by Giorgio V. Dal Piaz, Andrea Bistacchi, and Matteo Massironi

Geological outline of the Alps

Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, via Giotto 1, 35137 Padova, Italy.
E-mail: *giorgio.dalpiaz@unipd.it*

The Alps were developed from the Cretaceous onwards by subduction of a Mesozoic ocean and collision between the Adriatic (Austroalpine-Southalpine) and European (Penninic-Helvetic) continental margins. The Austroalpine-Penninic wedge is the core of the collisional belt, a fossil subduction complex which floats on the European lower plate. It consists of continental and minor oceanic nappes and is marked by a blueschist-to-eclogite-facies imprint of Cretaceous-Eocene age, followed by a Barrovian overprint. The collisional wedge was later accreted by the Helvetic basement and cover units and indented by the Southalpine lithosphere, which in turn was deformed as an antithetic fold-and-thrust belt.

Introduction

The Alps are the typical example of a collisional belt, the mountain range where the nappe theory was conceived and rapidly consolidated (see Dal Piaz, 2001, and Trümpy, 2001, for historical reviews). This belt was generated by the Cretaceous to present convergence of the Adriatic continental upper plate (Argand's African promontory) and a subducting lower plate including the Mesozoic ocean and the European passive continental margin. 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, showing that even coherent fragments of light continental crust may be deeply subducted in spite of their natural buoyancy.

In a map view, the Alps extend from the Gulf of Genoa to Vienna, through the French-Italian western Alpine arc and the east-west-trending central and eastern Alps (Figure 1). South of Genoa, the Alpine range disappears, because it collapsed and was fragmented during the Late Neogene opening of the Tyrrhenian basin (southern segments of the Alpine belt are preserved in Corsica and Calabria). To the east, the former connection between the Alpine and Carpathian belts is buried below the Neogene fill of the Vienna and Styria (Pannonian) basins. The maximum elevations of the Alps are the Mont Blanc (4888 m) and some dozen of summits which exceed 4000 m, whereas most of the Alpine orogen extends below the surface, to a depth of nearly 60 km. Large-wave undulations coupled with orogen-parallel denudation by low-angle normal faults and differential uplift expose the 20–25 km thick upper part of the nappe edifice, going from structural depressions, where the capping Austroalpine units are preserved, to the core of the deepest Penninic Ossola-Ticino window. The remaining buried part has been imaged by deep reflection seismic profiles and other geophysical soundings (Roure et al., 1990; Pfiffner et al., 1997; Transalp Working Group, 2002).

Our aim is a synthetic overview of the structural framework and geodynamic evolution of the Alps, mainly addressed to geoscientists from far-off countries. Tectonic units and essential lithology are represented in the northern sheets (1–2) of the Structural Model of Italy, scale 1:500,000 (Bigi et al., 1990; edited by SELCA, Firenze, e-mail: *selca@selca-cartografie.it*). These maps facilitate readers' approach to the complex geology of the Alps. Due to space limitations, only a few special publications and regional syntheses with extended references are quoted here, concerning the French-Italian Alps (Roure et al., 1990; Michard et al., 1996; Dal Piaz, 1999), Switzerland (Trümpy et al., 1980; Pfiffner et al., 1997), Austria (Flügel and Faupls, 1987; Plöchinger, 1995; Neubauer and Höck, 2000), Southern Alps (Bertotti et al., 1993; Castellarin et al., 1992), tectonics (Coward et al., 1989, Ratschbacher et al., 1991), pre-Mesozoic geology (von Raumer and Neubauer, 1993), metamorphic features (Frey et al., 1999) and geochronology (Hunziker et al., 1992). Daniel Bernoulli and Gabriel Walton are warmly acknowledged for reviews.

Structural framework

According to the direction of tectonic transport, the Alps may be subdivided into two belts of differing size, 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 Southern Alps, a minor, shallower (non-metamorphic) and younger (Neogene) thrust-and-fold belt displaced to the south (Adria-vergent), which developed within the Alpine hinterland of the Adriatic upper plate, far from the oceanic suture. These belts are separated by the Periadriatic (Insubric) lineament, a major fault system of Oligocene-Neogene age.

