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Alpine Sections Through Time: A Mirror of Evolving Observations and Thoughts on the Tectonics of the Alps

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1.1. Introduction

Cross-sections are the most commonly used tool to represent the deep structure of orogens, hence to constrain their three-dimensional anatomy. In the Italian publications of the 18th century, and of the first half of the 19th century (e.g. Villa and Villa 1844; Taramelli 1870), cross-sections were commonly termed "spaccato", meaning "broken up", suggesting that something is taken away from the landscape to show and disclose what would otherwise remain hidden. In the second half of the 19th century, the terms "taglio naturale" (natural section) and "taglio dimostrativo" (illustrative section) also appeared (e.g. Pantaloni et al. 2016) to describe and distinguish natural, steeply inclined surface outcrops from cross-sections that are constructed on vertical, planar surfaces, which are not visible in nature. The term "spaccato" has also been used to show geological structures on vertical, idealized

Geodynamics of the Alps 1,
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planar surfaces (Stoppani 1857; Omboni, 1879), but in such cases, until the 1870's, the authors specify that it is a "geological theoretical section". The term "taglio" is similar to the terms used in the German ("Querdurchschnitt", e.g. Ebel 1808), British ("section") and French ("coupe") literature, which expressed the idea of cutting across, hence also to disclose something, but by an artificial physical process. All these terms relate to the illustration of what is underneath the earth's surface, but not to what is above it.

In the 19th century, the term (geological) section was often associated with the adjective "ideal" (e.g. Studer 1834; Rogers 1836), when it illustrated structures that did not strictly reproduce what was visible in the landscape. Studer (1834) uses the term "Ideale Profile" for those Alpine sections in which he reduces the amount of 3D topographic effects that are observable in the field. The term "theoretical" section (e.g. Lory 1860; Favre 1867; Jaccard 1869) is often used to characterize sections in which stippled lines have been added to complete the structures of the eroded beds above the surface. The term "schematic sections" was first used by Termier (1903), when sketching orogen-scale sections that show both the inferred deep structure of the chain and the inferred eroded uppermost structures. Argand (1909) also mentions that his section is schematic, but he drops this adjective in 1924 when showing an even more simplified and schematic section of the same area of the Western Alps. From that moment onwards, the term "cross-section", generally without any other adjective, was used in Alpine literature.

The transition between landscape drawings, in areas characterized by well-exposed outcrops of sedimentary beds and/or tectonic structures, to cross-sections in a geological sense, takes place gradually through time. While the former ones simply reproduce a natural scenery, the latter focus on specific geological features of such sceneries, first documenting them by the addition of symbols linked to a legend in the drawings, and later by progressively removing all elements that are not strictly of geological nature. Eventually, cross-sections become fully independent of any specific point of observation of the author, hence showing constant thickness and dip of the beds throughout the section.

Modern sections through the Alps are constructed along ideal vertical planes that may integrate geological information from areas located tens of km away from the trace of the section plane (Argand 1911), and geophysical data imaging the structures of the mantle lithosphere (e.g. Giese et al. 1970) and the underlying asthenosphere (e.g. Lippitsch et al. 2013). This evolution took several centuries, and it is the aim of this chapter to show that it was marked by numerous, discrete steps.

How and why scientists came to accomplish such steps, both in terms of their innovative representation technique and their understanding of the tectonics of the Alps is discussed in the following.

Numerous papers traced the history of tectonic research in the Alps (e.g. Masson 1983; Dal Piaz and Dal Piaz 1984; Sengör 1989; Dal Piaz 2001, 2010; Trümpy 2001; Schaer 2010, 2011; Debelmas 2011), or the history of more specific aspects of Alpine tectonic research (Bailey 1935; Masson 1976; Greene 1982; Dal Piaz and Dal Piaz 1984; Trümpy 1991; Letsch 2014, 2017), or the contribution of individual Alpine geologists (e.g. Dal Piaz 1996; Trümpy and Lemoine 1998; Durand-Delga 2007; Dullo and Pfaffl 2019). In this chapter, the evolution of ideas concerning the structure and tectonics of the Alpine chain is also discussed, but only through the analysis of cross-sections from the early 18th century to the end of the 20th century. Therefore, the present text does not accord a lot of space to great Alpine geologists whose scientific contributions are not based and illustrated by innovative cross-sections, as is the case for Eduard Suess, Emile Haug and Hans Stille. A discussion of their achievements for the advancement of tectonic ideas on the Alps can be found in Dal Piaz and Dal Piaz (1984) and Sengör (1989, 1990, 2014). Because the Alps have been so intensely studied in the past centuries and many important steps in the understanding of orogenic processes were accomplished there, the following history of Alpine cross-sections since the 18th century is very much representative of the evolution of cross-sections and tectonic knowledge worldwide.

1.2. Transition from landscape drawings to cross-sections: beginning of the 18th to the first half of the 19th century

Given the subtle nature of the transition from landscape drawing of geological outcrops and cross-sections, it is difficult to pinpoint the precise initiation of drawing of cross-sections. Natural outcrops of sedimentary beds are masterly painted in the Renaissance, as shown and discussed by Ceregato and Vai (2017), but the scope of these landscapes was not a geological one. The first paintings and sketches of natural landscapes depicting the structure of exposed beds, with the specific goal to understand their origin, were those of Marsigli (1705; Figures 1.1(a–c)), reproduced by Gortani (1930), depicting the cliffs around Lake Uri (Figures 1.1(b) and (c)) in the Helvetic nappes of northern Switzerland. Indeed, Marsigli points out in the text of one figure describing an open antiform, that the lower part of the structure consists of an artificial wall, thereby focusing the attention of the reader only on the folded strata of the depicted landscape. Marsigli also proposes a classification of mountain types based on their internal structure and illustrated in schematic cross-sections. He defines 10 different types based on the dip, the orientation and the folding of the beds. It was the first structure-based classification of mountain belts.

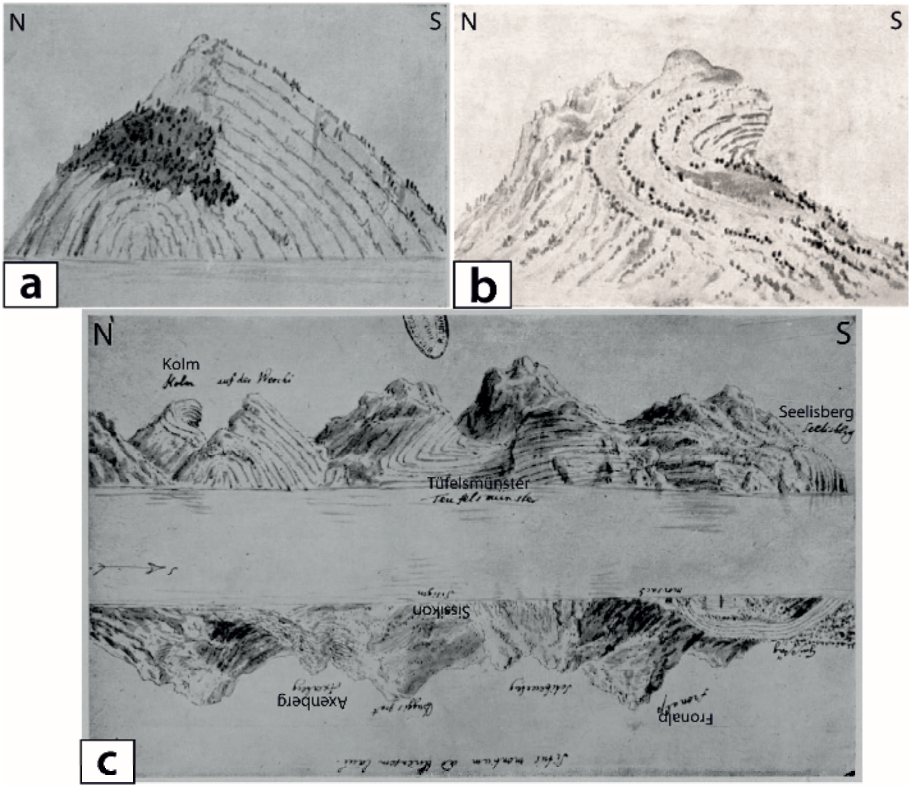


Figure 1.1. *Paintings of the shores of the Urnersee, eastern lobe of Lake Lucerne (Switzerland), by Marsigli (1705). Reproduced and modified from Gortani (1930). (a and b) Folded sedimentary beds. (c) The mountain flanks of each shore can be observed without any perspective-induced distortions by turning the picture upside down. Marsigli explicitly mentions folding of the beds in the legend to his figure, which is otherwise just the reproduction of an Alpine landscape. He writes: "Mons Kolm dictus ad lacum Uriensem, e stratis ita compositus ut vertex eius supra incurvatus quasi videatur, et stratorum positura quasi perpendiculariter arcuata videatur"*

One of his paintings (Figure 1.1(c)) shows the two sides of the lake that face each other, each of them painted as if they were observed from the opposite shore, hence providing the reader with an excellent, undistorted view of the structures and stressing the continuity of the structures from one shore to the other.

Panoramas focusing on the geometry of outcropping beds were rarely drawn in the first half of the 18th century, and interestingly, the ones that were published in the most famous books of that time are new drawings of the same outcrops of Lake Uri, previously shown by Marsigli (1705; Figure 1.1). They were redrawn using a different style by Johann Scheuchzer in 1708, and published by his brother Johann Jakob Scheuchzer in 1716 (Figure 1.2(a); Scheuchzer 1716). Johann Scheuchzer was aware of the original drawings by Marsigli (Vaccari 2001), but he made his own observations around Lake Uri (Koch 1952; Ellenberger 1990), and these are very relevant for the understanding of mountain building. Scheuchzer describes the geometry of the folded beds and their steep dip in the outcrops around Lake Uri. He mentions that sedimentary beds in the great planes (Flanders, Germany, Poland and Hungary) are horizontal and concludes (following Steno) that mountain building is associated with displacement and fracturing of the originally horizontal strata. Based on his observations around Lake Uri, Schechuzer also concludes that the geometry and orientation of the sedimentary beds controls the morphology of the mountainous topography. The drawings of Scheuchzer were modified and republished by Vallisneri (1715, 1726; Figure 1.2(b)), in his treaty on the origin of water sources. In 1732, Johann Jakob Scheuchzer, the brother of Johann Scheuchzer, published three new drawings of these same outcrops, drawn from a new perspective, to accompany a text on the Book of Genesis (Scheuchzer 1732), in which he discusses the origin of the Earth from the water. Finally, Moro (1740) again published the drawings of Vallisneri (1726) in his work on fossils exposed in mountainous regions. Hence, it appears as if the illustrations of folded beds around Lake Uri had a great impact on the naturalistic community of the first 18th century, and strangely, no attempts to reproduce drawings of sedimentary beds from areas other than that of Lake Uri are known from this period.

In a modern sense, the first cross-section in the history of Alpine research is the one of Giovanni Arduino (1758; Figure 1.3). He illustrates part of the Agno Valley (Italian Southern Alps) and shows for the first time the geometry of the beds and their lithological nature, using different symbols and short descriptions. A legend briefly describing the lithological units accompanies the section. Although the base of the section of Arduino is cut by a horizontal line (Figure 1.3), thus artificially interrupting the naturalistic character of his picture, many contacts between the lithological units are separated by irregular lines, representing the margins of cliffs that stand in front of other ones. Several lines at high angle to the orientation of the beds seem to represent topographic elements, such as little rivers (bottom, left-hand side of the figure). A small monastery is also shown at the southeastern end. All these features underline the fact that the figure was sketched in the field in front of the cliffs. However, the introduction of symbols (e.g. letters, and dots in the white pattern for unit R, continuous, parallel lines for unit P; Figure 1.3) transforms the section into something that is no longer the faithful reproduction of a landscape. It is now unambiguously the documentation and interpretation of a sedimentary tilted sequence.

The section of Arduino (1758) remained the most innovative one in the Alpine literature until the end of the 18th century. No other attempts to draw such sections are known. Although De Saussure's (1780) descriptions of geological outcrops and his thoughts about tectonic structures were very modern and innovative in his time, they were still based on classic drawings of mountain landscapes that cannot be distinguished from those of an artist who bears no specific interest in geology. Indeed, the excellent outcrop illustrations in De Saussure's book are not drawn by himself, but by a professional painter.

At the beginning of the 19th century, Ebel (1808) provided a new type of section, linked to a geological map (Figure 1.4). He shows three geological sections ("Querdurchschnitte") across the entire Alpine chain, one passing through the Gotthard Massif, one through the northeastern side of the Mt Blanc and one through the southwestern side of the Mt Blanc Massif, accompanied by a geological map of the entire Alpine realm. Given that no proper geological maps existed and that the topographic ones were rather poor (Ebel 1808), and that no cross-sections of the Alps had ever been drawn excepted for the small one of Arduino, both the idea and the achievement of Ebel's project must be considered as a scientific revolution and an immense piece of work. Indeed, the second attempt to depict the entire Alpine chain in one section would only be performed after one century (see below). Why did Ebel start such a project, instead of depicting smaller parts of the chain in more detail? He wished to show that rock units on the scale of the entire Alpine chain follow a specific order, which was still not known at that time. By providing one of the very first maps of the Alpine region (mainly Switzerland), and a series of sections, Ebel discloses a rational spatial pattern in the distribution of rock bodies:

> Nothing in nature is without order and law. Where these appear to be absent, it is only the fault of limited senses. The scouting eye and the investigating mind of the observers already found some great relationships and general laws of order in the terrible tangle of wild disorder, so that the mind is set in astonishment and comes to the certitude that a general order exists in the structure of the Earth.

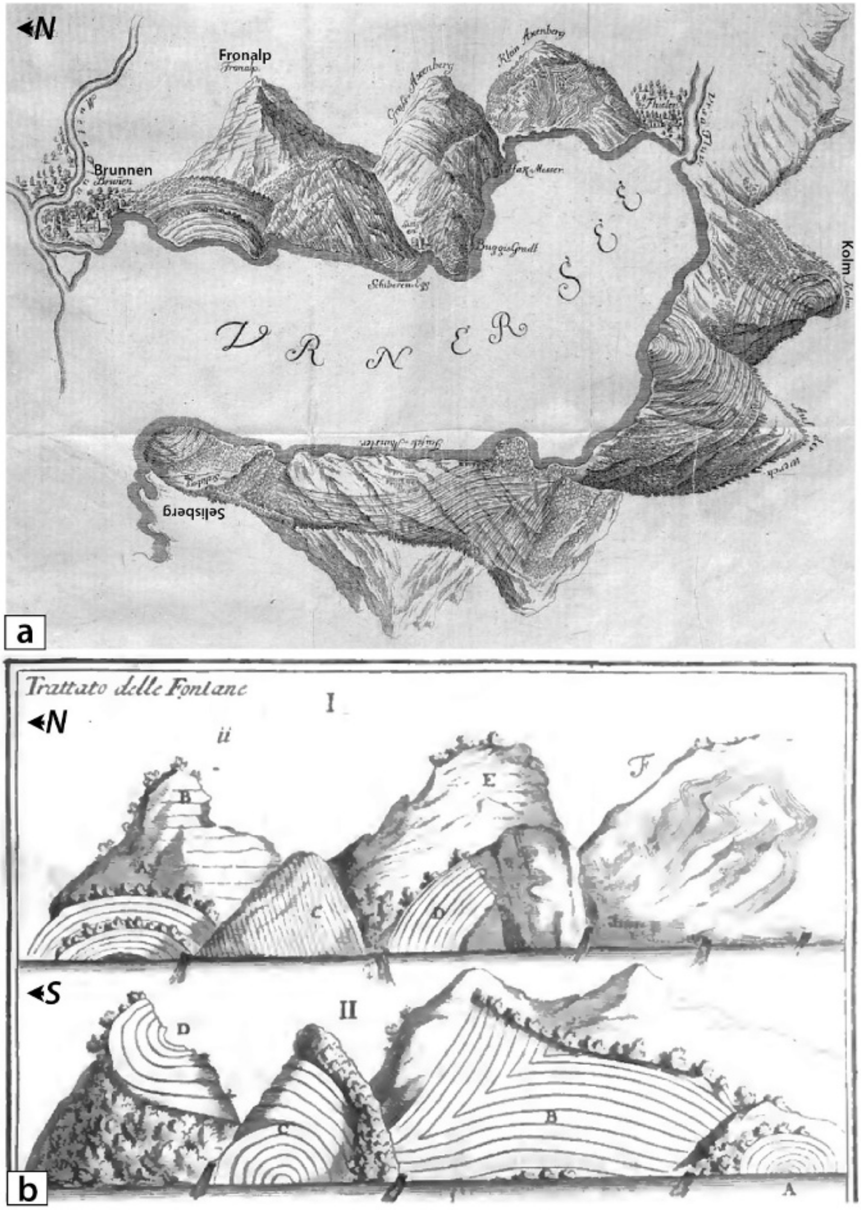


Figure 1.2. *Structures around Lake Uri (Urnersee). a) Scheuchzer (1716). The same approach of Marsigli (1705) is used for the perspective and expanded to the southern shore of the lake. b) Vallisneri (1726). The upper panel is the eastern shore, and the lower panel is the southwestern shore of Lake Uri, redrawn from Scheuchzer (1716)*

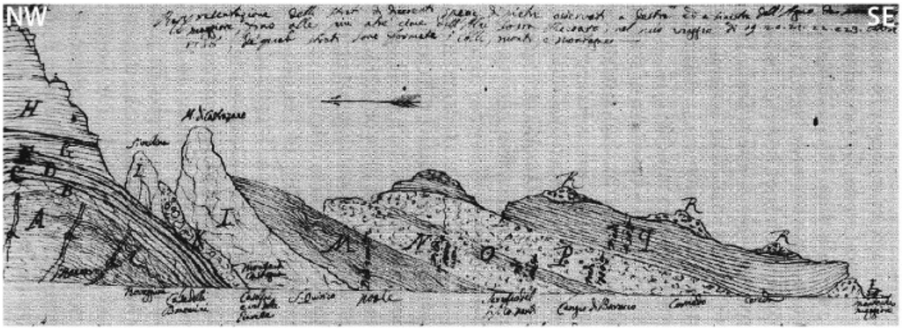


Figure 1.3. *Cross-section of Arduino (1758) from the Agnolo Valley (between Montecchio and Recoaro, near Vicenza, Southern Alps). The figure reproduces a Paleozoic-Tertiary sequence, exposed along natural, steeply dipping cliffs. The drawing does not merely represent a landscape, since different lithologies are distinguished and represented by symbols instead of their natural appearance. Symbols (letters) are described in a legend, not shown in Figure 1.3*

Ebel (1808) insists on the fact that rock bodies have a very conspicuous lateral extent in map view and questions their mutual, spatial relationships, even in a vertical direction: “The aim of these sections is to show the position of some rock bodies lying on top of others, and the steepening and deepening of some of the beds of the main rock body”. Indeed, by simply drawing what he observes, Ebel depicts the Cenozoic Molasse sediments lying underneath the Mesozoic ones in the northern parts of the Alpine chain (Figure 1.4). The age of these units was not known in his time, hence Ebel is not irritated by the nature of this anomalous contact.

At the beginning of the 19th century, mapping of the Alps was carried out on a very large scale. Detailed mapping on smaller scales progressively developed throughout the 19th century. Hence, the type of reasoning of Ebel on the geology of the Alps is also on the scale of the entire mountain belt. The map of Ebel provides a step forward, because he introduces 10 mappable units for the entire Alpine chain, whose contacts are more precisely mapped than in previous maps (e.g. Heitzmann 2008).

