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The Glarus Double Fold: a serious scientific advance in mid nineteenth century Alpine Geology

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Abstract The Glarus overthrust is one of the best known examples of a thrust fault. Prior to its explanation as the base of an overthrust mass, this anomaly of the stratigraphic column had been explained by the Double Fold model, two recumbent folds facing each other. This model, advocated by Arnold Escher and Albert Heim, has been discredited by later geologists as a tectonically unsound concept which retarded the progress of science in this field of research. This article challenges parts of this view and tries instead to demonstrate that the Double Fold concept, though obviously wrong in retrospect, was a considerable scientific advance compared to the situation around 1850 when it was first proposed. To this end, the article summarizes the development of Swiss Alpine geology between 1800 and 1850 and places the Double Fold into its proper historical context. Earlier tectonic models (mostly proposed by Bernhard Studer) viewed crystalline rocks as the main driver of Alpine orogeny: due to somewhat mysterious metamorphic processes these rocks were supposed to have changed their lithology and physical properties and ascended vertically through small fissures. They uplifted, folded and eventually overflowed their sedimentary cover. The Glarus overthrust was also explained in this manner, probably even by Arnold Escher until the late 1840s. He later changed his mind and proposed the Double Fold concept which can be considered as one of the earliest attempts to apply the global contraction theory to the Alps. The global contraction theory later became the base of the geotectonic model of Eduard Suess and contributed to the final acceptance of large-scale horizontal displacements of rock masses around 1900. From this perspective, the Double Fold can be considered as a first step towards the nappe tectonic revolution and we suggest that its proposal was the expression of a fundamentally new way of thinking in Alpine tectonics.

Keywords History of geology · Alpine tectonics · Orogenic processes · Glarus Alps · Arnold Escher · Bernhard Studer · Albert Heim

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1 Introduction

The Glarus overthrust, marked by the thin calc-mylonite known as the "Lochseitenkalk", ranks among the world's most famous examples of a thrust plane. Due to the marvellous outcrops in the canton of Glarus (Eastern Switzerland), exposing the juxtaposition of intensely reddish to greenish coloured Upper Palaeozoic redbeds and volcanics (Glarus Verrucano) onto grey Lower Tertiary shales and sandstones, this thrust plane was chosen as an UNESCO world natural heritage in 2008. However, prior to the acceptance of the nappe tectonic theory, the anomalous stratigraphy so spectacularly exposed in Southern Glarus was partly explained by the notorious *Glarus Double Fold* (Fig. 1), a model first proposed by Arnold Escher (Anonymous 1866) and later substantiated and vigorously defended by his follower, Albert Heim (Heim 1871, 1878a, b). Heim's stubborn insistence on this wrong tectonic concept, his refusal to consider Bertrand's (1884) elegant alternative, and his polemic counterattacks against some colleagues (e.g. Michael Vacek, or August Rothpletz), have been reviewed several times (e.g. Bailey 1935;

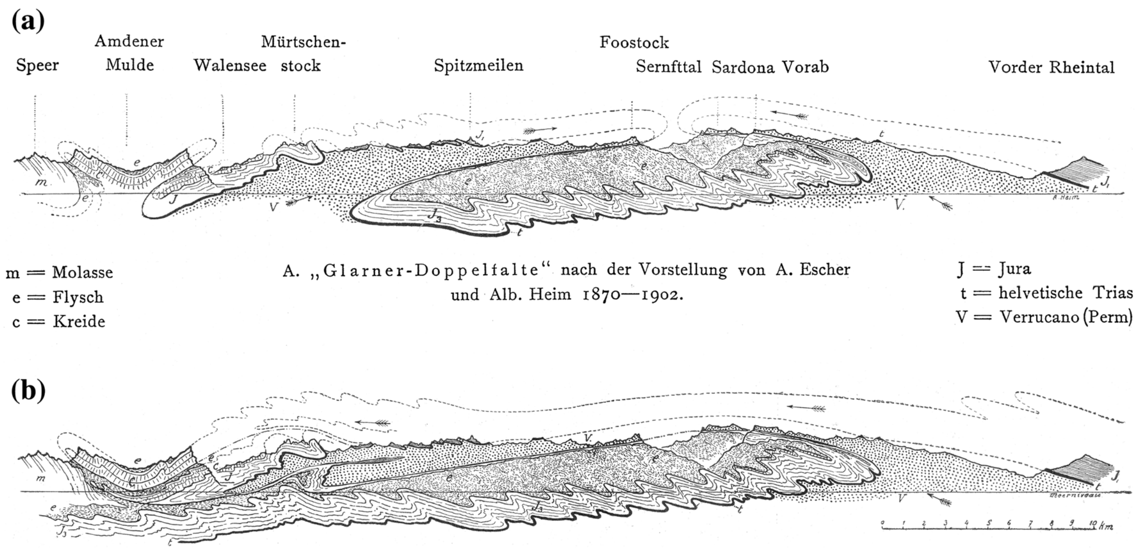


Fig. 1 Two tectonic interpretations of the geology of the Glarus Alps: the Glarus Double Fold (**a**) and the Glarus nappes (**b**). Figure is taken from Heim (1921: 12)

Trümpy 1991; Trümpy and Westermann 2008) and it has been declared repeatedly that the Double Fold theory was a reactionary concept that retarded the progress of Alpine tectonics considerably (see especially Trümpy 2001 and Trümpy and Westermann 2008: 73).

The present article proposes a different view. It does not focus on the well-known declining phase of the Double Fold theory with its tedious and epic polemics (between 1884 and 1901) but instead concentrates on the time before the Double Fold concept arose (1800–1854) and on its early phase (between 1854 and 1878) which has hitherto been almost totally neglected in the literature. By tracing the origin of this tectonic concept, an attempt is made to show that the Double Fold was indeed a clear scientific advance compared to the tectonic concepts envisaged earlier in Alpine tectonics. On a broader view, its invention around 1854 can even be viewed as part of an important change of thinking in Swiss Alpine tectonics which was necessary for its later development, leading finally to what has been termed the nappe tectonic revolution.

2 Developments in Swiss Alpine Geology in the first half of the nineteenth century

In order to judge the quality of the Double Fold concept, it is necessary to review first the developments and objectives of Swiss Alpine Geology in the first half of the nineteenth century. To this end, the course of Alpine geological research during this time span is divided into three periods which seem to be characterized by sufficiently different observations, models, and ideas as to justify the admittedly somewhat arbitrary tripartite division.

2.1 Before 1810: the classic "Wernerian" model

Continental European geology was dominated during the last quarter of the eighteenth century and the first decade of the nineteenth by ideas and concepts summarized under the heading *Neptunism* which were eloquently taught by the charismatic German geologist and miner Abraham Gottlob Werner (Ospovat 1969). According to Werner (1787), crystalline rocks, such as granite, gneiss, or mica schist (the so-called "*uranfängliche Gebirgsarten*" or just "*Ur-Gebirge*"), were precipitated early in Earth history out of an ocean which covered the whole surface of the Earth. Hence, a temporal connotation was attached to these rocks, i.e. that they are by definition very old (primordial). Later in Earth's history, the ocean's level supposedly lowered and its chemistry changed, thus permitting the precipitation of other rock types (the "*Flötzgebirgsarten*" such as limestone, sandstone, or gypsum), which were deposited as lateral attachments to topographic highs composed of previously deposited "*Ur-Gebirge*". Even later, the ocean further receded and the youngest "rocks" (or rather sediments), loose gravels, sand etc. (the "*aufgeschwemmtes Gebirge*") were deposited in a patchy manner filling some previously built depressions on the continents. Tectonics was not considered by Werner and he did not ascribe much importance to volcanic processes. Applied to mountainous areas, his model resulted in a relatively simple structural scheme: the core of a mountain chain (including its highest parts) is composed of very old crystalline rocks (with some subordinate limestone layers or wedges, see Werner 1787: 9) which are laterally coated by younger sedimentary rocks dipping away from the central crystalline core.

The Wernerian model (or at least some fundamental parts of it) was applied to the Alps by the leading Alpine geologists at the turn of the eighteenth to the nineteenth centuries. Horace-Bénédict de Saussure, for instance, started his geological studies in the Alps as a moderate adherent of Werner's doctrine (de Saussure 1786: 339). However, impressed by the complex structures he found in the Alpine rocks (especially folds) and the seeming lack of any constant succession of different rock types, he arrived at some fundamental deviations from the Neptunian model, being compelled to assume tectonic movements which affected rock layers originally deposited horizontally (de Saussure 1786: 105). On the other hand, de Saussure followed Werner by maintaining that crystalline rocks (e.g. the granites found in the Mont Blanc area) compose the core of the Alps and represent the oldest part of this mountain chain. The Neptunic template was applied much more rigidly to the Alps by Leopold von Buch (1809) early in his career (later, he changed his position) and by Johann Gottfried Ebel (1808a, b, see Franks et al. 2000). Hans-Conrad Escher, a meticulous observer, cautious author and probably the most dedicated Alpine geologist of his days, never gave a clear statement of his theoretical ideas about the geological structure of the Alps (cf. his son's useful summary of his father's studies, Escher 1852). In his petrographic descriptions and classifications, he obviously followed the useful approach of Werner, but like de Saussure, he was forced to accept that tectonic movements had affected the Earth's strata long after their deposition. Furthermore, he observed areas which differed from Werner's general scheme of superposition of the different rock types. One of the most prominent areas where nature did not follow the accepted Neptunian model, was in the Glarus Alps (Escher 1809). The controversy between von Buch and Escher which resulted from the latter's description of what is known today as the Glarus nappes, has been well summarized by Staub (1954: 131–133) and illustrates the immense problems inevitably encountered by a rigid application of Werner's system to a complex mountain system like the Alps.

