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Geological features between Chamonix and Geneva: facts and controversies

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Abstract
Summarizing a lecture given by the author at the 2013 SASEG annual convention in Chamonix, this paper first provides the essential background information required for a good comprehension of the regional geology between Chamonix and Geneva. It then briefly outlines the main tectonic units exposed between these two localities: the Jura fold and thrust belt, the Molasse basin, the Helvetic-Subalpine zone (cover and basement), and the Prealps. Finally, three debated and/or debatable topics pertaining to the regional geology are presented: the allochthony of the Prealps (i. e. the nappe theory), the correlation between the Helvetic nappes of Switzerland and the northern Subalpine chains, and the structure of the Rochers de Leschaux in the Bornes massif.

Résumé
Cet article synthétise une conférence donnée par l'auteur lors de la convention annuelle de la SASEG à Chamonix en 2013. Il donne d'abord les notions de base nécessaires à une bonne compréhension de la géologie régionale entre Chamonix et Genève. Il décrit ensuite brièvement les principales unités tectoniques affleurant entre ces deux localités: les chaînons du Jura, le bassin molassique, la zone delphino-helvétique (socle et couverture) et les Préalpes. Finalement, trois controverses passées et/ou actuelles se rapportant à la géologie de la région sont présentées: la question de l'allochtonie des Préalpes (i. e. la théorie des nappes), celle de la corrélation entre les nappes helvétiques de Suisse occidentale et les chaînes subalpines septentrionales, et enfin celle de la structure des Rochers de Leschaux dans le massif des Bornes.

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1 Introduction

The Arve valley between Chamonix and Geneva offers a spectacular geological cross-section through the external part of the Western Alps. Quite accessible, this area has been studied by numerous scientists for more than 200 years and is also the cradle of the nappe theory (Lugeon 1901). After summarizing some basic tenets of Alpine geology, the main structural units exposed between Chamonix and Geneva, part of which were visited during the post-convention field trip, will be presented, and some of the past and present geological controversies that have been addressed in the regional literature will be examined.

2 Basic concepts of Alpine geology

The history of the Alps began in the Late Triassic with the break-up of the mega-continent Pangea and the subsequent birth of the East-West oriented Tethys Ocean between the continental masses of Laurasia in the North and Gondwanaland in the South. In the following divergence phase, which lasted until the Early Cretaceous, lesser land masses separated by relatively small oceanic basins were generated. These include, from the NW to the SE, Europe, the Valais Ocean, the Briançonnais terrane (related to the Iberian plate), the Piemont Ocean, Apulia, the Neotethys, and, last but not least, the African continent (Fig. 1). During the Jurassic and the Cretaceous, sediments, which are now found as rocks in the Western and Central Alps, were deposited in various paleogeographic domains determined by this geodynamic setting. These comprise, from the NW to the SE, the Helvetic and Ultrahelvetic realms (proximal and distal part of the European passive margin, respectively), the oceanic Valais domain, the Subbriançonnais and Briançonnais realms (NW and SE margins of the Briançonnais terrane), the oceanic Piemont domain, and the Austro-Alpine and South-Alpine domains (Apulian margin; Fig. 2). During the subsequent phase of convergence, triggered by the opening of the South Atlantic Ocean in the Late Cretaceous (Stampfli et al. 2002), these continental and oceanic domains were subducted below, and accreted to the Apulian microplate. The formation of the Alpine orogenic wedge itself began in the Middle Eocene, when the two continental masses of Apulia and Europe collided, and reached a climax in the Early Oligocene, when the oceanic slab of the subducting European plate was detached (Stampfli 2001). At that time, two flexural (foreland) basins were created north and south of the emergent Alps due to the weight of the orogenic wedge. Detrital sediments (flysch and later molasse) accumulated in these asymmetric basins between the Early Oligocene and the Late Miocene. Continuing compressive regime led to folding and thrusting in the Jura mountains, the most external domain to be incorporated in the Alpine chain in the Late Miocene and Pliocene.

3 Main structural units between Chamonix and Geneva

3.1 The Jura fold and thrust belt

The Jura is a small (300 km long, 70 km wide, maximum elevation 1.720 m), arcuate mountain chain located in the NW part of the Alps,

Fig. 1: Paleogeographic reconstruction of the future western Alpine region in Albian times (about 100 Ma ago). Dark blue = oceans; light blue = submerged continental shelves; brown = emerged areas. See text for more explanations (modified from http://cpgeosystems.com).