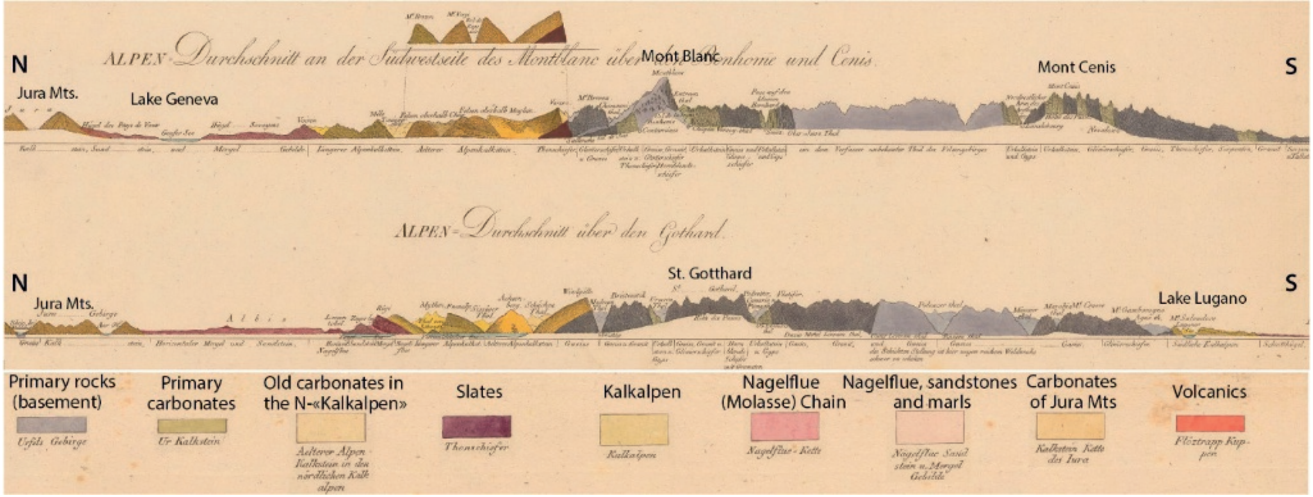


Figure 1.4. *N-S striking geological sections across the entire Alpine chain, modified from Ebel (1808). Upper panel: Mt Blanc section. Lower panel: Gotthard section*

Ebel's sections (1808; Figure 1.4) terminate at the bottom of the valleys, only showing what can be observed directly in the landscape and always showing a 3D view, representing more than a single "topographic steep plane" of the landscape in the sections. Although they locally show which lithological unit lies above the other, many of the contacts between different lithologies are merely apparent contacts between distinct topographic surfaces located one in front of the other. Topographic details are sketched in various parts of the section, always providing a 3D impression of the topography.

In the following two decades, cross-sections on smaller scales became very precise and commonly accompanied papers describing the geological maps of different Alpine countries. They document both the structure and the landscape surrounding the outcrops, as beautifully shown by Brongniart (1823; Figure 1.5(a)), where a 3D perspective and details of vegetation and urbanization are included. Even the shadows of the cliffs are shown in this section, showing that it is a drawing of nature as it can be seen from a specific place at a specific time of the day, rather than a construction from a geological map. Brongniart (1823) also shows 2D vertical sections (Figure 1.5(b)), where the different stratigraphic units are schematically depicted, but leave empty areas between some of the stratigraphic units, where no outcrops are visible. This indicates that the sections only show what the geologist sees in the field and nothing is added to that. Studer (1834) writes about his profiles: "In the sections, the outlines are as close to Nature as I could possibly draw them". This sentence indicates that Studer's attempt is to reproduce how things are as precisely as possible, and interpretative lines in the drawing would go against his goal. Interestingly, Studer (1834) presents two series of sections: one that he defines as "Profile" and another one that he defines as "Ideale Profile" (idealized sections; Figure 1.6), suggesting that the latter ones must provide some degree of abstraction with respect to the direct observation of the landscape. However, his "ideal profiles", in spite of their significantly smaller amount of topographic detail compared to the "profiles", still show several distinct topographic steep planes, set one in front of the other, thus creating some apparent contacts and discontinuities between different geological units (Figure 1.6).

This rigorous reproduction of what the eye sees in the field makes the geological interpretation more difficult. Studer (1834) seems to realize that geological interpretations need to filter topographic 3D effects, but he is not ready to give them up completely, and hence take a bigger step toward abstraction. Only in his "Geologie der Schweiz", in 1851, does he draw cross-sections that are entirely 2D in vertical planes. Most cross-sections until the end of the first half of the 19th century show such topographic elements (e.g. von Morlot 1847; von Cotta 1851).

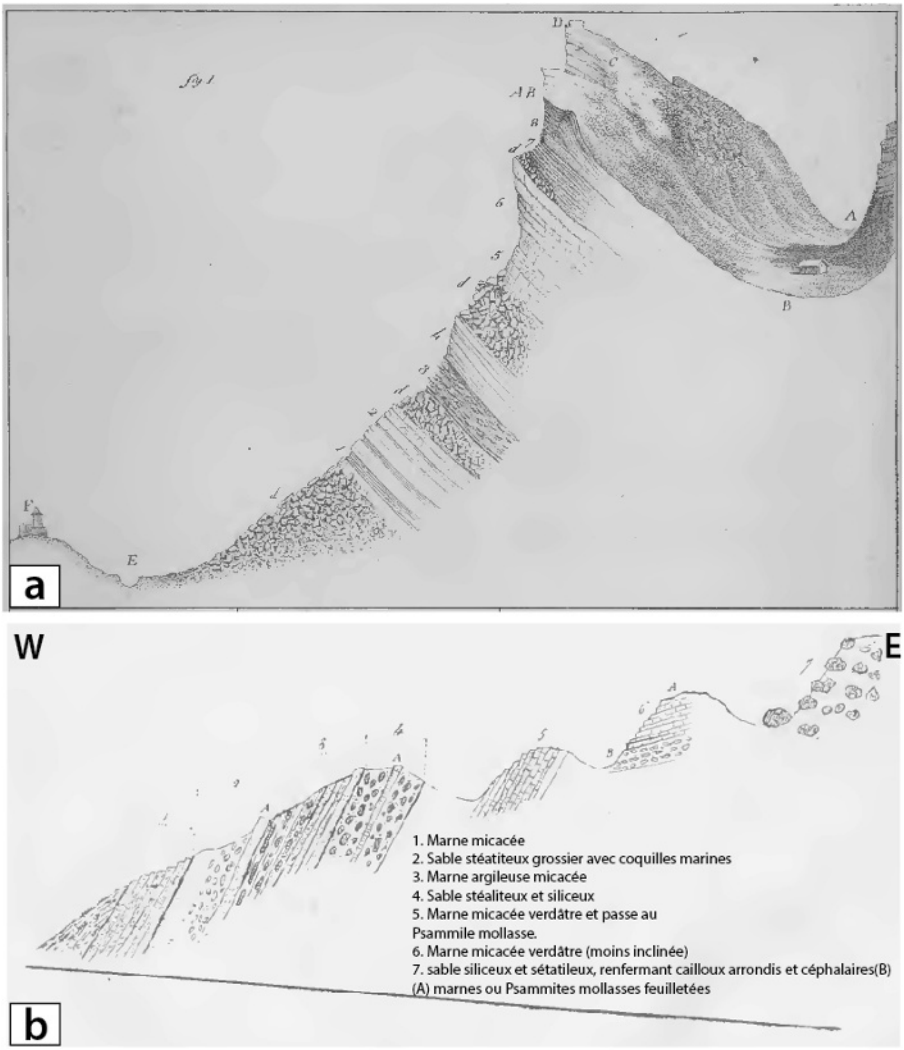


Figure 1.5. *Cross-sections after Brongniart (1823). a) Section through the Montagne des Fis, Servoz Valley (close to Chamonix, Western Alps). Note the details on 3D elements such as the little house on top of the hill and the shade of the cliffs. b) Cross-section of the Superga Hill (Torino). Note the discontinuous structure of the sedimentary beds, with "voids" where outcrops are not present*

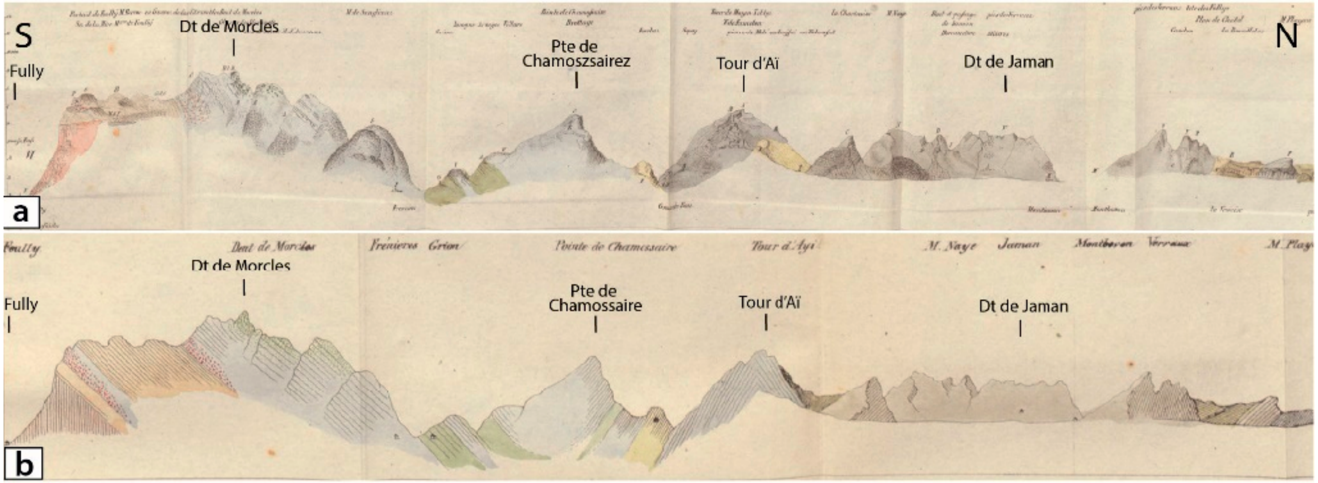


Figure 1.6. *Cross-sections of the western Swiss Alps, after Studer (1834). (a) Section termed "Profil", showing both 3D topographic features and geological units. (b) Section termed "Ideales Profil", representing the same area as that of (a), almost without 3D topographic features, but still far from a planar, vertical surface. Some structural information is shown, as the antiform at Tour d'Aï*

1.3. Cross-sections between 1840 and 1880: first attempts toward interpretative sections

Cross-sections representing a 2D vertical plane, in which sedimentary beds continuously fill the entire space between topographic surface and the horizontal “base line” of the section, have been published by Escher and Studer (1839, their Figures 3 and 4), Sismonda (1839; Figure 1.7) and Villa (1844). For the first time, these sections trace the geometry and location of beds, even across areas that are not exposed and visible at the surface and do not depict 3D topographic elements. Although not representing an Alpine example, some sections of Dufrénoy and Elie de Beaumont (1841) are very emblematic for that time, because they combine the 3D panorama-type of view of landscapes, with the 2D abstract illustration of geological structures, keeping them strictly separated in space, but as part of one and the same figure (Figures 4, 5 and 25 in Dufrénoy and Elie de Beaumont (1841)). This type of illustration creates a transition between the representation of natural landscapes and the construction of vertical, planar surfaces that are not directly observable in the field.

At the end of the first half of the 19th century, Alpine cross-sections looked close to what may be considered a cross-section in the modern sense of this term. The sections of Arnold Escher von der Linth (1848; Figure 1.8), published in Murchison (1848), as well as those of Murchison himself in the same manuscript (Figure 1.9), are definitely drawn as 2D, vertical and planar surfaces. As shown in the beautiful series of parallel sections of the Helvetic cover in the Säntis area, in eastern Switzerland (Figure 1.8), the orientation and geometry of the contacts, and the thickness of the beds, are represented in a way that is fully independent of 3D topographic effects and the location and point of view taken by the geologist while sketching the section. This allows for “lateral” correlations of beds and structures between different sections (stippled lines in Figure 1.8). The addition of stippled lines to show such a lateral continuity between sections had never been shown before.

The focus of the work of Murchison (1850) is mainly devoted to the determination of the age of stratigraphic units that he mapped in the Central Alps. However, as previously done by Escher von der Linth (1841), he probably notes that the Mesozoic Units lie above the younger Molasse beds in the northern part of his section (Figure 1.9), hence he draws a vertical fault, probably to avoid a large thrust. However, this fault is known to gently dip southward (Buxtorf 1914). Escher von der Linth (1841) shows a section of this contact (Figure 1.10), and clearly describes it as a thrust:

> [...] the well-known, abnormal height of the secondary carbonate units above the Tertiary Molasse, across all of Switzerland, is the consequence of a thrust of the Cretaceous Units (at least in eastern Switzerland) above the Molasse.

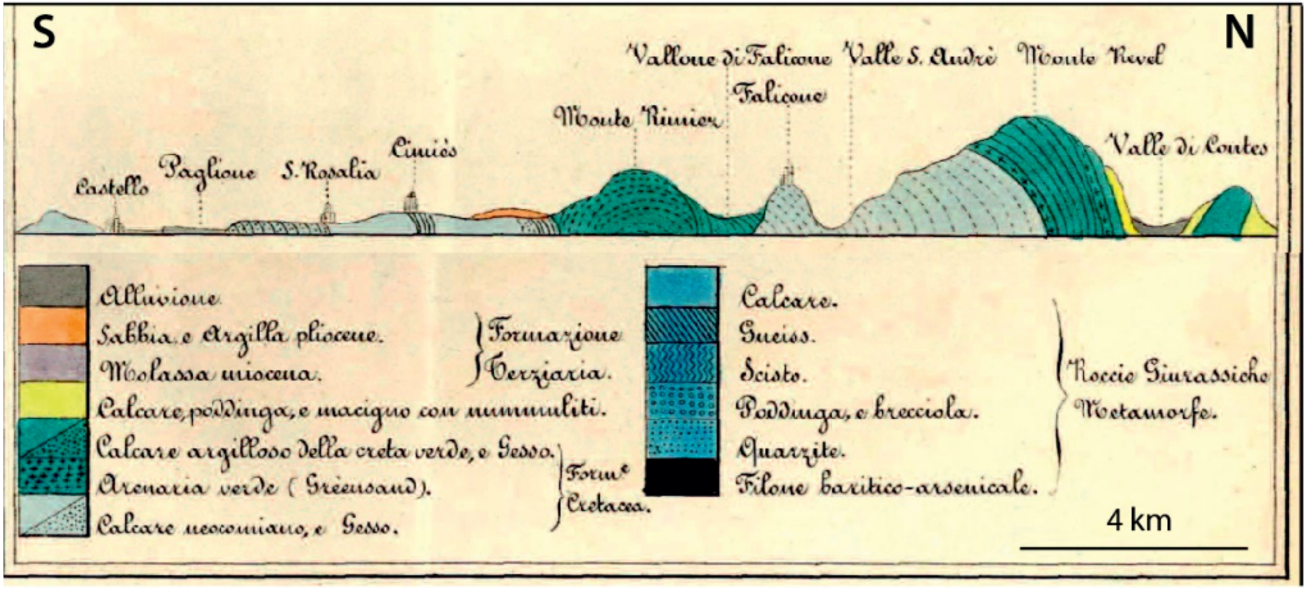


Figure 1.7. *N-S striking section, north of Nice (France, but "Regno di Sardegna in Terra Ferma" at that time). Adapted from Sismonda (1839)*

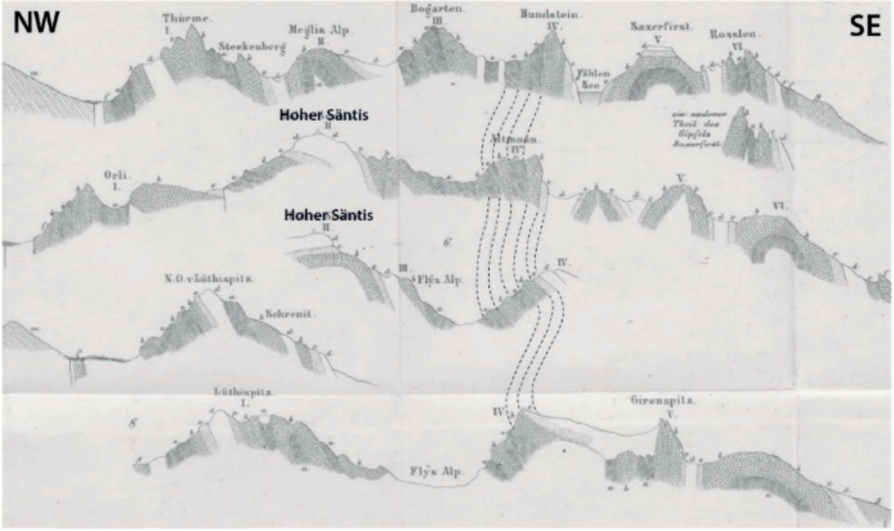


Figure 1.8. *Some of the serial sections across the Säntis Mountains, by Escher von der Linth, in Murchison (1850). Note the absence of any interpretations above the topographic surface. The lateral correlation of structures using stippled lines (accentuated here) was only added to the German edition of Murchison (1850). The English edition of 1848 does not show them*

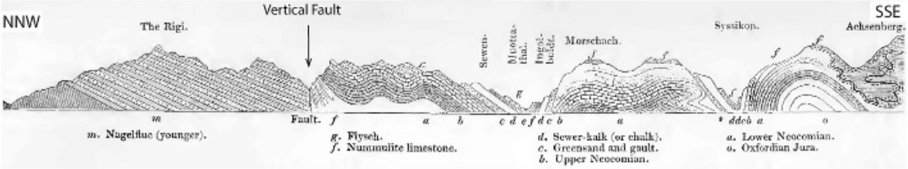
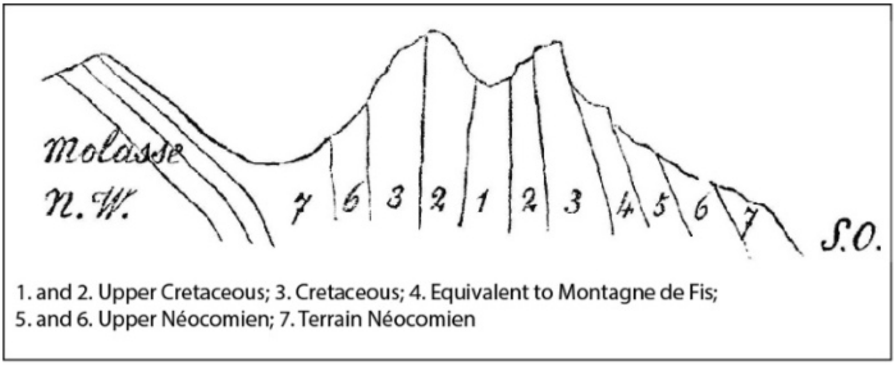


Figure 1.9. *Murchison's (1848) cross-section from the Molasse (The Rigi) to Lake Uri (Syssikon in the section). Inferred vertical fault marks the contact between Molasse and Helvetic nappes. See the text for further explanation*

Only the thrust plane itself is missing in the section (Figure 1.10). This may be the reason for ignoring his discovery in most studies on the history of tectonics and attributing the first descriptions of thrust faults to the early eighties of the 19th century (Callaway 1883; Lapworth 1883; Bertrand 1884; Geikie 1884). Ebel (1808) correctly represented the contact showing the Molasse below the Mesozoic (Figure. 1.4) at the beginning of the 19th century (Figure 1.4), possibly because he was not aware of the age of the sediments, hence he was not worried about the need to explain an inverted stratigraphic contact. Murchison (1848, 1850) shows the southward dip of the Molasse/Mesozoic contact (Figure 1.9), but did not dare to sketch a gently dipping thrust. It is only some 30 years later that thrusts and nappes are accepted by most of the geological community.

In the years following the memoir of Murchison (1848), Alpine sections became a commonly used tool to document regional geological settings. They are presented as vertical and planar surfaces, with no 3D topographic details. In addition, the discontinuous structural information of previous sections is completed by interpreting the trend of contacts between the visible outcrops below the topographic surface (e.g. Escher von der Linth 1850; Lachat 1858; Müller 1862; Theobald 1864). However, the addition of these few thin lines often became the subject of long-lasting debates at that time. An excellent example is described by Debelmas et al. (2011), comparing the same section of the Maurienne (French Alps) by Charles Lory in 1866 and by Sismonda in 1867. The rather monotonous east dip of all beds in the section is shown (by stippled lines below the surface) to be the result of tight, east-dipping folds in the first interpretation, whereas it is a monoclinal, unfolded sequence in the latter interpretation.



