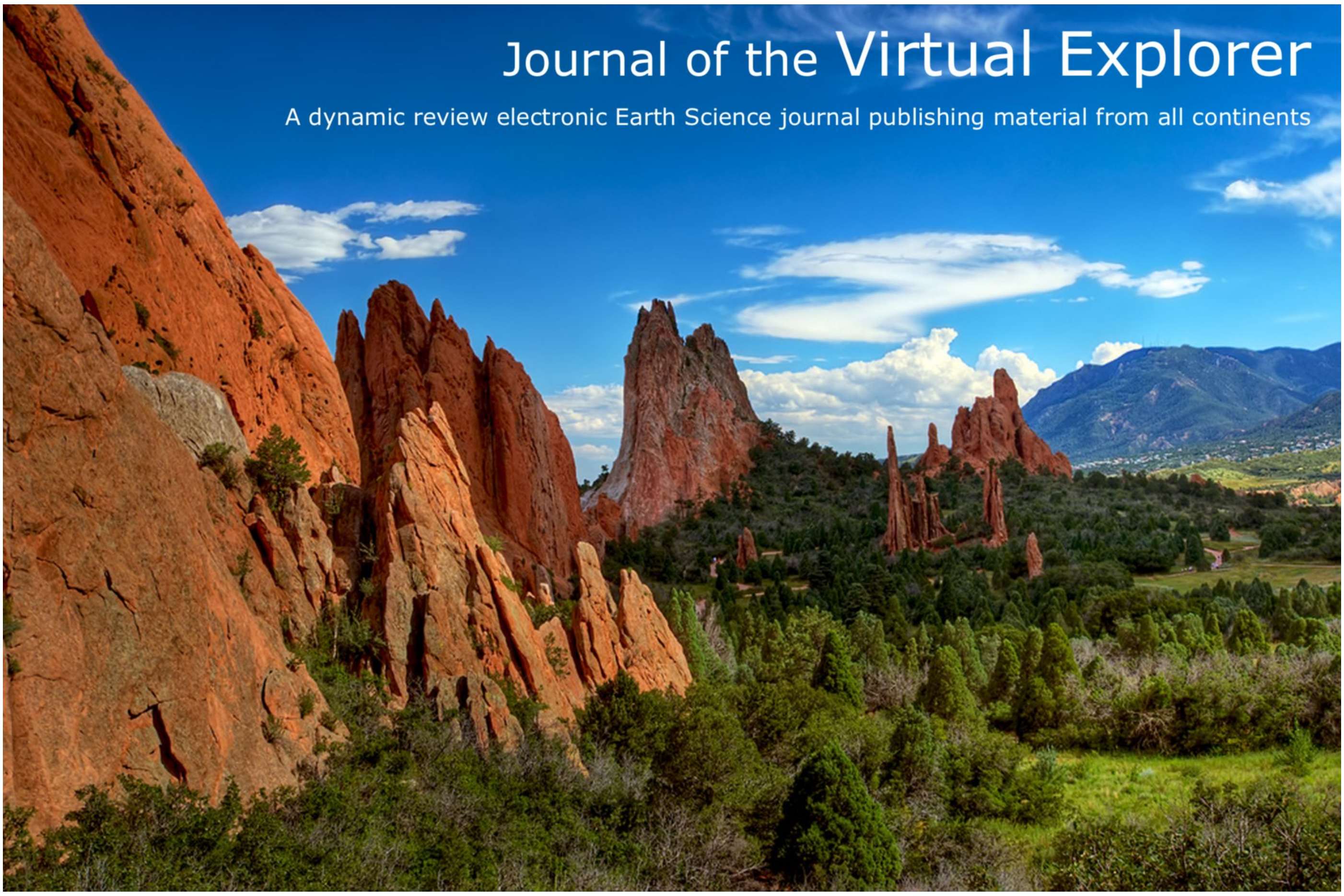

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The Italian Alps: a journey across two centuries of Alpine geology

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Abstract: This review is first and mainly an historical journey across two centuries of Alpine geology, from the early fixist views to the mobilist revolutions produced by the nappe theory and, later, by the global theory of plate tectonics, including the important developments of the last decade. This review is addressed to the Italian students and non-alpine geoscientists, and mainly focusses on the hard rock geology of the Austroalpine-Penninic wedge which is closest to my direct experience. The Alps, made popular by the "Voyages" of Horace-Bénédict de Saussure, are the mountain range where the nappe theory was conceived and rapidly consolidated. Mobilist views, cleverly foreseen by Eduard Suess, were developed by Bertrand, Schardt, Lugeon, Termier, Argand and Staub, and between the two world wars the Alps became a model for the evolution of collisional mountain belts. Wegener's theory of continental drift was endorsed by Argand and Staub in the Alpine-Himalayan ranges, and their tectonic views dominated until the unexpected impact of plate tectonics. In a few years the plate tectonic re-interpretation of the Alps was generally accepted and regionally improved by integration of classic groundwork with modern field and laboratory advances, mainly concerning refinements in stratigraphy, sedimentology, structural analysis, petrology of metamorphic units, isotope dating, deep geophysical experiments, paleostructural restoration back to Tethys, the Pangea supercontinent and older creative reconstructions, as well as numerical and analogical models. The existence of a pre-Gosau orogenic event was confirmed, better documented and related to the closure of the Triassic Meliata ocean. At the beginning of the 1970s, the eclogitic metamorphism in the Sesia-Lanzo zone, firmly related to Paleozoic events, yielded Cretaceous isotope ages, and became the signature of an early Alpine deep subduction of the continental crust. From the half of 1990s, a new generation of isotope dating on retentive systems began to spread in the Western Alps and then in the entire belt, providing robust Eocene ages for the closure of the Piedmont ocean and the subduction metamorphism in oceanic and continental units. A growing number of innovative, provocative, and sometimes repetitive papers appeared in the last decade. Based on actualistic models, the concept of ocean-continent-transition was tested in the Central Alps, became popular and rapidly expanded in the western Alps, from the Canavese zone to the ophiolitic Zermatt-Zaas nappe, without trace, however, of continental basement slices as extensional allochthons inside the Combin zone.

In the second part of the paper, the Structural Model of Italy at 1:500,000 scale and its contribution to Alpine geology are reappraised. This was the most relevant product in Italy of the fruitful integration of geological and geophysical working groups promoted by the National Geodynamic Project. The entire Alpine chain is represented by the sheets 1-2 (Bigi *et al.*, 1990) and 3 (Bigi *et al.*, 1993), that were printed without explanatory notes. Based on updated general lines of the Structural Model, the third and last part summarizes the structural features and kinematic evolution of the Alps. The Alpine orogeny developed from the Cretaceous through subduction of Mesozoic oceans and the European passive margin below the Adriatic leading plate, including the pre-Gosau Eastern Austroalpine thrust system and the underlying Western Austroalpine wedge. The latter derived from some extensional allochthons with Adriatic affinity, still connected to the Adriatic margin and/or trapped within the Piedmont-Ligurian ocean that completely closed during the Eocene. The Western Austroalpine and Penninic wedge is the core of the collisional belt, a fossil subduction complex which in deep seismic images floats over the European foreland lower plate. It is marked by a blueschist to eclogite facies, locally ultrahigh-P imprint of Late Cretaceous-Eocene age, followed by a post-nappe thermal re-equilibration developing Barrovian greenschist to amphibolite facies mineral assemblages throughout the nappe stack. Soon after, a post-collisional magmatic cycle with calc-alkaline to ultrapotassic affinity widely developed during the Eocene (Adamello) and mainly the Oligocene (32-30 Ma) along the Periadriatic igneous belt and fault system, from the lower Aosta valley to the Slovenian eastern edge of the Alps, and fed from partial melting of previously enriched mantle sources. Thermal perturbation and igneous activity are generally related to slab break-off of the lower plate after continental collision, and rising of hot asthenospheric bodies. During the Neogene the exhumed collisional wedge was accreted outside and below the Penninic frontal thrust by a stack of Helvetic basement slices and decollement cover nappes, pushed up and backward indented by the Southalpine lithosphere which in turn was deformed as an antithetic fold-and-thrust retro-belt. The Alpine tectonics is still active, as documented by seismicity, GPS measurements and foreland subsidence.

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Introduction

The Alps are the most studied segment of the Alpine-Himalayan mountain ranges which extend from Gibraltar to the far Asia, and are considered as the typical example of a continent-continent collisional belt. The Alps have been generated by the Cretaceous-Present convergence of the Adriatic leading plate (Argand’s African promontory) and the subducting lower plate, including the Piedmont-Ligurian branch of the Mesozoic ocean (Western Tethys) and the European passive continental margin. The complete closure (Eocene) of the ocean marked the onset of the Adria/Europe collision. The collisional zone is represented by the Austroalpine-Penninic wedge, a fossil subduction complex and a ductile to brittle “collisional damage zone” showing that even large and coherent fragments of light continental crust may be deeply subducted in spite of their natural buoyancy (Dal Piaz *et al.*, 1972).

The Alps extend from the Gulf of Genoa to Vienna, through the French-Italian arc of the Western Alps and the east-west-trending central and eastern Alps, where their connection with the Carpathians is buried below the Neogene infill of the Pannonian basins (Fig. 1).

Figure 1. Satellite image of northern Italy.

Alps, nortern Apennines and Po plain (Padane-Adriatic) foreland from satellite image; geology in Sheets 1, 2 and 3 of the Structural Model of Italy at 1:500,000 scale (Bigi *et al.*, 1990, 1993).

The Alps, made popular by the "Voyages" of de Saussure (1779-1796) and mountaineering exploration, rapidly became the most attractive natural laboratory in Europe for interpreting the anatomy and development of mountain ranges, the classic model of collisional belts (Argand, 1916, 1924; Staub, 1924). Indeed, from 1884 to the early 1900s, Alpine geology played a central role in the development of the nappe theory and modern tectonics. Mobilist concepts, cleverly foreseen by Eduard Suess (1875, 1885, 1894), were established by Bertrand, Schardt, Lugeon, Termier, Steinmann, Argand and Staub (historical reviews and refs. in Dal Piaz, 2001a, and Trümpy, 2001). In the 1920s Wegener's theory of continental drift was endorsed by Argand and Staub in the Alpine-Himalayan ranges, in contrast with hostility on the western side of the Atlantic. Later, gravity and gliding nappes were preferred by some geologists, but this return to neo-fixist views waned, and Argand's and Staub's classic tectonic lines dominated until the beginning, in the late 1960s, of the plate tectonics age. The Alps did not play any relevant role in the birth of the new global theory: as pointed out by Trümpy (2001), this was the unhappy fate of land geology, since it was the ocean which gave birth to the new global theory, favoured by the explosive development of marine geophysics and exploration techniques (e.g., Hallam, 1973; Smith, 1976; Sengör, 1990; Dal Piaz, 1995). The unexpected impact of the plate tectonics theory on classic Alpine geology was initially suffered and not welcomed (Dal Piaz, 1995; Trümpy, 2001). This was not only due to its conceptual novelty, but also to the geophysical supporters of the new global views neglecting reference to some fundamental concepts provided by a century of geological studies in the Alps. In a few years, however, the plate tectonic reinterpretation was generally accepted and regionally perfected by integration of classic stratigraphic and tectonic works with modern advances in structural geology, petrology, geochronology and geophysics (Dal Piaz & Gosso, 1984). After half a century, the Alps are continuing to play as one of the most attractive chains in the world, even if there are clues that the classic field work is becoming less appreciated than in the past as essential milestone for laboratory analysis and numerical modeling.

The paper is deliberately addressed to Italian students and non-alpine geoscientists. In the framework of this volume, this review deals mainly with the Italian part of the collisional belt, without forgetting, however, the essential features of other structural domains.

I am aware of having overdeveloped self-referencing of my work and personal comments, but I was unable to prevent at all this last chance. This contribution was warmly requested by Carlo Doglioni and Marco Beltrando, even long after I had retired. I thank them very much,

for their kindness and tolerance. Particular thanks are addressed to Marco Beltrando for his very accurate and fruitful review of a first version of the paper. Obviously, any error is mine, and any comment and criticism, especially the most severe, will be welcomed, being a sign that I am somehow still alive in the Alpine geological community.

Two centuries of geological history

Two centuries of geological research on the Alps have produced a huge literature body that exponentially grew in the last decades with field and laboratory work, modelling and synthetic interpretations at a regional to global scale. Our histhorical journey begins by briefly recalling older views on Earth's dynamics, and then moves to the Alps and the evolution from fixist to mobilist concepts. Then it focuses on the period from the late nineteenth to first half of the twentieth century, emphasizing the troubled birth and successful development of the nappe theory, and the genius of those who founded the modern tectonics without knowing the oceanic magnetic reversal, geophysical sounding, petrology, isotopic dating, and other currently availabe facilities. It is also the appreciation of the generally forgotten researchers who provided the first modern geological maps of the Alps.

Older orogenic concepts

In 1785, Hutton presented his “Theory of the Earth” to the Royal Society of Edimbourg (printed in 1788), going beyond the static and biblic views of neptunism. This global theory recognized igneous and other endogenous processes as the essential driving forces of the earth's dynamics, and in this view Hutton is rightly regarded as the founder of modern geology and plutonism (Bailey, 1966). At that time also Lomonosof supported the earth's internal forces and envisaged earthquakes as the principal cause of the sinking and rising of the earth surface (uplift theory; Beloussov, 1980). Hutton and Lomonosof views were ignored by most of their colleagues until, some decades later, Christian von Buch (1774-1853) and Alexander von Humboldt (1769-1859) came to the plutonist conclusion, against Werner (1750-1817) neptunist beliefs, that deep igneous processes did indeed exist and that they were the principal cause of the growth of montain ranges (Dal Piaz, 1997).

In spite of this, the igneous origin of the Mont Blanc granite was recognized only in the second half of the eighteenth century, thanks to Gerlach (1871) and Viollet-le-Duc (1876). It had long been envisaged as a primitive rock and thus termed “protogine” (first-born), the popular name coined by Jurine in 1802. Indeed, the Mont Blanc granite and other gneissic core bodies (crystalline masses according to Murchison, 1849) were wrongly regarded as the oldest rocks of the Alpine basement, a tenet which influenced the debate on the age of metamorphic rocks and the structural setting of the Alps, and was particularly favoured in Italy by Gastaldi (1871) and Baretti (1893).

The growth of mountain ranges continued to be ascribed only to vertical movement (fixist views), disregarding any lateral displacement and crustal shortening. For instance, Von Buch explained the uplift of mountain chains by upward intrusions of igneous bodies and Studer (1851) postulated that rising granite from the interior of the Alpine central massifs could also generate lateral gliding and folding of capping beds. By contrast, Elie de Beaumont (1829, 1852) favoured the view that the orogeny was ruled by cooling and contraction of solid earth.

The contraction theory of Elie de Beaumont was developed by Hall and Dana in the United States and by Suess in Europe. From 1859 to 1873 Hall and Dana introduced the concept of geosyncline, a subsiding basin with sedimentary infilling which would evolve by lateral shortening into the American mountain chains. This model was soon applied by Neumayr (1885), Suess (1893) and Haug (1900) to the former Mesozoic seaway which extended from Gibraltar to Eastern Asia: this basin was named Central Mediterranean by Neumayr and renamed Tethys (the sister and wife of Oceanos) by Suess (1893), pointing out its oceanic features and the concept that the Alpine-Himalayan orogenic sistem was generated from its contractional obliteration (Sengör, 1987, 1990). In 1875, Eduard Suess published Die Entstehung der Alpen, a memoir which greatly influenced the development of modern orogenic views. First, against the plutonist tenet, he sustained the passive role of granitic intrusions during the orogeny, a concept definitively established by Albert Heim (1878). Second, he documented the structural asimmetry of the Alps and their unilateral vergence towards the European foreland, generated by horizontal stresses tangential to the earth's geoid. At the meantime, Heim in his famous work Untersuchungen über Mechanismus der Gebirgsbildung (1878), corroborated the fixist double fold theory early postulated by Escher in the Glarus Alps to explain the presence of older beds over younger ones (Milnes, 1979; Funk *et al.*, 1983).

In 1889 Dutton codified the physical principle of crustal buoyancy (isostasy), later developed by Airy, Pratt and Hayford, and introduced the idea of a plastic-fluid layer below the rigid crust (Hallam, 1995). This model was followed by Suess (1885-1901) in his grandiose work Das Antlitz der Erde, by suggesting that the lighter material, named Sial (Al-rich silicates), rose to the surface during solidification of the earth's molten interior, to form a crust over heavier Mg-rich rocks (Sima) like basalt and peridotite. Crustal contraction during cooling earth continued to be the most likely way in which the mountains and oceans (subsided continents) were formed.

Stratigraphic advances and geological mapping

The principal target of Alpine geologists in the first two thirds of the nineteenth century was the establishment of stratigraphy, the essential starting-point for recognition of doubled or overthrown sedimentary sequences and thereby of thrust nappes. Similar stratigraphic advances also concerned Scotland and Sweden, where the Caledonian nappes could be recognized only once the pre-Ordovician age of the Moines was deciphered (Trümpy, 1996; Butler, 2010).

The first geognostic map of the Austrian empire was producted in 1847, and two years later Franz Joseph founded the imperial-royal Geological Survey, located in the Rasumofsky palace. Between 1864 and 1887, the 21 sheets of the Carte géologique de la Suisse at 1:100,000 scale had been completed (Masson, 1983), including the northern side of the Aosta valley, Piedmont and Lombardy, mapped by Gerlach. The project of a first geological map of the Sardinia Mainland States (Savoy, Piedmont, Liguria) at 1:500,000 scale was entrusted by the King Carlo Alberto to Angelo Sismonda and accomplished in 1862 and 1866 (2nd Ed)(Corsi, 2003, 2007). In the same period Gastaldi and coworkers produced the magnificent Geological Map of the Piedmont Alps (1860-79), consisting of 29 sheets at 1:50,000 scale, hand painted with bright colors (Campanino & Polino, 2002). Never printed, it was spread to the European scientific community at the international Exhibitions of Vienna (1873), Paris (1879) and Turin (1884).

As geological mapping of the Alps developed, the stratigraphy of sedimentary successions was refined and better established. On the other hand, the nature and age of protoliths of metamorphic cover and crystalline basement units long remained uncertain. For instance, Studer & Escher (1839) recognized in Graubünden the anomalous occurrence of granite over a calcschist-greenstone complex (modern ophiolite) but concluded that the former rock (which later studies demonstrated to be older that the ophiolites) was a lateral modification of the greenstone. In the Western Alps, the regular stack of different metamorphic units was regarded by Gastaldi (1871-74) and Giordano (1869) as a normal sequence of three younging-upward layers: the Monte Rosa-Gran Paradiso gneiss and granite was the oldest basement and the overlying “talc-gneiss” (gneissic granite) in the Matterhorn-Dent Blanche region the youngest layer, with the “zone of green rocks” (Piedmont ophiolitic zone) of intermediate age between them. The latter zone was considered by Gastaldi to be Precambrian, whilst its correct Mesozoic age, already envisaged by Elie de Beaumont (1828), Sismonda (1845) and Lory (1873), was definitively established by Franchi (1898) throughout the Western Alps on the basis of paleontological evidence (Sturani, 1975; Dal Piaz & Dal Piaz, 1984).

With the unification of Italy in 1861, the need for a modern chartography showing the lithology, geological setting and resources of the national country led to the foundation of the Royal Geological Service (1862) and the Geological Map of Italy at 1:100,000 scale, a project conceived by Quintino Sella (1862), that started in 1871 and was managed by his friend Felice Giordano (Baldacci, 1911, Caruana *et al.* 1996; Corsi, 2003, 2007). This project consists of 277 sheets and was accomplished in 1976.

Focusing on the Western Alps, the survey at the 1:25,000 scale of this immense and difficult area (28 sheets at a scale 1:100,000) was performed in a relatively short time (1888-1906) by Franchi, Mattirolo, Novarese, Stella and Zaccagnia, engineers of the R. Mining Corp and then of the R. Geological Survey. A syntheis of this superlative work was anticipated in the Geological Map of the Western Alps at the 1:400,000 scale, published in 1908, four years before the printing (1912) of the first 1:100,000 sheets (Monte Bianco, Aosta, Monte Rosa, Gran Paradiso, Ivrea) of the Aosta valley and surroundings. In the map margin we can read this notice: “According to the engineers Zaccagna and Mattirolo most of the rocks mentioned in this maps as calcschist and specially those with greenstones, together with micaschists and gneiss, would belong to the Precarboniferous instead of the Jura and Trias crystalline facies units". This advice recalls the fierce scientific dispute between these surveyers, the likely cause of the delay with which the 1:100,000 geological sheets of the Western Alps were printed. Let's briefly outline the matter of dispute.

Following the intuition of Sismonda and against the opposite view of Gastaldi and Baretti, the Mesozoic age of the calcschists (also labeled schists lustrés) was supported by Lory (since 1857) in the Dora Riparia valley, Favre (1862-67) in the Courmayeur zone, and in part by Gerlach (1869. The Mesozoic age was sustained again by Franchi (1898), documented by the finding of Triassic, Rhaetian and Liassic fossils and extended to the entire ophiolite-bearing Piedmont calcschist-greenstone zone. Franchi's reconstruction was shared by Haug, Kilian, Revil, Lory, Novarese and Stella and quickly accepted by the plurality of foreign geologists of the time, but were fought by the colleagues Zaccagna and Mattirolo, as mentioned above. The debate was formally settled only in the 1911 when a commission of the Geological Committee, chaired by Torquato Taramelli, approved Franchi's interpretation for the official geological maps.

Going now to the Italian side of the Eastern Alps in the last decades of the 1800, when Trentino and Alto Adige (Sud Tyrol) were still countries of the Austro-Hungarian empire, the Geologische Bundes-Anstalt of Vienna promoted the geological mapping of the wide area extending from the Ortler massif to the Pusterthal, assigning the survey to a handful of valent geologists. The first survey was provided by Koch, Lepsius, Stache and Teller, but their maps remained unpublished. At the beginning of the twentieth century the Geologische Bundes-Anstalt charged Hammer, Sander and Trener (brother in law of irredentist hero Cesare Battisti) with the mapping ex novo of sheets Bormio und Passo del Tonale, Glurns und Ortler, Nauders and Sterzing of the Austrian Geological Map at 1:75.000 scale, which cover most of western Trentino and Alto Adige. The first three were mapped by Hammer with the contribution of Trener for the Presanella massif, the last one by Sander.

After the war, thanks to a specific agreement between the Magistrato alle Acque of Venice and the Geological Institute of Vienna, these inedited maps were revised and published as sheets Bressanone (1924), Merano (1924) and Passo di Resia (1925) of the Carta Geologica delle Tre Venezie, 1:100,000, edited by the Geological Section of the Idrographic Office of Magistrato alle Acque, directed by Giorgio Dal Piaz (my grandfather). The target of this great project was the survey and printing of 41 sheets: it was accomplished in 1962 and integrated within the Carta Geologica d'Italia at 1:100,000. In this way, Venice gained the regional knowledge of Austrian geologists who, in turn, benefited from Italian funding, when after the tragic war their country was economically exhausted.

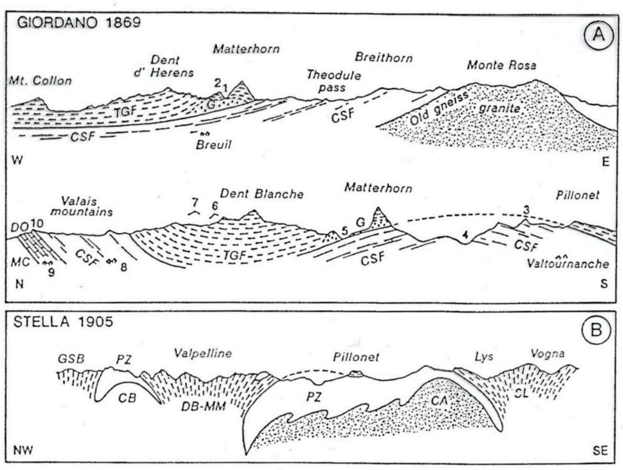
Towards the nappe theory

The mobilist revolution developed only in the late 1800s, when some thrust structures were concurrently discovered in the Alps and northern Europe and the nappe theory was conceived (Dal Piaz & Dal Piaz, 1984; Trümpy, 1991, 1996, 2001; Butler, 2010). The starting point was the recognition of inverted sequences and the intuition that, instead of the classic double fold model, this anomaly could even be interpreted through extensive sideways displacements. Unlucky steps in this direction were first attempted by Arnold Escher in the cover sequences of the external Swiss Alps, thanks to fossiliferous sediments and inferred datation, then by Giordano and Gerlach in the extremely more difficult metamorphic domain of the Pennine Alps.

During a field trip in the Glarus Alps, Escher illustrated to Sir Roderick Murchison (1849) the possibility that the occurrence of Verrucano beds over younger deposits was the result of "one enormous overthrow", a term which recalls the nappe concept. Unfortunately, Escher (1866, in Trümpy, 1991) changed his intuitive idea, favouring the illogical solution of two opposite-vergent anticlinal folds (double fold). Firmly supported by the authority of Albert Heim (1878, 1891), the double fold became a model and was rapidly extended to the Mont Blanc and Gotthard massifs, and then to the Penninic zone and other Alpine domains.

The existence of a large gneissic nappe in the Matterhorn and surrounding mountains - i.e. the Argand's Dent Blanche fold-nappe - was clearly realized and thoroughly evaluated by Felice Giordano (1869a, 1869b) during his trips around and across the peak (Dal Piaz, 1996a). Giordano's perfect profiles (Fig. 2) show, rightly, that this huge gneissic body overlies everywhere the Mesozoic "green rock zone" (ophiolite) over a distance of at least 35 km, and cannot have risen from below to form a double fold. Therefore, Giordano's crucial question was the age of the capping granitic gneiss (Argand's Arolla series). If it were older than its sole, the only solution explaining its present location was that "the gneiss of the Matterhorn, Pillonet, and other more distant mountains was overthrown in the form of huge nappes" (Giordano wrote: "..... rovesciatosi poi in falde enormi", 1869a, and "..... se serait épanché en nappes énormes", 1869b). Nevertheless, this hypothesis sounded too creative to the rational mind of Giordano, a mining engieneer who favoured the neptunist conclusion (mainly in his French paper, 1869b) that these crystalline rocks were the Mesozoic top of a normal stratigraphic sequence.

Figure 2. Giordano's and Stella's geotectonic views.



A) Giordano's cross-sections from Valais to the Monte Rosa massif, through the Matterhorn (1869a), showing the continuous overlap of the "talc-gneiss formation" (TGF), including the Matterhorn gabbro (G), over the "calcareous-serpentinite formation" (CSF = green rock zone), in turn resting over the Monte Rosa old gneiss and granite or, to the north, over a dolostone-quartzite suite (DQ) and underlying older micaschists (MC); 1: Lion Pass, 2: Lion Head, 3: Roisetta and Gran Tournalin, 4: Tournanche valley, 5: Stokje, 6: Gabelhorn, 7: Weisshorn, 8: Haudères, 9: Evolene. B) The fixist fan to mushroom fold interpretation of a nearby cross-section along the northern flank of the Aosta valley (Stella, 1905); DB-MM: Dent Blanche-Mt Mary zone, SL: Sesia-Lanzo zone, PZ: Piedmont zone (green rock zone), MR: Monte Rosa basement, AD-BD: Arceza and Boussine domes, GSB: Grand St Bernard zone (Dal Piaz, 1997).

The same hypothesis was envisaged and likewise rejected by Heinrich Gerlach (1869, 1871) who have carefully mapped the whole Pennine Alps and the Matterhorn itself. He believed, rightly, in the older age of the capping protogine-type granitic gneiss, but favoured the fixist double-fold model, disregarding the natural evidence correctly documented by Giordano's profiles. In conclusion, if Giordano's geometry and Gerlach's chronology had been mutually integrated, the Dent Blanche nappe would have been discovered some decades before it actually was by Lugeon & Argand (1905).

Birth and establishment of the nappe theory

After the unlucky attempts at unravelling the structural setting of the Western Alps a stroke of genius was needed to go beyond established concepts. It came from Marcel Bertrand, a brillant French geologist at the Ecole des Mines, who was not influenced by traditional tenets on Alpine orogeny: indeed, he had never worked in the Alps nor visited the Swiss Glarus range but, in 1884, he compared the subsurface structure of the French-Belgian coal-field – his working place - with Heim's classic profile of the Glarus double fold, re-drowning it as one recumbent fold-nappe laterally displaced over a distance of 40 km, the simplest way of explaining the presence of Permian rocks over younger sediments (Trümpy & Lemoine, 1988). Bertrand's paper was the first formal step towards the nappe theory in the Alps, but it was too heretical for overcoming conventional concepts. His mobilist insight was completely ignored by Heim and other influential Alpine geologists, except for Suess (1892), who had never completely convinced by the double fold reconstruction (Trümpy, 1991, 1996).

As pointed out by Trümpy (1991), the factual breakthrough came with Hans Schardt, a professor of geology in Neuchâtel and Zürich. On the basis of a systematic field work, Schardt demonstrated between 1893 and 1898 that some prominent rocks around the Lake of the Four Cantons and the Chablais-Romandes Prealps were exotic remnants of gigantic nappes originating 100 km further to the south-east, later dismembered by erosion to form isolated outliers (Klippen). Gravitational sliding was the favoured mechanism. The importance of Schardt's reconstruction was immediately realized by the geological community, although it was initially criticized. However, the nappe theory rapidly reached almost general acceptance essentially because it was validated by Suess's authority (1901), applied to the whole of the external Swiss Alps by Maurice Lugeon (1902) and finally also blessed by Albert Heim (1902) in a famous open letter to

Lugeon. In 1903, a memorable debate broke out at the 9th International Geological Congress in Vienna between the Austrian and German defenders of fixist orthodoxy and the French and Swiss supporters of the new mobilist revolution, a theory which rapidly advanced and became definitively consolidated thanks to the genius of Emile Argand and the authority of Robert Staub. In particular, Pierre Termier (1904), Bertrand's best disciple, successfully extended the mobilist concept to the entire Eastern Alps which suddently lost its traditional autocthony, becaming a stack of basement and cover nappes. Termier (1906) distinguished the first-rank nappes, envisaged as classic recumbent folds, and the second-rank nappes, described as thrust-sheets, developing in the deeper and shallower parts of the orogen respectively, with transitional features between them. This happened some decades before shearing was recognized as generation mechanism of some Alpine basement nappes. Termier conceived the notion of tectonic window, as deep cuts across the eastern Austroalpine tectonic lid of the orogen, where the underlying Penninic units are exposed, and in the meantime Haug (1906) described the cover nappes in the Northern Calcareous Alps.

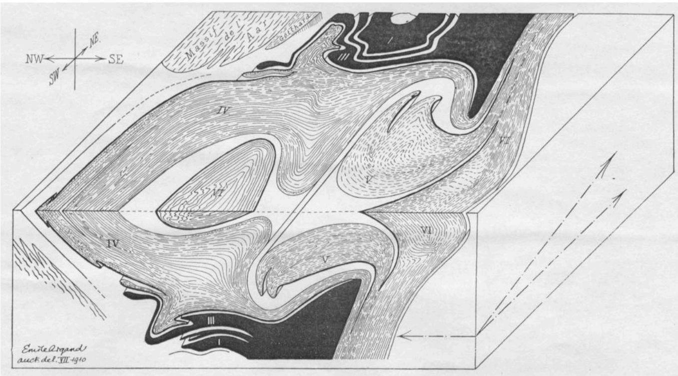
In the Southalpine hinterland, the fixist fault-controlled staircase structure of the Venetian Alps long sustained by Suess and other reputed geologists was re-interpreted at the century turn by as a typical fold-belt with Adriatic vergence (G. Dal Piaz, 1905, 1912).

Emile Argand and the Penninic fold-nappes

In the early 1900s the Dent Blanche and other nappes of the Penninic zone were revealed and carefully reconstructed throughout the Western Alps by Emile Argand (1908, 1909, 1911). His papers are illustrated with splendid geological pictures, explanatory sketches, tables of cross-sections and tridimensional views which make easier and more immediate understanding Argand's ideas. His work began with perfect geological mapping at 1:50,000 scale of the Dent Blanche-Matterhorn mountain group (1908, 1909) and was then addressed to the mobilist reinterpretation of the entire arc of the Western Alps, fully represented by a tectonic map, scale 1:500,000, and a series of detailed cross-sections (Argand, 1911a-b). The accuracy of his tectonic map greatly benefited, as was fairly acknowledged by Argand himself, from the perfect fit of the main lithological units, detailed internal subdivisions and mutual boundaries shown in the already mentioned 1:400,000 geological map of the Western Alps, published in 1908 by the R. Servizio Geologico of Italy (Argand said "d'avoir connu, dès sa publication en 1908, l'inestimable document moderne qu'est la carte géologique des Alpes occidentales, au quatre-cent millième, bientôt suivie des premières feuilles alpines, au cent-millième, de la Carte géologique d'Italie, oeuvre distinguée des maîtres du R. Ufficio Geologico"). See Escher & Masson (1984) and Dal Piaz (1996b, 1997, 2001) for reviews of Argand's work on the Matterhorn and the Penninic pile of nappes.

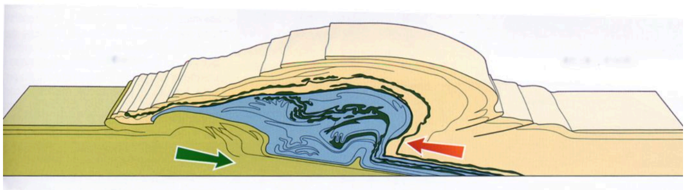
Following Argand's block-diagram (Fig. 3), the axial part of the Western Alps, called the Penninic zone, is a stack of six recumbent fold-nappes, physically continuous and extensively displaced to the north-west, each consisting of old metamorphic and igneous rocks (crystalline basement) regularly mantled by Mesozoic sediments, and locally associated with injections of mafic-ultramafic igneous bodies (ophiolites). Essential features of the Penninic zone are pervasive metamorphism and folding, generated by dynamic crystallization and ductile deformation during the Alpine orogeny. The capping unit is the partly eroded Dent Blanche fold-nappe (VI), which extends from the Valais to the Aosta valley, across the Matterhorn; its origin is recognized in the internal side of the Alpine arc, represented by the Sesia-Lanzo zone (VI'). Below them, are the Mid-Penninic Monte Rosa (V) and Grand St Bernhard (IV) fold-nappes which are separated from the Dent Blanche by a syncline of Triassic marbles, calcschists and greenstones (metamorphic ophiolites) of the Piedmont zone (Giordano's "green rocks zone"). Below them is the Lower Penninic domain, a multiple overthrust system represented by the Monte Leone (III), Lebendun (II) and Antigorio (I) fold-nappes and the Verampio dome (0), the lowermost unit now exposed in the Alps. The Lower Penninic system is restricted to the Ossola-Ticino window, where the nappe stack is domed (tectonic culmination) and the higher nappes have been stripped out; by contrast the higher nappes are preserved in areas of tectonic depression (Valais-Aosta valley to the west and Graubünden to the east). The frontal part of the Penninic nappe stack is thrusted over the Helvetic zone, consisting of decollement cover nappes and the sliced basement of Aar-Gotthard and Mont Blanc massifs; on the opposite side is the Insubric hinterland block (Southern Alps, Po Plain, Dinarides) which, moving north-west, functioned as a rigid indenter against the back of the Penninic nappe pile (the so-called root zone) which was consequently forced to become steeper and bend backwards (Fig. 4). The antithetical slicing of the Southalpine upper crust was an effect of this process.

Figure 3. Argand's fold-nappes.



Tridimensional view of the North-Western Alps by Emile Argand. Penninic fold-nappes: Dent Blanche (VI) and its root (Sesia-Lanzo zone: VI'), Monte Rosa (V), Grand St Bernard (IV), Monte Leone (III), Lebendun (II), Antigorio (I), Verampio dome (0).

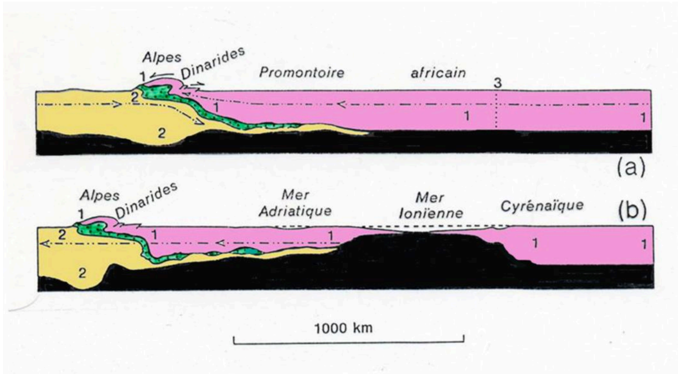
Figure 4. Argand and the Alpine belt.



Argand's generalized view of the Europe-vergent Alpine belt. Note that the Eastern Alps (beige) are displaced over the western Alpine nappe stack, and the root zone is indented and back-folded by the Southalpine hinterland, in turn deformed by south-vergent thruSt The Western Alps consist of six Penninic Penninic nappes (blue) and ophiolitic sequences (black), overthrown onto the sliced Helvetic domain and undeformed European foreland (greenish).

In the short work Des Alpes et de l'Afrique Argand (1924a) presented a geotraverse extending from Northern Africa to Central Europe, through the Alps (Fig. 5). This global view shows the collisional structure of the Alps generated by the paroxistic stages of the Tertiary orogeny (Fig. 5a) and a late-orogenic stage dominated by extensional tectonics and crustal stretching to the opening of Ionian basin floored by simatic (mantle) material (Fig. 5b). The Penninic nappe pile and its roots form a flattened zone sandwiched between the rigid toe of the African promontory and the underlying European continent. In addition, if the configuration of the continental crust and its simatic substrate (rich in Mg-silicates) is compared, the essence of two fundamental tenets of Argand's orogenic theory can be appreciated, i.e. contraction-induced crustal thickening and extension-induced crustal downbulge and attenuation at the back of the Alps.

Figure 5. Argand's Europe-Africa geotraverse and mantle denudation.



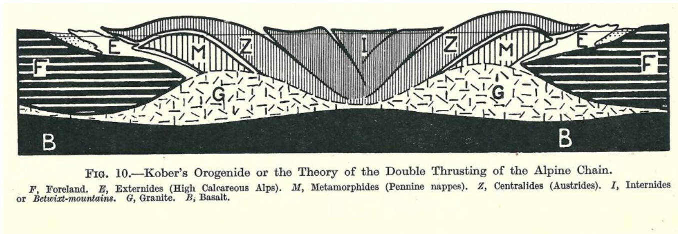
Argand's two-stage reconstruction of a north-south geotraverse from Central Europe to Africa, through the African promontory and the Alps: a) Synthetic structure of the Alpine-Dinarides belt which originated from the collision between Africa (1: pink) and Europe (2: beige), whilst the original Penninic Tethys (green) was shortened and sutured between them; b) Late-orogenic crustal thinning and upheaval of simatic substrate (black), both induced by the northward drift of Europe from a disjunction zone (3), and related opening of Mediterranean and Ionian basins.

Argand (1916, 1924) also reconstructed the kinematic evolution of the Western Alps through thirteen steps of incremental contraction of the Tethyan geosyncline, gradually progressing from embryonic structures, through the generation of second-order geo-anticlines (cordilleras) and synformal depressions (later called Valais and Piedmont basins), towards a pile of recumbent fold-nappes to the ultimate configuration. This evolutionary cartoon was the groundwork for new directions in geodynamics, named embryotectonics, i.e. sequential analysis of the evolving structure (kinematics) and, vice versa, the unrolling of the nappe stack by elimination of overthrusts and shortening (retrodeformation) back to the originally undeformed configuration of Tethys (palinspastic restoration). Large-scale folding was the ductile mode envisaged by Argand to generate the Penninic nappes, supposedly forming a laterally continuous pile of antiformal and synformal recumbent folds. Therefore this view assumes the lengthwise correlation of nappes (cylindristic concept) based on geometry and sedimentary facies development. This view was soon emphasized by Leopold Kober (1923), Rudolf Staub (1924) and Léon W. Collet (1927), who in their great syntheses on the Alps strengthened the genetic link between paleogeographic belts (sedimentary facies zones) and tectonic nappes (Trümpy, 1996).

Argand accepted the essence of Wegener's theory realizing that continental drift could offer driving forces consistent with his kinematic views. Thereby, Argand conceived an innovative model of the Tertiary orogeny in Eurasia and corroborated the concept of continental drift through new geological observations and tectonic reasoning. As a result of his work, Argand was chosen to deliver the inaugural lecture at the 13th International Geological Congress in 1922, where he presented his famous memoir La Tectonique de l'Asie (published in 1924) in which the mobilist concept was thoroughly tested and definitively consolidated. Dealing now only with the evolution of the Alps, it can be stressed that Argand partly abandoned his previous belief (1916) in a continuous orogenic contraction of Tethys from the Carboniferous to the Neogene and suggested the existence of intervening extensional pulses, chiefly in the Triassic-Jurassic geosyncline times. Crustal extension and thinning were envisaged also in a late-orogenic stage, giving rise to the opening of the modern Mediterranean and Ionian basins, locally floored by simatic material. Crustal stretching was supposedly induced by the northward drift of Europe and its moving away from a disjunction zone located to the south. This mode of crustal attenuation provided a suitable analogue for the generation of the Alpine geosyncline, the cradle of the orogeny, where the Penninic zone could play the role of the mobile geosyncline core. In this view, Argand (1924) innovated his previous belief on ophiolites as syn-orogenic injections of mafic melts (1916), partly envisaging the modern notion of crustal tearing and mantle denudation. This promising direction was no longer developed and, in 1934, Argand went back to the injection concept in his conclusive work La zone pennique (Escher & Masson, 1984).

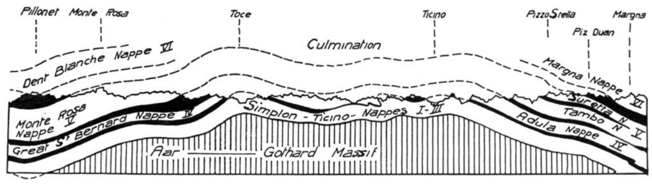
In the meantime Kober and Staub published their synthetic reconstruction of the entire Alpine chain. Kober (1923) fully accepted the nappe theory, but envisaged a symmetrical structure of the Alps thought to be generated by a double thrusting mechanism, with crustal attenuation of the axial zone (Fig. 6) and a reduced extent of the bilateral nappe displacement. Staub (1924) referred the Austroalpine nappe stack to the front of the Adriatic-Apulian promontory, detached from its Southalpine hinterland and thrusted over the ophiolite-bearing Pennine nappes, which in turn override the continental units of the Helvetic external domain. Based on an extremist use of cylindristic canons, Staub proposed the eastward and physical continuous extension of the western Penninic nappes beyond the Ossola-Tessin dome and their reappearance in the Grisons and Hoen Tauern area below the Austroalpine basement and cover nappes (Fig. 7). His memoir is illustrated with a tectonic map of the Alps, one million scale, and three color plates of transversal and longitudinal profiles.

Figure 6. Kober’s bilateral thrusting.



Kober's Orogenide theory of double thrusting of Alpine chain (in Collet, 1927). Structural elements: Foreland (F), Externides (E: High Calcareous Alps), Metamorphides (M: Pennine nappes), Centralides (Z: Austrides), Internides (I), granite (G), basalt, sima (B).

Figure 7. Staub’s longitudinal correlations.



Staub's longitudinal correlation of Alpine nappes on both sides of the Simplon-Ticino culmination (in Collet, 1927).

Criticism and further advances

The tectonic views of Argand and Staub dominated the Alpine scenario until the end of the 1960s, with some fixist reactions (gravitational tectonics) and some innovative contributions on the debated mechanism of nappe generation. Opposite to Argand's fold-nappes, also emphasized by Albert Heim after his mobilist conversion (1902), Staub (1937) and the lesser known Austrian geologists Ampferer and Hammer (1906, 1911) recognized in the central and eastern Alps the existence of thrust-planes at the base of most nappes, instead of the alleged reversed limbs. As pointed out by Trümpy & Oberhauser (1999) and Trümpy (2001), it can be mentioned that Otto Ampferer (1906, 1911) introduced the notion of underthrusting or subfluence (Verschluckung) of crustal slices into the interior of the Alpine edifice, before the term subduction was coined by Amstutz (1955) in the Ossola valley, without any plate tectonic meaning. Ampferer's innovative ideas were dispersed in short notes that were little understood or ignored by his contemporaries.

Since the 1930s, a modern description of the tectono-metamorphic evolution of the Italian Eastern Alps were made by Angelo Bianchi (1934) and Giovanbattista Dal Piaz (1934), based on detailed mapping, structural analysis, laboratory work and mobilist views, whilst the personality of Sander and Cornelius emerged among other distinguished Austrian geologists, dealing with the fabric of the rocks, the Eastern Austroalpine and the Tauern window.

Back to the Western Alps, it is worth mentioning that in 1925 Hermann proposed a provocative restoration of Argand's Penninic zone, envisaging the Dent Blanche, Monte Rosa and Grand St Bernard nappes as deriving from individual continental fragments - named microcratons - scattered within the Tethyan geosyncline between the European and African continents, and alternating with deep marine basins floored by simatic crust, the source of the Alpine ophiolites. Note that this forgotten palinspastic reconstruction does not much differ from Trümpy's (1980) and Platt's (1986) classic cartoons. Modern descriptions of petrographic and chemical features of Piedmont ophiolites and related eclogites were given by Zambonini (1906) in the Cottian Alps and by Gb. Dal Piaz (1928) in the Aosta valley.

From 1937 onwards, Staub displaced Argand's Dent Blanche nappe from the Penninic to the Austroalpine domain, hence to Africa, owing to the lithological affinity clearly documented by the surveyors of the Geological Map of Italy. In 1938 the Swiss students Stutz and Masson replaced the Dent Blanche fold-nappe, including its Mesozoic envelope, with gliding thrust sheets bounded by mylonitic shear zones. In spite of this, Argand's concept of fold-nappe generation by primary foldings was long maintained until, from the early 1970s onwards, it came to be severely criticized.

Alpine geology after World War II

After the war, Alpine geology was gradually reappraised, leading to significant improvements in field work, stratigraphy, structural geology of sedimentary cover units, and retrodeformation of the Alpine nappe stack into various paleogeographic scenarios (e.g., Ellenberger, 1953, 1958; Elter, 1960; Trümpy, 1960; Tollmann, 1963, 1977). In particular, Ellenberger (1953) recognized the Briançonnais affinity of the Barrhorn series (Fig. 8), previously included in the Piedmon zone, and of similar sequences in the Mediane Prealps.

Figure 8. Briançonnais series near Zermatt.

The Barrhorn series, near Zermatt, displays a Briançonnais affinity (Ellenberger, 1953; Sartori, 1987, 1990) and is interpreted as the detached cover of the Siviez-Mischabel (Grand St Bernard) nappe. This figure shows a typical occurrence of white pelagic marbles (Malm) and yellowish impure marbles (Cretaceous), and the overlying Dent Blanche nappe (Arolla gneiss); the ophiolitic Combin zone, running between them, is hidden beneath the Turtmann glacier.

The geosyncline concept continued to be developed by regional reconstructions of Tethys from the Mediterranean to the far east (Stille, Aubouin and co-workers; in

Aubouin, 1965). By contrast, the understanding of geodynamic processes went through a period of relative stagnation, characterized even by the exhumation of neo-autochthonist models supported by some French and German geologists. In the late 1950s and 1960s, the principal lines of Argand and Staub's work were generally accepted in the Alps and corroborated by detailed regional studies, so a sort of mobilist Renaissance may be recognized (Trümpy, 1996).

From the early 1970s onwards, the fold-nappe model was severely criticized, since the recumbent folding was shown to be a post-nappe deformation and the existence of decollement and shear mechanisms was revealed for most of the Alpine nappes (Milnes and his students, in Dal Piaz & Gosso, 1984). It can also be recalled that Milnes (1974, 1978) in his pioneering works suggested the Sub-Penninic affiliation of the lowermost Penninic nappes exposed in the Ossola-Tessin window, including also the Gotthard and Tavetsch massifs traditionally referred to the Ultrahelvetic-Helvetic domain (Spicher, 1980; Bigi *et al.* 1990). Mesozoic normal faults inside Tethys and the contrasting evolution of individual fault-bounded units were discovered across the Alps, whilst controversial amounts of crustal shortening were suggested through retrodeformation of some Alpine nappes. In the Eastern Alps, nappe emplacement and concurrent metamorphic imprint were anticipated to the Cretaceous by Flügel (1960) and other Austrian geologists, owing to the relation between the Austroalpine thrusts and sealing Gosau sediments (Oberhauser, 1980, 1995, and refs. therein). In the early to mid-1960s geochronological data on igneous and metamorphic rocks started to emerge in the Alps (Hunziker *et al.*, 1992, and refs. therein) and thereby new constraints were established on the orogenic evolution at depth. Meantime, field surveys, theoretical groundwork, laboratory experiments and geophysical techniques greatly expanded in Europe and all over the world.

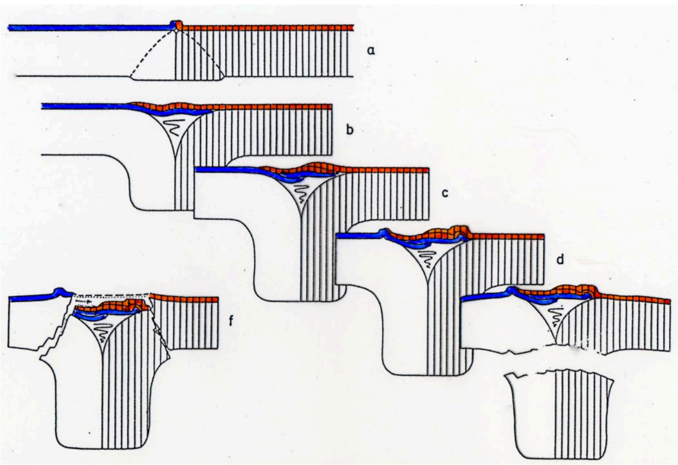
Plate tectonics and its impact on Alpine geology

It is well known that the global theory of plate tectonics was conceived in the 1960s through the contemporary contribution of a handful of brilliant scientists and research teams. Its conceptual birth goes back to the American geologists Harry Hess and Robert Dietz, the English geophysicist Fred Vine and some distinguished precursors, whilst it is generally acknowledged that the theory was promoted and established by geophysicists such as the Canadian Tuzo Wilson, the Americans Jason Morgan, Bryan Isacks, Jack Oliver, Lynn Sykes and the French Xavier Le Pichon (Hallam, 1973; Bosellini, 1978).

This global theory of earth's dynamics developed outside the Alps in spite of the decisive contribution they had provided for centuries to fundamental advances in the orogenic concept. It suddently appeared to the world of Alpine geology in the latest 1960s and its impact was not welcomed enthusiastically. Like Venus, this theory born out of the sea (Trümpy, 2001), far from the classic highland geology of the Alps, and clearly it was to dismantle the latest refinement of the geosyncline model and other traditional milestones, ignoring any Alpine inheritance for the mobilist tenets and collisional features. Actualist reconstructions were mostly provided by outsiders who were not introduced enough into, or not biased by, any complex details of the Alps. By contrast, partial remakes or quite heterodox models were chiefly suggested by Alpine geologists induced to privilege each alleged regional constraint over potential modern homologues. Personal study areas were aften regarded as a special case where only plate tectonic canons fitting regional data could be applied, whereas those supposedly contrasting them were discarded or ignored.

Laubscher (1969, 1970) depicted two opposite subductions converging down into a mutual vertical root (Fig. 9), inspired by the crustal downbulge envisaged long before by Hess (1939). In the meantime global models of Tethyan evolution were suggested by Dewey & Bird (1970), Smith (1971) and Dewey *et al.* (1973). The sialic geosyncline became an immense basin floored by a basaltic crust and laterally bounded by faulted and attenuated passive continental margins, whilst ophiolites become remnants of lost ocean floors (see Bernoulli & Jenkyns, 2009, for review). A modern reconstruction of various mountain belts in the world was given by Dewey & Bird (1970), particularly evaluating the closure of the Tethyan ocean and continental collision in the Alpine-Himalayan realm, a concept quite obvious in Argand's and Staub's models. The evolution of the Atlantic ocean and relative motion between Africa and Europe were computed by Smith (1971) and Dewey *et al.* (1973); this allowed the recognition of a left-lateral fault zone in the Mediterranean until 90-80 Ma ago and of NW-trending oblique convergence (of about 800 km) from the Late Cretaceous to the Present. In this view Europe became the lower plate since the onset of subduction. All ophiolitic units of the Alpine, Apenninic and Hellenic belts were immediately reinterpreted as lithospheric remnants squeezed out from the suture of western Tethys oceanic branches separating the European and African continental margins (Laubscher, 1969, 1971; Dercourt, 1970; Boccaletti *et al.*, 1971; Dal Piaz, 1971, 1974; G. Elter, 1971; Hsü & Schlanger, 1971; Wezel & Ryan, 1971; Dal Piaz *et al.*, 1972; Haccard *et al.*, 1972; Lemoine, 1972, 1975, 1977; references and review in Abbate & Bortolotti, 1984). In particular, the Alpine-Apenninic (Piedmont-Ligurian) ocean was envisaged as a rhomboidal basin dominated by strike-slip deformations, where thinning and tearing of the continental crust progressed up to its complete splitting, leading to mantle denudation (Decandia & Elter, 1969; Elter, 1972). In this view, a pre-oceanic process of gabbro underplating was figured by Elter (1972) in a pure-shear thinning model of the Ligurian domain.

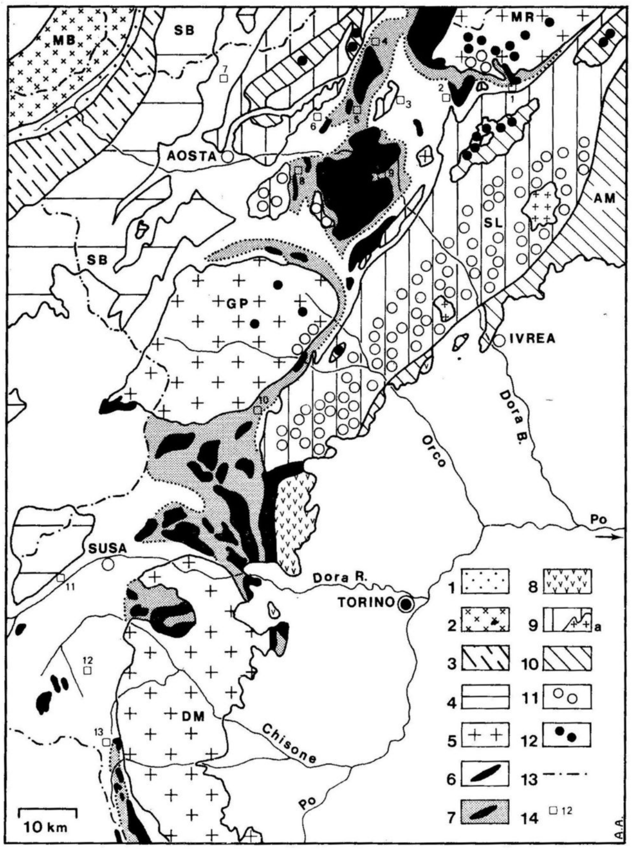
Figure 9. Laubscher's opposite subductions.



Opposite subductions of Africa (red) and Europe (blue), converging down into a mutual vertical root (Laubscher, 1969, 1970), inspired by Hess (1939) crustal downbulge.

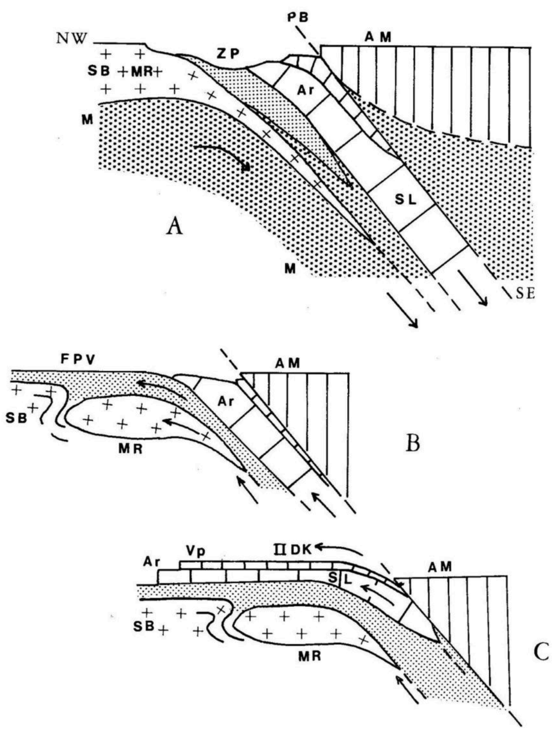
At the beginning of the 1970s, the convergent plate margins were thermally modelled (Oxburg & Turcotte, 1970) and the blueschist to eclogite facies metamorphism, recognized in the Alps since the late 1800s (e.g., Stella, 1984, 1903; Franchi, 1895, 1897, 1902; Novarese, 1985; Frey *et al.*, 1974, and refs. therein), became the signature of fossil subduction zones around the Pacific ocean and in the Alps (Ernst, 1971; Dal Piaz, 1971, 1974; Dal Piaz *et al.*, 1972) (Fig. 10). The Sesia-Lanzo zone, some basement slivers of the Dent Blance nappe s.l. (called outliers), and the underlying Piedmont ophiolitic units were a key for understanding the subduction metamorphism in granitoid, pelitic and mafic rocks, its timing, and the exhumation of high-P units from mantle depths.

Figure 10. Subduction metamorphism in the Western Alps.



Tectono-metamorphic map and geodynamic evolution of North-Western Alps (Dal Piaz, 1971).

A) Map - Helvetic-Ultrahelvetic zone: sedimentary cover units (1) and crystalline basement (2); Subbriançonnais zone (3); Grand St Bernard nappe (4); Penninic crystalline units (5) of Monte Rosa (MR), Arcesa-Brusson, Gran Paradiso (GP), Dora-Maira (DM); Piedmont zone, including prasinite-bearing calcschist units (6), and ophiolite-rich eclogitic units (7), with major serpentinite bodies (black); Lanzo lherzolite (8); Sesia-Lanzo zone (SL) and Dent Blanche Arolla series (9), intruded by late Alpine Biella-Traversella plutons (9a); 2nd Diorite-kinzigitic zone and Valpelline series (10); probably Alpine eclogitic imprint in the Sesia-Lanzo, Dent Blanche, Monte Rosa and Gran Paradiso (11); eoalpine kyanite-chloritoid ± glaucophane assemblages (12); national boundaries (13); Cu-Fe ore deposits (14).



B) Profiles – Eoalpine subduction (A) of a composite plate, involving the Grand St Bernard (SB), Monte Rosa (MR), Piedmtont sediments and ophiolites (ZP), upper mantle (M) and probably the Arolla series (AR), Sesia-Lanzo zone (SL), Valpelline series (VP) and 2nd Diorite-kinzigitic zone (IIDK), below the continental basement of the Souther Alps (AM); Benioff plane (PB); upflit and nappe emplacement (B-C).

It can be remembered that, when the memoir on the Sesia-Lanzo zone was printed (Dal Piaz *et al.*, 1972), this classic eclogitic metamorphism was firmly tought to be pre-Permian (Bianchi & Dal Piaz, 1963; Gb Dal Piaz, 1965), pre-Carboniferous (Carraro, 1966, 1972) or even Caledonian (Mottana, 1972), due to the alleged Permian age of post-metamorphic porphyritic dykes and volcanic agglomerates of the Sesia-Lanzo zone. It can also be remembered that, at the beginning of the 1970s, the tectono-metamorphic evolution of the Western and Central Alps was considered as a single polyphase cycle of burial type and Tertiary age only (e.g. Niggli, 1970; Trümpy, 1971). The breakthrough could have been an oral presentation held by Hunziker (1970) in a Swiss meeting, but new dating was strongly contrasted by an influential Swiss geologist and the paper was not puplished. A new collaboration started and the field and laboratory work was improved. Two years later, the innovative Rb-Sr and K-Ar ages on white micas from eclogitic granitoids and micaschists of the Sesia-Lanzo zone and their geodynamic interpretation were presented to the Società Geologica Italiana and published (Dal Piaz *et al.*, 1972), supporting the existence of a subduction-related tectono-metamorphic event of Late Cretaceous age (90-65 Ma; detailed isotope data in Hunziker 1974). Criticism vanished with finding and dating (31.6 ± 1.3 Ma; Dal Piaz *et al.*, 1973) of a post-metamorphic lamprophyre dyke across the contact between the Sesia-Lanzo and the Combin zone, near the Passo Palasina (Ayas valley), and with the extension of this chronology to the identical dykes (previously Permian) that constrain the upper age limit of the eclogitic metamorphism (32-30 Ma; Dal Piaz *et al.*, 1977). The eclogitic Sesia-Lanzo zone rapidly became the best evidence that also large and coherent slices of light continental crust could be deeply dragged down in the subduction zone (Dal Piaz *et al.*, 1972; Compagnoni *et al.*, 1977), contrary to theoretical views that ruled out the subduction of continental crust due to its buoyancy. The interest for this topic allowed the development of the triennial “Italy-U.S.A. cooperative project on high pressure to low temperature metamorphism in the Western Alps”, funded by C.N.R. and N.S.F., and lead by Robert Coleman, Gary W. Ernst and myself. The first issue was the internal report “The Sesia-Lanzo zone, a slice of continental crust with Alpine high pressure-low temperature assemblages in the western Italian Alps” (Compagnoni *et al.*, 1975) that was distributed to all participants at the Special session of the Soc. Italiana di Mineralogia e Petrografia on “High Pressure-low temperature metamoprhism of the oceanic and continental crust”, held in Genova 23-29 September 1976, and re-printed the year later (Compagnoni *et al.*, 1977).

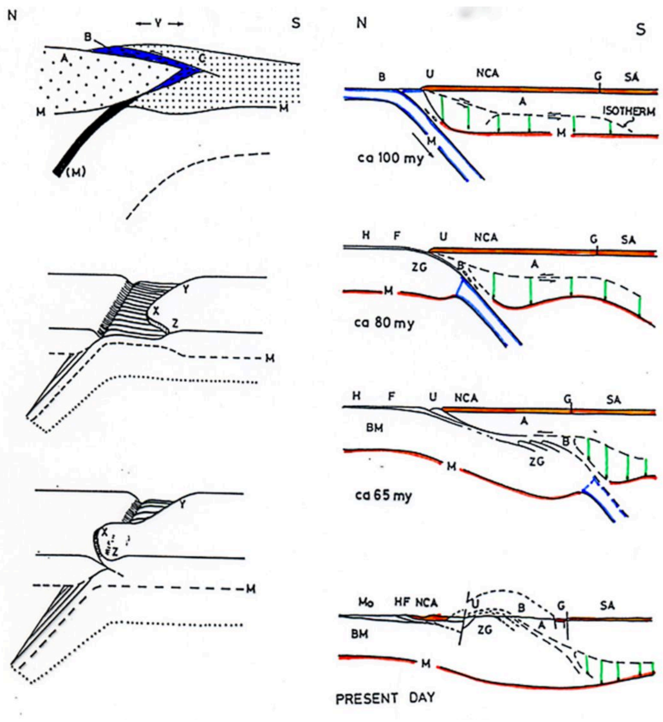
The kinematic modelling and paleostructural restoration of the Alpine nappe stack, traditionally inferred from facies analyses of cover sequences, became to be extended to deeper crustal levels, and integrated with structural, petrological and isotope data from tectono-metamorphic units. When these powerful tools to trace and date the vertical component of kinematic trajectories were properly evaluated, each evidence from metamorphic continental and ophiolitic nappes contributed to reconstruct the tectono-thermal evolution of the Western Alps (Dal Piaz *et al.*, 1972; Compagnoni & Maffeo, 1973; Bocquet, 1974; Frey *et al.*, 1974; Hunziker, 1974; Pasquarè, 1975), and the Eastern Alps, from eoalpine subduction to mesoalpine collision and thermal restoration

(Oxburgh, 1972; Oxburgh & Turcotte, 1974; Hawkesworth *et al.*, 1975; Dietrich, 1976).

Exhumation of eclogitic nappes, a recurrent matter of debate, immediately appeared more problematic than their subduction at depth. Buoyancy-dominated uplift (Ernst, 1971) or forced upward movement of imbricated slices, moving parallel to and over the still active subduction zone were hypothesized (Dal Piaz *et al.*, 1972; Hunziker, 1974). The latter mechanism was favored because surface uplift and erosion appeared inadequate to produce the required unloading, and also because the Oligocene-Miocene molasse was deposited after most of the exhumation had already been accomplished. This is demonstrated, for instance, in the Sesia-Lanzo zone, where Oligocene clastic and volcanic sequences discordantly cover the eclogitic basement units (Dal Piaz *et al.*, 1972; Sturani, 1975).

Mountain building in the Eastern Alps was interpreted with an innovative model based on flake tectonics and an unusual northward subduction of the southern plate (Oxburgh, 1972; Oxburgh & Turcotte, 1974): in this view, collisional crustal thickening was generated by a southward indentation of the European continental prong (Tauern and Bohemian massifs), wedging apart the Austroalpine nappe system and the underlying delaminated mid-lower lithosphere of the southern African plate (Fig. 11). Such possibility was soon ruled out. Crustal delamination was broadly utilized by Hawkesworth *et al.* (1975) in a kinematic model carefully accounting for the polyphase metamorphic signatures (Oxburgh & Turcotte, 1974; Bickle *et al.*, 1975). Paired metamorphic belts and a thermally-controlled delamination of the Adria upper plate were suggested, and supposedly generated by the colliding continental crust of the European lower plate: the upper crust of Adria overrides the flysch-ophiolite suture, forming the Austroalpine nappe system, whilst its mid-lower lithosphere is pushed away to the south, beneath the Southalpine domain. This reconstruction supported the Cretaceous closure of the Tethyan ocean, suggesting that major changes in the Europe-Africa movement likely occurred in the Lower Cretaceous, contemporaneously with the opening of southern Atlantic (Hawkesworth *et al.*, 1975; Fig. 11).

Figure 11. Plate tectonic models in the Eastern Alps.



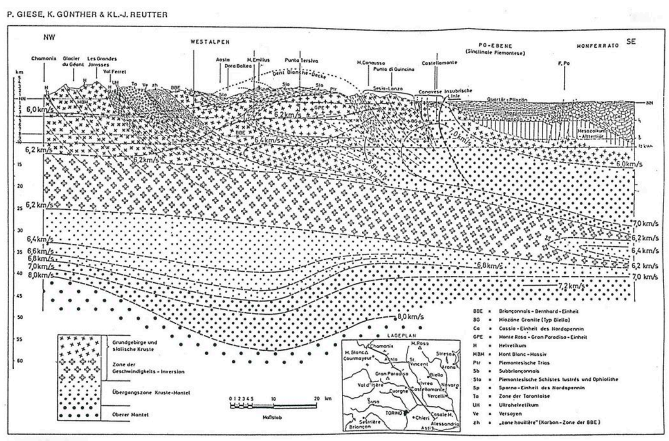
Left - Flake tectonics and northward subduction of the southern plate (Oxburgh, 1972): Bohemian massif and Tauern gneiss (A), ophiolite-bearing calcscshists (B), Austroalpine nappes (C), Moho (M), oceanic crust (black), base of northward subducting African lithosphere (dotted line).

Right - Mesozoic-Tertiary evolution of the Eastern Alps (Hawkesworth *et al.*, 1975), with continental collision and thermally-controlled delamination of the Adria upper plate: Austroalpine old basement (A), ophiolte-bearing calcschists (B), Bohemian massif (BM), flysch (F), Gailtal line (G), northern limit of Southern Alps (SA), Lower Austroalpine (U), Northern Calcareous Alps (NCA), Penninic Central gneiss inside the Tauern window (ZG), Helvetic zone (H), Molasse basin (Mo), Moho (M).

Field work and isotope dating (Borsi *et al.*, 1973, 1978; Sassi *et al.*, 1974) provided new constraints to the evolution history of the upper Austroalpine polymetamorphic basement (Mules-Merano complex, Baggio *et al.*, 1969), south of the Tauern window. The basements is subdivided in two blocks by the Deferegger-Anterselva-Valles fault (DAV), early depicted by Gb. Dal Piaz (1934) in his Carta geo-tettonica dell'Alto Adige orientale, 1: 200,000 scale: whilst the southern block displays only Variscan isotope ages, the northern one is characterized by an eoalpine (Cretaceous) overprint, as evidence of differential uplift between them (details in Mancktelow *et al.*, 2001).

At the end of the 1970s, the appeal of the new global tectonics among Alpine geologists is documented by a growing number of palinspastic and kinematic reconstructions of the collisional belt, as a whole, or of its signifcant sections, and by reviews (e.g., Dal Piaz, 1974; Closs, 1975; Debelmas, 1975, 1976; Dietrich, 1976; Dietrich & Franz, 1976; Roeder, 1976; Compagnoni *et al.*, 1977; Frisch, 1977, 1979; Bickle & Hawkesworth, 1978; Caby *et al.*, 1978; Lombardo *et al.*, 1978; Mattauer & Tapponnier, 1978; Milnes, 1978; Roeder & Bögel, 1978; Tollmann, 1978; Gosso *et al.*, 1979; Hsü, 1979).

