, under low greenschist grade conditions, was a more difficult problem (see e.g. Labhart 1966).

During the «classical» period of alpine geology (1902-1934), the Aar massif, or at least its external offshoots (Erstfeld to the E, Gastern to the W) was generally considered to be rooted, autochthonous, although some authors already drew hypothetical thrusts under its northern border. The existence of such thrusts was only established by industry seismics (e. g. figure in Büchi & Trümpy 1976; Vollmayr 1992) and confirmed by the results of NRP 20 (Pfiffner et al., eds. 1997). They are quite important in western Switzerland but become less pronounced toward the E, especially near the eastern termination of the Aar Massif.

Refraction and reflection seismics have also shown that the massif is marked by a great thickening, practically doubling, of the European Upper Crust. The Lower Crust and the Moho are not affected. In principle, this thickening can be achieved either by ductile folding at depth or by stacking along thrusts. It has become fashionable to draw a great south dipping thrust underneath the massif and even to connect it with the front of the Apulian indenter (e. g. Pfiffner & Heitzmann 1997, figure 7). While the existence of such a thrust cannot be excluded and may be quite satisfying from a theoretical point of view, there is no seismic evidence to support this idea. Having seen the complex and often steep folds in the upper Ticino region, which were formed about 20 km below the land surface of the times, I can only admire the beautiful straight lines drawn at great depths by more optimistic interpreters of scattered seismic reflections.

3. The Helvetic nappes

In his beautifully illustrated Historia lapidum figuratorum Helvetiae (1708), CARL NIKOLAUS LANG (1670-1741), a Lucerne M.D., figured also fossils from Pilatus [Border Chain], i. a. nummulites (lapides frumentarios). Lang was one of the last followers of Lhwyd, according to whom the fossils had grown within the rocks. He noticed the presence of erratic boulders (frusta saxa ingentis magnitudinis) along the foot of the mountain, but did, of course, not yet think of glacial transport.

The same year, 1708, saw one of the most astonishing feats of early alpine geology. The italian count LUIGI FERDINANDO MARSIGLI (1658-1739) and his companion JOHANNES SCHEUCHZER (1684-1738) travelled by boat from Brunnen to Flüelen and observed the structures on both sides of the lake. Johannes was the young brother of the much more famous JOHANN JAKOB SCHEUCHZER (1672-1733); he later became a medical doctor in his home town of Zurich. In 1708, he sent a paper «De structura montium» to the French Royal Academy, which published only a short notice, referring to the author's theoretical views. Brother Johann Jakob included a condensed version in his Helvetiae Stocheiographia (1716), accompanied by a plate (our figure 1). The original manuscript has been found and published (in a german translation) by Margrit Koch, 1952; see also Ellenberger (1995). Marsigli's water colour paintings were discovered at Bologna and reproduced by Gortani (1930).

Thanks to Johannes Scheuchzer's and Marsigli's outstanding figures and descriptions, it is quite easy to correlate their observations with the tectonic features as interpreted today. From N to S, we can distinguish:

- The frontal anticline of the Morschach-Seelisberg fold in the Drusberg nappe, with its core of thin-bedded Kieselkalk, the wooded terrace on the Drusberg shales and the upper cliff of Schrattenkalk.

- The recumbent syncline between the Seelisberg and the Niederbauen folds of the Drusberg nappe, at Schiberenegg and especially on Teufelsmünster (the Devil's [gothic] cathedral).

- The northern plunging lobe (synform) of the Axen nappe, along Buggisgrat and below the mountain «Auf der Werchi». At the second locality, Scheuchzer exaggerates the importance of a secondary antiform (overturned syncline), exposed along the lakeshore.

- The synclinal bend on «Kolm» (Kulm), corresponding to the Axenmättli antiform between the two lobes of the Axen nappe.

- The complex folding in the lower, southern lobe of the Axen nappe, on Klein Axenberg.

Johannes Scheuchzer's theoretical views have been very pertinently analyzed by Ellenberger (1995). Johannes had read and understood Nicolaus Steno's Prodromus of 1669. He realized that the strata had been deposited on a near-horizontal plane and that their inclined and folded position was due to later effects. He differed from Steno, however, in ascribing both the deposition of the beds and their deformation to one and the same catastrophe, the Deluge. It first liquefied the rocks; then, when the waters were returning, at the behest of God Almighty, to their subterranean haunts, the strata were «broken, shifted from their place, some of them uplifted, others drawn down. This is the origin of mountains». Johannes amply refers to Burnet and Woodward. It is well known that brother Johann Jakob was one of the leading diluvianists of his time. Studer (1863) rightly calls Johannes Scheuchzer «the first Swiss geologist».

Fig 1: Johannes Scheuchzer's 1708 drawing of the upper reaches of Lake Lucerne. From Johann Jakob Scheuchzer (1716); reproduction by Urs Gerber. Also figured in Koch (1952) and Ellenberger (1995).

Johannes Scheuchzer's Zeichnung der beiden Ufer des Urnersees, 1708. Aus: Johann Jakob Scheuchzer (1716). Photographie von Urs Gerber. Auch in Koch (1952) und in Ellenberger (1995) abgebildet.