between Chambéry (France) and the southern edge of the Black Forest. In the area between Chamonix and Geneva, it is represented by the Salève chain (Fig. 3), one major component of the landscape around this city. Between 1 and 2 km thick, the stratigraphic succession exposed in the Jura extends from the Late Triassic to the Miocene. It mainly comprises carbonate-platform facies of Jurassic and Cretaceous age that were deposited on the proximal margin of the European plate, and Eocene to Miocene continental and marine deposits corresponding to the foreland-basin sedimentation stage. This succession overlies Middle Triassic evaporites that acted as a décollement horizon (Burkhard & Sommaruga 1998). The Jura belt is thus characterized by a typical thin-skin tectonic style and comprises two main structural zones: (1) the external Plateau Jura, where folds are embryonic and evaporite cored, and (2) the internal Folded Jura, or «Haute Chaîne», where folds are thrust-related with kilometric throws mainly to the NW. The faults affecting the sedimentary cover do not seem to penetrate the crystalline basement, the top of which appears on seismic lines as a smooth, subplanar surface with a low-angle dip towards the SE (Mosar 1999). This observation invalidates early hypotheses suggesting that cover deformation was related to gravitational gliding. Deformation is most probably due to the underthrusting of the Jura basement towards the SE, below the external crystalline massifs (Mosar 1999). Deformation in the Jura started about 11 Ma ago (Tortonian), climaxed between the Late Miocene and the Early Pliocene, and possibly still continues today. Shortening of the sedimentary cover has been estimated at about 25 km (Burkhard & Sommaruga 1998).

3.2 The Molasse basin

The Molasse basin is an elongated (ca. 700 km), SW–NE trending, low-elevation area (400 to 800 m), stretching at the front of the Alps between the cities of Chambéry (France) and Linz (Austria). It is only about 30 km wide in its western portion, but close to 200 km wide in Bavaria. In the Geneva

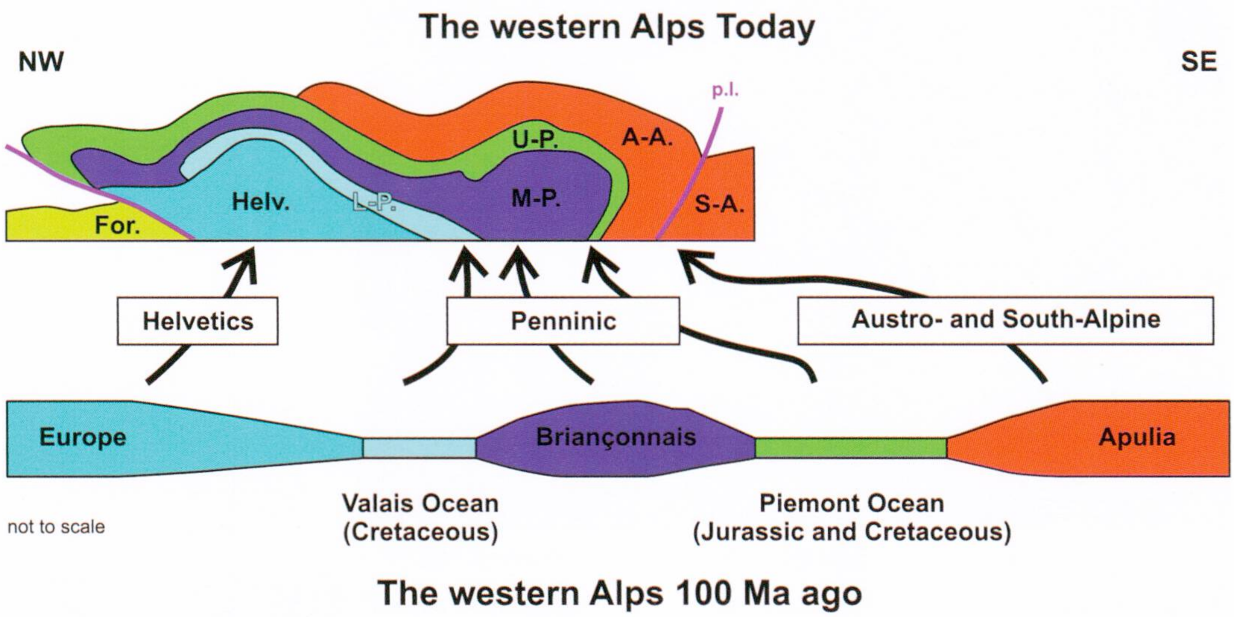

Fig. 2: Upper diagram: major tectonic units of the Alps; For. = foreland basin; Helv. = Helvetics; L-P. = lower-Penninic units; M-P. = middle-Penninic nappes; U-P. = upper Penninic nappes; A-A. = Austro-Alpine nappes; S-A. = South-Alpine zone; p.l. = peri-adriatic lineament. Lower diagram: reconstruction of the western Alpine region in Albian times (modified from Lemoine et al. 2000).