Figure 12. One Moho below the Western Alps.



Seismic transect from Chamonix to the Po plain (Giese *et al.*, 1970), nearly parallel to the CROP-ECORS profile, showing a thickened collisional crust (55 km) that includes the high-velocity Ivrea body and is underlain by a physically continuos Moho.

A crustal downbulge in the Alpine belt had long before been recognized by classic gravity modelling and seismic surveys whilst, as previously recalled, the existence of deep roots was hypothesized by Laubscher (1969, 1970). This insight was a direct consequence of kinematic constraints imposed by a two-sided subduction model supposedly involving equal amounts of lower lithosphere of the African and European plates, both converging down towards a vertical root. The existence of Alpine roots appeared to be confirmed when a relatively dense rigid body was detected inside the asthenosphere in the internal part of the Alpine arc, through seismic surface and body waves (Panza *et al.*, 1980) or teleseismic residuals (Babusca *et al.*, 1987). It should be pointed out that, till the late 1980's, the thickened collisional crust was thought to be underlain by a unique and physically continuos Moho, extending from the foreland to the hinterland (Giese *et al.*, 1970, Fig. 12; Angenheister *et al.*, 1975; see Roure *et al.*, 1990, for review).

Towards the end of the Twentieth Century

Significant advances of theoretical and laboratory research extended their benefic effects also to the Alps, whilst new structural and petrological investigations were systematically addressed to the continental and oceanic units of the collisional belt. The geochronological data base was noticeably enlarged (SIMP, 1985; Frank *et al.*, 1987b; Hunziker *et al.*, 1992, and refs. therein). The importance of a multi-disciplinary approach for unravelling the Alpine puzzle and its tectono-thermal evolution was definitively asserted, even if only little effort was devoted to harmonically integrate these constraints with data inferred from cover sequences and geophysical soundings (and vice versa). A new Structural Model of Italy - six maps at a 1:500,000 scale - was elaborated by the Italian Geodynamic Project (CNR); sheets 1-2 (Bigi *et al.*, 1990) and 3 (Bigi *et al.*, 1993) cover the entire Alpine chain, and are discussed in the second part of the paper.

For clarity, principal advances in the last decade of the Twentieth Century are grouped in some general topics, as follows.

Tectono-metamorphic evolution

New or better calibrated petrologic estimates progressively allowed new attempts at reconstructing the kinematic trajectories followed by individual tectonic units from the ocean floor or passive continental margin to the present surface, through the subduction thermal low, subsequent collisional relaxation and related polyphase deformation. This evolution is recorded by a few P-prograde relics, generally preserved inside eclogitic garnets, the eclogitic peak and a sequence of P-retrograde mineral transformations recognized in low-strain domains from oceanic and continental nappes of the Alps (Spalla *et al.*, 1996, and refs therein). Finite strain under different P-T regimes was investigated in the eclogitic Sesia-Lanzo continental crust (Pognante *et al.*, 1980; Passchier *et al.*, 1981; Lardeaux *et al.*, 1982; Williams & Compagnoni, 1983) and other domains (e.g., Ramsay & Allison, 1979; Milnes *et al.*, 1981; Ayrton *et al.*, 1982; Choukroune & Gapais, 1983; Steck, 1984; Ring *et al.*, 1988). The displacement of individual nappes or metamorphic coherent groups of nappes became to be inferred from shear indicators and stretching lineation patterns (e.g., Malavieille *et al.*, 1984; Baird & Dewey, 1986; Choukroune *et al.*, 1986; Lacassin, 1989; Merle *et al.*, 1989; Platt *et al.*, 1989; Ratschbacher *et al.*, 1989).

Balanced cross-sections of the entire collisional crust beneath the Mont Blanc massif (Butler, 1983) won little favour (Platt, 1984), as a thick-skinned mechanism of basement faulting and ductile deformation at depth appear more appropriate than this thin thrust-sheet model. Anyway, Butler was probably the first to have figured the existence of first-order ruptures involving the Moho surface in the Alpine lithosphere.

Physical conditions of the high-P metamorphism and related P-T paths were estimated in different tectonic units of the Western Alps, locally integrated by fission track evidence on their cooling evolution, e.g.: i) Austroalpine outliers: Mt Emilius klippe (Dal Piaz *et al.*, 1983) and Etirol-Levaz slice (Kienast, 1983), evolving from the Variscan granulite-facies lower crust to nearly Tethys floor, and then from subduction to final exhumation; ii) Sesia-Lanzo zone: kinematic and thermal modelling (Rubie, 1984; Hurford & Hunziker, 1985; Oberhänsli *et al.*, 1985; Gillet *et al.*, 1986; Koons *et al.*, 1987; Pognante, 1989); iii) Zermatt-Saas, Monviso, Voltri and other eclogitic ophiolites: e.g., Baldelli *et al.*, 1985; Barnicoat & Fry, 1986; Fry & Barnicoat, 1987; Kienast & Messiga, 1987; Martin & Kienast, 1987; Nisio *et al.*, 1987; Philippot, 1988; Philippot & Kienast, 1989); iv) Monte Rosa, Gran Paradiso and Dora-Maira basement nappes (Compagnoni & Lombardo, 1974; Chopin, 1984; Dal Piaz & Lombardo, 1986; Ballèvre, 1988), where the eclogitic imprint was dated as Late Cretaceous by supposedly retentive Rb-Sr and ^{40}Ar-^{39}Ar ages (Chopin & Maluski, 1980; Monié, 1985; Monié & Chopin, 1991, and refs therein); v) contrasting metamorphic signatures within the Austroalpine-Penninic nappe stack (Kienast, 1983; Ballèvre *et al.*, 1986; Goffé & Chopin, 1986; Gillet *et al.*, 1986; Pognante *et al.*, 1987). Systematic fission track analyses and mineral dating provided new temperature-time constraints for polyphase deformation and uplift patterns in various tectonic units throughout the Alps (Hurford *et al.*, 1989; Hurford, 1991, and refs. therein). In particular, the Oligocene exhumation of the Sesia-Lanzo eclogitic complex (Dal Piaz *et al.*, 1972; Compagnoni *et al.*, 1977) was inferred also from fission track data showing that it cooled below 250-200°C by ca 33 Ma and below 100°C by ca 25 Ma (Hurford *et al.*, 1991). The Late Oligocene-Early Miocene kinematics of the Periadriatic fault system (Bigi *et al.*, 1990, 1993), coupled with backfolding and uplift of the Penninic inner zone, were quantitatively evaluated by Schmid *et al.* (1987, 1989).

Coesite was discovered first in the eclogitic continental crust of the Dora-Maira nappe (Chopin, 1984; Kienast *et al.*, 1991), then in supra-ophiolitic metacherts of the Piedmont zone (Reinecke, 1991). This finding dramatically increased the depth to which these continental and relatively light (hydrated) oceanic units were dragged down into the subduction zone, and the extent of their upward trajectories, and so further difficulties were added to the debated problem of the exhumation mechanism.

Ballèvre *et al.* (1986) stressed the different tectonothermal signature shown in the Aosta valley by two couples of continental-oceanic nappes, i.e. the lower Austroalpine outliers and Zermatt-Saas ophiolite, both eclogitic, and the overlying Dent Blanche-Mt Mary-Pillonet thrust system and Combin zone, both eclogite-free. The traditional European provenance of the Penninic units, as a whole, was maintained by Debelmas (1986), Gillet *et al.* (1986), Mattauer *et al.* (1987), confirming that the orogenic wave progressively involved more external domains of the colliding lower plate. Fry & Barnicoat (1987) envisaged subcreting eclogitic ophiolites to the overriding slab in a thermally mature subduction zone, and their preservation thanks to combining buoyant uplift and persistent refrigeration by the collisional underthrusting of cold crustal materials. In the meantime, the Lausanne team provided a systematic field survey in the southern Valais with innovative contributions on the stratigraphy and structural setting of the Piedmont zone and the Mid-Penninic Grand St Bernard system (Marthaler, 1984; Steck, 1984; Sartori, 1987; Escher, 1988); this impressive field work is synthetized in regional sections across the north-western Alps, from the core of the Simplon-Tessin window to the Dent Blanche nappe and the outer molasse (Escher *et al.*, 1988).

An extensional west-dipping mylonitic fault between the Ruitor polymetamorphic basement and its Late Paleozoic metamorphic clastic cover within the Grand St Bernard system was thought to have exhumed the eclogitic and blueschist rocks from the subduction zone through an east-vergent, tangentially extrusive wedge (Caby & Kienast, 1989).

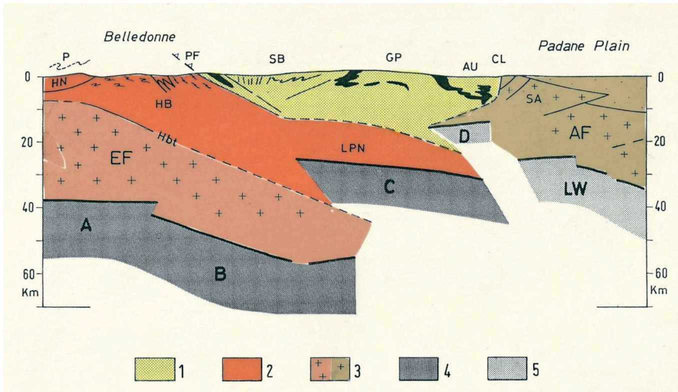
New petrologic estimates were given for basement, cover and ophiolitic units in the Central and Eastern Alps (e.g. Koller, 1985; Heinrich, 1986; Miller, 1986; Frank *et al.*, 1987; Zimmermann & Franz, 1989; Koller & Höck, 1990; and refs. therein), whereas the Alpe Arami-Cima di Gagnone garnet-peridotite and associated eclogitic ophiolites and metarodingites (Adula-Cima Lunga nappe) corroborated their international fame thanks to work of Evans and Trommsdorff team. Recognition of clastic glaucophane and lawsonite in a Late Turonian flysch unit below the Austroalpine frontal thrust near the Swiss-Austrian boundary confirmed the timing of the eoalpine subduction, and provided conclusive evidence for an early exposure of subducted ophiolites (Winkler & Bernoulli, 1986; Winkler, 1988).

The volume “Geodynamics of the Eastern Alps”, edited by Flügel & Faupl (1987), synthetizes principal results of an Austrian national research project mainly addressed to the eoalpine orogenic history in the Austrian Alps. It includes a number of analytical contributions on the Eastern Alps and two interpretative models (Tollmann, 1987; Frank, 1987). Tollmann (1987) confirmed the traditional arrangement of facies distribution at the end of the geosynclinal stage, evolving from Permian-Triassic crustal attenuation to Jurassic opening of two oceanic gateways, coupled with gravitational sliding in the Nortern Calcareous Alps. These decollement cover nappes were restored between the upper-inner Austroalpine domain and the Southern Alps, covering a basement presently buried in the Alpine infrastructure. Frank (1987) proposed a different paleogeographic restoration of the Northern Calcareous Alps, allocated along the outer Austroalpine, north of the Silvretta-Oeztal basement.

Deep structure

Systematic seismic soundings and exploration drilling in the Po plain by the Italian national petroleum company (AGIP) provided a detailed and chronologically well-constrained picture of the subsurface frontal thrust systems in the Southern Alps and northern Apennine (Pieri & Groppi, 1981). Former reconstructions of the buried Alpine infrastructure were completely renewed by the French, Italian and Swiss national projects of deep seismic sounding across the Western and Central Alps (CROP-ECORS, NFP-20, CROP-Central Alps) and by the European Geotraverse. The meeting "Deep structure of the Alps", jointly organized by the French, Italian and Swiss Geological Societies and held in Paris in December 1988, documented how profoundly these seismic experiments innovated traditional views on the deep structure of the Alps. The meeting volume, edited by Roure, Heitzmann & Polino, was issued in 1990. The most innovative result of the CROP-ECORS experiment was the recognition of a principal rupture within the Moho discontinuity instead of a continuous downbulge, or a not actualistic double subduction, so that the role of Adria as leading lithospheric plate and of Europe as subducting lower lithospheric plate was firmly established (Thouvenot *et al.*, 1990; Polino *et al.*, 1990; Fig. 13).

Figure 13. Two Moho surfaces in the core of the Western Alps.



Geological interpretation of crustal image from wide angle and vertical seismic reflection experiments, CROP-ECORS transect (Polino *et al.*, 1990): 1) remnants of Austroalpine-Penninic wedge, including Austroalpine (AU), ophiolitic (black), Gran Paradiso (GP), Grand St Bernard (SB) nappes; 2) deformed European passive margin: Helvetic-Ultraelvetic basement (HB) and cover nappes (HN), Lower Penninic nappe (LPN); 3) European foreland and its prolongation at depth (EF); 4) uplifted and back-thrusted crust of the Southern Alps (SA) and Adriatic foreland (AF). Canavese line (CL), Penninic frontal thrust (PF), Helvetic basal thrust (HbT), Prealpine nappes (P). Moho ruptures marked by European (A-B-C) and overlying Adriatic (LW) lithospheric mantle.

The seismic image well accounts also for a still ongoing indentation of the Southalpine prong into the back of the orogenic wedge, and for asymmetry of the collisional plate margin at a lithospheric scale. Similar Moho ruptures were found in the Swiss (NFP-20: Pfiffner *et al.*, 1997) and Central Italian Alps (CROP-Alpi Centrali: Montrasio & Sciesa, 1994). The CROP Atlas, edited by Scrocca *et al.* (2003), includes the entire seismic data-set acquired during the CROP Project. Further geophysical experiments, their geological interpretation and overall reviews may be found in the special volumes on the European Geotraverse (Freemann *et al.*, 1990; Pfiffner *et al.*, 1990; Blundell *et al.*, 1992, Capozzi & Castellarin, 1992, Schmid *et al.*, 1994). I have drawn for this project the geological map of the Apennine and also that of the Italian part of the Alps, reported as made by another author.

Exhumation and wedge accretion

The problem of bringing deeply subducted continental and oceanic units to shallow crustal levels was thoroughly re-evaluated, whilst extensional tectonics became relevant as a tool to control or facilitate the exhuming processes (reviews in Platt, 1992; Ballèvre & Merle, 1993; Michard *et al.*, 1993). These efforts produced a second-generation of kinematic models, some of them clearly influenced by exploration and modelling of modern accreting plate margins (details and refs. in Polino *et al.*, 1990). The existence of a pre-collisional accretionary complex in the Alps, early figured by Roeder & Bögel (1978), was taken up by Treves (1984) who compared the so-called root zone (steep belt by Milnes, 1978; Milnes *et al.*, 1981) to the inner sector of a modern tectonic wedge. A mechanism of upward flow (Pavlis & Bruhn, 1983) was thought to have assisted the uplift of subducted units, whereas a corner flow was favored by Winkler & Bernoulli (1986) in the Central Alps to generate the outer Penninic flysch prism and related ophiolitic detrital components.

An elegant underplating-wedge extension model under active convergence was proposed by Platt (1986, 1987) and then developed by Polino *et al.* (1990) with a different paleogeographic configuration of the intervening plates. The subduction-related high-P basement nappes were referred either to intra-oceanic microcontinents with European affinity (Platt, 1986), or to small fragments of the Adria active margin (Polino *et al.*, 1990).

Extension during Eocene active convergence was suggested by Philippot (1988, 1990) in the axial-internal part of the Cottian Alps, where a stack of mafic eclogites (Monviso-Rocciavrè), coesite-bearing and eclogitic basement slices (Brossasco-Isasca complex, Dora-Maira; Kienast *et al.*, 1990) and other lesser buried units are exposed. Continuous underthrusting of the colliding European lithosphere provided rapid uplift of the orogenic wedge, through concurrent development of synthetic and antythetic features and thrust-parallel low-angle normal faults. This was an alternative view to the classic twofold model of late-Alpine back-thrusting, a ductile to brittle deformation developed over the previous west-directed nappe stacking (e.g., Caby *et al.*, 1978; Ballèvre *et al.*, 1986). Neoalpine unroofing of the Lower Penninic nappes in the Simplon-Tessin area was assisted by the extensional low-angle Simplon fault (Mancktelow, 1985). A deep wedge was depicted by Hsü (1991), who still maintained the Briançonnais microcontinent and the Valais basin, even if no trace of the latter exists along the assumed Dora-Maira latitude, and referred the exhumation process to a persistent continent-ocean interaction, generating a tectonic melange at the plate boundary.

In the Eastern Alps, a pre-collisional sedimentary wedge of Eoalpine age and its collisional evolution were envisaged to explain the Matrei mixing zone and underlying Mesozoic calcschists at the tectonic boundary between the Tauern basement nappes and the Austroalpine leading edge (Frisch *et al.*, 1987). On the basis of structural, strain and kinematic data, the Arosa zone at the Austroalpine/Penninic boundary was interpreted as an upper unit of the Cretaceous-Paleocene orogenic wedge, generated by concurrent offscraping of the Austroalpine hangingwall and accretion of oceanic material with greenschist to very low-grade imprint; a rather continuous change in tectonic transport from top-to-the west into top-to-the north across the Cretaceous-Tertiary boundary and successive accretion of Penninic units during outward propagation of deformation were clearly documented (Ring *et al.*, 1988, 1989, 1990).

The generation of the Tauern window was adscribed to long-lived orogen-parallel extension of the Austroalpine orogenic lid, during active plate convergence, coupled with transversal shortening and doming of the Penninic basement nappes (Selverstone, 1985, 1988). The Tauern window is laterally limited by the antythetic Brenner and Katschberg normal faults (e.g., Fügenschuh *et al.*, 1997; Genser & Neubauer 1989). This orogen-parallel extension and tectonic denudation developed in a late collisional stage and was accomodated by two-sided lateral extrusion of continental blocks (Ratschbacher *et al.*, 1989, 1991). So, the traditional concept of alternating tensional and compressional episodes was ultimately abandoned, since active convergence actually persisted from the Cretaceous onwards (Dewey *et al.* 1989, and refs. therein).

Paleogeography and plate kinematics

The principal lithologies of modern oceans have been recognized in the Aosta valley-Valais area, internal Cottian Alps, Voltri Group and elsewhere throughout the Alps, showing mineral, isotope and geochemical evidence of ocean-floor igneous and hydrothermal activity (Mével *et al.*, 1978; Dal Piaz *et al.*, 1979, 1981; Bearth & Stern, 1979; Beccaluva *et al.*, 1984; Pfeifer *et al.*, 1989; Barnicoat & Cartwright, 1995; Cartwright & Barnicoat, 1999). In spite of this, the dominant stratigraphic setting can hardly be representative of a normal oceanic lithosphere because of: i) reduced overall thickness; ii) local absence of gabbros and/or basalts; iii) presence of abundant ophicarbonate breccias on top of serpentinized mantle peridotites, and of Jurassic metasediments with ultramafic detritus, or Mn-rich metacherts directly over serpentinites (Dal Piaz, 1969; Baldelli *et al.*, 1983; Martin *et al.*, 1994), indicating submarine mantle exposure before basalt extrusion. A sheeted dyke complex is missing everywhere, but some large fragments of serpentinized mantle peridotite that include hundreds and often thousands of iso-oriented rodingitic gabbro dykes may represent the remnants of a lithospheric-scale spreading center (e.g., Monte Rosso-Rocca di Verra and Mt Avic in the Aosta valley, Totalp and Oberhalbstein in Swiss Central Alps). Spalla *et al.* (1983) provided a detailed reconstruction of the folded contact between the Austroalpine Sesia-Lanzo inlier and the Lanzo ultramafic massif, and correlated the latter to the internal eclogitic unit (Zermatt-Saas) of the Piedmont zone.

Doubts were raised on the paleostructural meaning of the so-called ophiolitic sutures (e.g., Hawkesworth *et al.*, 1975; Caron *et al.*, 1987; Polino *et al.*, 1990), since extensive transposition and out-of-sequence resetting were generated by selective offscraping of ophiolitic units from oceanic morpho-tectonic highs, rootless folding of imbricated nappes within the subduction complex, ductile exhumation and differential uplift by extensional detachments. Other doubts concerned the original allocation of the Austroalpine and Penninic nappes presently surrounded by ophiolitic units. The popular assumption of lithospheric microcontinents and narrow oceanic seaways can hardly explain the continuing subduction and rapid exhumation of high-P units without periodical obstructions, and the growing of the orogenic wedge itself, including basement nappes which seldom exceed 1-2 kilometres in thickness (Polino *et al.*, 1990). Moreover, the huge amount of residual crust resulting from alleged collisional delamination of microcontinents must be stored in the orogenic roots or recycled into the mantle, but the expected anatectic melts are missing and it is unlikely that the mantle was energetic enough to recycle the crustal excess. Lastly, the minimum wavelength needed for multiple generation of rift-derived oceans alternating with microcontinents (400 km; Jolivet, 1995) implies an Alpine Tethys much wider than it probably was.

A renewed interest was directed towards the problems and global reconstruction of the Mediterranean area, i.e. motion of Africa relative to Europe, paleomagnetic and biostratigraphic constraints, palinspastic refinements of Tethys oceans, passive continental margins and intervening microcontinents, and the debated connection with the Atlantic spreading (e.g., Winterer & Bosellini, 1981; Frisch, 1981; Patriat *et al.*, 1982; Savostin *et al.*, 1986; Westphal *et al.*, 1986; Abbate *et al.*, 1988; Ziegler 1988; Dal Piaz & Polino, 1989; Dewey *et al.*, 1989; Platt *et al.*, 1989; Dercourt *et al.*, 1990). Classic models on relative plate motion and generation of the Alpine belt by northward movement of Africa against Europe from the “mid” Cretaceous (90-80 Ma) onwards were confirmed (e.g., Olivet *et al.*, 1984; Savostin *et al.*, 1986; Dewey *et al.*, 1989), or replaced with a dominantly NW- or WNW-directed convergence supported by kinematic indicators in major Alpine nappe systems (Baird & Dewey, 1986; Platt *et al.*, 1989).

The Lower Jurassic-Cretaceous (190-90 Ma) sinistral movement between Africa and Europe was emphasized in actualistic reconstructions accounting for the opening of the Alpine-Apenninic (Piedmont-Ligurian) ocean, a northern segment of the Mid-Atlantic ridge displaced eastwards by the Newfoundland-Gibraltar transform system. Moreover, since some ophiolitic gabbros of the Alpine-Apenninic ranges yielded Late Triassic-Early Jurassic fission-track ages (Carpena & Caby, 1984), the onset of spreading in the Piedmont-Ligurian basin was thought to have developed independently from and before the central Atlantic opening and Africa-Europe strike-slip motion (e.g., Abbate *et al.*, 1988). This is the case, however, only of pre-Jurassic gabbros that were generated and deformed during continental rifting (Lombardo & Pognante, 1982; Dal Piaz & Polino, 1989), opposite to

Jurassic ridge-derived Mg- and Fe-Ti-gabbro bodies. These views anticipate simple-shear rifting reconstructions in which the early stage of ocean opening was supposedly generated by asymmetric extensional denudation of the subcontinental mantle and related pre-oceanic gabbros, as predicted by Elter (1972), postulated by Lemoine *et al.* (1987) and then corroborated by Vissers *et al.* (1991) and other authors. Such a model, however, is contrasted by some gabbros actually generated and deformed during continental rifting (Lombardo & Pognante, 1982; Dal Piaz & Polino, 1989). These views anticipate simple-shear rifting reconstructions in which the early stage of ocean opening was supposedly generated by asymmetric extensional denudation of the subcontinental mantle and related pre-oceanic gabbros, as postulated by Lemoine *et al.* (1987) and then corroborated by Vissers *et al.* (1991) and other authors.

The puzzle of western Tethys in the Alpine domain noticeably benefited from actualistic comparisons and detailed stratigraphic analyses in the Piedmont-Penninic ophiolites. As in the Ligurian nappes (Abbate *et al.*, 1988), rather atypical ophiolitic associations with respect to the normal oceanic lithosphere were extensively recognized in the Alps: they consist of serpentinized mantle peridotite and/or discontinuos metagabbro bodies, directly covered by metamorphic ophiolitic sandstones, breccias or melange, in turn followed by tholeiitic metabasalts (locally absent), manganiferous quartzites (cherts) and other oceanic metasediments. Traces of a high-T oceanic metamorphism are scatterly preserved (Mevel *et al.*, 1978), but a diffuse low-grade oceanic alteration is indirectly documented by geochemical and mineral data from eclogitic to greenschist facies metabasalts derived from protoliths enriched in Na and OH. Inferred paleostructural settings were thus compared with fracture zones and various types of topographic elevations in modern oceans (Lombardo & Pognante, 1982; Auzende *et al.*, 1983; Beccaluva *et al.*, 1984; Lagabrielle *et al.*, 1984; Lemoine, 1984; Polino & Lemoine, 1984; Weissert & Bernoulli, 1985; Lagabrielle, 1987; Dal Piaz & Polino, 1989). The Piedmont-Ligurian ophiolites were genetically connnected to these paleostructures, thought to be selectively scraped off the oceanic lithosphere when they entered the subduction zone, were sliced and later exhumed through the orogenic wedge (see Polino *et al.*, 1990, for details and refs.). Accordingly, the original width of the ocean cannot be inferred from the extent of Alpine ophiolitic remnants, as an unknown amount of oceanic lithosphere was definitively subducted. This casts doubts on the traditional view of a very small Piedmont ocean. Indeed, the existence of a relatively larger Alpine ocean is favored by the long-lasting (ca 40 Ma) subduction-induced thermal low recorded by the Austroalpine and Penninic units with high-P imprint (Polino *et al.*, 1990; Dal Piaz, 1999). A minimum width of 300-400 km in the Piedmont-Ligurian ocean may be predicted if, in the Late Jurassic, Adria moved bodily with Africa (Abbate *et al.*, 1988).

It has been generally accepted that the Ligurian-Piedmont basin in the Apennine and western Alpine domain represented a unique ocean of Mid-Late Jurassic age, as documented by radiolarian cherts of Callovian-Oxfordian age (De Wever *et al.*, 1987, and refs. therein) and isotope dating (see Manatschal & Münterer, 2009, for review). Its NE-trend was depicted in most regional reconstructions (e.g., Dal Piaz, 1974; Winterer & Bosellini, 1981; Beccaluva *et al.*, 1984; Lemoine *et al.*, 1987; Abbate *et al.*, 1988; Dal Piaz & Polino, 1989; and refs. therein). North of the French-Italian Alps, the Piedmont ocean was thought to be bounded by an east-west-trending shear zone, extending along the Swiss-Austrian Alps and Northern Carpathians: in the Late Jurassic the shear zone functioned as a left-lateral transform system, displacing a few short ridge segments eastwards and/or initiating some Penninic transtensional basins discontinuously floored by oceanic crust (Winterer & Bosellini, 1981; Beccaluva *et al.*, 1984; Bernoulli & Weissert, 1985; Weissert & Bernoulli, 1985; Winkler & Bernoulli, 1986; Trümpy, 1988; Schmid *et al.*, 1990). This reconstruction may replace the classic paired North- and South-Penninic oceanic gateways along the Swiss-Austrian Alps, a model that, however, continues to be supported (e.g., Tollmann, 1989; Dercourt *et al.*, 1990; Thöni & Jagoutz, 1992, 1993). It does contrast also with the ENE-trending linear configuration of the Piedmon-Liguria ocean (Ziegler, 1988) and its orthogonal spreading (Dercourt *et al.*, 1990). The northern shear zone could have functioned as a kinematic connection between spreading in the Piedmont-Ligurian ocean and consumption in the older Meliata-North Vardar ocean from the Mid-Late Jurassic onwards: the opening of the former was coeval with, and probably balanced by, the closure of the latter in the Carpathian domain.

In the western Southern Alps, extensional detachments, marked by high- to mid-grade mylonites, were recognized within the pre-Alpine lower crust of the Ivrea-Verbano zone, representing the deepest signature of the Mesozoic continental rifting now exposed in the Alpine realm (Hodges & Fountain, 1984; Brodie & Rutter, 1987; Handy & Zingg, 1991, and refs. therein). This record was the structural ground for new directions on the thermal-mechanical evolution of the Ivrea zone, based on simple-shear lithosphere attenuation and igneous underplating (details in the second part of the paper). In conclusion, the Mesozoic continental rifting was established in different structural settings of the Southern Alps (Bertotti *et al.*, 1993, and refs. therein) and in other more fragmented segments of the Adria and Europe margins. Nevertheless, it can be historically interesting to recall that there was also a contrasting interpretation of the Middle-Triassic calc-alkaline magmatism in the Dolomites: alleged implications from the subduction-related geochemical affinity and local recognition of epidermic compressional features were believed to support the existence of a rapidly aborted Triassic orogeny also in the Southern Alps (Castellarin & Rossi, 1981; Bosellini *et al.*, 1982).

Orogenic models

Contrasting paleostructural and kinematic models were elaborated by Hunziker *et al.* (1989) and Polino *et al.* (1990), starting from the intriguing Late Cretaceous age of the subduction metamorphism in the Monte Rosa and other inner Penninic nappes, and their traditional restoration in the distal continental margin of Europe. Indeed, as previously mentioned, an eoalpine age had been early envisaged also for the eclogitic imprint in the whole inner Penninic nappes (Dal Piaz *et al.*, 1972), by extrapolation of Cretaceous-Paleocene K-Ar and Rb-Sr ages of white micas (90-53 Ma) regionally obtained in the eclogitic Sesia-Lanzo zone (Hunziker, 1974) and underlying Piedmont ophiolitic units (Bocquet *et al.*, 1974). This hypothesis was corroborated by Cretaceous ^{40}Ar-^{39}Ar dating, systematically obtained on high-P micas from the Gran Paradiso (Chopin & Malusky, 1978, 1980), Monte Rosa (Chopin & Monié, 1984; Paquette *et al.*, 1989) and Dora-Maira (Monié & Chopin, 1991) nappes. Interference patterns demonstrate that the high-P fabrics are overprinted by the Late Eocene-Early Oligocene (mesoalpine) greenschist to amphibolite facies metamorphism (Hunziker, 1974; Monié, 1985; Hunziker *et al.*, 1992). In conclusion, the problem of excess argon was underestimated and the existence of a subduction metamorphism of eoalpine age wholly across the Austroalpine-Pennidic collisional zone appeared to be established. In this view, however, the alleged Late Cretaceous age of the eclogitic imprint in the European distal passive margin (upper-inner Penninic nappes) was incompatible with the evolution of the Ligurian-Piedmont ocean, which was still open at that time, as documented by deposition of trench sediments.

This inconsistency was tackled by Hunziker *et al.* (1989) and Polino *et al.* (1990) through alternative paleostructural scenarios, suggesting that the high-P Penninic nappes could have been wholly allocated in the frontal active margin and scraped off its underside by tectonic erosion, a mechanism favoured also by Hsü (1991). Tectonic sampling of continental fragments from the previously dismembered and then inverted Adria passive margin was supposedly generated by topographic highs (indenters) on the ocean floor when they entered the subduction gateway (Polino *et al.*, 1990). This view avoided the problem of the Piedmont basin, but at the cost of an extreme resetting of classic paleogeography, as most units of the Penninic zone were removed from the European passive margin and allocated to the Adriatic one. A similar restoration was envisaged for the Monte Rosa domain also by Laubscher & Bernoulli (1982). Starting from this paleostructural setting, an even more complex tectonic mixing of continental and oceanic nappes by rootless folding and ductile shearing was assumed for generating the present structure of the collisional wedge.

Paired subduction zones inside a single ocean or of multiple oceanic branches were proposed by Radelli & Desmons (1987), Avigad *et al.* (1993), Michard *et al.* (1993). In particular, Avigad *et al.* (1993) again supported the classic provenance of the Dora Maira and other inner Penninic eclogitic nappes from the European passive margin, and supposed that these units were subducted beneath the Piedmont oceanic lithosphere, in turn consuming at the Adria margin, where a precollisional orogenic wedge (including the Sesia-Lanzo zone) was growing. As the Piedmont ocean was completely consumed, the subduction zone in the European side met the precollisional wedge at the opposite Adriatic side, generating an overthickened collisional wedge. From the Late Cretaceous onwards, extensional collapse and uplift of this gravitationally instable megasuture facilitated the Eocene collisional subduction of the Briançonnais domain which is recorded by a blueschist facies metamorphism. The Monte Rosa and Dora Maira nappes were restored in the European margin by Pfiffner (1992) and Avigad *et al.* (1993), whereas the Gran Paradiso nappe was allocated together with the Sesia-Lanzo zone along the Adriatic margin, in spite of the identical lithology, tectono-metamorphic features and structural position recorded by the Monte Rosa and Gran Paradiso basements.

The kinematic evolution of the Western Alps was tackled again by Ballèvre & Merle (1993) and Wheeler & Butler (1993), mainly dealing with extensional tectonics and exhumation of coesite-bearing and eclogite facies units from the subduction zone. Ballèvre & Merle (1993) envisaged the collisional stacking of Adriatic and Piedmont units over the European margin during the Lower-“mid” Cretaceous, followed by the activity of a late-eoalpine (90-60 Ma) crustal detachment, named Combin fault; this extensional event displaced the leading nappes toward the south-east, allowing the high-P units to be exhumed. Wheeler & Butler (1993) suggested the extensional displacement, to the south-east, of the Sesia-Lanzo basement with respect to the underlying ophiolitic Combin unit in the Ayas-Gressoney area (Aosta valley). It can be noted, however, that both units display the same polyphase imprint and an eventual unroofing detachment could better be located at a lower structural level, along the Combin/Zermatt-Saas tectonic contact which marks a first-rank metamorphic and chronological gap (Ballèvre & Merle, 1993; Dal Piaz, 1999; Dal Piaz *et al.*, 2001; De Giusti *et al.*, 2004). To sum up, most of Alpine Tethys reconstructions envisaged one or more microcontinents alternating with a number of oceanic channels (Piedmont and Valais ± Antrona ± Platta or Ligurian), merely inferred from the occurrence of three to four ophiolite-bearing structural levels within the orogenic wedge (e.g., Elter & Pertusati, 1973; Pasquarè, 1975; Trümpy, 1980; Platt, 1986; Mattauer *et al.*, 1987; Pfiffner, 1992; Ring, 1992). These reconstructions were essentially inferred from the implicit assumption that, during the orogeny, the paleogeographic domains were converted into a pile of nappes, the superposition of which wholly replicates their originally lateral juxtaposition as in Argand’s fold-nappe model.

Conceptual models of rifting and continental margins were critically discussed by Stampfli *et al.* (1991). Two rifting types of Mesozoic Tethys (Neotethys) were recognized: i) a Greece-Turkey system genetically connected eastwards to the Permian Tethys, with ocean spreading delayed until Middle Triassic; ii) an Alpine system, genetically linked to the opening of the central Atlantic and characterized by a Late Triassic transtensive phase, an Early-Middle Liassic break-away phase, and a Middle-Late Jurassic ocean spreading. In addition, Stampfli (1993) elaborated an innovative reconstruction of the Briançonnais (Grand St Bernard) domain. It was envisaged as an exotic terrane, formerly belonging to the European continental margin and then displaced eastwards during the Late Jurassic-“mid” Cretaceous drifting of Iberia, a process that in turn allowed the Cretaceous opening of the Valais ocean and the coeval closure of the Piedmont ocean. The resulting oblique collision between the Briançonnais microcontinent and the Adria margin supposedly generated the Cretaceous high-P metamorphism, whereas the westward thrusting of the Briançonnais over the European margin was the early Tertiary result of consumption of the Valais basin. As discussed in Dal Piaz (1999), this creative model does not account, however, for the absence of significant ophiolitic remnants along the Penninic/Helvetic boundary in the French-Italian Alps, where Stampfli’s southward extension of the Valais ocean should have been sutured.

In the Central Alps, the polyphase tectono-metamorphic evolution of the Shams and Tambo nappes and some N-Penninic ophiolitic units were investigated (Schmid *et al.*, 1990; Schreurs, 1993; Baudin & Marquer, 1993). Whilst previous strike-slip-dominated reconstructions of the Piedmont-Ligurian (S-Penninic) ocean in the central Alps were confirmed (e.g., Beccaluva *et al.*, 1984; Weissert & Bernoulli, 1985), opening of the Valais (N-Penninic) basin and its westward narrowing were noticeably innovated, suggesting that it developed within a left-lateral mega-shear zone. In particular, the Valais trough was extended to the Tauern domain, according to current Austrian views (e.g., Ring, 1992; Thöni & Jagoutz, 1993), the Suretta nappe was coupled with Tambo, forming an intra-oceanic eastwards extension of the Briançonnais high, characterized by high-P relics (Baudin & Marquer, 1993), and the eclogitic Adula nappe (Heinrich, 1986) was allocated in a very external position, near the Helvetic domain. The timing of the eclogitic metamorphism in the Adula nappe (Hunziker *et al.*, 1989) and the mechanism of its exhumation are enigmatic in this paleogeographic scenario, both related to the Oligocene-Neogene accretion of the Helvetic foreland. An Oligocene subduction of the N-Penninic ocean was supposedly corroborated by a zircon age (28.5 Ma) from the garnet-peridotite/eclogite association of the Adula-Cima Lunga nappe (Gebauer *et al.*, 1992). The geological meaning of this age is doubtful, since the eclogitic stage was followed by the Eocene-Lower Oligocene Barrovian overprint (Frey *et al.*, 1974), the Oligocene intrusion of the Bergell pluton and its erosion during the deposition of Upper Oligocene Gonfolite. Recent Sm-Nd dating of the same mafic-ultramafic association in the Adula-Cima Lunga nappe yielded more consistent mineral ages at around 40 Ma, rightly thought to be cooling ages that probably approximate the eclogite facies climax (Becker, 1993).

The geodynamic evolution of Pennine nappe stack in the eastern Central Alps was refined through thermobarometric and kinematic data (Ring, 1992), whilst interaction between deformation and metamorphic processes (Selverstone, 1993), thermal history and heterogeneous uplift (Reddy *et al.*, 1993) were estimated in the Tauern window. Updated reviews of pre-Mesozoic geology, radiometric dating, tectono-thermal evolution and kinematics in the Eastern Alps, particularly concerning the Austroalpine nappe system, was reported in the ALCAPA Field Guide (Neubauer, 1992).

The intrusion, thermal metamorphism and ductile deformation of the Oligocene Bergell pluton developed during contraction of the Central Alps, before the Neogene transpression of Periadriatic fault system, as accurately investigated by Rosemberg *et al.* (1994) and Berger *et al.* (1996), developing a topic previously described by Wenk (1973) and Conforto-Galli et al. (1988). The tectono-magmatic evolution of some sheeted intrusions (lamellae) along a proto-Giudicarie fault was described by Martin *et al.* (1993), as evidence of Late Oligocene ductile deformations during the strike-slip movement of the Tonale-Giudicarie fault system.

Extended reviews of the first twenty-five years of plate tectonics in the Alps and elsewhere are reported in the proceedings of the VIII Summer School, University of Siena, edited by Giorgio Ranalli (1995). In the last decade of the Twentieth Century the essential headlines of plate tectonics have not been significantly modified their influence on Alpine geology, continuing to provide a solid framework for refinement of classic interpretations or provocative views based on further geological, geophysical and petrological advances. Among them, overall plate kinematics was renewed envisaging a global westward drift of the lithosphere coupled with relative eastward counterflow of the asthenosphere (Doglioni, 1990). The model and its development well account for differing features of present and past opposite-vergent subduction zones, related foredeeps, accretionary wedges and thrust belts, particularly regarding the Alpine and Apennine domains (Doglioni, 1992, 1994; Doglioni *et al.*, 1997, 1999).

Geochronology: innovation and inferences

The Alpine overprint in the Eastern Austroalpine is documented by post-Variscan cover metasediments and had been dated as eoalpine (100-70 Ma) also in the crystalline basement (Thöni, 1999, and refs therein). Its ranges from very low-grade (Silvretta and northern Oetztal) to greenschist, amphibolite (staurolite-kyanite, southern Oetztal), and local eclogite facies conditions in mafic rocks (Frey *et al.*, 1999). Far to the east, in the Koralpe-Saualpe (Koriden) country - the type locality of eclogite (Godard, 2001) - two main basement units with contrasting metamorphic features were recognized and re-interpreted through innovative dating. The former, also occurring in the Pohorje ranges, consists of kyanite-rich paragneisses with abundant bodies of fresch to amphibolitised eclogite from basalt and gabbro protoliths of Permian age (Thöni & Jagoutz, 1992, 1993; Miller & Thöni, 1997; Thöni & Miller, 1996), manganiferous quartzites, marbles, calc-silicate rocks and pegmatites; its subduction metamorphism is eoalpine, effacing most of previous low-P (andalusite) features. The latter and overlying complex (micaschist group), including the ophiolite-bearing Plankogel unit, is characterized by an eoalpine medium-grade overprint.

In the Western Alps the subduction metamorphism was formerly referred to a single orogenic event of Cretaceous-Paleocene age (90-53 Ma), called eoalpine, as supposedly established by K-Ar, ^{40}Ar-^{39}Ar and minor Rb-Sr data (Hunziker, 1974; Bocquet *et al.*, 1974; Hunziker *et al.* 1992). As previously seen, this dating strongly influenced the paleostructural reconstructions of Alpine Tethys and its orogenic contraction (Dal Piaz *et al.* 1972; Dal Piaz, 1994, 1995; Avigad *et al.*, 1993; Michard *et al.*, 1993, 1996). In the secon half of 1990s, the age of subduction metamorphism was re-considered thanks to new dating on retentive systems (Gebauer, 1999, and Thöni, 1999, for reviews) and recognition of excess Argon in micas previously dated as eoalpine (Arnaud & Kelley 1995; Reddy *et al.* 1996; Ruffet *et al.* 1997). Hence, the eoalpine high-P event was consistently restricted to the Austroalpine by Late Cretaceous ages obtained in the Sesia-Lanzo zone (Ramsbotham *et al.* 1994; Venturini, 1995; Inger *et al.* 1996; Duchêne *et al.* 1997; Rubatto *et al.*, 1999). Similar ages clustering around 74 Ma were obtained also in the Austroalpine Pillonet klippe by coherent ^{40}Ar-^{39}Ar and Rb-Sr data on phengitic micas coexisting with glaucophane-crossite (Cortiana *et al.*, 1998).

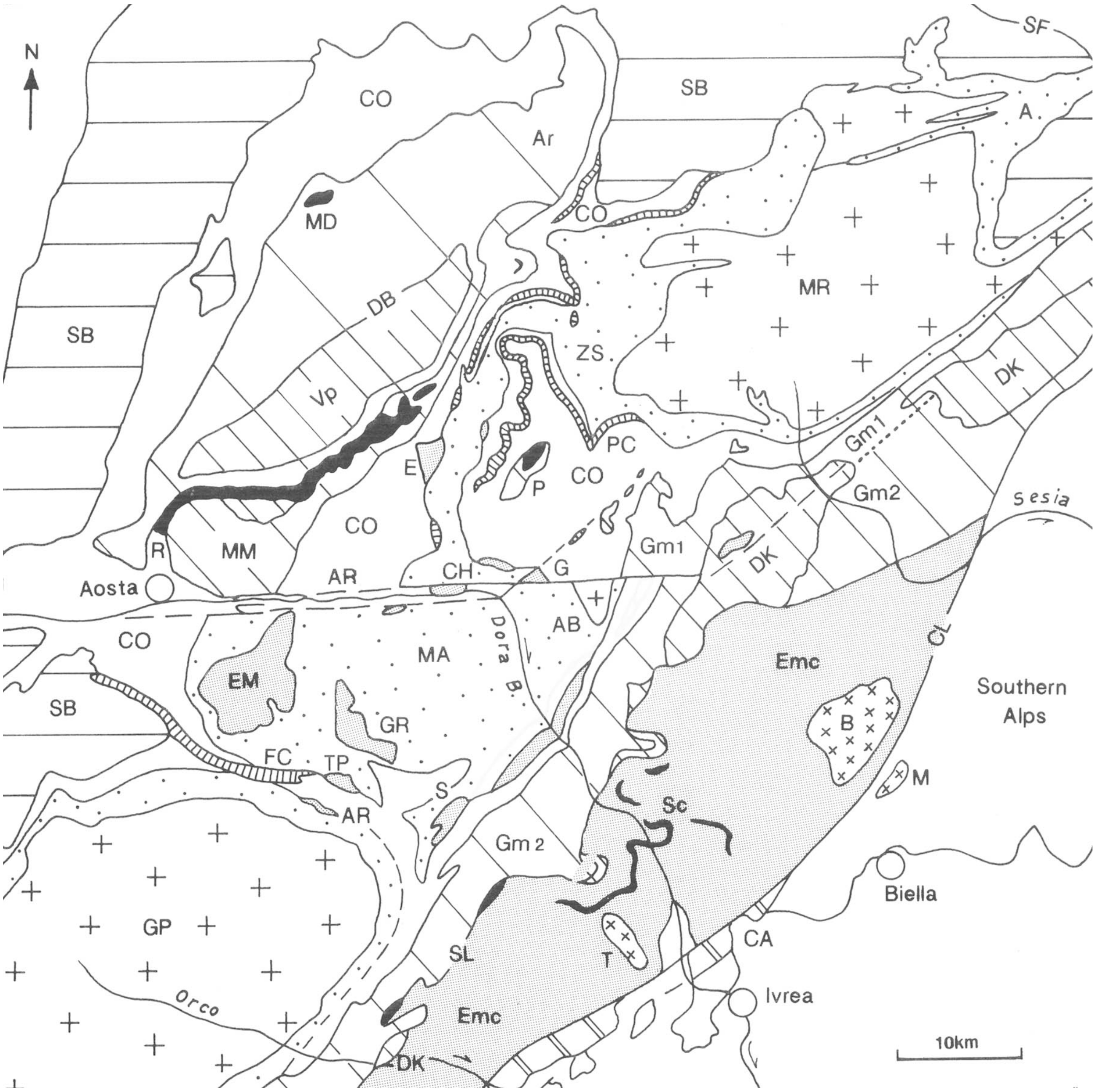
Conversely, the subduction metamorphism in the classic area of the Zermatt-Saas nappe (Valais-northern Aosta valley) was rejuvenated to the Early-Middle Eocene, based on dating of mafic eclogites from Zermatt (Bowtell *et al.* 1994, Sm-Nd: 50 ± 18 Ma) and St Jacques (Mayer *et al.* 1999, Sm-Nd: 49 ± 4 Ma, Rb-Sr: 46 Ma), and UHP metachert-eclogite couple of Cignana lake (Rubatto *et al.* 1998, U-Pb: 44.5 ± 2.3, 43.9 ± 0.9 Ma; Amato *et al.* 1999, Sm-Nd: 40.6 ± 2.6 Ma). Similar ages were obtained in the Monviso ophiolite (Monié & Philippot, 1989; Duchêne *et al.*, 1997; Cliff *et al.*, 1998; Rubatto *et al.*, 1998), and later in the Mt Avic massif, the southern extension of the Zermatt-Saas nappe south of the Aosta-Ranzola fault system (Dal Piaz *et al.*, 2001; Beltrando *et al.*, 2009). Furtermore, the Cretaceous ^{40}Ar-^{39}Ar ages obtained in the Monte Rosa and Gran Paradiso basement (Chopin & Maluski, 1980; Chopin & Monié, 1984; Monié, 1985) were supposed to be influenced by excess Argon, like those in the coesite-bearing Dora-Maira nappe (Arnaud & Kelley, 1995) which underwnt ultrahigh-P metamorphism in the Late Eocene (Tilton *et al.*, 1989, 1991; Gebauer *et al.*, 1995). The expected Eocene age of the eclogitic metamorphism in the Gran Paradiso and Monte Rosa nappes will be established ten years later, by Meffan *et al.* (2004), Lapen *et al.* (2007) and Gabudianu Radulescu *et al.* (2009), like in the Adula-Cima Lunga nappe (Becker, 1993: 44-35 Ma).

To sum up, an Eocene age has been documented for the subduction metamorphism in the Penninic continental and ophiolitic units, by extrapolation of available data throughout the Alps (e.g. Blankenburg & Davies, 1995; Froitzheim & Manatschal, 1996; Michard *et al.*, 1996; Schmid *et al.*, 1996, 1997). Even if the Eocene ages obtained in the Piedmont zone concern only the Zermatt-Saas nappe and similar units, the main chronological obstacle to the classic restoration of the Penninic continental nappes in respect with the Piedmont basin was finally overcame.

In this view, a new reconstruction of the Western Austroalpine and Piedmont units and their restoration back to the initial configuratin of Mesozoic Tethys were conceived by Ballèvre *et al.* (1986), corroborated by Cortiana *et al.* (1998) and refined by Dal Piaz (1999), Dal Piaz *et al.* (2001), Bistacchi *et al.* (2001), focusing on the multiple alternances of Austroalpine and Piedmont units in the structural depression of the Aosta valley and their significance. This reconstruction is based on the present geometry of the nappe pile, new isotope chronology of the Late Cretaceous-Eocene subduction metamorphism, and the existence of extensional allochthons instead of lithospheric microcontinents (Fig. 14). The starting point was an innovative subdivision of the Austroalpine-Piedmont nappe stack inferred from the correlation of the intra-ophiolitic northern Austroalpine outliers (Etirol-Levaz, Grun, Chatillon-St Vincent) with the southern Austroalpine outliers (Mt Emilius, Glacier-Rafray, Tour Ponton, Santanel, Verres), all eclogitic and located respectively north (hangingwall) and south (footwall) of the north-dipping Aosta-Ranzola normal fault (Fig. 14). This does mean that the overlying Combin zone could formerly extend southwards over the Mt Emilius klippe, but clearly below the Sesia-Lanzo frontal thrust. In this view, the Austroalpine outliers (Dent Blanche nappe s.l.) and Piedmont ophiolitic units can be subdivided into two groups of continental-oceanic nappes characterized by contrasting P-T-time trajectories, as follows (Dal Piaz *et al.*, 2001):

1) Eclogite-free upper group - It consists of the Dent Blanche-Mt Mary-Pillonet thrust system and the underlying Combin zone, both displaying a relatively high-P imprint which is dated as Late Cretaceous (74-73 Ma) in the Pillonet klippe by concordant Rb-Sr and Ar-Ar ages on white micas, coexisting with sodic amphiboles (Cortiana *et al.*, 1998). The age of the Combin blueschist mineral relics is still unknown, even if a Late Cretaceous and/or Paleocene age can not be excluded since this ophiolitic nappe acted as a tectonic sole of the accreting Dent Blanche-Mt Mary-Pillonet thrust system.

Figure 14. Tectono-metamorphic setting of the Western Austroalpine-Penninic wedge in the Aosta valley and surrounding areas.



Austroalpine: 1) Upper outliers (non eclogitic): Dent Blanche (DB)-Mt Mary (MM)-Pillonet (P) thrust system; 2) Lower outliers (eclogitic): Acque Rosse (AR), Chatillon (CH), Etirol-Levaz (E), Grun (G), Mt Emilius (EM), Glacier-Rafray (GR), Santanel-Verres (S), Tour Ponton (T); 3) Sesia-Lanzo zone (SL). Lithology: Valpelline-2nd Diorite-kinzigitic series (Vp-Dk), lower crust; Arolla series (Ar), Gneiss minuti complex (Gm1: non eclogitic, Gm2: eclogitic relics); Eclogitic micaschist complex (Emc); Mesozoic metasedimentary units: Roisan zone (R), Sesia-Lanzo (Sc). Ophiolitic Piedmont zone: 1) Relatively high-P (non eclogitic) Combin zone (CO), including Pancherot-Cime Bianche (PCB), Frilihorn and Cogne (FC) Permian-Mesozoic decollement cover units of continental affinity; 2) Eclogitic Zermatt-Saas zone (ZS) extending to the Mt Avic massif (MA); Antrona ophiolite (A). Penninic continental nappes: Monte Rosa (MR), Arcesa-Brusson (AB), Gran Paradiso (GP) inner-upper Penninic nappe system; mid-Penninic Grand St Bernard composite nappe system (SB). Canavese zone and Canavese tectonic line (CA), Aosta-Ranzola fault system (AR), Simplon normal fault (SF). Slightly modified from Dal Piaz (1999).

2) Eclogitic lower group – It consists of the Mt Emilius (Fig. 15) and other lower Austroalpine eclogitic outliers and underlying or interbedded units of the Zermatt-Saas nappe. Their typical eclogitic imprint yielded Early-Mid Eocene ages (50-44 Ma), opposite to the Late Cretaceous eclogitic micaschist complex in the inner Sesia-Lanzo zone. The original source of the Dent Blanche-Mt Mary-Pillonet thrust system and the Sesia-Lanzo zone may be a set of extensional allochthons probably juxtaposed to the Adriatic margin. Indeed, the oceanic seaway envisaged by Stampfli (1993) between the Dent Blanche-Sesia and Canavese domains is virtually possible but not supported by robust surface evidence (discussion in follows). The ophiolitic units of the Combin zone were located in the internal edge of the Piedmont ocean and then accreted, from the beginning of subduction onwards, below and in front of the Dent Blanche-Mt Mary-Pillonet thrust system. In contrast, the Zermatt-Saas ophiolite and the eclogitic lower Austroalpine outliers derived from one or more intraoceanic allochthons both originated far to the north-west and entered the subduction zone 30 Ma later than the upper group of continental-oceanic nappes. A relatively wide and now lost sector of the Piedmont-Ligurian ocean was probably interposed between the Combin and Zermatt-Saas oceanic domains, filling the gap in the chronological record.

Figure 15. Mt Emilius klippe.

South-eastern face of the Lower Austroalpine Mt Emilius outlier from Col di Leppe: Eclogitic micaschist complex with Eocene high-P imprint, derived from a kinzitite-type suite and minor granitoids (Dal Piaz *et al.*, 1983, 2001).

At the beginning of the Third Millenium

The last decade is characterized by the increasing number of papers, the development of international teams and the flowering of a new generation of gifted and very active young researchers, also positively inclined to the field work. This decade is too cloose for any historical overview of Alpine Geosciences. Therefore, I shall dwell only on some innovating or conflictual points, integrated by personal comments mainly concerning the continental and oceanic units with high-P imprint, their protoliths and the overall architecture and paleogeographic scenarios of the Alps.

Tectono-metamorphic evolution and geochronology

A new map at one million scale showing the metamorphic structure of the Alps has been compiled by an international working group and edited by Oberhänsli *et al.* (2004). It focuses on the polyphase Alpine metamorphism, disregarding older metamorphic events. The map is based on the spatial distribution of metamorphic facies, like former metamorphic maps did (Niggli *et al.*, 1978; Frey *et al.*, 1999), but is integrated by information on the type and grade of the Alpine metamorphism, interpreted as a geodynamic marker. The various metamorphic peak conditions are dated in a schematic inset which represents three chronological groups of P-dominated (subduction-related) metamorphism (110-90, 89-60 and 59-35 Ma) and two groups of T-dominated (syn- to post-collisional) metamoprhism (110-60 and 59-0 Ma, cooling ages). Fifteen metamorphic facies are chromatically distinguished and assembled in three groups which show the regional distribution of tectonic units dominated by subduction, continental collision and high-T exhumation features, regardless of their Cretaceous or Tertiary age. Summing up, the structural-metamorphic map simply shows the geodynamic evolution of the Alps that evolved through two subsequent orogenies (Cretaceous and Cenozoic).

Western Alps - Beginning with the ophiolitic Piedmont zone, a number of consistent U-Pb, Sm-Nd, Rb-Sr and ^{40}Ar-^{39}Ar dating confirmed the Mid-Eocene age of the eclogitic and ultrahigh-P metamorphism in the Zermatt-Saas nappe, within the 47-42 Ma time span, both north of the Aosta-Ranzola fault (Rubatto *et al.*, 1998; Lapen *et al.*, 2003; Gouzu *et al.*, 2006; Herwartz *et al.*, 2008) and south of it, from the Mt Avic massif to the Urtier valley (Rubatto *et al.*, 1998; Dal Piaz *et al.*, 2001;

Beltrando *et al.*, 2009a), as well as in similar occurrences of the Cottian Alps (Lombardo *et al.*, 2002; Rubatto & Hermann, 2003) and Voltri massif (Rubatto & Scambelluri, 2003; Federico *et al.*, 2007). The ultrahigh-P unit of Lago di Cignana was mapped in detail (Forster *et al.*, 2004) and became the object of further field and laboratory work (Lapen *et al.*, 2003; Gouzu *et al.*, 2006; Müller & Compagnoni, 2009; Skora *et al.*, 2009). In particular, Groppo *et al.* (2009) confirmed that the Lago di Cignana and Zermatt-Saas units display identical metamorphic evolutions, being differentiated only by the presence or absence of coesite, and restricting the pressure difference to less than 0.3 GPa. Diamonds long searched and never found within the garnet peridotite-eclogite bodies of the Central and Eastern Alps (do you remember the recurrent debate between Green and Trommsdorff ?) have been discovered in manganiferous garnet-rich nodules from the coesite-bearing Lago di Cignana unit (Selverstone *et al.*, 2010). It has to be emphasized that these are the first diamonds known in the Alps, the first from oceanic metasediments, and the lowest-T occurrence (≤600°C) yet reported from the ultrahigh-P rocks.

The predicted Eocene age of the relict eclogitic imprint in the underlying upper-inner Penninic basement nappes of the Graian and Pennine Alps (e.g. Dal Piaz, 1999), already assessed in the Brossasco-Isasca unit of the Dora-Maira nappe, was finally established, yielding 43 ± 0.5 Ma in the Gran Paradiso silvery micaschists (Meffan *et al.*, 2004: apatite-phengite Rb-Sr microsampling), and 42.6 ± 0.6 Ma (Lapen *et al.*, 2007: U-Pb on rutile, carbonate and quartz-white mica fractions from quartz-carbonate veins within the mafic eclogite) in an eclogitic boudin from the polymetamorphic Furgg Zone in the southern Monte Rosa (Dal Piaz, 2001b; Fig. 16). New petrological estimates and SHRIMP dating on the same silvery micaschists of the Gran Paradiso nappe have been recently presented by Gabudianu Radulescu *et al.* (2009), showing that the metamorphic peak (2.7 GPa / 515–600°C) of these metasomatic and mylonitic granitoids could have been developed near the ultrahigh-P field and at the Eocene-Oligocene boundary, based on U-Th dating of allanite (33.7±1.6 Ma) and prograde monazite (37.4 ± 0.9 Ma). Doubts on the geological meaning of the younger age arise from the Arcesa-Brusson window, southern Monte Rosa nappe and their Zermatt-Saas envelope, since these basements with eclogitic relics and greenschist facies regional fabrics were cooled below 250°C at 33 Ma (Gran Paradiso, Hurford A. J. & Hunziker, 1989) and rigid enough to be cut by lamprophyre dykes, listvenitic faults and gold-bearing quartz vein, yielding 32-29 Ma and 32-30 Ma, respectively (Dal Piaz *et al.*, 1979; Venturelli *et al.*, 1984; Pettcke *et al.*, 1999; Bistacchi *et al.*, 2001). The Arcesa-Brusson window is open in the footwall of the Aosta-Ranzola normal fault, of Oligocene age, between the Monte Rosa and Gran Paradiso massifs, and display the same basement units of these nappes (Bigi *et al.*, 1990). Therefore, I like better dating and interpretation of Meffan *et al.* (2004). Otherwise, the Gran Paradiso and Monte Rosa nappes followed very similar, but diachronous P-T-paths.

Figure 16. Eclogites of Monte Rosa nappe.

Mafic boudins with Eocene eclogitic imprint (42.6 ± 0.6 Ma; Lapen *et al.*, 2007) inside the polymetamorphic Furgg Zone, derived from pre-Variscan continental flood basalt; Indren glacier, southern Monte Rosa (Dal Piaz, 2001b).

Anyway, the supposed robust eoalpine Rb-Sr and ^{40}Ar-^{39}Ar ages of the Monte Rosa and Gran Paradiso internal nappes were ultimately dismissed, together with their role in costraining the age of the ocean closure, syncollysional subduction of the European distal margin, and alternative kinematic models (e.g. Polino *et al.*, 1990). Indeed, the nearly identical P-T evolution of the Gran Paradiso, Arcesa-Brusson, Monte Rosa and Zermatt-Saas nappes (Antrona included) suggests that these high-P continental and oceanic units shared a common tectono-metamorphic history during a crucial phase of the Alpine orogeny (for alternative views see Froitzheim, 1999; Schmid *et al.*, 2004; Pleuger *et al.*, 2006). Their close time-space association probably played a key role in exhumation and preservation of the eclogite-facies ophiolites through buoyancy-driven uplift of the underlying continental nappes (Lapen *et al.*, 2007), and with the significant help of highly hydrated fragments of oceanic lithosphere (Poli & Schmidt, 1995; Angiboust & Agard, 2010), mainly represented by serpentinized mantle peridotites (Breithorn-Verra, Avic, Voltri; Bigi *et al.*, 1990).

Detailed information on contraction and extension of the Austroalpine-Penninic collisional wedge based on isotope dating and kinematic analysis has been given by Reddy *et al.* (2003), dealing with a significant transect across the Gressoney, Ayas and Tournanche valleys, from the Sesia-Lanzo Zone to the Dent Blanche nappe, through the composite ophiolitic Piedmont zone. An initial phase of accretion and NW-directed thrusting at ca. 60 Ma is inferred from two white mica Rb-Sr ages of Bec di Nana basal milonite, the northern edge of the Pillonet klippe (Dal Piaz, 1976), where better preserved high-Si micas in equilibrium with blue amphiboles yielded Rb-Sr and ^{40}Ar-^{30}Ar ages of 74 Ma (Cortiana *et al.*, 1998), a more reliable age for thrusting of the upper Austroalpine outliers. Other Rb-Sr white mica dates (48-36 Ma) from different kinematic domains (Reddy *et al.*, 2003) document the age of deformation and fabric formation under greenschist facies conditions within the ophiolitic Combin zone, or cooling in the Zermatt-Saas nappe. Contrasting top-to-NW and top-to-SE kinematics are recognized: the latter deformation is related to crustal extension and is consistent with exhumation of underlying eclogitic units, whereas ^{40}Ar-^{39}Ar data, if not influenced by excess or loss Argon, reflect the cooling evolution of eclogitic and greenschist facies units between 40 and 32 Ma (Reddy *et al.*, 2003).

Eastern Austroalpine - A bimodal tectono-metamorphic model was envisaged also by Thöni (2006), based on an updated review of petrological estimates and isotope dating of eclogitic units in the Austroalpine and Penninic nappes of the Eastern Alps. Mafic eclogites and high-P metapelites along the inner Austroalpine in the Texel (1.3 GPa/520–600 °C), Schober (1.8 GPa/≤690 °C) and Saualpe-Koralpe-Pohorje units (2.2–≤2.7 GPa/≤750 °C), display a similar structural position and almost identical Cretaceous ages (90-85 Ma) on Sm–Nd, Lu–Hf, U–Pb and Rb–Sr systems, pointing for a common subduction and exhumation history. This “eoalpine high-pressure belt” is supposed to have been derived from the distal passive margin of a Meliata back-arc basin and, further west, from the Austroalpine crust along an intracontinental subduction zone during the Cretaceous Apulia-Europe plate convergence, with mean exhumation rates of 5–≤10 km/Ma between 90 and 85 Ma (Thöni, 2006). Otherwise, the underlying Penninic nappes display, in the Tauern window, an eclogitic imprint (2.4 GPa/≤630 °C) and a rapid exhumation/cooling dated as Eocene-Early Oligocene (<45–31 Ma) through amphibole and phengite ^{40}Ar–^{39}Ar and Rb–Sr multimineral isochron ages. The high-P event is related to the subduction of the former European continental margin after the closure of the Penninic ocean, and its accretion at the base of the Mesozoic ophiolitic units and capping Austroalpine nappe stack (Thöni, 2006). Further precise dating of eclogitic gabbros from the Kupplerbrunn–Prickler Halt eclogite type-locality (Haüy, 1822, in Godard, 2001) and other Saualpe localities can be found in Thöni *et al.* (2008).

In spite of this, the classic concept of older eclogites in the Eastern Austroalpine was not abandoned in the Eastern Austroalpine (Magetti *et al.*, 1987; Miller & Thöni, 1995; Godard *et al.*, 1996; Martin *et al.*, 1998, 2009; Tumiati *et al.*, 2003), as the existence of Variscan eclogites from MORB-type protoliths was confirmed and corroborated in the crystalline basement of central Ötztal (2.7 GPa/730 °C; mean Sm–Nd age: 347 ± 9 Ma), eastern Silvretta (ca 350 Ma), and Ulten units (336 ± 4 Ma), all thought to be representative of the North-Apulian (Austroalpine) paleostructural domain (Thöni, 2006). Earlier assumptions of an eclogitic event in the Eastern Austroalpine of Caledonian (Purtscheller & Sassi, 1975) or Neoroterozoic age (Manby *et al.*, 1988) was ultimately invalidated.

Pohorje massif - In the last decade, the eclogite and peridotite bodies long known inside the Slovenian Pohorje massif (Hinterlechner-Ravnik, 1982; Hinterlechner-Ravnik *et al.*, 1991a-b) at the easternmost edge of the Alps (Bigi *et al.*, 1990) became the subject of renewed interest (Sassi *et al.*, 2004; Janak *et al.*, 2006; Thöni *et al.*, 2008). The mafic rocks had been interpreted as relics of oceanic crust with a pre-Alpine, possibly Caledonian, high-P metamorphism (Hinterlechner-Ravnik *et al.*, 1991b). According to Sassi *et al.* (2004), lenses of kyanite- and quartz-rich eclogites derived from gabbroid cumulates and more fractionated protoliths are embedded within amphibolite-facies quartz-feldspathic gneisses, both characterized by a N-Morb type signature. Eclogitic P–T conditions were estimated 1.8–2.5 Gpa/630–700°C, consistently with the absence of coesite. By comparison with the similar Koralpe and Saualpe basement units, the high-P metamorphism of the Pohorje mafic rocks was referred to subduction of oceanic crust during the Cretaceous collision (ca 100 Ma) between the European and Apulian plates. The garnet-peridotites of the Pohorje massif were quoted as evidence of ultrahigh-P conditions (Janak *et al.* (2006): these rocks, which probably derive from a depleted mantle source, display four main stages of crystallization, evolving from a prograde path (spinel I → garnet) to a decompressional path (garnet → spinel II → amphibole-serpentine). This evolution is similar to that described in the Ulten unit (Godard *et al.*, 1996; Martin *et al.*, 2009), where similar Sm-Nd ages (330 Ma) suggest that all rock types shared a common history since the incorporation of the peridotite in the crust, and constrain the garnet-facies of peridotites to crustal subduction at the end of the Variscan orogeny (Tumiati *et al.*, 2003). Peak estimates by for garnet-peridotites are 900°C/4 Gpa (Janak *et al.*, 2006), and the inferred geodinamic interpretation suggests that the ultrahigh-P metamorphism is a result of deep subduction of continental crust which scraped mantle slices off the lithospheric upper plate. The principal unroofing stages developed from the Upper Cretaceous to the Miocene formation of an extensional core complex. The eoalpine age of the high-P imprint in the Pohorje massif was documented by Thöni *et al.* (2008), where a low-Mg eclogite provided a garnet–whole-rock Lu–Hf age of 93 Ma, similar to those reported by the same authors for various eclogites of Saualpe. In conclusion, Thöni *et al.* (2008) suggest that garnet growth in the Saualpe–Pohorje high-P units developed between ca 95–94 Ma and ca 90–88 Ma, probably at the final pressure peak. Rapid exhumation of the high-P units was related to the collision of the northern part of the Apulian plate with parts of the Austroalpine microplate, which developed after the Jurassic closure of the Permian-Triassic Meliata back-arc basin.

Tauern window – The physical conditions of eclogites occurring in some Penninic units are confirmed by recent calibrations of garnet-omphacite-phengite-kyanite-quartz mineral assemblages, giving values of about 2.5 GPa/630°C, which approach the stability field of coesite (Hoschek, 2007). The kyanite-eclogites include a strongly retrogressed jadeite-gneiss, derived from siliciclastic deposits and consisting of garnet-quartz-white micas, with kyanite and Na-pyroxene only as inclusion in garnet (Miller *et al.*, 2007). Peak metamorphic conditions of the relict primary assemblage are 2.4–2.0GPa/640°C. U–Pb zircon dating yielded only prealpine ages, supporting the existence of three igneous events in the source area of zircons, at 466 ± 2 Ma, 437 ± 2 Ma and 288 ± 9 Ma.