To summarize the situation of Alpine Geology around 1810, it seems well justified to state that a moderate version of Werner's Neptunian theory was the preferred model of most Alpine geologists (Studer 1847: 180). Even though some of them (even the Werner disciple, von Buch 1809: 121) admitted tectonic movements which affected originally horizontal strata long after their deposition, most of them still applied the Neptunist rock nomenclature and implicitly or explicitly assumed the crystalline rocks outcropping in the high mountain areas of, for instance, the Gotthard or the Mont Blanc to represent the incredibly old (primordial) core of the Alps (Studer 1863: 621).

2.2 1810–1830: biostratigraphy and the discovery of "young" granites and gneisses

Two major developments characterized Swiss Alpine Geology in the years between 1810 and 1830. Firstly, it experienced an enormous input through the first application of the newly developing technique of biostratigraphy, after the fundamental studies of Cuvier and Brongniart in the Paris Basin and Smith in Southern England. Early (pre-biostratigraphic) attempts to correlate sedimentary rocks in the Alps with certain members of the stratigraphic rock column in extra-Alpine Europe were mainly based on the petrographic appearance and the relative order of succession of the rocks. Following this purely lithostratigraphic approach, Leopold von Buch (before around 1825; see also von Buch 1809: 120) and Hans-Conrad Escher (see Studer 1825: VII–VIII) arrived at the erroneous conclusion that virtually the whole chain of the Calcareous Alps of Switzerland (encompassing roughly the external parts of the Swiss Alps between the Prealps south of Lake Geneva and the northern part of the Glarus Alps) was composed of "*Alpenkalk*" (limestone of Zechstein age—i.e. Upper Permian in modern nomenclature) or even "*Übergangskalk*" (pre-Zechstein transition limestone). This view, which banished all rocks younger than the Upper Permian from the Swiss Calcareous Alps, was challenged by William Buckland and Alexandre Brogniart (fide Studer 1825: IX and Studer 1834: 9), who correlated some fossil-bearing rocks from the Swiss Alps—because of their fossil content and not so much because of their petrographic appearance—with Jurassic and even Lower Tertiary formations in Southern England and the Paris Basin. In the following years, the increasing knowledge of both, the standard biostratigraphy of tectonically undisturbed areas of Europe and the geology of the Alps, led the still small but nevertheless growing community of Alpine geologist to accept that extensive parts of this mountain chain were built of relatively young rocks. However, a more detailed stratigraphy of the Alps, based on macrofossils, could only be worked out later, in the years between 1830 and 1880 (Dal Piaz 2001).

The second important development was the recognition that many of the supposedly very old central masses composed of granite and gneiss exhibit complexly structured contacts to the sedimentary rocks adjacent to them. Quite often, the former even overlap the latter. Excited by the (mostly unpublished) descriptions of some early Alpine explorers in the eighteenth century (Studer 1863: 590), Theodor Hugi organized several adventurous expeditions into the Bernese Oberland and adjacent areas in the late 1820s in order to study the alleged superposition of "*Ur-Gebirge*" onto "*Flötzgebirge*" (Hugi 1830). Summarizing his results from an expedition to the Jungfrau, Hugi clearly stated (1830: 52): "*Primordial rocks resting on the limestone formation* *just described, is a matter of fact and can only be denied by those who have not yet seen the area.*" (Author's translation; for original text, see Online Resource 1, quotation 1).

Furthermore, he described granite crosscutting older gneiss and he claimed that limestone was altered ("*Metamorphosen der Kalkgebilde*") at the contact to the granite (op. cit. 1830: 29–30). Hugi explained all these findings by assuming that *after* the deposition of many secondary rocks constituting the "*Flötzgebirge*", crystalline (metamorphic) rocks ascended in a half fluid state from the interiors of the Alps and elevated, broke and finally overflowed the secondary sedimentary rocks (e.g. Hugi 1830: 217, 298–299). As Hugi correlated the limestone, allegedly penetrated and metamorphosed by granite, with the Lowermost Jurassic (e.g. Table 2 in Hugi 1830), Sir Charles Lyell cited Hugi in the third volume of his "Principles of Geology" (Lyell 1833: 358) as an important reference for his proposal that the formation of rocks formerly called "primitive" (as e.g. granite, gneiss, or mica schist) was not restricted to an early period of Earth's history.

2.3 1830 to 1853: the Studer–Escher dyad

These two fundamental developments in Alpine Geology around 1830, namely, the application of biostratigraphical methods, and the recognition of complicated tectonics affecting both crystalline and sedimentary rocks (erroneously explained by assigning a Tertiary age to the former rocks), formed the conceptual base for the first detailed tectonic syntheses of the Swiss Alps (and adjacent areas) between 1834 and 1853. These syntheses were achieved and carried out by two of the most prominent protagonists in the history of Swiss geology: Bernhard Studer from Berne (Fig. 2) and Arnold Escher from Zurich (son of Hans-Conrad Escher, Fig. 3). Though of quite contrasting temperament and character, these two men proved to be a very successful team and provided the base for modern Alpine geology as laid down in Studer's two-volume magnum opus, "*Geologie der Schweiz*" (Studer 1851, 1853). As Studer frankly admitted (1851: III), he heavily relied on data from Escher and he even claimed that the two men's geologic views of the Alps had become so interwoven ("*durchdrungen*") during the years, that it often would be difficult to decide which part of the great stock of data and ideas should be ascribed to whom of the two friends (see also Carozzi 1983: 14). It has often been stated that Escher's theoretical views regarding Alpine tectonics differed fundamentally from Studer's, especially when treating the question whether crystalline rocks played an active (i.e. uplifting) role in Alpine orogenesis (as envisaged by Studer) or were passively deformed together with their sedimentary cover (e.g. Heim 1878b: 125, 135; Cadisch 1953: 12; or Trümpy 1980: 11, 1998: 165). As we tried to show elsewhere (Letsch 2011), there is rather scant evidence in Escher's published writings that there was really such a fundamental difference between his and Studer's theoretical concepts. Until around 1850, Escher's views were probably quite close to Studer's. However, it will be shown below that there is

Fig. 2 Bernhard Studer (1794–1887), Professor of Mineralogy at the University of Berne. Picture taken from Heim (1919, facing page 6)

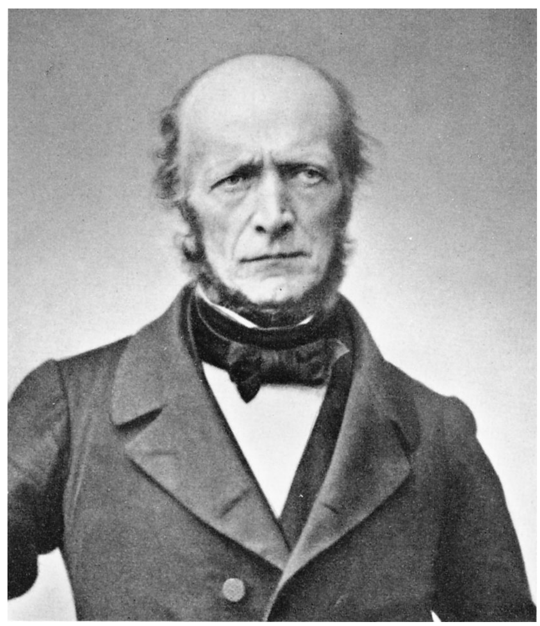


Fig. 3 Arnold Escher von der Linth (1807–1872), son of Hans-Conrad Escher von der Linth and first Professor of Geology at the University of Zurich and at the Swiss Federal Institute of Technology (ETH). Picture taken from the ETH Festschrift 1855–1955

good reason to believe that Escher, indeed, changed his mind sometime between 1850 and 1854 and that this change led him to fundamentally new concepts, such as the Glarus Double Fold. In order to do so, we first have to summarize the tectonic model of Studer and Escher during the classic period from 1830 to 1850 when both men seem to have shared most of their conceptual ideas.

The two basic principles of this Studer–Escher-model can be summarized as follows. First, crystalline and sedimentary rocks were affected by somewhat mysterious "metamorphic" processes (due to heat, vapor, percolating fluids, and pressure[1]) well into quite recent times (Lower Tertiary). Due to these metamorphic modifications, preexisting rocks sometimes totally changed their lithology and internal structure and expanded in their volume. These metamorphic processes could even change original sediments into rocks which today are considered to be magmatic or metamorphosed magmatic rocks, such as granite or serpentinite (Escher and Studer 1839: 202–203; Studer 1847: 153). Thus, most crystalline rocks were indeed considered to represent the end-members of metamorphic evolution chains (see also von Raumer and Neubauer 1993: 56).