area, the Molasse basin is subdivided in two sub-basins by the Salève thrust: the densely populated Geneva basin to the NW and the «Plateau des Bornes» to the SE (Fig. 3). It represents the internal, deformed part of the North-Alpine peripheral foredeep that became a piggy-back basin during the Jura overthrusting (Stampfli 2001). It comprises a 1 to 3 km-thick Mesozoic sedimentary cover similar to that of the Jura belt. An important erosional unconformity separates these predominantly carbonate-rich sediments from the overlying siliciclastic deposits of Late Eocene (the «Sidérolithique») and Early Oligocene to Late Miocene age (the «Molasse»), most of which originate from the erosion of the rising Alps. Due to the marked basin asymmetry, the thickness of these Tertiary clastics ranges from more than 5 km adjacent to the Alpine front to only a few tens of meters near the Jura mountains. In the southwestern part of Switzerland, the molasse wedge can be subdivided into three structural components (1) the Jura Molasse that is preserved in some of the major Jura synclines; (2) the most extensive Plateau Molasse, in the NW part of the basin, that has experienced weak deformation and shortening, as shown by open folds and tear faults; and (3) the Subalpine Molasse, in the internal (i. e. SE) portion of the basin, characterized by a stack of imbricate slices with a basal detachment fault in these Cenozoic layers. Early molasse deposits (e. g. the so-called North-Helvetic flyschs) have been deformed and incorporated in the orogenic prism.

3.3 The Subalpine-Helvetic zone

This zone comprises (1) the thick, detached sedimentary cover of Mesozoic and Cenozoic age exposed in the northernmost Subalpine chains (Platé, Aravis and Bornes massifs) along the lower course of the Arve river, and (2) the pre-Mesozoic crystalline basement and its thin autochthonous cover forming the Aiguilles-Rouges and Mont-

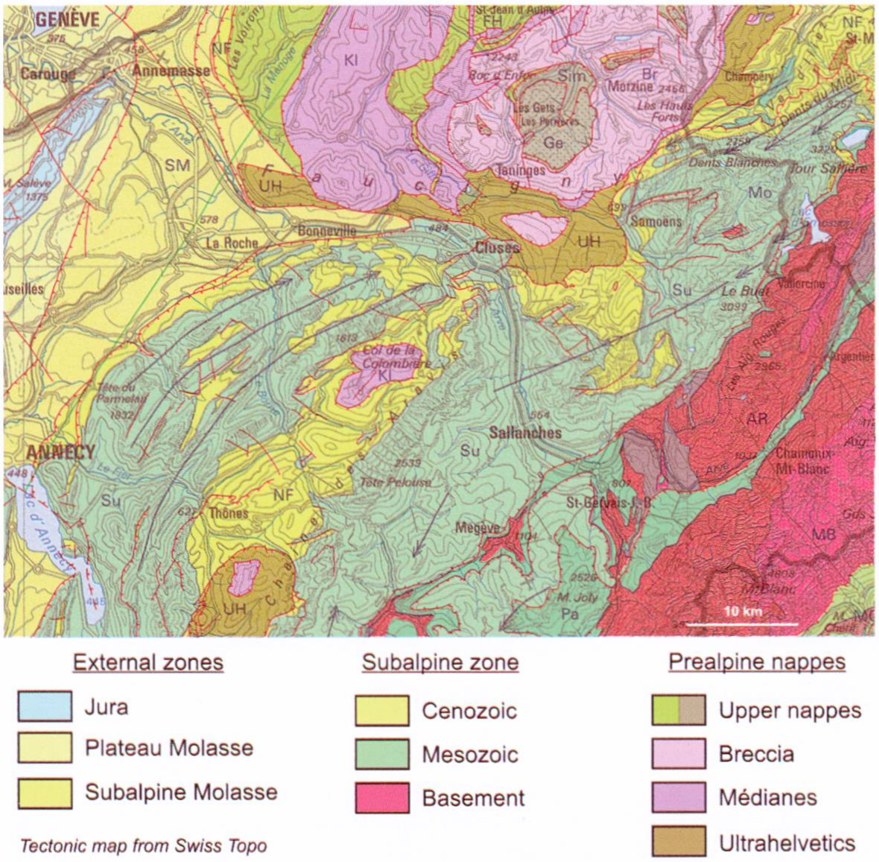

Fig. 3: Tectonic map showing the main structural units in the Chamonix – Geneva region.

Blanc massifs on both flanks of the Chamonix valley (Fig. 3). The Subalpine chains are moderate-altitude mountains, the morphology of which is dominated by vertical limestone cliffs of Late Jurassic and Early Cretaceous age (Fig. 4). The altitude of the Aiguilles-Rouges and Belledonne massifs ranges between 2.300 and 2.900 m, whereas the granite peaks of the Mont-Blanc massif reach close to 5.000 m.