Paleostructural restoration and Tethys reconstruction

A new tectonic map of the entire Alps at about 1:2,500,000 scale has been compiled by Schmid *et al.* (2004), starting from the Structural Model of Italy (Bigi *et al.*, 1990, 1992). The orogenic evolution of the Alps is discussed and based on the integration of surface and subsurface structural data, contrasting tectono-metamorphic events and paleogeographic restoration of cover and basement units back to Mesozoic Tethys. The concept that the Alps are a bimodal orogenic belt (Froitzheim *et al.*, 1996) is strenghtened and developed. The first orogeny of Cretaceous age (eoalpine) is recorded only in the Eastern Alps and is followed by a second orogenic cycle of Tertiary age, with a Late Cretaceous phase of extension and exhumation between them (Froitzheim *et al.* 1994; Ratschbacher *et al.*, 1989). The former orogeny is due to the subduction-related closure of the Triassic Meliata ocean, supposedly tailing into the Apulia (Adria) continental margin, the latter to the classic closure of the Jurassic Alpine Tethys between Apulia and Europe. For the sake of clarity, it may be recalled that the classic term Tethys has been recently used in various ways (e.g., Stampfli *et al.*, 2001a-b): i) Paleotethys, a mainly Paleozoic ocean restored north of the Cimmerian continent; ii) Neotethys, a late Paleozoic-Mesozoic ocean allocated south of this continent, including the Meliata, Vardar and other Triassic-Jurassic seaways, developing independently from the central Atlantic; iii) Alpine Tethys or Westewrn Tethys, the Middle Jurassic ocean including the Ligurian-Piedmont (South-Penninic) and Valais (North-Penninic) basins, and genetically linked to the opening of the central Atlantic. The original extension of the Meliata ocean into the future Alpine domain of the Adriatic plate is not documented by direct evidence, being limited to a few slices of serpentinite and Mesozoic basinal sediments in the eastern edge of the Northern Calcareous Alps. Schmid *et al.* (2004) have tentatively attributed the crystalline nappes of the Koralpe-Wölz high-P system (Miller & Thöni, 1997; Hoinkes *et al.*, 1999; Schuster *et al.*, 2001; Schuster, 2003) to Neothetys and its distal passive margin, being aware that this reconstruction is speculative. The Mesozoic cover of parts of this nappe system was detached before the eoalpine high-P metamorphism and final closure of the Meliata Ocean, like the Pancherot-Cime Bianche cover unit later did during the western Alpine contraction (Dal Piaz, 1999). In spite of the absence of a robust ophiolitic suture, the existence of a Triassic ocean and its consumption is indirectly inferred (Schmid *et al.*, 2004) as a geodynamic engine accounting for the generation of a pre-Gosau orogenic wedge and related eclogitic (subduction) imprint to high-T Barrovian (collisional) metamorphism of eoalpine age (Early-Mid Cretaceous, Thöni, 1999, 2006).

A similar reconstruction has been suggested by Dal Piaz *et al.* (2003), pointing for the different strutural position (early established by Argand) between the Eastern Austroalpine tectonic system and the underlying Western Austroalpine (Adria-derived Dent Blanche and Sesia-Lanzo nappes), as well as for their different tectono-metamorphic evolution. As clearly pointed out by Schmid *et al.* (2004), some points of their stimulating work may be controversial and deserve to be developed:

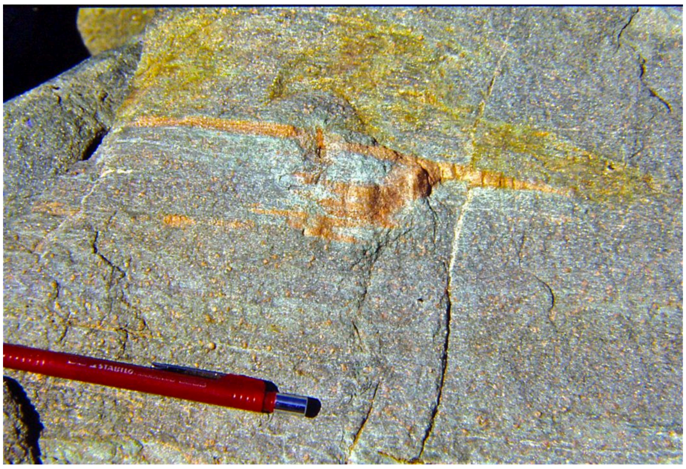
1) The existence in the Eastern Alps of two independent orogenies (Cretaceous vs. Tertiary), clearly separated by a syn-Gosau extensional phase, is a milestone of the memoir of Schmid *et al.* (2004). However, extension in the Eastern Austroalpine seems rather an exuming-accretion process in the leading edge during active plate convergence (Ratschbacher *et al.*, 1989). In any case, while the Eastern Alps enjoyed this break in shortening deformation, the Western Alps were involved into lithospheric contraction with top-to-the-west tectonic transport (Dal Piaz & Sacchi, 1969), and the Late Cretaceous subduction metamorphism recorded in the Sesia-Lanzo Zone and Pillonet klippe. Therefore, a transition (partial overlapping) rather than a clear-cut separation seems to be the better solution, as also suggested by Trümpy (1992).

2) The continental basement and cover units inside the Tauern window are wholly referred to the Sub-Penninic nappes (distal European margin), as the Ossola-Tessin dome, whereas the overlying Glocknerdecke (the fixist Obere Schieferhülle) becomes a North-Lower Penninic (Valais) unit, according to Froitzheim *et al.* (1996), who equated this ophiolitic nappe with the Bündnerschiefer of the Engadine window. The Glocknerdecke is capped in turn by the Matrai shear zone (Bigi *et al.*, 1990) interpreted as a S-Penninic (Piedmont) unit (Schmid *et al.*, 2004): it marks the Penninic/Austroalpine boundary and consists of tectonic mixing of ophiolitic calcschists, Triassic marbles and Austroalpine basement slices (Gb Dal Piaz, 1934; Frisch *et al.*, 1987; Kurz *et al.*, 1998 a-b). The absence of continental nappes between the North and S-Penninic units postulated by Schmid *et al.* (2004) implicitly supports the existence of a unique Penninic ocean. This paleogeographic reconstruction has been criticized by Kurz (2005) and confirmed by Schmid *et al.* (2005) with additional comments. In my opinion the problem is still open, since: i) the Glockner nappe display a close lithological and metamorphic affinity with the ophiolitic units of the Combin zone (South-Penninic); ii) the “non-eclogitic Sub-Penninic basement nappes” of the Tauern window includes bodies of fresch to retrogressed ecogites (Bianchi, 1934; Cortiana *et al.*, 2004; Thöni, 2006); iii) the blueschist and eclogite facies metamorphism in various oceanic and continental units of the Tauern window is dated as Eocene (Ratschbacher *et al.*, 2004; Glodny *et al.*, 2005; Thöni, 2006; Kurz *et al.*, 2008), like in the inner-upper Penninic Monte Rosa-Gran Paradiso nappes and overlying Zermatt-Saas ophiolite; iv) the garnet-kyanite-chloritoid quartzschists from the Eclogite Zone racall the eclogitic mylonites of the Monte Rosa nappe; v) in the central Lower Penninic zone only the Adula nappe displays a lithology and eclogitic imprint (Fig.17) similar to the Monte Rosa nappe, and its sub-penninic allocation is valid only from a geometrical point of view; vi) the Late Jurassic Hochstegen marble points for the extension of the Briançonnais facies into the Tauern window. For these reasons, I am inclined to like better the solution that it was preferred for these nappes when I compiled the Alpine area of the Structural Model of Italy (Bigi *et al.*, 1990).

3) Again about the Valais (N-Penninic) domain, the Antrona ophiolite is traditionally and better referred to the Zermatt-Saas nappe, instead of to the N-Penninic, due to their closely similar lithological, geochemical and metamorphic features (Beccaluva *et al.*, 1984; Colombi & Pfeifer, 1986; Pfeifer *et al.*, 1989; Dal Piaz, 1999), even if the Zermatt-Saas metabasalts display a much greater compositional variety and often a spilitic composition (pillow lavas) in respect with the Antona unit, the latter providing chemical evidence of fast spreading (Pfeifer *et al.*, 1989). The present position of Antrona at the base of the Monte Rosa fold-nappe is referred to the Alpine contraction and is incorporated into the Zermatt-Saas domain

(Dal Piaz *et al.*, 1972; Polino *et al.*, 1990). A different view is proposed by Froitzheim (2001).

Figure 17. Eclogites of Adula nappe.



Eclogite with isoclinal folding within high-P micaschists of Adula nappe, Fanella pass.

4) Traditionally coeval with the Piedmont-Ligurian ocean, the N-Penninic (Valais) basin has been rejuvenated to the Early Cretaceous, thanks to stratigraphic evidence in the central Alps (Froitzheim & Manatschal, 1996) and the kinematic connection with the Bay of Biscay (Stampfli, 1993). In addition, Stampfli (1993) postulated the extension of the Valais oceanic basin wholly along the French-Italian Alps, in spite of the absence of ophiolitic traces south of Moutiers, where the N-Penninic units disappear along the Briançonnais/Helvetic-Dauphinois boundary (e.g. Dal Piaz, 1974, 1999; Sturani, 1975; Compagnoni *et al.*, 1977). Starting from Stampfli's assumption, the Mid-Penninic Grand St Bernard tectonic system became a Briançonnais exotic terrane (extensional ribbon continent), that developed since the Cretaceous birth of the Valais basin and concurrent contraction of the Piedmont ocean (Stampfli, 1993, 1994, Stampfli & Borel, 2002; Stampfli *et al.*, 2002). The Briançonnais terrane also encompasses the Inner-Upper Penninic (prePiedmontese) Monte Rosa, Gran Paradiso and Dora-Maira nappes (Elter, 1960, 1972; Dal Piaz *et al.*, 1972; Dal Piaz, 1974; Sturani, 1975). The exotic terrane is believed to wedge out between the Engadine and Tauern windows and therefore it is no more present among the core nappes of the Eastern Alps (Trümpy, 1988; Schmid *et al.*, 2004, Figs 1 and 2). As figured in Bigi *et al.* (1990) and maintained by Dal Piaz *et al.* (2003), from the beginning of the Jurassic spreading the Monte Rosa-Gran Paradiso domain belonged to the ocean-facing distal edge of the European passive continental margin, since in the Eocene it was subducted below the Adriatic leading margin together with the Piedmont oceanic lithosphere and just after the Middle Eocene basin closure.

5) The Western Austroalpine Dent Blanche and Sesia-Lanzo tectonic system (Dal Piaz *et al.*, 1972; Compagnoni *et al.*, 1975, 1977) is renamed by Schmid *et al.* (2004) either Lower Austroalpine nappes (Plate 1) or Margna-Sesia fragment, according to Froitzheim *et al.* (1996). The former term rightly emphasizes the unquestionable low-standing position of these units in respect with the entire Eastern Austroalpine, a tenet firmly established by Argand through his famous figure in which the Eastern Austroalpine nappe stack is projected over the six Penninic fold-nappes, Dent Blanche included, but this name is misleading due to the existence of Lower Austroalpine units in the Eastern Alps, which are characterized by contrasting structural position, lithology and metamorphic features. Therefore, in the Western Alps it is preferred the neutral name Western Austroalpine, also because, as previously seen, this is a double nappe system grouping upper and lower outliers with a different and diachronous subduction metamorphism (Dal Piaz, 1976, 1999; Ballevre *et al.*, 1986; Dal Piaz *et al.*, 2001; Beltrando *et al.* 2010b).

6) The term Margna-Sesia fragment, recently rediscovered as Cervinia (Pleuger *et al.*, 2007), recalls the continental unit early envisaged by Compagnoni *et al.*, 1975, 1977), and the intraoceanic restoration of the Margna nappe and Sesia-Lanzo Zone supported by Froitzheim *et al.* (1996), even if the present structural settings of these nappes is different. Indeed, these units are separated by a Jurassic right-lateral shear zone (Dal Piaz, 1999) and while the Margna nappe is sandwiched between two distinct ophiolitic units (Pasquarè, 1975; Compagnoni *et al.*, 1975, 1977), the Sesia-Lanzo is thrusted over the entire Piedmont zone and on its internal side is laterally juxtaposed to the Ivrea-Verbano lower crust (Southern Alps), through the ophiolite-free Canavese zone (Ferrando *et al.*, 2004) and related bounding faults (Bigi *et al.*, 1990). As previously seen, a similar position is assumed for the non-eclogitic Dent Blanche-Mt Mary-Pillonet thrust system (upper Austroalpine outliers),

whereas the eclogitic Mt Emilius and other lower Austro-alpine outliers (Glacier-Rafray, Chatillon, Grun. Etirol-Levaz, Santanel, Verres) are presently located at the boundary between the Combin and Zermatt-Saas nappe, and within the latter. Back to the paleogeographic puzzle, a further oceanic gap has been postulated between the Sesia-Lanzo domain and the Southern Alps also by (Froitzheim *et al.*, 1994, 1996;; Froitzheim & Manatschal, 1996). This is virtually possible, since a subducted ocean may not leave superficial traces, but as a matter of fact it is not supported by an unquestionable ophiolitic suite, so that the classic allocation of the Dent Blanche-Sesia (extensional allochthons) along the proximal Adriatic margin (Dal Piaz, 1999) is considered more reliable. Their Adriatic affinity is documented by similar crustal protoliths (Franchi *et al.*, 1908; Novarese, 1931), and this was pointed out also by Trümpy (1992), grouping the Dent Blanche, Simme and Margna nappes as Ultrapennine units, with Triassic facies belts continuing into the western Southern Alps. An intraoceanic source is more likely in the case of the Mt Emilius and other lower Austroalpine outliers that entered the subduction zone and acquired their eclogitic imprint together the Zermatt-Saas nappe, 30 Ma after the Sesia-Lanzo zone and upper Austroalpine outliers acquired their subduction metamorphism (Dal Piaz, 1999; Dal Piaz *et al.*, 2001; Beltrando *et al.*, 2010b).

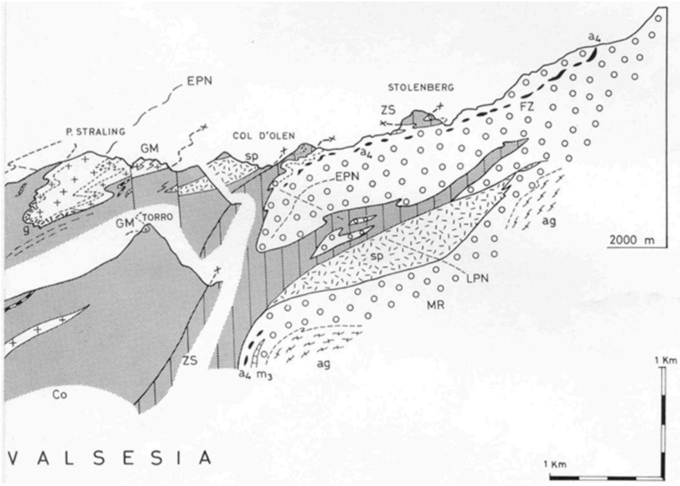
7) The classic and popular term “Penninic”, long consolidated in Alpine literature since Argand’s work, cannot be avoided even if it was and stil is used in different misleading ways. Indeed, as mentioned by Schmid *et al.* (2004), the term “Penninic nappes” generally indicates tectonic units coming from multiple continental and oceanic domains (European margin, Valais ocean, Briançonnais terrane, Piedmont-Ligurian ocean), and it was maintained by these authors in a reduced form, i.e. excluding the Sub-Penninic units coming from the European margin, north-west of the Valais basin. Alternatively, the Penninic term can be restricted to the continental nappes derived from the Jurassic European passive margin and eventually related ribbon continents (Dal Piaz, 1974, 1999), all characterized by an eclogitic or blueschist facies imprint of Eocene age, opposite to the Helvetic-Ultrahelvetic units that were accreted to the collisional belt later and only when the subduction-related thermal low had been definitively re-equilibrated. In addition, the precise provenance of the Piedmont-Ligurian ophiolitic units with respect to the unknown Jurassic spreading center can not be unequivocally defined, as they may be derived from the oceanic side of the Adriatic, European, or both plates, hence the uncertainty between a Penninic or non-Penninic affiliation.

8) A flake-tectonic model of the Eastern Alps has been proposed by Schmid *et al.* (2004) along the Transalp transect and the Austroalpine nappe stack east of the Tauern window, suggesting a provocative northward subduction of the Apulian plate. The former profile is a provisional alternative interpretation of the Transalp deep seismic experiment, whilst the latter is inferred only from tomographic information on mantle slab (Lippisch, 2002).

Western Austroalpine - Unforeseen Eocene ages on high-Si white micas (Rb-Sr, Ar-Ar: 49-42 Ma; Dal Piaz *et al.*, 2001; Beltrando *et al.*, 2009a) and zircon (U-Pb: 47.3 ± 1.3 Ma; Beltrando *et al.*, 2009b, 2010b) were obtained for the eclogitic imprint recorded by the lower Austroalpine outliers (Mt Emilius, Glacier-Rafray, Tour Ponton, Acque Rosse, Eirol-Levaz), previously believed to be essentially coeval with that in the inner Sesia-Lanzo zone (85-69 Ma). These basement slivers are intimately associated to fragments of oceanic lithosphere which display the same and coheval eclogitic imprint, suggesting that their former juxtaposition probably goes back to the rifting stage (Dal Piaz, 1999; Dal Piaz *et al.*, 2001, 2004; Beltrando *et al.*, 2010a-b). All this points for the existence of a peculiar oceanic lithosphere located near the passive continental margin, and characterized by oceanic crust locally roofed by some thin extensional allochthons that did not alter the essential features (sea-floor morphostructure, overall thickness) and properties (thermal setting, negative buojancy, rheology) of the Piedmont-Ligurian lithosphere at the end of spreading and thus favorable for deep subduction (Dal Piaz, 1999). By comparison with the Galicia-Iberia margin (Boilot *et al.*, 1995; Manatschal & Bernoulli, 1999; Peron-Pinvidic *et al.*, 2007), this peculiar crust has been reported as ocean-continent transition, a very popular term (Manatschal *et al.*, 2003; Ferrando *et al.*, 2004; Manatschal, 2004; Bernoulli & Jenkins, 2009; Beltrando *et al.*, 1910a-b). Anyway, this anomalous crustal zone is a proximal part of the Zermatt-Saas external sector of the Piedmont ocean, far from the internal Combin zone, where extensional allochthons of continental basement are lacking. Clues of ocean-continental transition are reported from the Gets decollement nappe which includes ophiolites of Jurassic age and continental crust elements (Bill *et al.*, 1997, 2000).

My opinion on the debated paleostructural reconstruction of the western Alpine Tethys (e.g., Froitzheim, 2001, Rosenbaum & Lister, 2005, for reviews) is based on these constraints and assumptions (Dal Piaz *et al.*, 1972, 2001; Bocquet, 1974; Compagnoni *et al.*, 1977; Cortiana *et al.*, 1998; Dal Piaz, 1999): i) stratigraphic and radiometric data indicate that the onset of subduction and orogenic contraction propagated from the Sesia-Lanzo inlier to the Grand St Bernard domain, through the consuming Piedmonte ocean; ii) Late Cretaceous age of the blueschist relics in the Pillonet klippe and other upper Austroalpine outliers; iii) concurrent development of the eclogitic imprint in the lower Austroalpine outliers and associated Zermatt-Saas ophiolites; iv) a delay of 30-25 Ma between the two recorded events; v) the occurrence of the Combin zone as a tectonic sole of the upper Austroalpine outliers, displaying similar blueschist relics of potential latest Cretaceous and/or Paleocene-Early Eocene age; vi) disappearence at depth of large portions of normal to anomalous oceanic crust; vii) close lithostratigraphic and metamorphic features of the prealpine Sesia-Lanzo and Dent Blanche protholiths with the Southalpine continental crust; viii) a certain pre-piedmontese and briançonnais affinity of the Permian-Mesozoic Pancherot-Cime Bianche decollement unit, clearly different from the Roisan zone; this exotic unit is presently interbedded within the oceanic units of the Combin zone (e.g. tectonic inset in Bucher *et al.*, 2003-04), and probably it had been detached from the cover-free lower Austroalpine outliers at incoming subduction. Evaluating pros and cons, I maintain the Austroalpine (Adriatic) affinity of the Sesia-Lanzo zone, the Dent Blanche-M.Mary-Pillonet upper Austroalpine outliers and their Mesozoic metasedimentary cover, regardless of the presence or absence of a thrue ophiolitic suite as evidence of an oceanic channel along the Canavese fault system. By contrast, the Mt Emilius, Glacier-Rafray, Etirol-Levaz and other lower Austroalpine eclogitic outliers probably derived from one or more extensional allochtons trapped within the Combin/Zermatt-Saas boundary zone and/or in the latter oceanic domain, thus assuming a proximal Penninic (European) affiliation and partly going back to Argand's views. Please note that this does not mean that I agree with an European origin of the Sesia-Lanzo inlier, a concept early alleged by Aubouin *et al.* (1977), Fudral & Deville (1986), Mattauer *et al.* (1987).

Figure 18. Recumbent backfolding in southern Monte Rosa massi.

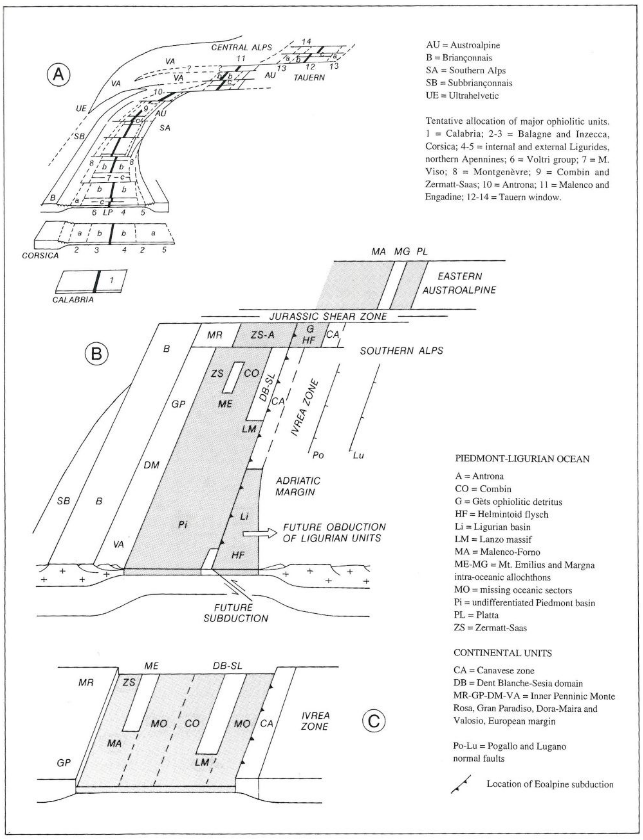


Section of the collisional suture along the ridge between the Lys and Sesia valleys (Gosso *et al.*, 1979). From top to bottom: 1) Sesia-Lanzo zone: Gneiss minuti (GM) and minor mylonitic gabbros (g); 2) Piedmont zone: Combin (Co) and Zermatt-Saas (ZS) units: major serpentinite bodies (sp); 3) Monte Rosa nappe: dominant garnet-micaschists (MR) with lenses of eclogite-amphibolite (a4) and rare beds of old marble (m3); augengneiss (ag) from Late Paleozoic granite. Monte Rosa and Zermatt-Saas nappes are folded together, independently from the later tectonic contact between the two ophiolitic units (named Combin fault by Ballevre & Merle, 1993). Early (EPN) and late (LPN) postnappe deformations.

Valais basin - Herwartz *et al.* (2008) and Pleuger *et al.* (2005, 2007) have enucleated from the Zermatt-Saas nappe a supposedly independent and younger ophiolitic unit - called Balma - that in the southern side of the Monte Rosa massif is involved within the recumbent back-folds of the Monte Rosa basement nappe (Gosso *et al.*, 1979; Dal Piaz, 1992). This reconstruction is based on U-Pb SHRIMP ages of ca 93 Ma yielded by zircon cores in a mafic eclogite collected near the Colle delle Pisse station of the Alagna-Passo dei Salati cable-car. On this ground, the eclogitic Balma ophiolite has been re-interpreted as a sliver of Late Cretaceous oceanic crust, extending from Alagna to the Stolemberg infrastructure, through the Bors valley, and believed to be representative of the N-Penninic (Valais) oceanic basin, like the Antrona unit and the ophiolitic slices inside the Swiss Furgg Zone. I do not agree with this interpretation, because of numerous cons in face of a doubtful meaning of zircon dating, e.g.: i) the Zermatt-Saas and Balma units in the Alagna-Gressoney area display the same lithostratigraphic features, structural setting, mineral composition, polyphase metamorphic evolution, deformation history, isotope dating and geochemical affinity (Dal Piaz *et al.*, 1981; Beccaluva *et al.*, 1984; Pfeifer *et al.*, 1989; Herwartz *et al.*, 2008); ii) the alleged two units are physically continuous even if boudinaged or sheared within tight synformal structures, including mylonitic serpentinites and chlorite-actinolithe schists (e.g., Stolenberg, Colle delle Pisse, Malfatta, Punta Perazzi; Fig. 18). Following previous reconstructions (Froitzheim & Manatschal, 1996; Froitzheim *et al.*, 1996; Froitzheim, 2001), Pleuger *et al.* (2007) have proposed the intra-Piedmontese to oblique opening of a Cretaceous Valais basin, the sub-penninic allocation of the Monte Rosa domain, the origin of the Sesia-Dent Blanche system from a continental fragment (labelled Cervinia) within the Alpine Tethyan ocean, and the suture of the ophiolitic Combin (Tsatè) unit between the Sesia-Lanzo and the Southern Alps, that I can not share at all.

An oceanic channel along the internal side of the Sesia-Lanzo fragment may be eventually conceived as the original country of the Ligurian-type (obducted) ophiolitic materials embodied within the sedimentary Gets nappe (e.g. Dal Piaz, 1999; Fig.19), that however was not dragged down into the subduction zone instead of the Combin zone. Ophiolitic gabbros from the Gets nappe yielded two identical U-Pb zircon ages of 166 ± 1 Ma and a $^{40}Ar/^{39}Ar$ plateau age on amphibole of 165.9 ± 2 Ma (Bill *et al.*, 1997), like in the Piedmon-Ligurian zone. Tectonic denudation of litospheric mantle and associated gabbros at the floor of the Jurassic Piedmont ocean is documented in the Lanzo massif (Lagabrielle *et al.*, 1989; Pelletier & Müntener, 2006) and in the huge Mt Avic massif (Tartarotti *et al.*, 1998; Dal Piaz *et al.*, 2010), a correlation that is strengthened by similar Eocene ages of the high-P metamorphism in the Lanzo (Rubatto *et al.*, 2008) and Avic massif (Dal Piaz *et al.*, 2001). Trace of tectonic mantle denudation in the Canavese area (discussion in Ferrando *et al.*, 2004) may be eventually envisaged within the scarce and scattered tectonic slices of serpentinized lherzolite and minor altered gabbro, long ago known within the Canavese region (Novarese, 1929; Elter *et al.*, 1966; Sturani, 1975), without supporting the existence of a true ophiolitic suite as envisaged in some modern works.

Figure 19. Western AlpineTethys.



Reconstruction of western Alpine Tethys in Late Jurassic (Dal Piaz, 1999). A) Overall restoration of Piedmont-Ligurian basin (Beccaluva *et al.*, 1984): oceanic crust with T-MORB (a) to N-MORB (b) affinity, fracture zones (c) with gabbro and/or serpentinite bodies on ocean floor. B) Details of central and western Alpine Tethys, showing Mt Emilius and Margna extensional allochthons dispersed within Mesozoic ocean. Note the Ligurian and Gets oceanic lithosphere inside the future upper plate. C) Alternative reconstruction assuming an intraoceanic origin also for Dent Blanche-Sesia domain. Not to scale.

While the existence of the Cretaceous Valais ocean (Balma units) south of the the Monte Rosa domain was suggested and emphasized, the classic Versoyen ophiolite (Martin *et al.*, 1994; Cannic *et al.*, 1996; Bousquet *et al.*, 2002) was losing their Mesozoic age and paleostructural role (Beltrando *et al.*, 2007; Masson *et al.*, 2008). Indeed, the mafic rocks of the Versoyen unit, long envisaged as derived from the Mesozoic oceanic floor of the Valais basin, recently provided Permian (Beltrando *et al.*, 2007: 272 ± 2, 267 ± 1) or Visean (Masson *et al.*, 2008: 337.0 ±

4.1) U-Pb zircon ages, resulting a Variscan ophiolitic suture (Schärer *et al.*, 2000; Masson *et al.*, 2008) or a post-Variscan igneous suite emplaced into the continental crust during a process of lithospheric stretching before the break-up of Pangea (Beltrando *et al.*, 2007, 2010a). In any case, whatever the age would be, the existence of a Cretaceous ocean in the external Penninic zone of the Western Alps becomes very improbable (Masson *et al.*, 2008), with inferences of the Briançonnais terrane itself.

Focusing on north-western Tethys, an innovative scenario of the Cretaceous tectonic setting has been proposed by Beltrando *et al.* (2007), starting from their work on the Versoyen, literature data on the Central Alps (Florinet & Froitzheim, 1994; Liati *et al.*, 2003), and previous paleostructural reconstructions given by Stampfli *et al.* (2002) and Pleuger *et al.* (2006). From south to north, a large Alpine Tethys and the Iberia-Briançonnais microplate can be recognized, followed by the Chiavenna-Balma oceanic branches (ca 95-90 Ma), the Valais intracontinental-oceanic basin and, between them, the Dora-Maira and Adula ribbon continent. This paleostructural configuration is the result of the left-lateral megashear zone operating between Europe and Iberia at ca 110-90 Ma.

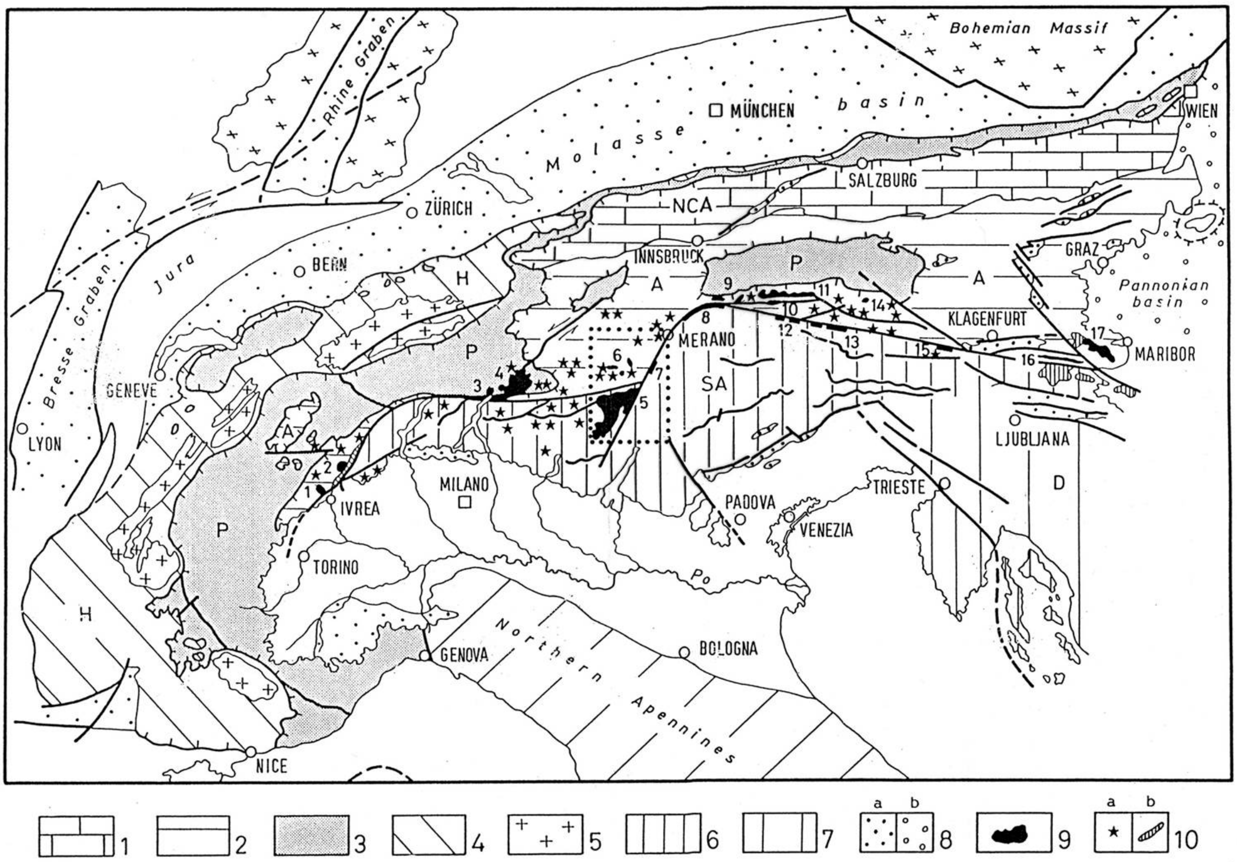
Mesozoic and older global reconstructions - Global tectonics of the perimediterranean orogenic belts was refined by Stampfli & Hochard (2009), suggesting that the East-Mediterranean basin belonged to the larger Neotethyan ocean that opened during the Permian. The Mesozoic Apulia domain grouped the autochthonous units of Greece and SW Turkey, and the unitary Adria-Apulia microplate since the Early Jurassic. A new post-Variscan continental fit for the western Tethys was presented, and inferred from the relationships between the Adriatic, Apulian and Iberian plates, as well as a detailed palinspastic model of the Alpine domain from the Late Triassic to the Miocene (Stampfli & Hochard, 2009). Thereby the geodynamic scenario for the Alpine orogeny is refined, emphasizing the contrasting evolution of the Eastern Alps-Carpathians belt with respect to the Western Alps. Generation of the former orogenic segment was related to a northward roll-back of the Maliac–Meliata slab and displacement of the Meliata suture and Austroalpine collisional belt into the eastern Alpine domain, whereas the Western Alps were characterized by the changing African plate boundary and the interaction between the Iberian–Briançonnais plate and the Austroalpine accretionary wedge (Stampfli & Hochard, 2009). The complex correlation of tectonic units within the Alps-Carpathians-Dinarides system is discussed by Schmid *et al.* (2008) and presented through a map and crustal-scale sections that provide a tridimensional view of the present structural setting and the overprinting effects of multiple deformations on these orogens.

Plate tectonic models of Paleozoic and older continental fit and geodynamic events, from spreading to subduction and continental collision, have been elaborated at a global scale by various authors (e.g. Stampfli & Borel, 2002; Stampfli *et al.*, 2002; Von Raumer & Stampfli, 2008), also strenghtening Irving's configuration of Pangea B in the Early Permian, and its transformation to Pangea B before the Late Permian (Muttoni *et al.*, 2003, 2009), or reconstructing the evolution of Adria and wandering of the Austroalpine and Southalpine basement units presently located in the Alps (Spiess *et al.*, 2010).

Adamello batholith and Periadriatic magmatism

As the Tertiary magmatism along the Periadriatic igneous belt from the Aosta Valley to the Pannonian basin is concerned (Bigi *et al.*, 1990) (Fig. 20), recent works essentially concentrated on the structural features, emplacement mechanism and rock analogue experiments, and also confirmed previous dating of intrusive bodies: see the updated review given by Rosemberg (2004), together with discussion on the problem of magma ascent and shear zones. Focusing on the composite Adamello batholith and its internal subdivision in several plutons (Bianchi *et al.*, 1970; Callegari & Gb. Dal Piaz, 1973; Callegari *et al.*, 1998), it can be mentioned that the intrusion age had been previously established for the Re di Castello southern pluton (U-Pb: 42-39 Ma; Hansmann & Oberli, 1991), whereas the great body of Rb-Sr and K-Ar mica ages (Del Moro *et al.*, 1985 a-b) well documented only the younging cooling history from the southern (42-38 Ma) to the central and northern plutons (30-29 Ma; discussion and complete refs. in Brack *et al.*, 2008). Innovating data were given for the intrusion age of the entire batholith by Mayer *et al.* (2003): U-Pb age determinations on single zircon (CRPG-Nancy) carried-out for the central and northern plutons document the existence of three main phases of zircon growth, statistically recognised at abouth 42, 37 and 31 Ma. The two older phases are mostly recorded in zircon cores, while the younger one are more frequent at the rims, regardless of zircon morphology and cathodeluminescence microstructures. The age of 42 Ma is well represented in the Corno-Alto trondhjemite (thus coeval with the Re di Castello pluton), but also in the zircon cores from Marser gabbro, Central Adamello tonalite and other northern plutons. The most frequent zircon age of 37 Ma is widespread in Central Adamello tonalites, and is often found in all other intrusive bodies. The younger ages at zircon rims (31 Ma) commonly occur (not exclusively) in the border plutons of Val d'Avio, Val di Genova and Nambrone. The presence of these three chronological clusters in several plutons suggests that zircons had been resided, episodically or continuously, in contact with a Zr-oversaturated magma over a long time-period. This also imply that the generation of the Adamello batholith was a long-lasting process involving an internal recycling of magmatic components formed in different times in a common magma chamber (Mayer *et al.*, 2003). Superheated friction-induced melts were carefully analysed in zoned pseudotachylytes occurring within the Adamello tonalites, and compared with laboratory experiments and earthquake simulations (Di Toro *et al.*, 2004, 1911; Pennacchioni *et al.*, 2006).

Figure 20. Periadriatic magmatism.



Tectonic map of the Alps and location of Tertiary magmatic bodies along the Periadriatic belt (Dal Piaz *et al.*, 1988): 1) Austroalpine decollement nappes of Northern Calcareous Alps (NCA); 2) Austroalpine basement and cover units (A); 3) Penninic nappe system (P), icluding undifferentiated flysch and ophiolite units; 4) Helvetic-Dauphinois decollement nappes and sedimentary cover (H); 5) Helvetic-Dauphinois basment units; 6) Southern Alps (SA); 7) Dinarides (D); 8) Oligocene and Neogene sedimentary basins: 8a) Bresse-Rhine graben system, Molasse foredeep, Piedmont-Langhe and Gonfolite basins, eastern Alpine intramontane basins; 8b) Vienna, Graz and Pannonian basins. Periadriatic Periadriatic magmatism: 9) intrusive bodies; 10a) dykes; 10b) flows, tuffs and volcaniclastic cover. Main plutons: 1. Traversella, 2. Biella, 3. Novate, 4. Bergell, 5. Adamello, 6. Gran Zebrù, Mare valley and Lago Verde, 7. Rumo and Samoclevo lamellae, 8. Bressanone border lamella, 9. Rensen and Mt Alto, 10. Cima di Vila, 11. Vedrette di Ries, 12-15. Lamellae and apophyses along eastern Periadriatic line, 16. Karawanken, 17. Pohorje.

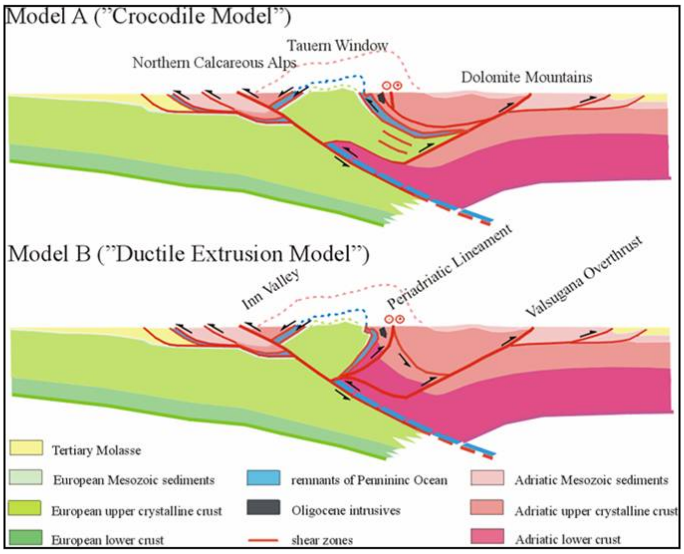
New geochemical and isotope data on some post-metamorphic lamprophyres cutting the Sesia-Lanzo zone (Owen, 2007) confirm their derivation from a metasomatized upper mantle source, as previously pointed out by Dal Piaz *et al.* (1977) and Venturelli *et al.* (1974). A questionable Rb-Sr isochron age of 44.2 ± 2.4 Ma has been obtained by Babist *et al.* (2006) from a trachyandesitic dyke which cuts the composite regional schistosity (S1+S2) and shear zones of the Sesia-Lanzo Eclogitic complex, ten years older than the well defined age of the post-metamorphic magmatism throughout the internal Western Alps, including the nearby Ayas valley.

Deep structure of the Eastern Alps

The detached Piedmont (European) slab beneath the Alpine retro-wedge, early suggested by the CROP-ECORS profile (Nicolas *et al.*, 1990; Polino *et al.*, 1990), was imaged by tomographic sounding (Lippitsch *et al.*, 2003; Kissling *et al.*, 2006) and corroborated by petrologic estimates suggesting a decrease of the thermal gradient between 50 and 44 Ma, probably due to a consistent increase of sinking velocity (Li *et al.*, 2004; Groppo *et al.*, 2009).

Passing to the Eastern Alps, a decisive step in reconstructing the deep structure of the collisional belt was given by the Transalp experiment, made by the joint efforts of Austrian, German and Italian working groups, the logical and long-awaited conclusion of CROP and NFP-20 deep seismic sounding across the Alps. This project carried out between Munich and Venice (1998-2001) simultaneous vibroseismic and explosive source recording, integrated by passive cross-lines (Bleibinhaus & Gebrande, 2005; Lüschen *et al.*, 2006). The Penninic nappe stack exposed in the Tauern window is imaged as a huge, south-vergent antiform above the Late Oligocene-Neogene tectonic ramp separating the former collisional wedge from the subducting continental crust of the European foreland down to about 55 km below the Dolomite area. The inner collisional zone and the Southalpine domain are characterized by thick-skinned backthrusting at the crustal scale. Two interpretations of the seismic image have been envisaged by the Transalp Working Group (2002), showing that the structural features of the collided European and Adriatic continental crust could be consistent to wedging of the former into the latter (crocodile model, Lammerer *et al.*, 2002) or viceversa (extrusion model: Castellarin *et al.*, 2002, 2006) (Fig. 21). The extrusion model is favoured, since indentation of the rheologically soft Penninic wedge into the relatively colder and more rigid Austro-Southalpine crust can be hardly sustained. It is also supported by the negligible Neogene uprising of the Dolomites, 6−7 times smaller than that estimated in the Tauern window. Therefore, the tip of the Southalpine lower crust is thought to have been moved against the ductile Penninic-Austroalpine wedge, along the northward dipping Periadriatic line, imaged to a depth of at least 20 km (Castellarin *et al.*, 2006).

Figure 21. Transalp deep seismic profile.



Contrasting interpretations of the Transalp deep seismic profile across the Eastern Alps: A) Crocodile model based on Pennidic wedging into the Adriatic lithosphere (Lammerer et al, 2002); B) Extrusion Model based on Adriatic indentation or northward protrusion (Castellarin *et al.*, 2002).

The combination of nonlinear inversion, high-quality teleseismic data, and a 3D crustal model allowed a reliable resolution of cells at 50 km × 50 km × 30 km (Lippisch *et al.*, 2003), hence structures as small as two cells can be resolved in the upper mantle. The tomographic images elaborated in this way by Lippisch *et al.* (2003) penetrate the upper mantle to 400 km depth, showing a high-velocity body that dips to the south-east beneath the Southern Alps in the Western and Central Alps. Anyway, the southward subduction of the European continental and oceanic lower plate along the entire Alps has been generally confirmed (e.g., Bleibinhaus & Gebrande, 2005; Castellarin *et al.*, 2006; Lüschen *et al.*, 2006).

Pre-Alpine evolution of the Grand St Bernard (Briançonnais) nappe system

The recurrent debate on the monocyclic (post-Variscan) vs polycyclic units, i.e. the “younger” and “older” basement in the Grand St Bernard (Briançonnais) nappe system, was enlivened by new dating of protoliths from various tectono-metamorphic units. Disregarding the Alpine blueschist and/or greenschist facies overprint, I refer to igneous bodies generally regarded as post-Variscan or Variscan in classic model of the French-Italian Alps (e.g. Ellenberger, 1958; Elter, 1960; Bearth, 1982; Platta & Lister, 1985; Escher, 1988; Desmons & Mercier, 1993), becoming older as follows: 1) Early Carbonifeous intrusion age of the Grand Nomenon metatonalite (356 ± 3 Ma; Bertrand *et al.*, 2000a); 2) Middle Cambrian emplacement age of metagranophyres from Mont Pourri (507 ± 9 Ma; Guillot *et al.*, 1991) and Rhemes valley (511 Ma ± 9 Ma; Bertrand, 2000a-b); 3) Cambrian-Ordovician U-Pb zircon ages (Bertrand *et al.*, 2000b) of the Peclet orthogneiss (482 ± 5 Ma), Modane-Sapey metagranite (452 ± 5 Ma) and Ambin metarhyolite (500 ± 8 Ma), showing that a major igneous and tectonic cycle developed at 450-500 Ma, with little evidence for a Variscan imprint well documented in the near Helvetic basement (Von Raumer & Neubauer, 1993; Frey *et al.*, 1999). Similar results and conclusions have been achieved in the Swiss side of the Grand St Bernard nappe system. After the new definition of the Siviez-Mischabel and Mont Fort nappes (Escher, 1988), the complex tectono-stratigraphic reconstruction was made more problematic due to the discovery of first-rank shear zones across the nappe stack and isotope dating of mafic and felsic igneous protoliths (504 ± 2 and 500 Ma ± 3: Bussy, in Sartori *et al.*, 2006). Below the Meso-Cenozoic Briançonnais cover, seven metamorphic units can be recognized (Sartori *et al.*, 2008), ranging from the Bruneggjoch (Eotriassic-Late Permian) and Col de Chassoure (Permian) monometamorphic formations to the Ergischhorn complex and Adlerflüe formation (probably Protérozoic), through the Lirec, Distulberg and Métailler formations (Cambrian ± Ordovician). Inherited zircon cores yielding 476 Ma and older ages have been recently dated within the calc-alkaline volcanic units of Permian (285-258 Ma) age occurring in the southernmost Briançonnais domain of the Ligurian Alps (Dallagiovanna *et al.*, 2009). All this opens the intriguing question on the possibility that the Brianconnais basement units underwent Cambrian events (magmatic and tectono-metamorphic) and escaped the Variscan orogeny, similar to the far French Massif Central and opposed to the near Helvetic-Dauphinois domain (e.g., Malusà *et al.*, 2005).

Western Austroalpine and ocean-continent transition

Back to the Western Alps, some contributions are really innovative, mainly through refinement of petrological estimates and new isotope dating on retentive systems, confirming the age of subduction metamorphism in the Western Austroalpine (Late Cretaceous) and in the Penninic nappe systems (Eocene), oceanic units included, as well as on their paleogeographic reconstruction. I refer to papers by Beltrando *et al.* (2010b) and Angiboust & Agard (2010) on the lower Aosta valley, and to the monography by Beltrando, Compagnoni & Lombardo (2010a) on the high-P metamorphism and the orogenic evolution of the entire Western Alps, that I have seen when long I was struggling with this Alpine review.

Roisan zone - Focusing on the Roisan zone, generally referred to as a detached metasedimentary cover unit of the upper Austroalpine Dent Blanche-M.Mary thrust system (Hagen, 1948; Diehl *et al.*, 1952; Elter, 1960; Compagnoni *et al.*, 1977; Ayrton *et al.*, 1982; Escher *et al.*, 1997; Dal Piaz, 1999; Steck *et al.*, 1999, 2001; Bucher *et al.*, 2003-04), it can be mentioned the discovery of a rich association of Late Triassic benthic foraminifers, occasionally preserved within dolomitic bodies in the Grand Pays range, high St Barthélemy valley (Ciarapica *et al.*, 2010). A comparative work (Passeri *et al.*, in progress) shows the important lithostratigraphic differences between the Roisan and Mt Dolin successions (Fig. 22).

A pending problem is the unique outcrop of banded micro-quartzites discovered by Ballevre & Kienast (1987) inside the Arolla series, over the Cignana lake, referred to the Mesozoic metasedimentary cover of the Dent Blanche nappe (Roisan Zone), and interpreted as a metamorphic derivative of a Mn-rich and oxidized siliceous deposit (metaradiolarite?). This is a metric bed included within a folded and boudinaged horizon of calcschists and impure marbles, often mylonitic, consisting of the alternance of white, black, pink and purplish thin quartzitic layers with various amounts of almandine and spessartine-rich garnet, hematite, blue amphiboles (crossite-magnesioriebeckite), Fe-epidote, Piedmontite, chlorite, biotite, stilpnomelane, apatite, allanite, titanite. Preliminar SHRIMP dating on allanite (Manzotti *et al.*,

2009) provided Permian (ca 280 Ma) and scattered Jurassic ages (190-160 Ma), whereas titanite in associated marbles yielded apparent spot ages between 284 and 160 Ma. The hydrothermal mineralization and the Jurassic age point for an oceanic environment, and thus for a Piedmont affinity because i) similar Mn- and Fe-rich quarzites are relatively abundant within the underlying Combin Zone (Dal Piaz & Omenetto, 1978; Dal Piaz *et al.*, 1978), ii) the post-Triassic Dolin-Roisan sequences are represented by micritic marbles and polymict sedimentary breccias (Hagen, 1948; Ayrton *et al.*, 1982), iii) no further Fe-Mn quartzites have been recognized throughout the Roisan zone, recently mapped at 1:10.000 scale (Foglio Monte Cervino of the 1:50.000 Carta Geologica d'Italia, data set at Regione Autonoma Valle d'Aosta). The allanite Permian ages (Manzotti *et al.*, 2009), if confirmed and geologically meaningful, could be referred to clastic materials supplied by eroded granitoids of the Arolla series that yield a similar primary age (Bussi *et al.* 1998), making questionable, in this case, the favoured Piedmont affiliation.

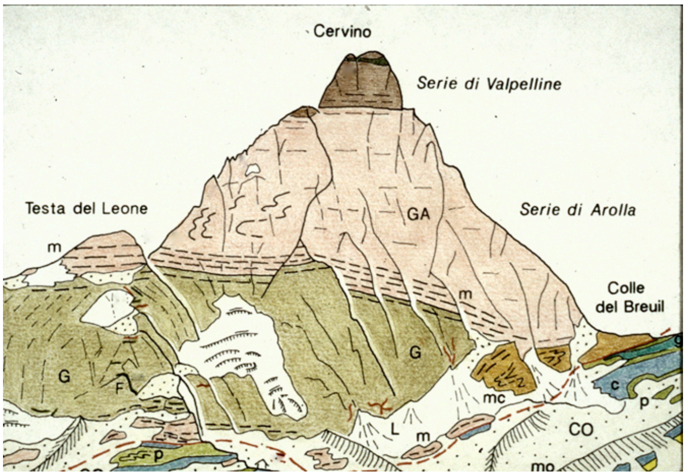
Figure 22. Roisan and Mt Dolin metasedimentary cover units.

Left – Collapsed Grand Pays summit (trench), consisting of dolomitic marble and breccia with Late Triassic foraminifers (Ciarapica *et al.*, 2010). Right - Mt Dolin: sedimentary breccia of assumed Jurassic age (Hagen, 1948; Ayrton *et al.*, 1982).

Permian gabbros - The already envisaged Permian age of the monometamorphic Matterhorn-Mt Collon gabbros (Fig. 23) inside the Arolla series of the Dent Blanche nappe (Dal Piaz *et al.*, 1977) has been confirmed and refined by Monjoie *et al.* (2007), providing concordant U-Pb zircon ages of 284.2 ± 0.6 Ma and 282.9 ± 0.6 Ma for the layered mafic complex of the Mt Collon body and a crosscutting leucocratic dyke, respectively, togheter with a ^{40}Ar/^{39}Ar age of 260.2 ± 0.7 for a later Fe-Ti-rich lamprophyre. Similar Early Permian ages had been obtained by Bussy *et al.* (1998) for the protoliths of the Sermenza metagabbro (288 Ma), north-eastern edge of the Sesia-Lanzo zone, and the gneissic granitois of the Italian southern face of the Matterhorn (289 ± 2 Ma).

Sesia-Lanzo zone - Working on the entire Sesia-Lanzo Zone, Babist *et al.* (2006) corroborated the concept that this composite nappe system is a relic of the subducted part of the Adriatic continental margin along the internal boundary of Tethyan ocean (Dal Piaz *et al.*, 1972; Compagnoni *et al.*, 1977). Three basement nappes have been recognized therein, that developed during the Late Cretaceous (80-65 Ma) subduction-related reworking of shear zones, early generated by continental rifting, i.e.: i) Bard nappe, mostly corresponding to the Gneiss minuti complex (Gastaldi, 1871-74), ii) Mombarone nappe, corrsponding th the Eclogitic micaschists complex (Stella, 1894), iii) IIDK, high-grade basement rocks similar to the diorito-kinzigitic Ivrea Zone (Artini & Melzi, 1900). The Bard and Mombarone nappes are partly separated by a discontinuous horizon of Mesozoic metasedimente (Bonze unit; Venturini, 1995). Five Alpine deformations phases and six fabric domains have been distinguished and schematically figured. New Rb-Sr mineral dates constrain the age of D2 transpressional blueschist shearing D2 (60–65 Ma) and D3 extensional greenschist facies shearing (45–55 Ma), indicating that, in Eocene times, top-SE extensional exhumation of Sesia-Lanzo was coeval with SE-directed subduction of the Ligurian-Piedmont oceanic lithosphere. This reconstruction goes against the recurrent hypothesis of exhumation through an extensional phase developed after any high-P metamorphic event in the Austroalpine-Penninic collisional wedge (e.g., Ballèvre & Merle, 1993; Avigad *et al.*, 2003; Rosembaum & Lister, 2005). In particular, the latter authors envisaged a widespread phase of tectonic extension troughout the collisional belt at about 42–38 Ma, thought to be induced by a rapid retreat of the subduction hinge below the accreting Grand St Bernard (Briançonnais) nappe system (Stampfli *et al.*, 1998; Stampfli & Hochard, 2009).

Figure 23. Geology of Italian southern face of the Matterhorn.



From top to bottom: mainly retrogressed kinzigitic complex of Valpelline series; coarse- to fine-grained and folded gneissic granitoids of Arolla series (GA), from Permian protoliths; Permian gabbro (G) with a thick mylonitic horizon (m) between them and at the base; basal slice of micaschists; calcschists (c), prasinites (p) and mylonitic gabbros (dark green) in the underlying Combin zone (Dal Piaz, 1992; Bucher *et al.*, 2003, 2004).

Ocean-continent transition in the lower Aosta valley – Three classic sections of the eclogitic Zermatt-Saas ophiolite (Mt Avic, Breuil-Ayas and Täsch, near Zermatt) have been carefully mapped and investigated by Angiboust & Agard (2010) for evaluating the extent to which the hydration of the oceanic lithosphere and related density decrease would have prevented the definitive disappearance into the subduction zone of detached high-P fragments of the oceanic lithosphere, and assisted their rapid uplift along a serpentinized subduction channel. Large amounts of fluids were provided by sea-floor alteration and hydrothermal processes to oceanic basalts and mantle peridotites, now represented by various high-P mafic rocks (lawsonite eclogites, glaucophanites, garnet-chloriteschists) and serpentinites. Additional references may be suggested for the Italian areas, concerning: i) Savoney-Mezove (Avic) ophiolitic complex, at the base of the Glacier-Rafray continental basement slices: this zone, also mapped by Dal Piaz, Nervo & Polino (1979), was described in detail by Dal Piaz & Nervo (1971), including four whole-rock analyses of the same ophiolitic suite studied by Angiboust and Agard; ii) Breuil-upper Courtod valley (Ayas): see “From the European continental margin to the Mesozoic Tethyan ocean: A geological map of the upper Ayas valley (Western Alps)” (Dal Piaz, 2004), in “Mapping Geology in Italy”, by APAT-Servizio Geologico d’Italia.

The eclogitic lower Austroalpine Etirol-Levaz slice has been studied and dated by Beltrando *et al.* (2009b, 2010b). A mylonitic orthogneiss from the bottom of the slice, near the contact with the underlying serpentinites and gabbros of the Zermatt-Saas zone, and an eclogitic boudin inside paraschists from the middle of the slice were analyzed, both providing in situ U-Pb zircon ages. The former sample yielded Permian and Jurassic (166–150 Ma) zircons, and the latter ages are attributed to melt infiltration associated with the intrusion of the underlying gabbros. Zircons from the eclogitic boudin yielded Late Permian ages (ca. 263-253 Ma) in zoned cores, and Eocene ages (47.5 ± 1.0 Ma) in unzoned rims, like in several previously quoted eclogitic occurrences of the Zermatt-Saas zone. In spite of the existence of a tectonic contact between the continental and oceanic units, the interpretative model proposed by Beltrando *et al.* (2010b) suggest the existence of a primary lithostratigraphic association of mantle serpentinites, continent-derived allochthons, Jurassic oceanic gabbros and post-rift sediments, typical of an ocean-continent transition, and probably representative of a hyper-extended margin related to Tethys opening. This heterogeneous crustal association, acquired before the Alpine orogeny, was characterized by a negative buoyancy that facilitated, as pointed aut in previous works (e.g., Dal Piaz, 1999), the onset of lithospheric subduction.

Subduction metamorphism and orogenesis: a last Alpine perspective.

The monography by Beltrando, Compagnoni & Lombardo (2010) on the high-P metamorphism and the orogenic evolution of the Western Alps is a detailed, updated and well documented contribution that I am pleased to agree with as a whole (not only for the kindness with which they have reported my previous work). The Western Alps are described as the amalgamation of a Cretaceous and an Eocene orogen, which developed at the expense of the Adriatic and European rifted margins. This concept is supported (apparently) by the gap of about 30 Ma between the subduction age of the Sesia-Lanzo and upper Austroalpine outliers and that of the Zermatt-Saas, Monte Rosa and Gran Paradiso nappes. I am sure, however, that authors share the paradigm that, instead of two distinct orogens, in the Western Alps there is only a lack of surface records (lithotectonic bodies and/or isotope dating and partitioning effects), or of information on lesser appealing non-eclogitic units, since plate convergence was a continuous global process at least from the “mid” Cretaceous. It is right that the Combin and Zermatt-Saas ophiolitic units were juxtaposed during exhumation in the Late Eocene (38 Ma), but is not documented and unlikely that these oceanic fragments underwent their contrasting pressure peaks at the same time (40-44 Ma): it can be recalled that the age of the poorly preserved blueschist facies relics in the Combin zone across the Aosta valley and southern Valais is essentially unknown, but it is probably older (at least in places) than the eclogitic imprint in the Zermatt-Saas nappe, since the former acted as tectonic sole of the upper Austroalpine units during their accretion-exhumation history. Moreover, it can be remembered the evidence of orogenic deposits accumulated in the outward migrating oceanic trench and later displaced in various decollement nappes (see Caron *et al.*, 1989, and Polino *et al.* 1990, for reviews). Hence, in my opinion the paradigm that the Alpine orogeny is a discrete process related to the episodic accretion and exhumation of continental and oceanic units (e.g., Rubatto *et al.*, 1998; Gebauer, 1999; Rosenbaum & Lister, 2005) is a reductive and unilateral view. I thank very much the authors (and also Handy *et al.*, 2010) for having attributed the original idea of the so-called “tectonic erosion” to the subduction model elaborated by Dal Piaz *et al.* (1972), but I do not believe that this is actually true, at least in the sense of Polino *et al.* (1990), a theory not yet conceived at that time and in any case unkown to me. In subsequent papers (Dal Piaz, 1974; Compagnoni *et al.*, 1977; Dal Piaz & Polino, 1989), the boundary of the convergent plate margin at the incoming subduction is mapped along the contact between the Austroalpine and Southalpine domains, becoming intraoceanic within the Ligurian basin, allowing the obduction of the Ligurian ophiolitic nappe. 4) Among the main four age groups of high-P minerals recognized in the Western Alps (70Ma; 55 Ma; 48–42Ma; 38–33 Ma) after more than four decades of extensive geochronological studies, the second one (ca 55-47 Ma) deserves a short comment. It is based on high-P zircon and allanite dating from the Lanzo massif (Rubatto *et al.*, 2008) and K-Ar white mica ages from the detached Mesozoic cover (Mt Dolin) of the Dent Blanche nappe (Ayrton *et al.*, 1982), with a large spread from 55 to 34 Ma. Whilst the former is a robust dating of the high-P metamorphism in a slice of oceanic lithosphere, the latter probably groupes mixed to greenschist facies ages as it can be inferred from the Rb-Sr white mica mixed (57 ± 6, 52 ± 1.3) and blueschist facies (75-74 Ma) ages recorded at the same strutural level in the frontal part of the Sesia-Lanzo Gneiss minuti complex and in the Pillonet klippe, respectively (Cortiana *et al.*, 1998). I shall also mention that the Rb-Sr and ^{40}Ar-^{39}Ar dates of Cortiana *et al.* (1998) on the Sesia-Lanzo mylonitic metagranitoids in the Ayas valley are ignored by Babist *et al.* (2006).

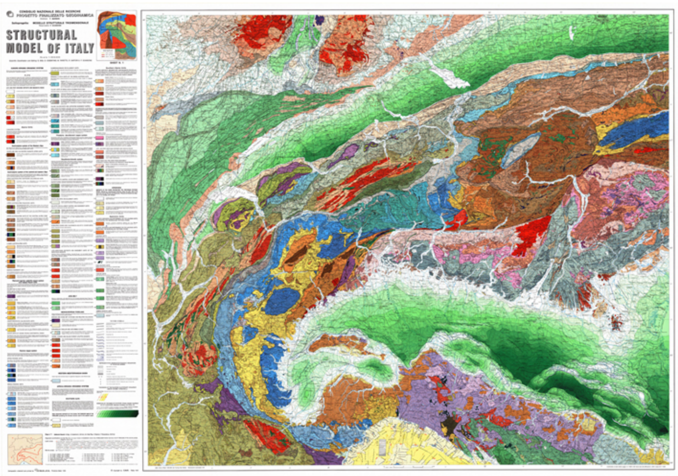
The new Geological Map of Italy

Our historical journey is ended and it may be concluded with some informations and comments on the new Carta Geologica d’Italia at 1:50,000 scale (Progetto CARG). The project started in the 1988 and it was based on the cooperation between the Italian State (SGN-ISPRA) and the Regions, involving more than 60 local authorities, CNR Institutes and University Departments. The mapping project consists of 652 geological sheets, surveyed at 1:10,000 scale and completed with sections, explanatory notes and digital database. Only 257 sheets are currently printed or in progress, covering 40% of Italy (for the state of the art, see the site ISPRA, Progetto CARG). In the Western Alps only the Bardonecchia, Chatillon, Torino, Sanremo and Susa sheets are printed, and in the Eastern Alps the sheets Adamello, Ampezzo, Appiano, Asiago, Cortina, Malè, Maniago, Merano, Rabbi, Riva del Garda, San Vito al Tagliamento. Tione, Trento, Udine. The great delay has many causes and is often attributable to the authors, but also to national and local authorities. For instance, the Vetta d'Italia sheet was printed as a 1:25,000 regional map in the 2004, but the 1:50,000 sheet (003) and its explanatory note, long ready for printing, have not been appeared yet only for an inexplicable negligence of the Provincia Autonoma di Bolzano. Anyway, even sadder for the degraded national environment is that most of the maps have not been assigned yet. The completion of the mapping project is a primary need, since a modern geological sheet and its database are the unavoidable groundwork for a correct recognition of natural risks and their mitigation.

Explanatory notes of the structural model of Italy

The Alpine chain and its tectonic and lithological features are represented in the sheets 1, 2 and 3 of the Structural Model of Italy, scale 1:500,000 (Bigi *et al.*, 1990, 1993), printed by SELCA, Firenze. Sheet 1 represents two-thirds of the Alps, from the western arc to the middle of the Tauern window.

Figure 24. Structural Model of Italy.



Sheet 1 of the Structural Model of Italy, scale 1:500,000 (Bigi *et al.*, 1990), extending from the Western and Central Alps to the middle of the Eastern Alps (Tauern window). The entire model can be seen in the site e-Geo (http://www.egeo.unisi.it/).

Sheet 2 shows the easternmost Austrian and Slovenian part of the belt, up to the Neogene Vienna and Styria (western Pannonian) basins, including the famous high-P Saualpe-Koralpe-Pohorje basement units and the most eastern ophiolitic occurrence inside the Rechnitz window. Sheet 3 comprises only a minimal part of the belt, i.e. the south-easthern edge of the French-Italian arc, from the Penninic Helmintoid flysh and Subalpine chains to the foreland basement and cover units of Provence. These maps can be seen in the site e-Geo (http://www.egeo.unisi.it/), and a low-resolution image of sheet 1 is included here as Figure 24.

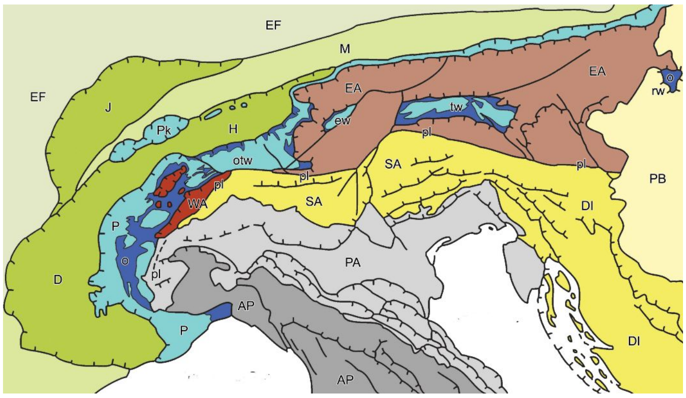
The Structural Model of Italy was the central task of the Progetto Finalizzato Geodinamica promoted by the Italian Research Council (CNR). It constituted the most important and fruitful integration of scientists with geological and geophysical background towards a three-dimensional reconstruction of the anatomy of Italy and its geodynamic evolution, supported by Antonio Praturlon and led by Paolo Scandone and Carlo Morelli. Focusing on Alpine maps, I have drown the entire Europe-vergent chain, by generalizing regional and local maps at various scales, with contributions of Messiga (Voltri Group), Vanossi (Ligurian Briançonnais), Pognante and Polino (Lanzo and Susa ophiolites), Bigioggero, Montrasio, Notarpietro and Potenza (Ossola-Valtellina), Gatto and Gregnanin (Venosta valley-Brenner Pass), Rybach (isobaths of Molasse foredeep), Plöchinger (Northern Calcareous Alps), Beck-Mannagetta (northern Grauwackenzone), Austrian Oil Agency (isobaths of Austrian basins). The Adria-vergent Southern Alps were compiled by the Southalpine working group coordinated by Castellarin and Vai, and the Po plain subsurface features by AGIP Mineraria. The elaboration of these maps was an exciting adventure, but it was a long and exhausting work: the enthusiasm and forces of coordinators and authors ran out, so that the maps were printed without the explanatory notes. This is probably the principal reason because the Structural Model is poorly mentioned. I warmly recommend the use of these maps that can facilitate the first approach of students and non-specialist readers toward the Alpine geology, together with special issues and regional overviews, concerning for instance the French-Italian Alps (Roure *et al.*, 1990; Dal Piaz, 1992, 1999; Vanossi, 1992; Michard *et al.*, 1996; Beltrando *et al.*, 2010; Compagnoni *et al.*, this volume), Switzerland (Trümpy *et al.*, 1980; Pfiffner *et al.*, 1997), Austria (Flügel & Faupls, 1987; Neubauer, 1992; Plöchinger, 1995; Kurz *et al.*, 1998b; Neubauer & Höck, 2000), Southern Alps (Bertotti *et al.*, 1993; Castellarin *et al.*, 1993, 2006; Cita & Forcella, 1998; Castellarin & Cantelli, 2000; Vai *et al.*, 2002; Doglioni & Carminati, 2008; Gaetani, this volume), tectonics (Coward *et al.*, 1989, Ratsbacher *et al.*, 1991; Schmid *et al.*, 2004), paleostructural restorations and pre-Mesozoic geology (von Raumer & Neubauer, 1993; Schmid *et al.*, 2008; Stampfli & Hochard, 2009), metamorphic features (Frey *et al.*, 1999; Oberhänsli *et al.*, 2004) and geochronology (Hunziker *et al.*, 1992; Rubatto *et al.*, 1998; Gebauer, 1999; Thöni, 1999).

Geological outline of the Alps

According to the sense of tectonic transport toward the foreland, the Alps are currently subdivided into two belts of differing size, internal frame, age and geological meaning: 1) the Europe-vergent belt, a thick collisional wedge of Cretaceous-Neogene age, consisting of continental and minor oceanic units radially displaced towards the Molasse foredeep and European foreland; 2) the Adria-vergent Southern Alps, a minor, shallower (non-metamorphic), ophiolite-free and younger (Neogene) thrust-and-fold belt displaced southwards to the Padane plain, which developed inside the previous Alpine hinterland (retro-wedge) of the Adriatic upper plate, far from the oceanic suture. These antithetical belts are juxtaposed along the Periadriatic (Insubric) lineament, a major fault system generated or re-activated during Oligo-Neogene times.

This structural reconstruction is synthetized in Fig. 25, a tectonic map of the Alps and Northern Apennine directly inferred from the Alpine sheets of the Structural Model of Italy, showing the main structural domains and thrust planes. The map covers nearly the same area of the satellite image in Fig. 1, including the Po plain and Northern Apennine. From top to bottom and from the inner to the outer side, the principal Europe-vergent tectonic domains are: i) the Austroalpine multi-nappe and polyphase system, derived from the Adriatic (s.l.) continental margin, which mainly developed during the Cretaceous (eoalpine orogeny); ii) the Penninic zone, a stack of metamorphic nappes scraped off the subducting oceanic lithosphere, European passive margin and ribbon continents, characterized by Tertiary high-P metamorphism and mainly accreted during the Paleogene; its outer boundary is the Penninic frontal thrust; iii) the Helvetic zone, consisting of shallower basement slices and decollement cover units derived from the European margin after the closure of the Valais basin, mainly imbricated from the Late Oligocene onwards. The stacking order of nappes and the age of metamorphic events and related deformations are tought to be representative, with caution and generally, of the outward propagation of the orogenic wave.

Figure 25. Tectonic map of the Alps.