From top to bottom and from the internal to the external side, the principal Europe-vergent tectonic domains are (Figure 1): i) the Austroalpine composite nappe system, derived from the distal (ocean-facing) part of the Adriatic passive continental margin, which mainly developed during the Cretaceous (Eoalpine) orogeny; ii) the Penninic zone, a stack of generally metamorphic nappes scraped off the subducting oceanic lithosphere and European passive continental margin (distal part), mainly accreted during the Paleogene; its outer boundary is the Penninic frontal thrust; iii) the Helvetic zone, consisting of shallower basement slices and décolled cover units derived from the proximal part of the European margin, mainly imbricated from the Oligocene onwards. The vertical nappe sequence and their deformation age generally reflect the outward propagation of the orogenic front.

The Helvetic zone is thrust over the Molasse foredeep, a northward-thinning sedimentary wedge which developed from the Oligocene to the Late Miocene, with repeated alternations of shallow marine and freshwater deposits. Its imbricated inner zone (Subalpine Molasse) was buried to a distance of over 20 km below the frontal thrust belt. 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 anatomy of the Alps has been explored by the deep seismic experiments mentioned above, identifying two distinct Moho surfaces, i.e., the Adriatic and the deeper European Moho, gently bending from the Alpine foreland to the deep base of the collisional wedge (Figure 2). This means that the overall setting of the Alps is asymmetric, the orogen was dominated by Europe-vergent displacements, and the antithetic Southalpine belt is only a superficial feature