1. and 2. Upper Cretaceous; 3. Cretaceous; 4. Equivalent to Montagne de Fis;
5. and 6. Upper Néocomien; 7. Terrain Néocomien

Figure 1.10. *NE-SW cross-section showing the Molasse dipping at high angle below the subvertical Mesozoic cover (numbered units). The original figure illustrates the report of a presentation of Escher von der Linth, published by Studer and Desor (1841)*

The addition of interpreted lines to constrain the structures below the topographic surface observable in the field precedes interpretations of the same kind above the surface, which only appeared in the late 1960s (Favre 1867; Giordano 1869; Heim 1871). Interestingly, Favre (1867) shows some cross-sections with contacts extrapolated above the surface from the Mont Blanc area, stating that they are reproduced from his own early work from 1859. Indeed, Favre shows these interpretations above the surface for the first time in 1867, in a publication that recounts in great detail the debate on the Carboniferous terrains in the Alps, specifically in the locality of Petit-Coeur, close to Moutiers (France). Favre wanted to terminate a long-standing debate that lasted for decades on the structure of the “Petit Coeur” area, in the Western Alps. In order to clarify whether the subvertical and symmetrical distribution of sedimentary strata results from a synclinal or anticlinal fold, Favre presents two sections of the same structure, one with stippled lines that form an anticlinal hinge above the topographic surface, and one with stippled lines forming a synclinal hinge below the observable topographic surface. Thus, Favre (1867) oversteps the boundaries of the visible topographic surface for the sake of clarifying the structure of a complex area. Interestingly, Favre terms his old cross section of "Petit Coeur" published in 1859 without interpretative stippled lines (Favre, 1859) as "coupe classique", whereas he terms his new, interpreted version "coupe théoriqueé" (Favre, 1867). (For a historical overview, see Grandchamp (1997)).

Another significant advancement in the interpretation of cross-sections is the one provided by Felice Giordano (1869; Figure 1.11). In his sections across the Matterhorn at the Italian-Swiss border, Giordano dares to draw a very thin and light stippled line above the surface to underline the lateral continuity of the contact between his “talc-bearing gneisses” and the “calc-serpentinite formation” below. The second innovative aspect in the sections of Giordano concerns the drawing of structures down to the sea level, and possibly below, in areas where the valleys are still at altitudes above 1,500 m (Figure 1.11). Giordano does not draw any clear contact lines at such depth, but he writes the name of the geological unit with a folded shape that mimics the geometry of the contacts at depth (Figure 1.11). Thus, it takes over 100 years to arrive from the first illustrations of naturally occurring structures (Arduino 1758) to the latter ones that show some still very cautious and only indirect signs of the inferred extrapolation of exposed geometries both below and above the visible surface. Giordano dares to take this step for two main reasons: first he realizes the existence and importance of the lateral continuity of structures in spite of their interruption due to erosion (lithological similarity between M.te Cervino/Matterhorn and Dent Blanche, Figure 1.11), and second he is aware of the kinematic implications of such a lateral continuity. As described by Dal Piaz (1996), Giordano accurately assesses the large-scale geometry of three gently dipping units lying above each other (Figure 1.11): the "Formazione di Gneis Talcoso" lying above the "Formazione Calcareo-serpentinosa", which lies itself above the "Granito antico" (Monte Rosa basement, not visible in Figure 1.11). Because the intermediate unit consists of dolomites, quartzites and cargnieules, it is inferred to be Permo-Triassic, by analogy with other Alpine areas. But the presence of ancient granitoid gneiss in the "Formazione di Gneiss Talcoso" located at a higher structural level makes it difficult to infer a post-Triassic age for this unit, hence a normal stratigraphic sequence. Giordano (1869) is conscious that attributing an older age to the hanging wall unit would require its upwelling from below and its spreading out laterally: "[...] *overthrown in the form of huge nappes* (... *rovesciatosi poi in falde enormi*"), and in a second article in French "[...] *se serait épanché en nappes énormes*" (Giordano 1869b). In spite of this lucid kinematic concept, Giordano considers this process unlikely (Dal Piaz 1996), because it would correspond to a "*frightful overthrow*". Thus, Giordano precludes an older age of the upper unit, and interprets it as Cretaceous, denying the existence of nappes immediately after having coined their idea and name for the first time (Trümpy 2001).

In the same year, Jaccard (1869) also interprets the geometry of folded beds of the Jura Mountains with few stippled lines above surface and calls these sections "coupes théoriques". This shows that although these stippled lines complete the eroded parts of folds in a very obvious and intuitive way, Jaccard still wants to demark the difference between reproducing and interpreting the observable.

In spite of the publications of Lory (1867), Giordano (1869), Jaccard (1869), Gerlach (1871) and Heim (1871), sections were rarely interpreted above the topographic surface before the end of the 1870s. Only where folds are very clearly recognizable, but eroded in their hinges, would their eroded parts be represented locally by stippled lines, to document the continuity of the structures (e.g. Jaccard 1869; Gerlach 1871; Escher von der Linth 1878; von Gümbel 1878). Moreover, some geologists are seriously concerned about the lack of reality of such sections. Pfaff (1873) discusses the problems of documenting real (only observed) versus unreal structures (interpreted parts) in cross-sections. He takes the section of Favre (1867) as an example, probably the one that more boldly interprets the geometry of eroded structures at that time. Pfaff (1873) redraws the same topographic profile of Favre, showing those parts that can really be observed in the field, hence critically concluding that most of the section is not based on "real observations".

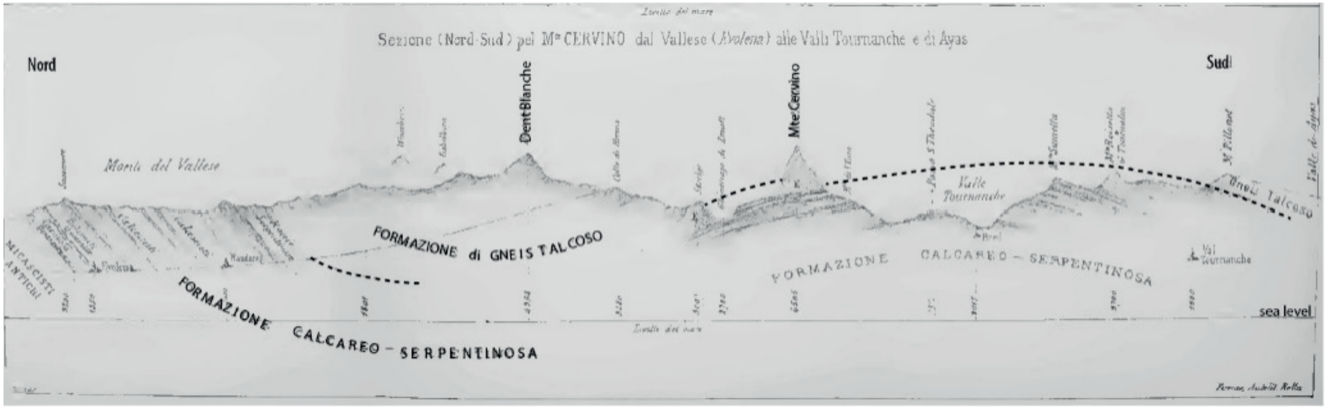


Figure 1.11. *N-S striking section across the Matterhorn (Cervino), and Dent Blanche, modified from Giordano (1869). Note the gently folded shape of the inscription "Formazione calcareo-serpentinosa", which points to the deep, folded structure of this unit, even below the sea level: an unprecedented interpretation and representation of the deep crustal structure. The stippled line (redrawn to make it more visible) along the base of the "Formazione di Gneis Talcoso" corresponds to the base of the Dent Blanche nappe*

1.4. Cross-sections in the last two decades of the 19th century: the first kinematic interpretations

In the last two decades of the 19th century, a new debate changed the way of thinking about tectonics and structure of the Alps: the nappe theory. The cross-sections of Heim (1878) are influential for the birth of this debate, and they are very innovative from a graphical point of view (Figure 1.12). One group of sections represents the structure of the Tödi-Windgällen Group (Figure 1.12(a)), nowadays famous for the outcrops of the Glarus thrust. The other sections represent the first structural synthesis of a large part of the Alpine chain (Figure 1.12(b)), from the Molasse Basin north of Lake Zürich, to the Lepontine Dome, south of Campo Lungo, hence covering almost 100 km length. In both sections, Heim interprets the structure of the eroded units far above and below the topographic surface (Figure 1.12(a)), but he mentions in the preface of his book that “everything being beyond the real observation is only stippled”. Heim quotes the debate started by Pfaff (1873) on the cross-sections of Favre (1867) in the Mont Blanc area, and states very clearly that everything that is not stippled corresponds to “real observations”.

The stippled lines of Heim are no longer the geometrically obvious and simple continuation of contacts that are exposed in different areas below the topographic surface. Heim interprets complex structures that are not yet understood by the geological community. Because the interpretation is complex, Heim needs to overstep the conventional boundaries of cross-sections and use the space above and below the observable surface to make his interpretation visible. One of these complex structures is the Glarus “double fold” (Figure 1.12(a)). The fascinating historical debate on this structure has been summarized several times (Heim 1908; Trümpy and Lemoine 1998; Letsch 2011, 2017), thus it is not re-proposed in the following. For the present subject, it is more important to recall that a discussion to explain the puzzling presence of Permian, Verrucano beds above the Tertiary Flysch starts several decades before the book by Heim (1878), hence the need for clarification is big. Heim dares to clearly show that the observed geometries below the surface can possibly be interpreted with a double fold inferred to lie above the surface, with hinges showing opposite vergence (Heim 1878; Figure 1.12(a)).

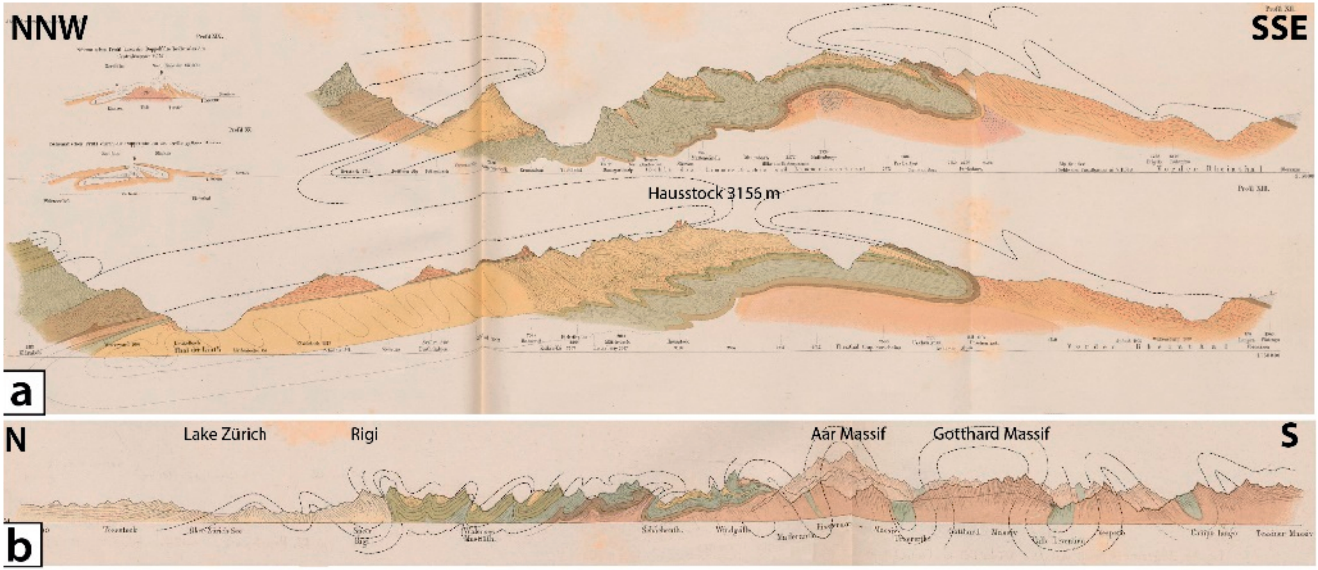


Figure 1.12. *Cross-sections from Heim (1878). a) Glarus Alps, showing the famous "double fold". b) Section striking from the Molasse Basin, north of Zürich, to the Lepontine Dome, showing a structural interpretation before the nappe theory*

COMMENT ON FIGURE 1.12.– *Shortening is only accommodated by folding, including the double Glarus fold. The Upper Jurassic units in the northern part of the section are interpreted to be in lateral continuity with the Mesozoic cover of the Aar Massif, the Gotthard Massif and the Lepontine Dome, thus forming a single folded layer throughout the chain. No thrusts are shown, but the inverted limb of the Mesozoic cover above the Molasse (S of Rigi) is severely thinned out.*

Concerning the larger scale section (Figure 1.12(b)), Heim also has a good reason to overstep the commonly accepted boundaries of the topographic surface: he constructs for the first time a synthesis of the structure of a larger part of the Alpine chain in one and the same section, in which a marker (Jurassic units) could be continuously followed all along the 100 km length of the section. This is only possible if the marker is shown both where it is eroded and where it is at great depth, hence at several kilometers above and below the topographic surface. This section is not only of great interest because of its graphic innovation, but also because it shows the state of understanding of the Alpine structure immediately before the general acceptance of the nappe theory. The structure of the Alps at this point (Figure 1.12(b)) is only represented by the basement/cover discordance, which is harmonically folded throughout the orogen. In the axial zone of the chain, folds affect the cover and the basement in the same manner. Not a single thrust or nappe accommodates shortening at this stage.

Bertrand (1884), without having visited the Glarus Alps, reinterprets the cross-sections of Heim (1878, Figure 11(a)), in a paper often considered as the first step of the nappe theory (e.g. Bailey 1935; Trümpy and Lemoine 1988; Durand-Delga 2010). After studying the geological maps of the Glarus area and Heim's cross-sections exhibiting the double fold (Heim 1878), he re-interprets the cross-section in a simpler and kinematically more plausible way. Bertrand (1884) replaces the double fold with a single, large-scale thrust (Figure 1.13(a)), thus defining the base of a nappe.

Bertrand (1881) interpreted inverted stratigraphic contacts by the presence of thrusts, and the approach followed by him in the Glarus area is emblematic for the historical evolution of ideas. He did not base his interpretation on additional field observations compared to those of his predecessors; on the contrary, his observational base is only the one filtered by Heim (1878) in his publication. On the one hand, Bertrand is guided by his impressive understanding of the link between kinematics and associated geometrical evolution and, on the other hand, by a synthetic capacity, which allows him to detect the structural similarity between two distinct areas. One of these areas being already interpreted (Gosselet 1879) as the result of thrusting: "I simply tried to apply to the Alps the so simple and rational explanation that Gosselet gave for the North (meaning the Bassin Houiller)" (Bertrand 1884). Bertrand's approach is purely structural. He explains in detail how the enormous thinning of the inverted fold limbs below the Glarus thrust (Bertrand 1884; Figure 1.12) results from simple shearing of layers that are not parallel to the shear plane. He interprets these as drag folds, resulting from displacement along the overlying thrust plane. Bertrand (1884) describes these folds with a term already coined at that time in French mining literature: "cran de retour". Based on his kinematic model, Bertrand rectifies the inferred finite geometry of geological units in the cross-sections of the Glarus Alps above the topographic surface, leaving the rest untouched because it is a "real observation", as already stated by Heim.

However, the interpretation of the Glarus thrust of Bertrand (1884) is still far from the present-day one. Although he recognizes the subhorizontal, top-to-the north displacement along the Glarus thrust, he summarizes his own interpretation as that of "a single fold instead of the double fold of Escher". He also states that "all glide phenomena could be brought back to folds". His interpretation remains that of a cooling Earth whose contraction is accommodated by a steeply inclined, folded area that can flow laterally, thus forming a recumbent fold of large amplitude, whose inverted limb evolves into a thrust.

These interpretations can be found again in his later cross-sections of the Mont Blanc-Mont Joly area (Bertrand and Ritter 1896; Figure 1.13(b)), where the Mesozoic cover is shown to be folded in a stack of recumbent, isoclinal folds of approximately 10 km of amplitude, all terminating in the sub-vertically folded basement-cover interface, whose folding amplitude is only of 1 km amplitude (Figure 1.13(b)). This area represents the inferred root of the nappes. These sections (Bertrand and Ritter 1896; Figure 1.13(b)) are the first to show the complete geometry of nappes, from their inferred root to their folded front, and more generally, they are also the first ones to provide such a detailed structural picture of an area above the topographic surface (Figure 1.13(b)). Bertrand and Ritter (1896) do not show this anymore with mere stippled lines, but with bold patterns, just like those that are conventionally used for the area below and at the topographic surface. Bertrand and Ritter (1896) term these sections as schematic, but they are based on sound assumptions and lateral projections, namely the idea that the Mont Joly area (line a-a′ in Figure 1.13(b)) represents a higher structural level compared to the Mont Blanc Massif (line b-b′ in Figure 1.13(b)).

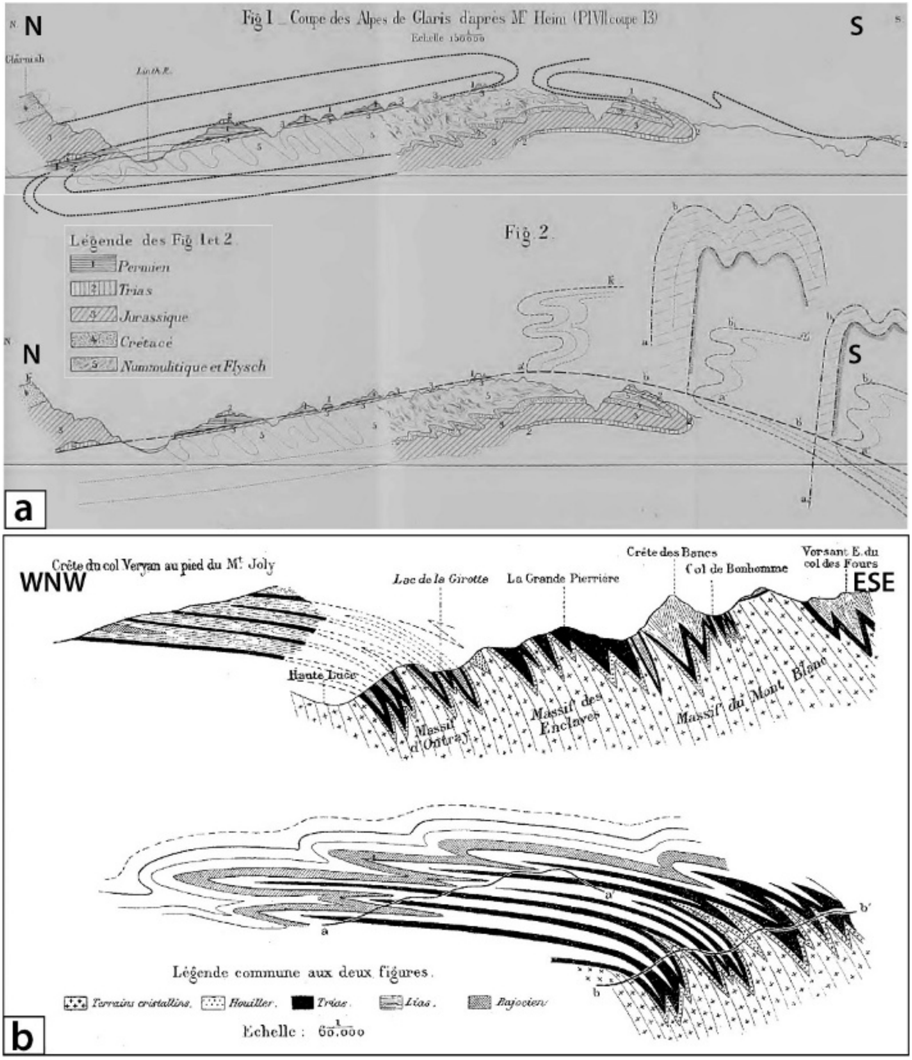
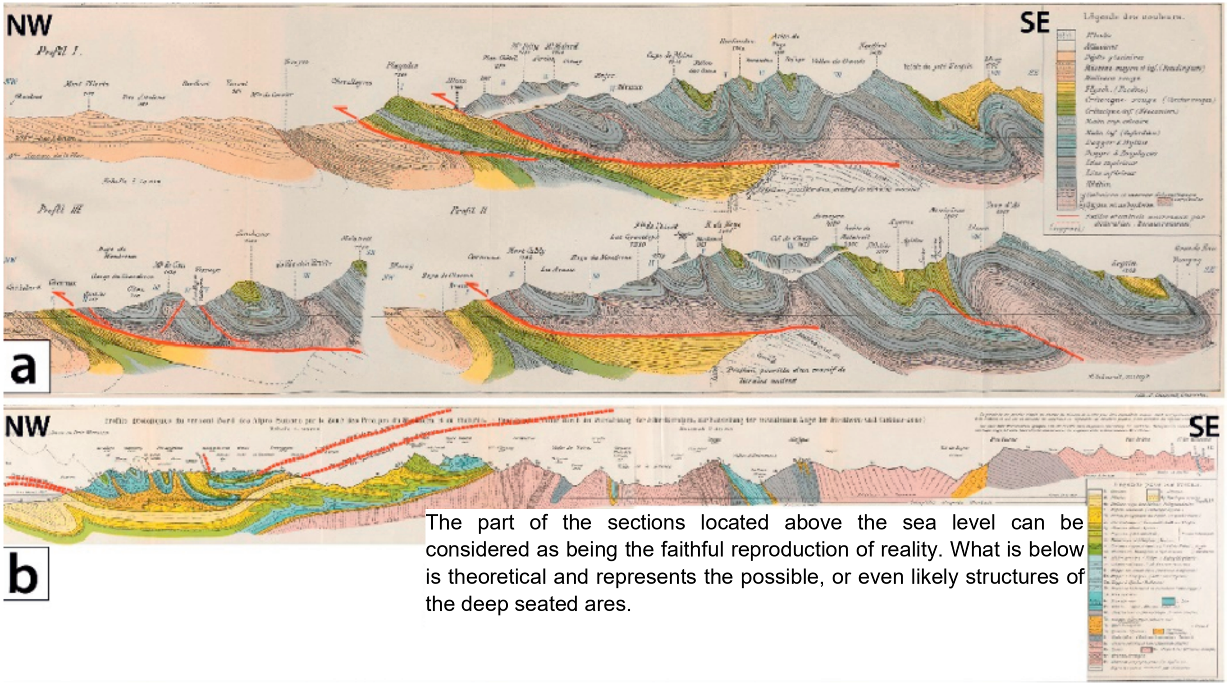


Figure 1.13. *Cross-sections of Marcel Bertrand. a) Re-interpretation of the cross-section of Heim (1878, Figure 11(a)). Bertrand deleted the southern half of Heim's section and replaced it by the trace of a large thrust that is now termed the Glarus thrust. Modified from Bertrand (1884). b) Cross-sections of the Mont Blanc-Mont Joly area, modified from Bertrand and Ritter (1896). Note the detailed representation of the area above the topographic surface and the low amplitude of the steep, basement-cover folded surface ("root zone"), compared to the cover nappes*



The part of the sections located above the sea level can be considered as being the faithful reproduction of reality. What is below is theoretical and represents the possible, or even likely structures of the deep seated ares.