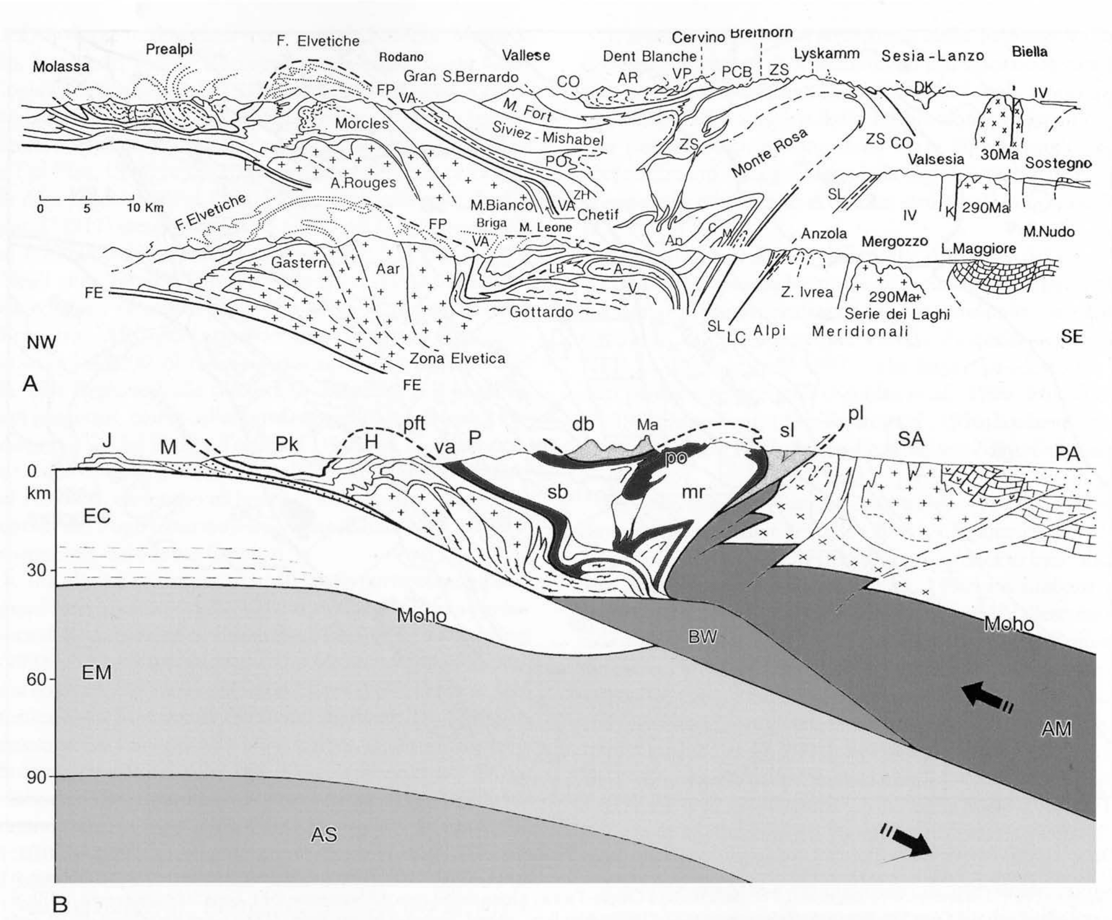


Tectonic map of the Alps. (1) Europe-vergent collisional belt: i) Western (WA) and Eastern (EA) Austroalpine; ii) Penninic domain: continental and ophiolitic (o) nappes in western Alpine arc (P) and tectonic windows (otw: Ossola-Tessin, ew: Engadine, tw: Tauern, rw: Rechnitz); Prealpine klippen (Pk); iii) Helvetic-Dauphinois (H-D) domain and Jura belt (J); iv) Molasse foredeep (M). (2) Post-collisional antithetic (south-vergent) belt of Southern Alps (SA), bounded by the Periadriatic lineament (pl). Dinaric (DI) and Apenninic (AP) thrust-and-fold belts. Pannonian basin (PB), European (EF) and Padane-Adriatic (PA) forelands (Dal Piaz *et al.*, 2003).

The Helvetic units are thrust over the Molasse foredeep, a northward-thinning sedimentary wedge which developed from the Oligocene to the Late Miocene, with multiple successions of shallow marine and freshwater deposits. Its imbricated inner zone (Subalpine Molasse) was extensively dragged southwards below the frontal nappe stack. In the outer French-Swiss Alpine arc, the Molasse basin is bounded by the thin-skinned Jura fold-and-thrust belt of Late Miocene-Early Pliocene age.

The interior of the Alps has been revealed by the above-mentioned deep seismic experiments: two independent Moho surfaces have been recognized (Fig. 13, 21), i.e. the Adriatic and the underlying European Moho, the latter gently bending from the undeformed foreland to the base of the thick collisional wedge and further south (Figure 26). This means that the Alps display a lithospheric asymmetry, the orogeny was dominated by Europe-vergent displacements, and the antithetic Southalpine belt is only a superficial and late feature of the Adriatic upper plate. If surface geology is integrated with interpretation of seismic images, the Europe-vergent orogen is a mantle-free crustal wedge which tapers to the north, floating over the current European lower plate, and indented, to the south, by the current Adriatic (Southalpine) lithosphere (Figure 26).

Figure 26. Crustal and litospheric section of North-Western Alps.



(A) Crustal section (modified from Dal Piaz, 1992) - Main structural features of the exposed collisional belt in the north-western Alps by superposition of the Aosta-Valais section (structural depression) over of the Ossola-Tessin dome, modified from Argand (1909), Escher *et al.* (1988) and Dal Piaz (1992). From top to bottom 1) Western Austroalpine: 2a Diorite-kinzigitic zone (DK), Valpelline series (VP), Arolla series (AR), Sesia-Lanzo zone (SL), Fobello-Rimella (FR) shear zone along the Canavese line (CL). 2) Ophiolitic Piedmont zone derived from the closure of the Ligurian-Piedmont ocean, including the composite Combin zone (CO), Zermatt-Saas unit (ZS) and Antrona unit (An). 3) Upper-Lower Penninic basement and cover nappes: Monte Rosa, Portiengrat (Pt), Camughera-Moncucco (CM), Pontis (PO), Zone houillère (ZH), Berisal (B), Monte Leone (ML), Lebendun (LB), Antigorio (A), Verampio (V); outer-lower Penninic Sion-Courmayeur and Valais units (VA). 4) Helvetic-Dauphinois domain: see cartoon for details. 5) Frontal-basal thrusts of the Penninic (FP) and Helvetic (FE) nappe stack. 6) Southern Alps: Laghi series (SLA), including Permian granites, and Ivrea-Verbano (IV) lower crust. Oligocene magmatism (32-30 Ma): Biella and Miagliano intrusives (30 Ma) are also shown, without labels.

(B) Lithospheric section (from Dal Piaz, 1997, modified) - 1) Western Austroalpine: Sesia-Lanzo inlier (sl) and Dent Blanche nappe s.l. (db), including the Matterhorn-Monte Cervino (Ma). 2) Penninic domain (P): Piedmont ophiolitic units (po), Monte Rosa (mr) and Grand St Bernard (sb) nappes, lower-outer Penninic Valais zone (va), Penninic klippen (Pk), Penninic frontal thrust (pft). 3) Helvetic basedment slices (crosses, dashed), adherent cover units and decollement cover nappes (H). 4) Oligocene-Neogene Molasse foredeep (M). 5) Jura belt (J). 6) Buried wedge (BW) of European mantle or high-P lower crustal units. 7) European lithosphere: continental crust (EC) and mantle (EM) of subducting lower plate; asthenosphere (AS). 8) Adriatic lithosphere (SA): antithetic (south-vergent) retro-wedge belt of the Southern Alps (SA) and mantle (AM); Canavese line, Periadriatic fault system (pl). 8) Padane-Adriatic foreland (PA).

The orogenic wedge groups the Austroalpine, Penninic and Helvetic superunits, and may be subdivided into three diachronous parts: 1) the older and upper part (Eastern Austroalpine) is a large nappe stack, including a subduction complex which developed before the Late Cretaceous deposition of Gosau beds; 2) the inner-axial part (Western Austroalpine-Penninic) is a pre- to syn-collisional subduction complex that was generated from the Late Cretaceous to the Eocene, includes the Adria/Europe collisional zone marked by one or more ophiolitic units (at different structural levels), and displays polyphase metamorphism evolving from diachronous blueschist or eclogite facies imprint (Late Cretaceous-Eocene subduction), locally coesite- and diamond-bearing, to high-T Barrovian overprint (mature collision, slab breakoff) of Late Eocene-Early Oligocene age, cut in turn by the Periadriatic magmatism (32-30 Ma); 3) the outer and younger part (Helvetic-Dauphinois) consists of shallower basement slices and largely detached cover nappes which derived from the European continental margin, escaped the subduction low thermal regime and, from the Oligocene, were accreted in front of the exhumed Austroalpine-Penninic wedge; pre-Alpine features are well preserved in the basement units even if in places they display a Barrovian metamorphic overprint (Frey *et al.*, 1999; Oberhänsli *et al.*, 2004).

The essential features of the Europe-vergent Austroalpine, Penninic and Helvetic tectonic domains and the antithetic Southern Alps are briefly outlined in follows, starting from the Structural Model of Italy (updated legend) and based on the review of the Alps (Dal Piaz *et al.*, 2003) elaborated for the International Geological Congress in Florence (2004), and on the recent, previously cited literature.

Austroalpine

The Austroalpine is subdivided into two sectors (eastern and western), based on contrasting distribution, structural position, and main deformation age, as pointed out in the first part (Bigi *et al.*, 1990; Dal Piaz *et al.*, 2003; Oberhänsli *et al.*, 2004; Schmid *et al.*, 2004).

Eastern Austroalpine

The Eastern Austroalpine tectonic system is a thick stack of cover and basement nappes located on top of the Europe-vergent belt, extending from the Swiss/Austrian border to the Vienna and Pannonian basins (Fig. 27). Its allocthony over the Penninic zone is marked by some ophiolitic units of debated provenance exposed in the Engadine, Tauern and Rechnitz windows. To the north, the Austroalpine system overrides the outer-lower Penninic Rheno-Danubian flysch belt of Cretaceous-Eocene age and, to the west, the ophiolitic Platta-Arosa nappe, as well as, south of the Engadine sinistral strike-slip fault, the Margna basement unit, generally correlated since Staub’s work (Fig. 7) to the Dent Blanche nappe. To the south it is juxtaposed to the continental crust of the Southern Alps along the Tonale-Pusteria-Gailtal-Karawanken (Periadriatic) fault system. The kinematic evolution of the Eastern Austroalpine is constrained by eclogitic to Barrovian fabrics dated as “mid” Cretaceous (eoalpine), and by Gosau beds (Coniacian-Eocene intramontane basins) that seal major thrusts, therefore the essential tectono-metamorphic history of the Eastern Austroalpine is older than that (Late Cretaceous-Eocene) recorded by the Western Austroalpine. The main tectonic transport inferred from kinematic indicators was first to the north or north-west and then to the north.

The Eastern Austroalpine is subdivided into two (Matura *et al.*, 1980; Spicher, 1980: Tectonic Map of Switzerland; Structural Model of Italy, 1990; Schmid *et al.*, 2004; Schuster *et al.*, 2004) or three main groups of nappes (classic Austrian literature, e.g. Neubauer & Höch, 2000, Fig. 27), often with different assumptions and results. The Upper and Middle Austroalpine correspond in general to the Upper Austroalpine in the Structural Model of Italy. The subdivision used in follows is based on the present-day geometrical sequence of the nappe stack, from top to bottom, without paleogeographic inferences.

Upper Austroalpine – On the top of the nappe stack we can see the Northern Calcareous Alps and some Paleozoic basement nappes. The Northern Calcareous Alps are an imbricated pile of decollement cover nappes forming a 500 km-long belt extending from the Swiss eastern edge to the Vienna basin (Plöchinger, 1995; Mandl, 2000; Behrmann *et al.*, 2006). These cover sheets are made up of Permian and/or Mesozoic clastic to carbonate deposits, including platform (Hauptdolomit) and basin (Hallstat) sequences, mainly detached from the Graywacke zone along evaporite-bearing shales. Their origin is controversial. The Paleozoic basement units are located west (Steinach klippe), south-east (Gurktal nappe, Graz Paleozoic) and north (Graywacke zone, Grauwackenzone) of the Tauern window. These units consist of Early Paleozoic to Middle Carboniferous metasediments and discordant Late Carboniferous to Tertiary covers, with a greenschist to very-low-grade Alpine imprint (e.g., Sassi & Menegazzo, 1971; Oberhänsli *et al.*, 2004; Schuster *et al.*, 2004).

The underlying group of nappes (Middle Austroalpine in Neubauer & Höch, 2000, and some other reconstructions) put together most of the huge crystalline basement and minor cover units of the Eastern Alps, i.e. the Silvretta, Oetztal and Ortler-Campo nappes, west of the Tauern window, followed to the south by the Ulten-Tonale nappe, a fragment of Variscan lower continental crust with eclogitic relics and slices of garnet-spinel peridotite (Godard *et al.*, 1996; Martin *et al.*, 2009; Scambelluri *et al.*, this volume). The Silvretta nappe is a large crustal fragment located north-west of the Engadine window, which overrides the ophiolitic Platta-Arosa nappe and the Lower Austroalpine Bernina (to the south-west) and Landeck Phyllite units (to the north). It consists of a polymetamorphic basement which is dominated by Variscan and older mineral assemblages in various P-T conditions (sillimanite, kyanite and later andalusite), and is discontinuously overprinted by a very low-grade to greenschist facies Alpine retrogression (Magetti *et al.*, 1987; Frey *et al.*, 1999). Its Mesozoic cover is only preserved in the south-western edge of the nappe.

The Oetztal nappe is exposed between the Engadine and Tauern windows. It is a large and essentially coherent fragment of polymetamirphic basement which overrides the Penninic units of Engadine, the Landeck Phyllite and the Mesozoic metasediments of Scarl nappe, along the Schlinig thrust. Moreover, the Oetztal nappe plays as the hangingwall of the Brenner detachment and is juxtaposed to the Lower Austroalpine Insbruck Phyllite along the northern extension of the Brenner line. The basement is represented by paragneisses and micaschists with gneissic granitoids (Late Ordovician protoliths), minor mafic bodies, and some marbles. Scattered remnants of Permian-Eotriassic silico-clastic metasediments and Mesozoic marbles are preserved in the eastern side, tectonically capped by the Steinach nappe. The high-grade fabric is mainly Variscan, marked by kyanite, sillimanite or andalusite index-minerals in distinct sectors (Neubauer *et al.*, 1999; Neubauer, 2002; Schuster *et al.*, 2004). The eolpine overprint (Thöni, 1999) ranges from very low-grade (northern Oetztal) to greenschist (chloritoid), amphibolite (staurolite-kyanite, southern Oetztal), and local eclogite facies conditions on mafic rocks in a south-eastern lower subunit (Hoinkes *et al.*, 1991, 1999; Miller. & Thöni, 1995; Schuster *et al.*, 2004; Thöni, 2006).

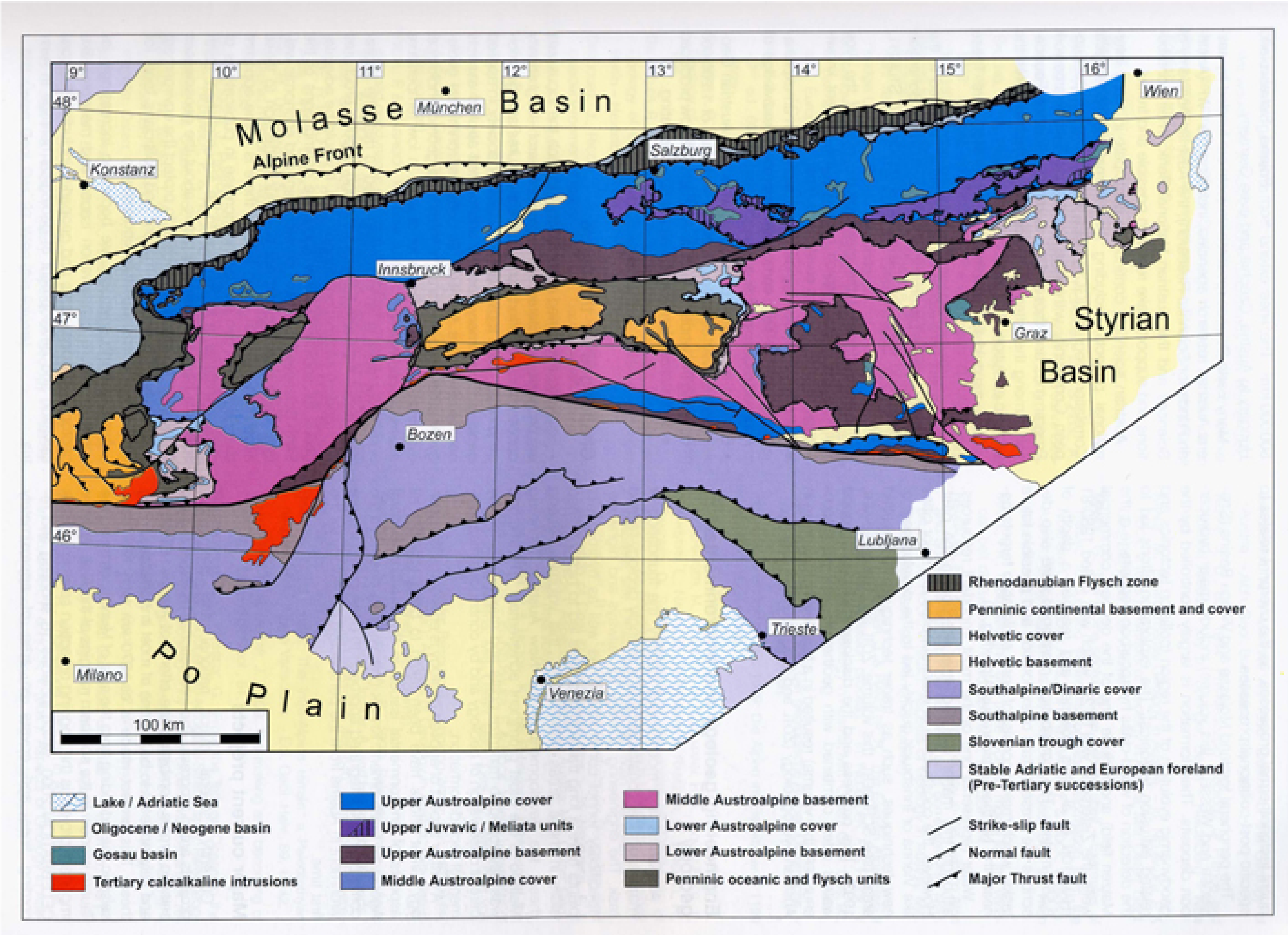
The Ortler-Campo nappe nappe groups crustal slices of polimetamorphic basement and monometamorphic Permian-Mesozoic cover sequences. The former mainly consists of quartz-phyllites, micaschists and paragneisses with beds of marble and quartzite, and transposed bodies of gneissic granitoids from pre-Variscan protoliths. The latter consists of a Permian-Eotriassic clastic and evaporitic basal series, followed by dominant Triassic dolostones and marbles, extending from the Engadine to the Ortler massif. The nappe is characterized by a pre-Alpine greenschist to amphibolite facies imprint and an eoalpine low-grade retrogression mainly along shear zones, cut in turn by andesitic dykes and tonalite-gabbro intrusions of Oligocene age (Martin *et al.*, 2009).

The central sector of the Easter Austroalpine, south of the Tauern window, is represented by the Mules-Merano-Anterselva complex and Schober-Kreuzeck groups, the narrowed eastern extension of the Oetztal basement. Differential uplift along the Deferegger-Anterselva-Valls fault (DAV) allowed the preservation of pre-Alpine amphibolite facies features and radiometric dating in the southern block, formed by micaschists, paragneisses, migmatites, amphibolites, marbles and gneissic granites from pre-Variscan protoliths, whereas in the northern block retrogressed rocks and phyllonites of eoalpine and later age are dominant (Borsi *et al.*, 1973, 1978; Sassi *et al.*, 1974), including relict eclogites of debated eoalpine age (Schober group).

From the Tauern window to the eastern end of the Alps, the Upper Austroalpine groups various basement and cover units, partly similar to those summarized above. The most important are, from top to bottom: the polyciclic Muralpen units, including the Micaschist-Marble complex (Niedere Tauern), the Speick complex (early Variscan ophiolite) and the Gleinalpe-Rennfeld core complex, followed by the Koralpe-Saualpe (Koriden) and Sieggraben basement units and the Pohorje massif which, as previously seen, are characterized by the occurrence of eoalpine eclogites from Permian mafic protoliths (Thöni, 1999, 2006; Sassi *et al.*, 2004; Janak *et al.*, 2006).

Lower Austroalpine - The Lower Austroalpine includes some basement and cover units located below the Upper (Middle) Austroalpine system and generally referred to as Lower Austroalpine: these units are exposed in the western (Err-Bernina), central (Innsbruck Quartz-Phyllite, Radstatt system) and eastern (Semmering-Wechsel window) ranges of the Eastern Austroalpine.

Figure 27. Overview map of the Eastern Alps.

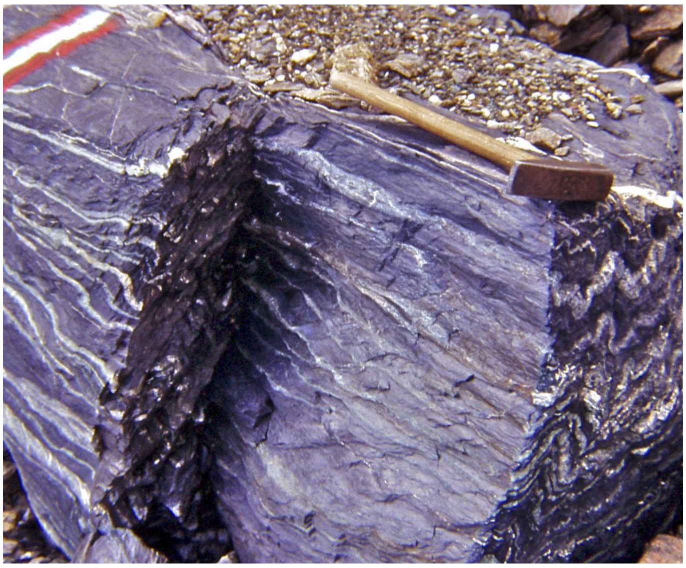


Overview map of the Eastern Alps (Neubauer & Höch, 2000). The crystalline basement is mainly related to the Middle Austroalpine, including the eclogitic and high-grade units.

The Err-Bernina is the lowermost group of basement and cover units sandwiched between the overlying Silvretta and Campo nappes and the underlying Margna and Platta-Arosa nappes. The basement consists of gneissic granitoids and minor paraschists, and is transected by numerous post-Variscan mafic dykes. The cover units consist of Permian-Cenomanian sequences, including the Saluver formation (Samedan zone, Graubünden) of Early-Middle Jurassic age, which is characterized by submarine breccias and sandstones deposited by mass-flow and turbidity currents. This formation is representative of an ocean-continent transition and a part of the distal margin of Adria (Froitzheim & Manatschal, 1996; Manatschal & Nievergelt, 1997; Manatschal & Bernoulli, 1999), like the Canavese zone (Ferrando *et al.*, 2004).

The Innsbruck Phyllite is a large basement unit located between the Tauern window and the Inn valley, cosists of thick sequences of low-grade quartz-phyllites with interbeddings of quartzite, marble, metavolcanic rocks, and is capped by a few remnants of Permian-Triassic cover rocks. The Insbruck Phyllite is imbricated by the Hippold and Rechner nappes (Fig. 28): the former includes Eotriassic to Late Jurassic metasediments, the latter a typical ophiolitic suite which displays a blueschist facies imprint of Eocene age (Dingeldey *et al.*, 1997), pointing for its Penninic affinity.

Figure 28. Rechner ophiolite.



Jurassic metasedimentary cover: bluish slaty-meta-chert with abundand Mg-riebeckite and thin quartzitic bands.

The Radstadt units, which crop out around the north-eastern edge of the Tauern window (Radstätter Tauern), consist of Lower Paleozoic quartz-phyllites, mafic meta-volcanics, marbles, paragneisses and metagranitoids, with greenschis facies eoalpine overprint, and of various cover sheets, including Permian-Triassic clastic and platform carbonate sequences, Liassic basinal limestones and breccias, Middle Jurassic-Lower Cretaceous radiolarian cherts, olistoliths and breccias.

The Semmering and Wechsel basement and cover units are exposed within a large window and to the east override the Bernstein-Rechnitz metaophiolite or disappear below the Neogene infill of the Vienna and Styria basins (Bigi *et al.*, 1993; Oberhänsli *et al.*, 2004). The Semmering system consists of a polymetamorphic basement, with migmatites, gneissic to mylonitic granites, and of Permian-Triassic clastic to carbonate and evaporitic sequences. It is underlain by a stack of basement units and related Permian-Triassic metasediments which constitute the Wechsel dome. The basement display an amphibolite facies regional metamorphism of Variscan age, marked by sillimanite or andalusite, whereas the phyllitic lower units show a greenschist facies imprint of debated age (Permian ?). The eoalpine oveprint increases southwards from greenschist to amphibolite facies (staurolite, kyanite).

The Matrai zone has been reported in the Structural Model as the lower Austroalpine units inside the Tauern window, even if it actually is a tectonic melange of basement sheets, Triassic marbles and ophiolite-bearing calcschists of debated Piedmont-Ligurian (Combin-type) affinity.

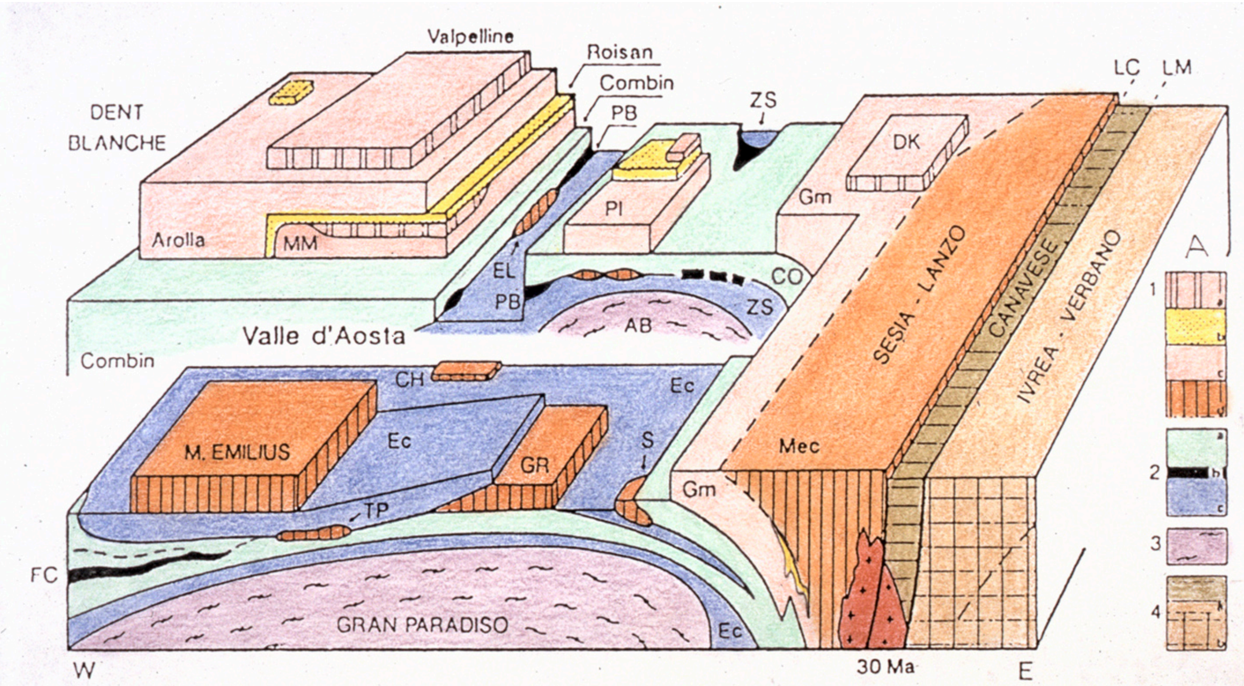
The Margna nappe is reported by the Structural Model as the lowermost composite unit of the Austroalpine system in the Central and Eastern Alps, highlighting its debated origin and close similarity with the Dent Blanche nappe, long ago supported by Staub (1957). The Margna nappe consists of Mesozoic metasediments, including radiolarian cherts and scarp breccias, and upper crust (paraschists and gneissic granitoids) and lower crust units (Fedoz high-grade metagabbro). The long-lasting debate on its paleostrucural position and my opinion on this issue have been reviewed and referenced in previous chapters.

Western Austroalpine

As shown in Fig. 29, the Western Austroalpine is a structurally composite nappe system, which is exposed in the Pennine and Graian Alps, from the southern Valais to the central and lower Aosta valley and north-western Piedmonte, and narrowing to the north-east along the internal side of the Ossola-Lugano steep belt (Argand's root zone), south of the Ossola-Tessin dome. It consists of the Sesia-Lanzo zone (inlier) and numerous external slices (outliers), traditionally reported and grouped as Argand's Dent Blanche nappe s.l. and its root zone. These continental units override or are tectonically interleaved with the structurally composite ophiolitic Piedmont zone, the major remnant of the Mesozoic ocean. The Structural Model (sheet 1) simply distinguishes three principal units with polyphase tectono-metamorphic features: i) Valpelline and 2nd Diorite-kinzigite upper units, thin rootless sheets of granulite-amphibolite facies lower continental crust of pre-Alpine age, similar to the Ivrea-Verbano zone, except for a weak and discontinuous blueschist or greenschist facies Alpine metamorphic reworking and shear zones (Ridley, 1989; Stünitz, 1989; Babist *et al.*, 2006); in the Artogna valley the kinzigitic suite includes a large body of mantle peridotite (Dal Piaz *et al.*, 1971; Beccaluva *et al.*, 1979), not shown in the Structural Model; ii) Roisan zone and Mt Dolin cover metasediments of

Mesozoic age, and basement units consisting of greenschist facies gneissic granitoids from Permian protoliths (Argand's Arolla Series and Gneiss minuti complex, a term introduced by Gastaldi, 1871-74), layered Permian gabbros and Fobello-Rimella mylonitic shear zone along the contact with the Southalpine Ivrea lower crust, with strongly reduced (or missing) sequences of the Canavese zone between them (Artini & Melzi, 1900; Carraro *et al.*, 1970; Schmid *et al.*, 1987); iii) Eclogitic micascist complex (Stella, 1894) derived from Early Permian granitoids and older high-T paragneiss with kinzigitic affinity, including marbles, eclogitic gabbros (Corio and Monastero) and other mafic bodies. The Eclogitic micascist complex crops out in the internal part of the Sesia-Lanzo zone, up to the upper Sesia valley, and is tectonically juxtaposed to the underlying Gneiss Minuti complex.

Figure 29. Austroalpine-Penninic nappe stack in Aosta valley.



Simplified block diagram of the Austroalpine-Penninic wedge in Aosta valley. Upper Austroalpine outliers: Dent Blanche-Mt Mary (MM)-Pillonet (P) thrust system. Lower Austroalpine eclogitic outliers: Etirol-Levaz (EL), Chatillon (CH), Mt Emilius, Glacier-Rafray (GR), Tour Ponton (TP), Santanel (S). Sesia-Lanzo zone: Gneiss minuti complec (Gm), Eclogitic micaschist complex (Mec).

Legend: 1) Austroalpine: a) Valpelline and 2nd Diorite-kinzigitic unit, b) Roisan, Pillonet and Mt Dolin metasedimentary units, c) Arolla series and Gneiss minuti complex, d) Eclogitic micaschist complex. 2) Piedmont zone: a) Combin zone, b) Pancherot-Cime Bianche (PB) and Cogne (FC) units, c) Zermatt-Saas (ZS) and its extension south of Dora Baltea (Ec). 3) Arcesa-Brusson (AB) and Gran Paradiso nappe (GP). 4) Canavese zone (a), Southern Alps (b). Outer (LC) and inner (LM) Canavese lines.

The contact between the Valpelline and 2nd Diorite-kinzigitic units with the underlying gneissic granitoids (Arolla series, Gneiss Minuti complex) and eclogitic ortho- and paraschists (Eclogitic micaschists complex) is marked by polyphase shear zones, without trace of Mesozoic metasediments (Fig. 30). In the Structural Model this contact is marked by a second-rank thrust, suggesting ductile shear during differential exhumation, instead of a far origin from the Ivrea zone (Carraro *et al.*, 1970). Rock-types similar to those of the Eclogitic micaschist complex also occur in the Mt Emilius, Rafray-Glacier, Tour Ponton, Santanel, Chatillon and Etirol-Levaz slices. The latter two are barely represented in the Structural Model that ignores the Acque Rosse slice, as it was discovered only later (Paganelli *et al.*, 1995; Beltrando *et al.*, 2009a). The different structural position of the non eclogitic upper Austroalpine Dent Blanche-Mt Mary-Pillonet thrust system in respect with the eclogitic lower

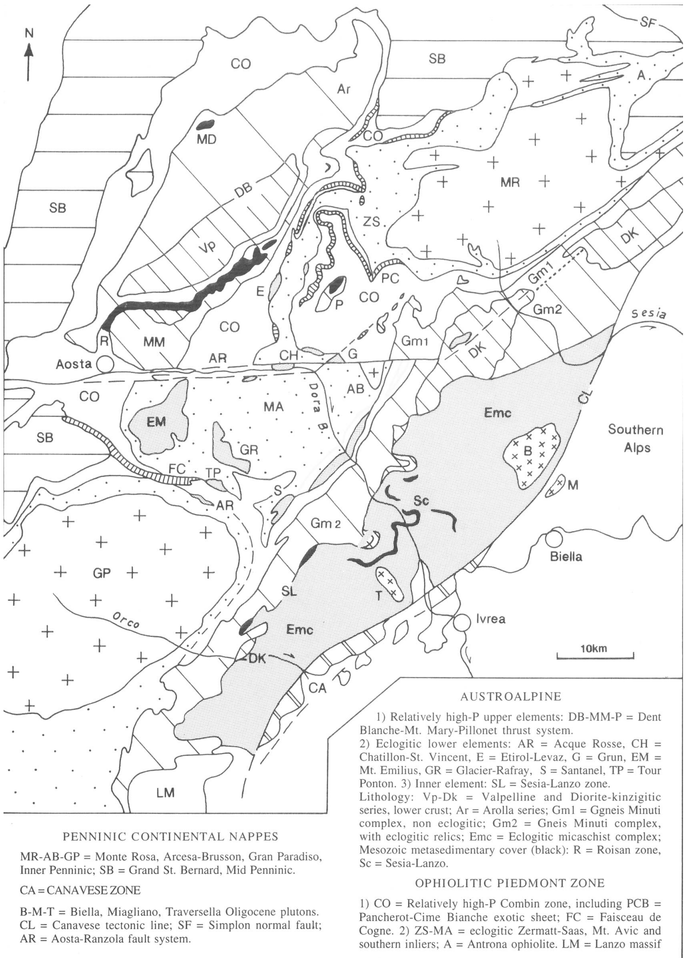
Austroalpine outliers was cleverly recognized by Ballevre *et al.* (1986), but the younger age (Eocene) of the eclogitic imprint in the latter units (Dal Piaz *et al.*, 2001) was stil unknown at that time, as well as the already mentioned Late Cretaceous isotope dating on retentive system from the Sesia-Lanzo Eclogitic Micascists complex. Focusing on the original version of the Structural Model, the eclogitic basement slice brought to light by road excavations near Grun (Rolfo *et al.*, 2004) was erroneously linked to the Arcesa-Brusson dome. The Verres slice was attributed to the frontal part of the Sesia-Lanzo Gneiss Minuti complex, through a couple of antiformal and synformal folds with high-angle axial plane (Lardeaux & Spalla, 1991; Spalla *et al.*, 1991). As previously discussed, the Verres unit is now included within the group of eclogitic outliers (strongly retrogressed), as a northeast extension, together with the new Tilly sliver, of the eclogitic Santanel unit (Battiston *et al.*, 1987).

Figure 30. Mylonitic contact between Arolla and Valpelline units of Dent Blanche nappe.

Tectonic contact between the Arolla gneissic granitoids (gray, left) and the overlying kinzigitic complex of Valpelline unit (reddisch, right), marked by a thick mylonitic shear zone, Comba de la Sassa, Valpelline (Dal Piaz, 1992; Pennacchioni & Guermani, 1993; Bucher *et al.*, 2003, 2004).

Summing up, two groups of Austroalpine outliers can be identified in the Aosta valley, based on their structural position and contrasting P-T-time evolution history (Ballèvre *et al.* 1986; Ballèvre and Merle 1993; Dal Piaz 1999; Dal Piaz *et al.*, 2001): i) the upper one is represented by the Dent Blanche-Mt Mary-Pillonet thrust system which, like the Sesia-Lanzo inlier, occurs on top of the collisional nappe stack, over the entire ophiolitic Piedmont zone; ii) the lower one is represented by the Mt Emilius, Glacier-Rafray, Etirol-Levaz and other minor basement slices, presently located along the tectonic contact between the upper (Combin) and lower (Zermatt-Saas) Piedmont ophiolitic nappes, or within the latter (Fig. 31).

Figure 31. Tectonic map of North-Western Alps.



Tectonic map of the North-Western Alps (Dal Piaz, 1999). Western Austroalpine: 1) Upper outliers (non eclogitic): Dent Blanche (DB)-Mt Mary (MM)-Pillonet (P) thrust system; 2) Lower outliers (eclogitic): Acque Rosse (AR), Chatillon (CH), Etirol-Levaz (E), Grun (G), Mt Emilius (EM), Glacier-Rafray (GR), Santanel-Verres (S), Tour Ponton (T); 3) Sesia-Lanzo zone (SL). Lithology: Valpelline (Vp) and 2nd Diorite-kinzigitic series (Dk); Arolla series (Ar), Gneiss minuti complex (Gm1: non eclogitic, Gm2: eclogitic relics); Eclogitic micaschist complex (Emc); Mesozoic cover units: Roisan zone (R); Scalaro, Sesia-Lanzo (Sc). Piedmont zone: 1) Relatively high-P (scarce blueschist relics) Combin zone (CO), including Pancherot-Cime Bianche (PCB), Frilihorn and Cogne (FC) Permian-Mesozoic decollement cover units of debated continental affinity; 2)

Eclogitic Zermatt-Saas zone (ZS) and its extension to the Mt Avic massif (MA), beyond the Aosta-Ranzola fault; Antrona ophiolite (A); Lanzo Massif (LM). Inner-upper Penninic Monte Rosa (MR), Arcesa-Brusson (AB), Gran Paradiso (GP) and mid-Penninic Grand St Bernard (SB) nappe systems. Canavese zone and Canavese tectonic line (CA), Aosta-Ranzola fault system (AR), Simplon normal fault (SF).

This subdivision is corroborated by a contrast of metamorphic and chronological constraints: i) the upper Austroalpine outliers display blueschist facies relics dated as Late Cretaceous in the Pillonet klippe (Cortiana *et al.*, 1998), and similar to those of unknown age in the Combin footwall; ii) the lower Austroalpine outliers and Zermatt-Saas ophiolite display a similar eclogitic imprint of Early-Middle Eocene age (Dal Piaz *et al.*, 2001; Beltrando *et al.*, 2009a, 2010b), disregarding the ultrahigh-P conditions documented in the Lago di Cignana unit (Compagnoni & Rolfo, 2003; Forster *et al.*, 2004).

The metamorphic ($P \geq 0.5$ GPa) and temporal (25-30 Ma) gap between them does mean that these groups of Austroalpine-Piedmont nappes were diachronously subducted, followed independent paths and were finally coupled during the late exhumation stage, when both were overptinted by the Late Eocene-Early Oligocene greenschist facies regional metamorphism. During the Oligocene, the Sesia-Lanzo Eclogitic complex reached the surface and was coverd by volcaniclastic deposits (Scheuring *et al.*, 1974). In the meantime, the collisional nappe pile was fragmented and noticeably displaced by the east-west trending Aosta-Ranzola normal fault system (Bistacchi *et al.*, 2001), taking the upper Austroalpine outliers north of the Aosta valley about to the same altitude of the lower outliers in the southern side. As a matter of fact, the entire Austroalpine-Piedmont nappe stack is presently exposed in the lowered northern block, whereas only the lower Austroalpine outliers and Zermatt-Saas ophiolite are preserved in the footwall southern block, due to differential uplift and erosion (Fig. 31).

The principal prealpine protoliths of the Western Austroalpine system are represented by the following rocks (Diehl *et al.*, 1952; Kienast & Nicot, 1971; Dal Piaz *et al.*, 1972; Boriani *et al.*, 1974; Compagnoni *et al.*, 1977; Gosso *et al.*, 1979; Vuichard, 1987, 1989; Stünitz, 1989; Dal Piaz, 1993; Gardien *et al.*, 1994; Venturini, 1995): i) pre-granitic felsic granulites, amphibolite-facies metapelites, garnet-rich restites and migmatites with interbeddings of mafic granulite, amphibolite and marble, and concordant to discordant leucocratic dykes; ii) Lower Permian granite-quartzdiorites and gabbros in the Dent Blanche nappe (Diehl *et al.*, 1952; Dal Piaz *et al.*, 1977; Bussy *et al.*, 1998; Monjoie *et al.*, 2007) and Pillonet klippe (Dal Piaz, 1976); iii) detached remnants of a Triassic-Cretaceous sedimentary cover. These protolith are wholly to partly preserved in Alpine low-strain domains of the Valpelline series and 2nd Diorite-kinzigitic zone (Fig. 32), and can also be recognized in the underlying Austroalpine basement units, strongly reworked by the polyphase Alpine overprint, thanks to scattered megascopic, mesoscopic or mineral relics. Typical cases are the gneissic bodies with kinzigitic affinity partly preserved within the Eclogitic micaschist complex in some tributaries of the Gressoney valley. The pre-Permian, probably Variscan age of the pre-Alpine tectono-metamorphic history is firmly established only where some Permian granitoids sharply intrude the high-T schistosity and anatectic fabric, as it can be observed, for instance, in the Mt Morion massif which is poorly affected by Alpine transposition (Burri *et al.*, 1998). This conclusion, however, can not be generalized as the contact between the metamorphic and igneous bodies is often a mylonitic shear zone, therefore we can not exclude a thermal reworking during the Permian lithosphere extension and emplacement of gabbro at the base of a thinned continental crust, as it is attested and dated in the Ivrea zone. Elsewhere, especially in the eclogitic lower outliers and Sesia-Lanzo inlier the high-grade prealpine basement is pervasively retrogressed or converted to Alpine eclogite facies micaschists and pegmatite-derived micaceous quartzites.

A few mafic bodies are also included in the eclogitic lower Austroalpine outliers, i.e. the granulitic gabbros of the Etirol-Levaz slice (Kienast, 1983; Ballèvre *et al.*, 1986) and Mt Emilius klippe (Dal Piaz *et al.*, 1983; Pennacchioni, 1996), Mt Emilius websterite, which is associated to a partly serpentinized mantle peridotite slice (Benciolini, 1989). Further metagabbros are reported from the eclogitic Sesia-Lanzo basement (Venturini, 1995; Rebay & Spalla, 2001).

To sum up, multiple intrusions of granitoids and gabbro emplaced in the Austroalpine domain between the end of the Variscan metamorphism and the Triassic, based on field evidence. Radiometric zircon dates on some granitoid and mafic bodies are bracketed between 293 and 288 Ma (Bussi *et al.*, 1998), whereas biotite cooling ages at the Permian-Triassic boundary were obtained in the Matterhorn and Collon gabbros (Dal Piaz *et al.*, 1977).

Figure 32. Southern face of Mt Nery.

The granulite-amphibolite facies kinzigitic complex is perfectly preserved in the Mt Mary massif, between Ayas and Gressoney valleys. A large greenschist-facies schear zone (clear band)overprints previous blueschist-facies mylonites (late eoalpine ?) along the contact between the 2nd Diorite-kinzigitic unit and underlying metagranitoids and eclogitic micaschists, and in turn is transected by a thick andesitic dyke (Dal Piaz *et al.*, 1971, 1972; Stünitz, 1989; Babist *et al.*, 2006).

The scattered remnants of the metasedimentary cover are mainly represented by Triassic platform carbonates with Late Triassic microfossils (Ciarapica *et al.*, 2010; Fig. 22), rift breccias (Jurassic?), basinal limestones (Late Jurassic?) and flysch-type calcschists (Cretaceous?). As previously discussed, the affiliation of the Fe-Mn quartzite over the Cignana lake (Ballevre & Kienast, 1987) is an open problem. These ophiolite-free sequences are associated to the upper outliers (Roisan zone) and, locally, to the Sesia-Lanzo inlier. The original sedimentary cover of the lower Austroalpine basement outliers, if really did exist, could be represented by the Permian-Mesozoic decollement unit (Pancherot-Cime Bianche) presently transposed at the base of the Combin zone or inside its lower part, between two ophiolitic Combin units (Dal Piaz, 1999; Bucher *et al.*, 2003, 2004).

The Western Austroalpine was metamorphosed and ductilely deformed from the Late Cretaceous to the Early Oligocene under blueschist or eclogitic and then overall greenschist facies conditions (Dal Piaz *et al.*, 1972; Compagnoni & Maffeo, 1973; Frey *et al.*, 1974, 1999; Compagnoni, 1977; Compagnoni *et al.*, 1977; Passchier *et al.*, 1981; Lardeaux *et al.*, 1982; Dal Piaz *et al.*, 1983; Ballèvre *et al.*, 1986; Polino *et al.*, 1990; Lardeaux & Spalla, 1991; Scambelluri *et al.*, 1998; Spalla *et al.*, 1996; Konrad-Schmolke, 2006; Rebay & Messiga, 2007; Beltrando *et al.*, 2010a).

The eclogitic metamorphism is extensively preserved in the internal Sesia-Lanzo zone, partly in the Mt Emilius klippe, and poorly in other lower Austroalpine outliers (Fig. 31). It is recorded by almandine-rich garnet, sodic pyroxenes, phengitic mica, rutile ± glaucophane, Mg-chloritoid, kyanite aggregates (after sillimanite) and zoisite, generating typical eclogitic micaschists from kinzigitic-type paragneisses and granitoids. Among them, it may be recalled the famous eclogitic granitoids of Mt Mucrone, near Biella (Compagnoni & Maffeo, 1973). Peak conditions are estimated around 550°C and 1.5-1.8 GPa. In contrast, the upper Austroalpine outliers only display a blueschist facies imprint, presently recorded by a few relics of aegirine, sodic amphiboles and white mica with high Si content (Ayrton *et al.*, 1982; Cortiana *et al.*, 1998). It can be recalled once again that the eclogite to blueschist facies metamorphism developed during the Late Crecaeous in the Sesia-Lanzo inlier and upper Austroalpine outliers, whereas the similar eclogitic imprint in the lower Austroalpine outliers is of Early-Middle Eocene age. These differences point to a north-westward prograding subduction and distant paleostructural sources of the concerned continental crust units. In the Late Eocene-Early Oligocene a greenschist facies overprint developed to different extent across the nappe stack. It is particularly pervasive in most of the Austroalpine outliers (except of the Valpelline top unit) and the external sector (Gneiss Minuti complex) of the Sesia-Lanzo zone, generally marked by the abundance of porphyroblastic albite.

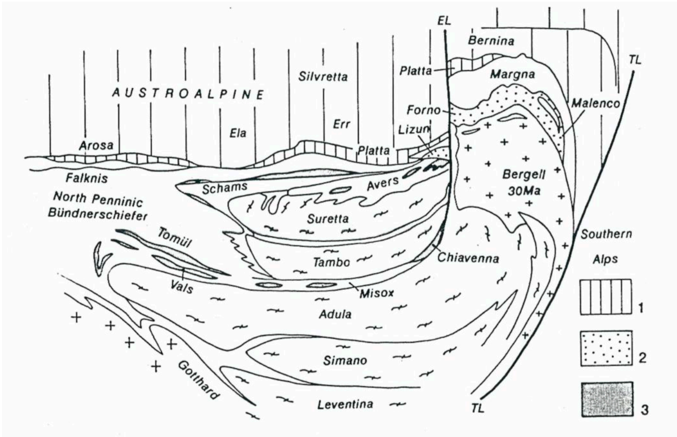
Penninic Zone

Penninic is the classic name used to group the continental and oceanic nappes which originated from the European continental margin and the Mesozoic ocean. At the onset of plate convergence, both domains belonged to the subducting lower plate and in this sense the term Penninic is correct and is here maintained. However, since the original source of the ophiolitic units with respect to the spreading center is generally unknown, these units could be representative of the Mesozoic oceanic lithosphere potentially related either to the European or Adriatic or both diverging plates. Anyway, restoration of the collisional belt back to Alpine Tethys is complicated by simple-shear rifting, hyper-extended continental margins, mantle denudation and ribbon continents, whilst the frequent anomalies of the ophiolitic stratigraphy in respect with the normal oceanic crust point for a paleostructural setting characterized by active transform faults and fracture zones.

The Penninic zone is a thick pile of continental cover and/or basement nappes capped by and locally interlayered with large or minor ophiolitic units. As shown in the Structural Model, the upper part of the Penninic nappe stack is continuously exposed on both sides of the domal structure of the Lower Penninic nappes in the Ossola-Simplon-Tessin window, the major correlation gap along the longitudinal axis of the orogen. In the Western Alps, the top unit is the structurally composite ophiolitic Piedmont zone which extends from the Voltri massif, near Genoa, through the French-Italian Cottian and Graian Alps, to the structural depression of the Aosta valley and southern Valais, where it is capped by the Austroalpine system. In the Western Alps the Piedmont zone is underlain by the Upper-Inner Penninic Dora-Maira, Gran Paradiso and Monte Rosa nappes, often referred to as Internal Massifs (fixist name). These continental nappes are exposed as large domal structures and disappear below the overlying ophiolitic units in intervening structural depressions (Lanzo and middle Aosta valleys). The Dora-Maira and Monte Rosa nappes are partly underlain by the thinned and back-folded inner sector (Argand's root zone) of the Grand St Bernard system, the bottom of Money unit (Gran Paradiso) is buried, whereas the Monte Rosa nappe appears to be underlain by the Antrona eclogitic ophiolite, a downward extension of the Zermatt-Saas nappe.

The Mid-Penninic Grand St Bernard system is a large belt of multiple basement and cover units which extends along the entire western arc, from the Ligurian to the Pennine Alps. It is frontally accreted by the Helvetic-Dauphinois basement and cover units along the Maritime and Cottian Alps, through a strip of Subbriançonnais (outer Briançonnais) embricated cover units. North of Moutiers, near the French-Italian boundary, the Subbriançonnais domain is replaced by the Outer Penninic Sion-Courmayeur or Valais zone, including the Versoyen-Roignais ophiolitic unit, externally delimited by the Penninic frontal thrust, the first-rank tectonic boundary between the Penninic and the Helvetic-Ultrahelvetic structural domains. The Lower and Inner Penninic nappe system groups the deepest nappes presently exposed in the core of the Ossola-Tessin window. They consist of basement units, mainly gneissic granitoids, minor sedimentary covers and scarce ophiolitic sequences with amphibolite facies Lepontine metamorphism of Late Eocene-Oligocene age.

Figure 33. The nappe stack in eastern Switzerland.



Collisional nappe stack in eastern Switzerland (simplified from Schmid *et al.*, 1996, 1997): 1) Platta nappe; 2) Malenco-Forno-Lizun nappe, S-Penninic; 3) other North and S-Penninic ophiolites; Engadine line (EL); Tonale (Insubric) line (TL).

In the Central Alps, east of the Ossola-Tessin dome, we can see the overlying stack of oceanic and continental nappes, from top to bottom (Fig. 33): i) Platta-Arosa ophiolite; ii) Margna-Sella continental nappe (uppermost Penninic or lowermost Austroalpine); iii) Malenco-Avers calcschist-ophiolite unit; iv) Suretta and Tambo basement and cover nappes and allochtonous cover sheets with Briançonnais affinity (Schams, Falknis-Sulzfluh); v) Adula nappe, an eclogitic continental fragment of debated affiliation (top of the Lower Penninic: Bigi *et al.*, 1990; Subpenninic: Schmid *et al.*, 2004; Upper Penninic, by comparison with the Monte Rosa nappe). The Tambo nappe overrides the Chiavenna ophiolite slice (internal side) and the Misox zone (external side), connecting northwards to the Valais (N-Penninic) calcschists (Bündnerschiefer) and related flysch units (Trümpy, 1980; Bigi *et al.*, 1990; Schmid *et al.*, 1997, 2004; Liati *et al.*, 2003, 2005). The southern part of the nappe stack is perturbed by the Oligocene Bergell intrusion and Engadine fault.

Passing to the Eastern Alps, the Penninic units are confined inside the Engadine, Tauern and Rechniz windows. These windows across the Austroalpine lid are described later and independently from the western units, in order to avoid univocal correlations among them.

Piedmont-Ligurian ophiolite system

The Piedmont zone is a structurally composite ophiolitic nappe system which in places includes exotic decollement cover units or small slivers of continental affinity.

The Alpine metamorphic ophiolites of the Piedmont zone and most of their eastern extension can be subdivided into non-eclogitic and eclogite facies units, both reworked by a greenschist to amphibolite facies overprint. Other differences concern the lithostratigraphic setting, varying between: i) carbonate to terrigenous flysch-type metasediments (calcschists s.l.), with multiple interleavings of tabular metabasalt and major ophiolitic bodies, including serpentinites mantled by ophicarbonate breccias or occasional Mn-rich metacherts; ii) large slices of normal to anomalous oceanic lithosphere, consisting of antigorite serpentinites (from mantle peridotite), often covered by ophicarbonate-ophicalcite breccias (Western Alps, Platta), followed by discontinuous metagabbro bodies, massive to pillow tholeiitic metabasalts, manganiferous metacherts (Middle-Late Jurassic), impure marbles, orogenic deposits, and subduction melanges (Cretaceous?).

In the Aosta valley and southern Valais the Piedmont zone is currently divided into two main ophiolite-bearing nappes: i) the overlying eclogite-free Combin (Tsaté) unit, which is characterized by scattered blueschist facies relics and a pervasive greenschist facies overprint, and ii) the underlying eclogitic Zermatt-Saas unit. North of the Aosta-Ranzola fault, the Piedmont zone includes the ophiolite-free Permian-Cretaceous decollement cover sheet which is located at the base of the ophiolitic Combin unit, or inside it, both forming the composite Combin zone. Disregarding the Alpine metamorphic imprint, the Combin unit roughly recalls the External Ligurides (Northern Apennines), which are characterized by melanges and olistolith-rich flysch sequences, whereas the Zermatt-Saas unit may be correlated with the fragments of oceanic lithosphere of the Internal Ligurides.

As previously outlined, the ophiolitic Combin unit is the tectonic sole of the Dent Blanche-Mt.Mary-Pillonet thrust system, altogether forming a tectonic multilayer which shares a similar blueschist (rare relics) to greenschist facies metamorphic evolution, starting with a Late Cretaceous subduction. The underlying Zermatt-Saas is overlain by or interleaved with the lower Austroalpine outliers, altogether forming a couple of nappes with Eocene eclogitic signature. The Zermatt-Saas ophiolite overrides the Monte Rosa and Gran Paradiso nappes and disappears beneath the Gran Nomenon and Mischabel back-folds (Dal Piaz, 1928; Elter, 1960; Escher *et al.*, 1988, 1997), or back-thrusts (Freeman *et al.*, 1997; Butler & Freeman, 1999; Markley *et al.*, 1999), within the inner Grand St Bernard system. By contrast, in its external side the ophiolitic Combin unit is decoupled from the Zermatt-Saas unit and largely extends over the Grand St Bernard system (Fig. 31). The Combin unit consists of carbonate to terrigenous flysch-type metasediments (calcschists s.l.), often including tabular interleavings of greenschist facies metabasalts (prasinites) and lenticular slices of metagabbro and serpentinite, in places with adherent remnants of oceanic metasediments and Mn-rich deposits. Larger ophiolitic bodies are locally dominant especially in the upper part of the nappe. The Zermatt-Saas unit displays the best preserved remnants of subducted oceanic lithosphere. The ophiolitic suite consists of: i) thick basal titanclinohumite-rich antigorite serpentinites (from mantle peridotites), including pods and dykes of rodingitic gabbro, and locally mantled by ophicarbonate breccias (ophicalcites); ii) discontinuous bodies of Mg-rich and minor Fe-Ti-rich metagabbro and related cumulus ultramafics; iii) massive and pillowed metabasalts, first discovered by Bearth (1959), near Zermatt. The overlying sedimentary cover consists of impure quartzites, locally manganiferous, followed by marbles and minor calcschists, a sequence which roughly recalls the supraophiolitic oceanic cover (Callovian-Oxfordian radiolarian chert and Calpionella limestone) in the Northern Apennine. The cover ends with, or is merely represented by orogenic metasediments (ankerite-bearing garnet micaschists, often rich in large Mg-chloritoid ± glaucophane ± rare sodic pyroxene) and the Rifelberg-Garten unit (Bearth, 1953, 1967; Dal Piaz, 1965, 1974; Bucher *et al.*, 2004). The latter is a peculiar metasedimentary formation of garnet calcschists and micaschists with dominant matrix supporting roundish to lenticular pebbles, generally 1-15 cm in size, of fresch to retrogressed eclogite from tholeiitic metabasalts. In addition, similar and contiguous horizons contain metric or larger boudins of glaucophane-rich eclogites and garnet amphibolites. The Rifelberg-Garten has been interpreted as a subduction melange. The Zermatt-Saas ophiolite displays an eclogitic imprint of Early-Middle Eocene age (49-43 Ma). The maximum peak conditions are recorded by coesite- and diamond-bearing eclogites found in Valtournanche, near the dam of the Cignana lake (Reinecke., 1991; Groppo *et al.*, 2009; Selverstone *et al.*, 2010). The post-eclogitic evolution is characterized by a continuum of re-equilibrations at decreasing pressure, first in relatively high-T blueschist facies conditions and later in Ab-amphibolite or greenschist facies conditions.

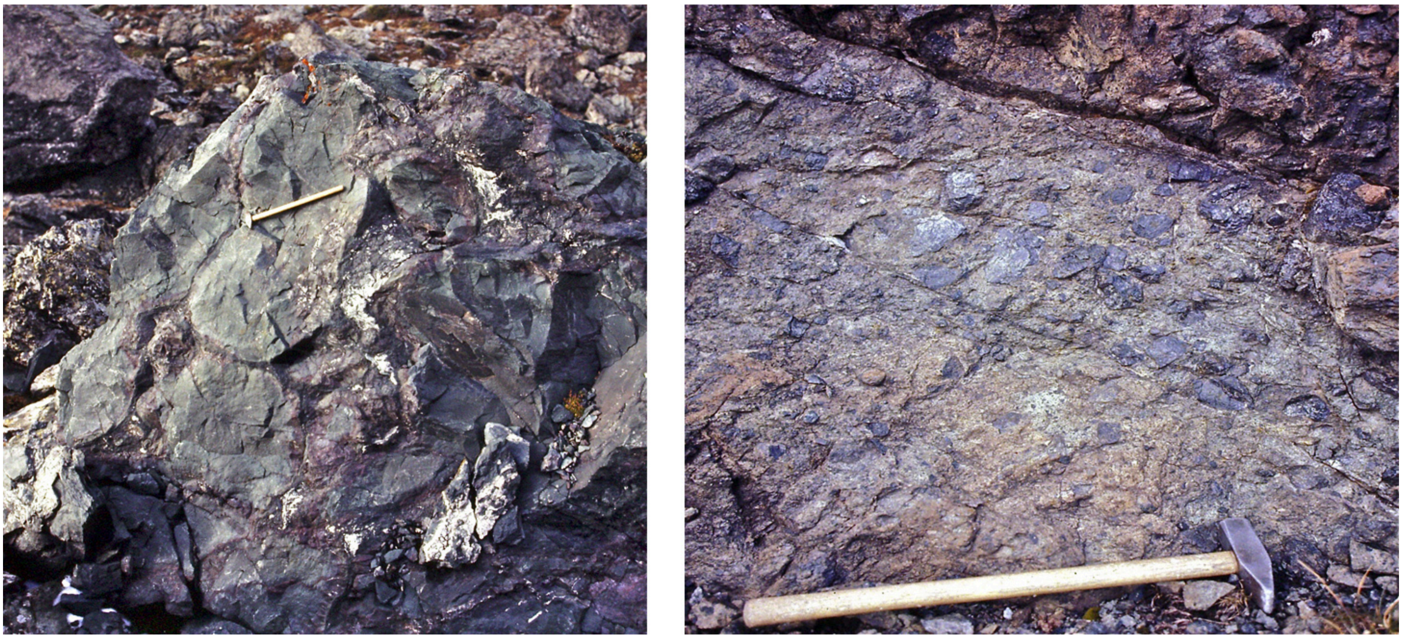
This tectonic and metamorphic subdivision of the Piedmont zone has been extended southwards to the Voltri Group, through the entire French-Italian Alps. Blueschist facies units, similar to the Combin sequences, extensively occur from the upper Lanzo and Susa valleys to the Queyras and Voltaggio-Montenotte zone, whereas eclogitic ophiolites similar to those of the Zermatt-Saas unit occur in the inner Lanzo and Susa (Rocciavrè) valleys, Monviso massif and Voltri Group (Bigi *et al.* 1990; Desmons *et al.*, 1999). The best ophiolite suite is preserved in the Chenaillet area, between Susa and Briançon, consisting of Jurassic radiolarian chert, thick pillow lava, gabbro with high-T oceanic alteration, serpentinitic breccia with a sedimentary matrix and serpentinite, all poorly reworked by the Alpine overprint (Mevel *et al.*, 1978; Lagabrielle, 1987). It can be outlined that these gabbros were emplaced before the onset of oceanic spreading, as attested by Triassic isotope ages, pervasive foliation and metamorphic re-equilibration that are absent in the overlying spilitic basalts (Costa & Caby, 2001).

Antrona unit - The Antrona unit is sandwiched between the Monte Rosa nappe and the underlying “root zone” (Camughera-Moncucco) of the Grand St Bernard nappe according to Argand's reconstruction (Fig. 26, 31). As previously discussed, this ophiolite is probably a slice of the Zermatt-Saas unit, tectonically infolded at the base of the Monte Rosa recumbent fold, rather than a North-Penninic derivative (Schmid *et al.*, 2004; Pleuger *et al.*, 2005; Herwartz *et al.*, 2008): this is supported by lithological, geochemical and metamorphic features closely similar to those recorded in the Zermatt-Saas nappe.

Among the ophiolitic units exposed east of the Ossola-Tessin window, the Malenco-Avers nappe (Fig. 33) is located at the same structural level as the Piedmont zone (Bernoulli *et al.*, 2003). The best ophiolitic exposures are provided by the overlying Platta-Arosa nappe.

Platta-Arosa nappe - In 1905, Gustav Steinmann recognized in this region the close association of serpentinites, diabase and radiolarite and considered this greenstone as characteristic for the axial part of the geosyncline and the deep ocean floor (Bernoulli *et al.*, 2003; Bernoulli & Jenkyns, 2009). The Platta-Arosa nappe is closely similar to the Zermatt-Saas unit from a lithological point of view, but displays a less severe metamorphic imprint. It occurs below the entire western border of the Eastern Austroalpine nappe stack and reappears as uppermost Penninic unit inside the Engadine window (Dietrich, 1969, 1970, 1980; Bernoulli & Weissert, 1985; Bigi *et al.*, 1990; Frisch *et al.*, 1994; Bernoulli *et al.*, 2003). The nappe can be subdivided into some sub-units: the Platta s.s., north of the amphibolite facies Malenco complex (Trommsdorff & Evans, 1977; Trommsdorff *et al.*, 1993), beyond the Engadine line, followed northwards by the Arosa zone and then by Totalp zone, near Davos. The Platta nappe (s.l.) consists of supraophiolitic cover rocks with a close Liguride affinity, pillow lavas, gabbros transected by undeformed basaltic dykes, and ophicarbonate breccias which support the exposure of partly serpentinized mantle peridotite on the ocean floor at the end of rifting (Fig. 34). As previously recalled, this is the best example in the Alps of ocean-continent transition (Bernoulli & Weissert, 1985; Froitzheim *et al.*, 1994; Froitzheim & Manatschal, 1996; Manatschal & Nievergelt, 1997; Desmurs *et al.*, 2001, 2002; Schaltegger *et al.*, 2002; Manatschall *et al.*, 2003; Ferrando *et al.*, 2004; Bernoulli & Jenkyns, 2009). The paleostructural setting has been clearly synthetized and figured by Bernoulli *et al.* (2003), showing that in continent-facing (proximal) sector of the ocean-continent transition, reconstructed from the upper serpentinite unit, the exhumed mantle is locally overlain by extensional allochthons, continental basement slices, pre-rift sediments and syn-rift marine breccias, that emplaced along extensional detachment faults. Otherwise, in the ocean-facing (distal) side of the ocean-continent transition, inferred from the lower serpentinite unit, the mantle is intruded by pods of gabbro and covered by pillow lavas and breccias that, as a whole, are sealed by a classic suite of deep-water sediments (Radiolarite Fm., Calpionella Limestone and Argille a Palombini). Summing up, this reconstruction is similar to the Early Cretaceous ocean-continent transition along the west Iberian passive margin where the subcontinental mantle was exhumed to the sea floor before the onset of ocean spreading (Bernoulli *et al.*, 2003).

Figure 34. Platta ophiolitic nappe.



Spilitic pillow-lava (left) and serpentinite breccia (right), Falotta, Oberhalbstein.

Focusing on the igneous activity, both mafic rock types are characterized by εNd values typical for an asthenospheric mid-ocean ridge source, suggesting the existence of concurrent extensional tectonics with magma emplacement, at the onset of sea floor spreading across an exhumed subcontinental mantle. The igneous activity developed at the Callovian-Oxfordian boundary, documented by concordant U-Pb ages of 161 ± 1 Ma on gabbro zircons (Schaltegger *et al.*, 2002). Submarine lava flows, dykes and gabbros show geochemical features typical of tholeiitic magmas (Frisch *et al.*, 1994), evolving from T-MORB to N-MORB composition as they crystallized away from the continental margin (Desmurs *et al.*, 2002). Note that simila results were obtained on selected samples of Piedmont ophiolites in the Aosta valley (Beccaluva *et al.*, 2004).

The Platta-Arosa units can be restored near the Apulian continental margin (Schmid *et al.*, 2004) and were accreted to the Eastern Austroalpine since the Cretaceous (Froitzheim *et al.*, 1994). The Alpine metamorphism is recorded by blueschist facies minerals in mafic ophiolites (lawsonite, blue amphiboles) and metasediments (carpholite, phengite), and/or a low-grade overprint.

Penninic continental nappes

Upper-Inner Penninic units - The Dora-Maira, Gran Paradiso and Monte Rosa nappes and the Arcesa-Brusson window (Ayas valley) occur at the same structural level within the inner part of the collisional wedge, below the Piedmont zone, as lithologically similar but independent crustal fragments. They are made up of a polymetamorphic basement (Variscan plus Alpine), gneissic granitoid and augengneiss from Late Paleozoic intrusives, and a few remnants of Permian and/or Mesozoic cover metasediments (metaconglomerate, quartzite, dolostone, marble, calcschists). The pre-granitic basement consists of high-grade metapelites with abundant sillimanite-cordierite-bearing migmatites (Fig. 35), amphibolite facies mafic bodies from continental flood basalts and scarce marbles. The dominant Alpine derivatives are represented by various kinds of garnet-chloritoid ± kyanite micaschists, albite- or oligoclase-epidote-two micas schists, eclogite to albite-amphibolitic boudins and massive metagranites to schistose augengneisses, that record an eclogitic imprint of Eocene age and a greenschist to amphibolite facies evolution of Late Eocene-Early Oligocene age (Bearth, 1952; Michard, 1967; Dal Piaz, 1971; Compagnoni *et al.*, 1974; Compagnoni & Lombardo, 1974; Dal Piaz & Lombardo, 1986; Ballèvre, 1988; Meffan-Main *et al.*, 2004; Ring *et al.*, 2005; Bertrand *et al.*, 2005; Le Bayon & Ballèvre, 2006; Gabudianu *et al.*, 2009; Beltrando *et al.* 2010a). In addition, the Brossasco-Isasca felsic unit of the Dora-Maira nappe displays the first occurrence of coesite found in the Alps (Chopin, 1984).

Figure 35. High-grade pre-granitic complex of Monte Rosa nappe.

The Variscan pre-granitic complex (mainly migmatites) is relatively well preserved between the Indren and Garstelet glaciers, head of Gressoney valley, south of Rifugio Mantova. This figure shows a pegmatitic dyke with large crystals of cordierite (altered to pinite).

In the eastern Switzerland, the Suretta nappe is mainly built up of a polymetamorphic basement with intercalations of high-P mafic rocks, and of metagranitoids and augengneiss extensively developed in its norther side. Detached Mesozoic metasediments are concentrated along the upper flank of the nappe, and in tight synforms inside the northern basement. Its classic correlation with the Monte Rosa nappe is also adopted by the Structural Model.