Second, as a consequence of their expansion and the accompanying decrease in density, metamorphic rock masses were forced to flow vertically upwards in a ductile or mush-like (but not necessarily molten or very hot, cf. e.g. Studer 1851: 167) manner. The resulting metamorphic domes (or diapirs in today's parlance) elevated the overlying sedimentary strata, bent them either into large-wavelength folds or dragged them towards the centres of the domes and thereby folded them into isoclinal folds (see Fig. 4[2]). Eventually, the sedimentary cover was torn apart and the metamorphic rock masses extruded at the surface, thereby laterally overflowing their original sedimentary covers (at the time referred to as "vertical tectonics", see further discussion below). An excellent illustration of this model is provided by Studer's (1837) description of the mountains between the Lenzerheide and Arosa in the canton of Graubünden (see Fig. 5). From a central vent below the Rothhorn, a vertically risen mass of amphibolite-bearing gneisses laterally overflowed in a mushroom-style its original cover consisting of white limestone and dolomite at the Weisshorn or the Lenzer Alp (Studer 1837: 29; cf. also Theobald 1862: 42). It is important to note that Studer's model did not require a net crustal contraction across the whole Alpine chains. Of course, he acknowledged the fact that parts of this mountain system, as e.g. the Helvetic zone of the Swiss Alps (Studer 1847: 215, 1860) or the Jura Mountains (Studer 1847: 235), have been horizontally contracted up to half of their original horizontal extension. However, as can be seen from his theoretical diagram (Fig. 4) and his descriptions of the process of mountain building (cf. e.g. Studer 1834: 2–3, cf. also Heim 1919: 8), he considered mountain building to be a mainly "neutral" process i.e. he thought the central parts of a mountain chain would expand during orogenesis and that this expansion would be compensated within the adjacent zones ("*sedimentäre Nebenzonen*"). That orogeny is rather an extending and not so much a contracting process, was a common assumption in European geology around 1850 (see e.g. Naumann 1858: 941). Even in later years, Studer clearly adhered to this model as the following quotation demonstrates (Studer 1860: 15–16): "*I think it* [the lateral force which folded the Helvetic zone of the Swiss Alps and the Jura Mountains] *is rather due to the development or the broadening of the crevasse dissecting the Earth's crust by means of which the central zone of the Alps, composed of protogine, serpentinite, metamorphic schist, anthracite rocks, Verrucano, and all that is to be found there, was exposed, like a body that is pressed through a buttonhole, thereby pushing aside its margin in order to provide space*." (Author's translation; for original text see Online Resource 1, quotation 2).

Even though Escher rarely spoke of theoretical issues in his publications, there is good evidence that he shared Studer's belief in metamorphic processes and that he accepted them as a main driver of Alpine orogenesis—at least before around 1854. For instance, he clearly accepted the occurrence of solid-state metamorphism when discussing some granitoid clasts in the Middle Penninic Falknis breccia from the Rhätikon area (Escher 1846a: 440): "*I have referred to these granitoid bodies as segregations in this description, as I think that they originated indeed in situ by means of molecular movements and maybe other unknown processes out of the surrounding*

[1] It has to be pointed out that only pressure due to gases and vapors (elastic fluids) was subsumed under this heading. Pressure due to the overlying rock column (lithostatic pressure) was explicitly excluded as a possible agent of metamorphism (see e.g. Studer 1847: 116).

[2] Figure 4 is copied from Studer's influential textbook "Lehrbuch der physikalischen Geographie und Geologie". In drawing this figure he was inspired by a figure of the the famous British geologist and politician George Poulett Scrope (1825: Fig. 29), however, with the remarkable deviation that in Studer's figure the axial planes of the folds are systematically inclined *away* from the central mass, whereas on Scrope's figure they dip *towards* the central mass. Naumann (1858: 947) copied Studer's version without citing either Studer or Scrope. As a consequence of this, Haarmann (1930: 43) claimed that Naumann should be considered the first geologist having discussed and illustrated the mechanism of gravity gliding. In regard of this statement, we would like to point out that Naumann neither drew the geological section under consideration himself nor that it shows folding due to gravity gliding. Haarmann (1930: 104) frankly admitted himself that the vergence of the folds is *not* in accord with the gravity gliding mechanism. This is due to the fact, that Studer did not want to illustrate this folding mechanism but rather drag folding due to vertical uplift of underlying metamorphic domes (see text). We are tempted to regard this episode as a nineteenth century case of plagiarism in the German academic community.

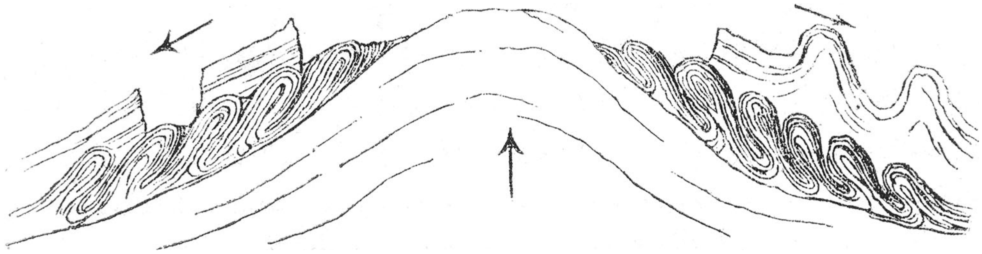


Fig. 4 Theoretical scheme of mountain building due to an uprising mass of metamorphic rocks, according to Studer (from Studer 1847: 183). The sedimentary cover immediately overlying the metamorphic core of the mountain range is supposed to have been dragged towards the central vent or fissure, causing folding as indicated

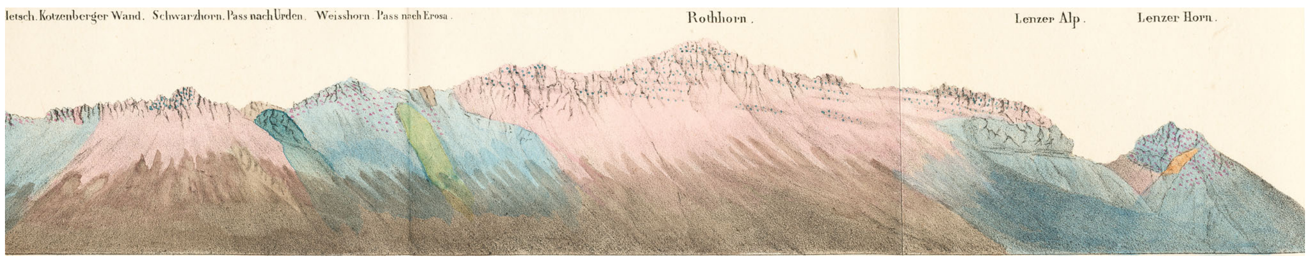


Fig. 5 Geological panorama view of the mountains between Arosa and Lenzerheide, as seen from Parpan (from Studer 1837: Table 2). It illustrates Studer's tectonic model of vertically upward movement of metamorphic rocks (*pink* mica schist, quartzite, gneisses, *blue dots* denote hornblende rich parts), which crosscut and eventually overflow their sedimentary cover (*blue* limestone, *blue with red dots* dolomite, *light green* gypsum, *brown* Bündnerschiefer). The *dark green* body just below "Pass nach Urden" is composed of serpentinite. For a more recent geological explanation of this section, the reader is referred to Roesli and Trümpy (1967)

rock mass. It is nevertheless uncertain whether these peculiar phenomena allow us to draw any conclusions in regard of the widespread processes of talcization and the metamorphism of neptunic sediments." (Author's translation; for original text see Online Resource 1, quotation 3).

He furthermore clearly linked the metamorphic change of sedimentary rocks to the disturbance of the ordinary stratigraphic column in the Alps (i.e. Alpine tectonics), when he argued (Escher 1846b: 53): "*Such disturbances of the original stratification of sedimentary rocks are displayed most impressively in the areas adjacent to crystalline rocks, as we can observe in the Alps, and they weaken and eventually disappear as the distance to the latter increases. Thus we may conclude with some certainty that these disturbances and the inequalities of the Earth's surface they must have caused, were the consequence of the processes which determined today's nature and distribution of the crystalline rocks.*" (Author's translation; for original text see Online Resource 1, quotation 4).

Thus, like Studer, he ascribed metamorphism and tectonics to the same causes, namely to the localized action of pressure and temperature, assisted by some hot fluids or gases, acting from the interior of the Earth vertically upwards, as can be seen from his description of the Aar massif (Escher 1846b: 84): "[…] *the forces operating in the Earth's interior seem to have acted preferentially from certain central points or lines, whereby more or less independent mountain massifs such as the Finsteraarhorn mass* [i.e. the Aar massif] *originated.* […] *An approximate model of such a massif can be produced, at a much smaller scale, when a moderately stiff horizontal mass is subjected over a certain length to a vertical pressure acting from below. As a consequence, the mass is warped up until it bursts whereby longitudinal and transverse furrows are created and the surface of the mass is elevated in a crescent shape at the ends of its long axis.*" (Author's translation; for original text see Online Resource 1, quotation 5).