Figure 1.14. *Sections across the Préalpes. (a) Section (modified from Schardt (1893)) showing the Préalpes with a thrust at their base, lying above the Eocene Flysch. (b) Section (modified from Schardt (1898)) from Lake Geneva across the Préalpes and the northernmost Mont-Blanc Massif to the Austroalpine basement. Two major thrusts are shown: the basal thrust of the Préalpes and the overlying basal thrust of the Nappe de la Brèche. Both of them are shown far above the topography in the SE part of the section, suggesting that they must be rooted further SE*

The nappe theory and its representation in cross-sections mark a new step forward, with the description of the structure of the Préalpes by Schardt (1893, 1894). His numerous and considerate arguments are accompanied by a cross-section, which beautifully depicts the internal structure of the Préalpes resting on a thrust, above the Helvetic Flysch (Figure 1.14(b)). Schardt (1893) mentions that the construction of his sections is extended below the sea level "[...] against the common habit of doing it". Indeed, these sections represent the very first extrapolation and construction of structures at greater depth. On the figure showing the sections, Schardt writes explicitly that everything below the sea level should be considered as possible and probable, unlike what is above the sea level, which is ascertained.

Extending the depth of sections by a couple of kilometers should not be taken as a simple change in image formatting. Schardt (1893) increases the depth of his section, and explicitly justifies this act, in order to show for the very first time that the deeper level of the studied area is entirely different from the upper one exposed at the surface, hence to document the presence of a major thrust plane separating these two structural levels.

The structural approach of Bertrand (1884) only requires the sections previously drawn by Gosselet (1879) and Heim (1878), in which the thrust plane can be rooted in one and the same section. However, the observations of Schardt (1893, 1894) are of a different nature. What leads him to the concept of a nappe is both the geometric relationship between footwall and hanging wall, as in the case of Bertrand (1884), but also the different stratigraphy of a sequence compared to its surroundings. As he writes in 1894: "If the tectonics of the Chablais area do not show any relationship to their surroundings, this is even more the case when considering the sedimentary facies of the units that form this area". Indeed, the sedimentary facies of the Préalpes does not show the typical Helvetic, Mesozoic sequence; hence, it is recognized by Schardt as exotic compared to its Helvetic surroundings. This is the fundamental observation that leads him to assume that the Préalpes are far-traveled units originating from the southern part of the chain.

It was only in 1898 that Schardt constructed new sections (Figure 1.14(b)), interpreting the basal thrust of the Préalpes and the "nappe de la Brèche" (a nappe derived from the southeastern margin of the Briançonnais domain as thrust planes that continue southeastward, up in the air, for tens of kilometers). This construction is a big step forward in the representation of structures in cross-sections. These studies of Schardt (1893, 1894, 1898) increase the spatial dimension of cross-sections both toward deeper (not exposed) and higher (eroded) tectonic units. The lateral dimension also increases, as shown by the base of the nappes, which is still high above the surface at the right end of the section, hence rooted outside of the plane of the section (Figure 1.14(b)).

Schardt (1898) does not connect the large thrusts to any folds (Figure 1.14(b)). He is the first to decouple the concept of a nappe from that of a recumbent fold. In his description of the historical debate about his own idea of the nappes of the Préalpes, he states: “I am not talking about a recumbent fold, but about a glided nappe”.

1.5. The beginning of the 20th century: first orogen-scale sections and the description of nappe piles

Geological mapping of the Alps was very advanced by the end of the 19th century. As summarized by Dal Piaz (2010), the first “geognostic” map of the Austrian empire was published in 1847. In 1887, the 21 sheets of the Geological map of Switzerland at the 1:100,000 scale were completed, including large parts of the northwestern Italian Alps. The geological map of the “Sardinia Mainland States”, including the Western Alps of Savoy, Piedmont, and Liguria, was accomplished in 1866 by Sismonda, at the 1:500,000 scale, and at the 1:50,000 scale for the “Alpi Piemontesi”, with 29 sheets that appeared between 1860 and 1879 by Baretti, Gastaldi and Gerlach (Campanino and Polino 2002). Hence, at the beginning of the 20th century, synthetic views of the Alps, from one side to the other, were made possible by the large number of existing geological maps.

Maurice Lugeon (1901) widens the horizon provided by Schardt (1898) by constructing a cross-section of the Helvetic nappe stack (Figure 1.15a) and showing that this nappe stack lies below the nappes of the Préalpes (Figure 1.15b). He constructs two parallel sections (Figure 1.15(a)), but shifts upward the one located further to the NE, in order to compensate for the northeastward dip of the basement and all the nappes above it (see the shift in the base line of A and B in the lower part of Figure 1.15(a)). By doing so, Lugeon (1901) achieves what is later performed by Argand (1909) by projecting structures parallel to fold axes into the plane of the cross-section. The result is the very first illustration of a stack of three nappes (Dent de Morcles, Diablerets and Wildhorn; Figure 1.15(a)) that are shown to lie below the basal thrust of the Préalpes. These sections represent the first descriptions and documentations of nappe stacks. In addition, because Lugeon was aware of the fact that the three Helvetic nappes (Figure 1.15(a)) lie below the nappes of the Préalpes, he constructed a schematic section showing both the Préalpes and the Helvetic nappes (Figure 1.15(b)). This impressive stack consisting of eight distinct cover nappes, and the observed ductile fold structures bring Lugeon (1901) to a lucid discussion on the depth conditions for the formation of the nappes, reflecting which units may have created the necessary pressure (temperature was not considered as the main factor) to induce ductility in the underlying nappes. Lugeon (1901) writes: “The nappes bearing helvetic facies [...] therefore postdate the prealpine nappes, and as a consequence, they very clearly formed at depth after, or maybe also during the displacement of these nappes of the Préalpes”. In contrast, concerning the formation of the nappes of the Préalpes themselves he states: “it is known that the poudingues were formed at the expense of the Prealpine nappes that cover them. Hence, thrusting appears to have taken place at the surface [...]”.

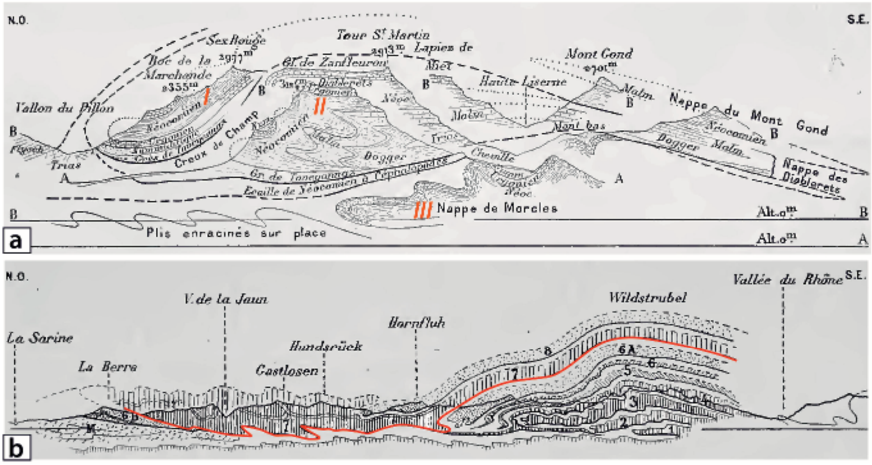


Figure 1.15. *Cross-sections after Lugeon (1901). (a) Section across the Helvetic nappes of western Switzerland. I: Mont Gond Wildhorn Diablerets nappe; III: Morcles nappe. (b) Schematic section from the Rhone Valley to the Sarine, crossing both the Helvetic nappes and the Préalpes. 1: Morcles nappe; 2: Diablerets nappe; 3: Mt Gond-Wildhorn nappe; 4–6: Nappes of the “Zone interne”; 7 and 8: Préalpes.*

In 1902, Termier (Figure 1.16(a)) published four sections across most of the Western Alps, from the Molasse basin to the “Zone du Piemont”. Only the upper plate of the orogen, which does not crop out in these sections located in the very SW of the arc, and the Italian Molasse basin are missing. They show that the orogen consists of a pile of six major nappes. The two uppermost nappes are suggested to be linked; hence, the structure consists of five orogen-scale nappes, only vaguely resembling the major tectonic (paleogeographic) units that are identified in present Alpine studies. The Schistes Lustrés nappe corresponds to the Liguro-Piemont Unit, and the Flysch and Nummulitique correspond to part of the Helvetic nappes, but the “Massifs granitiques” show one continuous basement unit throughout the chain, just as the “Terrains secondaires” (Figure 1.16(a)). The lowest nappe (number I in

Figure 1.16(a)) consists of “Terrains secondaires” that are rooted in the Pelvoux Massif (Figure 1.16(a)). All other nappes are rooted further east in a very large area of distributed folding, inferred to be the root zone of Alpine nappes (Figure 1.16(a)). A sixth and structurally highest nappe, not clearly described, must be rooted even further east, in an area not shown in the section (Figure 1.16(a)).

In 1903, Termier published a new set of five sections (Figure 1.16(b)), across the entire width of the Alps, two in the Eastern Alps, one in the Central Alps and two in the Western Alps, accompanied by a simplified, tectonic map of the Alps (“Essai à une carte structurale des Alpes”). These can be considered the first modern orogen-scale sections of the Alps and probably of a mountain range in general. Ebel (1808, Figure 4) did not illustrate the structure of an orogen, but merely the lithologies exposed at its surface. Termier (1903; Figure 1.16b) shows the continuity of the internal structure of the orogen crust, from one side to the other.

It is noteworthy that Termier did not start with the publication of one orogen-scale section, but rather with five at the same time. These sections are conceived and sketched during a short time, namely after Termier’s field trip to the Eastern Alps and to the Tauern Window in 1903, where, accompanied by Friedrich Becke and Ferdinand Löwl, he understood that the structural position and age of the “Bündnerschiefer” (or “schistes lustrés”) is exactly the same as the one that he already assessed in the Western Alps (e.g. Termier 1902), namely below the Austroalpine. Termier (1903) recognizes that the “Hochstegenkalk” (carbonates of the Helvetic cover, lying below the Schistes Lustrés) is not Paleozoic, but Triassic (it is now ascertained that it is Upper Jurassic: Kiessling (1992)) and he knows (based on the work of Franchi (1898); Frech (1901)) that the “Schistes Lustrés” are Mesozoic. Therefore, he understands that, like in the Western Alps, a Mesozoic cover sequence (Helvetic) is overlain by another Mesozoic series (Schistes Lustrés) that is eventually covered by a Paleozoic one (Austroalpine). Based on these observations, Termier is the first to interpret the structure of the Eastern Alps as a pile of nappes, as already inferred for the Western Alps.

Termier’s (1903) section across the Western Alps (Figure 1.16(b)) is similar to the ones in his 1902 paper, but differs in at least one important aspect, which is the root of the uppermost nappes. The base of the Austroalpine, that is, the base of the “surface de traînage des Dinarides”, is now clearly rooted in the southernmost basement as a line and no longer as a tightly folded region (Figure 1.16(b)). In contrast, all other nappes terminate, like in Termier (1902), in an area of steeply inclined, low-amplitude folds, reflecting his idea of nappe root. As he states in 1906: “Instead of land of the roots we could call it land of the folds, or even, following M. Lugeon, autochthonous land”. His idea is that the root is shortened, but not displaced from its footwall. Only the upper part of the nappe is sheared and displaced northward along a flat-lying surface:

> Like the trees of the Rhône Valley under the irresistible push of the Mistral, like the smoke of an industrial country under the wind that folds it down and rolls it, the folds of the Alps were laid down northward towards the external part of the chain. And the force that laid them down was so full of energy to pile them up one on top of the other, to laminate them, stretch them, fragment them, so much and so well that the nappes formed in such manner up to 100, 120, maybe 150 kilometers away from their origin. (Termier 1903)

The sections of Termier (1903; Figure 1.16(b)) show several first-order innovative features and similarities between them, pre-announcing that tectonic processes must have been similar all along strike in the Alpine chain. These innovative features are as follows: (1) the Alpine chain consists everywhere of a pile of basement and cover nappes. Their geometry varies from one section of the Alps to the other, but the nappe sequence is the same everywhere on the very first order; (2) all sections show the "Surface de traînage des Dinarides", a very large thrust that is above the topographic surface in all sections and rooted in the "Dinarides" (the South-Alpine) basement. This surface corresponds to what is considered the base of the Austroalpine, that is, the base of the upper Plate in modern Alpine literature; (3) all sections show a south-verging fold belt in the southern, "Dinaric" part of the chain, in contrast to the rest of the orogen; (4) tertiary deposits (Molasse) on the European side of the chain are overthrust toward the N (in the Eastern and Central Alps) and WNW (in the Western Alps) over long distances (up to 60 km in the Eastern Alps) by the basement and its Mesozoic cover units. The amount of Cenozoic displacement dramatically decreases in the Western Alps.

Termier terms these sections as "schematic" and indeed they are far from depicting the geometry of the units as we know them from present-day reconstructions. The basement and its cover are affected by immense amounts of folds that are schematically drawn and, according to modern surveys, either not existing or of entirely different geometry. However, the sections do show a surface topography that links these Alpine structures to specific areas where they are truly exposed. Termier has extensive mapping experience in the Western Alps (e.g. Termier 1894, 1901), where he constructs numerous detailed and accurate sections, very different in style from those of 1902 or 1903. In the latter publications, Termier illustrates in one and the same figure something that is not visible as such in the field, but which synthesizes all field observations and interpretations.

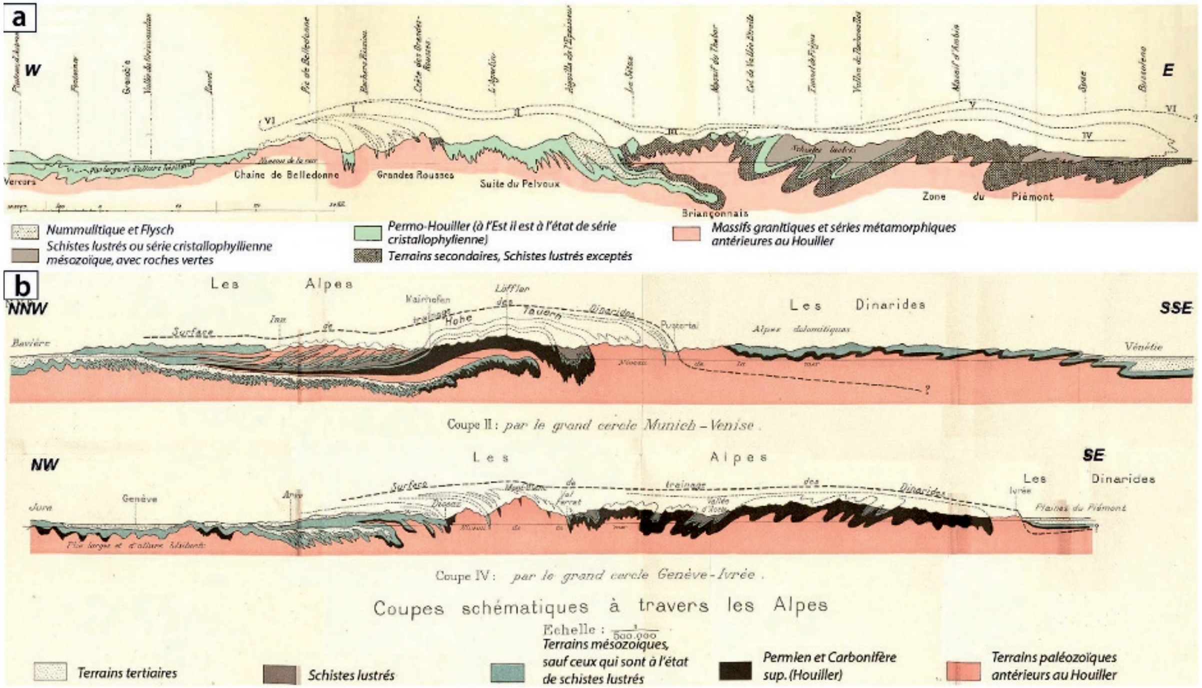


Figure 1.16. *Cross-sections after Termier. (a) Section across the W-Alps. The Alps are categorized into six major nappes (roman numbers) that are all rooted in a southeastward-located zone of distributed folding. Modified from Termier (1902). (b) Sections across the Eastern Alps (top) and the NW Alps (bottom). Note the presence of an "upper plate". Modified from Termier (1903)*

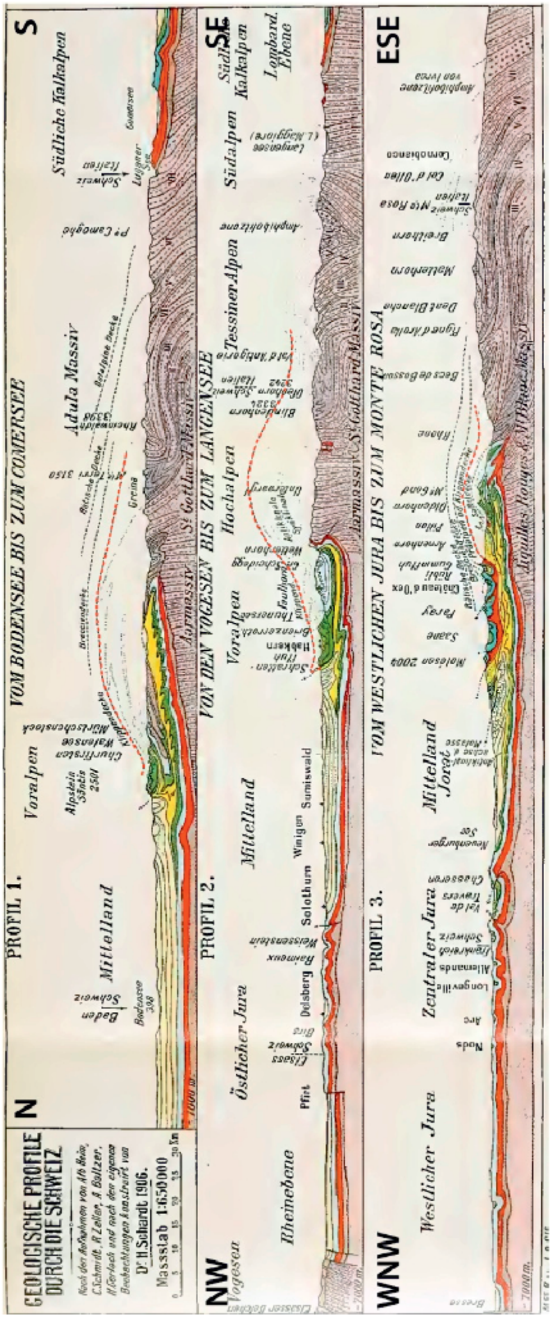


Figure 1.17. *Orogen-scale sections across the Western and Central Alps (from Schardt (1906)), showing the seven recumbent basement fold nappes (I–VII) of the Pennine Lepontine Alps. Stippled red lines: base of the Préalpes médianes*

Even if schematic, these sections show the very first-order and most important structural features of the Alpine chain. The work of Termier is a world-wide revolution in the field of tectonics. Indeed, it opens the way for rapidly increasing attempts to synthesize the structure of the entire chain in cross-sections.