Middle Penninic units - The Grand St Bernard (Briançonnais) tectonic system is a group of basement and cover nappes which extends from the Ligurian Alps to the Valais and Ossola valley, where it is the hangingwall of the Simplon normal fault (Mancktelow, 1992, 1995; Seward & Mancktelow, 1994). It also includes the Ambin massif, initially correlated by Argand to the overlying Monte Rosa fold-nappe. The structural position, facies evolution and metamorphic features allow the recognition of internal and intermediate-external basement and cover units which display a polyphase Alpine metamorphism marked by blueschist and/or greenschist facies fabrics of post-Luthetian age. The subduction-related blueschist facies imprint is particularly well recorded in the Acceglio, Ambin, Vanoise, Ruitor and some Valais areas. Four groups of nappes can be generally distinguished (Ellenberger, 1958; Lorenzoni, 1965; Michard, 1967; Caby, 1968; Frey *et al.* 1974, 1979; Lefèvre & Michard, 1976; Caby *et al.*, 1978; Vanossi, 1992; Cortesogno, 1984; Escher, 1988; Desmons & Mercier, 1993; Gouffon, 1993; Cortesogno *et al.*, 1997; Escher *et al.*, 1997; Steck *et al.*, 1997, 2001; Malusà *et al.*, 2005; Sartori *et al.*, 2006): i) polymetamorphic basement units which predate the Variscan unconformity, clearly documented by relict eclogite and amphibolite facies mineral assemblages which are preserved despite the Alpine overprint (e.g. Ambin, Ruitor, Siviez-Mischabel); ii) basement units of debated age, which are free from significant pre-Alpine relics and can be interpreted either as a Late Paleozoic monocyclic silicoclastic cover (tegument) of the older basement or as an older basement slice in which the penetrative Alpine overprint erased all previous fabrics; iii) Zone houillère, a large external unit consisting of thick sequences metaclastic deposits of Late Carboniferous-Permian age, with conglomerate and coal interbeddings, which marks the Variscan unconformity (Gb. Dal Piaz, 1939); iv) Briançonnais sedimentary cover (Ellenberger, 1953, 1958; Sturani, 1975; Sartori, 1990).

The polymetamorphic basement includes pre-Namurian paraschists and igneous bodies generated by a bimodal magmatism, and is characterized by an amphibolite facies regional metamorphism (Bearth, 1963; Giorgis *et al.*, 1999), and traces of an older eclogitic event (Thelin *et al.*, 1990; Cortesogno *et al.*, 1997). Isotope dating of igneous protoliths from various basement units has noticeably aged the classic sequence of geological events (Bertrand *et al.*, 2000a-b; Guillot *et al.*, 2002; Gaggero *et al.*, 2004; Sartori *et al.*, 2006), and poses serious problems to the existence of the Variscan orogeny itself within the Briançonnais microcontinent. U-Pb zircon dating on metamorphic igneous bodies from Ambin, Vanoise and Ruitor massifs (Guillot *et al.*, 1991, 2004; Bertrand *et al.*, 2000a-b), previously regarded as Permian (eg. Mon Fort and Mt Pourri), yielded Cambrian and Ordovician ages, ranging from 512 ± 7 to 479 ± 5 Ma (Vanoise) and from 471 ± 2 to 460 ± 7 Ma (Ruitor), without clear evidence of polymetamorphic fabrics. Similar results have been obtained in the Briançonnais basement of the Ligurian Alps (Gaggero *et al.*, 2004) for the bimodal (Cambrian-Ordovician) and acidic (Ordovician) igneous suites, as well as in the Swiss sector of the Grand St Bernard system (Bussy *et al.*, 1996; Sartori *et al.*, 2006). Cambrian zircon ages were obtained in the Siviez-Mischabel nappe from the Thyon granophyre (ca 500 Ma, Bussy *et al.*, 1999) and a gabbro body (504 ± 2 Ma) emplaced into the Ergischorn ensemble (Bussy in Sartori *et al.*, 2006). The long debated French-Swiss correlations across the Aosta valley have been reconsidered by Guillot *et al.* (2004), suggesting the existence of two paired igneous provinces, represented by the Ruitor-Sapey-Pontis external belt, characterized by 480-450 Ma-old aluminous intrusives and Variscan high-grade metamorphism (ca 330 Ma, Giorgis *et al.* 1999), and by the Vanoise-Mont Fallère-Siviez-Mischabel internal belt, characterized by 520-480 Ma-old alkaline magmatism and few traces of Variscan metamorphism. The massive to gneissic tonalite of the Grand Nomenon (Valsavarenche) backthrust with a greenschist facies monometamorphic imprint (Amstutz, 1962; Elter, 1987; Freeman *et al.*, 1997), traditionally regarded as a Permian intrusion (e.g., Ellenberger, 1958; Desmons & Mercier, 1993), yielded similar U-Pb conventional and SHRIMP zircon ages of 357 ± 24 and 356 ± 3 Ma (Bertrand *et al.*, 2000b). In spite of the perfect concordance of U-Pb dating, the absence of pre-Alpine metamorphic relics makes doubtful the geological meaning of the isotope data and their inference on the absent or poorly represented Variscan orogeny (discussion in Malusà *et al.*, 2005).

The older basement is intruded by Late Paleozoic granites and subvolcanic acidic bodies, and unconformably covered by Late Paleozoic-Early Triassic clastic deposits and volcanic-subvolcanic bodies, followed by the Briançonnais cover suite, consisting of Triassic shelf carbonates and evaporites, Middle Jurassic-Late Cretaceous pelagic to neritic deposits, and Lutethian-Priabonian turbidites, carefully described in Ellenberger's (1958) memoir on the Vanoise, showing that the Briançonnais domain played as a structural high during the early stages of Mesozoic rifting (Sturani, 1975; Trümpy, 1980). Detailed descriptions of the Cottian and Ligurian Alps are provided by Guillaume (1969), Sturani (1975), Vanossi *et al.* (1984), Vanossi (1992), Desmons *et al.* (1999), Carminati & Gosso (2000). Three major post-Variscan volcanic units with calc-alkaline to alkaline features are described and dated in the Ligurian Alps by Dallagiovanna *et al.* (2009), yielding 285.6 ± 2.6, 272.7 ± 2.2 and 258.5 ± 2.8 Ma U-Pb zircon ages.

The Subbriançonnais is the outer domain of the Grand St Bernard nappe system in the French-Italian Alps. It is a group of Meso-Cenozoic decollement cover sheets detached from an unknow basement along an evaporitic horizon and displaced westwards over the Dauphinois domain in the Autapie-Embrunais region.

In the eastern Switzerland, the potential counterpart of the Grand St Bernard system is represented by the already mentioned Tambo nappe and related decollement cover units which display a close Briançonnais affinity.

Lepontine basement units - The Lower Penninic (Lepontine) system encompasses the deepest nappes presently exposed in the Alpine belt. From top to bottom, it mainly consists of the Monte Leone, Lebendun, Antigorio and Verampio nappes, in the Italian side, and the Bellinzona-Dascio, Adula, Maggia and Simano nappes in the Swiss side. These units display the features of a high-grade domal complex, due to dominant pre-Triassic basement nappes with an amphibolite facies regional (Lepontine) metamorphism and kilometric post-nappe recumbent folds (Monte Leone, Antigorio; Milnes, 1978; Milnes *et al.*, 1981). Most nappes mainly consist of Alpine gneisses derived from Late Paleozoic granitoids, even if polymetamorphic paraschists, migmatites and ultramafic slices are locally widespread. The basement nappes are directly superposed along shear zones or are separated by thin sheets of cover metasediments, including Permian-Eotriassic metaconglomerate and quartzitic schists, Triassic marble, Jurassic breccia and dominant flysch-type calcschists.

Outer Penninic Valais domain

Focusing on the existence of a second oceanic basin (North-Penninic) within Alpine Tethys (Trümpy, 1980), we deal with the Valais zone in the external part of the Penninic domain, and with its ophiolitic units that have long been known as an oceanic suite. This outer-lower Penninic domain is an arcuate thin-skinned belt which extends from Moutiers to the upper Rhone valley, between the Briançonnais and Penninic frontal thrusts (Bigi *et al.*, 1990). The Valais zone groups a stack of decollement flysch units of Cretaceous age (Brèches de Tarentaise, Sion-Courmayeur zone; Trümpy, 1954, 1980; Elter & Elter, 1965; Antoine, 1971; Fugenschuh *et al.*, 1999), accreted in front of the Grand St Bernard nappe, together with a basal tectonic complex of Late Paleozoic-Jurassic metasediments. The Valais zone also includes some ophiolitic units: the most important and debated is the Versoyen (Roignais) unit, which tectonically overlies the Tarentaise breccia near the French-Italian boundary (Martin *et al.*, 1994; Cannic *et al.*, 1996; Bousquet *et al.*, 2002; Beltrando *et al.*, 2007; Masson *et al.*, 2008), along a thrust contact (Bigi *et al.*, 1990). The contact with the overlying Triassic-Liassic sequences of the Piccolo San Bernard zone (Elter & Elter, 1965) is of controversial interpretation, although a stratigraphic origin has recently been proposed (Masson *et al.*, 2008). The Versoyen unit consists of serpentinite, massive to pillowed metabasalts and minor metagabbro, closely associated, together with some exotic bodies (Paleozoic micaschists, granite and impure quartzite), as tectonic slices or olistoliths, within a dominant sequence of Mesozoic flysch-type calcschists, phyllites and marbles of supposed Mesozoic age (Elter & Elter, 1965; Antoine, 1971; Antoine *et al.*, 1973). The mafic rocks display N-T-MORB-type and island arc tholeiitic affinity (Mugnier *et al.*, 2008), hydrothermal alteration and polyphase Alpine overprint recorded by blueschist and eclogite facies relics and greenschist facies re-equilibration (Cannic *et al.*, 1986; Bousquet *et al.*, 2002; Beltrando *et al.*, 2007; Masson *et al.*, 2008).

As previously seen, the opening of the Valais (N-Penninic) basin had originally been considered as a coeval aulacogen of the Jurassic Piedmont ocean, prior to being referred to the Cretaceous, and connected to the generation of the Briançonnais terrane (Stampfli, 1993; Stampfli *et al.*, 2002; Rosenbaum & Lister, 2005). The mafic rocks of the Versoyen unit, long envisaged as derived from the Mesozoic oceanic floor of the Valais basin have recently provided Permian (Beltrando *et al.*, 2007: 272 ± 2, 267 ± 1) or Visean (Masson *et al.*, 2008: 337.0 ± 4.1) U-Pb zircon ages, resulting a Variscan ophiolitic suture (Schärer *et al.*, 2000; Masson *et al.*, 2008) or a post-Variscan igneous suite emplaced into the continental crust during a process of lithospheric stretching before the break-up of Pangea (Beltrando *et al.*, 2007, 2010a-b). In front of these conflicting ages and geological meaning, I prefer the interpretation given by Beltrando *et al.* (2007): Early Carboniferous dating poses problems, like that obtained from the Gran Nomenon metatonalite (Bertrand *et al.*, 2000), on the Variscan orogeny and its regional metamorphism which are well recorded in the Ruitor basement and in the Helvetic massifs. In any case, whatever the age would be, the existence of a Cretaceous ocean in the Western Alps becomes very improbable (Masson *et al.*, 2008).

Ophiolite-bearing calcschists are exposed in the Ossola-Tessin window (Martin *et al.* 1994). This unit is interbedded between the Lebendun and Monte Leone nappes and is generally related to the outer-inner Penninic (Valais) domain. Similar sequences of Mezozoic calcschists (Bündnerschiefer) and oceanic ophiolites extensively occur in the Grison area (Fig. 33), in front of and below (Misox zone) the Tambo-Shams-Suretta nappes (Steinmann & Stille, 1999). These metasediments grade upwards to the Turonian-Lower Eocene Prättigau flysch unit. Traces of Cretaceous magmatism or mantle denudation in units supposedly issued from the North-Penninic basin are reported in the Central Alps, either in the Chiavenna ophiolite (Liati *et al.*, 2002), or in the Tasna nappe (Florineth & Froitzheim, 1994).

Penninic windows in the Eastern Alps

The continental and ophiolitic units exposed in the Engadine, Tauern and Rechnitz windows are briefly reviewed here, independently from their discussed connections (buried and eroded) to the Penninic zone in the Western Alps. The Lepontine (Lower Penninic) nappe stack is buried and only the Rheno-Danubian flysch belt extends from the Central to the Eastern Alps.

Engadine window - The Engadine window cuts the Eastern Austroalpine system at the Swiss-Austrian boundary, and exposes a stack of ophiolitic nappes and other thin units, mainly derived from turbiditic sequences of Mesozoic-Paleogene age (Oberhauser, 1980; Trümpy, 1980; Waibel & Frisch, 1989. Hoinkes *et al.*, 1999).

Below the previously described Platta-Arosa nappe, the following units crop out from top to bottom: i) Tasna nappe, a metasedimentary sequence of Permian to Late Cretaceous age and Briançonnais affinity, including slices of granitic basement; ii) ophiolitic Ramosch slice; iii) Roz-Tschampatsch cover unit; iv) lower calcschist unit (Grava-Tomül) with some greenschist facies metabasalts.

The Platta-Arosa ophiolite is referred to as South-Penninic (Piedmont-Ligurian), the underlying units as N-Penninic (Valais). Transition from continental to oceanic basement has been recognized in the Tasna nappe and Ramosch zone by Florineth & Froitzheim (1994). The latter mainly consists of serpentinized mantle peridotite, with ophicarbonates, serpentinite breccias, and basaltic pillow lavas (Vuichard, 1984).

Tauern window - The Tauern window is surrounded and overrided the central Eastern Austroalpine, showing a domal stack of oceanic and continental nappes of debated provenance. As reviewed in the first part, these nappes are supposed to be derived from the N-Penninic (Valais) and/or S-Penninic (Piedmont-Ligurian) basin, and from the Briançonnais microcontinent, the European distal passive margin or the Subpenninic domain (e.g., Bigi *et al.*, 1990; Schmid *et al.*, 2004; Kurz, 2007; Mattern & Wang, 2008). Anyway, the oceanic fragments were accreted to the Cretaceous Austroalpine wedge from the onset of the lower plate subduction, followed by the continental cover and basement nappes from the ocean closure onwards. The geological features described in the following update the structural and lithological subdivisions of the Structural Model of Italy, and mainly deals with the Italian south-western edge (Sander, 1929; Bianchi, 1934; Dal Piaz, 1934; De Vecchi & Baggio, 1982; De Vecchi, 1989; Bistacchi *et al.*, 2004, 2007). Classic and modern referencing is essentially done in the first part of this review.

The capping unit of the Tauern window is the oceanic and structurally composite Glockner nappe (Obere Schieferhülle in fixist view) (Fig. 36). The underlying continental system is exposed in the western, central and south-eastern sides of the Tauern window, and is represented by basement sheets and/or decollement cover nappes (Untere Schieferhülle) and prominent crystalline basement massifs. An eclogite-bearing nappe is interposed between them in the southern part of the central window (Miller, 1977; Ratschbacher *et al.*, 2004). Mineral-textural relics of high-P metamorphism are also recorded in the Glochner nappe (blueschist) and Grossvenediger basement (eclogitic boudins; Bianchi, 1934; Cortiana *et al.*, 2004). The crystalline basement, often associated to remants of its post-Variscan cover, consists of Alpine gneissic granitoids and minor mafic bodies (Central Gneiss) from one or more Late Paleozoic batholiths, and various kinds of older (pre-granitic) host rocks with polymetamorphic features, which locally display significant relics of Ordovician eclogites (Sm-Nd: 421 Ma, U-Pb: 418-415 Ma; von Quadt *et al.* 1997) and an Early Paleozoic to Neoproterozoic oceanic suture, back-arc and island-arc settings (Grundmann, 1988; Reitz & Höll, 1988; Vavra & Frisch, 1989; Vavra & Hansen, 1991; Höck, 1993; Neubauer *et al.*, 1999; Thöni, 1999; Neubauer, 2002; Schuster *et al.*, 2004). The older Penninic basement was pervasively reworked by Variscan high-T metamorphism and anatectic migmatites associated with granitic intrusions.

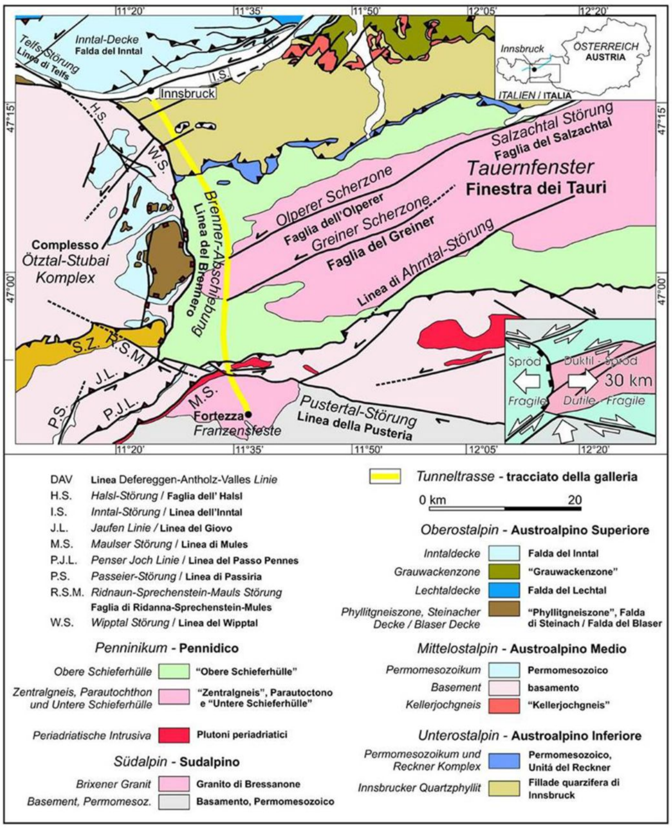
Figure 36. Grossglochner.

Grossglochner, the highest peak in Austria, gives its name to the major ophiolitic unit in the Eastern Alps.

The western Tauern window is dominated by the Venediger-Zillertal (internal) and Tux (external) nappes, forming the core of two gigantic east-west trending antiforms. In the central sector, the domal Granatspitz basement rises off the surrounding Mesozoic units, whereas in the south-eastern side the main basements are represented by the Sonnblick, Siglitz, Hochalm-Ankogel, Gössgraben, Mureck units (Oberhauser, 1980; Bigi *et al.*, 1990, 1993; Flügel & Faupl, 1987; Kurz *et al.*, 1996, 1998; Neubauer *et al.*, 1999; Schmid *et al.*, 2004). A peculiar feature of the Tauern nappe stack is the penetrative greenschist to amphibolite facies overprint and related ductile deformations of Tertiary age (collisional metamorphism), known from classic Sander's work on Tauern crystallisation (Morteani & Raase, 1974; Hoinkes *et al.* 1999; Thöni, 1999, 2006; Oberhänsli *et al.*, 2004; Schuster *et al.*, 2004). Therefore, igneous and older metamorphic fabrics can be preserved to different extent in small to megascopic low-strain domains of the Alpine orogeny. As previously reviewed, the Tauern window is the result of concurrent, late-collisional tectonic processes, i.e. active north-south Adria-Europe plate contraction, tectonic unroofing by orogen-parallel displacement of the Austroalpine along antithetic low-angle extensional detachments on both sides of the window (Brenner and Katschberg normal faults), and upward-lateral extrusion of the Penninic nappe stack (Selverstone, 1988; Behrmann, 1988; Genser & Neubauer, 1989; Ratschbacher *et al.* 1991).

Focusing on the Italian part of the western Tauern window and nearby areas (Fig. 37), the Glockner top nappe consists of dominant calcschists (Bündnerschiefer) of supposed Late Jurassic-Early Cretaceous age, mainly derived from orogenic trench deposits; minor interbeddings of marble, metachert and quartzite are interpreted as thin oceanic cover remnants still attached to ophiolitic bodies, or scattered inside the calcschists. The ophiolitic suite is represented by the Alpine derivatives of fresch to spilitic (oceanic alteration) submarine tholeiitic basalts, minor serpentinite-ophycarbonate slices, often mylonitic, and a few coarse-grained flaser metagabbro, generally embedded within calcschists (De Vecchi & Piccirillo, 1968; De Vecchi & Baggio, 1982; De Vecchi, 1989; Bistacchi *et al.*, 2003, 2007). The ophiolitic nappe is subdivided into subnappes thanks to the occurrence of scattered trails of exotic bodies, represented by boudinaged thin sheets of a continental cover suite made up of Permian-Eotriassic quartzitic schists and massive quartzites, as well as of Middle-Upper-Triassic marbles and dolostones (Dal Piaz, 1934). Similar rocks also occur, together with basement sliver, in the Matrai zone (Frisch *et al.* 1989), a relatively thick tectonic mixing shear-unit which discontinuously marks the contact with the overlying Austroalpine, and probably is representative of the original trench-slope transition.

Figure 37. Western Tauern window and surrounding units.

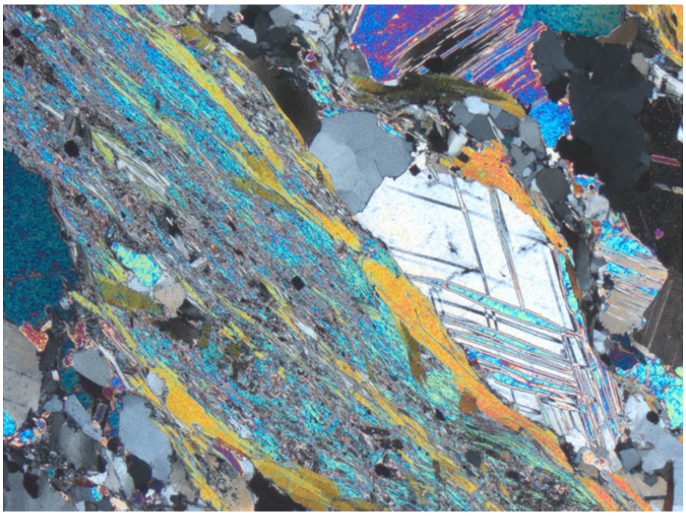


Tectonic map of the western Tauern window, surrounding Austroalpine nappes, Southalpine basement and Periadriatic intrusions. Inset: extensional mechanism for denudation of Penninic nappes. Geological study for Brenner Basis Tunnel, GBA-CFR-UIBK, 2006.

In the western Tauern window, the underlying stack of continental cover and basement nappes is regionally characterized by the east-west trending prominent antiforms of Gross Venediger-Zillertal and Tux, and a narrow subvertical synform (Greiner syncline) between them (De Vecchi & Baggio, 1982; Lammerer, 1986, 1988; Bistacchi *et al.*, 2004, 2007). The Tux-Gross Venediger nappe system consists of a dominant granitic-granodioritic gneiss (Central Gneiss) from intrusives emplaced at the Carboniferous-Permian boundary (Cesare *et al.* 2001), minor pre-granitic paragneiss (Altes Dach), and autochtonous to detached cover sequences of Permian-Mesozoic age (Untere Shieferhülle). The post-Variscan metasedimentary cover essentially includes: i)

Late Paleozoic-Eotriassic basal metaconglomerates (with basement pebbles), black schists, metamorphic arkose-sandstone successions and withish quartzites; ii) Middle-Late Triassic platform dolostones, calcitic-dolomitic marbles, evaporites (Fig. 38) and lagoonal deposits, with later terrigenous imputs; iii) Jurassic sedimentary scarp breccias (continental rifting), multiple alternances of pelitic, arenitic and carbonate metasediments with occasional metabasalts (Brennkogel facies), Late Jurassic finely banded radiolarian metacherts, and fossiliferous carbonates (Hocsteghen marble); iv) Cretaceous alternances of pelitic schists, impure quartzite and calcschists (Kaserer series).

Figure 38. Triassic evaporites.



Thin section from German-facies anydrite-rich beds drilled in the buried Greiner synform between Tux and Gran Veneziano antiforms, Vizze valley, Tauern window.

The underlying Storz nappe occurs only in the central and eastern Tauern window, and is made up of a basal polymetamorphic basement with remnants of a pre-Variscan volcanic arc-marginal basin system, orthogneiss from Variscan intrusives, and post-Variscan clastic to phyllitic metasediments. In the central-southern Tauern window, the Storz nappe is overlain by the already mentioned Eclogite zone, that is characterized by abundand boudins of mafic eclogites inside high-P arkosic-pelitic metasediments, quartzites and marbles, roughly recalling the Furgg zone in the southern Monte Rosa nappe. The eclogitic bodies are derived from basalt and gabbro protoliths, tentatively referred to an initial rifting stage (Miller *et al.*, 1980), and the high-P imprint yields the previously cited Eocene ages. The lowermost and largest nappes of the Tauern window mainly consist of gneissic intrusives from Late Paleozoic protoliths, and a pre-granitic polymetamorphic complex. The crystalline basement is unconformably covered by beds of Permian-Eotriassic basal metaconglomerate and/or quartzite, Triassic marbles with terrigenous interleavings and scarce metavolcanics, thick sequences of pelagic carbonates of Oxfordian-Early Titonian age (Hochstegen marble), and capping clastic metasediments of probably Cretaceous age, similar to Kaserer series in the Rote Wand-Modereck nappe.

The Penninic nappe stack is characterized by a pervasive Alpine greenschist to amphibolite facies overprint of Tertiary age (Tauernkrystallisation of Sander, 1911), but subduction blueschist facies metamorphism is locally documented by scattered mineral-textural relics (pseudomorphs after lawsonite) and thermodynamic modeling of mineral zoning (garnets) and fluid inclusions (Selverstone *et al.* 1984; Selverstone, 1985; Selverstone & Spear, 1985; Christensen *et al.*, 1994).

The Oligocene post-orogenic magmatism is testified in the Italian side by the granodioritic-tonalitic Rensen and Riesenferner plutons and by the Mules tonalitic to gabbro-dioritic lamellae; all of them were emplaced in the surrounding Austroalpine or along the Periadriatic system. Oligocene leucocratic dykes are also found near the Austroalpine-Penninic contact at the southern margin of the Tauern window.

The Penninic units of the Tauern window escaped the Cretaceous orogeny, since at that time they had not yet entered the subduction zone. Indeed, these oceanic and continental nappes display only a polyphase Tertiary metamorphism and related fabrics which developed before the Oligocene, as firmly constrained by the emplacement of andesitic dykes of the Periadriatic magmatism (Mancktelow *et al.*, 2001; Bistacchi *et al.*, 2004). The first metamorphic event is the eclogitic imprint recorded in mafic and metasedimentary rocks of the narrow Eclogite zone (Miller, 1974; Dachs, 1986; Hoschek, 2001, 2007), and as scattered relics in the Grossvenediger basement and elsewhere. P-T estimates are 1.9-2.2 Gpa and 550-630°C and some $^{40}Ar/^{39}Ar$ dates point for their Eocene age, between 50 and 40 Ma (Zimmermann *et al.*, 1994), as in the Western Alps. This may be confirmed by $^{40}Ar/^{39}Ar$ ages of high-Si phengites from the blueschist facies Mesozoic metasedimentary (Hippold) and ophiolitic (Reckner) units (Fig. 28) of the structurally composite

Tarntal nappe, yielding 44-37 Ma (Dingeldey *et al.*, 1997). This nappe, generally related to the Lower Austro-alpine (Bigi *et al.*, 1990; Dingeldey *et al.*, 1997; Kurz *et al.*, 1998) is probably a S-Penninic unit of the Tauern window embricated within the nearby Austroalpine system. Sheet 1 of the Structural Model schematically shows the Reckner serpentinite body inside the Lower Austroalpine sedimentary cover: it includes pods of pegmatoid gabbro and could be a further example of a denuded mantle slice covered by oceanic sediments.

The high-P event reached blueschist facies conditions in some Mesozoic units of the Tauern window, followed by the final and pervasive Barrovian oveprint which developed post-nappe greenschist to amphibolite facies mineral assemblages.

Dealing with the Penninic nappe stack in the western edge of the Tauern window (De Vecchi & Baggio, 1982; Hoschek, 1984; Selverstone, 1985; Selverstone *et al.*, 1984; Selverstone & Spear, 1985; De Vecchi & Mezzacasa, 1986), high-P conditions (1.0-1.1 GPa) are recorded by Lower Shieferhülle units during collisional accretion to the Austroalpine system (Eocene), reaching the metamorphic T-peak during later exhumation (550°C, 0.7 GPa). Otherwise, petrological estimates on the Glockner nappe (Upper Shieferhülle) display a lower P-maximum of 0.7 GPa and a T-maximum of 475°C at 0.6-0.5 GPa. The burial difference between these units (ca 10 km) is explained by thinning of the ophiolitic nappe during Tauern window unroofing (Selverstone, 1985, 1988, 1993), even if an influence of the Tauern thermal perturbation on studied mineral assemblages can not be excluded. Radiometric ages (Christensen *et al.*, 1994) show that garnet in the Lower Shieferhülle developed before garnet in the Upper Shieferhülle (55 Ma vs 35 Ma), both growing until the Oligocene (30 Ma). The shear sense indicators inferred from syn-kinematic garnet and s/c fabrics in Glockner metasediments and from post-kinematic garnet and honeblende cracking in Lower Shieferhülle show a generalized east-west extension with a top-down to the west kinematics (Selverstone, 1988, 1993; Lammerer & Weger, 1998). The greenschiest facies mylonites along the Brenner normal fault cut all previous foliations, but show the same kinematics detected in the Glockner nappe. Summing up, the tectonic denudation of the western Tauern window supposedly initiated since the Eocene-Oligocene boundary, the age of garnet growth in the Glockner nappe (Selverstone *et al.* 1993; Christensen *et al.*, 1994; Axen *et al.*, 1995; Bistacchi *et al.*, 2004). For maps and details of the geological and structural features on the Italian side of the Brenner Basis Tunnel transect, see Bistacchi *et al.* (2004, 2007) and reports given to GEIE-BBT.

Rechnitz windows - Blueschist facies ophiolitic units reappear at the eastern corner of the Alps, near the Austrian-Hungarian border, inside the Rechnitz window and other minor occurrences (Möltener, Bernstein, Eisenberg) named, as a whole, Rechnitz Window Group (Höch & Koller, 1989; Koller & Höch, 1990). As shown in the Structural Model (sheet 2, Bigi *et al.*, 1990), these units are discontinuously exposed below the Lower Austroalpine system, mainly surrounded or covered by Miocene-Pliocene deposits (Pahr, 1980). A thick Mesozoic cover sequence of calcareous to terrigenous metasediments is underlain by scattered bodies of metamorphic ophiolites, derived from tholeiitic basalt, gabbro, plagiogranite, ophicarbonate breccia and mantle ultramafics, showing diffuse traces of oceanic hydrothermal alteration. The Alpine evolution is characterized by a typical blueschist facies metamorphism (sodic pyroxene, glaucophane and crossite, lawsonite or epidote, high-Si phengites) of Eocene age (57 ± 3 Ma; Dunkl & Demeny, 1997), followed by a greenschist facies overprint (Koller, 1985; Schuster *et al.*, 2004).

The exhumation of these hig-P oceanic remnants was accomplished at the beginning of the Neogene at the footwall of low-angle normal faults. This is inferred from K-Ar white mica cooling ages (22-19 Ma; Frank in Koller, 1985) and fission-track ages (Dunkl & Demeny, 1997) for zircon (21.9-13.4 Ma) and apatite (7.3-9.7 Ma).

Prealpine decollement nappe system

As shown in the Structural Model of Italy, various remants of formerly larger decollement cover nappes are preserved to different extent in the French-Swiss Prealps and outer ranges, between Annecy and the Glarus Alps (Trümpy, 1980; Caron *et al.*, 1989). The nappe theory was born in this area, when Bertrand's insight and Shardt's regional work replaced Heim's double fold tenet by large thrusts (Trümpy, 1991). The Prealpine decollement nappes and klippen consist of Mesozoic-Paleogene sedimentary sequences which escaped subduction and Alpine metamorphism. Indeed, these units were decoupled from their oceanic and continental substratum since the beginning of the ocean closure and prograding collisional accretion of the European passive margin, and then they were displaced over the Helvetic-Ultrahelvetic foreland, in turn later rearranged as a thrust belt, and finally overrode the inner Molasse. The Chablis and Romandes Prealps are a stack of six major nappes preserved around the Lemano lake. The upper two nappes mainly consist of multiple Cretaceous (Helminotoid) or Cretaceous-Eocene flysch units, and the top one (Simme s.l.) also includes continental detritus of Southalpine affinity (Elter *et al.*, 1966; Caron, 1972), and olistoliths of Ligurian-type ophiolites (Gets unit), i.e. obducted fragments of oceanic lithosphere free of orogenic metamorphism (Dal Piaz, 1999). The Breccia nappe is characterized by Jurassic rift breccias, whereas the underlying Medianes (or Klippen) nappes, mainly of Triassic-Eocene age, are dominated by competent Triassic-Jurassic carbonates (Rigid Medianes) or relatively soft limestone-shale sequences (Plastic Medianes); these units are generally correlated to the Briançonnais domain and their distal (pre-Piedmont) and proximal (Subbriançonnais) margins. The lowest nappes, maily Upper Cretaceous flysch (Niesen) and overlying melange, were probably issued from the Valais (North-Penninic) basin (Trümpy, 1980). Note that the Ligurian-type ophiolites (Gets unit) and their paleostructural restoration near the Canavese zone, suggested by Dal Piaz (1999) and corroborated by Bernoulli *et al.* (2003), go against the concept of a single Margna-Sesia fragment (Froitzheim *et al.*, 1996).

Similar Helmintoid flysch nappes reappear in the southern Western Alps, either in the tectonic depression between the Pelvoux and Argentera basement highs (Parpaillon-Autapie), or south-east of the latter (Sanremo-Ventimiglia). Both are made up of arenaceous and/or calcareous turbiditic sequences of Upper Cretaceous to Paleocene and locally Eocene (?) age, probably coming from the Piedmont-Ligurian basin, and record the onset and outward propagation of orogenic contraction (Di Giulio, 1992). The Helmintoid flysch was displaced over and then beyond the Briançonnais zone, and lastly to the Dauphinois domain together with their sole of thin Subbriançonnais thrust sheets (Structural Model, sheets 1 and 3).

Rheno-Danubian flysch

The outer Penninic Rheno-Danubian thrust belt is a sedimentary wedge of Early Cretaceous to Late Eocene turbiditic sequences which extend along the entire northern margin of the Eastern Alps (Fig. 27), spanning the entire time of deposition of the Penninic and Helvetic flysch sequences (Oberhauser, 1995; Trautwein *et al.*, 2001; Mattern & Wang, 2008). Even if locally, the Rheno-Danubian flysch is associated to some Jurassic ophiolite fragments, suggesting an oceanic environment for these turbiditic deposits. Their provenance is debated, and ranges, as for the Prättigau flysch, from the conventional N-Penninic (Valais) basin to the S-Penninic (Piedmont-Ligurian) domain (Frisch, 1979; Winkler *et al.*, 1985; Oberhauser, 1995; Schmid *et al.*, 2004). The flysch succession begins with carbonate-rich turbidites and evolves towards mainly silicoclastic deposits, with heavy mineral populations fed from the prograding Austroalpine frontal belt and other sources. Bentonite beds occur at the Paleocene/Eocene boundary. The outer Penninic flysch belt is underlain by discontinuous Jurassic-Eocene cover units, which are exposed in small windows and constitute the stripped eastern extension of the Helvetic-Ultrahelvetic decollement nappes, and both units are displaced over the Subalpine molasse thrust sheets.

Helvetic-Dauphinois zone

The Helvetic and Dauphinois zone (French side) extends along the entire external part of the Western and Central Alps, and narrows towards the outer Eastern Alps, where it is reduced to a few decollement sheets underneath the Penninic Rheno-Danubian flysch. The Helvetic-Dauphinois zone consists of prominent crystalline massifs, discordant or detached post-Variscan sedimentary covers and the classic stack of decollement nappes which predominate in the outer Swiss side (Sturani, 1975; Ramsay & Allison, 1979; Trümpy, 1980; Butler, 1985; Dietrich & Casey, 1989; Ramsay, 1989; Bigi *et al.*, 1990; Sacchi, 1991; Compagnoni *et al.*, this volume). Facies differences and structural position allow this external domain to be subdivided into the underlying-outer (Helvetic-Dauphinois) and overlying-inner (Ultrahelvetic-Ultradauphinois) basement and cover units.

External massifs

The prominent crystalline basement is widely exposed in the Argentera-Mercantour, Pelvoux (Haut-Dauphiné), Belledonne-Grandes Rousses, Aiguilles Rouges-Mont Blanc-Mt Chetif and Aar-Tavetsch-Gotthard external massifs (Fig. 39). The Mt Chetif slice, at the head of the Aosta valley, and the Gotthard massif are referred to as

Ultrahelvetic basement units (Spicher, 1980; Bigi *et al.*, 1990). Schmid *et al.* (2004), however, point for a Subpenninic pertinence of the Gottarhard massif, like the entire Lepontine nappe stack (Engi *et al.*, 2004). Polymetamorphic (Variscan and older) and monometamorphic (only Variscan) basement units may be distinguished, evolving from an Early Paleozoic subduction cycle, through Variscan collision, Laurussia nappe stacking and regional metamorphism, to Carboniferous erosion, orogenic collapse, Late Paleozoic intrusions and wrench faulting (von Raumer, 1987, 1998; Bogdanoff *et al.*, 1991; Bonin *et al.*, 1993; von Raumer *et al.*, 1999; von Raumer & Stampfli, 2008). Relics of Precambrian events are locally preserved. Scattered fossils in anchi-metamorphic or low-grade metasediments document the presence of Cambrian-Ordovician and Early Carboniferous deposits. Isotope dating provides additional information, concerning: i) Archean and Proterozoic cores of exotic detrital zircons; ii) Early Paleozoic (500-420 Ma) ophiolite-plagiogranite, eclogitic imprint, island arc gabbro, granitoids and migmatites; iii) Devonian (400-350 Ma) eclogites, mylonitic shear zones, rifting trondhjemites; iv) Late Variscan (340-300 Ma) greenschist to amphibolite facies metamorphism with widespread crustal anatexis and a Visean thermal peak; gabbro and granitoid intrusions; v) Early Permian granitoids and acidic volcanics (Bonin *et al.*, 1993; von Raumer *et al.*, 1999).

Figure 39. Mont Blanc external massif.

Left – Italian side of Mont Blanc massif, consisting of Late Paleozoic granite and minor capping paraschists.

Right – Arête de Peuterey: the Dames Anglaises, at the center, are modelled in a roof pendant of paraschists with a basal intrusive contact, and lowered into surrounding granitic rocks as a small graben bounded by high-angle faults.

Sedimentary cover

The Variscan basement is unconformably covered by thick sedimentary sequences of Late-Carboniferous to Oligocene age, characterized by asymmetric rifting, fault-bounded basins and passive-margin sequences (Malaroda, 1957; Sturani, 1962, 1963, 1975; Trümpy, 1980; Bigi *et al.*, 1990). The discordant cover locally begins with continental clastic deposits of Late Westfalian and/or Stephanian age, in places coal-bearing. The Permian is represented by clastic sequences, locally including conglomerates (Verrucano facies) and acidic volcanics. Triassic formations consist of thin basal quartzites (Lower Scythian) and/or German-type successions, with shales and abundant evaporites (Keuper) that became the principal decollement horizons during Alpine contraction. In the Pelvoux massif there are spilitic lava flows, tuffs and dykes of Triassic age (Aumatre & Buffet, 1974; Bigi *et al.*, 1990), roughly coheval with the calc-alkaline and shoshonitic extensional magmatism in the Southern Alps (Dal Piaz & Martin, 1998). Jurassic sediments are a thick sequence of limestone, marly limestone and shale, which record a period of rapid subsidence and include submarine sliding breccias and slumps. Cretaceous sediments display pelagic features, with thick limestone-marl alternances and black shales. However, the pelagic sequences are laterally replaced by neritic limestones or dolostones (Jurassic), and glauconitic-phosphatic deposits (Cretaceous), pointing to the existence of distinct paleostructural domains.

The Cretaceous-Tertiary transition is marked by a general emergence, that continued until the Lowermost, Middle or Upper Eocene when, in different sectors, the Helvetic domain was again flooded by the Tethyan sea, generally progressing from the outer to the inner side. This was roughly the time of the ocean closure, continental collision and rapid subduction of the European distal passive margin. The sedimentary evolution of the Helvetic realm is outlined by lagoonal sediments and/or transgressive nummulitic limestones, followed by pelagic marls, and then by thick flysch-type clastic sequences (Taveyanne sandstone-greywacke and similar units) of Priabonian-Lowermost Oligocene age, often including abundant volcanic detritus of diabase-andesite composition and Oligocene age (Ruffini *et al.*, 1995, 1997). Afterwards, sedimentation was interrupted by submarine thrusting of the Helmintoid flysch nappes or ultimate emergence of the Helvetic domain, whereas in the external side the Helvetic sequence graded upwards to the molasse deposits of Oligocene-Miocene age (e.g., Val d'Illiez unit).

The Helvetic-Dauphinois cover units were strongly deformed during the Late Oligocene-Neogene (neoalpine) event, when the orogenic wave propagated from the Austroalpine-Penninic collisional wege to the evolving foreland. Basement and cover units were accreted in front of the exhumed collisional wedge, below the Penninic frontal thrust, and partly recrystallized in anchizone (sedimentary cover), greenschist and locally amphibolite facies conditions (southern Gotthard), with no traces of high-P subduction metamorphism (Frey *et al.*, 1974, 1999).

Helvetic-Ultrahelvetic decollement cover nappes

The Helvetic and Ultrahelvetic cover nappes are decollement thrust sheets and minor recumbent folds which occur between the Penninic frontal thrust and the Molasse foredeep, from the Annecy and Lemano lakes to the Rhine valley (Trümpy, 1980; Ramsay, 1981, 1989; Ramsay *et al.*, 1983; Bigi *et al.*, 1990). The root zone steeply extends from the external basement massifs to the stripped footwall of the Penninic front. These nappes mainly consist of Mesozoic shelf to carbonates and flysch sequences of Upper Eocene-Lower Oligocene age, including the Taveyanne volcaniclastic beds. Permian conglomerates occur in the Glarus Alps. The cover nappes detached along incompetent horizons, such as Triassic evaporites and Middle Jurassic-Cretaceous shales. Oligocene thrusting of the Ultrahelvetic cover sheets developed before that of the underlying Helvetic units. Folds are persistent often for tens of kilometres and the overall structural pattern is representative of a relative Adria-Europe movement evolving from north-south to NW-SE and lastly east-west directions (Ramsay, 1989). The sequence of along-axis tectonic culminations and depressions of the nappe stack has been interpreted as a result of complex ramp-duplex geometry or post-nappe east-west shortening. From bottom to top, we may see the Morcles recumbent fold and the overlying trinity of Diablerets-Gellihorn and Wildhorn nappes, extensively preserved in the structural low between the prominent Mont Blanc and Aar massifs, and capped in turn by remnants of the Ultrahelvetic cover sheets. The pile of Helvetic nappes extends to the east, externally of the Aar massif: it is represented by the Säntis-Drusberg, Axen, Mürtschen and Kammlistock decollement nappes, consisting of Mesozoic (or Permian) to Eocene sedimentary sequences (Spicher, 1980; Trümpy, 1980; Bigi *et al.*, 1990). Similar cover nappes occur in the Chaînes Subalpines (French Alps), west (Chartreuse) and south (Devoluy-Ventoux) of the Belledonne and Pelvoux massifs (Gratier *et al.*, 1989). The Dauphinois sedimentary cover detached along its flat contact with the basement and was strongly deformed by folds, thrust-faults and strike-slip faults, mainly with a dextral kinematics. Slices of crystalline basement are locally displaced over the Subalpine Chaînes. Also in this area, the normal and transcurrent faults of the rifting stage were largely reactivated and inverted by Alpine tectonics, from the Oligocene to the Present.

Molasse Foredeep

The Molasse is a southward thickening sedimentary wedge a few tens kilometres wide, extending from Annecy and Geneva lake area to Vienna, partly buried below the frontal Alpine nappe stack. Its subsurface geometry is inferred from extensive geophysical and drilling exploration, and in the Structural Model of Italy (sheets 1-2) the contour lines (isobaths in metres) of the base of Oligocene are represented. The Molasse foredeep developed from the Oligocene to the Late Miocene, when the Helvetic-Ultrahelvetic basement and cover units were detached from the lithospheric lower plate, and progressively accreted in front of the Austroalpine-Penninic collisional wedge. Lithic clasts, heavy minerals and fission-track dating provide essential information on uplift, cooling and erosion of the Alpine nappe stack (eg., Frisch *et al.*, 1999; Spiegel *et al.*, 2000; Garzanti *et al.*, 2007).

The Molasse infill of the basin is represented by clastic sediments fed by foreland sources and mainly by the erosion of the rising and outward prograding Alpine belt, and deposited during repeated alternances of shallow marine and freschwater conditions, both related to sea-level changes and regional tectonics (Fuchs, 1980; Trümpy, 1980). Older Molasse sediments are mainly shallow marine shales and sandstones of Lower Oligocene age, with ripple-marks to turbiditic features, and multiple intercalations of conglomerate bodies. The overlying Upper Oligocene-Lowermost Miocene freshwater deposits are represented by thick conglomerate sequences alternating with silty and marly shales, or by freschwater limestones and fining-upwards fluvial cycles including coal beds with a subtropical flora and mammalian fauna. Shallow marine conditions renewed in the late Lower Miocene. Deposition was dominated by sandstones and minor conglomerates along channeled tidal flats and fan delta. The sea ultimately retreated from the Molasse basin in the Middle to Upper Miocene. The drainage became dominated by a proto-Rhone river, flowing from the Austrian Alps and Bohemian massif to the west, a large fan delta from Alpine ranges, providing sands and gravels from recycled Alpine cover and basement units.

From a tectonic point of view, the Molasse sequences are subdivided into two main parts, i.e. an inner strip of embricated sheets (Southalpine Molasse), extensively dragged southwards below the low-angle basal thrust of Helvetic-Penninic and Eastern Austroalpine nappe stack (seismic evidence: Pfiffner *et al.*, 1997; Bleibinhaus & Gebrande, 2005; Luschen *et al.*, 2006), and the gently deformed to flat central-outer zone (Tabular-Folded or Plateau Molasse). The former consists of older marine and freeshwater deposits of Oligocene-Lower Miocene age, and constrains the onset of Molasse underthrusting. The latter grades and thickens from the external tabular and poorly deformed zone to the internal zone characterized by large open folds which involve the entire Molasse sequence up to the Late Miocene deposits.

Jura belt

The French-Swiss Jura is an arcuate thin-skinned belt of Mesozoic sediments which were detached from the European foreland basement along evaporite horizons of Middle-Late Triassic age (German facies), severely folded and faulted during the Late Miocene-Early Pliocene outward propagation of the neoalpine orogeny (Trümpy, 1980). This tectonic reconstruction was cleverly envisaged by Buxtorf, more than 100 years ago (Laubscher, 2008).

Deformation was facilitated by reactivation of normal faults generated during the Oligocene opening of the Rhine and Bresse graben, or before, and concentrated along soft beds (evaporite and minor shale) or bedding surfaces of Jurassic sequences.

The sedimentary succession is represented by a thinning nortward prism of limestone and shale mainly of Upper Jurassic age. Following classic Swiss reconstructions, two parallel belts are mapped in the Structural Model: the inner belt (Folded Jura) is dominated by thin-skin ramp-flat thrusts and related folds, mainly disharmonic, while the central-outer belt (Tabular Jura) is characterized by scattered and more gently folding. Both belts are obliquely fragmented by various fault systems, mainly with strike-slip kinematics.

Southern Alps

The Southern Alps are a typical example of deformed passive continental margin well exposed in a mountain range (e.g., Winterer & Bosellini, 1981; Bertotti *et al.*, 1993; Carminati *et al.*, 2010; Gaetani, this volume), including the magnificent natural monument of the Dolomites (Bosellini, 1996; Gianolla & Panizza, 2009), and many other wonders, as the Eocene fossils plants and fish at Bolca (Papazzoni & Trevisani, 2006), the dinosaur ichnosite at the Lavini di Marco (Avanzini *et al.*, 2005), and the Paleozoic fossils recently discovered in the Venetian metamorphic basement (Dieni *et al.*, 2005), together with the Adamello massif (Callegari & Brack, 2002) and related pseudotachylytes (Di Toro *et al.*, 2004; Pennacchioni *et al.*, 2006), as well as the Ivrea-Verbano zone, one of the most spectacular sections across the lower crust (Rutter *et al.*, 2009). Until the Oligocene, this Adriatic domain was the gently deformed retro-wedge hinterland of the Alps, intensively reworked only at its eastern edge by the Paleogene SW-vergent Dinaric belt. From the Neogene, the Southalpine thrust-and-fold belt developed and progressively propagated towards the Padane-Adriatic foreland, reactivating rifting faults (Castellarin *et al.*, 1992, 1993, 2006; Zattin *et al.*, 2006; Doglioni & Carminati, 2008; Cuffaro *et al.*, 2010). Its front is mainly buried beneath the alluvial deposits of the Po Plain and sealed by Late Pliocene or Quaternary deposits. To the north, the Southern Alps are bounded by the Periadriatic fault system. The Canavese zone (Elter *et al.*, 1966; Sturani, 1975; Ferrando *et al.*, 2004), with the related open problems and different interpretations, has been discussed in the previous part.

The Structural Model (sheets 1-2) represents the entire Southern Alps. This map was elaborated by the Southalpine working group, coordinated by Castellarin and Vai, and from surface geology it can be inferred a complete crustal cross-section of the Southern Alps. Thick cover successions are dominant in the eastern sector (Bosellini *et al.*, 1996; Doglioni & Carminati, 2008; Gaetani, this volume), whereas the basement is nearly continuous from the central sector (upper-intermediate crust: Orobic Alps and Como and Maggiore-Verbano lakes area) to the western Southalpine edge where the lower continental crust is exposed in the Ivrea zone.

The crystalline basement encompasses various kinds of Variscan and older metamorphic granulite-amphibolite facies units derived from sedimentary, felsic and mafic igneous protoliths, later intruded by granitoids and gabbros of Permian age, and then deformed by Late Triassic-Jurassic rifting and passivce margin evolution (D’Amico & Mottana, 1976; Boriani *et al.*, 1992; Bonin *et al.*, 1993; Handy *et al.*, 1999). Among them, it can be mentioned the Massiccio dei Laghi (Boriani *et al.*, 1990), which outcrops in northern Piedmonte and southern Switzerland, grouping the famous Ivrea-Verbano zone and the nearby Serie dei Laghi (Maggiore, Varese and Como lakes): the complex features, pre-Alpine evolution and detailed references of this basement, carefully reviewed by Rutter *et al.* (2009), are summarized as follows.

Ivrea-Verbano zone

The Ivrea-Verbano zone consists of the Ivrea gabbro (a Permian batholith) and the roofing kinzigitic complex, both well exposed and extensively studied in the last decades, since modern pioneering works (e.g., Bertolani, 1969; Rivalenti *et al.*, 1981, 1984; Hodges & Fountain, 1984; Pin, 1986; Brodie & Rutter, 1987), therefore becoming a classic model for igneous underplating below extending continental crust (e.g., Rutter *et al.*, 1993, 1999, 2009; Schnetger, 1994; Quick *et al.*, 1994; Henk *et al.*, 1997; Sinigoi *et al.*, this volume). The higher grade (originally deeper) kinzigitic paragneiss include beds of pure and impure marble and thin to thick (1-200m) bands of mafic granulite-amphibolite that have been interpreted as lava flows or intrusives within the primary (Paleozoic or older) sedimentary sequence of the accretionary complex represented by the kinzigitic unit (Sills & Tarney, 1984), showing different rare-earth element patterns with respect to the Permian mafic rocks. Towards its base, the kinzigitic unit includes an increasing number of mainly concordant, occasionally discordant sheets of Permian mafic intrusions, that can not be easily distinguished in the field from the older amphibolitic bands within the kinzigites. The southern edge of the Ivrea-Verbano zone is dominated by a huge layered mafic complex, some 10 km wide and extending along strike for some 40 km. This is the “mafic formation” (Rivalenti *et al.*, 1981; Zingg, 1983), radiometrically dated as Permian (Pin, 1986: 295-280 Ma; Peressini *et al.*, 2007: 288 ± 4). The western and originally deeper part of the batholith displays a vertical igneous layering and metamorphic granular fabrics, indicating that the layered rocks resided in the subsolidus regime sufficiently long for developing metamorphic granular fabrics; by contrast, the eastern and relatively shallower part of the mafic formation is characterized by igneous textures.

As shown in the Foglio Varallo of the Carta Geologica d’Italia at 1:100,000 scale, in the Structural Model and, with great detail, in the splendid modern map by Quik *et al.* (2003; also reproduced in Sinigoi *et al.*, this volume), the Ivrea-Verbano zone includes some ultramafic bodies (peridotites, dunites and pyroxenites), mainly located towards its south-western edge and locally interacting with crustal magmas (Sinigoi *et al.*, 1991). According to Quick *et al.* (1995), none of these ultramafic bodies would extend at depth, beyond the Ivrea Zone, even if some of them are clearly upper mantle slices, evidencing a petrological transition between the lower crust and the lithospheric mantle (e.g., Boudier *et al.*, 1984). In this view, these slices may have been detached from upper mantle and accreted to the kinzigitic unit in Palaeozoic times (Quick *et al.*, 1995). In any case, the existence in the discussed area of the positive gravity anomaly, long known as the geophysical Ivrea body (Berkhemer, 1968; Compagnoni *et al.*, 1977; Roure *et al.*, 1990; Carrozzo *et* *al.*, 1991), suggests that the Adriatic lithospheric mantle lies beneath and not very far from the Ivrea-Verbano zone. The regional schistosity and associated folds developed in high-grade metasediments have been refolded, with associated axial-plane crenulation cleavages that overprint the partial melting leucosomes of kinzigitic migamitites. The Valle d'Ossola transect displays a sequence of large antiformal structures (Southern fold, Candoglia, Massonne, Proman), without evidence of synforms beween them, and interpreted as large-scale Type-2 fold interference patterns (Ramsay, 1967; details and refs. in Rutter *et al.*, 2009). These folding and metamorphic episodes predate the emplacement of the mafic formation (Boriani & Villa, 1997). Its intrusion generated contact migmatization and granulite facies conditions on the immediate roofing kinzigites (Schmid & Wood, 1976; Schmid, 1977; Henk *et al.*, 1997). Partial melting processes in the kinzigitic unit, wholly attributed to the mafic intrusion (Schmid & Wood. 1976), were later restricted to the contact zone, where it overprinted a previous metamorphic event with migmatization and degranitization processes (Barboza *et al.*, 1999, 2000; Peressini *et al.*, 2007; Rutter *et al.* 2007).

Extensive partial melting of crustal sources was envisaged to be responsible for the generation of the Permian epigranites and the rhyolitic caldera in the lower Sesia valley, andesitic melt included (Quick *et al.*, 2009).

The emplacement of the Permian intrusive complex was accompanied by stretching recorded by metamorphic and igneous rocks, with regional lineations plunging NE at about 30° (Rutter *et al.*, 1993). Crustal stretching continued during post-intrusive cooling, mainly accommodated by discrete high-T shear zones with the same kinematics of earlier deformation history (Brodie & Rutter, 1987).

Serie dei Laghi

As shown in the Structural Model and summarized by Rutter *et al.* (2009), the Ivrea-Verbano zone is laterally juxtaposed along its south-eastern boundary to the Serie dei Laghi (Boriani *et al.*, 1990a). The contact is marked by the Cossato-Mergozzo-Brissago line (Boriani *et al.*, 1990a-b), with mylonites and mafic-intermediate intrusives of appinitic affinity and Permian age (Boriani & Giobbi, 2004). This tectonic discontinuity is cut, in turn, by the Pogallo fault, a younger mylonitic shear zone that is interpreted as a low-angle extensional detachment of Triassic or Jurassic age (Hodges & Fountain, 1984, Schmid *et al.*, 1987; Zingg *et al.*, 1990), even if it displays the same kinematic feature of previous high-T events.

Summing up, the Serie dei Laghi was probably juxtaposed to the underlying Ivrea-Verbano zone along the Cossato-Mergozzo-Brissago shear zone during the Late Paleozoic extensional event and related igneous underplating. Note that this tectonic line is not deformed by and therefore probably postdate the multiple generations of folds recognized in the Ivrea-Verbano zone and Serie dei Laghi. This is also the case of the Schlingen structure (vertical-axis foldding) that is related to the Variscan orogeny (Zurbriggen *et al.*, 1997, 1998). The Serie dei Laghi consists of a suite of metasedimentary schists and gneisses (Scisti dei Laghi, Cenerigneiss, Gneiss Minuti), as well as of large bodies of orthogneiss derived from calc-alkaline Ordovician protoliths (Boriani *et al.*, 1990b; Bigi *et al.*, 1990; Zurbriggen *et al.*, 1997, 1998). Relics of pre-Alpine ophiolites (amphibolites and ultramafic rocks) have been found inside the Serie dei Laghi (Giobbi *et al.*, 1997); this zone is cut by the Pogallo fault, showing a large left-lateral displacement. Lastly, the Serie dei Laghi includes large post-metamorphic granitic intrusions of Permian age (280-275 Ma; Boriani *et al.*, 1992, 1995) and contemporaneous volcanic extrusives.

Central-Eastern side of the Southern Alps

Low-grade metamorphic basement - The Variscan regional metamorphism decreases from the high- and medium-grade (western and central Southern Alps) to greenschist facies (Venetian region, east of Adamello) and very low-grade (Carnian Alps) conditions (e.g., Boriani *et al.*, 1974; Frey *et al.*, 1974, 1999; Castellarin & Vai, 1982; Sassi *et al.*, 1985; Sassi & Zirpoli, 1989; Sassi & Spiess, 1993; Brack *et al.*, 2008; Cesare *et al.*, 2010; Spiess *et al.*, 2010). This imprint and related ductile deformations predate the discordant deposition of the Westphalian (Lombardy, Ticino) or Lower Permian clastic and volcanic sequences. The easternmost evidence of the Variscan amphibolite facies regional metamorphism (garnet-biotite-staurolite) is presently recorded in the country schists of the Adamello batholith (Brack *et al.*, 2008), whereas the two basement occurrences in the eastern Southalpine (Alto Adige and Valsugana) show a greenschist facies imprint which predates the discordant deposition of Permian volcanic sequences and the intrusion of

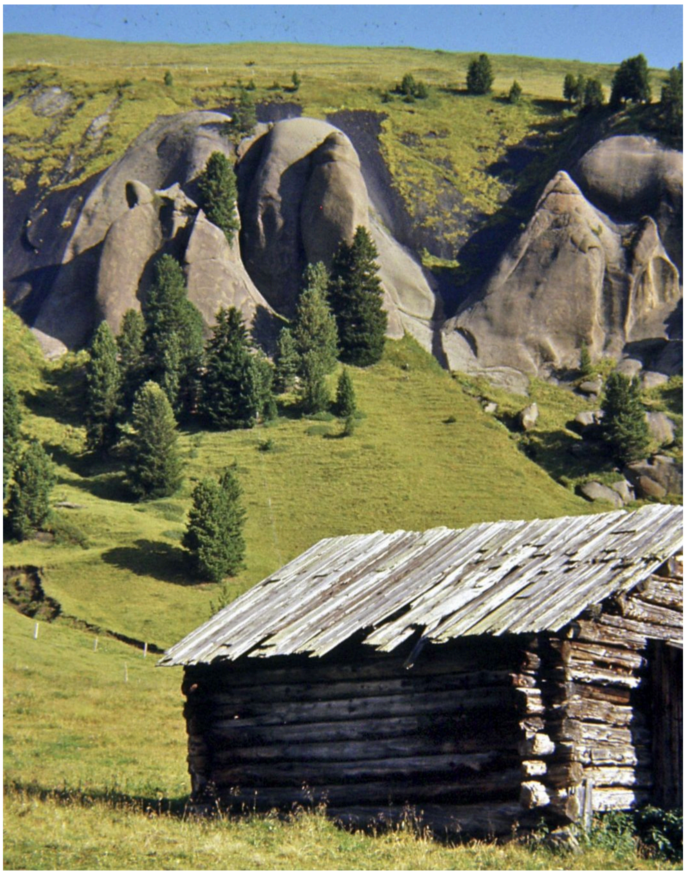
Permian plutons, mapped in the Structural Model (Bonin *et al.*, 1993; Bellieni *et al.*, 2010). The metamorphic basement (Sassi & Spiess, 1993; Spiess *et al.*, 2010) is dominated by low-grade quartz-phyllitic metasediments with documented Cambrian-Silurian ages (Dieni *et al.*, 2005, 2006; Sassi *et al.*, 2008), including acidic metavolcanic bodies of Ordovician age and minor mafic rocks. Recent Rb-Sr and ^{40}Ar-^{39}Ar dating (Meli, 2004) confirms the Early Carboniferous age of the principal Variscan metamorphism also in the Southalpine domain, clustering at 350 Ma (Rb-Sr whole-rock and mica ages), whereas younger ^{40}Ar-^{39}Ar dates obtained from post-kinematic micas (330-325 Ma) may be interpreted as cooling ages of a second metamorephic pulse which would be closer to the principal Variscan event that it was previously envisaged (ca 330 Ma: Sassi *et al.*, 1985; Thöni, 1999). Paleogeographic reconstructions suggest that, from the Silurian to the Devonian, the Southalpine and Austroalpine phyllitic units belonged to a southern passive continental margin, whereas paleoclimatic data show that, during the Carboniferous, the Southalpine was displaced to a more southern latitude than the Austroalpine (Spiess *et al.*, 2010).

Permian igneous activity – The Permian magmatic activity extensively developed in the Adria-derived Austrolpine and Southalpine domains (Bigi *et al.*, 1990; Bonin *et al.*, 1993) as a post-Variscan extensional-transtensional lithospheric event (e.g., Dal Piaz & Martin, 1996; Rottura *et al.*, 1998; Schaltegger & Brack, 2007; Bellieni *et al.*, 2010), and is widely recorded also in the eastern Southern Alps (Bonin *et al.*, 1993; Bellieni *et al.*, 2010). From north to south, we can recognize: i) the Bressanone-Ivigna-Monte Croce plutons, intruded into the Bressanone quartz-phyllite and externally bounded by the Pusteria an North-Giudicarie lines; ii) minor bodies inside the phyllitic basement (Visonà *et al.*, 1997); iii) the Monte Sabion pluton, intruded into the Rendena schists; iv) the large Cima d'Asta pluton and related satellites. The Permian intrusion age and geochemical features of this calc-alkaline suite is documented by classic and recent works (Del Moro & Visonà, 1982; Barth *et al.*, 1993; Visonà *et al.*, 2007; Marocchi *et al.*, 2008; Avanzini *et al.*, 2010), it consists of granodiorite, S-type granite, minor tonalite and, occasional gabbro, diorite and cordierite-orthopyroxene-bearing granite.

Also the Athesian volcanic group, wholly filling the structural depression open between the prominent metamorphic and intrusive basements of Bressanone and Valsugana-Cima d'Asta is Permian in age (Bosellini, 1996; Klötzli *et al.*, 2003; Visonà *et al.*, 2007; Marocchi *et al.*, 2008; Avanzini *et al.*, 2010). The volcanic sequence is a manly rhyolitic wedge which reaches its maximum thicknes of about 2 km along a border extensional fault of Permian age. The volcanic activity began in the Lower Permian, during the deposition of Ponte Gardena conglomerates (290.7 ± 3 Ma, U–Pb zircon age, Visonà *et al.* 2007b). In the central sector it started with andesitic lava flows (286.0 ± 3.0 Ma, U–Pb zircon age, Avanzini *et al.* 2010) and ended with rhyolitic ignimbrites and the development of large calderas (275.0 ± 4.9 Ma, U–Pb zircon age, Avanzini *et al.* 2010). In the western sector, the first volcanic pulse is rhyolitic (285.9 ± 1.6 Ma, U–Pb zircon age, Marocchi *et al.* 2008), and the subsequent activity was dominated by extrusion of rhyolitic ignimbrites (274.1 ± 1.6 Ma, U–Pb zircon age; Marocchi *et al.* 2008).

Triassic magmatism - A new sedimentary cycle developed in the Upper Permian, marked by continental deposits grading eastwards to shallow marine sediments (Gaetani, this volume). In the Triassic, the Southalpine domain was flooded and characterized by carbonate platform and basin systems, with regional evidence of continental rifting developed from the Norian to the Middle-Upper Jurassic boundary, when the Austroalpine and Southalpine domains became the subsiding passive continental margin of Adria. The magmatic activity developed during the Middle Triassic (mainly Ladinian) in the Predazzo-Monzoni-Fassa (Fig. 40) and Recoaro areas, both with shallow intrusions and volcanic activity, and rapidly exhausted (Castellarin & Rossi, 1981; Barbieri *et al.*, 1982; Bosellini *et al.*, 1982; Bonadiman *et al.*, 1994; Visonà, 1997; Dal Piaz & Martin, 1998; Brack *et al.*, 2005). It is also recorded in the Alpi Giulie (Gianolla, 1992). Following the review of Bellieni *et al.* (2010), the shallow intrusive and subvolcanic bodies consist of olivine–gabbro, monzonite to late granite and syenite, whereas the volcanic products are olivine-bearing basalts to rhyolites. Eruptions in the Predazzo-Monzoni area evolved from initial basaltic to lati-andesitic and latitic lava flows and ended with the a dyke swarm of K-basanites and lamprophyres with carbonatitic and occasionally spinel-peridotite xenolits (Carraro & Visona, 2003).

Figure 40. Triassic magmatism.



Middle Triassic submarine volcanics in high Duron valley, Fassa Dolomites.

The calc-alkaline and shoshonitic affinity of the Triassic magmatism has been interpreted as evidence of extensional tectonics and partial melting of previously enriched mantle sources, instead of igneous products of active subduction. This interpretation, early envisaged by Dal Piaz *et al.* (1979) for Oligocene andesitic to high-K lamprophyric dykes in the Western Alps, was applied to the Triassic and Permian magmatism and further confirmed (e.g., Bonadiman *et al.*, 1994; Dal Piaz & Martin, 1998; Rottura *et al.* 1998; Schaltegger & Brack 2007).

Venetian volcanic province – As reviewed in detail by Bellieni *et al.* (2010) and shown in the Structural Model, the Venetian province groups volcanic and sub-volcanic bodies occurring in the Southalpine thrust-and-fold belt and its Padane foreland, from the Adige valley and Lessini–Marostica area to the Berici-Euganei hills; its age is Paleocene to Middle Eocene (Visonà *et al.*, 2007a) or Paleocene to Oligocene, west and east of the Castelvero tectonic line, respectively. The igneous suite consists of dominant basic-ultrabasic volcanic rocks which are representative of an alkaline series (mela-nephelinites, nephelinites, basanites, alkali basalts, hawaiites, trachybasalts) and of a moderately sub-alkaline series (transitional basalts, basaltic andesites), the latter occasionally including mantle xenoliths of spinel lherzolite and spinel harzburgite (Bellieni *et al.*, 2010, and refs. therein). The geodynamic significance of the Venetian Volcanic Province is debated, as its deleopment is related to a mantle-plume inferred from tomographic images (Macera *et al.*, 2003), or to a rifting and trans-tensional conditions supposedly associated with the Alpine event (Beccaluva *et al.*, 2007; Bianchini *et al.*, 2008).

Periadriatic Magmatism

A post-collisional magmatic cycle with calc-alcaline affinity mainly developed during the Oligocene (32–29 Ma) and was rapidly exhausted (Bigi *et al.*, 1990; Blanckemburg *et al.*, 1998). It was the object of the meeting “Il magmatismo tardo alpino nelle Alpi”, held Padova in the 1983, and related excursions to the Euganei hills and to the southern Adamello and Valmasino-Bregaglia massif (Proceedings in Mem. Soc. Geol. It., vol. 26, 1985). Traditionally called Periadriatic magmatism (Exner, 1976), it is represented by plutons, intrusive apophyses and a great number of dykes emplaced around the Periadriatic fault system, from the lower Aosta valley (Venturelli *et al.*, 1984) to the eastern edge of the Alps (Faninger & Strucl, 1978), either across the inner part of the Austroalpine-Penninic wedge or in the nearby northern Southalpine (Fig. 20). Plutons and dykes (stars) are mapped in the Structural Model (sheets 1-2), together with the scarce remnants of volcanic products which escaped erosion in the Biellese and Bacher range. The Adamello batholith (Callegari *et al.*, 1998; Callegari & Brack, 2002) is essentially older. Indeed, even if its northern pluton (Presanella) was generated concurrently with the Periadriatic magmatism, the emplacement of central and southern plutons gos back to the Eocene (42-37 Ma; Mayer *et al.*, 2003).

The generation of the Adamello batholith and eventual other igneous bodies of Eocene age can be directly linked to active subduction at the onset of continental collision (Dietrich, 1976). This is not the case, however, of the Oligocene Periadriatic magmatism which developed about 20 Ma after the ocean closure. Major constraints that need to be evaluated are: i) regional extension in the country crust, facilitating the passive emplacement (rarely forced) of plutons and dykes; ii) variously enriched mantle sources; iii) thermal perturbation allowing partial melting of sources. The better solution is the chronological separation between subduction-related source enrichment and later melting of anomalyzed sources.