Stratigraphic anomalies, such as the juxtaposition of older rocks onto younger ones, were also ascribed by Escher to the action of metamorphic rocks overflowing younger sedimentary rocks (Escher 1846b: 54): "*If, for instance, a rock of unquestionable sedimentary origin is covered by a flat lying crystalline rock, it becomes immediately clear that the sedimentary rock was already there before it was covered by the crystalline blanket. Furthermore, if the sedimentary rock shows any clear signs of changes it suffered after its deposition, it becomes at least highly probable that its cover was emplaced onto it not due to a merely mechanical disturbance but that rather the* *changes of the sedimentary rock and the formation and emplacement of the crystalline blanket happened simultaneously and were due to one and the same cause* […].” (Author’s translation; for original text see Online Resource 1, quotation 6).

It seems worth noticing that Escher, during the 1840s, repeatedly questioned the possibility of purely mechanical explanations of large-scale overthrust masses of this size (cf. e.g. quotation 6, or Anonymous 1841: 61–62). However, he accepted this explanation for such phenomena on a smaller scale such as local thrusts in the Helvetic zone (in the Rigihochfluh area, cf. Escher 1853: 56 and his Fig. 10), or for the overthrusting of the Helvetic nappes over the southern margin of the Subalpine Molasse (see Escher 1845: 549, 1846b: 76; see also Letsch 2011: 35).

3 The Glarus Alps

3.1 Interpretations before 1847: “vertical tectonics” and “metamorphism”

So far, we have sketched the basic principles of Studer’s tectonic model of Alpine geology in general and tried to demonstrate that Arnold Escher’s early thoughts on these issues were strongly influenced by his friend Studer. In this section we will focus on the special case of the Glarus Alps, where Studer’s model encountered severe problems which finally led Escher to abandon it.

The stratigraphic anomaly in the Glarus Alps (the Glarus overthrust) was first described by Hans-Conrad Escher (1809: 345, cf. also the discussion in Staub 1954). He mentioned a brick-red greywacke (Glarus Verrucano) resting on Alpine limestone (“*Alpenkalkstein*”) on the right side of the Linth valley above Glarus. However, according to Wernerian global lithostratigraphy, greywacke should only occur in the so-called transition rocks which occur between the “*Uranfänglichen Gebirgen*” and the “*Flötz-Gebirgen*” (see Sect. 2.1), whereas the “*Alpenkalkstein*” was considered to be part of the “*Flötz-Gebirge*”. In Glarus, therefore, older rocks clearly rested on younger ones. Von Buch (1809): 175 ff.) removed this anomaly by denying the greywacke-character of the Verrucano and instead classified it as a member of the “*Flötz-Gebirge*”.

A fundamental change in the geologic interpretation of the Glarus area was brought about by Studer (1827) in one of his first papers on Alpine geology. He described the Glarus Verrucano in quite some detail (and first mentioned volcanic rocks from the Kärpf area) and came to the conclusion that it should not be considered as an individual formation of defined age but rather as a secondary modification of other rocks belonging to different formations (see also Studer 1851: 412). Implicitly, he thus interpreted the Glarus overthrust as a volcanic or a metamorphic phenomenon (see also Milch 1892: 17–20). The juxtaposition of Verrucano on fossil-bearing and thus truly neptunic rocks (i.e. unaltered to slightly modified sedimentary rocks) was explained by Studer in terms of vertical tectonics and he explicitly refuted a mechanical (i.e. thrust) explanation (Studer 1851: 421): “*In order to explain these occurrences* [the Glarus overthrust] *by means of an overthrow* [Umstürzung], *one would have to assume that the whole southern part of the Canton* [Glarus] *is in a state of inverted bedding; and even with this assumption one could not explain the phenomenon sufficiently. It seems easier to assume that the conglomerates of the Verrucano ascended from the depth accompanied by deeply penetrating metamorphic processes. They thereby partially bent up, pushed aside, and partially covered their sedimentary cover*. […] *this upward movement* [of the Verrucano] *seems to have taken place along a fracture* [Spalte] *extending from the Kärpf Mountain to the Murgthal* […].” (Author’s translation; for original text see Online Resource 1, quotation 7). The mechanism thus described is in accordance with Studer’s general view of mountain building as exposed in Studer 1860 (cf. quotation 2 of this paper). Even though Studer made a clear statement in the passage quoted, he nevertheless remained rather reluctant with making any further interpretations. The accompanying figure (see Fig. 6) clearly shows the juxtaposition of Verrucano and Jurassic limestone over Tertiary sediments but the figure does not allow the recognition of the hypothetic fracture beneath the Kärpf Mountain.[3]

This kind of vertical tectonic interpretation was taken up to some degree by Arnold Escher in his early descriptions of the Glarus area (Escher 1846b), as we tried to demonstrate elsewhere (Letsch 2011). Even though Escher’s cautious way of writing allows for some space for interpretation, we know of no statement in his published work (except the often cited sentence in Anonymous 1841 which—however—seems not to stem directly from Escher’s pen) which would justify Staub’s (1954), Trümpy’s (e.g. in Funk et al. 1983: 103, or Trümpy 2001; Trümpy and Westermann 2008), or Dal Piaz’s (2001: 103) suspicion that Escher initially correctly assumed *one single* overthrust of older Verrucano (called “Sernifit”, “Sernfschiefer”, or “Sernfconglomerat” by him) onto younger flysch, and only later changed his mind and instead advocated the untenable model of two recumbent folds facing each other (the Glarus Double Fold). On the contrary,

[3] This discrepancy between the rather explicit formulations in the text and the rather reluctant drawing might be an indication that the text was written by Studer whereas the figure was drawn by Escher. This kind of labour-division had already been practised in Escher and Studer (1839).