The stratigraphic successions of the Platé, Bornes and Aravis massifs are roughly similar and include Lower Liassic to Upper Cretaceous carbonates and shales deposited on the distal margin of the European continent. Compared to the stratigraphy of the Jura mountains to the West, the Jurassic to Cretaceous succession exposed in the Subalpine chains is thicker, due to increased subsidence during this time interval, and comprises deeper-water, more clay-rich deposits (Charollais & Lombard 1966). The only exception is the Urgonian Limestone (Early Cretaceous) which consists of shallow-platform carbonates in both paleogeographic domains. Nonetheless, this formation is about twice as thick in the Bornes massif as in the Salève chain. An angular unconformity separates these Mesozoic lithologies from the overlying Cenozoic deposits, representing the first filling stage of the North-Alpine foreland basin: the Nummulitic Limestone, the «Marnes à Foraminifères» and the flysch.
The Subalpine chains represent a fine example of fold and thrust belt (Huggenberger & Wildi 1991), where the throw of thrust faults rarely exceeds a few kilometers. The basal detachment of the Subalpine succession is situated in the Liassic shales, but secondary décollement horizons occur also within younger shaly lithologies, the most important of which being located in Lower Cretaceous marls. Above this detachment, deformation style is controlled by the brittle

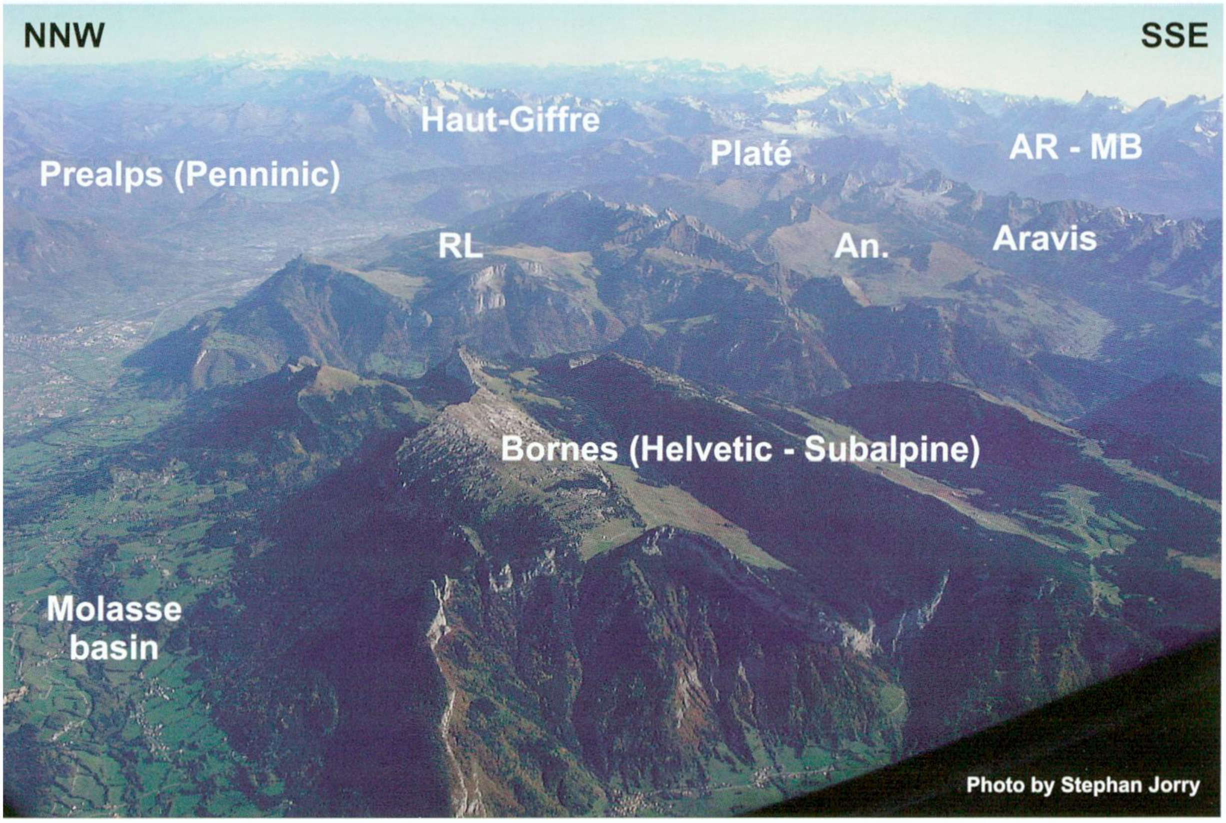

Fig. 4: Oblique airphoto showing the main structural units in the Chamonix – Geneva region. AR = Aiguilles-Rouges massif; MB = Mont-Blanc massif; RL = Rochers de Leschaux; An. = Annes klippe. Prominent cliffs consist of Urgonian Limestone (Early Cretaceous).