MORITZ ANTON KAPPELER (1685-1769) obtained degrees as doctor of philosophy at Milano and as doctor of medicine at Pont-à-Mousson. He served as surgeon and engineer with the Imperial Army at Naples. In 1710, he returned to Lucerne, where he became an important member of the medical profession and of the Great Council (city parliament). He was a man of many accomplishments, among others a pioneer of crystallography, a term which he coined in 1723 (or 1719). Around 1726, Kappeler wrote his «Pilati montis historia», the first scientific monograph of a Swiss mountain; it was only published shortly before his death (Capellerius 1767; see Kappeler 1960). His geological views are quite modern. He has a valid concept of the origin of sources, and he is one of the first scientific speleologists. Like Lang before him, Kappeler was struck by the boulders of gneiss and granite (Geissberger, from the high goat mountains) lying along the foot of the mountain. An Obwalden woodcutter of the early 19th century, whose name has not been transmitted to posterity, was the first to understand that the Geissberger rocks had been transported by glaciers.

HORACE-BÉNÉDICT DE SAUSSURE's account of his 1783 boat trip on Lake Lucerne is rather short (1796). De Saussure apparently knew Johannes Scheuchzer's paper only through the simplified figures in Vallisneri (1715). He saw the intricate folds N of Flüelen, and he understood that the strata were broken «during the act of their flexion». He also noted S-shaped folds and the C-shaped one on Teufelsmünster. There (p. 115; quoted by Masson 1976) he makes the remarkable statement: «The hypothesis of a lateral displacement (refoulement) appears to me as much more probable than that of an explosion». He observed the monolith of thin-bedded Kieselkalk, now called Schillerstein and then Wyber-Morgegab, which de Saussure, whose knowledge of german was patchy, translated as «Le Déjeuné des Dames». (He renders Pfaffensprung, the priest's jump, in the Uri valley, as «Le Saut du Singe» [Affensprung, the monkey's jump]).

Another distinguished voyager was JOHANN WOLFGANG VON GOETHE. In 1797, he saw the contortions of the strata, which nevertheless seemed to correspond on both sides of the Uri lake. These observations troubled his concept of geognosy, which, at that time, was largely influenced by the teachings of Werner (see Trümpy 1968).

J. G. EBEL (1808) tried to follow four parallel chains in the northern limestone ranges. He did note contorted strata, e. g. in the Axen section, but seems to have considered deformations as a rather subordinate feature. In his view, the beds of the northern chains had been attracted by the force of gravity towards the crystalline, primitive core of the Alps.

During the second quarter of the 19th century, the method of biostratigraphy, introduced by French and British scientists, brought a great advance to the understanding of the Alps, especially of the northern and southern sedimentary belts. The 1851-53 volumes of BERNHARD STUDER provide a good summary of the state of the art in the middle of the century. For Central Switzerland, Studer relied mainly on communications from his friend ARNOLD ESCHER. By then, most of the Jurassic and Cretaceous formations in the Helvetic nappes had been dated. The Eocene age of the rocks with nummulites was only accepted after the publication of the influential paper by R. I. Murchison (1849). The Cretaceous rocks were subdivided into Neocomian or Spatangenkalk [various Lower Cretaceous formations], Rudistenkalk [Schrattenkalk or Urgonian, Upper Barremian to Lower Aptian], «Gault» [Upper Aptian to Lower Cenomanian] and Seewerkalk [Upper Cretaceous platy