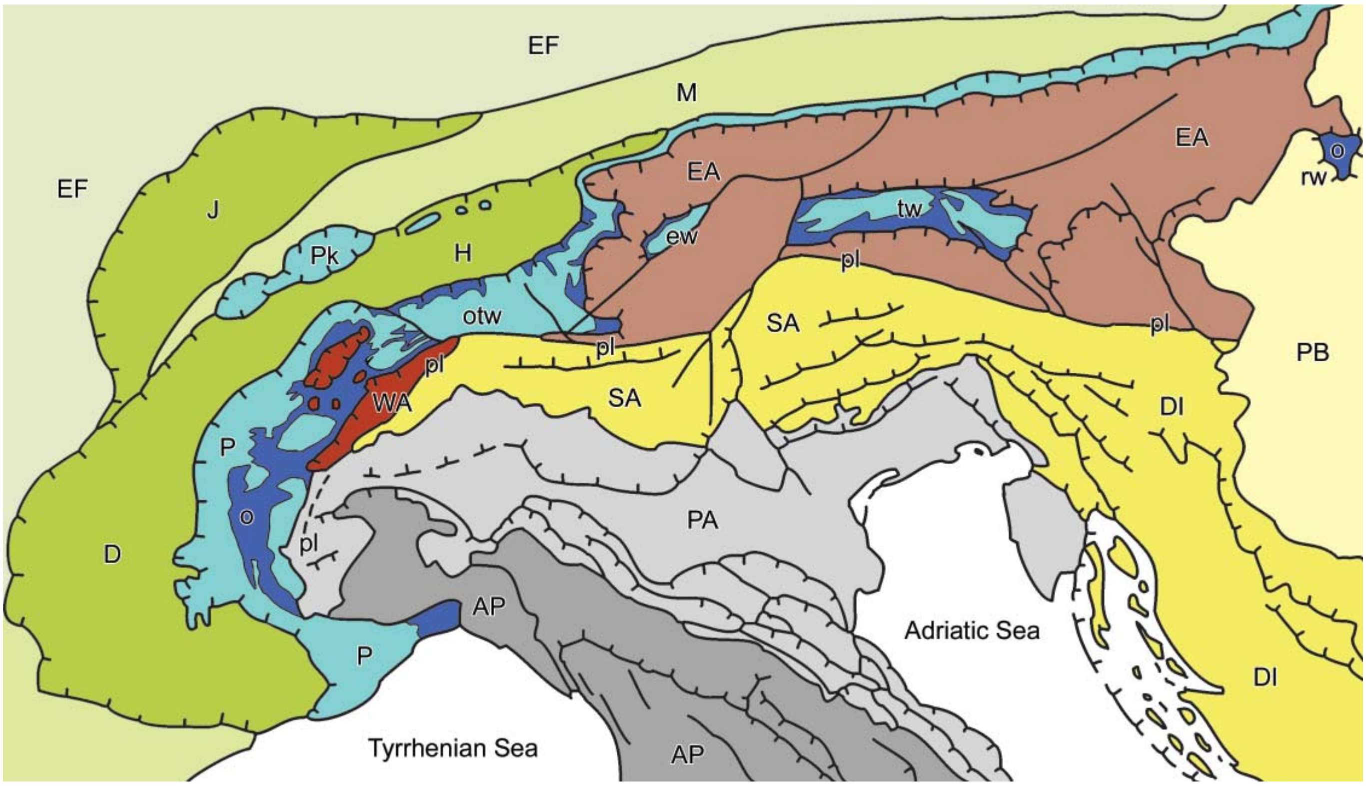

Figure 1 Tectonic map of Alps - (1) Europe-vergent collisional belt: i) Western (WA) and Eastern (EA) Austroalpine; ii) Penninic domain: continental and ophiolitic (o) nappes in western Alpine arc (P) and tectonic windows (otw: Ossola-Ticino, ew: Engadine, tw: Tauern, rw: Rechnitz); Prealpine klippen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

within the Adriatic upper plate. If we integrate surface geology with interpretation of seismic images, the Europe-vergent belt is a mantle-free crustal wedge which tapers to the north, floats on top the European lower plate and is indented, to the south, by the present Adriatic (Southern Alps) lithosphere (Figure 2). Both continental plate margins originally extended way into the Penninic-Helvetic and Austroalpine domains presently incorporated into the collisional belt. This wedge groups the Austroalpine, Penninic and Helvetic units, and may be subdivided into two diachronous parts: i) the internal, older part (Austroalpine-Penninic), which forms now the axial zone of the Alps, is a fossil subduction complex which includes the Adria/Europe collisional zone; it is marked by one or more ophiolitic units (in different areas) and displays polyphase metamorphism evolving from blueschist or eclogite facies imprint (Cretaceous-Eocene subduction), locally coesite-bearing, to a Barrovian overprint (mature collision, slab break-off) of Late Eocene-Early Oligocene age (Frey et al., 1999); ii) the outer, younger part (Helvetic) is made up of shallower basement thrust-sheets and largely detached cover units derived from the proximal European margin, which escaped the low-T subduction regime and, from the Oligocene, were accreted in front of the exhumed Austroalpine-Penninic wedge.

In the following, we outline the essential features of the Europe-vergent Austroalpine, Penninic and Helvetic tectonic domains and the antithetic Southern Alps.

The Austroalpine thrust units

The Austroalpine is subdivided into two sectors (western and eastern), based on contrasting distribution, structural position, and main deformation age.

The western Austroalpine consists of the Sesia-Lanzo zone and numerous more external thrust units traditionally grouped as Argand's Dent Blanche nappe. These units override and are partly tectonically interleaved with the structurally composite ophiolitic Piedmont zone, the major remnant of the Mesozoic ocean. Two groups of Austroalpine units are identified: i) the upper outliers (Dent Blanche-Mt. Mary-Pillonet) and the Sesia-Lanzo inlier occur on top of the collisional nappe stack; they overlie the entire ophiolitic Piedmont zone and display a blueschist to eclogite facies metamorphism of Late Cretaceous age; ii) the Mt. Emilius and other lower outliers are interleaved with the Piedmont zone, along the tectonic contact between the upper (Combin) and lower (Zermatt-Saas) ophiolitic nappes, and display an eclogitic imprint of Eocene age. Therefore, these groups of nappes originated from different structural domains, were diachronously subducted to various depths, and finally juxtaposed during their later exhumation.