Urgonian Limestone, resulting in the occurrence of fault-bend folds, box folds and imbricate slices, whereas below it, more plastic deformation locally produced overturned folds (Huggenberger & Wildi 1991). The Subalpine chains are considered by these authors as a textbook example of decoupled tectonic deformation. Several deformation phases, including both extensive and compressive episodes (Gidon 1996) have affected the Subalpine-Helvetic zone in this area, but the main one occurred during the Late Oligocene and Early Miocene. This thrust belt is thus older than the Jura mountains. Displacement of this sedimentary cover has been estimated between 30 ± 3 and 60 ± 3 km depending upon the restauration model used (Affolter et al. 2008).

The tectonic substrate of the Subalpine-Helvetic succession consists of Paleozoic gneisses, Permo-Carboniferous meta-sediments, Lower Permian granitoids, and of a thin sedimentary cover of Mesozoic age. Described in details in von Raumer (1987), this substrate is presently exposed in the Aiguilles-Rouges and Mont-Blanc massifs that are separated by the narrow Chamonix valley. These crystalline massifs are large slabs of upper continental crust generated during the Caledonian and the Hercynian orogenies (Paleozoic) and subsequently incorporated into the Alpine chain. Actually adjacent, the Aiguilles-Rouges and Mont-Blanc massifs were likely separated by a ca. 25 km-wide basin during the Mesozoic (Affolter et al. 2008). Geophysical investigations (Mugnier et al. 1990) show a thickening of the crust below the Aiguilles-Rouges and Mont-Blanc massifs, which explains their marked structural relief. Whether they can be interpreted as stacked basement imbricates, deep-seated fault-bend folds or buckle folds (Affolter et al. 2008) remains to be elucidated. The characteristics of the sedimentary cover of the Aiguilles-Rouges and Mont-Blanc massifs (thinness, numerous discontinuities) indicates they were topographic highs during the Mesozoic. They have been interpreted as the sub-emergent portions of tilted crustal blocks that were down-dropped during the opening phase of the Tethys Ocean (Gidon 2001). In this interpretation, the SE flank of the Aiguilles-Rouges massif would correspond to an ancient extensive fault of Liassic age, similar to those observed in the southwestern Alps.

3.4 The Penninic zone

The Penninic zone is a large and complex structural unit exposed in two distinctive regions: (1) the axial part of the Alpine chain (in the so-called «Alpes valaisannes») and (2) the Prealps, which consist of moderate-elevation (just over 2.000 m) mountains forming two sizeable lobes: the Chablais Prealps located to the south of Lake Geneva (Fig. 3) and the Swiss Prealps («Préalpes Romandes») stretching between Lake Geneva and Lake Thun. The Prealps comprise a ca. 2.000 m-thick stack of cover nappes, uncomformably overlying the internal part of the Molasse basin, to the NW, and the external part of the Subalpine-Helvetic zone, to the SE (Fig. 3). This exotic terrain is composed of the following elements (from base to top; Fig.5):

- the Ultrahelvetic nappes derived from the distal margin of the European continent;
- the Niesen nappe derived from the Valais Ocean and only exposed in the Swiss Prealps;
- the Préalpes Médianes nappe originating from the Briançonnais terrane;
- the Brèche nappe representing the former rifted northern margin of the Piemont Ocean;
- the «Nappes supérieures» derived from the Apulian margin of the Piemont Ocean.

These structural units are separated by tectonic mélange zones of various thicknesses (e. g. the Submédiane zone). There is an almost perfect inverse relationship between the structural position of each nappe in the

Prealpine stack and its paleogeographic origin with respect to the European continent (e. g. the «Nappes supérieures», forming the top of the stack, originate from far away). The more internal units (i. e. the «Nappes supérieures») were thrust over the depositional basins of the Brèche and Préalpes Médianes nappes during the middle/late Eocene, and then transported passively on the top of the latter during their translation towards the NW in the Oligocene.

Well exposed on the left bank of the Arve River (Fig. 3), the Préalpes Médianes nappe is the most extensive unit of the Prealps. It is further subdivided in two subunits (Fig. 5):

- the Préalpes Médianes Plastiques nappe, representing a former rim basin at the NW margin of the Briançonnais terrane;
- the Préalpes Médianes Rigides nappe, derived from the former northern rift shoulder of the Piemont Ocean (i. e. Briançonnais s.s.).

The former unit comprises a succession of carbonates and shales of Late Triassic to Eocene age and is characterized by a predominantly ductile deformational style. The latter one is essentially composed of competent rocks of Middle Triassic and Late Jurassic age, showing typical brittle-deformation structures. The Breccia nappe is mainly composed of two thick series of Jurassic breccias that were deposited during episodes of tectonic activity on the rifted northern margin of the Piemont Ocean. Exposed at the front of the Prealpine stack (e. g. in the Voirons massif; Fig. 3), the Gurnigel nappe essentially consists of deep-water siliciclastic turbidites and debris-flow deposits of Tertiary age. Its paleogeographic origin is uncertain and disputed (Ospina et al. 2013).