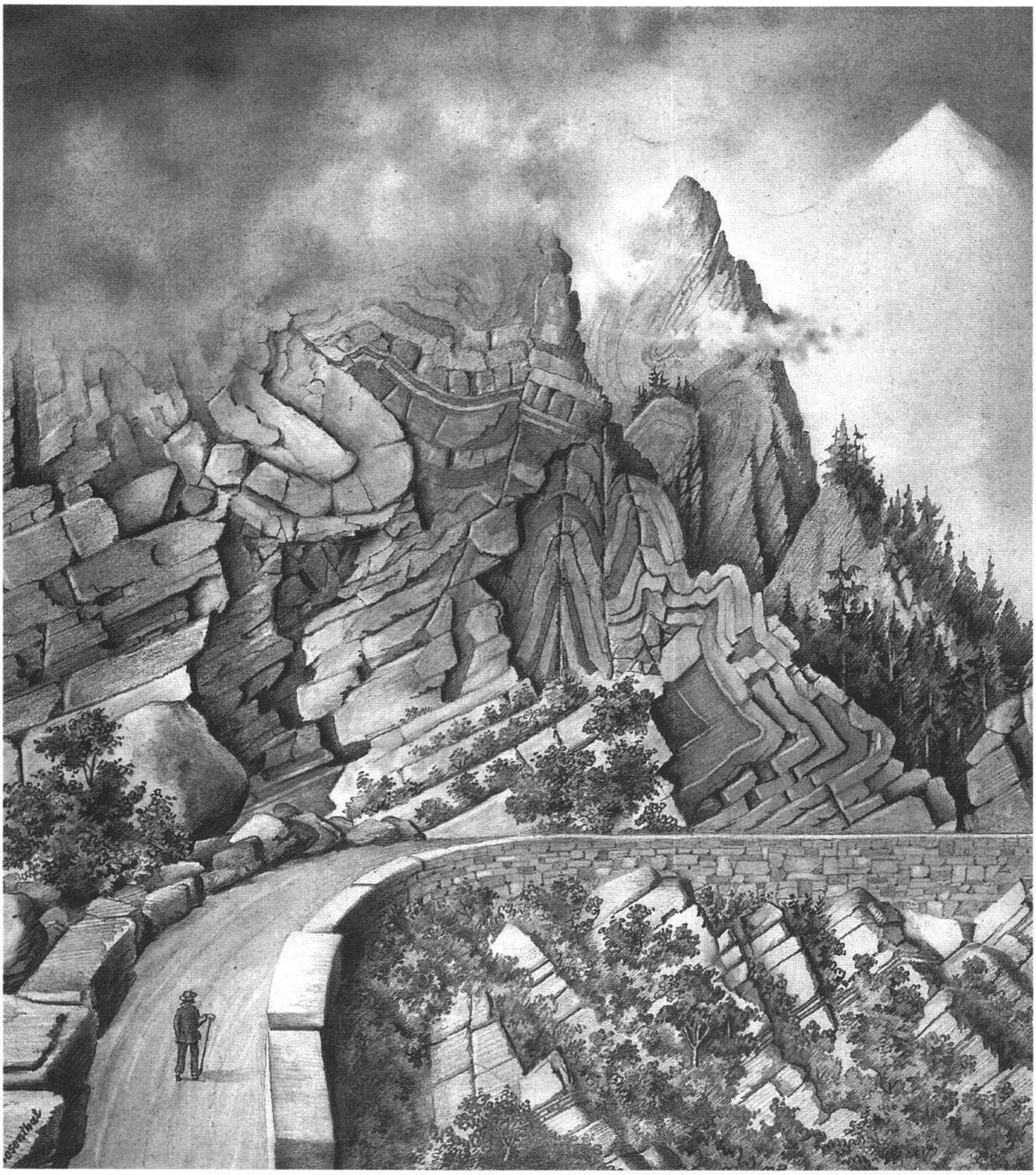


Fig. 2: Ductile-brittle folds in Lower Cretaceous (Berriasian) bedded limestones along the old Axen road on Axenfluh, southern plunging lobe (synform) of the Axen nappe; view toward SE. The locality is no more accessible. Drawing by Louis Rosenthal (around 1870?). Rosenthal (1846-1921) was a german mining engineer, who had travelled several times to the Americas. About 1911 he settled at Basel. The drawing is accompanied by a short text «a geological curiosity», in which he expounds his poetic and rather vague geological views. Drawing and information kindly communicated by Dr. Hans Dürst, Basel.

Falten in den Kalken der Unterkreide (Berriasian) des Axen-Südlappens an der Axenfluh; Blick gegen SE. Die Stelle ist heute nicht mehr zugänglich. Zeichnung (ca. 1870?) von Louis Rosenthal (1846 - 1921). Rosenthal wurde in der Nähe von Kassel geboren, studierte in Göttingen und Clausthal Bergbau und war u. a. in Südamerika tätig. Ab ca. 1911 wohnte er in Basel, wo er auch das Kino «Fata Morgana» gründete. Die Zeichnung und die biographischen Angaben verdanke ich meinem Cousin Dr. Hans Dürst in Basel.

limestones]. Studer's cross-sections are coarsely drawn but quite accurate. On Jochpass, W of Engelberg, he notes (1853, p. 99) that «the entire alpinic Jurassic system seems to have been thrust (weggeschoben) over the sandstones with Nummulites». We may recall that Escher had tentatively recognized the Glarus thrust in 1841 and thoroughly convinced Murchison in 1848.

ALBERT HEIM's 1878 volumes concerned the Helvetic Alps of Central Switzerland only marginally. He fully endorsed the theory of the Glarus Double Fold, conceived by his mentor and idol Arnold Escher at some time between 1848 and 1866, according to which the limestone mountains of Central Switzerland should belong to the south-vergent «North Fold». In the Glarus section, its root would lie somewhere between Schwanden and the northern edge of the Alps.