Following the publications of Termier, several cross-sections showing the simplified nappe structure of the Alps were published (e.g. Steinmann (1906) for the Eastern Alps). Hans Schardt (1906; Figure 1.17) constructed three cross-sections to compare the orogen structure along the Central Alps, the NW Alps and the Western Alps on the 1:650,000 scale. The sections are interpreted down to a depth of –7,000 m and locally up to over 10,000 m. Alpine nappes and structures in these sections are shown with unprecedented detail on the scale of the orogen. Some areas are very precisely depicted, especially the cover nappes of the northern part of the Chain.

Other parts are not yet geometrically well constrained, such as the Southern Alps and to a certain degree the Lepontine nappe stack. However, for the very first time, the entire Alpine crust is shown to consist everywhere (except in the Southern Alps) of nappe piles, and the specific geometry of these nappes is also constructed and recognizable, even in the basement. Structures illustrated at that time are largely derived from sparse observations and fantasy, especially in the basement (Schmidt 1907). Some thrusts forming the base of nappes are projected upward to heights larger than 10,000 m (Figure 1.17). As later stated by Heim (1908): “Schardt has drawn the first Alpine section in which an entire folded part of the chain is thrust over a younger one”. However, where and how these thrusts penetrate into the basement is still not entirely clear (Figure 1.17).

Understanding the structure of the Penninic basement nappes and that of the basement nappes in general is not achieved within a few years; it is the result of a long standing work of mapping, interpretation and re-interpretations (Schardt 1904; Figure 1.18). Schardt (1904) excellently summarizes the history of research in the Simplon area (Western Lepontine dome, Central Alps), where many studies were performed before the construction of the Simplon Tunnel. He reproduces 10 different interpretations performed between 1851 and 1903, showing how the inferred structure of the (almost) same, 20 km long, section, changes throughout the last decades of the 19th century (Figure 1.18). Constructing sections across these basement nappes at the end of the 19th century is no longer a mere reproduction of what the eyes see in the field, otherwise the cross-sections of different authors would be more similar to one another. Schardt (1904) states this clearly when commenting on the previous literature: “One cannot say that Gerlach was ahead of his time”. Gerlach saw “what there was to be seen”, and in Schardt (1898), commenting on the excellent work of Gillerin: “He only tried to assess with the greatest precision what is really visible”. Indeed, the last decades of the 19th century are those where the main concern of geologists is no longer restricted to documenting what the eyes see (e.g. Studer 1834), but also and mainly to show what the mind adds to the eye. This explains why the 10 sections of the same area reproduced by Schardt (1904) are so different from each other (Figure 1.18). Schardt (1904) writes about the section construction of Lugeon (1901; Figure 1.18): "M Lugeon also applies the concept of recumbent folds to the gneiss of the Simplon [...]". Hence, it is now a matter of conceptual interpretation, and no longer one of direct observations.

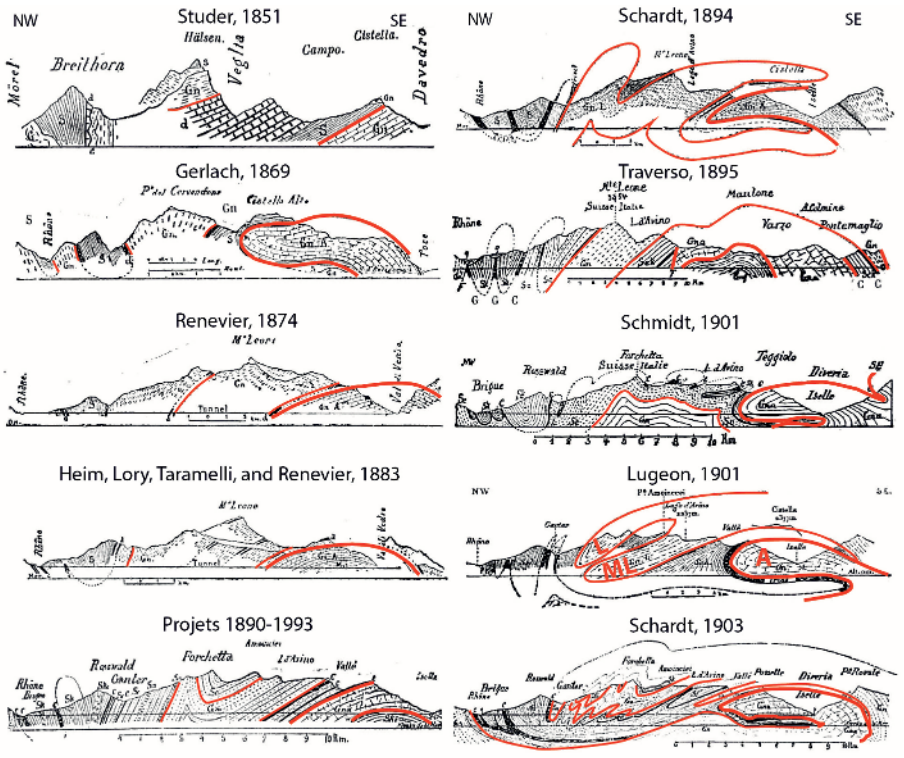


Figure 1.18. *Different interpretations the Simplon area, Western Alps, through the second half of 19th century. Thick red line: boundary of Antigorio gneiss (nappe). Thinner red line: boundary of gneiss units. A: Antigorio nappe; ML: Monte Leone nappe; L: Lebendun nappe. Modified from Schardt (1904)*

Indeed, it is with concepts of fold vergence and nappes in mind that Lugeon (1901; Figure 1.18) "solves" the problem of the Simplon structure, understanding that the basement synforms north of the Antigorio nappe are refolded anticlines, which represent the front of a higher nappe (Monte Leone and Lebendun). Hence, as anticlines, they are like the Antigorio recumbent fold (Figure 1.18) and separated from the latter by recumbent synclines. The result is a pile of gently dipping basement nappes: the first one ever described.

A significant improvement in the drawing of Alpine-scale sections is performed by Heim (1908; Figure 1.19), showing a "schematic attempt of illustrating the Alpine nappe stack along the Säntis-Chiasso line", in the Central Alps. The improvement in these sections is in terms of the geometry of the nappe stack that is more accurate than that of Termier (1903), Schardt (1906) and Schmidt (1907). The geometry of the External Aar and Gotthard massifs is quite similar to the one that is reconstructed in present-day studies (e.g. Schmid et al. 1996). The same is true for the nappe stack of the eastern Lepontine dome, showing very nice details like the back folds of the Suretta nappe (Figure 1.19). All these nappes are overlain by the Austroalpine ones that are vertically rooted in a region of very large N-S extent, between the Tambo nappe in the North and the Southern Alps (M.te Generoso) in the South, as inferred by present-day interpretations. The entire chain, including the Southern Alps, shows a northern vergence, instead of a south-directed one in the Southern Alps, as already pointed out by Termier (1903) and unanimously recognized by modern studies (e.g. Laubscher 1985). In fact, the section of Heim (Figure 1.19) indicates that the Southern Alpine basement represents the root zone of a large number of nappes of the orogen, which were all emplaced by top-to-north displacement. In spite of these inaccuracies, this section is the first to integrate the information of a vast area in map view into one and the same vertical plane, by lateral projection parallel to the main fold axes. In contrast to Termier (1903), the structures projected far above the topographic surface do not only consist of long sub-horizontal lines, but of quite accurately constructed nappe contacts, each with a specific size and geometry.

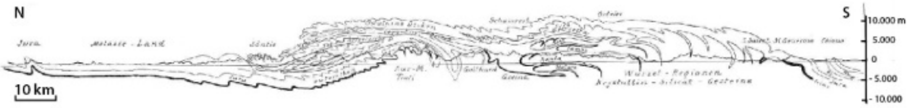


Figure 1.19. *Cross-section of the Central Alps, modified from Heim (1908). The structure of the entire Central Alpine nappe stack is shown here for the first time*

Heim's concept of nappes appears to be similar to that of Termier: they are squeezed out ("*herausgepresst*") from an area consisting of their roots, the latter being subvertical. Interestingly, after having denied their existence at the end of the 19th century, Heim states that the idea of the nappes

> is neither a hypothesis nor a theory, but a summary of observations. The theory, i.e. the true mechanical explanation of the processes and their causes, will be later deduced from additional and thorough observations.

The N-vergence of all nappes including the Southern Alps in the section of Heim (Figure 1.19) probably results from the well-constrained, north-verging fold geometries in the eastern Lepontine, in addition to the following observations reported by Heim: (1) nappes usually show a sedimentary facies that is characteristic of areas located further south compared to the underlying units, whereas the contrary is never true; (2) the small-scale geometry of the folds inside the nappes generally suggests a top-to-the-north shear sense; (3) if most nappes are displaced northward, it is mechanically very unlikely that some of them moved southward.

In 1909, Schardt presented several sections striking across most of the Western Alps (his Figure 4). Schardt shows the nappe pile, correlating their gently dipping parts in the west with their vertical roots in the east. As in the case of Heim (1908) for the Central Alps, the Internal Zone is now shown with its nappe structure, with roots remaining vertical down to 10,000 m and no longer showing their folded base close to the surface, as in Termier (1903), or a distributed basement folding as in Schmidt (1907).

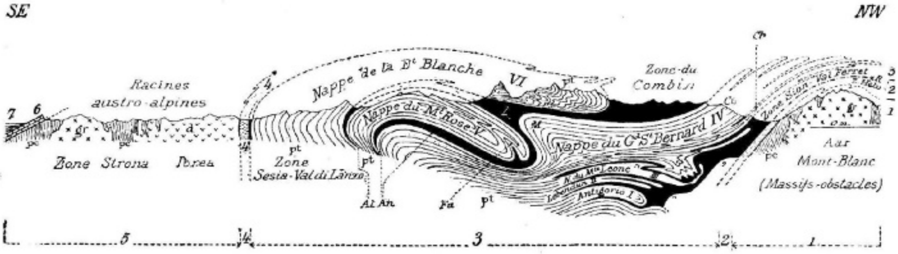


Figure 1.20. *Schematic cross-section of Argand (1909), of the Pennine Alps, from Aar/Mont Blanc Massif to Ivrea-Strona zones, through the I-VI Pennine fold-nappes*

In the same year, Argand published his first orogen-scale, "schematic" section (Figure 1.20), striking from the Ivrea-Strona Zone in Piedmont (Italy) to the External Massifs (Aar-Mt Blanc), and crossing the Matterhorn and Monte Rosa. Although the topography of the Matterhorn is clearly recognizable, his unifying term Mont Blanc-Aar Massif given to what he calls the "Massif-obstacle" at the NW margin of the section shows that Argand constructed a general external massif and not a specific one. The scale of the section is not provided, but based on the topographic features the entire section appears to represent a vertical distance of nearly 20 km, hence significantly more than previous sections. The nappe geometries of Argand (1909) are very accurate and do not differ significantly from his later sections and the ones of the present-day literature.

Argand (1909) discusses the “déroulement” (retro-deformation) of the cross-section, without yet showing it. His reasoning is in terms of paleo-geographic position of the nappes based on their structural levels in the constructed section, that is, the higher the structural level, the farther southeastward the corresponding unit before Alpine stacking. His approach is very quantitative for his time: he estimates 50 km displacement along the base of the Dent Blanche nappe, and in 1916, he even explains that retro-deformation can be performed by volume balancing.

In 1911, Argand shows a block diagram of the Northwestern Alps (Alpes Pennines, from the Simplon-Tessin dome to the Dent Blanche nappe), showing a tectonic map at the surface and a NW-SE cross-section on the side (Figure 1.21). The section is largely constructed by projecting nappe contacts from different parts of the map into the vertical plane of the cross-section, parallel to the fold axes that dip gently southwestward and quite homogeneously in the latter area. As a result, the geometries and depths of the structures in cross-section are the result of the projection of numerous surface structures that are not lying in the same vertical plane. The section is “the best representative” of this broad area, but not the exact (precise) representation of the geology along a specific vertical plane. Lateral shifts of the section trace in this area would not show any changes in the cross-section.

In the same year, Ampferer and Hammer (1911; Figure 1.22(a)) depicted the entire structure of the Eastern Alps, along an N-S section. Their paper has the explicit title: “Cross-section through the Eastern Alps, from the Garda Lake to the Allgäuer Alps” (translated from the original German). It is 183 pages long and its orogen-scale section, in color, documents in detail some 200 km horizontal length and a vertical extent usually attaining a maximum of a few 100 m only. As a result, the proportion of this cross-section, which is presented in a fold out of 11 pages all horizontally bound together, is rather unusual. Their very detailed legend consists of 58 lithological and stratigraphic units, ordered by age. No attempt is performed to simplify them into a smaller number of tectonic units. No correlations, aimed to provide a geometrical and structural continuity between one part of the section and the other, are shown.

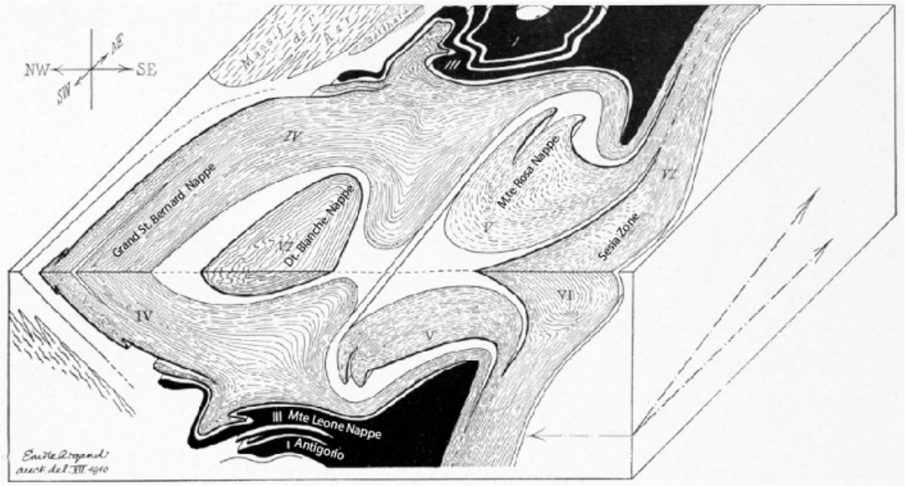


Figure 1.21. *Block diagram of the Western Alps, in which the Lower Penninic fold-nappes (I–III, black), exposed in the Tessin dome, are projected downward to the west, parallel to fold axes; modified from Argand (1911)*

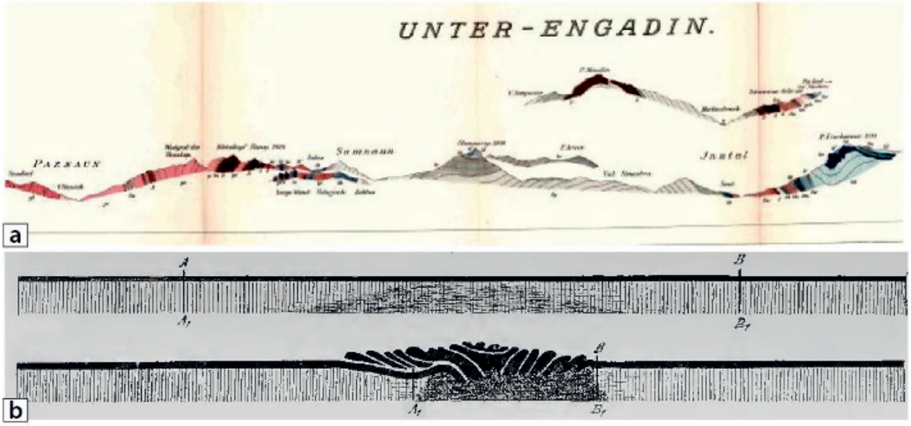


Figure 1.22. *a) Segment of cross-section through the Eastern Alps, after Ampferer and Hammer (1911). b) Schematic section illustrating how shortening accommodated by nappe stacking in the upper crust needs to be compensated by shortening (“Verschluckung”) at depth (see the text for explanation)*

This section does not attempt to achieve a synthetic representation as Argand (1909, 1911) did, and underlines that at this time it was an exceptional representation.

The E-Alpine section of Ampferer and Hammer (1911) does not provide newer insight into the structure of a mountain chain. However, in addition to this section, their paper shows some extremely schematic drawings that do synthesize the structure of the Alps, but to such a degree that, geometrically speaking, nothing of the sections described in their long manuscript can be recognized in the latter pictures (Figure 1.22(b)). These schematic sections, which do not appear to be more specifically related to the Alps than to any another orogen, are the base for the first discussion on the quantitative relationship between shortening in the upper and lower (middle?) crust. Ampferer and Hammer (1911) infer that shortening in the cover, as can be deduced from the cross-sections, is by far more important than in the basement:

> If we imagine the nappe of the younger strata retro-deformed to its original position, then we get a 2-3 times wider band as that of the retro-deformed young basement folds, even if the thickness of the basement beds is considered as very small.

As a result, Ampferer and Hammer (1911) show and discuss for the first time that a nappe pile in the upper crust may possibly be compensated by the disappearance of middle and lower crust at deeper levels (“mass suction towards depth”; “absorption of the deeper zones”; “huge sinking”). This discussion allows the authors to use for the first time the term “Verschluckungszone” (swallowing zone), which is classically considered to be the ancestor of the term subduction zone.

While these brave attempts to depict the structure of the entire Alpine chain within cross-sections are making progress, the construction of detailed and precise sections of specific segments of the Alpine Chain continues to be remarkably refined. Without being able to cite them all, we should recall those of Buxtorf (1908) for the Jura Mts, Sander (1911) for the Tauern Window, Lugeon (1914) for the Aar Massif and its cover, Dal Piaz (1912) for the eastern Southern Alps, Heim (1919) and Staub (quoted in Heim 1922) for the Eastern Central Alps and Western Eastern Alps.