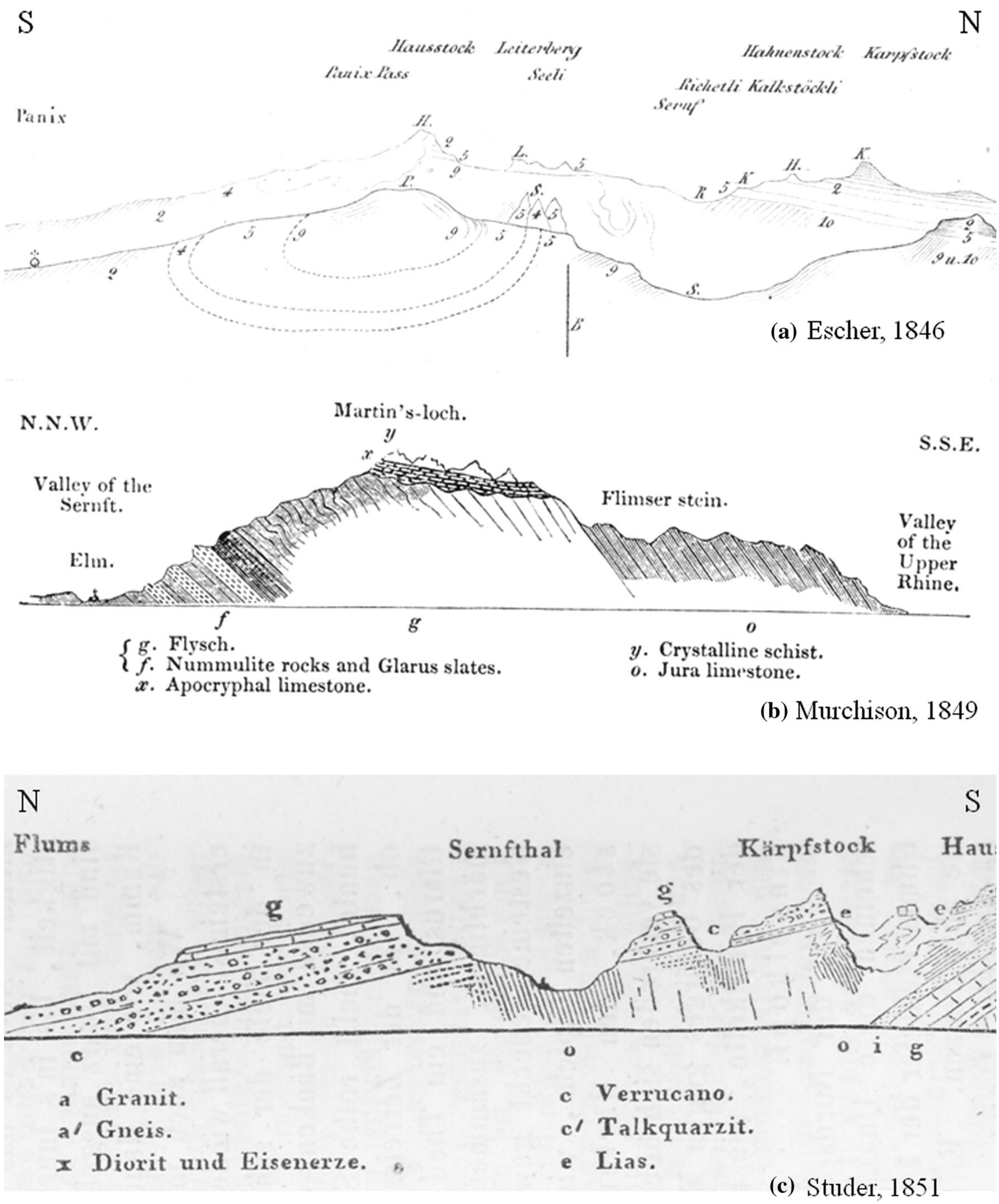


Fig. 6 Three different mid nineteenth century geological cross-sections illustrating different view of the Glarus overthrust. Abbreviations and numbers: **a** Escher (1846b: Fig. 2): *1* quartzose talc schists, *2* Verrucano, *3* coal bearing shale, *4* Lower oolite (Jurassic), *5* Middle and Upper oolite (Jurassic), *6a*,*b* Lower Cretaceous, *7* Gault (Middle Cretaceous), *8* Upper Cretaceous, *9* Nummulitic limestone (Eocene), *10* Flysch (Tertiary), *B* Fault zone ("Bruch und Verschiebungsflächen"); **b** Murchison (1849: Fig. 28): for abbreviations see legend (below the cross-section); **c** Studer (1853: p. 423): *a* granite, *a′* gneiss, *x* diorite and iron ore, *c* Verrucano, *c′* talc bearing quartzite, *e* Lower Jurassic, *g* Middle Jurassic limestone, *i* Lower Cretaceous, *o* Nummulitic limestone and Flysch (Tertiary)

Escher made his point rather clear that he did not consider the Glarus overthrust as a mechanical (even though he accepted this explanation for smaller thrusts as shown in Sect. 2.3) but rather as a metamorphic phenomenon which juxtaposed a heterogeneous mélange of crystalline (metamorphic) and sedimentary rocks (Glarus Verrucano and some tectonic slivers at its base) onto the Glarus flysch (1846b: 54–55): "*Thus we can conclude from the experience gained in the Glarus Alps, which will be described in the following, that the crystalline rocks, generally called*

Urgebirge [primordial], *were formed not only long after the creation of the vegetable and animal kingdoms, but even in relatively modern times. The revolution which shaped the present-day physical appearance of the Glarus Alps was thus one of the last ones that had affected the Earth's crust in that area before the creation of man. In a country whose subsurface had been affected by such profound changes, we may well expect to find obvious proofs for these changes as e.g. fractured and contorted layers, juxtaposition of crystalline rocks onto sedimentary rocks, engulfment of single blocks of sediments by masses of crystalline rocks, etc. However, the geologist's expectations are exceeded enormously by the facts encountered in the Glarus Alps which still remain to be sufficiently explained in the future*." (Author's translation; for original text see Online Resource 1, quotation 8).

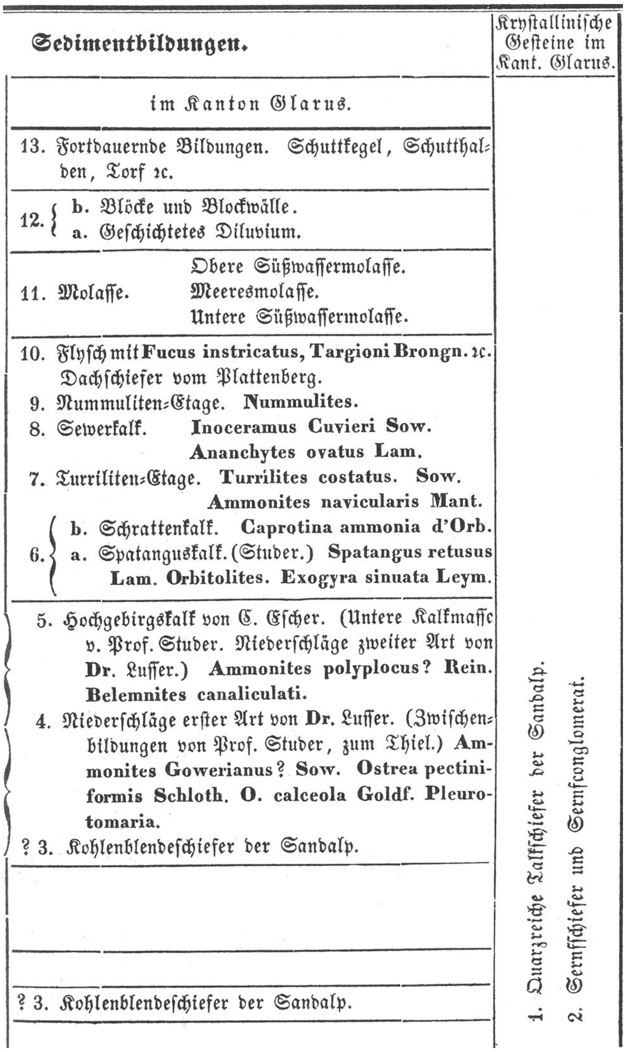
Studer's and Escher's geological cross-sections from the southern part of the Canton Glarus (partly reproduced in Fig. 6) clearly show that they correctly observed the Glarus overthrust (i.e. Verrucano and Jurassic limestone overlying Tertiary rocks). However, to draw from these figures the conclusion that they consequently also accepted a thrust interpretation in the modern sense seems not to be justified. In retrospect, this conclusion may appear rather straight forward but we have also to bear in mind what was the state of the art at the time when these figures were drawn. We have quoted above some examples which illustrate Escher's and Studer's reluctance to accept mechanical (i.e. thrust tectonic) explanations for tectonic phenomena of the scale of the Glarus overthrust. On the other hand, the same two geologists were rather easily inclined to invoke "metamorphic" or "volcanic" interpretations for many overthrusts in the Swiss Alps (including the Glarus area, cf. the quotations in this and the preceding chapter). Escher did indeed (1846b, see our Fig. 6) indicate some mechanical ruptures (faults) on his cross-section (marked with "B" and a vertical line pointing to the fault plane) but all of them describe rather small scale features (e.g. a local thrust of Jurassic rocks over Tertiary rocks just beneath "Seeli" in Fig. 6). The extremely prominent Glarus overthrust (e.g. between "Kärpfstock" and "Hahenstock") is not marked with a B. This omission cannot have happened by accident: Escher just did not consider the Glarus overthrust as a mechanical feature at that time.

We tried to demonstrate above and elsewhere (Letsch 2011) that Arnold Escher still in 1846 seems to have favored a metamorphic rather than a mechanical interpretation of the Glarus overthrust. In a public lecture held in Zurich in 1847 (Escher 1847), he seems to have made a step forward as he described the geology of Glarus and surrounding areas as a "*breaking and overthrust of whole rock masses*" ("[…], *Brechung und Überschiebung ganzer Gebirgsmassen* […]"). However, he still doubted the very existence of non-metamorphic sedimentary rocks older than the Jurassic in the Swiss Alps (Escher 1847: 21).

3.2 Escher's conversion to the Double Fold concept (1847–1854)

An important step towards a modern interpretation of the Glarus anomaly was the increasing awareness that the Glarus Verrucano or Sernifite (and related formations in other parts of the Alps) has to be considered as an only slightly metamorphic, sedimentary formation (with some volcanic intercalations) of a defined age. Even though Escher noticed early on that some parts of the Verrucano show clear signs of a mechanical i.e. sedimentary origin (e.g. Anonymous 1841: 59; Escher 1846a: 436), he hesitated to draw the conclusion that this formation really represents the old, more or less sedimentary, basement of the normal stratigraphic column of the Glarus Alps (see Fig. 7). However, without making the point that the Verrucano is the oldest sedimentary formation exposed in the Glarus Alps, one of the most striking attributes of the Glarus overthrust (namely the marked age contrast implied by the juxtaposition of pre-Triassic over Tertiary rocks) could not be demonstrated. Furthermore, a vertical tectonic model as envisaged by Studer (and probably also by Escher in the early 1840s) did not imply any net horizontal contraction of the area of the Glarus Alps, in accordance with Studer's theoretical model of mountain building (cf. Sect. 2.3).

In the summer of 1848, Escher guided the eminent British geologist, Sir Roderick Impey Murchison through the Swiss Alps (Murchison 1849). They also visited the Glarus Alps and crossed the Segnes pass between Elm and Flims. Murchison seems to have been deeply impressed by the juxtaposition of "*hard grey subcrystalline limestone*" of Jurassic age (the Lochsiten mylonite; labeled as "apocryphal limestone" in Fig. 6) onto Tertiary flysch (loc. cit.: 247). Murchison further wrote: (loc. cit.: 248): "*But it became necessary to admit, that the strata had been inverted, not by frequent folds, as on the sides of the lake of Altdorf or in the Hoher Sentis, but in one enormous overthrow; so that over the wide horizontal area abovementioned, the uppermost strata which might have been lying in troughs or depressions due to some grand early placation, were covered by the lateral extrusion over them of older and more crystalline masses; the latter having been forced from their central position by a movement operating from centre to flanks, or in other words, from the axial line of disturbance towards the sides of the chain*." These often cited words can indeed be taken as evidence that Murchison (and probably also his guide Escher) recognized the true nature of the "Glarus anomaly" as a thrust in the mechanical and modern sense (e.g.