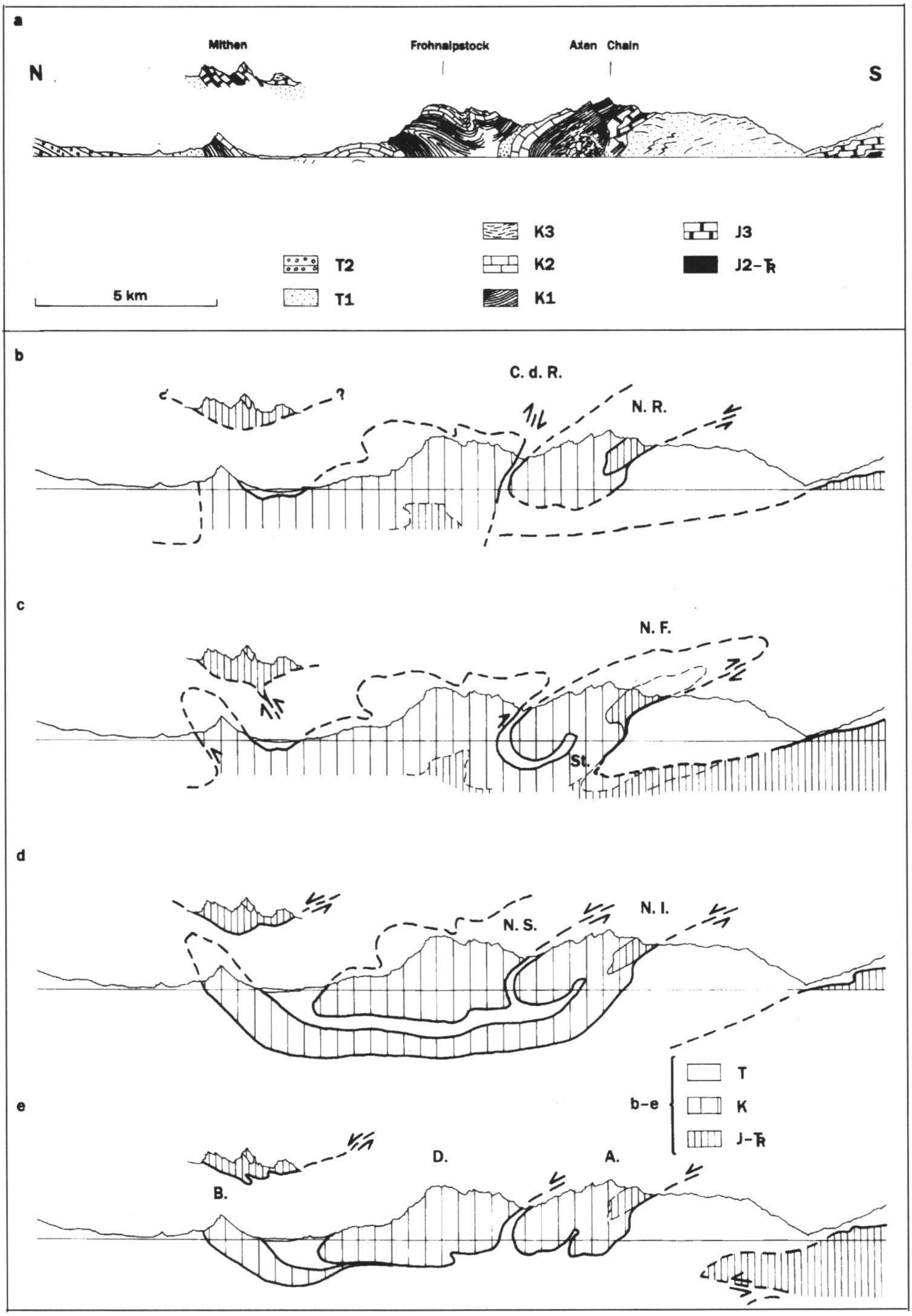
In 1884, MARCEL BERTRAND (1847-1907; see Bailey 1935; Bork 1991; Trümpy 1991; Trümpy & Lemoine 1998) published his famous paper on the Glarus Alps. In a convincing and perfectly logical manner, he showed that a single thrust, with transport from S to N, was far more probable than Escher's and Heim's two recumbent folds, facing each other above the narrow gap due to subrecent erosion. At least the Axen nappe was clearly recognized to be allochthonous and to have been moved for many km from S to N. This date, 1884, is generally accepted to mark the birth of the nappe theory in the Alps.

Curiously enough, Bertrand excluded the rock body which was to become designed as Drusberg nappe from his «lambeaux de recouvrement». In an attempt to establish an exact correspondance between the structures of the French-Belgian coal basin and that of the Glarus Alps, he sought for an equivalent of the «cran du retour», a normal fault limiting the coal basin against the Brabant high to the N, and believed to have found it in the band of Eocene rocks [cover of the Axen nappe], which can be followed from the village of Sisikon into the Glarus valley to the east (see figure 3b).

ALBERT HEIM returned to the eastern shore of the Uri lake in his «Hochalpen» memoir of 1891. His drawings (e. g. his plate III, our fig. 3a) are stupendous. Every bend of the strata is rendered with marvellous precision and with a true feeling for tectonic structures. Heim, who has been severely criticized (also by the author of this paper) was undoubtedly a great geologist.

In the field summer of 1882, Heim had recognized the antiform (inverted syncline) of the Axenmättli [between the two lobes of the Axen nappe]. He joined its Tertiary rocks with the Eocene glauconitic beds on top of the Axen nappe, near Sisikon. This led him to construe a folded fold, a monstrous mushroom, overlying to the N but at the same time limited by a «fold-thrust» to the S (his plate I, figure 2; our figure 3c). Consequently, the stem of this fold had to lie in what we now consider as the southern lobe of the Axen nappe. There, Heim himself had observed the synformal bending of the Lower Cretaceous strata; but he played down the significance of his own observation, which contradicted his theory, by stating that «we may not conclude from *one* bend of the strata on their structure at depth» (p. 67).

We are torn between our admiration for Heim's observations and our incomprehension for his failure to realize that *both* lobes of the Axen nappe represented plunging folds. In the Glarus traverse alone, the «North Fold» could theoretically



a
Mithen
Frohnalpstock
Axen Chain
N
S
K3
J3
T2
K2
J2–Ŧr
5 km
T1
K1
b
C. d. R.
N. R.
c
N. F.
St.
d
N. S.
N. I.
T
b–e
K
J–Ŧr
e
D.
A.
B.

be considered as rooted; but this was not the case along the axial culmination of the Uri valley, where the base of the nappe was almost exposed, lying little below the lake level. Heim had all the data which should have allowed him to understand that the Axen nappe could not be rooted, but had to have been overthrust from the S. He was also aware of Bertrand's 1884 paper, as it is listed in his bibliography, although he does not refer to it in the text. In the face of all this, Heim persisted to uphold the Double Fold theory, most probably out of reverence for Arnold Escher.