In the central Alps, east of the Ossola-Tessin window, the western Austroalpine may be correlated to the Margna nappe (Staub's interpretation), which is thrust over the Malenco-Avers ophiolite and overlain by the Platta ophiolite, both being potential homologues of the Piedmont zone. The Platta nappe is in turn the tectonic substratum of the eastern Austroalpine system. This means that the western Austroalpine and Margna nappes are presently located at a structural level lower than that of the capping eastern Austroalpine.

The eastern Austroalpine is a thick pile of cover and basement nappes which extends from the Swiss/Austrian border to the Pannonian basin (Figure 1). Its allochthony with respect to the Penninic zone is documented by Mesozoic and ophiolitic units exposed in the Engadine, Tauern and Rechnitz windows. To the north, the Austroalpine overrides the outer-Penninic Rheno-Danubian flysch belt; to the south, it is juxtaposed to the Southalpine basement along the Periadriatic fault system. Part of the Austroalpine displays an eclogitic to Barrovian metamorphism dated as early-mid Cretaceous (Eoalpine; Frey et al., 1999). In addition, thrust surfaces are sealed by Gosau beds (Coniacian-Eocene intramontane basins), testifying that the principal tectono-metamorphic history of the eastern Aus-

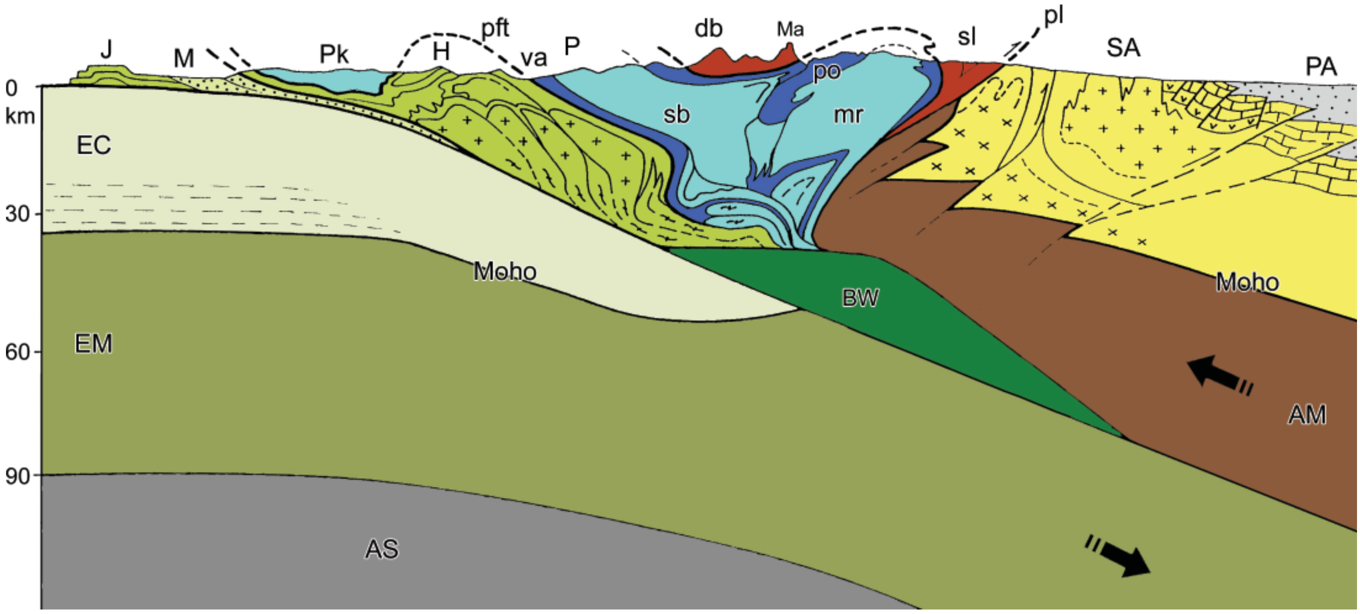

Figure 2 Lithospheric section of north-western Alps - 1) Austroalpine: Sesia-Lanzo inlier (sl) and Dent Blanche nappe s.l. (db), including Matterhorn (Ma); 2) Penninic domain (P): Piedmont ophiolitic units (po), Monte Rosa (mr) and Grand St. Bernard (sb) nappes, underlain by lower Penninic and outer Penninic Valais zone (va), Penninic klippen (Pk), Penninic frontal thrust (pft); 3) Helvetic basement slices and cover nappes (H); 4) Molasse foredeep (M); 5) Jura belt (J); 6) buried wedge (BW) of European mantle or eclogitized crustal units; 7) European lithosphere: continental crust (EC) and mantle (EM); asthenosphere (AS); 8) Adriatic lithosphere: antithetic belt of Southern Alps (SA) and mantle (AM); Periadriatic fault system (pl); 9) Padane-Adriatic foreland (PA).