1.6. Argand and the invention of crustal plate tectonics (1916–1924)

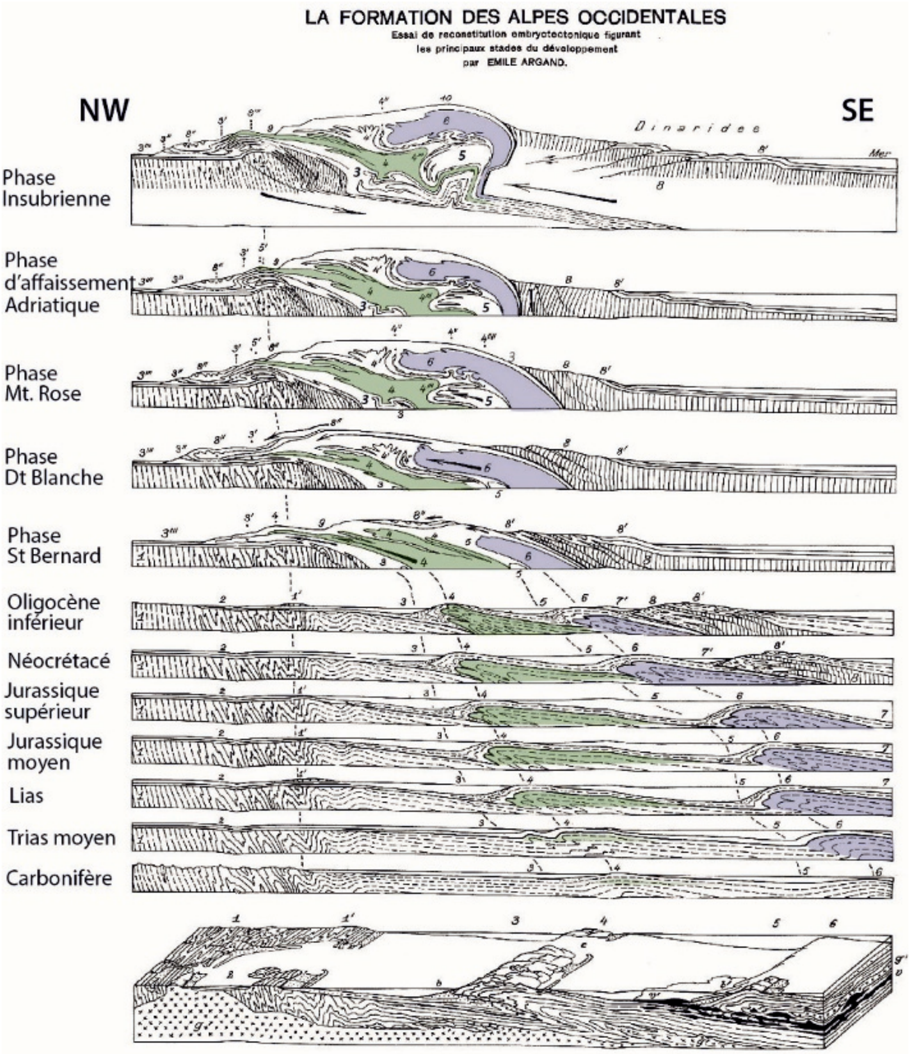


Figure 1.23. *Cross-section through the Western Alps and its retro-deformation, modified from Argand (1916). Two nappes are colored to facilitate comparison of their geometric evolution through time. The purple nappe (6) corresponds to Sesia-Dt Blanche, and the green nappe (4) corresponds to the St Bernhard nappes*

In 1916, Argand published his seminal paper "Sur l'arc des Alpes Occidentales", describing the geometry of the first-order structures of the Western Alps and interpreting both their kinematics and mechanics. Without giving any arguments on this subject, Argand explains in the first paragraph of his article that the structure and orientation of mountain chains depend on three major factors: first, on the orientation of pre-existing obstacles: the hercynian basement, forming the External Massifs, termed the hercynian hemicycle; second, on the rheological characteristics of the nappes (their "plasticity"); and third, on the intensity and duration of the applied "effort" (the force of convergence), which influences the plasticity. A fourth factor, but of subsidiary importance, is the angle of convergence between the continental blocks.

For the first time in the history of Alpine Geology, Argand performed a retro-deformation of a cross-section (Figure 1.23), and of the orogen in map view (or at least a reference line of the orogen), as he consciously notes: "the evolution of a tectonic object has never been depicted in such a way, which combines its large size and complexity". Besides the great quality of his construction, his section (upper panel of Figure 1.23, "Phase Insubrienne") brings major advancements in the understanding of Alpine Tectonics: (i) The "Dinaric" (South-Alpine) block only shows modest shortening accommodated by south-verging thrusts, which form in the most recent deformation phase ("Insubric"). As a whole, due to the very small offsets of the thrusts, it has a rather rigid behaviour compared to the Penninic nappe stack that accommodates shortening by ductile folding and adapts to the shape of the "Dinaric" block. This is what modern literature describes as indentation of the upper plate (Dinaric block) during Alpine collision. (ii) Between Europe and the Dinaric block, a nappe stack forms, characterized by very ductile, mainly isoclinal, recumbent fold nappes. In the later stages of tectonic evolution, these nappes become folded, thus accommodating additional convergence between the European and the Dinaric blocks. These structures correspond to what is termed "post-nappe folds" (Milnes 1974) and inferred to represent syn-collisional shortening that overprints the subduction nappe stack. Most of this shortening, in the structural evolution sketched by Argand, is accommodated in the immediate vicinity of the indenter (Dinaric block), where the nappes become verticalized and thinned by vertical stretching. This area was classically defined as the root zone of the nappes (e.g. Termier 1903). In contrast to Bertrand (1884) and Termier (1903), Argand shows for the first time that the steeply oriented roots of the nappes are not a primary structure, but rather the result of late refolding of previously formed, gently dipping nappes. (iii) The lowermost unit of the nappe stack, immediately above the Europe-derived basement (number 3 in Figure 1.23), forms the core of an orogen-scale antiform and continues to the southeast, below the lowermost Dinaric Units. This unit 3 corresponds to the lower crust of the Penninic zone that is shown to underthrust (subduct?) below the Dinaric block. The same result is shown by seismic interpretations of the nineties (e.g. Polino et al. 1990; Schmid et al. 1996), and corroborated by geophysical studies in the past 20 years. It is amazing that Argand is able to infer such a structure without any geophysical data or the knowledge of subduction. (iv) The external massifs represent antiformal basement culminations that result from high angle, N-vergent basement thrusts, as suggested by modern reconstructions (e.g. Boutoux et al. 2016), except for some minor gently dipping thrusts in the northern flank of the massif. (v) Two arrows pointing in opposite directions (upper panel of Figure 1.23) indicate that the southeastern “Dinaric” block moved toward the NW on top of the European block. An arrow pointing to the SE is depicted on the European block. The arrows are subparallel to the main contact between these two blocks, and they are drawn on the least deformed parts of the two continents, clearly indicating the movement of the entire continental blocks, not the one of individual nappes (see also Figure 1.24). This is the very first illustration of one continental margin thrust on top of the other as a result of convergence. From a kinematic point of view, the youngest stages depicted in the retro-deformed sections of Argand (Figure 1.23) are not significantly different from those that are still published since the discovery of Plate Tectonics.

The structural evolution of the Alpine nappe stack of Argand shows that nappes represent the amplification of recumbent folds that nucleate on preexisting, hercynian “ge-anticlines”. Stretching of their lower, reverse limbs leads to the formation of discrete thrusts, hence of fold nappes in their hanging walls (e.g. evolution of unit 6, Dent Blanche in Figure 1.23). This evolution is very different compared to that suggested by Bertrand (1884), Termier (1903) and Schardt (1909). The latter authors consider a nappe as the lateral flow of vertically folded units due to the drag of orogen-scale thrust (“traîneau écraseur”) at the top of the folded area, which is consequently termed the root zone of the nappe. It is also the first time that displacement, implicit in the geometry of the cover nappes, is somehow balanced with respect to displacements accommodated within their basement.

After 1916, Argand does not construct any new Alpine cross-sections. He does not add more details to his section or construct any new ones in other parts of the Alpine chain. This task is continued by many other Alpine geologists like Heim (1919), Staub (quoted in Heim 1922) and Lugeon (1932). Heim (1919) constructs an accurate section of the Penninic nappe pile, including the base of the Austroalpine, up to 20 km height. In this section and even more in those of Staub (1924) in the Eastern Alps, the influence of Argand (1911, 1916) is very visible, maybe even too visible for Argand’s taste (see Sengör and Bernoulli (2011, pp. 903–904)).

In 1924, Argand published his seminal work (“La tectonique de l’Asie”). As stated by Lugeon (1940), the book title does not fit its content: “One imagines that it will only be about that old continent, whereas it is about the entire Earth”. Indeed, Argand (1924) shows there a simplified and more schematic version (Figure 1.24) of his Alpine cross-section of 1916. The only structural elements that are still recognizable are the backfold of the Monte Rosa nappe and the smaller amplitude antiform of the external massif. The major changes compared to 1916 consist of the addition of the “sima” to the “sal”-crust and the inclusion of a discontinuous horizon of basic rocks inferred to be related to the “sima” all along the contact between Penninic and underlying European units (Figure 1.24). These sima-derived lenses correspond to what is presently termed ophiolitic units. Argand shows that they exist in all orogens, and that they are always located in a similar position along the interface of converging continents (Argand 1924). Both the over- (Austroalpine nappes) and underthrust (European nappes) margins are shown to thin out severely before wedging out completely (Figure 1.24), as inferred today from seismic imaging of continental margins (e.g. Boillot et al. 1995). The schematic character of this section of Argand shows that, in this phase of his research, he no longer tries to define the precise anatomy of the Alpine orogen, but rather to compare it with other Cenozoic orogens to understand what the first-order similarities are, and hence the general process of orogeny. Based on his sections (Argand 1924 and Figure 1.24), these similarities are as follows: (1) thrusting of one, thinned continental margin on top of the other, similar to a “flat subduction” of one margin; (2) intrusion of sima from the mantle along the plate interface; and (3) folding of a nappe stack between continental blocks.

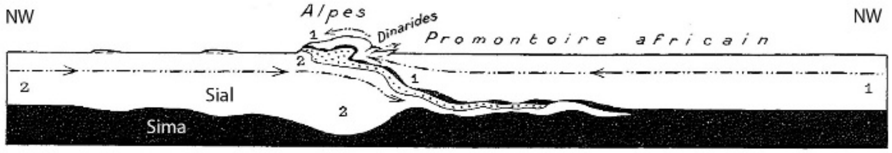


Fig. 24, Argand 1924

Figure 1.24. *Cross-section of the Alps, modified from Argand (1924). The section is reduced to its first-order structures and taken from a series of figures used by Argand to compare sections of several orogens, each of them showing only the very first-order, orogen-scale structures: number 1 corresponds to the “Promontoire Africain”, Adria in the present-day terminology. Number 2 corresponds to Europe*

1.7. Alpine cross-sections after Argand and before Plate Tectonics (1924–1960)

In 1934, for the 50th celebration of the Swiss Geological Society, a geological guide of Switzerland was published, in which Lugeon presented a series of five orogen-scale sections (one of which is shown in Figure 1.25(b)) through the Swiss Alps, all constructed and redrawn down to –10,000 m, after Buxtorf, Gagnebin, Alb, Heim, Oberholzer, Preiswerk and Staub. These sections nicely show the nappe structure of both basement and cover, differentiating the European, Penninic and Dinaric basements. Almost 50 years later, in the classical book "Geology of Switzerland" (Trümpy et al. 1980), a major reference on the Alpine chain for decades, three orogen-scale cross-sections were constructed by Spicher (Figure 1.25(a)). These sections are interpreted down to –7,000 m and no significant differences can be assessed compared with those of Lugeon (1934). The time interval between 1930 and 1980 does not bring any significant improvements to Alpine orogen-scale sections. The structure of the chain has been well known since the 1920s and additional studies only refine it to the second order.

An exception to the latter trend comes from very few scientists that start to imagine and image the deeper parts of the chain (Heim 1927; Kraus 1932, 1954; Kober 1942, 1955), but their illustrations are rather schematic, lacking both physically sound models to assess what may be expected at depth and more importantly, geophysical data to provide robust constraints on such deeper structures. Heim (1927) attempts to include the new knowledge derived from gravity surveys into a schematic section showing a subsided nappe pile, due to the effect of isostatic compensation. Kober (1942; Figure 1.26(a)) shows that the Alpine orogen is underlain by a stratified area going from magma at the base of the crust, to migmatite in the middle crust and to granite in the upper crust. Africa and Europe converge and squeeze this central area that escapes by diverging magma flow both laterally at depth and upward, where it leads to the crystallization of granites.

Kober (1955) modifies the latter models showing a series of three sections across the Western, Central and Eastern Alps, interpreted down to 70 km depth. The latter section is shown in Figure 1.26(b). In contrast to Kober (1942), this section is simplified, and schematic, but strongly inspired by the known structure of the Alpine nappe stack. The novelty concerns the deeper part of the section, imaging the 30–70 km depth range, and showing how northern and southern thick continental blocks (from 5 to 35 km depth below the foreland) gently and symmetrically bend below the nappes, overlying two thick zones of magma that also bend below the orogen.

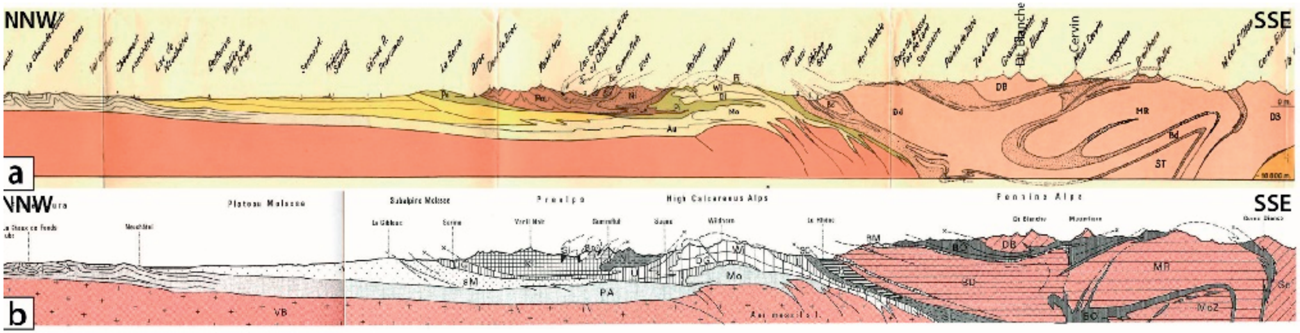


Figure 1.25. *Cross-sections of the NW Alps. a) Section constructed and compiled by Lugeon (1934) on the base of sections of Arbenz, Argand, Buxtorf, Gagnebin, Heim, Lugeon, Oberholzer, Preiswerk and Staub. b) Section following exactly the same trace of upper section a). After Spicher, in Trümpy (1980)*

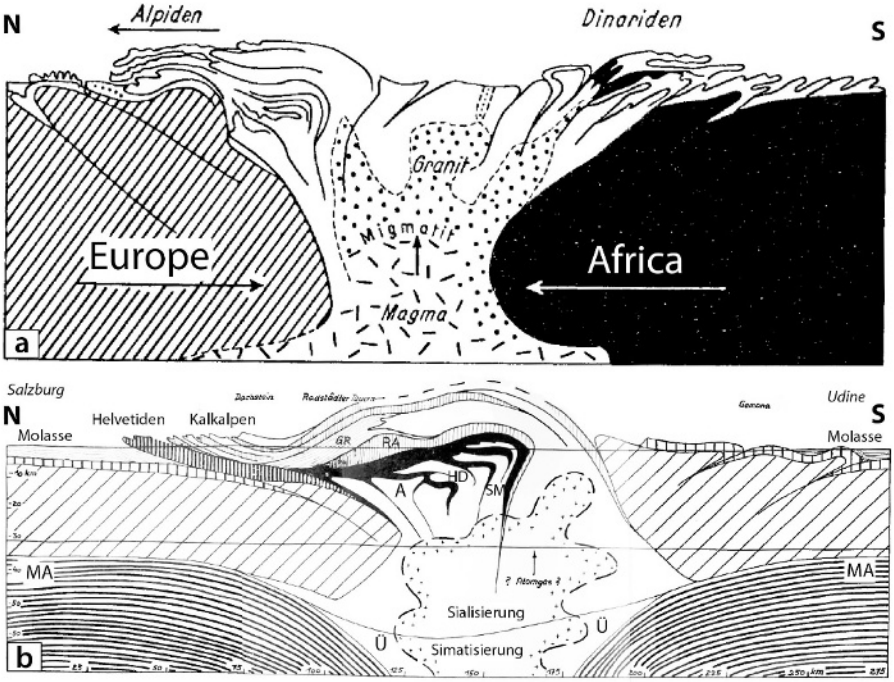


Figure 1.26. *Speculative models of the deep structure of the Alpine orogen in the time between Argand and Plate Tectonics. (a) Section through the Alpine orogen, after Kober (1940). The convergence between Africa and Europe is accommodated within a very large area characterized by magma at depth and a transition to migmatite and granite toward higher crustal levels. (b) Eastern Alpine cross-section, after Kober (1954). The crust (ca. 35 km thick) floats on an inferred "Magma Zone" (MA in b) that symmetrically warps downward in a sort of "Verschluckungungszone" of Ampferer type. The asymmetry of the nappe stack corresponds to an apparent plunge of Europe below Adria, which only affects the crust. A: Ankogel nappe; HD: Hochalm nappe; SM: Sonnblick–Modereck Dome; Ü: transition zone*

Neither the magma zones nor the continental blocks touch each other, because they are separated, respectively, by the "Simatization" and "Sialization" zones (Figure 1.26(b)). This cross-section is inspired by the conceptual models of Ampferer (1906) and Ampferer and Hammer (1911), rather than by observations of nappe structures, which are only schematically depicted.

1.8. Alpine cross-sections after Plate Tectonics

1.8.1. *Geophysical interpretations*

The 20th century brought a wealth of new geophysical data that was integrated in cross-sections. At the beginning of the 20th century, gravity measurements were performed in Switzerland (e.g. Niethammer 1904). The resulting mass deficit is already discussed by Heim (1921), who refrains from interpreting it in terms of differences in sial versus sima composition of the magma, inferred to lie at depth, below the chain. Heim explains that it is the result of thickening the crust by folding (Heim 1927). In the following decades, gravity anomalies are interpreted on the basis of different hypotheses concerning the density of rocks at depth, hence an image of the inferred “Sial/Sima” (crust/mantle) boundary below the Alps, showing its synformal structure with a maximum depth between 30 and 50 km, is provided (Gassman and Prosen 1948). From the end of the 1950s onward, seismic experiments (wide angle reflection) provide images of the deep structure of the Alpine orogen (e.g. Closs and Labrouste 1963; Berkhemer 1968; Giese 1968; Choudhury et al. 1971) and innovative Alpine sections are published by the geophysical community, interpreting the geometry and depth of the Moho in cross-sections (Figure 1.27). Contour maps of the Moho (e.g. Berkhemer 1968; Labrouste et al. 1968; Choudhury et al. 1971) and iso-velocity lines of the crust in cross-sections (e.g. Giese 1967, 1968; Giese et al. 1970; Choudhury et al. 1971; Perrier 1973; Müller et al. 1976) widen the image of the orogen from approximately 20 (e.g. Argand 1916) to over 60 km depth (e.g. Giese et al. 1970). Serial, radial sections (Giese 1968; Choudhury et al. 1971; Figure 1.27) illustrate for the first time the superposition of two Mohos in the Western Alps, or, more precisely, the superposition of two crust-mantle transition zones. The proper mantle, characterized by the 8 km/s velocity, is still shown as one continuous surface (Figure 1.27).

In spite of some differences in the absolute values of the Moho depth, most models show it as a single and continuous surface (Figure 1.28), which passes from a depth of approximately 30 km below the external massifs to almost 50 km in the Internal Zone (e.g. Berkhemer 1968) or almost 60 km below the Lepontine (Müller et al. 1976). Some models show that the Moho surface is folded by two open synforms, the eastern one located below the Ivrea body (Berkhemer 1968; Miller et al. 1982; Figure 1.28(a)), or by a single synform whose hinge, corresponding to the thickest part of the Alpine crust, is located below the Lepontine in the Central Alps and below the “Internal Zone” in the Western Alps (Giese 1968; Giese et al. 1973; Müller et al. 1976; Müller et al. 1980; Müller 1984; Figure 1.28(b)).