4 Past and present geological controversies in the Geneva-Chamonix area

4.1 The birth of the nappe theory

The nappe concept was first proposed by Bertrand (1884) to elucidate the structure of the Helvetic Alps from Glarus. Possibly too innovative, this notion was inappropriately ignored by most Alpine geologists of that time (e. g. Maillard 1889; Fig. 6). About 10 years later, the theory was reformulated by Schardt (1894) on the basis of observations made in the Swiss and Chablais Prealps. This author was bewildered by the lack of tectonic connection and by the difference in the stratigraphic record of the mountains located on either side of the relatively narrow Arve valley (i. e. the Bornes massif on the left bank; the Môle and the Brasses massif on the right flank; Fig. 3). He therefore suggested that the entire Chablais region, and also the area comprised between the Rhône and the Aare valleys in Switzerland,

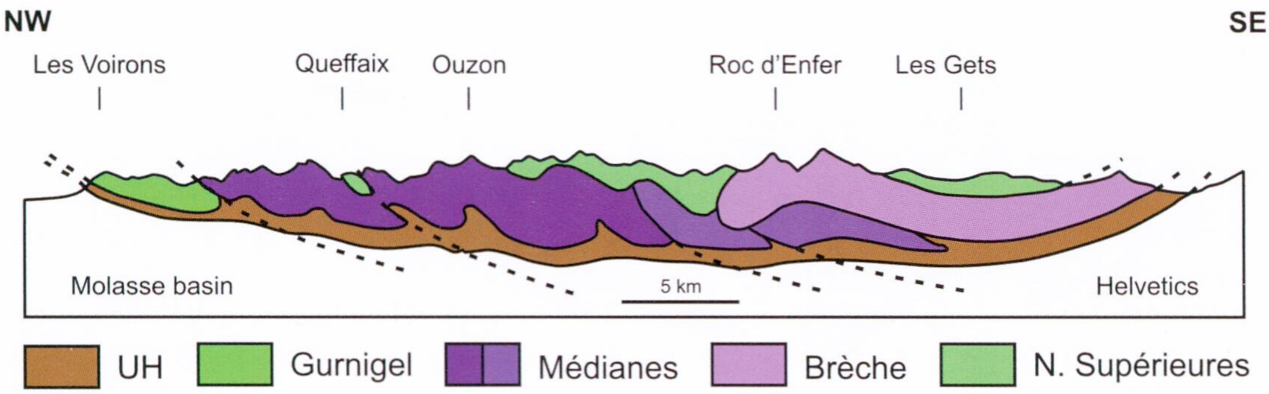

Fig. 5: Geological section across the Chablais Prealps showing the different constitutive units (modified from Caron 1972). UH = Ultrahelvetic units.

was one large allochthonous sheet of rocks originating from the South. The nappe theory was born and, under the influence of Schardt and later Lugeon, all but few geologists soon adopted this new concept (Masson 1976). It is worth noting that Marcel Bertrand, the father of the nappe theory, made the same geological observations as Schardt in the Chablais area, but that he connected the folds across the Arve valley, and figured that the contrast in stratigraphic records was due to differences in paleogeographic settings (Bertrand 1892).

4.2 The correlation between Helvetic and Subalpine zones

The connection between the Helvetic nappes recognized in Switzerland (Morcles and Wildhorn – including Diablerets, Mont-Gond and Sublage) and the Subalpine massifs of Haute-Savoie (Platé, Bornes, Aravis) has long been, and still is controversial. This controversy partly stems from the difference in structural style on either side of the political border: a fold nappe with an inverted limb in Switzerland (Dents du Midi) and a fold and thrust belt in France (Subalpine chains). Collet (1943) and his followers (e. g. Augustin Lombard) considered the external part of the Bornes massif as parautochthonous, and correlated the Platé-Aravis massif with the Morcles nappe (Fig. 7). In contrast, based on the petrography of Tertiary flyschs, the Chambery school (Doudoux et al. 1982) associated the Bornes massif with the Morcles nappe (characterized by the Val d'Illiez Sandstones), the main part of the Aravis chain with the Diablerets nappe (typified by the Taveyannaz Sandstones), and one small portion of the Aravis chain, the Charvin unit, with the rest of the Wildhorn nappe (distinguished by a so-called «transitional» flysch). Epard (1990), then a student of the Lausanne school, strongly rejected this interpretation, and correlated both the Bornes and the Aravis massifs with the Morcles nappe. Relying on tectonic and cinematic arguments, Pfiffner (2009) more recently correlated all the Subalpine chains, from the Vercors (S of Grenoble) to the Platé massif, with the Wildhorn nappe, thus placing them above the Morcles nappe identified as part of an «Infrahelvetic complex». The controversy is not yet resolved and more hypotheses will likely be proposed on this matter in the years to come.