In this view, generation and ascent of Periadriatic melts to upper crustal reservoirs can be the igneous feedback of slab break-off and related thermal perturbation, coupled with extension and rapid uplift of the wedge and retro-wedge pair during active plate convergence (Dal Piaz & Gosso,1994; von Blankemburg & Davies, 1995; Blanckemburg *et al.*, 1998).

Geological history

The Alpine-Meditarranean area is a mobile zone which, from the Precambrian, was reworked and rejuvenated by recurring divergent, transcurrent and convergent geodynamic processes. The pre-Alpine history may be reconstructed in the Southern Alps and, to various extents, also in the polycyclical basement units of the Austroalpine, Helvetic and Penninic domains, weakly overprinted by the Alpine orogeny.

Variscan and older evolution

The Paleozoic orogeny and Variscan collision gave rise to Pangea supercontinent by linkage of the Gondwana and Laurasia megacontinents and the consumption of intervening oceans. The future Alpine domains were located along the southern flank of this orogen. The classic Variscan term was coined to define the Carboniferous orogenic paroxysm in central Europe, but precursor events of Ordovician to Devonian age were later documented, suggesting the existence of an essentially continuous Paleozoic orogeny. Traces of older events are locally preserved, becoming more abundant in the last decade, a sort of renaissance of old ideas in vogue before the impact of isotope chronology. As a whole, the pre-Permian evolution of the Alps may be summarized as follows:

1) U-Pb data on zircon and Nd model ages suggest the existence of a Precambrian history. The oldest zircons found in various polymetamorphic basements refer to Precambrian clastic material eroded from extra-Alpine sources (Boriani *et al.*, 1974). The occurrence of Proterozoic-Early Cambrian ocean spreading, island-arc activity, and bimodal volcanism is documented in the European and Adriatic basement, with debated traces of Precambrian amphibolite-eclogite facies metamorphism (Silvretta). Cambrian fossils are occasionally found.

2) Early Paleozoic northward subduction of the ocean flanking Gondwana to the north is recorded in the eastern Austroalpine and Helvetic basement, with recycled Precambrian rocks, mafic-ultramafic ophiolites and marginal basin remnants. Subduction is inferred from the accretion of a Paleozoic orogenic wedge, eclogitic mineral assemblages in mafic and felsic rocks, and calc-alkaline island-arc magmatism (460-430 Ma): these relics are mainly preserved in the Variscan metamorphic basement of some Southalpine, Austroalpine and Helvetic-Dauphinois units.

3) The Silurian-Lower Carboniferous continental collision (classic Variscan orogeny) generated crustal thickening by nappe stacking, low- to high-grade regional metamorphism in relaxed or thermally perturbed conditions, pervasive anatectic processes, post-nappe deformations, flysch deposition, and syn-orogenic igneous activity (350-320 Ma; Compagnoni *et al.*, this volume). From the Late Carboniferous, the collapsed Variscan belt was sealed by clastic deposits (Hercynian unconformity) and intruded by post-orogenic plutons.

Permian-Mesozoic evolution

The Variscan plate convergence ended around the Carboniferous-Permian boundary, when transcurrent and transtensive tectonics became dominant on the scale of the Eurasian plate (Muttoni *et al.*, 2009; Gaetani, this volume). Asthenosphere upwelling, thermal perturbation and lithosphere attenuation marked the Lower Permian onset of a new geotectonic regime in the future Adriatic domain. The Permian evolution was characterized, on a lithospheric scale, by extensional detachments, asymmetric extension (with Adria as upper plate) and widespread igneous activity from asthenospheric sources. In the Austroalpine and Southalpine basement, igneous activity began with underplating of Lower Permian gabbro batholiths, emplaced below and inside rising sections of attenuated continental crust, and then recrystallized in granulitic conditions. The overheated roofing crust generated anatectic melts which partly migrated to upper crustal levels. This cycle is also recorded by shallower granitoids and fault-bounded basins filled by clastic sediments and volcanic products.

A calc-alkaline to shoshonitic igneous pulse developed in the Middle Triassic, mainly and better preserved in the Southern Alps, and was produced by partial melting of previously enriched mantle sources (Variscan subduction) during lithosphere attenuation (Piccardo, this volume). From the Late Triassic, continental rifting between Adria (Africa) and Europe generated the Alpine Tethys, a deep-water seaway marked by listric faults, half-grabens and syn-rift deposits. Rifting ended at the Middle-Upper Jurassic boundary when the Mesozoic ocean began to spread. This age is constrained by deposition of radiolarian cherts on subsiding continental blocks in late syn-rift Early Bajocian times, and then developed in the oceanic crust from the Middle Bathonian onwards, nearly coeval with the oldest occurrences in the Central Atlantic. The Austroalpine-Southalpine domains became parts of the Adriatic continental passive margin, opposite to the European margin formed by the Penninic and Helvetic-Dauphinois domains. The subsidence history of the Adriatic margin is well recorded in the sedimentary successions of the Northern Calcareous Alps and the less deformed Southern Alps. The subsidence history of the European margin is recorded in the Prealpine klippen, the metamorphic Briançonnais cover, and the better preserved Helvetic-Dauphinois sedimentary sequences.

Continental rifting was probably generated by simple shear mechanisms, with Europe as extensional upper plate (opposite to the Permian setting). The continent-to-ocean evolution is particularly complex. From some central and western Alpine ophiolites, the local exposure on the ocean floor of a denuded and altered peridotitic basement (e.g., Malenco, Arosa and Aosta areas) may be envisaged. This hypothesis is corroborated by ophicarbonate breccias, continental detritus or cherts and deep water sediments deposited on top of mantle serpentinites, recalling modern exposures along fracture zones and ocean-continent transitions. In this view, coherent continental remnants of the extremely thinned extensional upper plate may have been lost inside the Tethyan ocean, as isolated allochthons and potential sources for some Western Austroalpine and Penninic continental nappes presently inserted between ophiolitic units. As previously seen, other units recall either fragments of normal oceanic lithosphere, or tectonic slices and olistoliths of oceanic suites inside dominant turbiditic deposists.

Restoration of the Tethyan ocean is a long and intriguing problem, mainly due to the occurrence of multiple ophiolitic horizons inside the collisional zone. Indeed, this complex multilayer may represent two or more oceanic branches, or merely the ultimate result of orogenic dispersal by polyphase folding, ductile shear and transposition. The Piedmont zone is the largest ophiolite in the Alps. It extends over most of the western Alps and, also named South-Penninic, reappears beyond the Ossola-Tessin window in the central (Malenco-Avers, Platta) and eastern Alps (Glockner, Rechnitz), below the eastern Austroalpine. Minor ophiolites, generally associated with flysch-type metasediments, are located at lower structural levels, mainly in the outer-lower Penninic domain from the north-western (Ossola-Tessin) to the central Alps (Grisons) and Engadine window, whereas the ophiolitic Versoyen (Valais) unit has recently lost its oceanic igneous nature and Mesozoic age. De-imbrication of the nappe stack in the Central Alps suggests that these ophiolitic units are derived, respectively, from the Piedmont-Ligurian (S-Penninic) ocean and a northern basin (N-Penninic, Valais), supposedly separated by the Briançonnais microcontinent or exotic terrane. Alternative reconstructions include i) a single Jurassic ocean with ribbon continents and/or variously-sized extensional allochthons, or ii) younger (Cretaceous) opening of the N-Penninic basin, partly contemporaneous to the closure of the Piedmont ocean.

Alpine orogeny

The Alpine orogeny first operated in the Eastern Austroalpine and then extended to the entire Alpine Tethys, gradually progressing from internal to external domains.

The earliest Alpine orogeny developed in the Eastern Austroalpine and was accomplished before the deposition of the Late Cretaceous Gosau beds: it has been related to the closure of a western branch of the Triassic Meliata ocean, extending to the Eastern Austroalpine domain through the Carpathians, and leading to a pre-Gosau continental collision. This reconstruction does account for the eclogitic (subduction) to Barrovian (collisional) metamorphism of eoalpine (Early-mid Cretaceous) age and wedge generation, although the oceanic suture is poorly preserved and the axial trend of the Triassic ocean (parallel or transversal to the future Alpine belt) is uncertain.

The subsequent orogeny developed in the entire Alpine belt from the Late Cretaceous (Western Austroalpine) onwards, and was closely related to the subduction of Piedmont (South-Penninic) oceanic lithosphere below the Adriatic active continental margin, leading to Eocene collision between Europe and Adria. The first stage of

Alpine contraction was dominated by a subduction-related low thermal regime which initiated with the onset of oceanic subduction (Mid Cretaceous ?): this is revealed by the oldest (Late Cretaceous) high-P peak in the western Austroalpine, and lasted until the Eocene syncollisional subduction of the distal (pre-Piedmont) European margin, clearly recorded by the eclogitic to blueschist imprint in the upper and middle Penninic continental units. This stage was characterized by the growth of a pre-collisional to collisional (Austroalpine-Penninic) wedge at the Adria active margin. Since the beginning, it was devoid of a proper lithospheric mantle, being first underlain by the subducting oceanic lithosphere and, after ocean closure, by the passive margin of the European lower plate undergoing syncollisional subduction and accretion. The evolution of the Cretaceous-Eocene Alps has been alternatively interpreted to reflect: i) accretion of delaminated fragments of lithospheric microcontinents separated by oceanic channels; ii) tectonic erosion of the Adriatic active margin; iii) accretion, by tectonic underplating, of originally thin crustal fragments resulting from an extended or hyper-extended upper plate margin (ocean-continent transition). Exhumation of the high-P Penninic nappes was allowed by periodic extension in the wedge suprastructure, associated with nappe accretion at depth under active plate convergence.

From the Late or Latest Eocene (in differing areas), the subduction-related cool regime was replaced by relaxed and perturbed thermal conditions. Indeed, the high-P units of the subduction complex were rapidly and progressively exhumed to shallower structural levels and overprinted by a Barrovian metamorphism of Late Eocene-Lower Oligocene age, characterized by high thermal gradient (35 to 50°C/km; Frey *et al.*, 1999). Soon after, a post-collisional magmatic cycle widely developed and was rapidly exhausted during the Oligocene (32-30 Ma). It is recorded along the Periadriatic fault system (Bigi *et al.*, 1990). Older magmatic products (42-37 Ma) occur in the central-southern part of the Adamello batholith. The Periadriatic magmatism was generated by partial melting of lithospheric mantle sources previously enriched by fluids released by the subducting lithosphere during the Cretaceous-Eocene, and its generation is generally referred to slab break-off and related thermal perturbation, coupled with extension and rapid uplift of the wedge during active plate convergence. The Periadriatic magmatism ceased at the Oligocene-Miocene boundary, when renewed collisional shortening disactivated the magmatic sources.

The continuing plate convergence progressed and was accomodated mainly through accretion both in the foreland and interland, coupled with ultimate extrusion and cooling of the Austroalpine-Penninic wedge. The Helvetic basement slices and decollement cover nappes were accreted to the Austroalpine-Penninic wedge and displaced over the sinking Molasse foredeep, whereas an opposite-vergent thrust-and-fold belt developed in the Southalpine upper crust, mainly generated by indentation of the Adria mid-lower lithosphere into the wedge rear. In the meantime, the overthickened Austroalpine-Penninic nappe stack underwent orogen-parallel tectonic denudation along low-angle detachments (e.g., Ratschbacher *et al.*, 1991).

At a lithospheric scale, the mature collisional belt continued to maintain its asymmetry. Seismicity, GPS measurements and foreland subsidence provide evidence of a still active Alpine contraction and tectonic extension (e.g., Sue & Tricart, 2003; Delacou *et al.*, 2004; Chiarabba *et al.*, 2005; Sue *et al.*, 2007; Cuffaro *et al.*, 2010; Devoti *et al.*, this volume).

References

Abbate E. & Bortolotti V., 1984. Le Unità Liguri dell'Appennino Settentrionale: sintesi dei dati e delle interpretazioni dal 1970 in poi. In: Cento anni di geologia Italiana, vol. giubilare Soc. Geol. It., Pitagrora-Tectoprint, pp. 215-240.

Abbate E., Bortolotti V., Conti M., Marcucci M., Principi G., Passerini P. & Treves B., 1988. Apennines and Alps ophiolites and the evolution of the Western Tethys. Mem. Soc. Geol. It., 31 (1986), 23-44.

Amato J.M., Johnson C., Baumgartner L.P. & Beard B.L., 1999. Rapid exhumation of the Zermatt-Saas ophiolite deduced from high-precision Sm-Nd and Rb-Sr geochronology. Earth Planet. Sci. Lett., 171, 425-438, 10.1016/S0012-821X(99)00161-2

Ampferer O., 1906. Ueber das Bewegungsbild von Faltenge birgen. Jb. Geol. Reichsanst, 56, 539-622.

Ampferer O. & Hammer W., 1911. Geologischer Querschnitt durch die Ostalpen. Jb. Geol. Reichsanst, 61, 531-711.

Amstutz A., 1955. Subductions successives dans l'Ossola. C.R. Acad. Sci. Paris, 241, 967-972.

Amstutz A., 1962. Notice pour une carte géologique de la vallée de Cogne et de quelques autres espaces au sud d'Aoste. Archives Sci Genève, 15/1, 1-104.

Angenheister G., Bögel H. & Morteani G., 1975. Die Ostalpen im Bereich einer Geotraverse from Chiemsee bis Vicenza. N. Jb. Geol. Pal. Abh., 148, 50-137.

Angiboust S. & Agard P., 2010. Initial water budget: The key to detaching large volumes of eclogitized oceanic crust along the subduction channel? Lithos-02319, 22 p.

Antoine P., 1971. La zone des bréches de Tarentaise entre Bourg Saint Maurice (vallée de l'Isère) et la frontière italo-suisse. PhD Univ. Grenoble, 367 p.

Antoine P., Loubat H. & Vatin Perignon N., 1973. Hypothèses nouvelles sur la signification des "ophiolites" du domaine pennique externe (Savoie Valais). Géol. Alpine, 49, 21-39.

APAT, 2004. Mapset. Repertorio completo della cartografia geologica d'Italia. Dipartimento Difesa del Suolo, Servizio Geologico d'Italia, Roma.

Argand E., 1908. Carte géologique du massif de la Dent Blanche, 1:50.000. Mat. Carte géol. Suisse, N.S., 23, carte spéc. n. 52, Berne.

Argand E., 1909. L'exploration géologique des Alpes pennines centrales. Bull. Soc. Vaudoise Sci. nat., 45, 217-276.

Argand E., 1911a. Les nappes de recouvrement des Alpes pennines et leurs prolongements structuraux. Mat. Carte géol. Suisse, 31, 25 p.

Argand E., 1911b. Les nappes de recouvrement des Alpes occidentales et les territoires environants. Essai de carte structurale. Matériaux pour la carte géologique de la Suisse. Carte spéciale n. 64, 1911.

Argand A., 1916. Sur l'arc des Alpes occidentales. Eclogae geol. Helv., 14, 145-191.

Argand A., 1924a. Des Alpes et de l'Afrique. Bull. Soc. Vaudoise Sci. Nat., 214, 233-236.

Argand A., 1924b. La tectonique de l'Asie. XIII Intern. Geol. Congr., Liège 1922, 171-372.

Argand A., 1934. La zone pennique. Guide géol. Suisse, Wepf & Co., Basel, pp. 149-189.

Arnaud N.O. & Kelley S.P., 1995. Evidence for excess argon during high pressure metamorphism in the Dora Maira Massif (western Alps, Italy), using an ultra-violet laser ablation microprobe ^{40}Ar-^{39}Ar technique. Contrib. Min. Petrol., 121, 1-11, 10.1007/s004100050086

Artini E. & Melzi G., 1900. Ricerche petrografiche e geologiche sulla Valsesia. Mem. R. Ist. Lombardo Sci., Lett. Arti, 18, 219-390.

Aubouin J., 1965. Geosynclines. Developments in Geotectonics, Elsevier, Amsterdam, 335 p.

Aubouin J., Blanchet R., Labesse B. & Wozniak J., 1977. Alpes occidentales et Alpes orientales: la zone du Canavese existet-elle? C.R. Somm. Soc. Géol. France, 19/3, 155-158.

Aumatre R. & Buffet G., 1974. Minéralogie, pétrographie et géochimie des laves spilitiques et des filons basiques associés du massif des Ecrins-Pelvoux (Alpesa françaises occidentales). Thèse 3e cycle Univ. Grenoble, 301 p.

Avanzini M., Bargossi G.M., Borsato A. & Selli L., 2010. Foglio 060 Trento e Note illustrative. Servizio Geologico d'Italia e Provincia Autonoma di Trento.

Avanzini M., Leonardi G., Mietto P. & Piubelli D., 2005. The dinosaur ichnosite at the Lavini di Marco (Calcari Grigi Group, Lower Jurassic). Studi Trentini Sci. Nat., Acta Geol., 80, 31-38.

Avigad D., Chopin C., Goffé B. & Michard A., 1993. Tectonic model for the evolutionnof the western Alps. Geology, 21, 659-662.

Avigad D., Chopin C. & Le Bayon R., 2003. Thrusting and extension in the Southern Dora-Maira ultra-high pressure massif (Western Alps): view from below the coesite-bearing unit. J. Geol., 111, 57-70, 10.1086/344664

Axen G.J., Bartley J.M. & Selverstone J., 1995. Structural expression of a rolling hinge in the footwall of the Brenner Line normal fault, eastern Alps. Tectonics, 14, 1380-1392, 10.1029/95TC02406

Ayrton S., Bugnon C., Haarpaintner T., Weidmann M. & Frank E., 1982. Géologie du front de la nappe de la Dent Blanche dans la région des Monts-Dolins, Valais. Eclogae Geol. Helv., 75, 269-286.

Babist J., Handy M.R., Konrad-Schmolke M. & Hammerschmidt K., 2006. Precollisional, multistage exhumation of subducted continental crust: the Sesia Zone, western Alps. Tectonics, 25. 10.1029/2005TC001927

Babuska V., Plomerova J. & Silen'y J., 1987. Structural model of the subcrustal lithosphere in Central Europe. Am. Geophys. Union, Geodyn. Ser., 16, 239-251.

Baggio P., Bosellini A. et al., 1969. Carta Geologica d'Italia 1:100.000, F. 1-4, Passo del Brennero-Bressanone e Note illustrative. Serv. Geol. It., 120 p.

Bailey E.B., 1966. James Hutton-the founder of modern geology. Elsevier, 161 p.

Baird A.W. & Dewey J.F., 1986. Structural evolution in thrust belts and relative plate motion: the Upper Pennine Piedmont zone of the internal Alps, Southwest Switzerland and northwest Italy. Tectonics, 5, 375-387, 10.1029/TC005i003p00375

Baldelli C., Dal Piaz G.V. & Polino R., 1983. Le quarziti a manganese e cromo di Varenche-St.Barthélémy, una sequenza di copertura oceanica della falda piemontese. Ofioliti, 8, 207-221.

Baldelli C., Dal Piaz G.V. & Lombardo B., 1985. Ophiolite eclogites from Verres, Val d'Aosta, Western Alps, Italy. Chemical Geol., 50, 87-98, 10.1016/0009-2541(85)90113-5

Ballèvre M., 1988. Collision continentale et chemins P-T. Mém. Doc. CAESS Rennes, 19, 332 p.

Ballèvre M. & Kienast J.R., 1987. Découverte et signification de paragenèses à grenat-amphibole bleue dans la couverture mésozoïque de la nappe de la Dent- Blanche (Alpes occidentales). C.R. Acad. Sci. Paris, 305, 43-47.

Ballèvre M., Kienast J.R. & Vuichard J.P., 1986. La nappe de la Dent Blanche (Alpes occidentales): deux unités austroalpines indépéndantes. Eclogae Geol. Helv., 79, 57-74.

Ballèvre M. & Merle O., 1993. The Combin Fault: reactivation of a detachment fault. Schweiz. mineral. petrogr. Mitt., 73, 205-227.

Barbieri G., De Vecchi Gp., De Zanche V., Mietto P. & Sedea R., 1982. Stratigrafia e petrologia del magmatismo triassico nell'area di Recoaro. In Castellarin A. & Vai G.B. (Eds): Guida alla geologia del Sudalpino centro-orientale. Soc. Geol. It., Guide Geologiche Regionali, pp 179-187.

Barboza S. A., Bergantz G. W. & Brown M., 1999. Regional granulite facies metamorphism in the Ivrea zone: is the mafic complex the smoking gun or a red herring? Geology, 27, 447-450, 10.1130/0091-7613(1999)027<0447:RGFMIT>2.3.CO;2

Barboza S. A. & Bergantz, G. W., 2000. Metamorphism and anatexis in the mafic complex contact aureole, Ivrea zone, northern Italy. Journal of Petrology, 41, 1307-1327, 10.1093/petrology/41.8.1307

Baretti M., 1893. Geologia della Provincia di Torino. Ed. Casanova, Torino, 732 p.

Barnicoat A.C. & Cartwright I., 1995. Focused fluid flow during subduction: oxygen isotope data from high-pressure ophiolites of the western Alps. Earth Planet. Sci. Lett., 132, 53-61, 10.1016/0012-821X(95)00040-J

Barnicoat A.C. & Fry N., 1986. High-pressure metamorphism of the Zermatt-Saas ophiolite zone, Switzerland. J. Geol. Soc. London, 143, 607-618, 10.1144/gsjgs.143.4.0607

Barth S., Oberli F., Meier M., Blattner P., Bargossi G.M. & Di Battistini G., 1993. The evolution of a calc-alkaline basic to silicic magma system: geochemical and Rb-Sr, Sm-Nd, and O18/O16 isotopic evidence from the Late Hercynian Atesina-Cima d'Asta volcano-plutonic complex, Northern Italy. Geochim. Cosmochim. Acta, 57, 4285-4300

Battiston P., Benciolini L., Dal Piaz G.V., De Vecchi G., Marchi G., Martin S., Polino R. & Tartarotti P., 1987. Geologia di una traversa dal Gran Paradiso alla Zona Sesia-Lanzo in alta val Soana, Piemonte. Mem. Soc. Geol. It., 29 (1984), 209-232.

Baudin T. & Marquer D., 1993. Métamorphisme et déformation dans la nappe de Tambo (Alpes centrales suisses): évolution de la substitution phengitique au cours de la déformation alpine. Schweiz. mineral. petrogr. Mitt., 73, 85-299.

Bearth P., 1952. Geologie und Petrographie des Monte Rosa. Beitr. Geol. Karte Schweiz, 96, 94 p.

Bearth P., 1953. Geologischer Atlas der Schweiz 1:25000, Blatt 29, Zermatt. Schweiz. Geol. Komm., Bern.

Bearth P., 1959. Ueber Eklogite, Glaucophanschiefer und metamorphe Pillowlaven. Schweiz. mineral. petrogr. Mitt., 39, 267-286.

Bearth P., 1962. Contribution à la subdivision tectonique et stratigraphique du cristallin de la nappe du Grand-St-Bernard dans le Valais (Suisse). Soc. Géol. France, mém. h. ser., 2, 407-418.

Bearth P., 1967. Die Ophiolite der Zone von Zermatt-Saas Fee. Beitr. Geol. Karte Schweiz, 132, 130 pp.

Bearth P. & Stern W., 1971. Zum Chemismus der Eklogite und Glaukophanite von Zermatt. Schweiz. mineral. petrogr. Mitt., 349-359.

Bearth P. & Stern W., 1979. Zur Geochemie von Metapillows der Region Zermatt-Saas. Schweiz. mineral. petrogr. Mitt., 59, 349-373.

Beccaluva L., Bianchini G., Bonadiman C., Coltorti M., Milani L., Salvini L., Siena F. & Tassinari R., 2007. Intraplate lithospheric and sublithospheric components in the Adriatic domain: Nephelinite to tholeiite magma generation in the Paleogene Veneto volcanic province, southern Alps. Geol. Soc. Amer. Special Paper, 418, 131-152.

Beccaluva L., Dal Piaz G.V., Macciotta G. & Zeda O., 1979. The Austroalpine harzburgite body of the Artogna valley (Italian Western Alps). Mem. Sci. Geol., 33, 173-181.

Beccaluva L., Dal Piaz G.V. & Macciotta G., 1984. Transitional to normal-MORB affinities in ophiolitic metabasites from the Zermatt-Saas, Combin and Antrona units, Western Alps: implications for the paleogeographic evolution of the Western Tethyan basin. Geol. en Mijnbow, 63, 165-177.

Becker B., 1993. The structural evolution of the Radstadt thrust system, Eastern Alps, Austria - Kinematics, thrust geometries, strain analysis. Tübinger Geowiss. Arb., A14, 92 p.

Becker H., 1993. Garnet peridotite and eclogite Sm-Nb mineral ages from the Lepontine dome (Swiss Alps): new evidence for Eocene high-pressure metamorphism in the central Alps. Geology, 21, 599-602, 10.1130/0091-7613(1993)021<0599:GPAESN>2.3.CO;2

Bellieni G., Fioretti A.M., Marzoli A. & Visonà D., 2010. Permo-Paleogene magmatism in the eastern Alps. Rendiconti Lincei, 21, Suppl. 1, 51-71, 10.1007/s12210-010-0095-z

Beloussov V.V., 1980. Geotectonics. Mir Publishers, Moscow.

Beltrando M., Compagnoni R. & Lombardo B., 2010a. (Ultra-) High-pressure metamorphism and orogenesis: An Alpine perspective. Gondwana Research, 10.1016/j.gr. 2010.01.009

Beltrando M., Hermann J., Lister G.S. & Compagnoni R., 2007a. On the evolution of orogens: pressure cycles and deformation mode switches. Earth Planet. Sci. Lett., 256, 372-388.

Beltrando M., Lister G.S., Hermann J., Forster M. & Compagnoni R., 2008. Deformation mode switches in the Penninic Units of the Western Alps. J. Struct. Geol., 30, 194-219.

Beltrando M., Lister G., Forster M., Dunlap W.J., Fraser G. & Hermann J., 2009a. Dating microstructures by the ^{40}Ar-^{39}Ar step-heating technique: deformation-pressure-temperature-time history of the Penninic Units of the Western Alps. Lithos 113. 10.1016/j. Lithos.2009.07.006

Beltrando M., Rubatto D., Compagnoni R. & Lister G., 2007. Was the Valais basin floored by oceanic crust ? Evidence of Permian magmatism in the Versoyen unit (Valaisan domain, NW Alps). Ofioliti, 32/2, 85-99.

Beltrando M., Rubatto D. & Manatschal G., 2009b. Preservation of an ocean-continent transition zone in the eclogitic Piemonte unit: implications for the dynamics of orogens. Alpine Workshop, Cogne 2009, Abstr.

Beltrando M., Rubatto D. & Manatschal G., 2010b. From passive margins to orogens: The link between Ocean-Continent Transition zones and (Ultra-)High-Pressure metamorphism. Geology. 38, 559-562, 10.1130/G30768.1

Berger A., Rosenberg C.L. & Schmid S. M., 1996. Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the Central Alps. Schweiz. mineral. petrogr. Mitt., 76, 357-382.

Behrmann J.H., 1988. Crustal scale extension in a convergent orogen: the Sterzing-Steinach mylonite zone in the Eastern Alps. Geodynamica Acta, 2, 63-73.

Behrmann J.H. & David C. Tanner D.C., 2006. Structural synthesis of the Northern Calcareous Alps, TRANSALP segment. Tectonophysics, 414, 225-240, 10.1016/j.tecto. 2005.10.018

Benciolini L., 1989. Eclogitized websterite-rich subcontinental mantle slice in the austroalpine Mt. Emilius nappe. Mem. Sci. Geol., 48, 73-91.

Berkhemer H., 1968. Topographie des "Ivrea-Korpers", abgeleitet aus seismischen und gravimetrischen daten. Schweiz. mineral. petrograph. Mitt., 48, 235-246.

Bernoulli D. & C. Jenkyns H.C., 2009a. Ophiolites in ocean-continent transitions: From the Steinmann Trinity to sea-floor spreading. C.R. Geoscience, 341, 363-381.

Bernoulli D. & C. Jenkyns H.C., 2009b. Ancient oceans and continental margins of the Alpine-Mediterranean Tethys: deciphering clues from Mesozoic pelagic sediments and ophiolites. Sedimentology, 56, 149-190.

Bernoulli D., Manatschal G., Desmurs L. & Müntener O., 2003. Where did Gustav Steinmann see the Trinity? Back to the roots of an Alpine ophiolite concept. In Dilek Y. & Newcombe S. (Eds): Ophiolite concept and the evolution of geological thought. Geol. Soc. Am. Spec. Publ., 373, 93-110.

Bernoulli D. & Weissert H., 1985. Sedimentary fabrics in Alpine ophicalcites, South Pennine Arosa zone, Switzerland. Geology, 13, 755-758, 10.1130/0091-7613(1985)13<755:SFIAOS>2.0.CO;2

Bertolani M., 1969. La petrografia delle Valle Strona (Alpi Occidentale Italiane). Schweiz. mineral. petrogr. Mitt., 49, 314-328.

Bertotti G., 1991. Early Mesozoic extension and Alpine shortening in the western Southern Alps: the geology of the area between Lugano and Menaggio (Lombardy, Northern Italy). Mem. Sci. Geol., Padova, 43, 17-123.

Bertotti G., Picotti V., Bernoulli D. & Castellarin A., 1993. From rifting to drifting: tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. Sedimentary Geol., 86, 53-76, 10.1016/0037-0738(93)90133-P

Bertrand J.M., Guillot F. & Leterrier J., 2000a. Age paléozoïque inférieur (U-Pb sur zircon) de métagranophyres de la nappe du Grand-Saint-Bernard (zona interna, vallée d'Aoste, Italie). C.R. Acad. Sci., D 330, 473-478.

Bertrand J.M., Paquette J.-L. & Guillot F., 2005. Permian zircon U-Pb ages in the Gran Paradiso massif : revisiting post-Variscan events in the Western Alps. Schweiz. mineral. petrogr. Mitt., 85, 19-29.

Bertrand J.M., Guillot F. & Leterrier J., 2000a. Age paléozoïque inférieur (U-Pb sur zircon) de métagranophyres de la nappe du Grand-Saint-Bernard (zona interna, vallée d'Aoste, Italie). C.R. Acad. Sci., D, 330, 473-478.

Bertrand J.M., Pidgeon R.T., Leterrier J., Guillot F., Gasquet D. & Gattiglio M., 2000b. SHRIMP and IDTIMS U-Pb zircon ages of the pre-Alpine basement in the internal western Alps (Savoy and Piemont). Schweiz. mineral. petrogr. Mitt., 80, 225-248.

Bianchi A., 1934. Studi petrografici sull'Alto Adige orientale e regioni limitrofe. Mem. Ist. Geol. Univ. Padova, 10, 240 p.

Bianchi A., Callegari E. & Jobstraibizer P.G., 1970. I tipi petrografici fondamentali del plutone dell'Adamello. Tonaliti, quarzodioriti, granodioriti e loro varietà leucocrate. Mem. Ist. Geol. Min. Univ. Padova, 27, 148 p.

Bianchi A. & Dal Piaz Gb., 1963. Gli inclusi di "micascisti eclogitici" della Zona Sesia-Lanzo nella formazione porfiritica permiana della zona del Canavese fra Biella ed Oropa. Caratteristiche ed età dei fenomeni metamorfici. Giornale di Geologia, 31, 39-76.

Bianchini G., Beccaluva L. & Siena F., 2008. Post-collisional and intraplate cenozoic volcanism in the rifted Appennines/ Adriatic domain. Lithos, 101,125-140, 10.1016/j.lithos. 2007.07.011

Bickle M.J. & Hawkesworth C.J., 1978. Deformation phases and the tectonic history of the eastern Alps. Geol. Soc. Am. Bull., 89, 293-306, 10.1130/0016-7606(1978)89<293:DPATTH>2.0.CO;2

Bigi G., Castellarin A., Catalano R., Coli M., Cosentino D., Dal Piaz G.V., Lentini F., Parotto M., Patacca E., Praturlon A., Salvini F., Sartori R., Scandone P. & Vai G.B., 1989. Synthetic structural-kinematic map of Italy. C.N.R., Progetto Finalizzato Geodinamica, SELCA Firenze.

Bigi G., Castellarin A., Coli M., Dal Piaz G.V., Sartori R., Scandone P. & Vai G.B., 1990. Structural Model of Italy, sheets 1-2. CNR, Progetto Finalizzato Geodinamica, SELCA Firenze, selca@selca-cartografie.it.

Bigi G., Coli M., Cosentino D., Dal Piaz G.V., Parotto M., Sartori R. & Scandone P., 1993. Structural Model of Italy, sheet 3. CNR, Progetto Finalizzato Geodinamica, SELCA Firenze.

Bill M., Bussy F., Cosca M., Masson H. & Hunziker J.C., 1997. High-precision U-Pb and $^{40}Ar/^{39}Ar$ dating of an Alpine ophiolite (Gets nappe, French Alps). Eclogae Geol. Helv., 90, 43-54.

Bill M., Nägler T.F. & Masson H., 2000. Major, minor, trace element, Sm-Nd and Sr isotope compositions of mafic rocks from the earliest crust of the Alpine Tethys. Schweiz. mineral. petrogr. Mitt. 80, 131-145.

Bistacchi A, Dal Piaz G.V., Massironi M., Zattin M. & Balestrieri M.L., 2001. The Aosta-Ranzola extensional fault system and Oligocene-Present evolution of the north-western Alpine nappe stack. Int. J. Earth Sci., 90, 654-667, 10.1007/ s005310000178

Bistacchi A., Dal Piaz G.V., Dal Piaz G., Martinotti G., Massironi M., Monopoli B. & Schiavo A., 2004. Carta geologica del transetto Val di Vizze-Fortezza (Alpi orientali). Mem. Sci. Geol., Padova, 55 (2003), 169-188.

Bistacchi A., Massironi M., Dal Piaz G.V., Dal Piaz G., Monopoli B., Schiavo A. & Toffolon G., 2007. 3D fold and fault reconstruction with an uncertainty model: an example from an Alpine tunnel case study. Computers & Geosciences, 10.1016/j.cageo.2007.04.002.

Blankenburg F. von & Davies J.H., 1995. Slab breakoff. A model for syncollisional magmatism and tectonics in the Alps. Tectonics, 14, 120-131, 10.1029/94TC02051

Blanckenburg F. von., Kagami H., Deutsch A., Oberli F., Meier M., Wiedenbeck M., Barth S. & Fischer H., 1998. The origin of Alpine plutons along the Periadriatic Lineament. Schweiz. mineral. petrogr. Mitt., 78, 55-66.

Bleibinhaus F. & Gebrande H., 2005. Crustal structure of the Eastern Alps along the TRANSALP profile from wide-angle seismic tomography. Tectonophysics, 414, 51-69, 10.1016/ j.tecto.2005.10.028

Blundell D., Freeman R. & Müller S. (Eds), 1992. A continent revealed. The European Geotraverse. Cambridge Univ. Press.

Bogdanoff S., Ménot R.P. & Vivier G., 1991. Les massifs cristallins externes des Alpes occidentales françaises, un fragment de la zone interne varisique. Sci. Géol., Bull., 44, 237-285.

Boillot G., Beslier M.O., Krawczyk C.M., Rappin D. & Reston T.J., 1995. The formation of passive margins: constraints from the crustal structure and segmentation of the Galicia margin, Spain. Geol. Soc. Spec. Publ. London, 90, 71-91, 10.1144/GSL.SP.1995.090.01.04

Bonadiman C., Coltorti M. & Siena F., 1994. Petrogenesis and T-fO2 estimates of Mt. Monzoni complex (Central Dolomites, Southern Alps): a Triassic shoshonitic intrusion in a transcurrent geodynamic setting. Eur. J. Min., 6, 943-966.

Bonin B., Brändlein P., Bussy F., Desmons J., Eggenberger U., Finger F., Graf K., Marro Ch., Mercolli I., Oberhänsli R., Ploquin A., von Quadt A., von Raumer J., Schaltegger U., Steyrer H.P., Visona D. & Vivier G., 1993. Late Variscan magmatic evolution of the Alpine basement. In von Raumer J. & Neubauer F. (Eds): The Pre-Mesozoic Geology in the Alps. Springer-Verlag, Heidelberg, 169-199.

Boriani A., Burlini L. & Sacchi, R., 1990a. The Cossato-Mergozzo-Brissago line (Southern Alps, Italy) and its relationships with late Hercynian magmatic and metamorphic events. Tectonophysics, 182, 91-102, 10.1016/0040-1951(90)90344-8

Boriani A., Caironi V., Origoni Giobbi E. & Vannucci R., 1992. The Permian intrusive rocks of Serie dei Laghi (western Southern Alps). Acta Vulc., 2, 73-86.

Boriani A., Dal Piaz G.V., Hunziker J.C., von Raumer J. & Sassi F.P., 1974. Caratteri, distribuzione ed età del metamorfismo prealpino nelle Alpi. Mem. Soc. Geol. It., 13, suppl. 1, 165-225.

Boriani A. & Giobbi E., 2004. Does the basement of western southern Alps display a tilted section through the continental crust? A review and discussion. Periodico Miner., 73, 5-22.

Boriani A., Origoni Giobbi E., Borghi A. & Caironi V., 1990b. The evolution of the 'Serie dei Laghi' (Strona-Ceneri and Scisti dei Laghi): the upper component of the Ivrea-Verbano crustal section; Southern Alps, North Italy and Ticino, Switzerland. Tectonophysics, 182, 103-118, 10.1016/0040-1951(90)90345-9

Boriani A., Origoni Giobbi E. & Pinarelli L., 1995. Palaeozoic evolution of southern Alpine crust (northern Italy) as indicated by contrasting granitoid suites. Lithos, 35, 47-63, 10.1016/0024-4937(94)00043-2

Boriani A. & Villa I., 1997. Geochronology of regional metamorphism in the Ivrea-Verbano zone and Serie dei Laghi, Italian Alps. 1997. Schweitz. mineral. petrogr. Mitt., 77, 381-401.

Borsi S., Del Moro A., Sassi F.P., Zanferrari A. & Zirpoli G., 1978. New petrologic and radiometric data on the Alpine history of the Austridic continental margin south of the Tauern window (Eastern Alps). Mem. Ist. Geol. Min. Univ. Padova, 32,17 p.

Borsi S., Del Moro A., Sassi F.P. & Zirpoli G., 1973. Metamorphic evolution of the Austridic rocks to the south of the Tauern window (Eastern Alps). Mem. Soc. Geol. It., 12, 549-571.

Bosellini A., 1978. Tettonica delle Placche e Geologia. Zanichelli, 144 p.

Bosellini A., 1996. Geologia delle Dolomiti. Athesia, Bolzano, 192 p.

Bosellini A., Castellarin A., Doglioni C., Guy F., Lucchini F., Perri M.C., Rossi P.L., Simboli G. & Sommavilla E., 1982. Magmatismo e tettonica nel Trias delle Dolomiti. In Castellarin A. & Vai G.B. (Eds): Guida alla geologia del Sudalpino centro-orientale, Soc. Geol. It., 189-210.

Bosellini A., Neri C. & Stefani M. (Eds), 1996. Geologia delle Dolomiti. Introduzione geologica, guida alla escursione generale. 78a Riunione estiva S.G.I., Litografia Tosi, Ferrara, 120 p.

Boudier F., Jackson M. & Nicolas A., 1984. Structural study of the Balmuccia Massif (Western Alps): A transition from mantle to lower crust, Geologie en Mijnbouw, 63, 179-188.

Bousquet R., Goffe B., Vidal O., Oberhansli R. & Patriat M., 2002. The tectono-metamorphic history of the Valaisan domain from the Western to the Central Alps: new constraints on the evolution of the Alps. Geol. Soc. Am. Bull., 114, 207-225, 10.1130/0016-7606(2002)114<0207:TTMHOT>2.0.CO;2

Brack P., Dal Piaz G.V., Baroni C., Carton A., Nardin M., Pellegrini G.B., Pennacchioni G. et al., 2008. Carta Geologica d'Italia alla scala 1:50.000. Foglio 58 Monte Adamello e Note illustrative. Servizio Geologico d'Italia e Provincia Autonoma di Trento, 140 p.

Brack P., Rieber H., Nicora A. & Mundil R., 2005. The global boundary stratotype section and point (GSSP) of the Ladinian Stage (Middle Triassic) at Bagolino (Southern Alps, Northern Italy) and its implications for the Triassic time scale. Episodes, 28, 233-244.

Brodie K.H. & Rutter E.H., 1987. Deep crustal extensional faulting in the Ivrea Zone of Northern Italy. Tectonophysics, 140, 193-212, 10.1016/0040-1951(87)90229-0

Bucher J., Dal Piaz G.V., Oberhänsli R., Gouffon Y., Martinotti G. & Polino R., 2003. Blatt 1347-Matterhorn mit Erleuterungen (2004). Geol. Atlas Schweiz 1:25.000, 107, 73 p.

Burri M., Alliman M., Chessex R., Dal Piaz G.V., Della Valle G., Du Bois L., Gouffon Y., Guermani A., Hagen T., Krummenacher D. & Looser M.O., 1998. Feuille 1346 Chanrion, avec partie nord de la feuille 1366 Mont Vélan, et Notice explicative. Atlas géol. Suisse 1:25.000, Serv. hydrol. et géol. national, Berne, 79 p.

Bussy F., Derron M.H., Jacquod J., Sartori M. & Thélin P., 1996a. The 500 Ma-old Thyon meta-granite: a new A-type granite occurrence in the western Penninic Alps (Valais, Switzerland). Eur. J. Mineral., 8, 565-575.

Bussy F., Sartori M. & Thélin P., 1996b. U-Pb zircon dating in the middle Penninic basement of the Western Alps (Valais, Switzerland). Schweiz. mineral. petrogr. Mitt., 76, 81-84.

Bussy F., Venturini G., Hunziker J.C. & Martinotti G., 1998. U-Pb ages of magmatic rocks of the western Austroalpine Dent-Blanche-Sesia Unit. Schweiz. mineral. petrogr. Mitt., 78, 163-168.

Butler R.W.H., 1985. The restoration of thrust systems and displacement continuity around the Mont Blanc Massif, NW external Alpine thrust belt. J. Struct. Geol., 7, 131-150, 10.1016/0191-8141(85)90029-X

Butler R.W.H., 2010. The Geological structure of the North-West Highlands of Scotland - revisited. Geol. Soc. London, Spec. Publ., 335, 7-27, 10.1144/SP335.2

Butler R.W.H. & Freeman S.R., 1999. Dating Alpine shear zones - using Rb-Sr geochronology on white micas to gain greenschist deformation ages in the western Alps. In G. Gosso et al. (Eds): Third Meeting on Alpine Geol. Studies. Mem. Sci. Geol., 51, 177-189.

Caby R., 1968. Contribution a l'etude structurale des Alpes occidentales; subdivisions stratigraphiques et structure de la zone du Grand-Saint-Bernard dans la partie sud du Val d'Aoste (Italie). Geol. Alpine, 44, 95-111.

Caby R., 1981. Le Mesozoïque de la zone du Combin en val d'Aosta (Alpes Graïes): imbrications tectoniques entre séries issues des domaines pennique, austroalpin et océanique. Geol. Alpine, 57, 5-13.

Caby R. & Kienast J.R., 1989. Meso-alpine high pressure assemblages and excavation of the Ruitor briançonnais basement (Savoie, Val d'Aoste, Graie Alps). Terra Abstracts, 1, 226.

Caby R., Kienast J.R. & Saliot P., 1978. Structure, métamorphisme et modèle d'évolution tectonique des Alpes occidentales. Rev. Géogr. Phys. Géol. Dyn., 20, 307-322.

Cadel G., Cosi M., Pennacchioni G. & Spalla M.I., 1996. A new map of the Permo-Carboniferous cover and Variscan metamorphic basement in the Central Orobic Alps, Southern Alps - Italy: structural and stratigraphical data. Mem. Sci. Geol., 48, 1-53.

Callegari E. & Brack P., 2002. Geological map of the Tertiary Adamello Batholith (Northern Italy). Explanatory notes and legend. Mem. Sci. Geol., Padova, 54, 19-49.

Callegari E. & Dal Piaz Gb., 1973 - Field relationships between the main igneous masses of the Adamello intrusive massif. Mem. Ist. Geol. Min. Univ. Padova, 29, 1-39.

Callegari E., Dal Piaz Gb., Gatto G.O. & Trommsdorff V., 1998. Carta geologica del Gruppo Adamello-Presanella,1:50000. CNR, SELCA Firenze.

Campanino F. & Polino R., 2002. Carta geologica delle Alpi Piemontesi (1860-1879 ca.). Fotomosaico al 1:380.000 dei 29 fogli al 1:50.000 rilevati da M. Baretti, B. Gastaldi, H. Gerlach, con la collaborazione di C. Bruno, L. Bruno e G. Michelotti. Regione Piemonte, Museo Regionale Sci. Nat. di Torino, Litografia Geda.

Cannic S., Lardeaux J.M., Mugnier J.L & Hernandez J., 1996. Tectono-metamorphic evolution of the Roignais-Versoyen unit (Valaisan domain, France). Eclogae Geol. Helv., 89, 321-343.

Capozzi R. & Castellarin A. (Eds), 1992. Studi preliminari all'acquisizione dati del profilo CROP 1-1A La Spezia-Alpi orientali. Studi Geol. Camerti, 1992/2, 303 p.

Carminati E., Cavazza D., Scrocca D., Fantoni R., Scotti P. & Doglioni C., 2010. Thermal and tectonic evolution of the Southern Alps (northern Italy) rifting: Coupled organic matter maturity analysis and thermokinematic modeling. Americ. Ass. Petrol. Geol. Bull., 94/3, 369-397.

Carminati E., Doglioni G. & Scrocca D., 2003. Apennines subduction-related subsidence of Venice (Italy). Geophys. Res. Letters, 30/13, 1717, 10.1029/2003GL017001

Carminati E. & Gosso G., 2000. A new structural map of the Ligurian Brianconnais cover nappe (Conca delle Carsene, Monte Marguareis, Ligurian Alps, Italy) and explanatory notes, Mem. Sci. Geol., Padova, 52, 93-99.

Caron C., 1972. La Nappe Superieure des Prealpes: subdivisions et prineipaux caracteres du sommet de l'edifice prealpin. Eclogae Geol. Helv., 65.57-73.

Caron C., Homewood P.& Wildi W., 1989. The original Swiss Flysch: a reappraisal of the type deposits in the Swiss Prealps. Earth Science Reviews, 26, 1-45, 10.1016/0012-8252(89)90002-0

Caron J.M., Polino R., Pognante U., Lombardo B., Lardeaux J.M., Lagabrielle Y., Gosso G. & Allenbach B., 1987. Ou sont les suture majeures dans les Alpes internes (transversale Briançon-Torino). Mem. Soc. Geol. It., 29, 71-78.

Carpena J. & Caby R., 1984. Fission-track evidence for Late Triassic oceanic crust in the French-Italian Alps. Geology, 12, 108-111, 10.1130/0091-7613(1984)12<108:FEFLTO>2.0.CO;2

Carraro A. & Visonà D., 2003. Mantle xenoliths in Triassic camptonite dykes of the Predazzo Area (Dolomites, Northern Italy): petrography, mineral chemistry and geothermobarometry. Eur. J. Min., 15, 103-115, 10.1127/0935-1221/2003/0015-0103

Carraro F., 1966. Scoperta di una serie carbonifera di copertura degli Gneiss-Sesia. Boll. Soc. Geol. It., 85, 241-252.

Carraro F. & Charrier G., 1972. Paleontological evidence for the late Carboniferous age of the volcano-detrital cover of the "Micascisti eclogitici" (Sesia-Lanzo Zone, Western Alps). Boll. Soc. Geol. It., 91, 185-194.

Carraro F., Dal Piaz G.V. & Sacchi R., 1970. Serie di Valpelline e II Zona Diorito-Kinzigitica sono i relitti di un ricoprimento proveniente dalla Zona Ivrea-Verbano. Mem. Soc. Geol. It., 9, 197-224.

Carrozzo M.T., Luzio D., Margiotta C. & Quarta T., 1991. Gravity Map of Italy, scale 1 :500,000. CNR, Progetto Finalizzato Geodinamica, SELCA Firenze.

Cartwright I. & Barnicoat A.C., 1999. Stable isotope geochemistry of Alpine ophiolites: a window to ocean-floor hydrothermal alteration and constraints on fluid-rock interaction during high-pressure metamorphism. International Journal of Earth Sciences, 88, 219-235.

Cartwright I. & Barnicoat A.C., 2002. Petrology, geochronology, and tectonics of shear zones in the Zermatt-Saas and Combin zones of the Western Alps. J. metam. Geol., 20, 263-281.

Castellarin A., Dal Piaz G.V., Fantoni R., Vai G.B., Nicolich R. & Transalp Working Group, 2002. Lower crustal style and models along the southern sector of the Transalp profile. Mem. Sci. Geol., 54, 245-248.

Castellarin A. & Cantelli L., 2000. Neo-Alpine evolution of the southern Eastern Alps. J. Geodynamics, 30, 251-274, 10.1016/S0264-3707(99)00036-8

Castellarin A., Cantelli L., Fesce A.M., Mercier J.L., Picotti V., Pini G.A., Prosser G. & Selli L., 1992. Alpine compressional tectinics in the Southern Alps. Relationships with the N-Apennines. Annales Tectonicae, 6, 62-94.

Castellarin A., Nicolich R., Fantoni R., Cantelli L., Sella M. & Selli L., 2006. Structure of the lithosphere beneath the Eastern Alps (southern sector of the TRANSALP sector). Tectonophysics, 414, 259-282, 10.1016/j.tecto.2005.10.013

Castellarin A., Piccioni S., Prosser G., Sanguinetti E., Sartori R. & Selli R., 1993. Mesozoic continental rifting and Neogene inversion along the South Giudicarie line (Nortwest Brenta Dolomites). Mem. Soc. Geol. It., 49, 125-144.

Castellarin A. & Rossi P.L., 1981. The Southern Alps: an aborted Middle Triassic mountain chain? Eclogae Geol. Helv., 74, 313-316.

Castellarin A. & Vai G.B. (Eds), 1982. Guida al Sudalpino centro-orientale. Geol. Soc. It., Guide Geol. Regionali.

Cavazza W. & Wezel F., 2003. The Mediterranean region - a geological primer. Episodes, 26/3, September, 160-168.

Cesare B., Mazzoli C., Sassi R., Spiess R. & Sassi F.P., 2010. Beauty and complexity of metamorphism: case studies from the frontal part of the Adria microplate. Rendiconti Lincei, 21, Suppl. 1, 73-94, 10.1007/s12210-010-0078-0

Cesare B., Rubatto D., Hermann J. & Barzi L., 2001. Evidence for Late Carboniferous subduction type magmatism in mafi c-ultramafi c cumulates of the SW Tauern Window (Eastern Alps). Contrib. Mineral. Petrol., 142, 449-464, 10.1007/s004100100302

Chiarabba C., Jovane L. & Di Stefano R., 2005. A new view of Italian seismicity using 20 years of instrumental recordings. Tectonophysics, 395, 251-268, 10.1016/j.tecto.2004.09.013

Chopin C., 1984. Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. Contrib. Mineral. Petrol., 86, 107-118, 10.1007/BF00381838

Chopin C., 1991. High-pressure minerals, burial and uplift of mountain chains: from field to experiment. Lectures V Summer School geol. petrol. basamenti cristallini: Pressure and temperature evolution of orogenic belts, 1991, Università di Siena 1992, pp. 221-234.

Chopin C. & Maluski H., 1980. ^{40}Ar-^{39}Ar dating of high-pressure metamorphic micas from the Gran Paradiso area (Western Alps): evidence against the blocking-temperature concept. Contrib. Mineral. Petrol., 74, 109-122, 10.1007/BF01131997

Chopin C. & Monié P., 1984. A unique magnesiochloritoid bearing, high-pressure assemblage from the Monte Rosa, western Alps: petrologic and ^{40}Ar/^{39}Ar radiometric study. Contrib. Mineral. Petrol., 74, 109-122.

Chopin C. & Schertl H.P., 1999. The UHP unit in the Dora Maira Massif, Western Alps. Int. Geol. Rev.,41, 765-780, 10.1080/00206819909465168

Choukroune P. & Gapais D., 1983. Strain pattern in the Aar Granite (Central Alps): orthogneiss developed by bulk inhomogeneous flattening. J. Struct. Geology, 5, 411-418, 10.1016/0191-8141(83)90027-5

Choukroune P., Ballèvre M., Cobbold P., Gautier Y., Merle O. & Vuichard J.P., 1986. Deformation and motion in the western Alpine arc. Tectonics, 5, 215-226.

Christensen J.N., Selverstone J., Rosenfeld J.L. & De Paolo D.J., 1994. Correlation by Rb-Sr geochronology of garnet growth histories from different structural levels within the Tauern window, Eastern Alps. Contrib. Mineral. Petrol., 118, 1-12, 10.1007/BF00310607

Ciarapica G., Dal Piaz G.V. & Passeri L., 2010. Late Triassic microfossils in the Roisan zone, Austroalpine Dent Blanche-Mont Mary nappe system, NW-Alps. Rendiconti on line, vol. 11/2010, 85° Congr. Naz. Soc. Geol. It., Riassunti, 259-260.

Cita M.B. & Forcella F., 1998. Alpi e Prealpi Lombarde. Guide Geologiche Regionali, Soc. Geol. It., BE-MA Milano, 314 p.

Cliff R.A., Barnicoat A.C. & Inger S., 1998. Early Tertiary eclogite facies metamorphism in the Monviso Ophiolite. J. Metam. Geol., 16, 447-455.

Closs H., 1975. A subduction model for the Alps derived from geophysical results. Rapp. Comm. Int. Mer Médit., 23, 55-57.

Collet L.W., 1927. The structure of the Alps. Edward Arnold & Co., London, 2nd Edition, 1935, 304 p.

Colombi A. & Pfeifer H.R., 1986. Ferrogabbroic and basaltic metaeclogites from the Antrona mafic-ultramafic complex and the Centovalli-Locarno region (Italy and southern Switzerland), first results. Schweiz. mineral. petrogr. Mitt., 66, 99-110.

Compagnoni R., 1977. The Sesia-Lanzo zone: high pressure-low temperature metamorphism in the Austro-Alpine continental margin. Rend. Soc. It. Min. Petr., 33, 335-374.

Compagnoni R., Dal Piaz G.V., Hunziker J.C., Gosso G., Lombardo B. & Williams P.F., 1975. The Sesia-Lanzo zone, a slice of continental crust with Alpine high pressure-low temperature assemblages in the Western Italian Alps. Italy-U.S.A. cooperative project on high pressure to low temperature metamorphism in the Western Alps, 54 p.

Compagnoni R., Dal Piaz G.V., Hunziker J.C., Gosso G., Lombardo B. & Williams P.F., 1977. The Sesia-Lanzo zone, a slice of continental crust with Alpine high pressure-low temperature assemblages in the Western Italian Alps. Rend. Soc. It. Min. Petr., 33, 281-334.

Compagnoni R., Elter G. & Lombardo B. 1974. Eterogeneità stratigrafica del complesso degli "gneiss minuti" nel massicio cristallino del Gran Paradiso. Mem. Soc. Geol. It., 13, Suppl. 1, 227-239.

Compagnoni R. & Lombardo B., 1974. The Alpine age of the Gran Paradiso eclogites. Rend. Soc. It. Min. Petr., 30, 223-237.

Compagnoni R. & Maffeo B., 1973. Jadeite-bearing Metagranites l.s. and related Rocks in the Mount Mucrone Area (Sesia-Lanzo Zone, Western Italian Alps). Schweiz. mineral. petrogr. Mitt., 53, 355-378.

Compagnoni R. & Rolfo F., 2003. UHPM units in the Western Alps. In Carswell T., Compagnoni R. & Rolfo F. (Eds): EMU notes in Mineralogy, vol. 5: Ultrahigh Pressure Metamorphosm, 13-50.

Conforto-Galli C., Spalla I.M., Gosso G. & Montrasio A., 1988. Syn-intrusive foliation of the Masino-Bregaglia (Bergell) tonalite and its roof pendants in Val Sissone (Valmalenco, Central Alps, Italy). Rend. Soc. It. Min. Petr., 43, 509-516.

Cornelius H.P. & Clar E., 1939. Geologie des Grossglocknergebietes. Abh. Geol. B-A. Wien, 25, 305 pp.

Cortesogno L., 1984. Metamorfismo e magmatismo prealpini nel basamento e nel tegumento delle Alpi liguri. Mem. Soc. Geol. It., 28, 79-95.

Corsi P., 2003. La Carta Geologica d'Italia: agli inizi di un lungo contenzioso. In Vai G.B. & Cavazza W. (Eds): Four centuries of the word 'Geology', Ulisse Aldrovandi 1603 in Bologna. Minerva Edizioni, Bologna, pp.255-279.

Corsi P., 2007. Much ado about nothing: the Italian Geological Survey, 1861-2006. Earth Sciences History, 26, 97-125.

Cortesogno L., Gaggero L. & Capelli C., 1997. Petrology of the pre-Alpine eclogites and amphibolites from the Ligurian Briançonnais basement. Atti Ticinesi Sc.Terra, 39, 3-29.

Cortiana G., Dal Piaz G.V., Del Moro A., Hunziker J.C. & Martin S., 1998. ^{40}Ar-^{39}Ar and Rb-Sr dating on the Pillonet klippe and frontal Sesia-Lanzo zone in the Ayas valley and evolution of the western Austroalpine nappe stack. Mem. Sci. Geol., 50, 177-194.

Cortiana G., Dal Piaz G.V., Pellegrini G.B., Tartarotti P. & Toffolon G., 2004. Foglio 003 Vetta d'Italia. Carta Geol. 1:25.000 Provincia Autonoma Bolzano.

Coward M.P., Dietrich D. & Park, R.G., 1989. Alpine Tectonics. Geol. Soc. London Spec. Publ., no. 45, 449 p.

Cuffaro M., Riguzzi F., Scrocca D., Antonioli F., Carminati E., Livani M. & Doglioni C., 2010. On the geodynamics of the northern Adriatic plate. Rend. Fis. Acc. Lincei, 21, Suppl 1, 253-279, 10.1007/s12210-010-0098-9

Dachs E., 1986. High-pressure mineral assemblages and their breakdown products in metasediments south of the Grossvenediger, Tauern Window, Austria. Schweiz. mineral. petrogr. Mitt., 66, 145-161.

Dallagiovanna G., Gaggero L., Maino M., Seno S. & Tiepolo M., 2009. U-Pb zircon ages for post-Variscan volcanism in the Ligurian Alps (Northern Italy). Journal Geol. Soc. London, 166, 101-114, 10.1144/0016-76492008-027

Dal Piaz G., 1905. Sulla tectonica dei monti fra il Brenta e i dintorni del Lago di S. Croce. Atti Acc. Sci. Veneto-Trentina-Istriana, 2, 31-36.

Dal Piaz G., 1912. Studi geotettonici sulle Alpi orientali. Mem. Ist.Geol. Univ. Padova, 1, 195 p.

Dal Piaz Gb., 1928. Geologia della catena Herbetet-Grivola-Grand Nomenon. Mem. Ist. Geol. Univ. Padova, 7, 82 p.

Dal Piaz Gb., 1934. Studi geologici sull'Alto Adige orientale e regioni limitrofe. Mem. Ist. Geol. Univ. Padova, 10, 245 p.

Dal Piaz Gb., 1939. La discordanza ercinica nella zona pennidica e le sue conseguenze nei riguerdi della Storia geologica della Alpi. Boll. Soc.Geol. It., 58, 105-152.

Dal Piaz Gb., 1965. Meditazioni geologiche sul "Cristallino antic0" delle Alpi. Atti Rassegna Tecnica Soc. Ing. Arch. Torino, 19, 573-576.

Dal Piaz Gb. & Dal Piaz G.V., 1984. Sviluppo delle concezioni faldistiche nell'interpretazione tettonica delle Alpi (1840-1940). Soc. Geol. It., vol. giubilare 1° centenario, Pitagora-Tecnoprint Bologna, pp. 41-70.

Dal Piaz G.V., 1965. La formazione mesozoica dei calcescisti con pietre verdi fra la Valsesia e la Valtournanche ed i suoi rapporti strutturali con il ricoprimento Monte Rosa e con la zona Sesia-Lanzo. Boll. Soc. Geol. It., 84/1, 67-104.

Dal Piaz G.V., 1969. Nuovo affioramento di quarziti e scisti a piemontite in Valle d'Aosta. Boll. Soc. Geol. It., 88, 613-619.

Dal Piaz G.V., 1971. Alcune considerazioni sulla genesi delle ofioliti piemontesi e dei giacimenti ad esse associati. Boll. Ass. Mineraria Subalpina, 8, 365-388.

Dal Piaz G.V., 1974. Le métamorphisme de haute pression et basse température dans l'évolution structurale du bassin ophiolitique alpino-apenninique (1ère partie: considérations paléogéographiques). Boll. Soc. Geol. It., 93, 437-468; 2e partie: Schweiz. mineral. petrogr. Mitt., 54, 399-424.

Dal Piaz G.V., 1976. Il lembo di ricoprimento del Pillonet, falda della Dent Blanche nelle Alpi occidentali. Mem. Ist. Geol. Min. Univ. Padova, 31, 60 pp, and 1:12,500 geol. map.

Dal Piaz G.V. 1992. Le Alpi dal M. Bianco al Lago Maggiore. I Volume: 13 itinerari. II Volume: 97 escursioni a piedi. Guide Geol. Regionali, Soc. Geol. It., BE-MA Milano, 311 pp, 209 pp.

Dal Piaz G.V., 1993. Evolution of Austro-Alpine and Upper Penninic basement in the northwestern Alps from Variscan convergence to post-Variscan extension. In J. Von Raumer & F. Neubauer (Eds): Pre-Mesozoic geology in the Alps. Springer-Verlag, 327-344.

Dal Piaz G.V., 1995. Plate tectonics and mountain building: the Alps. Historical review and personal comments. In: Ranalli G. (Ed): Plate Tectonics, the first twenty-five years, Proceedings VIII Summer School Earth Planet. Sci., Università di Siena, pp. 171-251.

Dal Piaz G.V., 1996a. Felice Giordano and the geology of the Matterhorn. Atti Acc. Sci. Torino, 130, 163-179.

Dal Piaz G.V., 1996b. La montagna misteriosa. Il Cervino dei geologi. Alps, n. 137, settembre 1996, 80-87.

Dal Piaz G.V., 1997. Alpine geology and hystorical evolution of the orogenic concept. Acc. Sci. Torino, Mem. Sci. Fis., 21, 49-83.

Dal Piaz G.V., 1999. The Austroalpine-Piedmont nappe stack and the puzzle of Alpine Tethys. In G. Gosso et al. (Eds): Third Meeting on Alpine Geol. Studies. Mem. Sci. Geol., 51, 155-176.

Dal Piaz G.V., 2001a. History of tectonic interpretations of the Alps. J. Geodynamics, 32, 99-114, 10.1016/S0264-3707(01)00019-9

Dal Piaz G.V., 2001b. Geology of the Monte Rosa massif: historical review and personal comments. Schweiz. mineral. petrogr. Mitt., 81, 275-303.

Dal Piaz G.V., Bistacchi A. & Massironi M., 2003. Geological outline of the Alps. Episodes, 26/3 September 2003, 174-179.

Dal Piaz G.V., Cortiana G., Del Moro A., Martin S., Pennacchioni G. & Tartarotti P., 2001. Tertiary age and paleostructural inferences of the eclogitic imprint in the Austroalpine outliers and Zermatt-Saas ophiolite, Western Alps. Intern. J. Earth Sci., 90, 668-684, 10.1007/s005310000177

Dal Piaz G.V., De Vecchi Gp. & Hunziker J.C., 1977. The Austroalpine layered gabbros of the Matterhorn and Mt. Collon-Dents de Bertol. Schweiz. mineral. petrogr. Mitt., 57, 59-88.

Dal Piaz G.V., Di Battistini G., Venturelli G. & Kienast J.R., 1979. Manganiferous quartzitic schists of the Piemonte ophiolite nappe in the Valsesia-Valtournanche area (Italian Western Alps). Mem. Sci. Geol., 32, 24 pp.

Dal Piaz G.V., Gianotti F., Monopoli B., Pennacchioni G., Tartarotti P. & Schiavo A., 2010. Carta Geologica d'Italia alla scala 1:50.000: Foglio 091 Chatillon e Note illustrative. Servizio Geologico d'Italia e Regione Autonoma Valle d'Aosta, 152 p.

Dal Piaz G.V. & Gosso G., 1984. Le moderne interpretazioni tettoniche delle Alpi. In A. Castellarin (Ed): Soc. Geol. It., vol. giubilare 1° centenario, Pitagora-Tecnoprint Bologna, 95-112.

Dal Piaz G.V. & Gosso G., 1994. Some remarks on evolution of the Alpine lithosphere. In A. Montrasio & E. Sciesa (Eds): Proceedings Symp. CROP-Alpi Centrali, Sondrio October 1993, Quaderni Geodin. Alpina e Quaternaria, 2, 91-99.

Dal Piaz G.V., Gosso G. & Martinotti G., 1971. La II Zona diorito-kinzigitica tra la Valsesia e la Valle d'Ayas (Alpi occidentali). Mem. Soc. Geol. It., 10, 257-276, 1 carta 1:75.000.

Dal Piaz G.V., Hunziker J.C. & Martinotti G., 1972. La Zona Sesia-Lanzo e l'evoluzione tettonico-metamorfica delle Alpi nordoccidentali interne. Mem. Soc. Geol. It., 11, 433-466.

Dal Piaz G.V., Hunziker J.C. & Martinotti G., 1973. Excursion to the Sesia Zone of the Schweiz. Mineralogische und Petrographische Gesellschaft from September 30th to October 3rd, 1973. Schweiz. mineral. petrogr. Mitt., 53, 477-490.

Dal Piaz G.V. & Lombardo B., 1986. Early Alpine eclogite metamorphism in the Penninic Monte Rosa-Gran Paradiso basement nappes of the northwestern Alps. Geol. Soc. Am. Mem., 164, 249-265.

Dal Piaz G.V., Lombardo B. & Gosso G., 1983. Metamorphic evolution of the Mt.Emilius klippe, Dent Blanche nappe, Western Alps. Am. J. Sci., 283A, 438-458.

Dal Piaz G.V. & Martin S., 1998. Evoluzione litosferica e magmatismo nel dominio austro-sudalpino dall'orogenesi varisica al rifting permo-mesozoico. Riunione estiva S.G.I. 1996, Mem. Soc. Geol. It., 53 (1996), 43-62.

Dal Piaz G.V., Nervo R. & Polino R., 1979. Carta geologica del lembo del Glacier-Rafray (Dent Blanche s.l.) e note illustrative. Centro studio problemi orogeno Alpi occidentali, CNR Torino, 2, 24 p.

Dal Piaz G.V. & Omenetto P., 1978. Brevi note su alcune mineralizzazioni della Falda Piemontese in Valle d'Aosta. Ofioliti, 3, 161-176.

Dal Piaz G.V. & Polino R., 1989. Evolution of the Alpine Tethys. Atti Conv. Acc. Naz. Lincei, 80, 93-107.

Dal Piaz G.V. & Sacchi R., 1969. Osservazioni geologiche sul lembo di ricoprimento del Pillonet (Dent Blanche l.s.). Mem. Soc. Geol. It., 8, 835-846.

Dal Piaz G.V., Venturelli G. & Scolari A., 1979. Calc-alkaline to ultrapotassic postcollisional volcanic activity in the internal northwestern Alps. Mem. Sci. Geol., 32, 16 p.

Dal Piaz G.V., Venturelli G., Spadea P. & Di Battistini G., 1981. Geochemical features of metabasalts and metagabbros from the Piemonte ophiolite nappe, Italian Western Alps. N. Jb. Min. Abh., 142, 248-269.

D'Amico C. & Mottana A., 1976. Hercynian plutonism in the Alps. A report. Mem. Soc. Geol. It., 13 (1974), suppl. 1, 49-118.

Debelmas J., 1975. Les Alpes et la théorie des plaques. Rev. Géogr. Phys. Géol. Dyn., 17, 195-208.

Debelmas J., 1976. Théorie des plaques et genèse des chaines de montagnes. Implications sur la notion de chaines "géosynclinales". Géologues, 37, 25-44.

Decandia F.A. & Elter P. 1969. Riflessioni sul problema delle ofioliti nell'Appennino settentrionale (nota preliminare). Atti Soc. Toscana Sci. Nat., A-76, pp. 1-9.

De Giusti F., Dal Piaz G.V., Massironi M. & Schiavo A., 2004. Carta geotettonica della Valle d'Aosta. Mem. Sci. Geol., 55 (2003), 129-149.

Delacou B., Sue C., Champagnac J.-D. & Burkhard M., 2004. Present-day geodynamics in the bend of the western and central Alps as constrained by earthquake analysis. Geophys. Journal Intern., 158, 753-774, 10.1111/j.1365-246X.2004.02320.x

Del Moro A., Ferrara G., Tonarini S. & Callegari E., 1985a. Rb-Sr systematics on rocks from the Adamello Batholith (southern Alps). In Dal Piaz G.V. (Ed): Il magmatismo tardo alpino nelle Alpi. Mem. Soc. Geol. It., 26 (1983), 261-284.

Del Moro A., Pardini G., Quercioli Q., Villa I.G. & Callegari E., 1985b. Rb/Sr and K/Ar chronology of Adamello granitoids, southern Alps. In Dal Piaz G.V. (Ed): Il magmatismo tardo alpino nelle Alpi. Mem. Soc. Geol. It., 26 (1983), 285-299.