Sedimentbildungen.	Krystallinische Gesteine im Kant. Glarus.
im Kanton Glarus.	
13. Fortdauernde Bildungen. Schuttkegel, Schutthalden, Torf ꝛc.	
12. { b. Blöcke und Blockwälle. a. Geschichtetes Diluvium.	
11. Molasse. Obere Süßwassermolasse. Meeresmolasse. Untere Süßwassermolasse.	
10. Flysch mit **Fucus instricatus, Targioni Brongn.** ꝛc. Dachschiefer vom Plattenberg. 9. Nummuliten-Etage. **Nummulites.** 8. Sewerkalk. **Inoceramus Cuvieri Sow. Ananchytes ovatus Lam.** 7. Turriliten-Etage. **Turrilites costatus. Sow. Ammonites navicularis Mant.** 6. { b. Schrattenkalk. **Caprotina ammonia d'Orb.** a. Spatanguskalk. (Studer.) **Spatangus retusus Lam. Orbitolites. Exogyra sinuata Leym.**	
5. Hochgebirgskalk von A. Escher. (Untere Kalkmasse v. Prof. Studer. Niederschläge zweiter Art von **Dr.** Lusser.) **Ammonites polyplocus? Rein. Belemnites canaliculati.** 4. Niederschläge erster Art von **Dr.** Lusser. (Zwischenbildungen von Prof. Studer, zum Thiel.) **Ammonites Gowerianus? Sow. Ostrea pectiniformis Schloth. O. calceola Goldf. Pleurotomaria.** ? 3. Kohlenblendeschiefer der Sandalp.	1. Quarzreiche Talkschiefer der Sandalp. 2. Sernfschiefer und Sernfconglomerat.
? 3. Kohlenblendeschiefer der Sandalp.	

Fig. 7 Stratigraphic column of the rocks exposed in the Glarus Alps (copied from Escher 1846b). Items 12–13 are unconsolidated Quaternary deposits; items 9–11 are Tertiary formations; items 4–8 are Mesozoic formations (with fossil content indicated in *bold* script), and item 3 is Carboniferous black shale with coal intercalations. Note that Escher obviously hesitated to integrate the Verrucano ("Sernfschiefer und Sernfconglomerat" named after the river Sernf, items 1 and 2) into the normal stratigraphic column. Instead, he put them into the column of the crystalline rocks (*column* to the *right*)

Staub 1954: 140; Trümpy in Funk et al. 1983: 103; or Dal Piaz 2001: 103).[4] However, as pointed out by Trümpy (1991) and Letsch (2011), Escher was still very reluctant to follow Murchison's thoughts. This is nicely illustrated in a letter written to Murchison in winter 1848 (cited in Trümpy 1991). Nevertheless, Murchison's text proves that Escher was very well aware of the difficulties that a metamorphic explanation for the Glarus overthrust, as hitherto assumed by Studer (and partly by Escher himself), inevitably encountered. His mind must have been in a deep twist.

Around 1850 Escher seems to have finally accepted that the Verrucano merely represents an ordinary sedimentary formation of pre-Triassic age. Thus, in his "*Uebersichtstabelle der geognostischen Formationen in Voralberg* [sic!] *und Lombardei nach verschiedenen Beobachtern*" (Escher 1853), he put the Verrucano at the base of the stratigraphic column, just below the "Bunter Sandstein" (Triassic). In the same study, we find Escher's first published suspicion that possibly Alpine tectonics were not merely due to forces acting laterally from well defined central masses (see Sect. 2.3), but that we, instead, also have to consider a more general cause which acted in a horizontal direction and affected the whole Alpine edifice thus implying a net horizontal crustal contraction (Escher 1853:64). Escher wrote (loc. cit.: 65): "[…] *but do these observations not rather lead towards the conclusion that the force which produced the central crystalline massifs and their margins has been surpassed in a way by the force which created the Alpine mountain chain as a whole?*" (Author's translation; for original text see Online Resource 1, quotation 9).

By now, the stage would have been set for a new model to account for the Glarus anomaly. However, Escher never published any such model, but there are some trustworthy witnesses confirming the suspicion that he was indeed thinking and talking about such a model. Eduard Suess, who later became one of the leading global geologists, visited Switzerland in 1854. He talked to both Studer and Escher and he wrote later in his autobiography (Suess 1916: 422–423): "*When I first visited Switzerland, in 1854, there was a severe debate between the two leading Swiss geologists Bernhard Studer and Arnold Escher. This debate concentrated onto the geologic structure of the high mountains in the Cantons of Glarus, St. Gallen and Appenzell. Escher himself explained to me his point of view while standing on top of the Säntis mountain. One encounters soft and easily erodible rocks of young age, the flysch which is composed of sandstone and shale, in the deeper parts of the valleys of the rivers Linth and Sernf. These rocks ascend up to the glaciers of the Clariden mountains. This flysch is covered in the aforementioned valleys by older rocks. This matter of fact has been accepted by Studer, but he hesitated to provide any explanation. The more adventurous Escher was inclined to distinguish two parts, or wings as he called them, in the juxtaposed older rocks. The southern wing would ascend from the Vorderrheintal towards the north up to the*

[4] Even though we admit that the exact meaning of words may change over the centuries, we would like to point out that we personally do not agree with Staub (1954), Trümpy (in Funk et al. 1983), and Dal Piaz (2001). The term "lateral extrusion" of rock masses is, according to our personal judgement, more reminiscent to a vertical tectonic model (a mushroom fold or diapir as proposed by Studer, cf. Fig. 5 or Fig. 3 in Letsch 2011) than to a mechanical overthrust of older rocks onto younger ones.

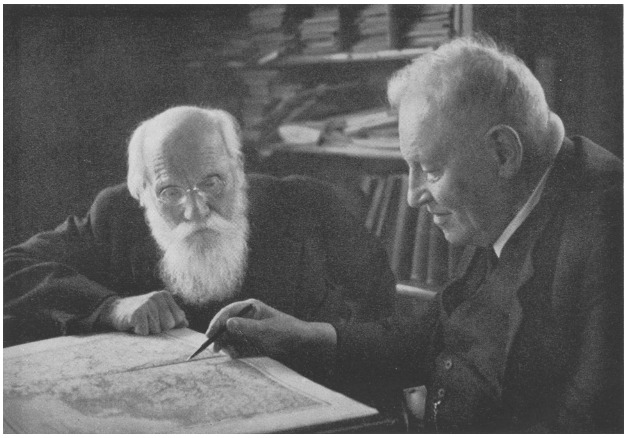


Fig. 8 Albert Heim (1849–1937), Arnold Escher's student and later successor as Professor of Geology in Zurich, together with his friend and scientific opponent Albrecht Penck, in 1921 (taken from Brockmann-Jerosch et al. 1952)

northern slopes of the mountains to the northeast of the Tödi mountain […]. Escher's hypothesis was that the more extended southern wing was moved towards the North and the slightly smaller northern wing towards the South onto the flysch." (Author's translation; for original text see Online Resource 1, quotation 10).

Beyond any doubt, Escher had envisaged the Double Fold theory by 1854 to account for the Glarus anomaly (see also Anonymous 1866 and many quotations in Heim 1878a, b, see also Heim 1907: 9). It thus seems that Escher had finally emancipated himself from the influence of his old friend Studer.

3.3 Articulation of the Double Fold concept by Albert Heim (1871–1878)

As stated above, Escher did not articulate his new hypothesis, at least not in any publications. Alpine geology had to wait some years until Escher's young and very productive student, Albert Heim (Fig. 8), entered the stage. From around 1870 onwards Heim conducted an incredible amount of meticulous mapping and geologic research in the Swiss Alps, first focusing on the areas around the eastern end of the Aar massif (Tödi-Windgällen area and the Glarus Alps, see Heim 1871, 1878a, b). Thanks to his fundamental contributions to as well as to such diverse fields as applied geology, Quaternary geology, and structural geology tectonics (see e.g. Milnes 1979), Heim quickly became the probably most influential Swiss geologist of his days and dominated Swiss geology for more than 50 years.