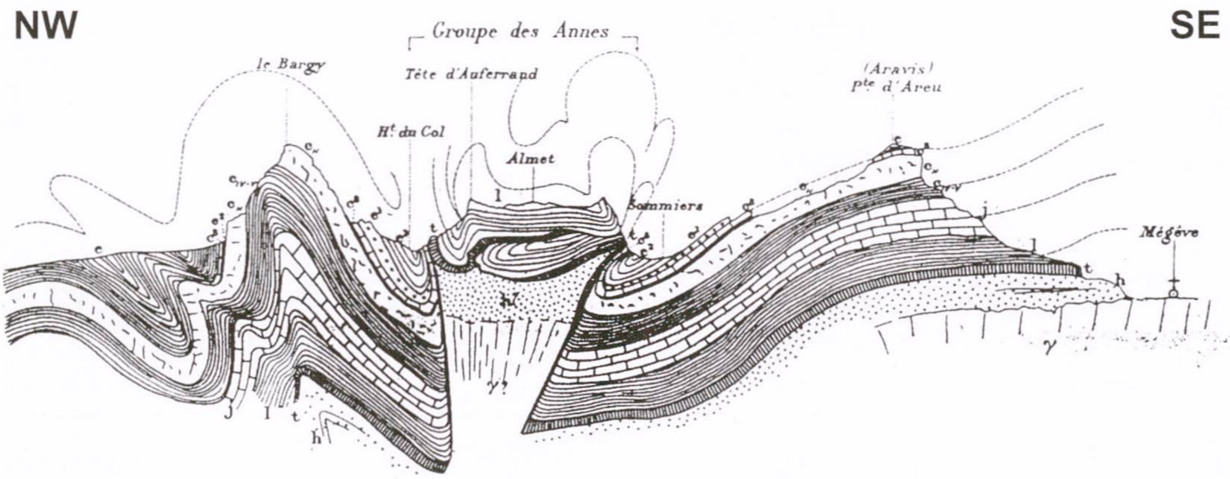

Fig. 6: Geological interpretation of the Annes klippe by Maillard (1889). Five years after the first presentation of the nappe theory by Bertrand, this author proposed that the Triassic and Liassic strata forming the Annes klippe were part of an uplifted block.

4.3 The Rochers de Leschaux

The Rochers de Leschaux are a moderate-elevation mountain located in the external part of the Bornes massif, on the right bank of the Borne river (Fig. 4). The nature of this complex structure has been hotly debated for more than 80 years. Although this looks like a «small-scale» local controversy, its resolution is important to correctly assess the amount of horizontal shortening in this portion of the Alps. The Rochers de Leschaux comprise two main lithologies of Lower Cretaceous age: siliceous limestones (the «Kieselkalk») and neritic carbonates (the Urgonian Limestone). The lower reaches of the mountain consist of two massive ledges of Urgonian Limestone (the Bouchats and the Gérats cliffs) separated by a re-entrant exposing siliceous limestones (the Cirque des Boitons; Fig. 8). The upper portion comprises the ca. 200 m-thick Leschaux cliff which caps the aforementioned elements (Fig. 8). The Rochers de Leschaux were successively interpreted as a faulted anticline (Butler 1923), a small thrust (throw < 1 km; Charollais et al. 1977) resulting from the inversion and overturning of an ancient normal fault, a medium-sized thrust (throw = ca. 4 km; Huggenberger & Wildi 1991), and ultimately a pop-up structure (http://www.geol-alp.com). Recently, Martin (2005) interpreted the Rochers de Leschaux as the product of three distinctive deformation phases: (1) an early extensional phase of uncertain age (Aptian or Late Eocene) that generated the N50-trending fault separating the Bouchats cliff from the Cirque des Boitons, (2) a compressional event of probable Late Oligocene age that resulted in the overall folding of the Bornes massif, the breaking of the N50 fault, and the thrusting of the Leschaux cliff over the Solaison syncline to the NW, and (3) a recent (Plio-Pleistocene?) extensional phase which produced a series of N150-trending normal faults, one of which down-dropped the Gérats cliff. Because this author was one of M. Martin's advisor, he considers this latest interpretation as the most accurate one.

Several past and ongoing debates related to geological features observed in the Chamonix-Geneva area could have been addressed such as the relationship between the Mont-Blanc basement and the Chamonix zone (Epard 1986; Gidon 2001), the origin of the Gurnigel nappe (Ospina-Ostios et al. 2013), and the nature of the chaotic complex separating the Helvetic units from the Prealps (Jeanbourquin et al. 1992). This shows the exceptional richness of the geology of this scenic region.