troalpine is older (pre-Late Cretaceous) than that of the western Austroalpine (Late Cretaceous-Eocene).

The eastern Austroalpine is subdivided into two (Structural Model of Italy) or three (Austrian literature) main groups of nappes. The Upper Austroalpine encompasses the Northern Calcareous Alps and some phyllitic basement nappes occurring west (Steinach klippe), south-east (Gurktal nappe, Graz Paleozoic) and north (Graywacke zone) of the Tauern window. The Northern Calcareous Alps are an imbricated pile of décollement cover nappes made up of Permian-Mesozoic clastic to carbonate deposits, including platform (Hauptdolomit) and basin (Hallstatt) sequences, mainly detached from the Graywacke zone along evaporite-bearing shales. The Middle Austroalpine groups most of the basement and minor cover units of the eastern Alps. The Silvretta, Oetztal and Ortler-Campo nappes occur west of the Tauern window, followed to the south by the Ulten-Tonale nappe. The latter is a fragment of Variscan lower continental crust with eclogitic relics and slices of garnet-spinel peridotite. Similar basement and cover nappes occur east of the Tauern window, including the Speick ophiolite (Variscan) and some basement units (Koralpe-Saualpe, Sieggraben) which display an Eoalpine eclogite-facies imprint in Permian mafic protoliths (Thöni, in Frey et al., 1999). The Lower Austroalpine includes some cover and basement units exposed along the western (Err-Bernina), central (Innsbruck Quartz-phyllite, Radstatt system) and eastern edge (Semmering-Wechsel) of the Austroalpine ranges. The Innsbruck Phyllite (Paleozoic) is overthrust by the Reckner nappe, a Mesozoic ophiolite which displays a blueschist facies imprint of Eocene age.

The Penninic zone

Penninic is the classic name used to group the continental and oceanic nappes which issued from the distal European continental margin and the Mesozoic ocean (one or more branches), all belonging to the subducting lower plate. The original position of the ophiolitic units with respect to the spreading center (now lost) is unknown.

In the western Alps, the Penninic zone includes, from top to bottom: i) the ophiolitic Piedmont zone; ii) the inner-Penninic Dora-Maira, Gran Paradiso and Monte Rosa continental basement nappes; iii) the middle-Penninic Grand St. Bernard (Briançonnais) composite nappe system; iv) the lower-Penninic nappes of the Ossola-Ticino window, and outer-Penninic Valais zone, including ophiolitic units and/or flysch nappes, bounded by the Penninic frontal thrust; v) the Prealpine klippen, a stack of décollement cover nappes in the French-Swiss Alps which, at the onset of subduction, were detached from various units of the Austroalpine-Penninic wedge and later displaced over the Helvetic domain. In the central Alps, the Ossola-Ticino window (lower Penninic) is overlain, to the east, by the Tambo and Suretta continental nappes (middle-inner Penninic), capped in turn, as previously seen, by the Malenco-Avers ophiolite, Margna nappe and Platta ophiolite.

The outer-Penninic extends from the Valais zone (northwestern Alps) through the Grisons to the Rheno-Danubian flysch belt (eastern Alps), constituting the frontal part of the Penninic wedge. It is composed of décollement units, mainly Cretaceous (western side) or Cretaceous-Eocene siliciclastic to carbonatic turbidites, locally with pre-flysch sequences. A few ophiolitic fragments point to the oceanic origin of these deposits.