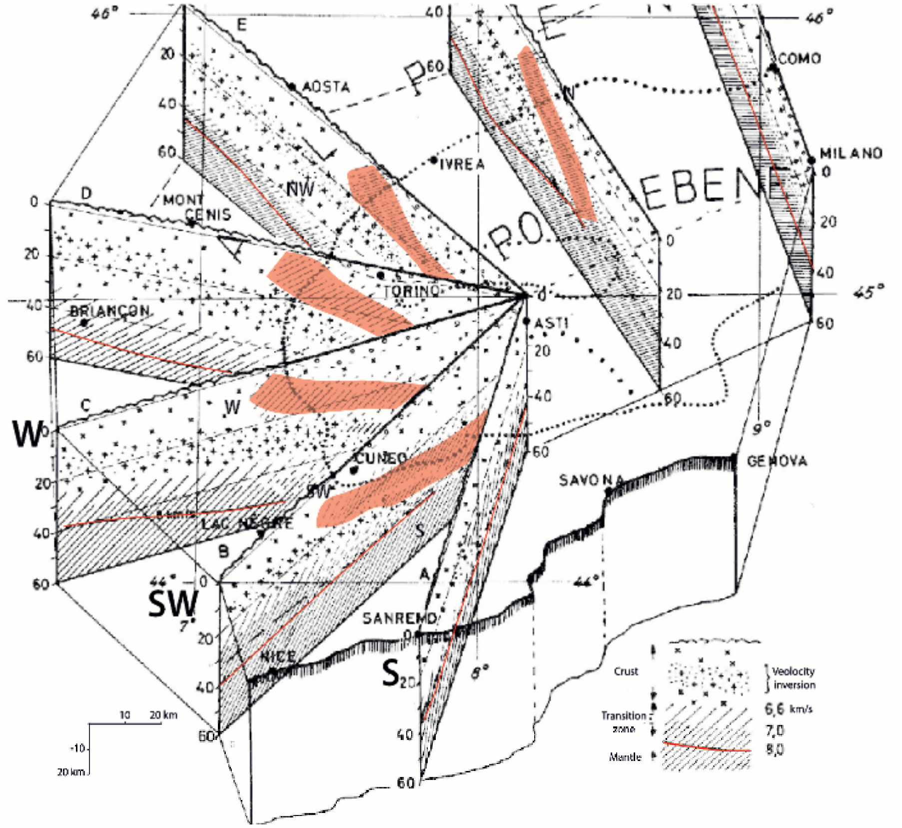


Figure 1.27. *Block diagram with cross-sections perpendicular to the arc of the Western Alps, showing the geometry of iso-velocity lines of seismic wave propagation. Orange shading: upper transitional zone. Modified from Giese (1968)*

Giese (1968) and Giese et al. (1968) showed for the first time in the Western Alps that the Ivrea body at depth represents the transition between lower crust and mantle that it is continuously linked to the Alpine (Adriatic?) mantle located at depth, further east. However, their serial sections (Figure 1.27) still show a single, continuous Moho surface below the Alps, from which the Ivrea slice penetrates into the crust. Giese (1967) notes that the Ivrea body lies above sialic rocks, which he thus interprets as a “tectonic slice or an intrusive body” (later described as a mafic-ultramafic body based on petrographic observations).

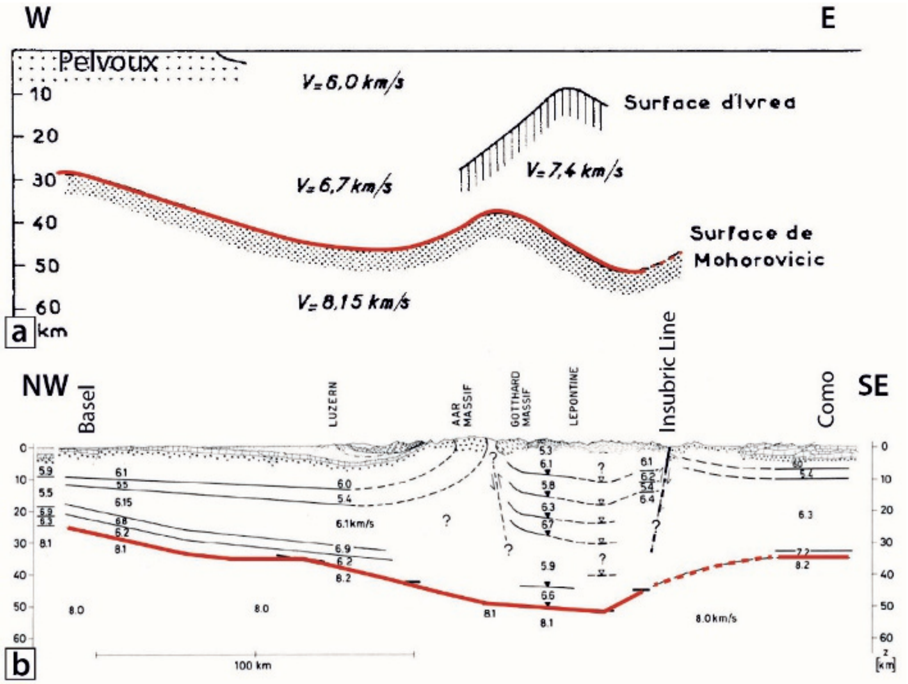


Figure 1.28. *Alpine Moho across the Alps. a) Section across the Pelvoux External Massif, showing a continuous Moho surface building two synforms, and a high velocity anomaly at higher crustal level termed the Ivrea surface. Modified from Berkhemer et al. (1967). b) Section across the Central Alps, illustrating the geometry of iso-velocity lines in the crust, and the Moho surface. A single Moho (red line) forms a large synformal structure whose hinge is located below the Lepontine Dome. Modified from Müller et al. (1980)*

The cross-section of the Western Alps of Giese et al. (1970; Figure 1.29) is the first one to integrate geological and geophysical data in a single section. The superposition of two distinct crust-mantle transition zones is still visible. The Ivrea body is shown as the termination of a larger, gently E-dipping body (Figure 1.29) consisting of crust-mantle transitional units, and this body lies above and is subparallel to the European Moho, even very far to the ESE (above the Monferrato, hence above the Apennines frontal thrust). This superposition is explicitly interpreted by Giese et al. (1970) as a thrust of the Adriatic mantle and overlying crust on top of the Penninic crust: “The Southern Alps-Po Plain with its crust and (crust-mantle) transition zone, and even with parts of its upper mantle must have been thrust over the simatic substratum of the Penninic Units”. However, the same authors (Choudhury et al. 1971; Giese et al. 1973) continue to show Moho maps of the Alpine realm with continuous contour lines from the European to the Adriatic plates.

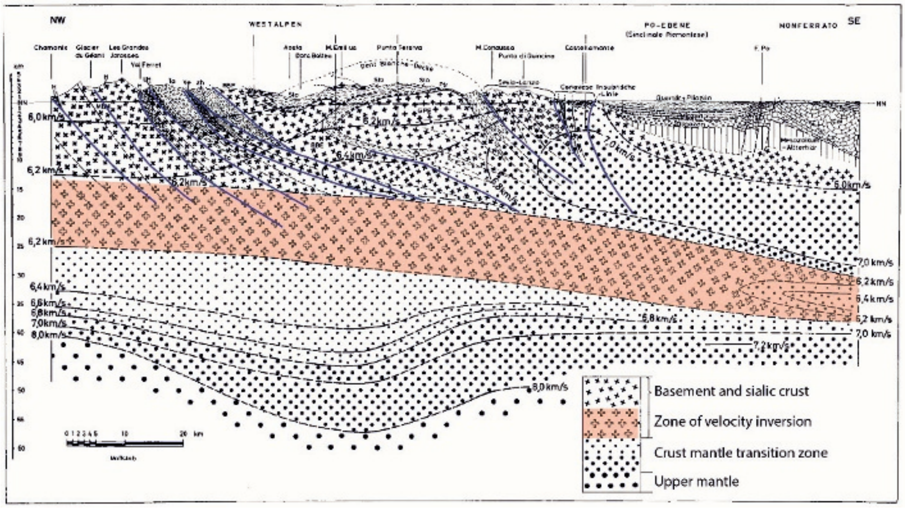


Figure 1.29. *Cross-section of the Western Alps integrating geological, tectonic and seismic data, modified from Giese et al. (1970). Note that major thrusts (blue lines) all terminate in the upper part of the “Zone of velocity inversion”*

Giese (1978) and Giese and Morelli (1978) finally present maps where the European and the Adriatic Mohos are distinguished, and where cross-sections show two distinct Moho’s instead of two crust-mantle transition zones (Figure 1.30). One Moho is thrust over the other, leaving a crustal volume in between them, as indicated by the velocity inversion zone. The base of the upper mantle dips eastward and steepens upward, where it joins the Insubric Line. More detailed cross-sections and Moho maps are shown by Giese et al. (1982). They state that “it is unrealistic to assume a crust/mantle boundary running through an Alpine orogen without any interruptions”, meaning that there must be a thrust plane (subduction interface in modern terms) that accommodates shortening within the mantle. In spite of the 20 years that passed since the formulation and first acceptance of Plate Tectonic processes, these figures and ideas are still in contrast with those of most other groups working on the deep structure of the Alps (e.g. Müller 1980; Miller et al. 1982) that suggest a continuous and rather symmetric synformal deflection of the Moho below the Alps (Figure 1.28(b)). The latter studies relate the symmetry of the Moho structure to an inferred symmetric type of subduction, as previously postulated by Ampferer (1906), Ampferer and Hammer (1911) and Laubscher (1969).

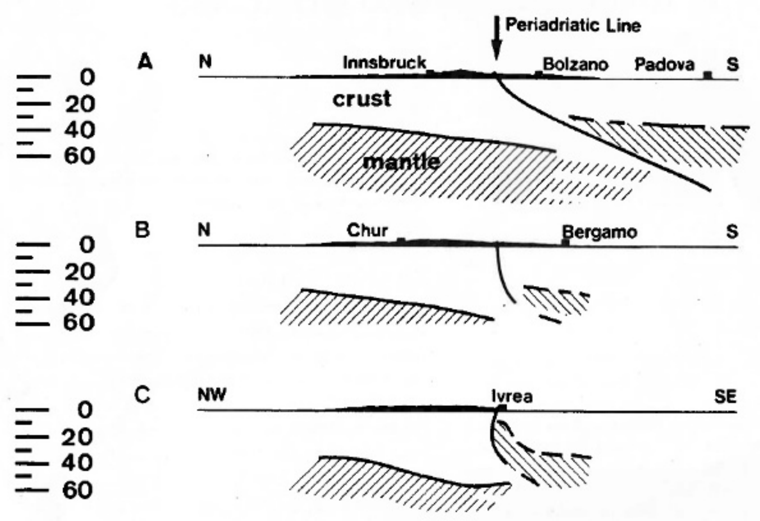


Figure 1.30. *Cross-sections showing the crust-mantle boundaries in the Eastern (A), Central (B), and Western Alps (C), after Giese (1978). Oblique-line pattern: mantle*

1.8.2. *Geological interpretations*

While the geophysical community tried to assess the deep structure of the Alpine crust-mantle transition based on the newest results of gravimetric and explosion seismic studies, geologists attempted to image the deep structure of the Alps in cross-sections that integrate the new concepts of orogeny based on Plate Tectonics. These studies resulted in lithospheric-scale cross-sections that image the Alps down to several hundreds of kilometer depth (Laubscher 1970, 1974, 1983; Dal Piaz et al. 1972; Hawkesworth et al. 1975; Dietrich 1976; Figures 1.31 and 1.32), thereby reducing the details of the crustal nappe stacks to only few schematic lines (e.g. Laubscher 1970, 1971, 1974, 1983; Hawkesworth et al. 1975; Dietrich 1976). The basis for all these sections is more conceptual than observational, the concept being that of subduction.

Laubscher (1970; Figure 1.31) was the first to sketch the evolution of the Alpine orogen, in which convergence of two plates is accommodated by subduction. It is a symmetric subduction of both plates, recalling the concepts of Ampferer (1906) and Hess (1962), and terminating by a break off of the lithospheric root. These schematic sketches show for the first time how the Alpine crust detaches from the subducting lithosphere, thus becoming accreted to the orogen. The paper illustrates the lithospheric-scale, structural evolution of the Alps in a series of cross-sections, from the Jurassic to the Present. After the kinematic evolution reconstructed by Argand and the similar ones (e.g. Staub 1924) that were inspired by him, Laubscher (1970) is the first to re-propose the structural evolution of the Alps, in a series of time slices, based on the new conceptual model of Plate Tectonics. Laubscher (1970) is conscious of the speculative character of these cross-sections that are based on a theory, not on observations. He states:

> [...] I left the subduction zone in the lithosphere in the south, without changes (compared to previous stages); there are no specific reasons for that; a shift to the north, for example through rolling of the plate hinges is absolutely possible.

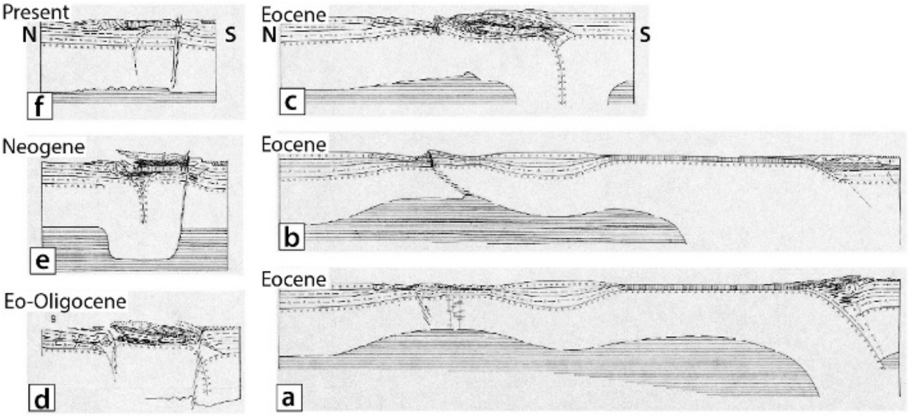


Figure 1.31. *Cross-sections illustrating the deep structure of the Alpine lithosphere and its evolution through time (from a to f). Modified from Laubscher (1970)*

Hence, the subduction zone shown in Figure 1.31 is drawn in one specific place, but it could just as well be elsewhere below the orogen. The model is well ahead of the geophysical data that could constrain it.

The theory of Plate Tectonics applied to the Alps also provides a refinement to the nappe concept. In the reconstruction of Argand, nappes result from the amplification of recumbent anticlines (Figure 1.23) and the entire crust is affected by these folds. In contrast, the "Plate Tectonics definition" of a nappe given by Laubscher (1970) is that an (Alpine) nappe is a crustal unit that detaches from a subducting lithospheric plate and becomes accreted to the orogenic wedge, building it at the same time.

Although the different phases of Argand are linked very strictly by geometric continuity, those of Laubscher are not. His concern is no longer the geometrical evolution of the nappes themselves, but the link between the nappes and the deeper lithospheric structure through time. The latter work focuses on the location of subducted Alpine slabs in relationship to the zones of deformation affecting the crust. Although the slabs represent a mere concept not yet physically linked to geophysical observations, deformation of the crust is well constrained at that time. The scarce data on the geometry of the Moho and the deeper mantle creates lots of space for interpretations and speculations. Laubscher (1970; Figure 1.31) discusses and sketches different possible locations for the inferred Cretaceous subduction below the Alps. The "late" localization of shortening below the External Massifs being well constrained, Laubscher suggests to relate it to a later, also symmetric subduction zone that develops below these massifs in the Neogene, as intracontinental European subduction (Figure 1.31(e)). A breakoff of the lithospheric root leading to a general isostatic uplift is also postulated by Laubscher (1970; Figures 1.31(e) and (f)). These concepts are amazingly modern. However, the cross-section representing the present-day structure (Figure 1.31(f)) becomes schematic to a degree that the Alpine structure cannot be recognized any more.

Following the first attempts of Laubscher to reconstruct the evolution of the Alpine lithosphere in cross-sections within the framework of Plate Tectonics, a new approach is undertaken by Dal Piaz et al. (1972; Figure 1.32) on the crustal scale. Their fundamental step forward is the ability to sketch specific nappes (Sesia-Lanzo and Monte Rosa) and show their kinematic evolution through subduction and collision. Their paper links the structure, the high-pressure metamorphic assemblages of these nappes and the radiometric ages based on the first age dating of that time (e.g. Hunziker 1970). In spite of the unprecise ages, setting these different data sets in the conceptual frame of Plate Tectonics, allows them to show for the first time the evolution of the western Alpine nappes throughout subduction and exhumation in cross-section (Figure 1.32).

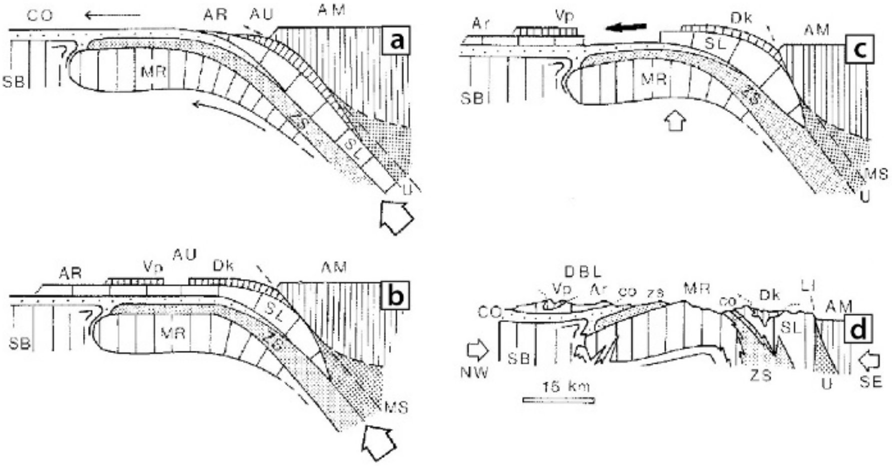


Figure 1.32. *Cross-sections illustrating the kinematic evolution of the western Alpine nappes through subduction and collision, modified from Dal Piaz et al. (1972). a) Subduction; b) exhumation; (c and d) collision. AM: Southern Alps; Co: Combin Zone; DBL: Dent Blanche Nappe; MR: Monte Rosa nappe; SL: Sesia Lanzo; ZS: Zermatt-Saas Zone*

The mismatch between the clarity of the Plate Tectonic theory and the lack of geophysical data providing insight into the deep structure of the Alps characterizes most of the papers that attempt to show the evolution of the Alpine lithosphere in the 1970s (Figure 1.33). A paper by Mattauer and Tapponnier (1978), explicitly about Plate Tectonics in the Alps, is very emblematic for that period. The authors sketch the evolution of the Western Alps through time, starting with Cretaceous subduction, based on a series of lithospheric cross-sections (Figure 1.33(b)). These show the subduction of oceanic crust, its partial exhumation by nappe stacking and erosion, the folding of these nappes after stacking, the bi-vergent thrusting of the continental crust, just as in modern interpretations, but they terminate this temporal evolution of the Alps at 40 Ma (Figure 1.33(b)). No lithospheric section of the present-state of the Alps is shown. The sections are not constructed by retro-deforming the present state, as the only one that can be really constrained. Paradoxically, the present state is the only unknown element of the temporal evolution shown by Mattauer and

Tapponnier (1978), in which the past is better constrained than the present thanks to a conceptual model: subduction followed by collision. The paper of Dietrich (1976; Figure 1.33(a)) on subduction-related magmatism of the Eastern Alps also shows the tectonic evolution of the Alps in a series of cross-sections starting at the Permian-Jurassic boundary and ending in the Oligocene. As in the case of Mattauer and Tapponnier (1978), no section of the present state is drawn. The reconstructions of Laubscher (1970, 1974, 1983) may show a section representing the present-day structure of the Chain, but the latter is less constrained than the ones showing the older stages of evolution.