Due to the authority of Albert Heim, Bertrand's 1884 paper at first drew hardly any attention in eastern Switzerland. It fell into far more fertile ground in the western part of the country. In 1893, HANS SCHARDT (1858 -1931) established the far-travelled nature of the Prealps and of the klippen (see chapter 4), but did not yet discuss the character of their Helvetic substratum. In the Bernese Oberland, Bertrand and Golliez (1897) found further evidence for large-scale thrusting of the Helvetic nappes.

MAURICE LUGEON (1870-1953) had at first opposed the nappe theory, but then became its most brilliant spokesman. His 1902 paper really meant the breakthrough of the new tectonics. He showed that not only the Axen nappe was thrust from the south, as Bertrand had proposed in 1884, but also the Drusberg nappe, which Bertrand had still considered as rooted. Lugeon thus distinguished a «nappe inférieure de Glaris» (Axen, with Mürtschen and Glarus) and a «nappe supérieure de Glaris» (Drusberg - Säntis). The separation between the two was determined by the narrow band of Eocene rocks, running from the Engelberg valley through the village of Sisikon to Lake Walenstadt, in eastern Switzerland.

With the acceptance of the nappe theory, in the first years of this century, the geology of the Alps, including that of the mountains of Central Switzerland, almost suddenly became intellegible. The folds drawn by Johannes Scheuchzer, the thrust on Jochpass described by Bernhard Studer, the Axenmättli antiform discovered by Albert Heim all received a logical explanation. It was also realized that the facies variations of the Cretaceous sediments obeyed a systematic order, with platform limestones wedging out and overall thickness increasing from the lowest nappes in the north to the highest ones in the south (Arnold Heim 1916). This allowed e. g. to

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Fig. 3: Section along the eastern shore of upper Lake Lucerne.

3a: after Heim 1891, only down to the lake level and without interpretations. J2-Tr Middle Jurassic and Middle to Upper Triassic; J3 Upper Jurassic; K1 Berriasian to Lower Barremian formations; K2 Schrattenkalk; K3 Upper Cretaceous; T1 Eocene and Lower Oligocene formations; T2 Molasse.

3b: Correlation according to Bertrand 1884 (interpreted from his text and map). N.R. - Nappe de recouvrement; C.d.R. - Cran du Retour.

3c: according to Heim 1891. N.F. - North Fold; St - «Stem» of the North Fold mushroom.

3 d: according to Lugeon 1902. N.I. - Nappe inferieure de Glaris; N.S. Nappe superieure de Glaris.

3e: present view. A - Axen nappe; B - Border Chain; D -Drusberg nappe.

The signature J-Tr of the legend to figures 3b to 3e also comprises the basement complex of the Aar massif. Another version of this figure may be found in Trümpy & Lemoine, 1998.

Profile am Ostufer des Urnersees.
a: aus Heim 1891, nur über dem Seespiegel. Interpretationen: b: Bertrand 1884; c: Heim 1891; d: Lugeon 1902; e: heutige Auffassung. Monogramme: siehe englischer Text.

show that the three digitations of the Border Chain were of more external origin than the Seelisberg and Brienzergrat front of the Drusberg nappe, of more internal origin than the Cretaceous cover on top of the Axen nappe. Lugeon had still connected the Border Chain with the southern (inferior) lobe of the Axen nappe (see figure 3d).

During the classical period of alpine geology, the Helvetic nappes of Central Switzerland were especially studied by Paul Arbenz from Berne (whose 1934 review still provides one of the best summaries), August Buxtorf and Louis Vonderschmitt from Basel, together with their students (e. g. Fichter 1934; Anderegg 1940; Bentz 1948). Good geological maps at the scales 1:50'000 and 1:25'000 were produced; unfortunately, they are all out of print. A paper by Hantke (1961) gives useful stratigraphical data and cross-sections.

The construction of palinspastic profiles and maps (Trümpy 1969; Ferrazzini & Schuler 1979) allowed a better understanding of the tectonic and paleogeographic relations between individual Helvetic nappes. They are all derived from a coherent prism of strata; Cretaceous formations of the upper nappe (Drusberg - Säntis) originally overlaid Jurassic formations of the lower one (Axen, Mürtschen). For this reason, it is hardly possible to assign different basement complexes as former substrata to different nappes.

The deformation of the Helvetic nappes is obviously a polyphase development; this is exemplified by the steepening of the base of the Drusberg nappe («Säntis thrust» of Pfiffner 1992) in front of the Axen nappe. In the broader context, as well as by detailed work (e.g. NAGRA 1995), S. Schmid's proposal (in Funk et al. 1983) to attribute this steep contact to a down-to-the-north normal fault is hardly probable. Spörli (1966) has tried to analyse the sequence of events in the Urirotstock mountain group. It is interesting to note that the youngest events (Kiental and Grindelwald phases of Pfiffner et al. 1997) occur only W of the Reuss valley, opposite to the Jura folds on the other side of the Molasse Basin. Another significant indication of polyphase evolution is furnished by the study of the very weak metamorphism (Breitschmid 1982; M. Frey 1986), which antedates movements along the Axen and perhaps also along the Drusberg thrust.

The construction of tunnels and the search for a site serving for the underground disposal of weakly radioactive waste have led to very detailed studies of some interesting sections (Schindler 1969; Schneider 1984; NAGRA 1995).