In the eastern Alps, the Penninic zone is exposed in the Engadine, Tauern and Rechnitz windows. The Tauern nappe stack consists of the ophiolitic Glockner nappe and the underlying basement and cover nappes of European origin (mid- and/or inner-Penninic), i.e., i) the Venediger-Zillertal and Tux, forming the core of two gigantic antiforms in the western side of the window; ii) the Granatspitz dome in the central window; iii) the Sonnblick, Siglitz, Hochalm-Ankogel, Gössgraben and Mureck units in the southeastern side.

The ophiolitic Piedmont zone and its eastern extension are subdivided into blueschist and eclogite facies units. Other differences concern the lithostratigraphic setting, varying between: i) carbonate to terrigenous flysch-type metasediments (calcschists s.l.), often including multiple interleavings of metabasalt and major ophiolitic bodies; ii) large slices of normal to anomalous oceanic lithosphere, consisting of antigorite serpentinites (from mantle peridotite), in places mantled by ophicarbonate-ophicalcite breccias (western Alps, Platta) and/or intruded by discontinuous metagabbro bodies, and overlain by massive to pillow tholeiitic metabasalts, manganiferous metacherts (Middle-Late Jurassic), impure marbles, syn-orogenic deposits, and subduction mélanges. Disregarding the metamorphic imprint, the former association roughly recalls the External Ligurides (Northern Apennines), which are characterized by mélanges and olistolith-rich flysch sequences, whereas the latter may be correlated with the slices of oceanic lithosphere of the Internal Ligurides.

Continental nappes of the Penninic zone are décolled cover units and large, generally thin basement slices, in places still carrying complete or partial cover sequences. The basement includes Variscan and locally older metamorphic units, intruded by Upper Paleozoic granitoids. The post-Variscan sedimentary cover begins with Upper Paleozoic and/or Lower Triassic clastic deposits (e.g., Grand St. Bernard, Tauern), followed by Triassic platform and Jurassic platform to basinal carbonate sequences, locally extending to the Cretaceous (internal Penninic) or Eocene (Briançonnais) synorogenic deposits. The entire zone is marked by a severe Alpine metamorphic overprint, with the exception of the Prealpine klippen. The internal Penninic basement in the western and central Alps displays eclogitic metamorphism (coesite-bearing in Dora Maira; Chopin, 1984, in Frey et al., 1999) of Eocene age, also recorded in a few lower Penninic basement nappes (e.g., Adula-Cima Lunga), whereas a blueschist facies imprint is shown by the Grand St. Bernard system. In contrast, the continental nappes of the Tauern window are dominated by a greenschist to amphibolite facies Barrovian overprint (collisional metamorphism), which obliterated most of the previous high-P features.

The Helvetic-Dauphinois zone

The Helvetic and Dauphinois zone (French part) consists of prominent crystalline duplexes, sedimentary cover units, and décollement nappes. Updomed basement thrust-sheets of metamorphic and granitoid composition are exposed in the Argentera-Mercantour, Pelvoux (Haut-Dauphiné), Belledonne-Grandes Rousses, Aiguilles Rouges-Mont Blanc and Aar-Gotthard external “massifs”. Polymetamorphic (Variscan and older) and monometamorphic (only Variscan) basement units may be distinguished, evolving from an Ordovician subduction cycle, through Variscan collision, nappe stacking and regional metamorphism, to Carboniferous erosion, orogenic collapse, later intrusions and wrench faulting. The Variscan basement is unconformably covered by thick sedimentary sequences of Late Carboniferous to Eocene/Oligocene age, characterized by early Mesozoic asymmetric fault-bounded rift basins and passive-margin sequences.

The Helvetic-Dauphinois domain was strongly deformed from the Late Oligocene onwards, when the orogeny propagated onto the proximal European margin. Rift faults were largely reactivated and inverted. Basement and cover units were accreted in front of the exhumed Austroalpine-Penninic collisional wedge, and partly recrystallized in anchizonal (deep burial diagenesis) to greenschist, locally amphibolite facies conditions (southern Gotthard).