One of his greatest early merits was that he demonstrated beyond any doubt the passivity of crystalline rocks during Alpine orogenesis. As shown above, Studer considered crystalline rocks as the main active motor of orogenesis, and thus attached a relatively young age to them. Cleavage planes in gneisses were explained by Studer as a kind of cooling fractures which the rocks had acquired after their final tectonic emplacement (e.g. Studer 1851: 167). Heim doubted these inferences—probably influenced by his teacher Escher (see Sect. 3.2). The most compelling evidence for the passivity of crystalline rocks could be demonstrated from the inverted contact between Mesozoic sedimentary rocks (iron-oolithic limestone of Mid-Jurassic age) and its overlying crystalline substratum (Upper-Carboniferous porphyry) in the Windgällen area in the Canton of Uri (see Heim 1871: 248, 1878a: 62–65, 1878b: 114–117). There, the, now underlying, Jurassic limestone contains reworked blocks and pebbles of the, now overlying, Windgällen porphyry (Fig. 9). The latter builds the core of a recumbent fold with the Mesozoic limestones enveloping the porphyry (see also Milnes 1979) which was considered by Studer (1847: 174–175, 1853: 179) to be of the same age as or younger than the folded Jurassic limestone. In accordance with Studer's general scheme of mountain building, the uprising porphyry was assumed to have uplifted and folded the overlying Mesozoic to Lower Tertiary sedimentary cover. However, the reworked pebbles of porphyry and the lack of any clear signs of contact metamorphism in the Jurassic limestone led Heim to abandon this theory. Due to this very compelling evidence, the Windgällen area became one of the cornerstones of Heim's view of Alpine tectonics, particularly with regard to the Double Fold model for the Glarus region.

The Glarus Alps constitute the along-strike continuation of the Tödi-Windgällen area. However, due to axial plunge to the ENE, higher tectonic units are exposed there (the Glarus nappes). The principles of Heim's Double Fold model which tried to explain the nappe structure of this area have been reviewed several times (see e.g. Trümpy 1991; Trümpy and Westermann 2008) and will not be repeated here (cf. Fig. 1). Nevertheless two important points should be mentioned. First, the Double Fold concept no longer called for any mysterious metamorphic fluids which changed the physical constitution of whole mountain masses and caused them to extrude out of narrow fissures, as envisaged by the Studer (and partly Escher) model. The Double Fold was a "mechanical" concept (as defined by Letsch 2011: 34–36) as it basically relied on pressure (a factor almost completely neglected by Studer, cf. Sect. 2.3). Heim (1878b) distinguished two types of pressure: vertical (lithostatic) pressure put solid rocks into a state of "latent plasticity", and a horizontally acting pressure (due to, he thought, the Earth's contraction) folded and deformed the rocks. Second, the new idea accepted a net horizontal crustal contraction of the whole Alpine chain (and even the whole circumference of the Earth). These two inferences later formed the base of the nappe concept

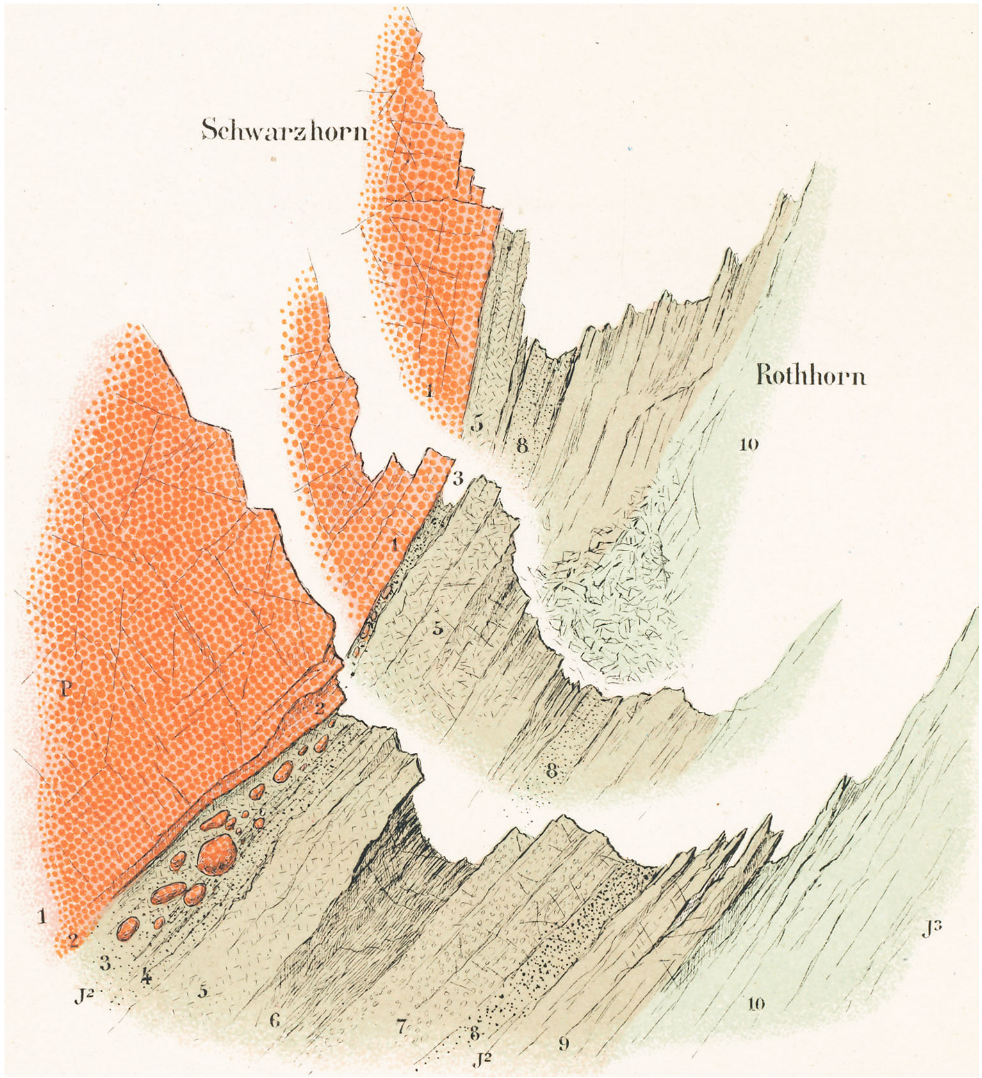


Fig. 9 Detailed section of the inverted stratigraphic contact between Upper Carboniferous porphyry (*red*, marked p, subdivided into two parts, 1 and 2) and Middle Jurassic iron-oolithic limestone (*brown*, marked J^2, subdivided into layers 3–9, from oldest to youngest) in the Windgällen area (Canton of Uri). Layer 3 contains reworked pebbles and blocks of the originally underlying porphyry thus proving the higher age of the latter. From Heim (1878a: Plate 4)

and they are essentially considered to be correct today, except for the assumption of global contraction.

Seen in a greater context, the proposal of the Double Fold concept marks the change from ideas based on "*vertical tectonics*" (deformation due to vertical extrusion of molten or semi-molten materials; *active* influence of the crystalline core of the Alps, pushing aside and intruding the sedimentary rocks) to ideas of "*contraction*" (deformation due to crustal shortening, at the time thought to be caused by global contraction; *passive* reaction of the ancient crystalline core of the Alps, deforming together with the sedimentary cover rocks) in Swiss Alpine geological research (cf. Sengör 1990). Parallel to the articulation of the Double Fold model, Heim reinterpreted the structure and origin of the external crystalline massifs of Switzerland (such as the Aiguilles rouges or the Aar massif) in a way which has proved to be essentially correct, still today. Contrary to the classic Studer model (i.e. the crystalline massifs as active uplifting and deforming agents of mountain building), Heim (1878b: 111–186) interpreted them as large-scale crustal folds which had been deformed mechanical together with their sedimentary cover due to a general horizontally acting force long after the granites and gneisses constituting them had been formed (Fig. 10). The crystalline massifs and the Glarus Double Fold were, according to Heim, two different expressions of the same cause (Earth's crustal shortening, cf. Arbenz 1937: 337) and they compensated each other along strike (Heim 1878a: 95.96, 1878b: 172) such that the total horizontal contraction remained constant along strike.[5] Heim was not

[5] This point is quite important as it is—to our knowledge—one of the earliest approaches to formulate the mass balance principle in tectonics, a principles which has been extensively used in the twentieth century after the fundamental discussion by Laubscher (1965: 256–257), and which formed one of the bases of the technique of constructing balanced cross section which developed from the late 1960 s onwards (see e.g. Ramsay and Huber 1987: 543–559 for a discussion).