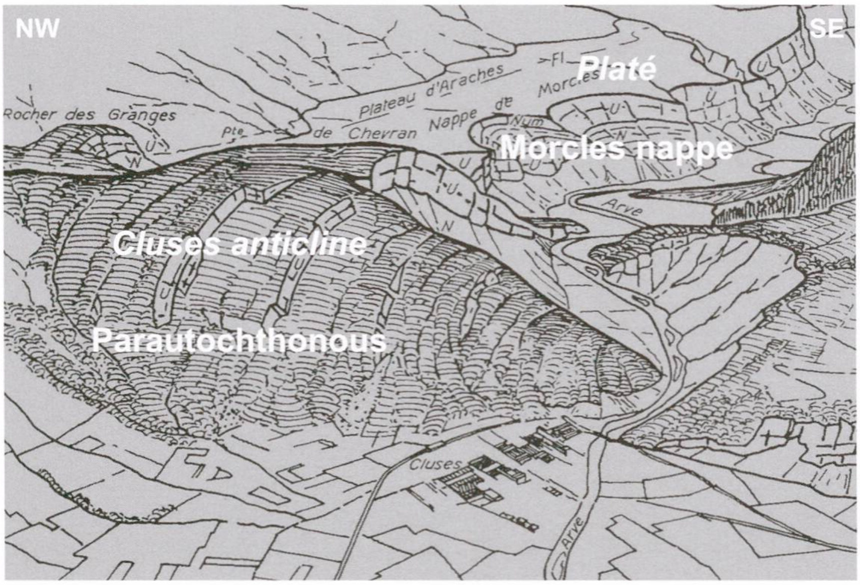

Fig. 7: Geological interpretation of the right flank of the Arve valley near Cluses by Collet (1943). This author considered the Cluses anticline and the external part of the Bornes massif (on the left side of the Arve valley) as parautochthonous and regarded the Platé massif as the continuation of the Morcles nappe towards the SW.

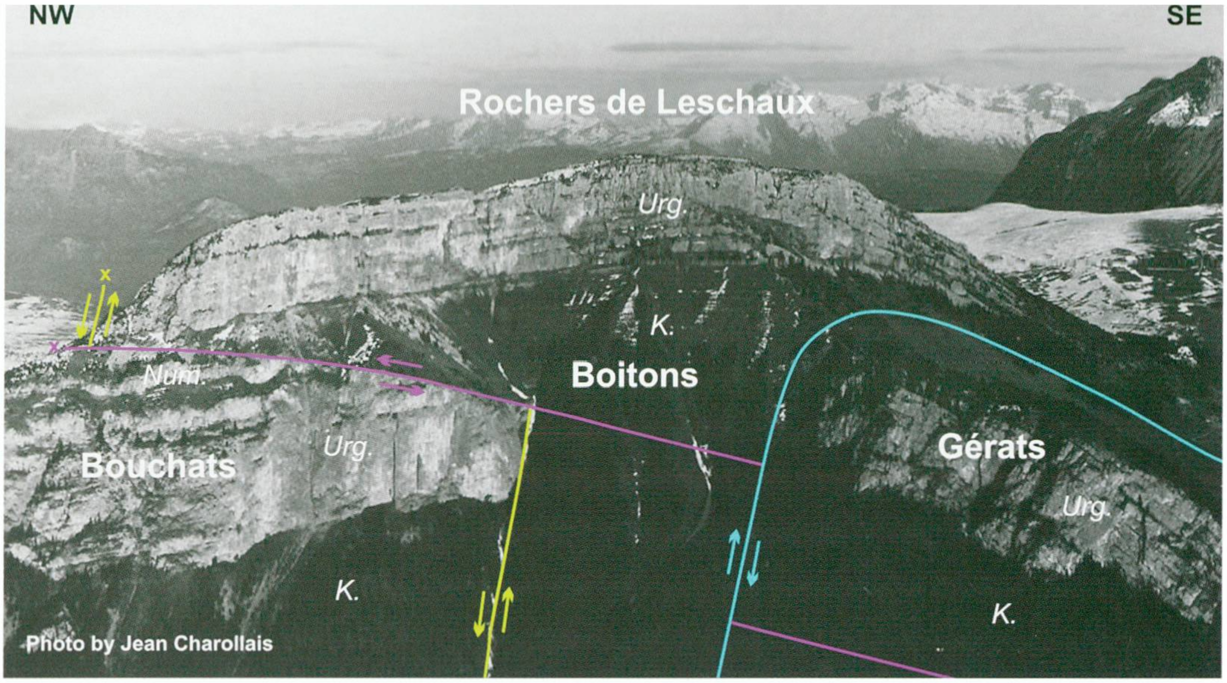

Fig. 8: Geological interpretation of the Rochers de Leschaux after Martin (2005). According to this author, this mountain results from three distinctive deformation phases: (1) an early extensional phase that generated N50 faults (in yellow), (2) a compressional event that caused the breaking of the N50 fault, and the thrusting of the Leschaux cliff towards the NW (in red), and (3) a late extensional phase which produced a series of N150-trending normal faults (in blue), one of which down-dropped the Gérats cliff. K. = Kieselkalk (Hauterivian); Urg. = Urgonian Limestone (Barremian); Num. = Nummulitic limestone (Priabonian).

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