Del Moro A. & Visona` D., 1982. The epiplutonic Hercynian complex of Bressanone (Brixen, Eastern Alps, Italy). Petrologic and radiometric data. N. Jb. Min. Abh., 145, 66-85.

Dercourt J. and other nine (1990). Anisian to Oligocene paleogeography of the European margin of Tethys (Geneva to Baku): Mém. Soc. géol. France, 154/3, 159-190.

De Saussure H.B., 1779-96. Voyages dans les Alpes. Fauche-Borel, Neuchâtel.

Desmons J., Aprahamian J., Compagnoni R., Cortesogno L., Frey M. & Coworkers, 1999. Alpine metamorphism of the Western Alps: I. Middle to high-P/T metamorphism. Schweiz. mineral. petrogr. Mitt., 79, 89-110.

Desmons J. & Mercier D., 1993. Passing through the Briançon zone. In Von Raumer J. & Neubauer F. (Eds): Pre-Mesozoic geology in the Alps. Springer-Verlag, Heidelberg, 279-295.

Desmurs L., Manatschal G. & Bernoulli D. 2001, The Steinmann Trinity revisited: mantle exhumation and magmatism along an ocean-continent transition. In Wilson R.C.L., Whitmarsh R.B., Taylor B. & Froitzheim N. (Eds): Non-volcanic rifting of continental margins: a comparison of evidence from land and sea. Geol. Soc., London, Spec. Publ., 187, 235-266.

Desmurs L., Müntener O. & Manatschal G., 2002. Onset of magmatic accretion within magma-poor passive margins: A case study from the Platta ocean-continent transition, eastern Switzerland: Contrib. Mineral. Petrol., 144, 365-382.

De Vecchi Gp., 1989. Metaophiolite suite in the south-western Tauern Window (Italian sector), Geochemistry and geological setting. Mem. Sci. Geol., Padova, 41, 51-59.

De Vecchi Gp. & Baggio P., 1982. The Pennine zone of the Vizze region in the western Tauern window (Italian eastern Alps). Boll. Soc. Geol. It., 101, 89-116.

De Vecchi Gp., De Zanche V. & Sedea R., 1974. Osservazioni preliminari sulle manifestazioni magmatiche triassiche nelle Prealpi Vicentine (area di Recoaro-Schio-Posina). Boll. Soc. Geol. It., 93, 397-409.

De Vecchi Gp. & Mezzacasa G., 1986. The Pennine basement and cover units in the Mesule group (south-western Tauern window). Mem. Sci. Geol., Padova 38, 365-392.

De Vecchi Gp. & Piccirillo E.M., 1968. Le ofioliti mesozoiche associate ai calcescisti negli Alti Tauri sud-occidentali (Valli di Vizze e di Fundres - Alto Adige). Mem. Mus. Tridentino Sci. Nat., 24, 99-152.

De Wever P., Baumgartner P.O. & Polino R., 1987. Précision sur les datations de la base des Schistes Lustrés postophiolitiques dans les Alpes Cottiennes. C.R. Acad. Sci. Paris, 305, 487-491.

Dewey J.F. & Bird J.M., 1970. Mountain belts and the new global tectonics. J. Geophys. Res., 75, 2625-2647, 10.1029/JB075i014p02625

Dewey J.F., Pitman W.C., Ryan W.B.F., & Bonnin J., 1973. Plate tectonics and the evolution of the Alpine system. Geol. Soc. Am. Bull., 84, 3137-3180, 10.1130/0016-7606(1973)84<3137:PTATEO>2.0.CO;2

Dewey J.F., Helman M.L., Turco E., Hutton D.H.W. & Knott S.D., 1989. Kinematics of the western Mediterranean. Geol. Soc. London Spec. Publ., 45, 265-283, 10.1144/GSL.SP.1989.045.01.15

Diehl E.A., Masson R. & Stutz A.H., 1952. Contributi alla conoscenza del ricoprimento Dent Blanche. Mem. Ist. Geol. Min. Univ. Padova, 17, 53 pp.

Dieni I., Giordano D., Loydell D.K. & Sassi F.P., 2005. Discovery of Llandovery (Silurian) graptolites and probable Devonian corals in the Southalpine Metamorphic Basement of the Eastern Alps (Agordo, NE Italy). Geol. Magazine, 143, 1-5, 10.1017/S0016756804009987

Dieni I., Giordano D. & Sassi F.P., 2006. Silurian and Devonian boudins within the Southalpine Metamorphic basement of the Agordo Area (Eastern Alps). Atti Ist. Veneto Sci. Lett. Arti, Cl. Sci. Fis., 164, 7-44.

Dietrich D. & Casey M., 1989. A new tectonic model for the Helvetic nappes. Geol. Soc., London, Spec. Publ., 45/1, 47-63, 10.1144/GSL.SP.1989.045.01.03

Dietrich V., 1969. Die Ophiolithe des Oberhalbsteins (Graubünden) und das Ophiolithmaterial der ostschweizerischen Molasse ablagerungen, ein petrographischer Vergleich. Bern, Verlag Herbert Lang, 179 p.

Dietrich V., 1970. Die Stratigraphie der Platta-Decke: Fazielle Zusammenhänge zwischen Oberpenninikum und Unterostalpin. Eclogae Geol. Helv., 63, 631-671.

Dietrich V., 1976. Evolution of Eastern Alps: a plate tectonic working hypothesis. Geology, 4/3, 147-152, 10.1130/0091-7613(1976)4<147:EOTEAA>2.0.CO;2

Dietrich V., 1980. The distribution of ophiolites in the Alps. Ofioliti, Spec. Issue Tethyan ophiolites, 1, 7-51.

Dietrich V. & Franz, 1976. Alpidische Gebirgsbildung in den Ostalpen: ein plattentektonisches Modell (Kurzfassung). Geol. Rundsch., 65, 361-374.

Di Giulio A., 1992. The evolution of the Western Ligurian Flysch Units and the role of mud diapirism in ancient accretionary prisms (Maritime Alps, Northwestern Italy). Geol. Rundschau, 81, 655-668, 10.1007/BF01791383

Dingeldey Ch., Dallmeyer R.D., Koller F. & Massonne H.J., 1997. P-T-t history of the Lower Austroalpine nappe complex in the "Tarntaler Berge" NW of the Tauern window: implications for the geotectonic evolution of the central Eastern Alps. Contrib. Mineral. Petrol., 129, 1-19, 10.1007/s004100050319

Di Toro G., Pennacchioni G. & Teza G., 2004. Superheated friction-induced melts in zoned pseudotachylytes within the Adamello tonalites (Italian Southern Alps). J. Structural Geol., 26, 1783-1801, 10.1016/j.jsg.2004.03.001

Di Vincenzo G., Tonarini S., Lombardo B., Castelli D. & Ottolini L., 2006. Comparison of ^{40}Ar-^{39}Ar and Rb-Sr data on phengites from the UHP Brossasco-Isasca Unit (Dora Maira massif, Italy): implications for dating white mica. Journal of Petrology, 47, 1439-1465.

Doglioni C. 1990. The global tectonic pattern. J. Geodynamics, 12, 21-38, 10.1016/0264-3707(90)90022-M

Doglioni C. 1992. Main differences between thrust belts. Terra Nova, 4, 152-164, 10.1111/j.1365-3121.1992.tb00466.x

Doglioni C. 1994. Foredeeps versus subduction zones. Geology, 22, 271-274, 10.1130/0091-7613(1994)022<0271:FVSZ>2.3.CO;2

Doglioni C. & Carminati E., 2008. Structural styles and Dolomites field trip. Mem. Descr. Carta Geol. It., 82, 1-299.

Doglioni C. & Flores G., 1997. Italy. In Moores E.M. & Fairbridge R.W. (Eds.): Encyclopedia of European and Asian regional geology. Chapman and Hall, London, 414-435.

Doglioni C., Guegen E., Harabaglia P. & Mongelli F., 1999. On the origin of west-directed subduction zones and applications to the western Mediterranean. In Durad B., Jolivet L., Horvath F. & Séranne, M. (Eds.): The Mediterranean Basins: Tertiary Extension within the Alpine Orogen: Geol. Soc. London, Spec. Publ., 156, pp. 541-561.

Doglioni C., Guegen E., Sébat F. & Fernandez M., 1997. The Western Mediterranean extensional basins and the Alpine orogen. Terra Nova, 9, 109-112.

Doglioni C., Harabaglia P., Merlini S., Mongelli F., Peccerillo A. & Piromallo C., 1999. Orogens and slabs vs their direction of subduction. Earth Science Reviews, 45, 167-208, 10.1016/S0012-8252(98)00045-2

Droop G.T.R., Lombardo B. & Pognante U., 1990. Formation and distribution of eclogite facies rocks in the Alps. In Carswell D.A. (Ed): Eclogite facies rocks, Blakie, 225-259.

Duchêne S., Blichert-Toft J., Luais B., Téluk P., Lardeaux J.-M. & Albarède F., 1997. The Lu-Hf dating of garnets and the ages of the Alpine high-pressure metamorphism. Nature, 387, 586-589.

Dunkl I. & Demeny A., 1997. Exhumation of the Rechnitz Window at the border of the Eastern Alps and Pannonian basin during Neogene extension. Tectonophysics, 272, 197-211, 10.1016/S0040-1951(96)00258-2

Ellenberger F., 1953. Sur l'extension des faciès briançonnais en Suisse, dans les Préalpes médianes et les Pennides. Eclogae Geol. Helv., 45, 285-286.

Ellenberger F., 1953. La série de Barrhorn et les retrocharriages penniques. C.R. Acad. Sci. Paris, 236, 218-220.

Ellenberger F., 1958. Etude géologique du pays de Vanoise. Mém. Ser. Carte géol. France, 561 pp.

Elter G., 1960. La Zona Pennidica dell'alta e media Valle d'Aosta e le unità limitrofe. Mem. Ist. Geol. Min. Univ. Padova, 22, 113 pp.

Elter G., 1971. Schistes lustrées et ophiolites de la zone piémontaise entre Orco et Doire Baltée (Alpes Graies). Hypothèses sur l'origine des ophiolites. Géol. Alpine, 47, 147-169.

Elter G., 1972. Contribution à la connaissance du briançonnais interne et de la bordure piémontaise dans les Alpes Graies nordorientales et considérations sur les rapports entre les zones du briançonnais et des schistes lustrés. Mem. Ist. Geol. Min. Univ. Padova, 28, 19 p.

Elter G., 1987. Carte géologique de la Vallée d'Aoste, échelle 1:100.000. - SELCA, Firenze.

Elter G. & Elter P., 1965. Carta geologica della regione del Piccolo S. Bernardo (versante italiano). Note illustrative. Mem. Ist. Geol. Min. Univ. Padova, 25, 53 p.

Elter G., Elter P., Sturani C. & Weidmann M., 1966. Sur la prolongation du domain ligure de l'Apennin dans le Montferrat et les Alpes et sur l'origine de la nappe de la Simme s.l. des Préalpes romandes et chablaisiennes. Archives Sci. Genève, 19, 279-378.

Elter P. 1972. La zona ofiolitica del Bracco nel quadro dell'Appennino settentrionale. Introduzione alla geologia delle Liguridi. 66° Congr. Soc. Geol. It., Guida alle escursioni, Pacini Pisa, pp. 5-35.

Elter P. & Pertusati P., 1973. Considerazioni sul limite Alpi-Appennino e sulla relazione con l'arco delle Alpi occidentali. Mem. Soc. Geol. It., 12, 359-375.

Engi M., Bousquet R. & Berger A., 2004. Explanatory notes to the map: Metamorphic structure of the Alps. Central Alps, Oesterr. Miner. Ges., 149, 157-173.

Ernst W.G., 1971. Metamorphic zonations on presumably subducted lithospheric plates from Japan, California and the Alps. Contrib. Mineral. Petrol., 34, 43-59.

Ernst W. G., 1973. Interpretative synthesis of the metamorphism in the Alps. Bull. Geol. Soc. Amer., 84, 2053-2078, 10.1130/0016-7606(1973)84<2053:ISOMIT>2.0.CO;2

Ernst W.G. & Dal Piaz G.V., 1978. Mineral parageneses of eclogitic rocks and related mafic schists of the Piemonte ophiolite nappe, Breuil-St.Jacques area, Italian Western Alps. Am. Miner., 63, 621-640.

Escher A., 1988. Structure de la nappe du Grand Saint-Bernard entre le val de Bagnes et les Mischabel. Rapport Serv. hydrol. géol. nat. suisse, 7, 26 pp.

Escher A., Hunziker J.C., Marthaler M., Masson H., Sartori M. & Steck A., 1997. Geologic framework and structural evolution of the western Swiss-Italian Alps. In O.A.Pfiffner, P. Lehner., P. Heitzmann, S. Mueller & A. Steck (Eds): Deep structure of the Swiss Alps. Birkäuser Verlag, Basel, 205-221.

Escher A., Masson H. & Steck, A., 1988. Coupes géologiques des Alpes occidentales suisses. Mém. Géol. Lausanne, 2, 11 p.

Evans B.W., Trommsdorff V. & Richter W., 1979. Petrology of an eclogite-metarodingite suite at Cima di Gagnone, Ticino, Switzerland. Am. Mineral., 64, 15-31.

Exner Ch., 1976. Die geologische Position der Magmatite des Periadriatischen Lineaments. Verh. Geol. B-A., 1976, 3-64

Faninger E. & Strucl I., 1978. Plutonic emplacement in the eastern Karawanken Alps. Geologija, 21, 81-87.

Federico L., Crispini L., Scambelluri M. & Capponi, G., 2007. Ophiolite mélange zone records exhumation in a fossil subduction channel. Geology, 35, 499-502.

Ferrando S., Bernoulli D. & Compagnoni R., 2004. The Canavese zone (internal Western Alps): a distal margin of Adria. Schweiz. mineral. petrogr. Mitt., 84, 237-256.

Florineth D. & Froitzheim N., 1994. Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubünden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. Schweiz. mineral. petrogr. Mitt., 74, 437-448.

Flügel H.W. & Faupl P. (Eds), 1987. Geodynamics of the Eastern Alps: Deutikle, Vienna, 418 pp.

Forster M., Lister G., Compagnoni R., Giles D., Hills Q., Betts P., Beltrando M. &Tamagno E., 2004. Mapping of oceanic crust with "HP" to "UHP" metamorphism: The Lago di Cignana Unit (Western Alps). In Pasquarè G., Venturini C. & Groppelli G. (Eds.), Mapping Geology in Italy. APAT - Dip. Difesa del Suolo, Serv. Geol. d'Italia, Roma 2004 (2006), Map 33, 279-286, S.EL.CA., Firenze

Franchi S., 1895. Notizie sopra alcune metamorfosi di eufotidi e diabasi nelle Alpi Occidentali. Boll. R. Comit. Geol. It, 26, 181-204.

Franchi S., 1897. Sopra alcuni nuovi giacimenti di rocce a lawsonite. Boll. Soc. Geol. It., 16, 73-76.

Franchi S., 1898. Sull'eta mesozoica della zona delle pietre verdi nelle Alpi Occidentali. Boll. R. Comit. Geol. It., 29, 173-247 e 325-482.

Franchi S., 1902. Contributo allo studio delle roccie a glaucofane e del metamorfismo onde ebbero origine nella regione ligure-alpina occidentale. Boll. R. Comit. Geol. It., 33, 255-318.

Franchi S., Mattirolo E., Novarese V., Stella A. & Zaccagna D., 1908. Carta geologica delle Alpi Occidentali alla scala 1:400.000. R. Ufficio Geologico, Roma. Riduzione al 400.000 di 28 fogli colorati a mano della Carta Geologica d'Italia alla scala 1:100.000, dedotti interamente dai rilievi di campagna alla scala 1:25.000 eseguiti dagli Autori dal 1888 al 1906. Le zone oltre il confine di stato sono tratte dalle carte francesi e svizzere esistenti. Ristampa anastatica 1990.

Frank W., 1987. Evolution of the Austroalpine elements in the Cretaceous. In Flügel H.W. & Faupl P. (Eds): Geodynamics of the Eastern Alps. Deuticke Vienna, pp. 378-406.

Frank W., Hock V. & Miller C., 1987a. Metamorphic and tectonic history of the Central Tauern Window. In Flugel H.W. & Faupl P. (Eds.): Geodynamics of the Eastern Alps. Deuticke, pp. 34-54.

Frank W., Kralik M., Scharbert S. & Thöni M., 1987 b. Geochronological data from the eastern Alps. In Flugel H.W. & Faupl, P. (Eds.): Geodynamics of the eastern Alps. Deuticke, pp. 272-281.

Freeman R., Giese P. & Mieller S., Eds. (1990). The European geotraverse: integrative studies. European Sci. Found., 404 pp.

Freeman S.R., Butler R.W.H., Cliff R.A., Inger S. & Barnicoat T.A.C., 1998. Deformation migration in an orogen-scale shear zone array; an example from the basal Brianconnais thrust, internal Franco-Italian Alps. Geol. Mag., 135, 349-367, 10.1017/S0016756898008693

Freeman S.R., Inger S., Butler R.W.H. & Cliff, R.A., 1997. Dating deformation using Rb-Sr in white mica: greenschist facies deformation ages from the Entrelor shear zone, Italian Alps. Tectonics 16, 57-76, 10.1029/96TC02477

Frey M., Hunziker J.C., Frank W., Bocquet J., Dal Piaz G.V, Jäger E. & Niggli E., 1974. Alpine metamorphism of the Alps. A review. Schweiz mineral. petrogr. Mitt., 54, 247-290.

Frey M., Desmons J. & Neubauer F. (Eds), 1999. The new metamorphic map of the Alps: Schweiz. mineral. petrogr. Mitt., 79, 230 pp.

Frisch W., 1977. Plate-tectonic evolution of the Eastern Alps. Acta geol. Acad. Sci. Hungaricae, 21, 223-228.

Frisch W., 1979. Tectonic progradation and plate tectonic evolution of the Alps. Tectonophysics, 60, 121-139, 10.1016/0040-1951(79)90155-0

Frisch W., 1981. Plate motions in the Alpine region and their correlation to the opening of the Atlantic ocean. Geol. Rundsch., 70, 402-411, 10.1007/BF01822122

Frisch W., Brügel A., Dunkl I., Kuhlemann & Satir M., 1999. Post-collisional large-scale extension and mountain uplift in the Eastern Alps. In G. Gosso et al. (Eds): Third Meeting on Alpine Geol. Studies. Mem. Sci. Geol., 51, 3-23.

Frisch W., Gommeringer K., Kelm U. & Popp F., 1987. The Upper Bündner Schiefer of the Tauern window. A key to understanding Eoalpine orogenic processes in the Eastern Alps. In H. Flügel & P. Faupl (Eds): Geodynamics of the Eastern Alps. Deutike, Vienna, 55-69.

Frisch W., Ring U., Dürr S., Borchert S. & Biehler D., 1994, The Arosa zone and Platta nappe ophiolites (Eastern Swiss Alps): geochemical characteristics and their meaning for the evolution of the Penninic ocean. Jb. Geol. B-A, Wien, 137, 19-33.

Froitzheim N., 2001. Origin of the Monte Rosa nappe in the Pennine Alps-a new working hypothesis. Geol. Soc. Am. Bull., 113, 604-614

Froitzheim N., Conti P. & Van Daalen M., 1997. Late Cretaceous synorogenic, low-angle normal faulting along the Schlinig fault (Switzerland, Italy, Austria) and its significance for tectonics of the Eastern Alps. Tectonophysics, 280, 267-293, 10.1016/S0040-1951(97)00037-1

Froitzheim N. & Manatschal G., 1996. Kinematics of Jurassic rifting, mantle exhumation, and passive margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). Geol. Soc. Am. Bull., 108, 1120-1133, 10.1130/0016-7606(1996)108<1120:KOJRME>2.3.CO;2

Froitzheim N. & Schmid S.M., 2009. Orogenic Processes in the Alpine Collision Zone. Swiss Journal of Geosciences, suppl. 1.

Froitzheim N., Schmidt S.M. & Conti P., 1994. Repeated change from crustal shortening to orogen-parallel extension in the Austroalpine units of Graubünden. Eclogae Geol. Helv., 87, 559-612.

Froitzheim N., Schmid S.M. & Frey M., 1996. Mesozoic paleogeography and the timing of eclogite-facies metamorphism in the Alps: a working hypothesis. Eclogae Geol. Helv., 89, 81-110.

Fry N. & Barnicoat A.C., 1987. The tectonic implications of high-pressure metamorphism in the western Alps. J. Geol. Soc. London, 144, 653-659, 10.1144/gsjgs.144.4.0653

Fuchs W., 1980. Die Molasse und ihre nichthelvetischer Vorlandanteil am Untergrund einschliesslich der Sedimente auf der Bömischen Masse. In Oberhauser R. (Ed): Der Geologische Aufbau Oesterreichs. Springer-Verlag Wien, 148-176.

Fugenschuh B., Loprieno A., Ceriani S. & Schmid S.M., 1999. Structural analysis of the Subbriançonnais and Valais units in the area of Moutiers (Savoy, Western Alps): paleogeographic and tectonic consequences. Int. J. Earth Sci., 88, 201-218, 10.1007/s005310050260

Fügenschuh B., Seward D. & Mancktelow N., 1997. Exhumation in a convergent orogen: the western Tauern window. Terra Nova, 9, 213-217.

Gabudianu Radulescu I., Rubatto D., Courtney G. & Compagnoni R., 2009. The age of HP metamorphism in the Gran Paradiso Massif, Western Alps: A petrological and geochronological study of "silvery micaschists". Lithos (2009), 10.1016/j.lithos.2008.12.008.

Gaggero L., Cortesogno L. & Bertrand J.-M, 2004. The pre-Namurian basement in the Ligurian Alps: a review of the lithostratigraphy, pre-Alpine metamorphic evolution, and regional comparisons. Periodico Min., 73, 85-96.

Gardien V., Reusser E. & Marquer D., 1994. Pre-Alpine metamorphioc evolution of the gneisses from the Valpelline series (Western Alps, Italy). Schweiz. mineral. petrogr. Mitt., 74, 489-502.

Garzanti E., Doglioni C., Vezzoli G. & Andò S., 2007. Orogenic belts and orogenic sediment provenances. Journal of Geology, 115, 315-334.

Gastaldi B., 1871-74. Studi geologici sulle Alpi occidentali. Mem. R. Comit. Geol. d'Italia, 1, 47 p., 2, 161 p.

Gebauer D., 1999. Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. Schweiz mineral petrogr Mitt., 79, 191-208.

Gebauer D., Grünenfelder M., Tilton G., Trommsdorff V. & Schmid S., 1992. The geodynamic evolution of garnet-peridotites, garnet-pyroxenites and eclogites of Alpe Arami and Cima di Gagnone (Central Alps) from Early Proterozoic to Oligocene. Schweiz. mineral. petrogr. Mitt., 72, 107-111.

Gebauer D., Schertl H.P. & Schreyer W., 1995. A 35 Ma old ultrahigh-pressure metamorphism in the Dora-Maira massif and its geodynamic implications for the Pennine zone of the central and Western Alps. Geol. Geotech. Arbeiten, 44, 49-52.

Genser J. & Neubauer F., 1989. Low angle normal faults at the eastern margin of the Tauern window (Eastern Alps). Mitt. Österr. Geol. Ges., 81, 233-243.

Gerlach H., 1869. Karte der Penninischen Alpen, Maastab 1:200,000. Lith. und top. Anstf. H. Furrer, Neuenburg.

Gerlach H., 1869. Die Penninischen Alpen. N. Denkschr. Schweiz. Natf. Ges., 23, 132 pp, reprinted in Beitr. Geol. Karte Schweiz, 27, 1883.

Gerlach H., 1871. Das Südwestliche Wallis. Beiträge Geol. Karte Schweiz, 9, 1-175.

Gianolla P., 1992. Evoluzione mediotriassica del vulcanismo di Rio Freddo (Api Giulie, Italia). Mem. Sci. Geol., Padova, 44, 193-209.

Gianolla P. & Panizza M., 2009. Le Dolomiti dichiarate dall'UNESCO patrimonio mondiale dell'Umanità. Geoitalia, 28, 56-58.

Giese P., 1980. Krustenstruktur der Alpen. Ein Ueberblick verbunden mit einigen tektonischen Betrachtungen. Berliner Geowiss. Abh., 20, 51-64.

Giese P. Günther K. & Reutter K.J., 1970. Vorgleichende geologische und geophysikalische Betrachtungen der Westalpen und des Nordapennins. Z. deutsch. geol. Ges., 120, 151-195.

Gillet Ph., Choukroune P., Ballèvre M. & Davy Ph. 1986. Thickening history of the Western Alps. Earth Planet. Sci. Lett., 78, 44-52.

Giobbi E., Zappone A., Boriani A., Bocchio R. & Morten L., 1997. Relics of pre-Alpine ophiolites in the Serie dei Laghi (Western Southern Alps). Schweiz. mineral. petrogr. Mitt., 77, 197-207.

Giordano F., 1869. Sulla orografia e sulla geologica costituzione del Gran Cervino. Atti R. Acc. Sci. Torino, 4, 304-321.

Giordano F., 1869. Notice sur la constitution géologique du Mont Cervin. Archives Sci. phys. nat. Genève, 34, 255-267.

Giorgis D., Thélin P., Stampfli G. & Bussy F., 1999. The Mont-Mort metapelites: Variscan metamorphism and geodynamic context (Briançonnais basement, western Alps, Switzerland). Schweiz. mineral. petrogr. Mitt., 79, 381-398.

Glodny J., Ring U., Kuhn A., Gleissner P. & Franz G., 2005. Crystallization and very rapid exhumation of the youngest Alpine eclogites (Tauern Window, Eastern Alps) from Rb/Sr mineral assemblage analysis. Contrib. Mineral. Petro., 149, 699-712, 10.1007/s00410-005-0676-5

Godard G., 2001. Eclogites and their geodynamics interpretation: a history. J. Geodynamics, 32, 165-203, 10.1016/S0264-3707(01)00020-5

Godard G., Martin S., Prosser G., Kienast J.R. & Morten L., 1996. Variscan migmatites, eclogites and garnet - peridotites of the Ulten zone, Eastern Austroalpine system. Tectonophysics, 259, 313-341.

Goffé B., 1982. Définition du faciès à Fe-Mg-carpholite-chloritoïde, un marqueur du métamorphisme de HP-BT dans les métasédiments alumineux. Thèse Doct. Sci. Paris, 2 vol., 212 p.

Goffé B., 1984. Le faciès à carpholite-chloritoïde dans la couverture briançonnaise des Alpes Ligures: un témoinde l'histoire tectono-métamorphique régionale. Mem. Soc. Geol. It., 28, 461-479.

Goffé B. & Bousquet R., 1997. Ferrocarpholite, chlorïtoide et lawsonite dans les métapelites des unités du Versoyen et du Petit St. Bernard (zone valaisanne). Schweiz. mineral. petrogr. Mitt., 77, 137-147.

Goffé B. & Chopin C. (1986). High-pressure metamorphism in the Western Alps: zoneography of metapelites, chronology and consequences. Schweiz. mineral. petrogr. Mitt., 66, 41-52.

Gosso G., Dal Piaz G.V., Piovano V. & Polino R., 1979. High pressure emplacement of early-alpine nappes, postnappe deformations and structural levels. Mem. Sci. Geol., Padova, 32, 15 pp.

Gouffon Y., 1993. Géologie de la nappe du Grand St. Bernard entre la Dore Baltée et la frontière suisse (Valle d'Aoste, Italie). Mém. Géol. Lausanne, 12, 147 p.

Guillaume A., 1969. Contribution à l'étude géologique des Alpes liguro-piemontaises. Doc. Lab. Géol. Sc. Lyon, 30, 658 p.

Gouzu C., Itaya T., Hyodo H. & Matsuda, T., 2006. Excess ^{40}Ar-free phengite in ultrahighpressure metamorphic rocks from the Lago di Cignana area, Western Alps. Lithos, 92, 418-430.

Gratier J.-P., Menard G. & Arpin, R., 1989. Strain-displacement compatibility and restoration of the Chaînes Subalpines of the western Alps. In Coward M.P., Dietrich D & Park R.G. (Eds): Alpine Tectonics. J. Geol. Soc., London, Spec. Publ., 45, 65-81.

Green D.H., 1991. The role of experimental petrology in determination of P-T paths. Lectures V Summer School geol. petrol. basamenti cristallini: Pressure and temperature evolution of orogenic belts, 1991, Università di Siena 1992, 177-201.

Groppo C., Beltrando M. & Compagnoni R., 2009. The P-T path of the ultra-high pressure Lago di Cignana and adjoining high-pressure meta-ophiolitic units: insights into the evolution of the subducting Tethyan slab. J. Metamorph. Geol., 27, 207-231.

Grundmann G., 1988. Metamorphic evolution of the Habach Formation; a review. Mitt. Oesterr. Geol. Ges., 81, 133-149.

Guillot F., Liegois J.P & Fabre J., 1991. Des granophyres du Cambrien dans le Mont Pourri (Vanoise, zone brianconnaise): première datation U-Pbsur zircon d'un socle des zones internes des Alpes francaises. C.R. Acad. Sci. Paris, 313, 239-244.

Guillot F., Ploquin A., Raoult J.-F. & Peruccio-Parison M.-D., 1986. Les series antépermiennes de Vanoise septentrionale (zone brianconnaise, Alpes de Savoie): lithologie et geochimie dans le massifs de Bellecote; arguments pour un age antéhouiller. C.R.Acad. Sci. Paris, 303, 1141-1146.

Guillot F., Schaltegger U., Bertrand J.M., Deloule E. & Baudin T., 2002. Zircon U-Pb geochronology of Ordovician magmatism in the polycyclic Ruitor Massif (internal W. Alps). Intern. J. Earth. Sci., 91, 964-978, 10.1007/s00531-002-0280-0

Habler G., Thöni M. & Sölva H., 2006. Tracing the high pressure stage in the polymetamorphic Texel Complex (Austroalpine basement unit, Eastern Alps): P - T -t-d constraints. Mineralogy and Petrology, 88, 269-296.

Hagen T., 1948. Geologie des Mont Dolin und des Nordrandes der Dent Blanche-Decke zwischen Mont Blanc de Cheilon und Ferpècle (Wallis). Beitr. Geol. Karte Schweiz, 90, 64 pp., Spezialkarte n. 119, Bern.

Hallam A., 1973. A revolution in the Earth Sciences. From continental drift to plate tectonics. Clarendon Press, Oxford, 127 p.

Handy M. R., Franz L., Heller F., Janott B. & Zurbriggen R., 1999. Multistage exhumation and accretion of the continental crust (Ivrea crustal section, Italy and Switzerland). Tectonics, 18, 1154-1177, 10.1029/1999TC900034

Handy M.R., Herwegh M., Kamber B.S., Tietz R. & Villa I.M., 1996. Geochronologic, petrologich and kinematic constraints on the evolution of the Err-Platta boundary part of a fossil continent-ocean suture in the Alps (eastern Switzerland). Schweiz. mineral. petrogr. Mitt., 76, 453-474.

Handy M. R. & Oberhänsli R., 2004. Metamorphic structure of the Alps, age map of the metamorphic structure of the Alps - tectonic interpretation and outstanding problems. In Oberhänsli R. et al. (Eds): Explanatory Notes to the Map: Metamorphic Structure of the Alps. Mitt. Oesterr. Mineral. Ges., 149, 201-226.

Handy M.R. & Zingg A., 1991. The tectonic and rheological evolution of an attenuated cross section of the continental crust: Ivrea crustal section, southern Alps, northwestern Italy and southern Switzerland. Geol. Soc. Am. Bull., 103, 236-253, 10.1130/0016-7606(1991)103<0236:TTAREO>2.3.CO;2

Hansmann W. & Oberli F., 1991. Zircon inheritance in an igneous rock suite from the southern Adamello batholith (Italian Alps). Contrib. Mineral. Petrol., 107, 501-518, 10.1007/BF00310684

Haug E., 1900. Les géosynclinaux et les aires continentales. Bull. Soc. géol. France, s. 3, 28, 617-711.

Haug E., 1906. Les nappes de charriage des Alpes septentrionales. Bull. Soc. géol. France, s. 4., 6, 359-422.

Hawkesworth C.J., Waters D.J. & Bickle M.J., 1975. Plate tectonics in the Eastern Alps. Earth Planet. Sci. Lett., 24, 405-413, 10.1016/0012-821X(75)90147-8

Heim A., 1902. Lettre ouverte de M. le professeur A. Heim à M. le professeur M. Lugeon. Bull Soc Géol France, 4/1, 823-825.

Heinrich C., 1986. Eclogite facies regional metamorphism of hydrous mafic rocks in the central alpine Adula nappe. J. Petrol., 27, 123-154.

Henk A., Franz L., Teufel S. & Oncken O., 1997. Magmatic underplating, extension, and crustal reequilibration: insights from a cross section through the Ivrea zone and Strona-Ceneri zone, Northern Italy. Journal of Geology, 105, 367-377, 10.1086/515932

Hermann F., 1925. Paléogéographie et genèse pennique. Eclogae Geol. Helv., 19, 604-618.

Hermann F., 1938. Carta geologica delle Alpi nord-occidentali alla scala 1:200.000, con note illustrative e carta strutturale alla scala 1:750,000. Tipografia Allegretti di Campi, Milano, 24 p.

Herwartz D., Münker C., Scherer E.E., Nagel T.J., Pleuger J. & N., 2008. Lu-Hf garnet geochronology of eclogites from the Balma Unit (Pennine Alps): implications for Alpine paleotectonic reconstructions. Swiss Journal of Geosciences, 101, Suppl. 1, 173-189.

Hinterlechner-Ravnik, A., 1982. Pohorski eklogit. Geologija, 25, 251-288.

Hinterlechner-Ravnik A., Sassi F.P. & Visonà D., 1991a. The Austridic eclogites, metabasites and metaultrabasites from the Pohorje area (Eastern Alps, Yugoslavia): 1. The eclogites and related rocks. Rend. Fis. Accad. Lincei, 9, 157-173.

Hinterlechner-Ravnik A., Sassi F.P. & Visonà D., 1991b. The Austridic eclogites, metabasites and metaultrabasites from the Pohorje area (Eastern Alps, Yugoslavia): 2. The metabasites and metaultrabasites, and concluding considerations. Rend. Fis. Accad. Lincei, 9, 175- 190.

Höck V, 1974. Lawsonitpseudomorphosen in den Knotenschiefern der Glocknergruppe (Salzburg-Kärten, Oesterreich). Karinthin, 71, 110-119.

Höck V, 1983. Mesozoic ophiolites and non-ophiolitic metabasites in the central part of the Tauern window (Eastern Alps, Austria). Ofioliti, 8, 103-126.

Höck V., 1993. The Habach-Formation and the Zentralgneis. A key in understanding the Palaeozoic evolution of the Tauern window. In von Raumer J.F. & Neubauer F. (Eds): Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin, 361-374.

Höck V. & Koller F., 1989. Magmatic evolution of the Mesozoic ophiolites in Austria. Chem. Geol., 77, 209-227.

Höck V. & Miller Ch., 1987. Mesozoic ophiolitic sequences and non ophiolitic metabasites in the Hohe Tauern. In H. Flügel and P. Faupl (Eds): Geodynamics of the Eastern Alps. Deutike, Vienna, 16-33.

Hodges K.V. & Fountain D.M., 1984. Pogallo line, South Alps, Northern Italy: an intermediate crustal level, low-angle normal fault? Geology, 12, 151-155, 10.1130/0091-7613(1984)12<151:PLSANI>2.0.CO;2

Hoinkes G., 1986. Eoalpine metamorphism of the Austroalpine Schneeberg-Complex and the adjacent Oeztal crystalline basement. Schweiz. mineral. petrogr. Mitt., 66, 135-138.

Hoinkes G., Koller F., Rantitsch G., Dachs E., Höck V., Neubauer F. & Schuster R., 1999. Alpine metamorphism of the Eastern Alps. Schweiz. mineral. petrogr. Mitt., 79, 155-181.

Hoinkes G., Kostner A. & Thöni M., 1991. Petrologic constraints for Eo-Alpine eclogite facies metamorphism in the Austro-Alpine Oeztal basement. Mineral Petrology, 43, 237-254.

Hoschek G., 1984. Alpine metamorphism of calcareous metasediments in the western Hohen Tauern, Tirol: mineral equilibria in COHS fluids. Contrib. Mineral. Petrol., 67, 120-137.

Hoschek G., 2001. Thermobarometry of metasediments and metabasites from the Eclogite zone of the Hohe Tauern, Eastern Alps, Austria. Lithos, 59, 127-150, 10.1016/S0024-4937(01)00063-9

Hoschek G., 2007. Metamorphic peak conditions of eclogites in the Tauern Window, Eastern Alps, Austria: Thermobarometry of the assemblage garnet + omphacite + phengite + kyanite + quartz. Lithos, 93, 1-16, 10.1016/j.lithos.2006.03.042

Hsü K., 1979. Thin-skinned plate tectonics during Neo-Alpine orogenesis. Am. J. Sci., 279, 353-366.

Hsü K.J., 1991. Exhumation of high-pressure metamorphic rocks (Alps). Geology, 19, 107-110.

Hsü K.J. & Schlanger S.O., 1971. Ultrahelvetic flysch sedimentation and deformation related to plate tectonics. Geol. Soc. Am. Bull., 82, 1207-1218.

Hunziker J.C., 1970. Beitrag zur Tektonik der Dent-Blanche Decke, radiometrische Altersbestimmungen und Feldevidenzen. Unpubl. Presentation at 45 Annual meeting Schweiz. Min. Petr. Mitt., Basel.

Hunziker J.C., 1974. Rb-Sr and K-Ar age determination and the Alpine history of the Western Alps. Mem. Ist. Geol. Min. Univ. Padova, 31, 54 p.

Hunziker J.C., Desmons J. & Hurford A.J., 1992. Thirty-two years of geochronological work in the Central and Western Alps: a review on seven maps. Mem. Geol., Lausanne, 13, 59 p.

Hunziker J.C., Desmons J. & Martinotti G., 1989. Alpine thermal evolution in the central and the western Alps. Geol. Soc. Spec. Publ., 45, 353-367, 10.1144/GSL.SP.1989.045.01.20

Hurford A.J. & Hunziker J.C., 1985. Alpine cooling history of the Monte Mucrone eclogites (Sesia-Lanzo zone): fission track evidence. Schweiz. mineral. petrogr. Mitt., 65, 325-334.

Hurford A. J. & Hunziker J. C.,1989. A revised thermal history for the Gran Paradiso massif. Schweiz. mineral. Petrogr. Mitt., 69, 319-329.

Inger S. & Cliff R.A., 1994. Timing of metamorphism in the Tauern window, Eastern Alps: Rb-Sr ages and fabric formation. J. metam. Geol., 12, 695-707.

Inger R., Ramsbotham W., Cliff R.A. & Rex D.C., 1996. Metamorphic evolution of the Sesia-Lanzo Zone, Western Alps: time constraints from multi-system geochronology. Contrib. Mineral. Petrol., 126, 152-168, 10.1007/s004100050241

Janak M., Froitzherim N., Luptak B., Vrabec M. & Krogh Ravna E.J., 2004. First evidence for ultrahigh-pressure metamorphism of eclogites in Pohorje, Slovenia: tracing deep continental subduction in the Eastern Alps. Tectonics, 23, TC5014. 10.1029/2004TC001641

Janak M., Froitzheim N., Vrabec M., Krogh Ravna E.J. & De Hoog J.C.M., 2006. Ultrahigh-pressure metamorphism and exhumation of garnet peridotite in Pohorje, Eastern Alps. J. metam. Geol., 24, 19-31.

Janak M., Vrabec M., Froitzherim N., Luptak B., & Hinterlechner-Ravnik A., 2005. Ultrahigh-pressure metamorphism of garnet peridotites from Pohorje Mts (Easten Alps, Slovenia). Mitt. Oesterr. Miner. Ges., 150.

Keller L.M. & Schmid S.M., 2001. On the kinematics of shearing near the top of the Monte Rosa nappe and the nature of the Furgg zone in Val Loranco (Antrona valley, N. Italy): tectonometamorphic and paleogeographical consequences. Schweiz. mineral. petrogr. Mitt. 81, 347-367.

Kienast J.R., 1973. Sur l'existence de deux séries différentes au sein de l'ensemble "schistes lustrés - ophiolites " du Val d'Aoste; quelques arguments fondés sur l'eéude de roches métamorphiques. C.R. Acad. Sci. Paris, 276, 2621-2624.

Kienast J.R., 1983. Le métamorphisme de haute pression et basse température (éclogites et schistes bleus): données nouvelles sur la pétrologie des roches de la croute océanique subductée et des sédiments associés. Thèse Doct. d'Etat Univ. P. et M. Curie, Paris VI, 484 p.

Kienast J.R., Lombardo B., Biino G. & Pinardon J.L., 1991. Petrology of very-high-pressure eclogitic rocks from the Brossasco-Isasca Complex, Dora-Maira Massif, Italian Western Alps. J. metam. Geol., 9, 19-34.

Kienast J.R. & Messiga B., 1987. Cr-rich Mg-chloritoid, a first record in high pressure metagabbros from Monviso (Cottian Alps, Italy). Mineral. Mag., 51, 681-687, 10.1180/minmag.1987.051.363.08

Kienast J.R. & Nicot E., 1971. Présence d'une paragenèse à disthène et chloritoide (d'âge alpin probable) dans les gneiss à sillimanite, grenat et cordiérite de Valpelline (Val d'Aoste, Italie). C.R. Acad. Sci. Paris, D 272, 1836-1839.

Kissling E., Schmid S.M., Lippitsch R., Ansorge J. & Fügenschuh B., 2006. Lithosphere structure and tectonic evolution of the Alpine arc: new evidence from high resolution teleseismic tomography. In Gee D. & Stephenson R.A. (Eds.): European Lithosphere Dynamics. Geol. Soc. London, Mem, 32, 129-145.

Klebelsberg R. von, 1940. Ein Ammonit aus dem Hochstegen-Kalk des Zillertals (Tirol). Zeitschr. Deutsch. Ges., 92, 582-586.

Klötzli U., Mair V. & Bargossi G.M., 2003. The ''Bozener Quarzporphyr'' (Southern Alps, Italy): single zircon U/Pb age evidence for 10 million years of magmatic activity in the Lower Permian. Mitt. Oesterr. Mineral. Ges., 148, 187-188.

Kober L., 1923. Bau und Entstehung der Alpen. Bornträger, Berlin, 283 p.

Koller F., 1985. Petrologie und Geochemie des Penninikums am Alpenostrand. Jb. Geol. B-A, Wien, 128, 83-150.

Koller F. & Höck V., 1990. Mesozoic ophiolites in the Eastern Alps. In Malpas J., Moores E.M., Panayiotou A. & Xenophontos C. (Eds): Ophiolites, oceanic crustal analogues. Proceedings symp. Troodos 1987. Minist. Agric. Nat. Resour., Nicosia, Cyprus, 253-263.

Konrad-Schmolke, M., Babist J., Handy M.R. & O'Brien P.J., 2006. Insight into the physico chemical properties of a subducted slab from garnet zonation patterns (Sesia Zone, western Alps), J. Petrol., 47, 2123-2148.

Koons P.O., Rubie D.C. & Frueh-Green G., 1987. The effects of disequilibrium and deformation on the mineralogical evolution of quartz-diorite during metamorphism in the eclogite facies. J. Petrol., 28, 679-700.

Kurz W., 2005. Tectonic map and overall architecture of the Alpine orogen: Comment on an article by Stefan M. Schmid, Bernhard Fügenschuh, Eduard Kissling & Ralf Schuster 2004 (Eclogae geologicae Helvetiae, 97, 93-117).- Eclogae geol. Helv., 98, 97-98, 10.1007/s00015-005-1151-z

Kurz W., 2005. Constriction during exhumation: Evidence from eclogite microstructures. Geology, 33, 37-40.

Kurz W., 2007. Penninic Paleogeography from the Western toward the Eastern Alps-Still Open Questions? Intern. Geol. Review, 48, 996-1022, 10.2747/0020-6814.48.11.996

Kurz W. & Froitzheim N., 2002. The exhumation of eclogite-facies metamorphic rocks - a review of models confronted with examples from the Alps. Intern. Geol. Review, 44, 702-743, 10.2747/0020-6814.44.8.702

Kurz W., Handler R. & Bertoldi C., 2008. Tracing the exhumation of the Eclogite Zone (Tauern Window, Eastern Alps) by $^{40}Ar/^{39}Ar$ dating of white mica in eclogites. Swiss J. Geosci., 101, Supplement 1, 191-206.

Kurz W., Neubauer F. & Dachs E., 1998a. Eclogite meso-and microfabrics: implications for the burial and exhumation history of eclogites in the Tauern window (Eastern Alps) from P-T-t paths. Tectonophysics, 285, 183-209, 10.1016/S0040-1951(97)00188-1

Kurz W., Neubauer F. & Genser J., 1996. Kinematics of Penninic nappes (Glockner nappe and basement-cover nappes) in the Tauern window (Eastern Alps, Austria) during subduction and Penninic-Austroalpine collision. Eclogae Geol. Helv., 89, 573-605.

Kurz W., Neubauer F., Genser J. & Dachs E., 1998b. Alpine geodynamic evolution of passive and active continental margin sequences in the Tauern window (eastern Alps, Austria, Italy): a review. Geol. Rundschau, 87, 225-242, 10.1007/s005310050204

Lacassin R., 1989. Plate-scale kinematics and compatibility of crustal shear zones in the Alps. Geol. Soc. London Spec. Publ., 45, 339-352, 10.1144/GSL.SP.1989.045.01.19

Lagabrielle Y., 1987. Les ophiolites: marquers de l'histoire tectonique des domaines océaniques. Le cas des Alpes franco-italiennes (Queyras Piemont), comparison avec les ophiolites d'Antalya (Turquie) et du Coast Range de Californie. Thèse doct. d'Etat, Univ. Bretagne occ., Brest, 350 p.

Lagabrielle Y., Fudral S. & Kienast J.R., 1989. La couverture océanique des ultrabasites de Lanzo (Alpes occidentales): arguments lithostratigraphiques et pétrologiques. Geodin. Acta, 3, 43-55.

Lagabrielle Y., Polino R., Auzende J.M., Blanchet R., Caby R., Fudral F., Lemoine M., Mével C., Ohnestetter M., Robert D. & Tricart P., 1984. Les témoins d'une tectonique intraoceénique dans le domaine Téthysien: analyse des rapports entre les ophiolites et leurs couvertures métasédimentaires dans la zone piémontaise des Alpes franco-italiennes. Ofioliti, 9, 67-88.

Lammerer B., 1986. Das Autochthon im westlichen Tauernfenster. Jb. Geol. B-A, 129, 51-67.

Lammerer B., 1988. Thrust-regime and transpression-regime tectonics in the Tauern window (Eastern Alps). Geol. Rundschau, 77, 143-156, 10.1007/BF01848681

Lammerer B., Schmidt K. & Stadler R., 1981. Zur Stratigraphie und Genese der penninisches Gesteinen der Südwestlichen Tauernfenster. N. Jb. Geol. Pal. Mh., 11, 678-696.

Lammerer B. & Transalp Working Group, 2002. The "crocodrile" model and balancing the seismic section. Mem. Sci. Geol., Padova, 54, 243-244.

Lammerer B. & Weger M., 1998. Footwall uplift in an orogenic wedge: the Tauern window in the Eastern Alps of Europe. Tectonophysics, 285, 213-230, 10.1016/S0040-1951(97)00272-2

Lapen T.J., Johnson C.M., Baumgartner L.P., Mahlen N.J., Beard B.L. & Amato J.M., 2003. Burial rates during prograde metamorphism of an ultra-high pressure terrane: an example from Lago di Cignana, Western Alps, Italy. Earth Planet. Sci. Letters, 215, 57-72.

Lapen T.J., Johnson C.M., Baumgartner L.P., Dal Piaz G.V., Skora S. & Beard B.L., 2007. Coupling of oceanic and continental crust during Eocene eclogite-facies metamorphism: Evidence from the Monte Rosa nappe, Western Alps. Contrib. Mineral. Petrol., 153, 139-157, 10.1007/s00410-006-0144-x

Lardeaux J.M., Gosso G., Kienast J.R. & Lombardo B., 1982. Relations entre le métamorphisme et la déformation dans la zone Sesia-Lanzo (Alpes occidentales) et le problème de l'éclogitisation de la croûte continentale. Bull. Soc. géol. France, 24, 793-800.

Lardeaux J.M. & Spalla I.M., 1991. From granulites to eclogites in the Sesia zone (Italian Western Alps): a record of the opening and closure of the Piedmont ocean. J. Metam. Geol., 9, 35-59, 10.1111/j.1525-1314.1991.tb00503.x

Laubscher H.P., 1969. Mountain building. Tectonophysics, 7, 551-563, 10.1016/0040-1951(69)90030-4

Laubscher H.P., 1970. Bewegung und Wärme in der alpinen Orogenese. Schweiz. mineral. petrogr. Mitt., 50, 503-534.

Laubscher H.P., 1971. The large-scale kinematics of the Western Alps and the Northern Apennines and its palinspastic implications. Am. J. Sci., 271, 193-226, 10.2475/ajs.271.3.193

Laubscher H.P. & Bernoulli D., 1982. History and deformation of the Alps. In K.J. Hsü (Ed): Mountain building processes. Academic Press, pp. 169-180.

Le Bayon B. & Ballèvre M., 2006. Deformation history of a subducted continental crust (Gran Paradiso, Western Alps): continuing crustal shortening during exhumation. Journal of Structural Geology, 28, 793-815.

Le Bayon R., de Capitani C. & Frey, M., 2006b. Modelling phase-assemblage diagrams for magnesian metapelites in the system K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O: geodynamic consequences for the Monte Rosa nappe, Western Alps. Contrib. Mineral. Petrol., 151, 395-412.

Lefèvre R. & Michard A., 1976. Les nappes briançonnaises internes et ultra-briançonnaises de la bande d'Acceglio (Alpes franco-italiennes). Une étude structurale et pétrographique dans le faciès des schistes bleus à jadéite. Sci. Géol. Bull., 29, 183-222.

Lemoine M., 1984. Rifting and early drifting: Mesozoic central Atlantic and Ligurian Tethys. In Sheridan, R.E., Gradstein, F.M. et al., Init. Rep. DSDP, 76, 885-895.

Lemoine M., Bas T., Arnaud-Vanneau A., Arnaud A., Dumont T., Gidon M., Bourbon M.,De Graciansky P.-C., Rudkiewicz J.-L., Mégard-Galli J. & Tricart P., 1986. The continental margin of the Mesozoic Tethys in the Western Alps. Mar. Petrol. Geol., 3, 179-199.

Lemoine M., Tricart P & Boillot G., 1987. Ultramafic and gabbroic ocean floor of the Ligurian Tethys (Alps, Corsica, Appennines): In search of a genetic model. Geology, 15, 622-625, 10.1130/0091-7613(1987)15<622:UAGOFO>2.0.CO;2

Li X.P., Rahn M. & Bucher K., 2004. Serpentinites of the Zermatt-Saas ophiolite complex and their texture evolution. J. Metamorph. Geol., 22, 159-177.

Liati A., Froitzheim N. & Fanning C.M., 2005. Jurassic ophiolites within the Valais domain of the Western and Central Alps: geochronological evidence for re-rifting of oceanic crust. Contrib. Mineral. Petrol., 149, 446-461.

Liati A., Gebauer D. & Fanning C.M., 2003. The youngest basic oceanic magmatism in the Alps (Late Cretaceous; Chiavenna unit, Central Alps): geochronological constraints and geodynamic significance. Contrib. Mineral. Petrol., 146,144-158.

Lippisch R., 2002. Lithosphere and upper mantle structure beneath the Alps by high-resolution teleseismic tomography. PhD Thesis, n. 14726, ETHZürich.

Lippitsch R., Kissling E. & Ansorge J., 2003. Upper mantle structure beneath the Alpine orogen from high-resolution teleseismic tomography. J. Geophys. Res., 108. 10.1029/2002JB002016

Lombardo B., Nervo R., Compagnoni R., Messiga B., Kienast J.R., Mevel C., Fiora L., Piccardo G.B. & Lanza R., 1978. Osservazioni preliminari sulle ofioliti metamorfiche del Monviso (Alpi Occidentali). Rend. Soc. It. Min. Petr., 34, 253-302.

Lombardo B. & Pognante U., 1982. Tectonic implications in the evolution of the Western Alps ophiolite metagabbros. Ofioliti, 2, 371-394.

Lombardo B., Rubatto D. & Castelli D., 2002. Ion microprobe U-Pb dating of zircon from a Monviso metaplagiogranite: implications for the evolution of the Piedmont-Liguria Tethys in the Western Alps. Ofioliti, 27, 109-117.

Lorenzoni S., 1965. Studio geo-petrografico del versante italiano del Massiccio d'Ambin. Mem. Ist. Geol. Min. Univ. Padova, 25, 25-88.

Lüschen E. et. al., 2006. TRANSALP-deep crustal Vibroseis and explosive seismic profiling in the Eastern Alps, Tectonophysics, 414, 9-38.

Macera P., Gasperini D., Piromallo C., Blichert-Tofl J., Bosch D., Del Moro A. & Martin S., 2003. Geodynamic implications of deep mantle upwelling in the source of Tertiary volcanics from Veneto region (southeastern Alps). J. Geodynamics, 36, 563-590, 10.1016/j.jog.2003.08.004

Magetti M., Galetti G. & Stosch H.-G., 1987. Eclogites from the Silvretta nappe (Switzerland): geochemical constraints on the nature and geotectonic setting of their protoliths. Chem. Geol., 64, 319-334.

Malaroda R., 1957. Studi geologici sulla dorsale montuosa compresa tra le basse valli della Stura di Demonte e del Gesso (Alpi Marittime). Mem. Ist. Geol. Univ. Padova, 20, 130 p.

Malavieille J., Lacassin R. & Mattauer M. (1984). Signification tectonique des linéations d'allongement dans les Alpes occidentales. Bull. Soc. géol. France, 26, 895-906.

Malusà M., Polino R. & Martin S., 2005. The Gran San Bernardo nappe in the Aosta valley (western Alps): a composite stack of distinct continental crust units. Bull. Soc. Géol. Fr., 176, 417-431.

Manatschal G., 2004. New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps. Int. J. Earth Sci., 93, 432-466.

Manatschal G. & Bernoulli D., 1999. Architecture and tectonic evolution of nonvolcanic margins: Present-day Galicia and ancient Adria. Tectonics, 18, 1099-1119, 10.1029/1999TC900041

Manatschal G. & Münterer O., 2009. A type sequence across an ancient magma poor ocean-continent transition: the example of the western Alpine Tethys ophiolites. Tectonophysics, 473, 4-19.

Manatschal G., Münterer O., Desmurs L. & Bernoulli D., 2003. An ancient ocean-continent transition in the Alps: the Totalp, Err-Platta and Malenco units in the eastern Central Alps (Graubünden and northern Italy). Excursion of the Swiss Geological Society, September 20 to 24, 2002. Eclogae Geol. Helv., 96, 131-146.

Manatschal G. & Nievergelt R., 1997. A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). Eclogae Geol. Helv., 90, 3-27.

Manby G.M., Thiedig F. & Millar I., 1988. Textural, chemical and isotopic constraints on the age of the Saualpe eclogites (Carinthia/Austria). In: Sassi F.P.& Bourrouilh R. (Eds.): IGCP 5 Newsletter, 7, 195-202, Cleup, Padova.

Mancktelow N.S., 1985. The Simplon line: a major displacement zone in the western Lepontine Alps. Eclogae Geol. Helv., 78, 73-96.

Mancktelow N.S., 1992. Neogene lateral extension during convergence in the Central Alps: Evidence from interrelated faulting and backfolding around the Simplon pass (Switzerland). Tectonophysics, 215, 293-317, 10.1016/0040-1951(92)90358-D

Mancktelow N., Stöckli D.F., Grollimund B., Müller W., Fügenschuh B., Viola G., Seward D. & Villa I.M., 2001. The DAV and Periadriatic fault system in the Eastern Alps south of the Tauern window. Intern. J. Earth Sci., 90, 593-622.

Mandl G.W. 2000. The Alpine sector of the Tethyan shelf - Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. Mitt. Österr. Geol. Ges. 92 (1999), 61-77.

Mandl G. & Ondrejickova A., 1993. Radiolarite und Conodonten aus dem Meliatikum im Ostabschnitt der NKA. Jb. Geol. B.-A., 136/4, 841-871.

Manzotti P., Regis D., Cenki-Tok B., Robyr M., Rubatto D., Thomsen T., Zucali M. & Engi M., 2009. Evidence of Jurassic rifting in the Dent Blanche nappe (near Cignana, Italy). Alpine Workshop Cogne 2009, Abstr.

Markley M.J., Teyssier C. & Caby R., 1999. Re-examining Argand's view of the Siviez-Mischabel nappe. Journal of Structural Geology, 19, 1119-1124, 10.1016/S0191-8141(99)00063-2

Markley M.J., Teyssier C., Cosca M.A., Caby R., Hunziker J.C. & Sartori M., 1998. Alpine deformation and $^{40}Ar/^{39}Ar$ geochronology of sinkinematic white mica in the Siviez-Mischabel nappe, western Pennine Alps, Switzerland. Tectonics, 17, 407-425, 10.1029/98TC00560

Marocchi M., Morelli C., Mair V., Klötzli U. & Bargossi G.M., 2008. Evolution of large silicic magma systems: new U-Pb zircon data on the NW Permian Athesian volcanic group (Southern Alps, Italy). J. Geol, 116, 480-498.

Marthaler M., 1984. Géologie des unités penniques entre le val d'Anniviers et le val de Tourtemagne. Eclogae Geol. Helv., 77, 395-448.

Marthaler M., 2002. Le Cervin est-il africain ? Une histoire géologique entre les Alpes et notre planète. L.E.P. Loisirs et Pédagogie S.A., Lausanne, 96 pp.

Martin S. & Kienast J.R., 1987. The HP-LT manganesiferous quartzites of Praborna, Piemonte ophiolite nappe, Italian Western Alps. Schweiz. mineral. petrogr. Mitt., 67, 339-360.

Martin S., Godard G., Prosser G., Schiavo A., Bernoulli D. & Ranalli G., 1998. Evolution of the deep crust at the junction Austroalpine/Southalpine: the Tonale nappe. Mem Sci. Geol., 50, 1-50.

Martin S. & Kienast J.R., 1987. The HP-LT manganesiferous quartzites of Praborna, Piemonte ophiolite nappe, Italian Western Alps. Schweiz. mineral. petrogr. Mitt., 67, 339-360.

Martin S., Montresor L., Mair V., Pellegrini G.B. et al., 2009. Carta Geologica d'Italia alla scala 1:50.000: Foglio 25 Rabbi e Note illustrative. Servizio Geologico d'Italia e Provincia Autonoma di Trento, 187 p.

Martin S., Prosser G. & Morten L. 1993. Tectono-magmatic evolution of sheeted plutonic bodies along the north Giudicarie line (northern Italy). Geol. Rundsch., 82, 51-66, 10.1007/BF00563270

Martin S., Rebay G., Kienast J.R. & Mevel C., 2008. An eclogitized oceanic palaeo-hydrothermal field from the St Marcel valley (Italian Western Alps). Ofioliti, 33, 49-63.

Martin S., Tartarotti P. & Dal Piaz G.V., 1994. Alpine ophiolites: a review. Boll. Geof. Teorica Appl., 36, n. 141-144, 175-220.

Masson H., 1976. Un siècle de géologie des Préalpes: de la découverte des nappes à la recherche de leur dynamique. Eclogae Geol. Helv., 69, 527-575.

Masson H., 1983. La géologie en Suisse de 1882-1932. Eclogae Geol. Helv., 76, 47-64.

Masson H., 2002. Ophiolites and other (ultra)basic rocks fromtheWest-Central Alps: new data for a puzzle. Bull. Soc. Vaudoise Sci. Nat., 88, 263-276.

Masson H., Bussy F., Eichenberger M., Giroud N., Meilhac C. & Presniakiv S., 2008. Early Carboniferous age of the Versoyen ophiolites and consequences: non-existence of a "Valais ocean" (Lower Penninic, western Alps). Bull. Soc. Géol. France, 179, 337-355.

Mattauer M., Malavieille J. & Moniè P., 1987. Une coupe lithosphérique des Alpes Occidentales dans l'hypothèse où Sezia n'est pas d'origine Sud-Alpine. C.R. Acad. Sci. Paris, 304, 43-48.

Mattauer M. & Tapponnier P., 1978. Tectonique des plaques et tectonique intracontinentale dans les Alpes franco-italiennes. C.R. Acad. Sci. Paris, 287, 899-901.

Mattern F. & Wang P.J., 2008. Out-of-sequence thrusts and paleogeography of the Rhenodanubian Flysch Belt (Eastern Alps) revisited. Intern. J. Earth Sci., 97, 821-833, 10.1007/s00531-007-0200-4

Matura A., Summesberger H. & Coworkers 1980. Geology of the Eastern Alps. Abh. Geol. B-A, Wien, 34, 103-170.

Mayer A., Abouchami W. & Dal Piaz G.V., 1999. Eocene Sm-Nd age for the eclogitic metamorphism of the Zermatt-Saas ophiolite in Ayas valley, Western Alps. EUG 10 Abstr, p. 809.

Mayer A., Cortiana G., Dal Piaz G.V., Deloule E., De Pieri R. & Jobstraibizer P., 2003. U-Pb single zircon ages of the Adamello batholith, Southern Alps. Mem. Sci. Geol., Padova, 55, 151-167.

Meffan-Main S., Cliff R. A., Barnicoat A.C., Lombardo B. & Compagnoni R., 2004. A Tertiary age for Alpine high-pressure metamorphism in the Gran Paradiso massif, Western Alps: a Rb-Sr microsampling study. J. metamorphic Geol., 22, 267-281.

Messiga B., 1987. Alpine metamorphic evolution of Ligurian Alps (Northwest Italy) - chemography and petrological constraints inferred from metamorphic climax assemblages. Contrib. Mineral. Petrol., 95, 3, 269-277, 10.1007/BF00371842

Messiga B., Kienast J.-R., Rebay G., Riccardi M.P. & Tribuzio R., 1999. Cr-rich magnesiochloritoid eclogites from the Monviso ophiolites (Western Alps, Italy). J. metam. Geology, 17, 287-300, 10.1046/j.1525-1314.1999.00198.x

Messiga B., Scambelluri M. & Piccardo G.B., 1995. Chloritoid-bearing assemblages in mafic systems and eclogite-facies hydration of alpine Mg-Al metagabbros (Erro-Tobbio unit, Ligurian Western Alps). Eur. J. Miner., 7, 5, 1149-1167.

Mével C., Caby R. & Kienast J.R., 1978. Amphibolite facies conditions in the oceanic crust: example of amphibolitized flaser-gabbro and amphibolites from Chenaillet ophiolite massif (Hautes Alpes, France). Earth Planet. Sci. Lett., 39, 98-108.

Michard A., 1967. Etudes géologiques dans les zones internes des Alpes Cottiennes. Editions du CNRS, Parigi, 447 p.

Michard A., Chopin C. & Henry C., 1993. Compression versus extension in the exhumation of the Dora-Maira coesite-bearing unit, Western Alps, Italy. Tectonophysics, 221, 173-193, 10.1016/0040-1951(93)90331-D

Michard A. & Goffé B., 2005. Recent advances in Alpine studies: tracking the Caledonian-Variscan belt in the internal western Alps. C.R. Geosciences, 337/8, 715-718.

Michard A., Goffé B., Chopin Ch. & Henry C., 1996, Did the Western Alps develop through an Oman-type stage? Eclogae Geol. Helv., 89, 43-80.

Miller Ch., 1970. Petrology of some eclogites and metagabbros of the Oetztal, Tyrol, Austria. Contrib. Mineral. Petrol., 28, 42-56, 10.1007/BF00389226

Miller C., 1974. On the metamorphism of the eclogites and high-grade blueschists from the Pennini terrane of the Tauern Window, Austria. Schweiz. mineral. petrogr. Mitt. 54, 371-384.

Miller Ch., 1977. Chemismus und phasenpetrologische Untersuchungen der Gesteine aus der Eklogitzone des Tauernfensters, Oesterr. Tschermaks Mineral. Petrogr. Mitt., 24, 221-277.

Miller Ch., 1986. Alpine high-pressure metamorphism in the Eastern Alps. Schweiz. mineral. petrogr. Mitt., 66, 139-144.

Miller Ch., Konzett J., Tiepolo R.A, Armstrong R.A. & Thöni M., 2007. Jadeite-gneiss from the Eclogite Zone, Tauern Window, Eastern Alps, Austria: Metamorphic, geochemical and zircon record of a sedimentary protolith. Lithos, 93, 68-88.

Miller Ch. & Thöni M., 1995. Origin of eclogites from the Austroalpine Oetztal basement (Tirol, Austria): geochemistry and Sm-Nd vs Rb-Sr isotope systematics. Chem. Geol. (Isotope Geosci. Sect.), 122, 199-225.

Miller Ch. & Thöni M., 1997. Eo-Alpine eclogitisation of Permian MORB-type gabbros in the Koralpe (Eastern Alps, Austria): new geochronological, geochemical and petrological data. Chem. Geol., 137, 283-310.

Milnes A.G. 1974. Structure of the Pennine zone (Central Alps): a new working hypothesis. Bull. Geol. Soc. Amer., 85, 1727-1732.

Milnes A.G., 1978. Structural zones and continental collision, Central Alps. Tectonophysics, 47, 369-392, 10.1016/0040-1951(78)90039-2

Milnes A.G., Greller M. & Müller R., 1981. Sequence and style of major post-nappe structures, Simplon-Pennine Alps. J. Structural Geol., 3, 411-420.

Monié P., 1985. La methode ^{39}Ar-^{40}Ar appliqée au métamorphisme alpin dans le massif du Mont Rose (Alpes occidentales). Chronologie détaillée depuis 100 Ma. Eclogae Geol. Helv., 78, 487-516.

Monié P. & Chopin C., 1991. ^{40}Ar-^{39}Ar dating in coesite-bearing and associated units of the Dora Maira massif, Western Aps. Eu. J. Miner., 3, 239-262.

Monié P. & Philippot P., 1989. Mise en evidence de l'age éocène du mètamorphisme de haute-pression dans la nappe ophiolitique du Monviso (Alpes Occidentales) par le méthode ^{40}Ar/^{39}Ar. CR Acad. Sci. Paris, 309, 245-251.

Monjoie Ph., Bussy F., Schaltegger U., Mulch A., Lapierre H. & Pfeifer H.R., 2007. Contrasting magma types and timing of intrusion in the Permian layered mafic complex of Mont Collon (Western Alps,Valais, Switzerland): evidence from U/Pb zircon and ^{40}Ar/^{39}Ar amphibole dating. Swiss Journal of Geosciences, 100, 125-135.

Montrasio A. & Sciesa E. (Eds), 1994. Proceedings of Symposium "CROP-Alpi Centrali". Quaderni Geodyn. Alpina e Quaternaria, 2, 296 p.

Morteani G., 1974. Petrology of the Tauern window, Austrian Alps. Fortschr. Min., 52, 195-220.

Morteani G. & Raase P., 1974. Metamorphic plagioclase crystallisation and zones of equal anorthite content in epidote-bearing, amphibolite-free rocks of the western Tauernfenster, Eastern Alps. Lithos, 7, 101-111, 10.1016/0024-4937(74)90023-1

Mottana A., 1972. Eclogite occurrences in gneiss as indicators of a Caledonian high-pressure metamorphism in the Western Alps. 24th Intern. Geol. Congress, section 2, 35-41.

Mottana A., 1986. Blueschist-facies metamorphism of manganiferous cherts: a review of the Alpine occurrences. Geol. Soc. Am. Mem., 164, 267-299.

Mugnier J.L., Cannic S. & Lapierre H., 2008. The tholeiites of the Valaisan domain (Versoyen, western Alps): a Carboniferous magma emplaced in a small oceanic basin. Bull. Soc. Géol. France, 179, 357-368.

Müller W.F. & Roberto Compagnoni, 2009. Eclogite from the ultrahigh-pressure metamorphic unit at Lago di Cignana, Western Alps: A process-oriented transmission electron microscope study. Lithos, 109, 323-332.

Münterer O. & Hermann J., 2001. The role of lower crust and continental upper mantle during formation of non-volcanic passive margins: evidence from the Alps. In Wilson R.C.L., Whitmarsh R.B., Taylor B. & Froitzheim N. (Eds): Non-volcanic rifting of continental margins: a comparison of evidence from land and sea. Geol. Soc. Sp. Publ. 187, 267-288.

Murchison R.I., 1849. On the geological structure of the Alps, Apennines and Carpathians. Quart. J. Geol. Soc. London, 5, 157-312.

Muttoni G., Kent D.V., Garzanti E., Brack P., Abrahamsen N. & Gaetani M., 2003. Early Permian Pangea 'B' to Late Permian Pangea 'A'. Earth Planet. Sci. Letters, 215, 379-394, 10.1016/S0012-821X(03)00452-7

Muttoni G., Gaetani M., Kent D. V., Sciunnach D., Angiolini A., Berra. F., Garzanti E., Mattei M. & Zanchi A., 2009. Opening of the Neo-Tethys Ocean and the Pangea B to Pangea A transformation during the Permian. GeoArabia, 4, 17-48.