4. Klippen and Flysch nappes

Early observers were impressed by the isolated mountains of the Mithen, E of Schwyz. After long hesitations, Arnold Escher (in Studer, 1853) had finally correlated the massive limestones [Upper Jurassic] with the Rudistenkalk, the flaggy red and grey limestones forming the summit of the Greater Mithen [Upper Cretaceous Couches Rouges] with the Seewerkalk. But he was puzzled by the absence of the «Gault» greensands between the two formations and by other anomalies. In 1868, Eugene Renevier (1831-1909), who was of course familiar with the Prealps of western Switzerland, suggested that the limestones forming the Lesser Mithen and the lower cliffs of the Greater Mithen were not of Cretaceous but of Late Jurassic age, corresponding to Studer's Chitelkalk.

FRANZ JOSEPH KAUFMANN (1825-1892) was for 38 years a schoolteacher at the Lucerne gymnasium. He was an extremely active field geologist, primarily a stratigrapher, and he mapped a large part of the limestone chains of Central Switzerland and of the adjacent Molasse Basin.

In 1876, Kaufmann published a paper on «Five new Jurassic mountains», not in a scientific journal but in the yearbook of the Swiss Alpine Club. Two summers before, he had found Jurassic fossils on these mountains, which occur in three clusters and which are now considered to represent outliers of Penninic nappes, notably of the Médianes or Klippen nappe. All around, the [Helvetic] mountains consist only of Cretaceous and Paleogene formations. Kaufmann regarded these five mountains as relics of a Jurassic chain, even if he admitted that some of them might have once been covered by Tertiary strata. This is the origin of the term of klippen (shoals, rocks or reefs in the sense of a hazard to [Cretaceous] seafarers). He sees them as «silent witnesses of the most magnificent changes» happening all around them.

Kaufmann gave a more detailed account of the Mithen in 1877. He rightly suspected the presence of Triassic rocks on the col between the two summits, dated Escher's «Neocomian» as Middle Jurassic and considered the massive limestones, Escher's «Rudistenkalk», as Oxfordian. As to the overlying gray and red limestones, they were «Tithonian» to Kaufmann, who had no use for any Cretaceous formations on his «Jurassic reef». Of course, he regarded the Mithen as rooted, in spite of the fact that their limestones, at least locally, rest upon Eocene greensands, as noted by Ebel way back in 1808.

An amusing thing happened a little further to the E, in the small mountains above the village of Oberiberg. There, Upper Jurassic and Cretaceous limestones, absolutely similar to those of the Mithen, are overlain by a higher Penninic nappe, with ophiolites, and then by Austroalpine Triassic dolomites. This pack of three nappes is clearly resting, all the way around, on Tertiary formations. So Kaufmann did not take the (for us) obvious step of correlating the lowest of the three nappes with the (supposedly rooted) Mithen. Instead, he had to create a new stratigraphic formation, the Ibergschichten, essentially of Tertiary age, for the three nappes.

ALBERT HEIM (1891) again considered the limestones on the summit of the Greater Mithen as Upper Cretaceous, following Escher but not Kaufmann. He must have felt that something was wrong with the current views on the position of the klippen, which break through the regular fold structures of the Cretaceous rocks «with almost incredible independence» (p. 42). He also noted that the Niederbauen fold [of the Drusberg nappe] «appeared to plunge underneath the Jurassic klippe of Klewenalp» (p. 46). Again, he did not dare to draw the conclusions from his pertinent observations.

Another two years, and HANS SCHARDT (1893) brought the solution to the problem of the klippen. He demonstrated that the Prealps of western Switzerland and Haute-Savoie were a rootless nappe or rather a set of two or three nappes, having been thrust from the south, at any rate from beyond the Montblanc and Aar massifs. He extended this concept to the klippen of Savoy, the allochthonous position of which had already been suspected by Marcel Bertrand, and to those of Central Switzerland. «The isolated slabs (lambeaux) of the Gyswylerstöcke [Obwalden klippen], of the Stanserhorn, the Buochserhorn [Nidwalden klippen], of the Mithen etc. [Schwyz klippen] are more than eloquent witnesses of the former extent of the Chablais nappe toward the NE, above the Unterwalden and Schwyz Alps» (p. 578).

In 1894, the 6th International Geological Congress was held in Switzerland. CARL SCHMIDT, from Basel (guidebook, p. 121) fully endorsed Schardt's view that the klippen were rootless masses, lying on top of the «Oligocene» [Upper Cretaceous to Eocene] flysch. But he tried to derive them from a hidden chain to the N, a westward prolongation of the Northern Calcareous Alps, with Austroalpine facies development - thus returning, in a way, to Studer's 1853 ideas (see chapter 5). Quereau, who produced an excellent map of the Iberg klippen (1893) and Hugi (1900), in the Obwalden klippen, held similar views.

Soon, however, the southerly origin of the klippen nappe came to be accepted by almost all geologists working in the area. The Giswiler Stöcke, with their Middle Triassic carbonate rocks, were compared to the Médianes Rigides, Alpboglerberg and most of the Nidwalden klippen to the Médianes Plastiques. Comparison with the Prealps was more problematic for the Rotspitz and especially for the Mithen. For Staub (1917) and Vonderschmitt (1923) they belonged to a northern facies belt, whereas Albert Heim (1922) and Smit Sibinga (1922) pleaded for a southerly position , the Mithen having been thrust over the Rotenfluh (with Plastiques affinities). The first view has prevailed. Among the monographs devoted to individual klippen of Central Switzerland, those by Christ (1920), Mohler (1966) and Felber (1984) deserve special mention.