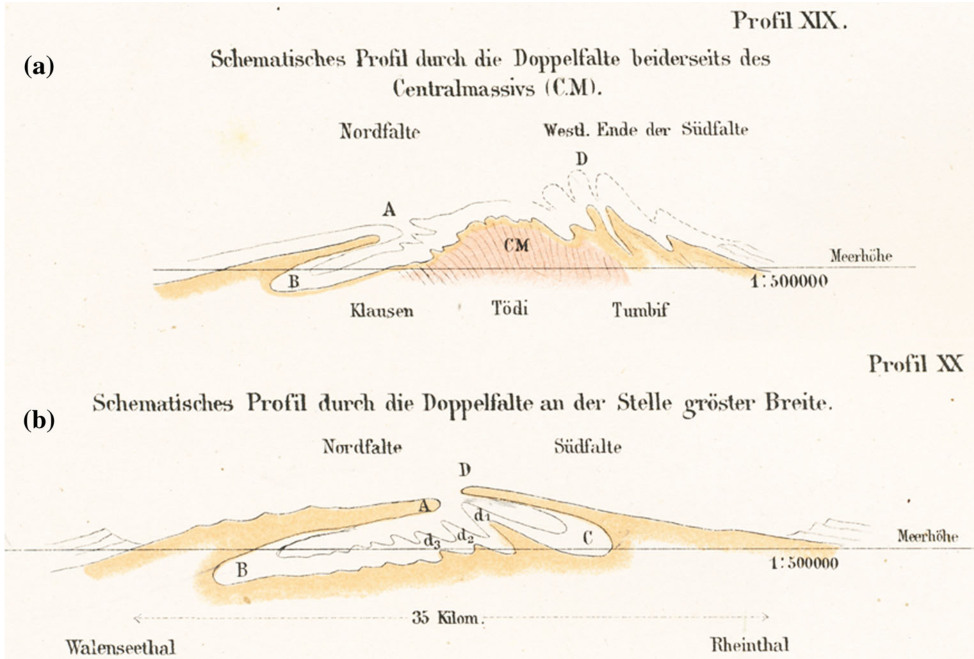


Fig. 10 Schematic drawing illustrating the spatial relationship between the Aar massif (CM, shown in *red*) and the Glarus Double Fold (*brown* Verrucano, *white* Mesozoic and Tertiary rocks). **a** Schematic N–S profile through the Double Fold on the west side of canton Glarus. **b** Schematic N–S profile through the Double Fold on the east side of canton Glarus, at its broadest point. Both profiles, looking E (in the direction of plunge of the folds). Figure is taken from Heim (1878a: Plate 7)

entirely alone in proposing such views which were not in accord with the ruling orthodoxy of his days: also, for example, Favre (1867a, b) and Suess (1875) arrived at similar conclusions. However, Heim was the first one to try to quantify the amount of horizontal contraction (1878b: 210–215). Heim explained plastic deformation (i.e. without any ruptures) of previously indurated rocks by the latent plasticity which develops under considerable lithostatic pressures. He thus displaced the realm where tectonic deformation takes place deep into the Earth's crust, whereas Studer and most other Alpine geologists of these days implicitly assumed that tectonics could and also does take place at the Earth's surface. They thus thought and spoke of extruding mush-like metamorphic masses and gaping fractures which formed as a corollary of these extrusions in the overlying rock masses directly at the Earth's surface (cf. the Jurassic and Cretaceous rocks on top of the Verrucano in Fig. 6). The gaping fractures supposedly also determined the courses of Alpine rivers and valleys. Heim, on the other hand, was forced to assume post-tectonic vertical uplift and a corresponding amount of erosion in order to explain the exhumation of rocks which had been deformed deep in the Earth's crust. This different view had thus also fundamental consequences for geomorphology as shown by Letsch (2014).

To sum up this discussion, the Double Fold concept was by no means just an isolated, erroneous tectonic monstrosity. It was, on the contrary, a rational tectonic scheme embedded into a totally new view of how to (even quantitatively!) explain and interpret Alpine orogenesis in terms of horizontal contraction (crustal shortening) and plastic deformation due to lithostatic overburden.

4 Some final thoughts: the Double Fold as an expression of a new way of thinking in Alpine tectonics

The aim of the present article is to demonstrate that the Double Fold concept has to be viewed as an important scientific step forward in Alpine geology as it marks the change from "metamorphic" to "mechanical" approaches in Alpine tectonics. However, the Double Fold has later been portrayed as an unnecessary detour (a tectonic monstrosity or even an absurdity) on the otherwise relatively straight route of Alpine geologic research, leading from Arnold Escher's meticulous field observations to the equally meticulous field mapping of numerous geologists, such as Marcel Bertrand, Hans Schardt and Maurice Lugeon, which led to what has been called the "nappe tectonic revolution". What might have been the reasons for this somewhat unfair treatment of such an important scientific achievement? Two quite different approaches seem feasible to answer that question.

For sure, the difficult character of its main proponent (Heim) and the very tedious, long lasting and polemic declining phase of the Double Fold concept prevented some members of the Swiss geological community from accepting its positive parts. This seems to apply especially to some influential successors of Heim in Zurich such as Rudolf Staub (1890–1961) and Rudolf Trümpy (1921–2009). Both men shared a dislike for Albert Heim as a person (Trümpy, oral communication 2008, cf. also Sengör and Bernoulli 2011: 930). Heim seems to have been of a very dogmatic character both in his scientific activities and in his way of life (Brockmann-Jerosch et al. 1952).

However, there may be a more fundamental reason for the later underrating of the Double Fold concept. We propose that Arnold Escher and especially Albert Heim developed between 1854 and 1878 a fundamentally new way of thinking in Alpine tectonics. Neither the proposition of the Double Fold nor the assumption of the passivity of the external crystalline massifs was merely founded on new, empirical evidence. That Verrucano rests on flysch in the Glarus Alps was common knowledge around 1850 and nobody who had personally seen the area could seriously deny this fact. Studer and Escher were thus not arguing over matters of fact when Suess visited them in 1854 (see Sect. 3.2) but rather over their different ways of viewing this phenomenon. If one adopted the metamorphic and vertical uplift model of Studer (and many other contemporary geologists in Central Europe), the Glarus overthrust was an impressive example of metamorphic Verrucano overflowing Mesozoic and Tertiary rocks. A net horizontal contraction of the Earth's crust was neither demanded by this particular example nor was it an integral part of the model. However, if one adopted the belief in a horizontally acting, global pressure, and if one viewed tectonic deformation as a mechanical process influenced by this horizontal pressure and by the vertical pressure due to overburden, the same phenomenon (i.e. the Glarus overthrust) became an impressive example of how the Earth's crust had reacted to horizontal compression. Another way to react was the development of the external crystalline massifs (Fig. 10). It has been argued that Escher tried to minimize the implied horizontal contraction when he developed the Double Fold instead of accepting the allegedly obvious interpretation as a thrust in the modern sense of the term (e.g. Bailey 1935: 49; Trümpy 1991, 2001). We think that this suspicion nicely illustrates that these later workers did not grasp the fundamental change in tectonic thinking which was brought about by Escher and Heim between 1854 and 1878. Bailey and Trümpy implicitly assume that Escher was well aware that the geological facts described by him, demanded for considerable horizontal contraction across the Glarus Alps. However, if we assume that Escher's mind was trained to view the world according to Studer's tectonic model in the 1830s and 1840s (as we tried to demonstrate in Sect. 3.1), the objective description of the stratigraphic anomaly in the Glarus Alps did not imply any net horizontal contraction at all (Letsch 2011: 37). It needed first a radical change of theoretical thinking in order to realize that the Glarus overthrust demanded indeed a considerable amount of horizontal crustal contraction. This new way to view tectonic phenomena was determined by horizontal contraction and mechanical deformation of rocks under considerable lithostatic pressure. The Double Fold was one of the early results (or articulations) of this new tectonic conception which later proved to be not in accordance with the increasing amount of field data and it was finally replaced by the Nappe model. However, as a closer look at both models (Fig. 1) reveals, they were not fundamentally different from each other. Both demanded horizontal contraction and both operated with large scale overfolding or overthrusting of older rocks onto younger ones. The first model might have led quite naturally to the second one. However, Heim's difficult character seems to have been the main obstacle to prevent this to happen. Only very few geologists seem to have felt this close connection between these two models, and that not only the proposition of the second one was a revolution (see Schaer 2010) but also the proposition of the first one, albeit maybe a rather quiet one.

At least, Eduard Suess, looking back at the end of his remarkable career in the last volume of his great "Antlitz der Erde" (1909: 133–135), gave a very balanced statement about Escher and Heim's Double Fold concept as he clearly acknowledged its merits. To end this historical essay, we would like to quote from a letter the aged German geologist Albrecht Penck (Fig. 8) wrote to his personal friend and scientific opponent Albert Heim in 1922 (from Brockmann-Jerosch et al. 1952: 112): "*Without your ideas about the Double Fold, we would not have arrived at the tectonic nappes because the former made us first familiar with the nature of overthrusts.* […] *The crucial point is, that one has to deal in each case with large-scale tangential movements of the Earth's crust; you gave these movements a firm place in every model of the Earth's crust.*" (Author's translation; for original text see Online Resource 1, quotation 11).

Acknowledgments We thank Nazario Pavoni for the many fruitful discussions about the history of Alpine Geology. He also generously provided us with a rare copy of Studer (1837). Walter Letsch is to be thanked for checking the language of this article (especially the many translations). Two anonymous reviews were extremely helpful in reshaping some of the more provocative parts of this paper. The Editor-in-Chief (A.G. Milnes) is to be thanked for his quite personal and very detailed comments which further helped to improve the manuscript and which provided us with much food for further thoughts. Finally, we are still very much indebted to the lasting inspiration we were privileged to receive from the late Rudolf Trümpy. Even though we arrived at quite different conclusions than he did, this small piece of work is nevertheless intended as a tribute to this great Alpine geologist.

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