Nervo R. & Polino R., 1976. Un lembo di cristallino Dent Blanche alla Torre Ponton (Valle d'Aosta). Boll. Soc. Geol. It., 95, 647-657.

Neubauer F. (Ed), 1992. The Eastern Central Alps of Austria. ALCAPA-Field Guide, IGP/KFU Graz, 245 pp.

Neubauer F., 2002. Evolution of late Neoproterozoic to early Palaeozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. Tectonophysics, 352, 87-103, 10.1016/S0040-1951(02)00190-7

Neubauer F., Fritz H., Genser J., Kurz W., Nemes F., Wallbrecher E., Wang X. & Willingshofer E., 2000. Structural evolution within an extruding block: model and application to the Alpine-Pannonian system. In F.K. Lehner, J.L. Urai (Eds): Aspects of tectonic faulting. Springer-Verlag, 141-153.

Neubauer F., Genser J. & Handler R., 2000. The Eastern Alps: result of a two-stage collision process. Mitt. Oesterr. Geol. Ges., 92 (1999), 117-134.

Neubauer F. & Höck V. (Eds), 2000. Aspects of Geology in Austria. Mitt. Oesterr. Geol. Ges., 92 (1999), 335 p.

Neubauer F., Hoinkes G., Sassi F.P., Handler R., Höch V., Koller F. & Frank W., 1999. Pre-Alpine metamorphism in the Eastern Alps. Schweiz. mineral. petrogr. Mitt., 79, 41-62.

Nicolas A., Bouchez J.-L. & Boudier F., 1972. Kinematic interpretation of plastic deformations in the lherzolite Massif of Lanzo (Piedmont Alps); comparison with other massifs. Tectonophysics 14, 143-171.

Nicolas A., Hirn A., Nicolich R., Polino R. and the ECORS-CROP Working Group, 1990. Lithospheric wedging in the western Alps inferred from the ECORS-CROP traverse. Geology, 18, 587-590, 10.1130/0091-7613(1990)018<0587:LWITWA>2.3.CO;2

Niggli E., 1970. Alpine metamorphose und alpine Gebirgsbildung. Fortsch. Miner., 47, 16-26.

Niggli E. & Coworkers, 1978. Metamorphic map of the Alps 1:1.000.000 and explanatory text. Subcomm. Carthography of metamorphic belts of the World, Unesco, Leiden, pp. 181-242.

Nisio P., Lardeaux J.M. & Boudeulle M., 1987. Evolution tectonométamorphique contrastées des éclogites dans le massif du Viso; conséquences de la fragmentation de la croûte océanique lors de l'orogenèse alpine. C.R. Acad. Sci. Paris, 304, 355-360.

Novarese V., 1895. Nomenclatura e sistematica delle rocce verdi nelle Alpi occidentali. Boll. R. Comit. Geol. It., 26, 164-181.

Novarese V., 1931. La formazione dioritico-kinzigitica in Italia. Boll. R. Uff. Geol. It., 56/7, 1-62.

Novarese V., 1943. Il sistema eruttivo Traversella-Biella. Mem. Descr. Carta Geol. d'It., 28, 90 pp. Oberhänsli R., Bousquet R., Engi M., Goffé B., Gosso G., Handy M., Höck V., Koller F., Lardeaux J.-M., Polino R., Rossi P., Schuster R., Schwartz S. & Spalla M. I., 2004. Metamorphic structure of the Alps 1:1.000.000 and explanatory note. Commission for the Geological Map of the World, Paris. Mitt. Oesterr. Miner. Ges., 149.

Oberhänsli R., Hunziker J.C., Martinotti G. & Stern W., 1985. Geochemistry, geochronology and petrology of Monte Mucrone: an example of Eoalpine eclogitizatio of Permian granitoids in the Sesia-Lanzo zone, western Alps, Italy. Chem. Geol., 52, 165-184.

Oberhauser R., 1995. Zur Kenntnis der Tektonik und Paläogeographie des Ostalpenraumes zur Kreide Paläozän- und Eozänzeit. Jb. Geol. B-A., 138, 369-432.

Oberhauser R. et al., 1980. Der geologische Aufbau Oesterreichs. Springer-Verlag, Wien, 695 p.

Ogniben L., Parotto M. & Praturlon A. (Eds) 1975. Structural Model of Italy: 1.000.000, maps and explanatory notes. Quaderni La Ricerca Sci., 90, 496 p.

Oxburgh E.R., 1972. Flake tectonics and continental collision. Nature, 239, 202-204 10.1038/239202a0

Oxburgh E.R. & Turcotte D.L. 1970. Thermal structure of island arcs. Geol. Soc. Am. Bull., 81, 1665-1688, 10.1130/0016-7606(1970)81[1665:TSOIA]2.0.CO;2

Owen J.P., 2007. Geochemistry of lamprophyres from the Western Alps, Italy: implications for the origin of an enriched isotopic component in the Italian mantle. Contrib. Mineral. Petrol., 155, 341-362, 10.1007/s00410-007-0246-0

Paganelli E., Compagnoni R., Nervo R. & Tallone S., 1995. Il lembo Austroalpino di Eaux Rousses e le sue relazioni con la Zona Ofiolitica Piemontese nell'alta Valle di Cogne, Valle d'Aosta meridionale. In Polino R. & Sacchi R. (Eds): Atti convegno Alpi-Appennino, Peveragno 1994. Scritti e Doc. Acc.Naz.Sci dei XL, 14, 335-354.

Pahr A., 1980. Die Fenster von Rechnitz, Bernstein und Möltern. In Oberhauser R. (Ed): Der Aufbau Oesterreichs. Springer Verlag Wien-New York, 320-326.

Panseri M., Fontana E. & Tartarotti P., 2008. Evolution of rodingitic dykes: metasomatism and metamorphism in the Mount Avic serpentinites (Alpine ophiolites, southern Aosta valley). Ofioliti, 33, 165-185.

Panza G., Calcagnile G., Scandone P. & Mueller S., 1980. La struttura profonda dell'area mediterranea. Le Scienze, 141, 276-285.

Paquette J.L., Chopin Ch. & Peucat J.J., 1989. U-Pb zircon, Rb-Sm and Sm-Nd geochronology of high- to very-high pressure meta-acidic rocks from the western Alps. Contrib. Mineral. Petrol., 101, 280-289, 10.1007/BF00375313

Papazzoni C.A. & Trevisani, E., 2006. Facies analysis, palaeoenvironmental reconstruction, and biostratigraphy of the "Pesciara di Bolca" (Verona, northern Italy): an early Eocene Fossil Lagerstätte. Palaeogeography, Palaeoclimatology, Palaeoecology, 242, 21-35.

Pasquarè G., 1975. Geological summary of the Central Alps. Quaderni La Ricerca Sci., CNR, Roma, 90, 121-148.

Passchier C.W., Urai J.L. van Loon J. & Williams P.J., 1981. Structural geology of the central Sesia-Lanzo Zone. Geol. en Mijnbow, 60, 497-507.

Patacca E., Scandone P., Fantozzi P.L., Carmignani L., Castagnini G. & Pirro A., 2004. The Structural Model of Italy: from paper maps to geodatabase. DVD Regione Toscana.

Patriat P., Segoufin J., Schlich R., Goslin J., Auzende J.M., Bonnin J. & Olivet J.L. (1982). Le mouvements relatifs de l'Inde, de l'Afrique et de l'Eurasie. Bull. Soc. géol. France, 24, 363-373.

Pawlig S. & Baumgartner L.P., 2001. Geochemistry of a talc-kyanitechloritoid shear zone within the Monte Rosa granite, Val d'Ayas, Italy. Schweiz. mineral. petrogr. Mitt., 81, 329-346.

Pavlis T.L. & Bruhn R.L., 1983. Deep seated flow as a mechanism for the uplift of broad forearc ridges and its role in the exposure of high P/T metamorphic terranes. Tectonics, 2, 473-497, 10.1029/TC002i005p00473

Pelletier L. & Müntener O., 2006. High pressure metamorphism of the Lanzo peridotite and its oceanic cover, and some consequences for the Sesia-Lanzo zone (northwestern Italian Alps). Lithos, 90, 111-130.

Pennacchioni G., 1996. Progressive eclogitization under fluid-present conditions of pre-Alpine mafic granulites in the Austroalpine Mt. Emilius Klippe (Italian Western Alps). J. Structural Geol., 18, 549-561, 10.1016/S0191-8141(96)80023-X

Pennacchioni G., Di Toro G. & Mancktelow N.S., 2001. Strain-insensitive orientation of porphyroclasts in Mont Mary mylonites. J. Structural Geol., 23, 1281-1298, 10.1016/S0191-8141(00)00189-9

Pennacchioni G., Di Toro G., Brack P., Menegon L. & Villa I.M., 2006. Brittle-ductile-brittle deformation during cooling of tonalite (Adamello, Southern Italian Alps). Tectonophysics, 427, 171-197, 10.1016/j.tecto.2006.05.019

Pennacchioni G. & Guermani A., 1993. The mylonites of the Austroalpine Dent Blanche nappe along the northwestern side of the Valpelline valley (Italian Western Alps). Mem. Sci. Geol., Padova 45, 37-55.

Peressini G., Quick J.E., Sinigoi S., Hofmann A.W. & Fanning M., 2007. Duration of a large mafic intrusion and heat transfer in the lower crust: a SHRIMP U-Pb zircon study in the Ivrea-Verbano Zone (Western Alps, Italy). Journal Petrology, 48, 1185-1218, 10.1093/petrology/egm014

Péron-Pinvidic G., Manatschal G., Minshull T.A. & Dean, S., 2007. Tectonosedimentary evolution of the deep Iberia-Newfoundland margins: evidence for a complex breakup history. Tectonics, 26. 10.1029/2006TC001970.

Pettke T., Kramers J.D. & Villa I., 1999. Isotope systematics in vein gold from Brusson, Val d'Ays (NW Italy): (U+Th)/He and K/Ar in native Au and its fluid inclusions. Chem. Geol., 135, 173-187, 10.1016/S0009-2541(96)00114-3

Pfeifer H.R., Colombi A. & Ganguin J., 1989. Zermatt-Saas and Antrona Zone: a petrographic and geochemical comparison of poliphase metamorphic ophiolites of the West-Central Alps. Schweiz. mineral. petrogr. Mitt., 69, 217-236.

Pfeifer H.R., Colombi A., Ganguin J., Hunziker J.C., Oberhänsli R. & Santini L., 1991 - Relics of high-pressure metamorphism in different lithologies of the Central Alps, an updated inventory. Schweiz. mineral. petrogr. Mitt., 71, 441-451.

Pfiffner O.A., 1992. Alpine orogeny. In Blundell D., Freeman R. & Mueller S. (Eds): A continent revealed. The European Geotraverse. Cambridge Univ. Press, pp. 180-190.

Pfiffner O.A., Lehner P., Heitzmann P., Mueller St. & Steck A. (Eds), 1997. Deep structure of the Swiss Alps. Birkhäuser Verlag, Basel, 380 p.

Philippot P., 1988. Déformation et éclogitisation progressives d'une croûte océanique subductée; l'exemple du Monviso, Alpes occidentales. Contraintes cinématiques durant la collision alpine. Travaux Centre Géol. Géophys. Montpellier, 270 p.

Philippot P., 1990. Opposite vergence of nappes and crustal extension in the French-Italian Western Alps. Tectonics, 9, 1143-1164, 10.1029/TC009i005p01143

Philippot P. & Kienast J.R., 1989. Chemical-microstructural changes in eclogite-facies shear zones (Monviso, Western Alps, north Italy) as indicators of strain history and mechanism and scale of mass transfer. Lithos, 23, 179-200, 10.1016/0024-4937(89)90004-2

Pieri M. & Groppi G., 1981. Subsurface geological structures of the Po Plain, Italy. CNR, Prog. Fin. Geodin., n. 414, 13 p.

Pin C., 1986. Datation U-Pb sur zircons à 285 Ma du complexe gabbro-dioritique du Val Sesia-Val Mastallone étage tardi-hercynien du métamorphism granulitique de la zone Ivrea-Verbano (Italie). C.R. Acad. Sci. Paris, 303, 827-830.

Platt J.P., 1984. Balanced cross-section and their implications for the deep structure of the northwest Alps: discussion. J. Struct. Geol., 6, 603-606, 10.1016/0191-8141(84)90072-5

Platt J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geol. Soc. Am. Bull., 97, 1037-1053, 10.1130/0016-7606(1986)97<1037:DOOWAT>2.0.CO;2

Platt J.P., Behrmann J.H., Cunningham P.C., Dewey J.F., Helman M., Parish M., Shepley M.G., Wallis S. & Weston P.J. 1989. Kinematics of the Alpine arc and the motion history of Adria. Nature, 337, 158-161, 10.1038/337158a0

Platt J. P. & Lister G.S., 1985. Structural history of high-pressure metamorphic rocks in the southern Vanoise massif, French Alps, and their relation to Alpine tectonic events. J. Structural Geol., 7, 19-35, 10.1016/0191-8141(85)90112-9

Pleuger J., Froitzheim N. & Jansen E., 2005. Folded continental and oceanic nappes on the southern side of Monte Rosa (western Alps, Italy): anatomy of a double collision suture. Tectonics, 24:TC4013. DOI 10.1029/2004TC001737 10.1029/2004TC001737

Pleuger J., Roller S.,Walter J.M., Jansen E. & Froitzheim, N., 2007. Structural evolution of the contact between two Penninic nappes (Zermatt-Saas zone and Combin zone, Western Alps) and implications for the exhumation mechanism and paleogeography. Intern. J. Earth Sci., 96, 229-252.

Plöchinger B., 1995. Tectonics of the Northern Calcareous Alps: a review. Mem. Sci. Geol., Padova 47, 73-86.

Pognante U., 1989. Tectonic implications of lawsonite formation in the Sesia zone (Western Alps). Tectonophysics, 162, 219-227, 10.1016/0040-1951(89)90245-X

Pognante U., Compagnoni R. & Gosso G. (1980). Micro-mesostructural relationschips in the continental eclogitic rocks of the Sesia-Lanzo Zone (Italian Western Alps). Rend. Soc. It. Min. Petr., 36, 169-186.

Poli S. & Schmidt M.W., 1995. H_2O transport and release in subduction zones: experimental constraints on basaltic and andesitic systems. Journal of Geophysical Research, 100 (B11), 22299-22314.

Polino R., Dal Piaz G.V. & Gosso G., 1990. Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps. Mém. Soc. Géol. France, 156, 345-36.

Polino R. & Lemoine M., 1984. Détritisme mixte d'origine continentale et océanique dans les sédiments jurassico-crétacées supra-ophiolitiques de la Téthys ligure: la série du Lago Nero (Alpes Occidentales franco-italiennes). C.R. Acad. Sci. Paris, 298, 359-364.

Purtscheller F. & Sassi F.P., 1975. Some thoughts on the pre-Alpine metamorphic history of the Austridic basement of the Eastern Alps. Tschermaks Mineral. Petrogr. Mitt., 22, 175- 199.

Quadt A.H. von, Günther G., Frischknecht R., Zimmermannn R. & Franz G., 1997. The evolution of pre-Variscan eclogites of the Tauern window (eastern Alps): A Sm/Nd-, conventional and Laser ICP-MS zircon U-Pb study. Schweiz. mineral. petrogr. Mitt., 77, 265-280.

Quick J., Sinigoi S. & Mayer, A., 1994. Emplacement dynamics of a large mafic intrusion in the lower crust, Ivrea-Verbano zone, N. Italy. J. Geophys. Res., 99, 21559-21573, 10.1029/94JB00113

Quick J., Sinigoi S. & Mayer A. 1995. Emplacement of mantle peridotite in the lower continental crust, Ivrea-Verbano zone, N. Italy. Geology, 23, 739-742, 10.1130/0091-7613(1995)023<0739:EOMPIT>2.3.CO;2

Quick J. E., Sinigoi S., Snoke A.W., Kalakay T.J., Mayer A. & Peressini G., 2003. Geologic map of the southern Ivrea-Verbano zone, Northwestern Italy. Geologic Investigations Series Map I-2776, U.S. Geological Survey, U.S. Government Printing Office.

Quick J.E., Sinigoi S., Peressini G., Demarchi G., Wooden J.L. & Sbisa A., 2009. Magmatic plumbing of a large Permian caldera exposed to a depth of 25km. Geology, 37, 603-606, 10.1130/G30003A.1

Radelli & Desmons J., 1987. Pennique, Téthys et orogenèse crétacé moyen dans les Alpes. C.R. Acad. Sci. Paris, 305, 1375-1378.

Ramsay J.G., 1967. Folding and fracturing of rocks. McGraw-Hill, New York, 568 p.

Ramsay J.G., 1981. Tectonics of the Helvetic nappes. Geol. Soc. London Spec. Publ., 9, 357-391, 10.1144/GSL.SP.1981.009.01.26

Ramsay J.G., 1989. Fold and fault geometry in the western Helvetic nappes of Switzerland and France and its implication for the evolution of the arc of the western Alps. Geol. Soc. London Spec. Publ., 45/1, 33-45, 10.1144/GSL.SP.1989.045.01.02

Ramsay J.G. & Allison I., 1979. Structural analysis of shear zones in an alpinised Hercynian granite. Schweiz. mineral. petrogr. Mitt., 59, 251-279.

Ramsay J.C., Casey M. & Kligfield R., 1983. Role of shearing development of the Helvetic fold-thrust belt of Switzerland. Geology, 11, 439-442, 10.1130/0091-7613(1983)11<439:ROSIDO>2.0.CO;2

Ramsbotham W., Inger S., Cliff B., Rex D. & Barnicoat A., 1994. Time constraints on the metamorphic and structural evolution of the southern Sesia-Lanzo zone, Western Italian Alps. Mineral. Mag., 58A, 758-759.

Ranalli G. (Ed), 1995. Plate Tectonics: the first twenty-five years. Proceedings of the VIII Summer School of Earth and Planetary Sciences, Università di Siena, 419 p.

Ratschbacher L., Dingeldey C., Miller C., Hacker B.R. &, Mc Williams M.O., 2004. Formation, subduction, and exhumation of Penninic oceanic crust in the Eastern Alps: time constraints from $^{40}Ar/^{39}Ar$ geochronology. Tectonophysics, 394, 155- 170.

Ratschbacher L., Frisch W., Linzer H.G. & Merle O., 1991. Lateral extrusion in the Eastern Alps, 2: structural analysis. Tectonics, 10, 257-271, 10.1029/90TC02623

Ratschbacher L., Frisch W., Neubauer F;, Schmid S.M. & Neugebauer J., 1989. Extension in compressional orogenic belts: the Eastern Alps. Geology, 17, 404-407.

Ratschbacher L., Merle O., Davy P.H. & Cobbold P., 1991. Lateral extrusion in the Eastern Alps. Part 1: boundary conditions and experiments scaled for gravity. Tectonics, 10, 245-256, 10.1029/90TC02622

Rebay G. & Messiga B., 2007. Prograde metamorphic evolution and development of chloritoid-bearing eclogitic assemblages in subcontinental metagabbro (Sesia-Lanzo zone, Italy). Lithos, 98, 275-291, 10.1016/j.lithos.2007.04.002

Rebay G. & Spalla M.I., 2001. Emplacement at granulite facies conditions of the Sesia-Lanzo metagabbros: an early record of Permian rifting? Lithos, 58, 85-104, 10.1016/S0024-4937(01)00046-9

Reddy S.M., Cliff R.A. & East R., 1993. Thermal history of the Sonnblick dome, south-east Tauern window, Austria: implicarions for heterogeneous uplift within the Pennine basement. Geol. Rundschau, 82, 667-675, 10.1007/BF00191494

Reddy S.M., Kelley S.P., Wheeler J., 1996. A ^{40}Ar/^{39}Ar laser probe study of micas from the Sesia Zone: Implications for metamorphic deformation histories. J. metam. Geol., 14, 493-50.

Reddy S.M., Wheeler J. & Cliff R.A., 1999. The geometry and timing of orogenic extension:an example from the Western Italian Alps. J. metam. Geol. 17, 573-589

Reddy S.M., Wheeler J., Butler R.W.H., Cliff R.A., Freeman S., Inger S., Pickles C. & Kelley S.P., 2003. Kinematic reworking and exhumation within the convergent Alpine Orogen. Tectonophysics, 365, 77-102, 10.1016/S0040-1951(03)00017-9

Regis D., Manzotti P., Boston K., Cenki-Tok B., Robyr M, Rubatto D., Thomsen T. & Engi M., 2009. Complexities in the high pressure metamorphic history of the central Sesia Zone near Cima di Bonze (NW Italy). Alpine Workshop Cogne 2009, abstr.

Reinecke T., 1991. Very-high-pressure metamorphism and uplift of coesite-bearing metasediments from the Zermatt-Saas zone, Western Alps. Eur. J. Min., 3, 7-17.

Reinecke T., 1998. Prograde high- to ultrahigh-pressure metamorphism and exhumation of oceanic sedimenrs at Lago di Cignana, Zermatt-Saas Zone, western Alps. Lithos, 42, 147-189, 10.1016/S0024-4937(97)00041-8

Reitz E. & Höll R., 1988. Jungproterozoische Mikrofossilien aus der Habachformation in den mittleren Hohen Tauern und im nordostbayirischen Grundgebirge. Jb. Geol. B-A., 131, 329-340.

Ridley J.R., 1989. Structural and metamorphic history of a segment of the Sesia-Lanzo Zone, and its bearing on the kinematics of Alpine deformation in the Western Alps. In Coward M.P. et al. (Eds): Alpine Tectonics. Geol. Soc. London Spec. Publ., 45, 189-201.

Ring U., 1992. The geodynamic evolution of Penninic nappes in the eastern Central Alps: geothermobarometric and kinematic data. J. metam. Geol., 10, 33-53, 10.1111/j.1525-1314.1992.tb00070.x

Ring U., Ratschbacher L. & Frisch W., 1988. Plate-boundary kinematics in the Alps: motion in the Arosa suture zone. Geology, 16, 696-698, 10.1130/0091-7613(1988)016<0696:PBKITA>2.3.CO;2

Ring U., Ratschbacher L., Frisch W., Biehler D. & Kralik M., 1989. Kinematics of the Alpine plate-margin: structural styles, strain and motion along the Penninic-Austroalpine boundary in the Swiss-Austrian Alps. J. Geol. Soc. London, 146, 835-849, 10.1144/gsjgs.146.5.0835

Ring U., Ratschbacher L., Frisch W., Durr F. & Borchert S., 1990. The internal structure of the Arosa zone. Geol. Rundschau, 79, 725-739, 10.1007/BF01879211

Ring U., Collins A.S. & Kassem O.K., 2005. U-Pb SHRIMP data on the crystallization age of the Gran Paradiso augengneiss, Italian Western Alps: Furter evidence for Permian magmatic activity in the Alps during break-up of Pangea. Eclogae Geol. Helv., 98, 363-370, 10.1007/s00015-005-1170-9

Ring U., Ratschbacher L. & Frisch W., 1988. Die Kinematik der Arosa Zone und Implikationen für die Entwicklung der Ostalpen. Erlanger geol. Abh., 116, 101-106.

Rivalenti G., Garuti G., Rossi A., Siena F. & Sinigoi S., 1981. Existence of different peridotite types and of a layered igneous complex in the Ivrea zone of the western Alps. Journal Petrology, 22, 127-153.

Rivalenti G., Rossi A., Siena F. & Sinigoi S., 1984. The layered series of the Ivrea-Verbano igneous complex, Western Alps. TMPM, 33, 77-99.

Roeder D., 1976. Die Alpen aus plattentektonischer Sicht. Z. dt. geol. Ges., 127, 87-103.

Roeder D. & Bögel H. 1978. Geodynamic interpretation of the Alps. Inter-Union Comm. Geodyn. Sci. Repts, 38, 191-212.

Rolfo F., Compagnoni R. & Tosoni D., 2004. Geology and petrology of the Austroalpine Châtillon Slice, Aosta Valley, Western Alps. Geodinamica Acta, 17, 91-105, 10.3166/ga.17.91-105

Rosenbaum G. & Lister G.S., 2005. The Western Alps from the Jurassic to Oligocene: spatio-temporal constraints and evolutionary reconstructions. Earth Sci. Rev., 69, 281-306.

Rosenbaum G., Lister G.S. & Duboz C., 2002. Relative motions of Africa, Iberia and Europe during Alpine orogeny. Tectonophysics, 359, 117-129.

Rosenberg C.L., 2004. Shear zones and magma ascent: A model based on a review of the Tertiary magmatism in the Alps. Tectonics, 23, TC3002, doi10.1029/2003TC001526, 10.1029/2003TC001526

Rosenberg C.L., Berger A., Davidson C. & Schmid S. M., 1994. Emplacement of the Bergell pluton, Central Alps. Atti Ticinensi Sci. Terra, serie spec., 1, 31-39.

Rottura A., Bargossi G.M., Caggianelli A., Del Moro A., Visonà D. & Tranne C.A., 1998. Origin and significance of the Permian high-K calc-alkaline magmatism in the central-eastern Southern Alps, Italy. Lithos, 45, 329-348, 10.1016/S0024-4937(98)00038-3

Roure F., Heitzmann P. & Polino R. (Eds), 1990. Deep structure of the Alps: Mém. Soc. géol. France, 156, 367 pp.

Roure F., Polino R. & Nicolich R., 1990. Early Neogene beneath the Po plain: constraints on the post-collisional Alpine evolution. Mém. Soc. géol. France, 156, 309-322.

Rubatto D., Gebauer D. & Compagnoni R., 1999. Dating of eclogite-facies zircons: the age of Alpine metamorphism in the Sesia-Lanzo Zone (Western Alps). Earth Planet. Sci. Lett., 167, 141-158, 10.1016/S0012-821X(99)00031-X

Rubatto D., Gebauer D. & Fanning M., 1998. Jurassic formation and Eocene subduction of the Zermatt-Saas Fee ophiolites: implications for the geodynamic evolution of the central and western Alps. Contrib. Mineral. Petrol., 132, 269-287, 10.1007/s004100050421

Rubatto D. & Hermann J., 2001. Exhumation as fast as subduction? Geology 29, 3-6.

Rubatto D.& Hermann J., 2003. Zircon formation during fluid circulation in eclogites (Monviso, Western Alps): implications for Zr and Hf budget in subduction zones. Geochim. Cosmochim. Acta, 67, 2173-2187.

Rubatto D., Müntener O., Barnhoorn A. & Gregory C., 2008. Dissolution-reprecipitation of zircon at low-temperature, high-pressure conditions (Lanzo Massif, Italy). Amer. Mineral., 93, 1519-1529.

Rubatto D.& Scambelluri M., 2003. U-Pb dating of magmatic zircon and metamorphic baddeleyite in the Ligurian eclogites (Voltri Massif,Western Alps). Contrib. Mineral. Petrol., 146, 341-355.

Rubie D.C., 1984. A thermal-tectonic model for high pressure metamorphism and deformation in the Sesia-Lanzo, Western Alps. J. Geol. Soc. London, 92, 21-36.

Rubie D.C., 1990. Role of the kinetics in the formation and preservations of eclogites. In Carswell D.A. (Ed): Eclogite facies rocks, Blackie, London, 111-141.

Ruffet G., Gruau G, Ballèvre M, Feraud G. & Philippot P., 1997. Rb-Sr and ^{40}Ar/^{39}Ar laser probe dating of high-pressure phengites from the Sesia zone (Western Alps): underescoring of excess argon and new age constraints on the high-pressure metamorphism. Chem. Geol., 141, 1-18.

Ruffini R., Polino R., Cosca M., Hunziker J.C. & Masson H., 1995. The Tertiary Alpine volcanism: data and hypotheses from the Taveyanne formation (Savoie, France). Atti Convegno Soc. Geol. It.: Rapporti Alpi Appennino, Peveragno 1994, Acc. Naz. Scienze dei XL, 359-376.

Ruffini R., Polino R., Callegari E., Hunziker J.C. & Pfeifer H.-R., 1997. Volcanic clast-rich turbidites of the Taveyanne sandstones from the Thônes syncline (Savoie, France): records for a Tertiary postcollisional volcanism. Schweiz. mineral. petrogr. Mitt., 77, 161-174.

Rutter E. H., Brodie K. H. & Evans, P., 1993. Structural geometry, lower crustal magmatic underplating and lithospheric stretching in the Ivrea-Verbano zone, N. Italy. J. Structural Geol., 15, 647-662, 10.1016/0191-8141(93)90153-2

Rutter E.H., Brodie K.H., James T. & Burlini, L., 2007. Large scale folding in the upper part of the Ivrea-Verbano zone. J. Structural Geol., 29, 1-17, 10.1016/j.jsg.2006.08.013

Rutter E. H., Khazanehdari J., Brodie K. H., Blundell D. & Waltham D., 1999. Synthetic seismic reflection profile through the Ivrea-Verbano zone - Serie dei Laghi continental crustal section, northwestern Italy. Geology, 27, 79-82, 10.1130/0091-7613(1999)027<0079:SSRPTT>2.3.CO;2

Rutter E.H. et al., 2009. The Ivrea-Verbano zone - Valle d'Ossola Excursion. September 18, 2009, Guidebook.

Sacchi R., 1991. Riflessioni sul cristallino dell'Argentera a venticinque anni dalla carta geologica di R. Malaroda. Boll. Museo Regionale Sci. Nat. Torino, 9, suppl.1, 45-56.

Sander B., 1911. Geologische Studien am Westende der Hohen Tauern (Erster Bericht). Denkschr. Akad Wiss. Wien, 82, 257-320.

Sander B., 1929. Erläuterungen zur geologischen Karte des Brixner und Meraner Gebietes. Der Schlern, Innsbruck, 16, 1-111.

Sartori M., 1987. Structure de la zone du Combin entre les Diablond et Zermatt (Valais). Eclogae Geol. Helv., 80, 789-814.

Sartori M., 1990. L'unité du Barrhorn (Zone pennique, Valais, Suisse). Mém. Géol. Lausanne, 6, 156 p.

Sartori M., Gouffon Y. & Marthaler M., 2006. Harmonisation et définition des unités lithostratigraphiques briançonnaises dans les nappes penniques du Valais. Eclogae Geol. Helv., 99, 363-407, 10.1007/s00015-006-1200-2

Sassi F.P., Borsi S., Del Moro A., Zanferrari A. & Zirpoli G., 1978. Contribution to geodynamic interpretations in the Eastern Alps. In H. Closs, D. Roeder and K. Schmidt (Eds): Alps Apennines Hellenides. Inter-Union Comm. Geodynamics, Sci. Report, 38, 154-160.

Sassi F.P., Cavazzini G. & Visonà D., 1985. Radiometric geochronology in the Eastern Alps: results and problems. Rend. Soc. It. Mineral. Petr., 40, 187-224.

Sassi R., Dieni I. & Sassi F.P., 2008. Geo-petrographic data on the metamorphic rocks with Cambrian, Silurian and Devonian fossils in the Agordo Area (Southalpine metamorphic basement of the Eastern Alps, Italy). Bull. Tethys Geol. Soc., Cairo, 3, 19-28.

Sassi F.P. & Menegazzo L., 1971. Contributo alla conoscenza della Falda di Steinach (Brennero). Mem. Ist. Geol. Min. Univ. Padova, 29, 1-27.

Sassi F.P. & Spiess R., 1993. The South-Alpine metamorphic basement in the Eastern Alps. In J.F. von Raumer J.F. & Neubauer F. (Eds): Pre-Mesozoic geology in the Alps. Springer-Verlag, Berlin, 599-607.

Sassi F.P. & Zanferrari A., 1972. Il significato geologico del Complesso del Turntaler (Pusteria) con particolare riguardo alla successione di eventi prealpini nel basamento austridico delle Alpi orientali. Boll. Soc. Geol. It., 91, 533-557.

Sassi F.P., Zanferrari A., Zirpoli G., Borsi S. & Del Moro A., 1974. The Austrides to the south of the Tauern window and the Periadriatic lineament between Mules and Mauthen. N. Jb. Geol. Pal. Mh., 7, 421-435.

Sassi F.P. & Zirpoli G., 1989. The lithostratigraphic sequences in the South-Alpine basement of the Eastern Alps. Rend. Soc. Geol. It., 12, 397-402.

Sassi R., Mazzoli C., Miller C. &, Konzett J., 2004. Geochemistry and metamorphic evolution of the Pohorje Mountain eclogites from the easternmost Austroalpine basement of the Eastern Alps (Northern Slovenia). Lithos, 78, 235-261, 10.1016/j.lithos.2004.05.002

Savostin L.A., Sibuet J.C., Zonenshain L.P., Le Pichon X. & Roulet M.J. (1986). Kinematic evolution of the Tethys belt from the Atlantic to the Pamirs since the Triassic. Tectonophysics, 123, 1-35, 10.1016/0040-1951(86)90192-7

Scambelluri M., Pennacchioni G. & Philippot P., 1998. Salt-rich aqueous fluids formed during eclogitization of metabasites in the Alpine continental crust (Austroalpine Mt. Emilius unit, Italian western Alps). Lithos, 43, 151-167, 10.1016/S0024-4937(98)00011-5

Scarascia S. & Cassinis R., 1997. Crustal structures in the central-eastern Alpine sector; a revision of the available DSS data. Tectonophysics, 271, 157-188, 10.1016/S0040-1951(96)00206-5

Schaltegger U. & Brack P., 2007. Crustal-scale magmatic systems during intracontinental strike-slip tectonics: U, Pb and Hf isotopic constraints from Permian magmatic rocks of the Southern Alps. Int. J. Earth Sci., 96, 1131-1151.

Schaltegger U., Desmurs L., Manatschal G., Müntener O., Meier M., Frank M. & Bernoulli D., 2002. The transition from rifting to sea-floor spreading within a magma-poor rifted margin: field and isotopic constraints. Terra Nova, 14, 156-162.

Schärer U., Cannic S. & Lapierre H., 2000. Preliminary evidence for a Hercynian age of the Versoyen Unit, Western Alps. C.R. Acad. Sci. Paris, 330, 325-332.

Scheuring B, Ahrendt H., Hunziker J.C. & Zingg A., 1974. Paleobotanical and geochronological evidence for the Alpine age of metamorphism in the Sesia-Zone. Geol. Rundschau, 63, 305-326, 10.1007/BF01820989

Schmid S.M., Aebli H.R., Heller F. & Zingg A., 1989. The role of the Periadriatic line in the tectonic evolution of the Alps. Geol. Soc. London Spec. Publ. 45, 153-171, 10.1144/GSL.SP.1989.045.01.08

Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K., 2008. The Alpine-Carpathian-Dinaridic orogenic system: correlation of tectonic units. Swiss Journal of Geosciences, 101, 139-183.

Schmid S.M., Froitzheim, Pfiffner A., Schönborn & Schreurs G., 1994. Geodynamic evolution of the Alps along the European geotraverse: from rifting to collision. Göttinger Arb. Geol. Pal., Sb 1, 5. Symp. TSK, pp. 112-114.

Schmid S.M., Fügenschuh B., Kissling E. & Schuster R., 2004. Tectonic map and overall architecture of the Alpine orogen. Eclogae Geol. Helv., 97, 93-117.

Schmid S.M., Fügenschuh B., Kissling E. & Schuster R., 2004. TRANSMED Transects IV, V and VI: Three lithospheric transects across the Alps and their forelands. In Cavazza W. et al. (Eds): The TRANSMED Atlas: the Mediterranean Region from Crust to Mantle. Springer Verlag.

Schmid S.M., Fügenschuh B., Kissling E. & Schuster R., 2005. Reply to comment by W. Kurz on "Tectonic map and overall architecture of the Alpine orogen", Ecloae Geol. Helv., 98, 99-101.

Schmid S.M. & Kissling E., 2000. The arc of the western Alps in the light of geophysical data on deep crustal structure. Tectonics 19, 62-85.

Schmid S.M., Pfiffner O.A., Froitzheim N., Schönborn G. & Kissling E., 1996. Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps. Tectonics, 15, 1036-1064.

Schmid S.M., Pfiffner O.A. & Schreurs G., 1997. Rifting and collision in the Penninic zone of eastern Switzerland. In O.A. Pfiffner et al. (Eds.): Results of NFP 20. Birkhäuser, Basel, pp. 160-185.

Schmid S.M., Rück P. & Schreurs G., 1990. The significance of the Schams nappes for the reconstruction of the paleotectonic and orogenic evolution of the Penninic zone along the NFP-20 East traverse (Grisons, eastern Switzerland). Mém. Soc. géol. France, 156, 263-287.

Schmid S.M., Zingg A. & Handy M., 1987. The kinematics of movements along the Insubric line and the emplacement of the Ivrea zone. Tectonophysics, 135, 47-66, 10.1016/0040-1951(87)90151-X

Schmid R., 1967. Zur petrographie und strukur der zone Ivrea-Verbano zwischen Valle d'Ossola und Valle Grande, Schweiz. mineral. petrogr. Mitt., 47, 935-1117.

Schmid R. & Wood B. J., 1976. Phase relationships in granulite metapelites from the Ivrea-Verbano zone (N.Italy). Contrib. Mineral. Petrol., 54, 255-279, 10.1007/BF00389407

Schnetger B., 1994. Partial melting during the evolution of the amphibilite to granulite facies gneisses of the Ivrea zone, northern Italy. Chemical Geol., 113, 71-101, 10.1016/0009-2541(94)90006-X

Schönborn G., 1992. Alpine tectonics and kinematic models of the central Southern Alps. Mem. Sci. Geol., Padova, 44, 229-393.

Schreurs G., 1993. Structural analysis of the Schams nappes and adjacent tectonic units: implications for the orogenic evolution of the Penninic zone in eastern Switzerland. Bull. Soc. géol. France, 164, 415-435.

Schuster R., 2003. Das eo-Alpidische Ereignis in den Ostalpen: Plattentektonische Situation und interne Struktur des Ostalpinen Kristallins. Arbeitstagung Geol. B.-A., Blatt 148 Brenner, Geol. B.-A., Wien, 141-159.

Schuster R., Koller F., Höck V., Hoinkes G. & Bousquet R., 2004. Explanatory notes to the map: Metamorphis structure of the Alps. In Oberhänsly R. et al. (Eds): Metamorphic structure of the Eastern Alps. Mitt. Oesterr. Miner. Ges., 149, 63-87.

Schuster R., Scharbert S., Abart R. & Frank W., 2001. Permo-Triassic extension and related HT/LP metamorphism in the Austroalpine-Southalpine realm. Mitt. Ges. Geol. Bergbaustud. Österr., 45, 111-141.

Scrocca D., Doglioni C., Innocenti F., Manetti P., Mazzotti A., Bertelli L., Burbi L. & D'Offizi S., 2003. CROP Atlas. Seismic reflection profiles on the Italian crust. Mem. descrittive Carta Geol. d'Italia, 62, 193 p, 36 Plates.

Sella Q., 1862. Sul modo di fare la Carta geologica del Regno d'Italia. Relazione del Commendatore Quintino Sella al Sig. Commendatore Cordova Ministro di Agricoltura, Industria e Commercio. Atti Soc It. Scienze Naturali in Milano, 4, 1-43.

Selverstone J., 1985. Petrologic constraints on imbrication, metamorphism and uplift in the WS Tauern-window, Eastern Alps. Tectonics, 4, 687-704, 10.1029/TC004i007p00687

Selverstone J., 1988. Evidence for east-west crustal extension in the Eastern Alps: implications for the unroofing history of the Tauern window. Tectonics, 7, 87-105, 10.1029/TC007i001p00087

Selverstone J., 1993. Micro- to macroscale interactions between deformational and metamorphic processes, Tauern window, Eastern Alps. Schweiz. mineral. petrogr. Mitt., 73, 229-239.

Selverstone J., Frank S., Spear F.S., Franz G. & Morteani G., 1984. High-pressure metamorphism in the SW Tauern window, Austria: P-T paths from hornblende-kyanite-staurolite schists. J. Petrology, 25, 501-531.

Selverstone J., Franz G., Thomas S. & Getty S., 1993. Fluid variability in 2 GPa eclogites as an indicator of fluid behavior during subduction. Contrib. Mineral. Petrol., 112, 341-357, 10.1007/BF00310465

Selverstone J., Frezzotti M.L. & Compagnoni R., 2010. Low-temperature diamond in oceanic rocks from the Western Alps. 2010 GSA Denver Annual Meeting (31 October -3 November 2010), Geological Society of America Abstracts with Programs, Vol. 42, No. 5, p. 49

Selverstone J. & Spear F.S., 1985. Metamorphic P-T paths from pelitic schists and greenstones from the south-west Tauern window, eastern Alps. J. metam. Geol., 3, 439-465.

Sengör A.M.C., 1990. Plate tectonics and orogenic research after 25 years: a Tethyan perspective. Earth Sci. Reviews, 27, 1-201.

Seward D. & Mancktelow N.S., 1994. Neogene kinematics of the central and western Alps: evidence from fission-track dating. Geology, 22, 803-806, 10.1130/0091-7613(1994)022<0803:NKOTCA>2.3.CO;2

Siegesmunt S., Heinrichs T., Romer R.L. & Doman D., 2007. Age constraints on the evolution of the Austroalpine basement to the south of the Tauern Window. Intern. J. Earth Sci., 96, 415-432, 10.1007/s00531-006-0115-5

Sills J. D. & Tarney J., 1984. Petrogenesis and tectonic significance of amphibolites interlayered with metasedimentary gneisses in the Ivrea zone, S. Alps, N. Italy. Tectonophysics, 107, 187-206, 10.1016/0040-1951(84)90251-8

Simon-Labric T., Rolland Y., Dumont T., Heymes T., Authermayou C., Corsini M. & Fornari M., 2009. ^{40}Ar/ ^{39}Ar dating of Penninic Front tectonic displacement (W Alps) during the Lower Oligocene (31-34 Ma). Terra Nova 21, 127-136.

SIMP, 1985. Geochronology in Italy: results and problems. Rend. Soc. It. Min. Petr., 40/1, 224 p.

Sinigoi S., Antonini P., Demarchi G., Longinelli A., Mazzuchelli M., Negrini L. & Rivalenti G., 1991. Interactions of mantle and crustal magmas in the southern part of the Ivrea zone (Italy). Contrib. Mineral. Petrol., 108, 385-395, 10.1007/BF00303445

Skora S., Lapen T.J., Baumgartner L.P., Johnson C.M., Hellenbrand E. & Mahlen N.J., 2009, The duration of prograde garnet crystallization in the UHP eclogites at Lago di Cignana, Italy. Earth Planet. Sci. Lett. 287, 402-411, 10.1016/j.epsl.2009.08.024

Smith A.G., 1976. Plate tectonics and orogeny: a review. Tectonophysics, 33, 215-285, 10.1016/0040-1951(76)90148-7

Spalla M.I., De Maria L., Gosso G., Miletto M. & Pognante U., 1983. Deformazione e metamorfismo della Zona Sesia-Lanzo meridionale al contatto con la Falda Piemontese e con il massiccio di Lanzo, Alpi occidentali. Mem. Soc. Geol. It., 26, 499-514.

Spalla M.I., Lardeaux J.M., Dal Piaz G.V. & Gosso G., 1991. Métamorphisme et tectonique à la marge externe de la Zone Sesia-Lanzo (Alpes occidentales). Mem. Sci. Geol., Padova, 43, 361-369.

Spalla I.M., Lardeaux J.M., Dal Piaz G.V., Gosso G. & Messiga B., 1996. Tectonic significance of Alpine eclogites. J. Geodynamics, 21, 257-285, 10.1016/0264-3707(95)00033-X

Spicher A., 1980. Tektonishe Karte der Schweiz 1:500,000. Schweiz. Geol. Kommission.

Spiegel C., Kuhlemann J., Dunkl I., Frisch W., von Eynatten H. & Balog K, 2000. The erosion history of the Central Alps: evidence from zircon fission track data of the foreland basin sediments. Terra Nova, 12, 163-170.

Spiess R., Cesare B., Mazzoli C., Sassi R. & Sassi F.P., 2010. The crystalline basement of the Adria microplate in the eastern Alps: a review of the palaeostructural evolution from the Neoproterozoic to the Cenozoic. Rend. Fis. Acc. Lincei, 21, Suppl. 1, 31-50, 10.1007/s12210-010-0100-6

Steinmann M. & Stille P., 1999. Geochemical evidence for the nature of the crust beneath the eastern North Penninic basin of the Mesozoic Tethys ocean. Geol. Rundschau, 87, 633-643, 10.1007/s005310050236

Stampfli G.M., 1993. Le Briançonnais, terrain exotique dans les Alpes? Eclogae Geol. Helv., 86, 1-45.

Stampfli G.M., 1994. Exotic terrains in the Alps: a solution for a single Jurassic ocean. Schweiz. mineral. petrogr. Mitt., 74, 449-452.

Stampfli G.M. & Borel G., 2002. A plate tectonic model for the Paleozoic and Mesozoic. Earth Planet.Sci. Lett., 196, 17-33, 10.1016/S0012-821X(01)00588-X

Stampfli G.M. & Borel G., 2004. The TRANSMED Transects in Space and Time: Constraints on the paleotectonic evolution of the Mediterranean domain". In Cavazza W., Roure F., Spakman W., Stampfli G.M. & Ziegler P. (Eds): The TRANSMED Atlas: the Mediterranean Region from Crust to Mantle. Springer Verlag, pp. 53-80.

Stampfli G.M., Borel G., Cavazza W., Mosar J. & Ziegler P.A., 2001b. The paleotectonic Atlas of the Peritethyan domain. CD ROM, European Geophysical Society.

Stampfli G.M., Borel G., Marchant R. & Mosar J., 2002. Western Alps geological constraints on western Tethyan reconstructions. J. Virtual Explorer, 8, 77-106.

Stampfli G. & Hochard C., 2009. Plate tectonics of Alpine realm. In Murphy J.B., Keppie J.D. & Hynes A.J. (Eds): Ancient Orogens and Modern Analogues. Geol. Soc. London, Special Publ., 327, 89-111.

Stampfli G.M., Marcoux J. & Baud A., 1991. Tethyan margins in space and time. Palaeogeogr. Palaeocl. Palaeoecol., 87, 373-409, 10.1016/0031-0182(91)90142-E

Stampfli G.M., Mosar J., Favre Ph., Pillevuit A. & Vannay J-C., 2001a. Permo-Mesozoic evolution of the western Tethys realm: the Neo-Tethys East Mediterranean Basin connection. In Ziegler P.A. et al. (Eds.): Peri-Tethyan rift/wrench basins and passive margins. Mém. Mus. Hist. Nat. Paris, 186, 51-108.

Stampfli G.M., Mosar J., Marquer, D., Marchant R., Baudin T. & Borel G., 1998. Subduction and obduction processes in the Swiss Alps. Tectonophysics, 296, 159-204.

Staub R., 1924. Der Bau der Alpen. Beitr. Geol. Karte Schweiz, 52, 272 p.

Staub R., 1957. Vom Bau der Dentblanche-Deke un seinen Beziehungen zum Bernina-System. Eclogae Geol. Helv., 50, 171-230.

Steck A., 1984. Structures et déformations tertiairs dans les Alpes centrales. Eclogae Geol. Helv., 77, 55-100.

Steck A., 1987. Le massif du Simplon - Réflexion sur la cinématique des nappes de gneiss. Schweiz. mineral. petrogr. Mitt., 67, 27-45.

Steck A., Bigioggero B., Dal Piaz G.V., Escher A., Marchant R., Martinotti G. & Payot S., 1999. Carte tectonique des Alpes de Suisse occidentale et des régions avoisinantes, 1:100.000, Feuilles 47, Monte Rosa. Carte géol. spec. N. 123-SE, Service hydrologique et géologique national, Berne.

Steck A., Epard J.-L., Escher A., Lehner P., Marchant R. & Masson H., 1997. Geological interpretation of the seismic profiles through Western Switzerland: Rawil (W1), Val d'Anniviers (W2), Mattertal (W3), Zmutt-Zermatt-Findelen (W4) and Val de Bagnes (W5). In O.A. Pfiffner, P. Lehner, P. Heitzmann, S. Mueller & A. Steck (Eds): Deep structure of the Swiss Alps. Birkäuser Verlag, Basel, 123-137.

Steck A., Epard J.-L., Escher A., Gouffon Y. & Masson H., 2001. Carte tectonique des Alpes de Suisse occidentale et des régions avoisinantes 1:100,000. Notice explicative. Office fédérale des eaux et de la géologie, 73 pp.

Steinmann G., 1905. Geologische Beobachtungen in den Alpen: Die Schardt'sche Ueberfaltungstheorie und die geologische Bedeutung der Tiefseeabsätze und der ophiolitischen Massengesteine. Ber. natf. Ges. Freiburg, 16, 18-67.

Stella A., 1894. Relazione sul rilevamento eseguito nell'anno 1983 nelle Alpi Occidentali (valli dell'Orco e della Soana). Boll. R. Comit. Geol. It., 25, 343-371.

Stella A., 1903. A proposito della diffusione delle rocce a giadeite nelle Alpi Occidentali. Boll. Soc. Geol. It., 22, 141-142.

Stella A., 1905. Il problema geo-tettonico dell'Ossola e del Sempione. Boll. R. Comit. Geol. It., 36, 5-41.

Stella A., 1927. Sezioni geologiche attraverso l'alta Valle di Aosta. Fogli 27-28-29-41-42. R. Ufficio Geol., Stabilimento L. Salomone. Roma.

Stella A., 1943. I giacimenti auriferi delle Alpi italiane. Mem. descrittive Carta Geol. d'Italia, 27, 134 pp.

Stünitz H., 1989. Partitioning of metamorphism and deformation in the boundary region of the "Seconda Zona Dioritico-Kinzigitica", Sesia Zone, Western Alps. Ph.D. Thesis ETH Zurich.

Sturani C., 1962. Il Complesso Sedimentario Autoctono all'estremo nord-occidentale del Massiccio dell'Argentera (Alpi Marittime). Mem. Ist. Geol. Min. Univ. Padova, 22, 206 pp.

Sturani C., 1963. La couverture sédimentaire de l'Argentera-Mercantour dans le secteur compris entre les Barricate et Sambuco (haute vallée de la Stura di Demonte, Italie). Trav. Lab.Géol. Grenoble, 39, 83-124.

Sturani C., 1975. Explanatory notes on the western Alps (from the Sestri-Voltaggio line to the Val d'Ossola. Structural Model of Italy, Quaderni La Ricerca Sci., CNR, 90, 149-174.

Stutz A.H. & Masson R., 1938. Zur Tektonik der Dent Blanche Decke. Schweiz. mineral. petrogr. Mitt., 18, 40-53.

Sue C. & Tricart P., 2003. Neogene to ongoing normal faulting in the inner western Alps: A major evolution of the late Alpine tectonics. Tectonics, 22, 10.1029/2002TC001426

Sue C., Delacou B., Champagnac G.-D., Allanic C., Tricart P. & Burkhard M., 2007. Extensional neotectonics around the bend of the Western/Central Alps: an overview. Earth Environmental Sci., 96, 377-385.

Suess E., 1875. Die Entstehung der Alpen. Braunmüller, Wien, 168 p.

Suess E., 1885-1901. Das Antlitz der Erde. Braunmüller, Wien, 778 p.

Suess E., 1894. The face of the Earth. Clarendon Press, Oxford, 604 p.

Tartarotti P., Benciolini L. & Monopoli B., 1998. Brecce serpentinitiche nel massiccio ultrabasico del Monte Avic (Falda ofiolitica piemontese): possibili evidenze di erosione sottomarina. Atti Ticinensi Sci. Terra, ser. spec., 7, 73-86.

Thélin P., Sartori M., Lengeler R. & Scharer J.-P., 1990. Eclogites of Paleozoic or early alpine age in the basement of the pennidic Siviez-Mischabel nappe, Wallis, Switzerland. Lithos, 25, 71-88.

Thiele O., 1976. Der Nordrand des Tauernfensters zwischen Mayrhofen und Inner Schmirn (Tirol). Geol. Rund., 65, 410-421, 10.1007/BF01808473

Thompson A.G., 1991. Some theoretical aspects of pressure-temperature-time (PTt) paths for metamorphism (and melting) of the continental lithosphere. Lectures V Summer School geol. petrol. basamenti cristallini: Pressure and temperature evolution of orogenic belts, 1991, Università di Siena 1992, pp. 65-82.

Thöni M., 1999. A review of geochronological data from the Eastern Alps. Schweiz. mineral. petrogr. Mitt., 79, 209-230.

Thöni M., 2006. Dating eclogite facies metamorphism in the Eastern Alps - approaching, results, interpretations: a review. Mineralogy and Petrology, 88, 123-148.

Thöni M. & Jagoutz E., 1992. Some new aspects of dating eclogites in orogenic belts: Sm- Nd, Rb-Sr and Pb-Pb isotopic results from the Austroalpine Saualpe and Koralpe type-locality (Carinthia-Styria, southeastern Austria). Geochim. Cosmochim. Acta, 56, 347-368.

Thöni M. & Jagoutz E., 1993. Isotopic constraints for eo-Alpine high-P metamorphism in the Austroalpine nappes of the Eastern Alps: bearing on Alpine orogenesis. Schweiz. mineral. petrogr. Mitt., 73, 177-189.

Thöni M. & Miller Ch., 1996. Garnet Sm-Nd data from Saualpe and the Koralpe (Eastern Alps, Austria): chronological and PT constraints on the thermal and tectonic history. J. metam. Geol., 14, 453-466.

Thöni M., Miller C., Blicher-Toft J., Whitehouse M.J., Konzett J. & Zanetti A., 2008. Timing of high-pressure metamorphism and exhumation of the eclogite typelocality (Kupplerbrunn-Prickler Halt, Saualpe, south-eastern Austria): constraints from correlations of the Sm-Nd, Lu-Hf, U-Pb and Rb-Sr isotopic systems. J. metam. Geol., 26, 561-581.

Thouvenot F., Paul A., Senechal G., Hirn A. & Nicolich R., 1990. ECORS-CROP wide-angle reflection seismic: constraints on deep interfaces beneath the Alps. Mém. Soc. Géol. France, 156, 97-106.

Tilton G.R., Schreyer W. & Schertl H.P., 1989. Pb-Sr-Nd isotopic behavior of deeply subducted crustal rocks from the Dora Maira massif, Western Alps, Italy. Geochim. Cosmochim. Acta, 53, 1391-1400, 10.1016/0016-7037(89)90071-9

Tilton G.R., Schreyer W. & Schertl H.P., 1991. Pb-Sr-Nd isotopic behavior of deeply subducted crustal rocks from the Dora Maira massif, Western Alps, Italy-II: what is the age of the ultrahigh-pressure metamorphism? Contrib. Mineral. Petrol., 108, 22-33, 10.1007/BF00307323

Tollmann A., 1963. Ostalpen synthese. Deuticke, Wien, 256 p.

Tollmann A., 1965. Die Fortsetzung des Briançonnais in den Ostalpen. Mitt Geol. Ges. Wien, 57, 469-478.

Tollmann A., 1975. Ozeanische Kruste im Pennin des Tauernfenster und die neugliederung des Deckenbaues der Hohen Tauern. N. Jb. Geol. Pal. Abh., 148, 286-319.

Tollmann A. 1977. Geologie von Österreich. Band 1. Die Zentralalpen. Deuticke, Wien, 766 p.

Tollmann A. 1978. Plattentektonische Fragen in den Ostalpen und der plattentektonische Mechanismus des mediterranen Orogens. Mitt. österr. geol. Ges., 69, 291-351.

Tollmann A., 1987. The Alpidic evolution of the Eastern Alps. In Flügel H.W. and Faupl P., Eds: Geodynamics of the Eastern Alps. Deuticke Vienna, pp. 361-378.

Transalp Working Group, 2002. First deep seismic reflection images of the Eastern Alps reveal giant crustal wedges and trascurrent ramps. Geophys. Res. Lett, 29/10, 1029-1032.

Trautwein B., Dunkl I. & Frisch W., 2001. Accretionary history of Renodanubian flysch zone in the Eastern Alps - Evidence from the fission-track geochronology. Intern. J. Earth Sci., 90, 703-713, 10.1007/s005310000184

Treves B., 1984. Orogenic belts as accretionary prisms: the example of northern Apennines. Ofioliti, 9, 577-618.

Trommsdorff V. & Evans B.W., 1977. Antigorite ophicarbonates: contact metamorphism in Val Malenco (Italy). Contrib. Mineral. Petrol., 62, 301-312.

Trommsdorff V. & Nievergelt P., 1985. The Bregaglia (Bergell)-Iorio intrusive and its field relations. In Dal Piaz G.V. (Ed): Il magmatismo tardo alpino nelle Alpi. Mem. Soc. Geol. It., 26 (1993), 55-68.

Trommsdorff V., Piccardo G.B. & Montrasio A., 1993. From magmatism through metamorphism to sea floor emplacement of subcontinental Adria mantle during pre-Alpine rifting (Malenco, Italy). Schweiz. mineral. petrogr. Mitt., 73, 191-203.

Trümpy R., 1954. La zone de Sion-Courmayeur dans le haut Val Ferret valaisan. Eclogae Geol. Helv., 47, 315-359.

Trümpy R., 1960. Paleotectonic evolution of the Central and Western Alps. Geol. Soc. Am. Bull., 71, 843-908.

Trümpy R., 1971. Stratigraphy in mountain belts. Quarterly J. Geol. Soc. London, 126: 293-318.

Trümpy R., 1988. A possible Jurassic-Cretaceous transform system in the Alps and the Carpathians: Geol. Soc. Am. Spec. Paper, 218, 93-109.

Trümpy R., 1991. The Glarus nappe, a controversy of a century ago. In: McKenzie, J., Müller, D. (Eds): Controversies in Modern Geology, Academic Press, 385-404.

Trümpy R., 1992. Ostalpen und Westalpen - Verbindendes und Trennendes. Jb. Geol. B.-A., Wien, 135, 875-882.

Trümpy R., 1996. Alpine geology: whence, whither? Eclogae Geol. Helv., 89, 7-12.

Trümpy R., 2001. Why plate tectonics was not invented in the Alps. Int. J. Earth Sci., 90, 477-483.

Trümpy R. with contributions by Bernoulli D., Grünenfelder M., Köppel V., Müller St. & Trommsdorff V., 1980 - An outline of the Geology of Switzerland. Geology of Switzerland, a guide-book. Part A: Schweiz. Geol. Kommission, Wepf & Co., Basel, pp. 1-104.

Trümpy R. & Lemoine M., 1988. M. Bertrand (1847-1907): les nappes de charriage et le cycle orogénique. C.R. Acad. Sci. Paris, Sci. Terre, 327, 211-224.

Tumiati S., Thoni M. Nimis P., Martin S. & Mair V., 2003. Mantle-crust interactions during Variscan subduction in the Eastern Alps (Nonsberg-Ulten zone): geochronology and new petrological constraints. Earth Planet. Sci. Letters, 210, 509-526, 10.1016/S0012-821X(03)00161-4

Vai G.B., Venturini C., Carulli G.B. & Zanferrari A., 2002. Alpi e Prealpi Carniche e Giulie. Guide Geologiche Regionali, Soc. Geol. It., BE-MA Milano, 392 p.

Van der Klauw S.N., Reinecke T. & Stöckhert B., 1997. Exhumation of ultrahighpressure metamorphic oceanic crust from Lago di Cignana, Piemontese zone, western Alps: the structural record in metabasites. Lithos, 41, 79-102.

Vanossi M., 1992. Alpi Liguri. Guide Geologiche Regionali, Soc. Geol. It., BE-MA Milano, 296 p.

Vanossi M., Cortesogno L., Galbiati B., Messiga B., Piccardo G. & Vannucci R., 1984. Geologia delle Alpi Liguri: Dati, problemi, ipotesi. Mem. Soc. Geol. It., 28, 5-75.

Vavra G. & Frisch W., 1989. Pre-Variscan back-arc and island-arc magmatism in the Tauern window (Eastern Alps). Tectonophysics, 169, 271-280, 10.1016/0040-1951(89)90091-7

Vavra G. & Hansen B.T., 1991. Cathodoluminescence studies and U/Pb dating of zircons in pre-Mesozoic gneisses of the Tauern Window: implications for the Penninic basement evolution. Geol. Rundschau, 80, 703-715, 10.1007/BF01803696

Venturelli G., Thorpe R.S., Dal Piaz G.V., Del Moro A. & Potts P.J., 1984. Petrogenesis of calc-alkaline, shoshonitic and associated ultrapotassic Oligocene volcanic rocks from the Northwestern Alps, Italy. Contrib. Mineral. Petrol., 86, 209-220, 10.1007/BF00373666

Venturini G., 1995. Geology, geochemistry and geochronology of the inner central Sesia Zone (Western Alps-Italy). Mém. Géol. Lausanne, 25, 1-148.

Venturini G., Martinotti G., Armando G., Barbero M. & J. C. Hunziker J.C, 1994. The central Sesia Lanzo Zone (western Italian Alps), new field observations and lithostratigraphic subdivisions, Schweiz. mineral. petrogr. Mitt., 74, 115-125.

Venturini G., J. C. Hunziker J.C. & Pfeifer H.R., 1996. Geochemistry of mafic rocks in the Sesia Zone (western Alps), new data and interpretations. Eclogae Geol. Helv., 89, 369 - 388.

Vialon P., 1966. Etude géologique du massif cristallin Dora-Maira, Alpes cottiennes internes, Italie. Phd Thèse Univ. Grenoble.

Villa I.M., Hermann J., Müntener O. & Trommsdorff V., 2000. ^{39}Ar-^{40}Ar dating of multiply zoned amphibole generations (Malenco, Italian Alps). Contrib. Mineral. Petrol. 140, 363-381.

Viollet-le-Duc E., 1876. Le massif du Mont Blanc; étude sur sa constitution géodésique et géologique, sur ses transformations, et sur l'état ancien et moderne de ses glaciers. Baudry, Paris.

Visonà D., 1997. The Predazzo multipulse intrusive body (Western Dolomites. Italy). Field and mineralogical studies. Mem. Sci. Geol., Padova, 49, 117-125.

Visonà D., Alberti F., Stefani C. & Scenico L., 1987. Le plutoniti di Chiusa, Dosso Lives e Luson. Una serie calc-alcalina ercinica nelle Alpi Orientali. Mem. Sci. Geol., Padova, 39, 85-99.

Visonà D., Caironi V., Carraro A., Dallai L., Fioretti A.M. & Fanning M., 2007a. Zircon megacrysts from basalts of the Venetian Volcanic Province (NE Italy): U-Pb ages, oxygen isotopes and REE data. Lithos, 94, 168-180, 10.1016/j.lithos.2006.06.007

Visonà D., Fioretti A.M., Poli E.M., Zanferrari A. & Fanning M., 2007b. U-Pb shrimp zircon dating of andesites from Dolomite area (ne italy): geochronological evidence for the beginning of the Permian volcanism in Eastern Southalpine. Swiss Journal of Geosciences, 100, 313-324, 10.1007/s00015-007-1219-z

Vissers R.L.M., Drury M.R., Hoogerduijn Strating E.H. amp; Van Der Wal D. (1991). Shear zones in the upper mantle: a case study in an Alpine lherzolite massif. Geology, 19, 990-993, 10.1130/0091-7613(1991)019<0990:SZITUM>2.3.CO;2

Von Raumer J., 1987. Le massifs du Mont Blanc et des Aiguilles Rouges: temoins de la formation de croute varisque dans les Alpes occidentales. Géol. Alpine, 63, 7-24.

Von Raumer J.F., 1998. The Palaeozoic evolution of the Alps: from Gondwana to Pangea. Geol. Rundschau, 87, 407-435, 10.1007/s005310050219

Von Raumer J., Abrecht J., Bussy F., Lombardo B., Menot J.-P. & Schaltegger U, 1999. The Paleozoic metamorphic evolution of the Alpine External Massifs. Schweiz. mineral. petrogr. Mitt., 79, 5-22.

Von Raumer J.F. & Neubauer F. (Eds), 1993. Pre-Mesozoic geology in the Alps. Springer-Verlag, 677 p.

Von Raumer J.F. & Stampfli G.M., 2008. The birth of the Rheic ocean. Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios. Tectonophysics, 461, 9-20, 10.1016/j.tecto.2008.04.012

Vuichard D., 1984. The ophiolitic suite of the Alp Champatsch (Lower Engadine Window, Switzerland): the metamorphic and tectonic evolution of a small oceanic basin in the Penninic Realm? Ofioliti, 9, 619-632.

Vuichard J.P., 1987. Conditions P-T du métamorphisme ante-alpin dans la "seconde zone diorito-kinzigitique" (Zone Sesia-Lanzo, Alpes occidentales). Schweiz. mineral. petrogr. Mitt., 67, 257-272.

Vuichard J.P., 1989. La marge austroalpine durant la collision alpine: évolution tectonométamorphique de la zone Sesia-Lanzo. Mém. Doc. Centre Armoricain Etud. Struct. Socles, 24, 307 p.

Waibel A.F. & Frisch W., 1989. The lower Engadine window: sediment deposition and accretion in relation to the plate-tectonic evolution of the Eastern Alps. Tectonophysics, 162, 229-241, 10.1016/0040-1951(89)90246-1

Wheeler J. & Butler R.W.H., 1993. Evidence for extension in the western Alpine orogen: the contact between the oceanic Piemonte and overlying continental Sesia units. Earth Planet. Sci. Lett., 117, 457-474, 10.1016/0012-821X(93)90097-S

Weissert H.J. & Bernoulli D., 1985. A transform margin in the Mesozoic Thetys: evidence from the Swiss Alps. Geol. Rundschau, 74, 665-679, 10.1007/BF01821220

Wenk H.-R., 1973. The structure of Bergell Alps. Eclogae Geol. Helv., 66, 255-291.

Westphal M., Bazhenov M.L., Lauer J.P., Pechersky D.M. & Sibuet J.C., 1986. Paleomagnetic implications on the evolution of the Tethys belt from the Atlantic ocean to the Pamirs since the Triassic. Tectonophysics, 123, 37-82, 10.1016/0040-1951(86)90193-9

Williams P.F. & Compagnoni R., 1983. Deformation and metamorphism in the Bard area of the Sesia-lanzo zone, Western Alps, during subduction and uplift. J. metam. Geol., 1, 117-140, 10.1111/j.1525-1314.1983.tb00268.x

Winkler W. & Bernoulli D., 1986. Detrital high-pressure/low temperature minerals in a late Turonian flysch sequence of the eastern Alps (western Austria): implication for early alpine tectonics. Geology, 14, 598-601, 10.1130/0091-7613(1986)14<598:DHMIAL>2.0.CO;2

Winkler W., Galetti J. & Maggetti M., 1985. Bentonite im Gurnigel-, Schlieren- und Wägital-Flysch: Mineralogie, Chemismus, Herkunft. Eclogae Geol. Helv., 78, 545-564.

Winterer E.L. & Bosellini A., 1981. Subsidence and sedimentation on Jurassic passive continental margin, Southern Alps, Italy. AAPG Bull., 65, 394-421.

Wortel M.J.R. & Spakman W., 2000. Subduction and slab detachment in the Mediterranean-Carpathian region. Science, 290 (5498), 1910-1917, 10.1126/science.290.5498.1910

Zambonini F., 1906. Ueber den metamorphosierten Gabbro der Rocca Bianca in Susa-Tale. N. Jb. Min. Geol. Pal., 105-134.

Zattin M., Cuman A., Fantoni R., Martin S. & Stefani C., 2006. From Middle Jurassic heating to Neogene cooling: the thermochronological evolution of the southern Alps. Tectonophysics, 414, 192-202, 10.1016/j.tecto.2005.10.020

Ziegler P.A., 1988. Evolution of the Arctic-North Atlantic and the Western Tethys. AAPG Mem., 43, 198 p.

Zimmermann R. & Franz G., 1989. Die Eklogite der unteren Schieferhulle, Frosnitztal-Sudvenediger (Tauern, Oesterreich). Mitt. österr. Geol. Ges., 81, 167-188.

Zimmermann R., Hammerschmidt K. & Franz G., 1994. Eocene high pressure metamorphism in the Penninic units of the Tauern window, Eastern Alps: evidence from ^{40}Ar-^{39}Ar dating and petrological investigations. Contrib. Mineral. Petrol., 117, 175-186, 10.1007/BF00286841

Zingg A., 1983. The Ivrea & Strona-Ceneri zones (Southern Alps, Ticino & N, Italy) - a review. Schweiz. mineral. petrogr. Mitt., 63, 361-392.

Zingg A., Handy M.R., Hunziker J.C. & Schmid S.M., 1990. Tectonometamorphic history of the Ivrea zone and its relationship to the crustal evolution of the Southern Alps. Tectonophysics, 182, 169-192, 10.1016/0040-1951(90)90349-D

Zingg A., Hunziker J.C., Frey M. & Ahrendt H., 1976. Age and degree of metamorphism of the Canavese Zone and of the sedimentary cover of the Sesia Zone. Schweiz. mineral. petrogr. Mitt., 56, 361-365.

Zurbriggen R., Franz L. & Handy M.R., 1997. Pre-Variscan deformation, metamorphism and magmatism in the Strona-Ceneri zone (southern Alps of northern Italy and southern Switzerland). Schweiz. mineral. petrogr. Mitt., 77, 361-380.

Zurbriggen R., Kamber B.S., Handy M.R. & Nägler T.F., 1998. Dating synmagmatic folds: a case study of schlingen structures in the Strona-Ceneri zone (Southern Alps, northern Italy). J. metam. Geol., 16, 403-414.