For a long time, Swiss geologists had considered the Prealps and Klippen nappes as Lower Austroalpine units. Their intra-Penninic (Briançonnais s.l.) origin, long postulated by French geologists and foreseen by Eduard Suess, was only accepted around 1950, thanks especially to the work of François Ellenberger. The Giswiler Stöcke now became Briançonnais s. str., most of the klippen Subbriançonnais and the Mithen relics of a northern rise (MMB rise of Boller 1963). This last-named belt very probably continues into the Sulzfluh nappe of Graubünden.

The *Flysch masses*, especially the large outcrop area of Obwalden, Lucerne and Bern (Schlieren Flysch) were at first naturally considered as youngest formations of the underlying [Helvetic] Cretaceous to Upper Eocene sequence. Consequently, the Schlieren Flysch was thought to be of Late Eocene and Oligocene age (Kaufmann 1867, 1886). A. Buxtorf (1908) was probably the first to uphold that the Schlieren Flysch and the underlying Habkern Wildflysch belonged to a separate nappe. The rise of micropaleontology showed that the Flysch was older (Late Cretaceous to Early Eocene) than its Late Eocene substratum (e.g. Schaub 1951). Along with the similar Gurnigel Flysch of the Prealps, the Schlieren Flysch was assigned to the Ultrahelvetic facies belt.

In the Prealps, Caron (1973) and others have shown that the Gurnigel Flysch was in fact of a more internal origin than the Médianes (Klippen) nappe, and that its present position below the front of the Médianes was due to a late advance of the latter. This result certainly also concerns the Schlieren Flysch. According to Bayer (1982), the Upper Cretaceous Leimern limestones, in the Wildflysch underlying the Schlieren nappe, may well be compared to the Couches Rouges of the Briançonnais s.l. The section on the northern ridge of Rotspitz, in the Obwalden klippen, where an inverted klippen succession overlies a mélange with Couches Rouges and this in turn inverted Schlieren Flysch, might be interpreted as a «normal» tectonic sequence (Schlieren Flysch above Klippen nappe) overturned by late folding.

The paleogeographic position of the Upper Cretaceous to Middle Eocene Wägital Flysch of the Schwyz foothills is still uncertain (Winkler et al. 1985). It shows affinities both to south- and to north-Penninic flysches.

5. Subalpine Molasse

M. A. Kappeler (1767, 1960) made some very pertinent remarks on the Molasse sediments in the vicinity of Lucerne. He wrote that conglomerates were deposited by rapid, torrential streams; sand was formed by weaker currents. He valued ripple marks, quite frequent in the steep-standing sandstones of the Upper Marine Molasse, as indicators of a marine environment. Since his stay at Naples (see chapter 3), he was of course familiar with the seashore.