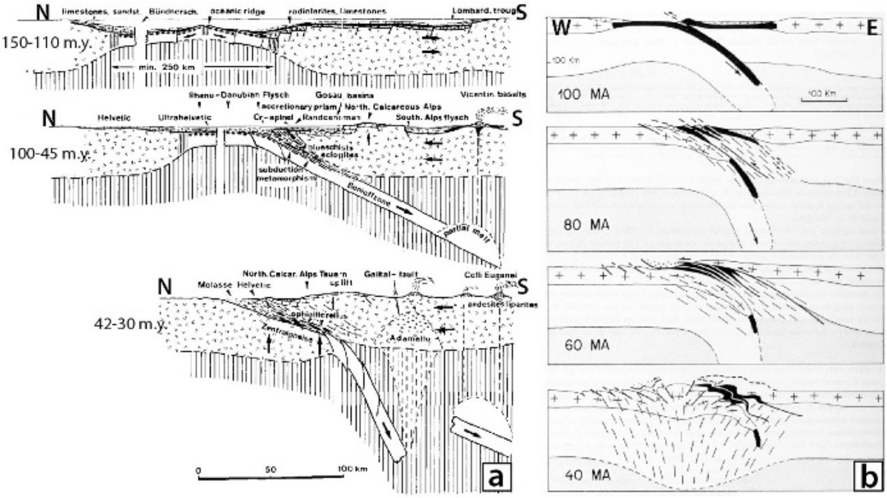


Figure 1.33. *Models showing the evolution of the Alpine Lithosphere during orogeny. a) Modified from Dietrich (1976); b) Modified from Mattauer and Tapponnier (1978)*

Interestingly, the Alpine section representing the Eocene stage of orogeny in Laubscher (1983) depicts the crustal structures from the surface topography down to the Moho (his Figure 16c), whereas the section illustrating the present state of the chain (his Figure 17) only shows the crustal structures of the upper third of the crust and a white surface below, showing that nothing is known about it! Similarly, alternative models to Plate Tectonics of that time (van Bemmelen 1973) also show the deepest part of the lithosphere in cross-sections with great detail throughout the Tertiary, but restrict their illustrations to the upper 8 km of the crust when it comes to the present.

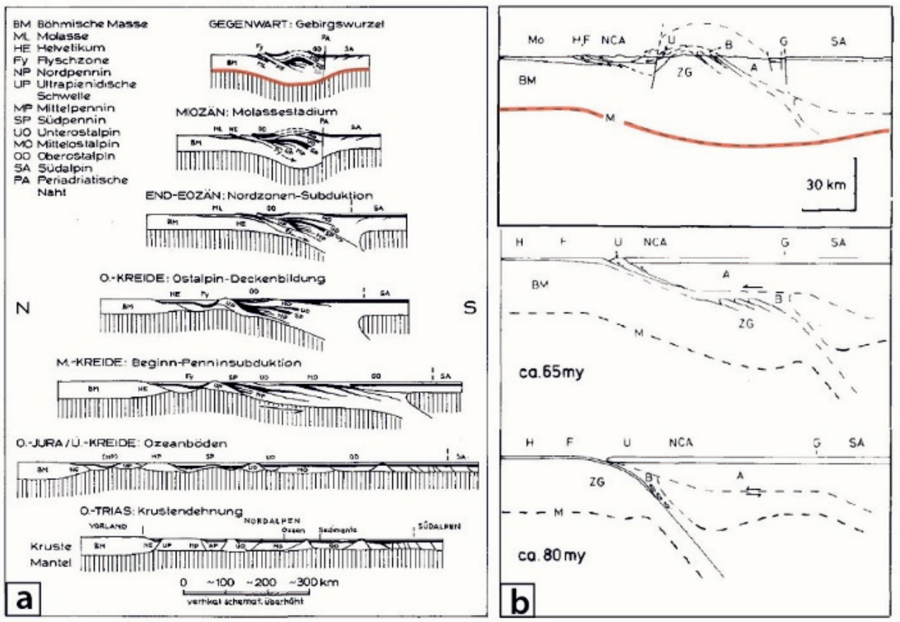


Figure 1.34. *Evolution of the Alpine crust and mantle from subduction to present. Red line: inferred present-day Moho. a) Modified from Tollmann (1980); b) Modified from Hawkesworth et al. (1975)*

1.9. Integrating deep geophysical imaging with surface structures (NFP20; Ecors-CROP)

Another breakthrough in the advancement of tectonic investigations in the Alps is marked by the integration of new geophysical results from the big trans-Alpine seismic campaigns of the beginning of the 1990s (ECORS-CROP in France and Italy, NFP20 in Switzerland). These new data are incorporated in cross-sections, in addition to the surface data (e.g. Nicolas et al. 1990; Pfiffner et al. 1990; Polino et al. 1990; Schmid et al. 1996), thus filling the gap that still exists throughout the 1970s. This step only precedes the one of seismic tomography, which images the "very" deep structure of the orogen, with subducted slabs down to 300 km depth (Lippitsch et al. 2003). The debates and type of imaging initiated by all these works are still ongoing at present.

1.10. Discussion and conclusion

1.10.1. *Changing style of cross-sections as a function of changing interpretations of the Alps*

The historical evolution discussed above traces a strong link between the advancement in the understanding of Alpine tectonics and the changes in the representation style of cross-sections. Why and how do cross-sections evolve from the illustration of the observable to its interpretation? Part of the answer lies in the nature of the object: outcrops and their representation in sections are not complete objects as fossils or plants. They are part of a larger scale entity that is never completely observable, and needs to be constructed. Advancements in geological understanding, hence interpretations, are themselves partly integrated, graphically, in the plane of the sections, requiring a continuous change in the style of representation.

The 18th century shows the evolution from paintings of outcropping sedimentary beds in Alpine landscapes (Marsigli 1705), only differing from artistic paintings by their purpose, to cross-sections that represent what the scientist's eyes are capable of discerning in the natural landscape (Arduino 1758). Which elements of the landscape are represented in the latter sections and which ones are not is based on specific criteria established by the scientist. Only by making such conscious choices, can the contacts between different lithological units be clearly depicted in figures. Symbols are added to the illustrations of natural outcrops to provide the reader with the key to geological interpretation. This change is the very first step toward a continuous increase in abstraction that will characterize the representation of geological structures in cross-sections. Marsigli (1705; Figure 1.1) illustrates a landscape, whereas Arduino (1758; Figure 1.3) illustrates an interpretation of the landscape.

In the first part of the 19th century, the evolution of cross-sections becomes more and more interpretative, in spite of some scruples, manifested by the adjectives "ideal" or "theoretical" that are added to the term cross-section. The example of Studer is emblematic for this approach. His sections of 1834 are either 3D representations showing all details of the 3D topographic surfaces of the outcrops (Figure 1.5), or what he terms "idealized" sections, where 3D effects of the topographic surface are reduced, but still clearly present. Eventually, in 1851 he draws a series of sections that are entirely bi-dimensional, as also performed by Sismonda (1839), Villa and Villa (1844), Lory (1846), Escher von der Linth (1848) and Murchison (1850). Hence, by the beginning of the second half of the 19th century, cross-sections are no longer reproducing landscapes, as observed from a specific point of view, but they are ideal, vertical, planar surfaces, in which the geological units are shown as if they were always continuously outcropping over their entire section, and sedimentary beds are shown with constant thickness. Therefore, although very closely related to the natural valley flanks that they represent, cross-sections no longer illustrate them in the naturalistic sense. This change takes place much earlier in the United Kingdom, where White Watson (Ford 1960) and later John Farey, inspired by the ideas of William Smith on correlating fossil-bearing units over large distances, present detailed maps and sections as early as 1808 (e.g. Ford 1967). These sections show laterally continuous beds in vertically interpreted planes, along more than 100 km length. The large lateral extent of stratigraphic units, as observed during mapping, provides the information to draw such interpreted cross-sections, but more importantly the geological maps allow us to construct cross-sections without drawing them from the visible landscape. Such maps of the Alpine realm only start to be published in the 1860s (Campanino and Polino 2002).

In the second half of the 19th century, when the valley flanks are sketched as if they were uninterruptedly outcropping along 2D, vertical planes, and the inferred geometry of beds both above and below surface topography (e.g. Favre 1867; Giordano 1869; Heim 1878; Bertrand 1884; Bertrand and Ritter 1900) are also represented, cross-sections start to document what is physically not visible in the natural landscape. This graphical change takes place at a time when different tectonic interpretations of the same area start to appear, and as stated by Schardt, we cannot only show what “the eyes see”. The wish to clarify long-standing debates finally moves scientists to draw geological contacts below and above the observable topographic surface to show explicitly how different parts of a section are correlated. But it is also the illustration of new concepts on the structure of the Alps that requires the space of the section to be widened: the very first ideas of nappe tectonics need larger vertical dimensions to illustrate the structure of the nappe pile (Giordano 1869; Schardt 1894, 1897; Figures 1.11 and 1.14).

The integration of parallel sections representing different structural levels in one and the same plane (Bertrand and Ritter 1896) is the first step toward the precise illustration of structures that are located well above the surface (Figure 1.13(b)). A different technique is used and explained by Argand at the beginning of the 20th century, with cross-sections that are constructed by lateral projection parallel to fold axes (Argand 1911; Figure 1.21). These sections integrate the geological information of areas that are exposed many kilometers away from the trace of the section itself. Hence, one and the same section represents a large area. It certainly is not the faithful representation of structures on a vertical plane striking along a specific trace, but it is the most representative illustration of the structures of one area, and this over vertical distances (over 20 km) that could not have been attained without such lateral projections.

The evolution of cross-sections is not only characterized by enlarging their upper and lower portions. At the beginning of the 20th century, they are the tool to present a synthetic view on the structure of the Alps (Termier 1902, 1903). In his paper "The synthesis of the Alps", Termier shows in a series of cross-sections that a relatively simple structure describes the architecture of the entire orogen, and this structure consists of a sequence of major nappes accommodating shortening between two rigid continental blocks. The structures themselves, in terms of geometry and rooting of the nappes, are mostly wrong, but the idea that the basic structure of the Alpine orogen can be shown and understood by sketching only few thrusts out of millions of existing structures remains true at present. Nowhere in the pre-1902 publications of Termier, is an attempt to construct orogen-scale sections found. The latter do not result from progressively increasing the size of his sections, nor by adding piece by piece individual segments of cross-sections to obtain a larger one, as in the case of Ampferer and Hammer (1911). It is Termier's understanding of the first-order tectonic relationships of the Western Alps and their analogies to the Eastern Alps that allows him to synthetize the structure of the Alpine orogen in 1903. As Termier (1906) states himself: "It is the assessment of the permanence all along the chain of one and the same structural plan". Previous existing examples of orogen-scale sections (Ebel 1808; Figure 1.4; or Rogers (1836), for the Appalachians) are performed in the style of Ampferer and Hammer (1911), as described above. The sections of Termier are world-wide, the first ones to reduce the picture of an orogen to its essential structures, namely its nappe stack.

Interestingly, Termier, as the first geologist to recognize that the structure of an orogen can be summarized into a stack of nappes, is, to say the least, highly skeptical about continental drift and the theory of Wegener (1912). Termier is a mobilist, but like many others he criticizes the physical process proposed by Wegner to explain continental drift. Termier believes in the "shifting of continental masses [...] to explain the formation of folded zones, that is to say the mountain chains [...]". But the larger shifts required to group all continents in the past is merely the "beautiful dream of a poet" (Termier 1925).

Argand (1924) continues to increase the depth of cross-sections, representing the base of the crust and the upper mantle (Figure 1.24). Like no one else before him, Argand strives for an understanding of the evolution of the Alpine crust, based on the assessment of its present-day geometry. Once this task is achieved, Argand devotes the rest of his studies to the understanding of the kinematic and mechanical processes that lead to such present-day structure. He does this by moving from the investigation of the Alps to other Cenozoic mountain belts (Argand 1924). At this stage, his Alpine sections become simplified to the most essential structures that can be observed in all other orogens too (Figure 1.24; Argand 1924), namely the geometry of superposition of two continental “blocks”, the lateral termination of the lower, thinned out “block” within the underlying sima, the 1st order fold geometry of the orogenic wedge, the buried penninic units inferred to derive from the axial zone of the Tethys, and the discontinuously “intruded” sima along the interface of the continental blocks. All this brings Argand to state that “Africa is thrust over Eurasia and the Austro-alpine nappes form its most distal salient”.

The drawing of Alpine sections, in the long period after 1924 and until the late 1960s shows a slowing down in scientific advancement compared to the preceding decades, in the sense that neither the style of the sections nor the first-order structures shown until the 1970s are significantly different than those published 50 years earlier. The cross-sections of Heim (1919) are very similar to those of the 1980s (Figure 1.25). This observation should not discredit the work of Alpine geologists of the mid-20th century, but it suggests that the first-order structure of the Alpine chain down to some 10–20 km is well assessed by 1920. The following decades do not provide the necessary geophysical data to extrapolate surface structures to greater depth, nor a new tectonic conceptual model to allow a soundly based rethinking of the geosynclinal type of orogeny. Both these elements appear at the beginning of the 1960s, with seismological experiments, on the one hand, and the theory of Plate Tectonics, on the other hand. From 1924 to 1970, only few Alpine geologists propose new ideas on orogeny and illustrate them with cross-sections (Figure 1.26). These are mainly the models of Kober (1942, 1955), partly, but not only, based on the symmetric “Verschluckung” (subduction) of Ampferer (1906). Their ideas are founded on logical reasoning and physical processes, but they have no observational basis to rely on: neither a direct one from geophysical data of the Alpine realm nor an indirect one like those underlying the theory of Plate Tectonics, which relies on geophysical observations, albeit far away from the Alps. It is probably for this reason that the models by Kraus (1932) and Kober appear to be the result of wild imaginations nowadays.

1.10.2. *Historical evolution of the nappe concept as shown by cross-sections*

The numerous works discussed above also illustrate the historical evolution of the nappe concept, whose contours are discontinuously, but uninterruptedly refined over more than a century. The very beginning of this idea may be in the observations and interpretations of Escher von der Linth (Figure 1.10), as described by Studer and

Desor (1841). Gerlach (1869, Figure 1.18) clearly maps and shows in cross-section the existence of an isoclinal recumbent fold in the Antigorio basement, and interprets it as the result of a thrust accommodating nearly 10 km of displacement, hence a nappe.

Bertrand (1884) re-interprets the sections of Heim (1878) based on the descriptions of thrusts of Gosselet (1879), thus suggesting that the stratigraphic inversion is not due to complex folding, but to a large, gently dipping thrust. His reasoning about this newly interpreted structure leads him to suggest that "[...] it is simply the hypothesis of a single fold replacing that of the "double" fold of Escher". And more generally,

> [...] there is a general rule, and the result of contraction of the globe due to cooling is not only the folding of the crust, but also the outflow from the center of the folded zone.

Hence, his view of nappes is that of a region shortening by folding, from which large recumbent folds pour out and glide over younger units, toward the foreland. His sections of the Mont Blanc area (Bertrand and Ritter 1896; Figure 1.13(b)) illustrate this very clearly; the cover nappes are all rooted in a zone of low amplitude subvertical folds, suggesting that folding of the basement is by far smaller than shortening of the cover. It is this inferred discrepancy that forms the main argument for Ampferer (1906) to suggest a sort of subduction process of the basement in order to balance such sections.

In contrast to the model above, Schardt (1894) clearly decouples the development and displacement of nappes from that of folds. Schardt notes the map-scale "cran de retour" of Gosselet (1879), that is, the drag fold that Bertrand (1884) "postulated all along the northern hillside of the Alps exists nowhere". Schardt (1894) also notes that "the entire sedimentary sequence, from the Triassic to the Cretaceous had been driven, without inversion, above the flysch and the Oligocene". These observations allow him to infer that "the formation of nappes can start by a simple thrust". Termier (1902) depicts every nappe of the Western Alps as being rooted in an area of distributed, low-amplitude folding, of the Internal Zone (Figure 1.16(a)). Only in his 1903 sections, does Termier root the "Dinaric thrust" in the basement of the Southern Alps, without a zone of folding, but also without a visible offset of this basement. However, all nappes below the Dinaric "traîneau écraseur" are still rooted in the above described areas of folding. The mechanical process behind these geometries is suggested to be the displacement of a higher nappe (Termier 1903), causing the underlying structures to parallelize to the basal thrust of the nappe.

In 1906, Termier made a clear distinction between two types of nappes: the first ones are folds which initiate being nearly vertical, and later rotate attaining the horizontal plane or even further. The second type is defined as

> a fragment of the Earth's crust detached from its original substratum, and transported, without significant folding, just by simple translation, under the effect of a tangential pressure, gliding on a frictional surface.

The important difference lies in the fact that the latter type is detached from its original substratum and folding does not play a major role. This second type of nappe corresponds to the "Dinarides" in the view of Termier (Figure 1.16(b)), who thinks that they are displaced northward above the rest of the Alps, thus causing themselves the re-orientation into recumbent and stretched folds in their footwall.

Ampferer and Hammer (1911) provide a mechanical explanation:

> Between these large, apparently rigid zones, comparable to the jaws of a vice, lies an extremely intensively compressed, deeply folded zone, from which a bunch of steep, ascending hinges was squeezed out and laid down northwards gliding down as stacked ice flows or lava outpours to the wide northern depression.

Argand (1916; Figure 1.23) eliminates the low-amplitude, distributed zones of folding from the roots of nappes in his sections. His nappes do not evolve in time from a vertical to a horizontal orientation, as suggested by some of his predecessors. His embryo-tectonic evolution shows that nappes are the amplification of large-scale recumbent folds that re-activate pre-existing, Variscan "ge-anticlines". Hence, the nappes initiate as gently dipping structures, and it is only in the mature stages of collision that they become refolded with steeply oriented roots. This view is not really modified until the establishment of the Plate Tectonic theory and the interpretation of Laubscher (1970), stating that nappes are crustal units that detach from a subducting lithospheric plate and become accreted to the orogenic wedge. However, even at this stage, the precise geometry of the rear part of Alpine nappes has not yet been described. Ramsay (1963) interprets the basement-cover interface geometry of the External Massifs in the Western Alps as pinched synclines produced by a competence contrast between cover and basement undergoing shortening. It was only around 1980 that overthrusting of basement was recognized as the cause of the apparently folded geometry of the basement-cover surface (Bravard and Gidon 1979; Thouvenot and Perrier 1980; Ayrton 1980; Beach 1981) and that the root of many cover nappes was identified in a basement thrust. A clear description and illustration of the root zone of Alpine nappes in cross-section was only published in 1981 by Beach. This work finally shows, with a series of detailed cross-sections, how the cover nappes of the External Zone in the Western Alps are rooted in the basement of the External Massifs, providing the picture of Alpine nappes that we still use nowadays.

1.10.3. *Plate Tectonics*

Plate Tectonics certainly represents a revolution for the interpretation of orogens, but besides the change of paradigm that it brings concerning the driving forces of horizontal displacements, it initiates an immense change in the way geologists look at the bulk structure of the Alpine orogen. As firstly shown by Laubscher (1970), the deep structure of the orogen no longer terminates at 5 or 20 km depth, but at >100 km, and this deep structure is first depicted following Plate Tectonics concepts, because geophysical data are not yet available. A new task of tectonicists is to relate deformation structures observed in the crust with conceptually derived structures describing the entire lithosphere. Laubscher (1969) states:

> Homo sapiens has been and still is much of a myth-maker; he cannot collect isolated data without employing his imagination. He must see facts as part of a pattern, of a story, of a myth [...] The favorite current myth in global tectonics is “ocean floor spreading”, which has produced a quantitative first approximation to global kinematics and although imperfect and questionable, is a concept, better than previous ones [...].

Laubscher (1970) draws cross-sections according to this myth, which are mainly conceptually derived. It is interesting to note that, as a consequence of Plate Tectonics, for the first time in the history of Alpine research, a theory becomes the main guide for geological understanding and representations of the Alpine orogen. The maxim of Studer (1834) to sketch cross-sections as close as possible to nature is abandoned in favor of the visualization of a concept explaining plate displacements. This is also manifested in the numerous papers of that time that illustrate the past phases of Alpine orogeny with cross-sections, based on the theory of subduction and collision, however not showing the link between structures in present-day cross-sections of the Alps and in their retro-deformed stages (e.g. Laubscher 1970; Dietrich 1976; Tapponnier and Mattauer 1978; Figure 1.33). This approach is exactly opposite to the one chosen by Argand (1916), who takes the precisely constrained geometry of the present-day cross-section as a starting point and retro-deforms it. The more Argand goes back in time, the more his retro-deformation also becomes guided by a tectonic conceptual model. In his case, it is that of geosynclines. In contrast, the aforementioned studies start from a tectonic conceptual model of inferred Cretaceous subduction, from which they develop the younger history, albeit without succeeding to attain the present-day structure.

From the beginning of the 1970s onwards, geophysical studies slowly fill the gap between theory and observations concerning the deeper parts of the lithosphere. By progressively assessing the structure of the deeper parts of the lithosphere, the a priori conceptually defined deep structure of the orogen is replaced by structures based on natural (seismic) experiments and observations. This effort is still ongoing at present.

1.11. References

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[1] This consists of three volumes. See in particular Volume 1, pp. 111–114 and pl. I.

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