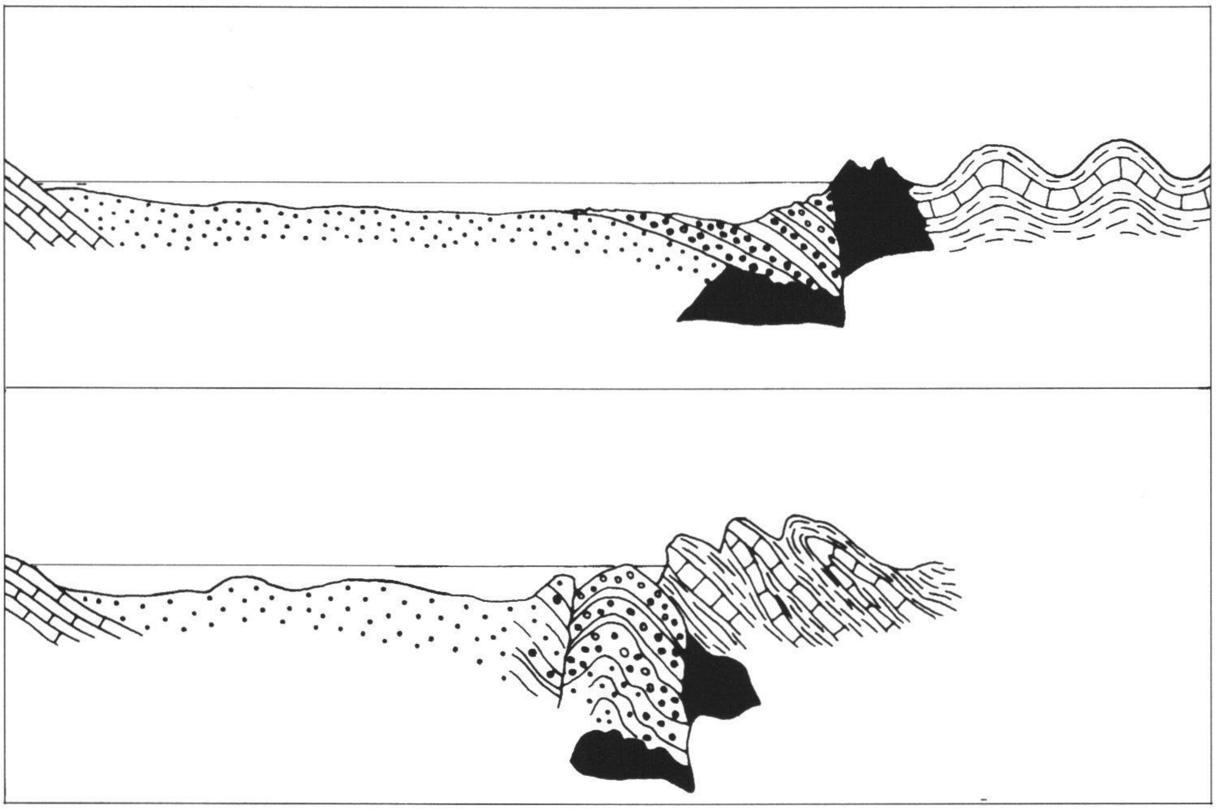

Fig. 4: Development of the contact between the Alps and the Molasse Basin. Copied from Studer (1853), p. 388. Upper figure: during the sedimentation of the Molasse; lower figure: after the overthrusting (sic) of the Calcareous Alps. Black: basement and cover rocks furnishing the pebbles in the Molasse; limestone signature: Jura; limestone-shale signature: Alps; conglomerate-sandstone signature: Molasse.

Entwicklung des Alpenrandes, «während der Ablagerung der Molasse» (obere Figur) und «nach Überschiebung der Kalkalpen». Kopiert aus Studer (1853), S. 388.

In the following, we shall only deal with the Rigi conglomerates and their contact with the limestone chains to the south.

During his boat voyage, H. B. DE SAUSSURE (1796) went ashore at Vitznau. He was impressed by the massive conglomerate beds, and he noted their content of porphyry pebbles [Lower Permian volcanic and subvolcanic rocks, similar to those of southern Ticino].

J. G. EBEL, in his 1808 book, is rather cautious as to the relation between the conglomerates and the limestones. Ebel's most important Swiss correspondent and, at times, antagonist was HANS CONRAD ESCHER (1767-1823). In 1807 (mainly written in 1795, according to Kaufmann, 1872), he gave a good description of the Rigi conglomerates, noting the pebbles of porphyry and of older conglomerates [Cretaceous Mocausa conglomerates from the Ultrapenninic Simme nappe]. He saw that the conglomerates were inclined at 30° toward the S, and that the limestones [Helvetic Border Chain] above them plunged in the same direction but at a much steeper angle. He concluded that this was no proof that the [Oligocene] conglomerates were older than the [Cretaceous] limestones. Escher (1809) also reviewed Ebel's treatise, politely but with quite pertinent objections.

In 1811, Ebel returned to the question of the relative age of the conglomerates and the limestones. In the obscure gorge of the Teufbachtobel, near Gersau, he thought to have found evidence for a stratigraphical contact between the two. Escher (1812) immediately visited the locality, was disgusted both by the ravine and by the outcrops and said that they did not prove anything. It is, in fact, a tectonic contact between Molasse beds and Eocene shales, with complex imbrications (see Stürm 1973, p. 76) - one of the worst possible places for deciding the question. This very uninspiring creekbed became a famous locality for a few years.

BERNHARD STUDER (1825) attempted the first comprehensive study of the Swiss (type) Molasse. In 1853, he gave much thought to the question of the origin of the pebbles in the Rigi conglomerates, clearly differing from rocks in the [Helvetic] northern limestone chains and in the basement massifs. He imagined the former existence of a chain of basement and sedimentary rocks at the border between the Molasse Basin and the Alps, which had since been covered by the thrusting (Ueberschiebung) of the Calcareous Alps (see figure 4). This cryptic multi-purpose chain, separating basins with differing evolution (e.g. Germanic vs. «Alpine» Triassic), shedding at first exotic blocks into the flysch and then pebbles into the molasse and even serving as homeland for the klippen (see chapter 4) comes close to Gümbel's (1861) equally apocryphal «Vindelician Chain» further east.

The provenance of the Molasse pebbles from eroded nappes formerly crowning the Alpine edifice could of course only be understood with the advent of the nappe theory. In the case of the Upper Oligocene - basal Miocene Rigi conglomerates, the pebbles can be traced to Austroalpine cover nappes (the westernmost testimony of the «real» Austroalpine domain), Penninic flyschs and Mesozoic to basement rocks, including Permian Baveno-type granites, from the Ultrapenninic Simme nappes s.l. (Speck 1953).

Studer (1853, p. 382) also figures a good section of the Rigi conglomerates and of their contact with the Helvetic Border Chain. Of course, he noted the angular unconformity between the dip of' the conglomerates and the frontal thrust of the Helvetic nappes, which still raises problems, as it did to Ebel and Escher almost two centuries ago. A tectonic truncation of the rigid conglomerate beds is not very probable, as the lowest Helvetic unit, the «Border Flysch», consists mainly of marl shales; it is difficult to scrape with butter. Arnold Heim (1906) postulated an intra-Miocene (most probably ante-Burdigalian) phase of erosion. At that time, prior to the arrival of the Helvetic nappes and to the northward transport and rotation of the Subalpine Molasse, the conglomerates should have shown a flat northward dip. While some geologists (including the author of this paper) think that Arnold Heim's hypothesis could explain many features, others oppose it. As so many theories advanced and abandoned during the past 290 years, it needs either confirmation or definitive refutation.

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