The Helvetic and Ultrahelvetic nappes are décolled cover sheets and minor recumbent folds, mainly consisting of Mesozoic carbonates and Paleogene flysch which were detached along Triassic evaporites and Middle Jurassic and/or Lower Cretaceous shales. Similar cover sheets occur in the Subalpine Ranges (French Alps), west (Chartreuse) and south (Devoluy-Ventoux) of the Belledonne and Pelvoux massifs, where the Dauphinois sedimentary cover was detached and extensively deformed.

At the Swiss-Austrian boundary, the Helvetic zone dramatically narrows and, in the Eastern Alps, is reduced to some décollement cover sheets discontinuously exposed in front and below the Rheno-Danubian flysch belt.

Southern Alps

The Southern Alps are the typical example of a deformed passive continental margin in a mountain range (Bertotti et al., 1993). 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 Dinaric belt. From the Neogene, the Southalpine thrust-and-fold belt developed and progressively propagated towards the Adriatic foreland, mainly reactivating Mesozoic extensional faults (Castellarin et al., 1992). Its front is mainly buried beneath the alluvial deposits of the Po Plain and sealed by Late Miocene to Quaternary deposits. To the north, the Southern Alps are bounded by the Periadriatic lineament.

A complete crustal section of the Southern Alps is exposed at the surface: thick cover successions are dominant in the central (Lombardy) and eastern sector (Dolomites), whereas the basement is nearly continuous from the central sector (upper-intermediate crust: Orobic Alps and area of the Como-Maggiore lakes) to the western edge (Ivrea zone), where the lower continental crust crops out.

The crystalline basement includes various kinds of Variscan metamorphic rocks derived from sedimentary and igneous protoliths, later intruded by igneous bodies of Permian age. Among them is the famous Ivrea gabbro batholith, which was emplaced at the base of an attenuated gneissic crust (Kinzigitic complex). Below the Variscan unconformity regional metamorphism increases from very low-grade (Carnian Alps), to greenschist facies (Venetian region, east of Adamello), and medium- to high-grade conditions (central and western Southern Alps). This imprint predates exhumation, extensive erosion and the discordant deposition of a Westphalian (Lombardy, Ticino) to Lower Permian clastic and volcanic sequences. A new sedimentary cycle developed in the Late Permian, marked by continental deposits grading eastwards into shallow marine sediments. In the Triassic, the Southalpine domain was flooded and characterized by carbonate platform and basin systems, with regional evidence of andesitic-shoshonitic magmatism, mainly Ladinian in age. Rifting developed from the Norian to the early Middle Jurassic, leading to the opening of the Piedmont-Ligurian ocean, when the Austroalpine and Southalpine domains became the subsiding passive continental margin of Adria. Pre-existing structures were reactivated as normal faults and persisted to the Middle Jurassic, when pelagic deposition became dominant. The Cretaceous-Paleogene sequences are discontinuously preserved pelagic and flysch deposits, whereas most of the subsequent succession was eroded during the Oligocene-Present orogenic evolution and related uplift.

Geological history

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

Variscan and older evolution

The Paleozoic orogeny and Variscan collision gave rise to Pangea by the merging 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 collision in central Europe, but earlier events of Ordovician to Devonian age were later documented, suggesting the existence of an essentially continuous Paleozoic orogeny. Traces of older orogeny are locally preserved. As a whole, the pre-Permian evolution of the Alps may be summarized as follows:

1) U-P data on zircon and Nd model ages document a Precambrian history. The oldest zircons found in various polymetamorphic basement units refer to Precambrian clastic material eroded from extra-Alpine sources. The occurrence of Proterozoic-Early Cambrian ocean-floor 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 eastern Austroalpine and Helvetic basement units, with recycled Precambrian rocks, mafic-ultramafic ophiolites and marginal basin remnants. Subduction is inferred from the accretion of a Paleozoic orogenic wedge, eclogitic relics in mafic and felsic rocks, and calc-alkaline island-arc magmatism (460–430 Ma): these traces are mainly preserved in the Variscan metamorphic basement of a few Southalpine, Austroalpine and Helvetic-Dauphinois units.
3) The Silurian-Early Carboniferous continental collision (classic Variscan orogeny) generated crustal thickening by nappe stacking, low- to high-grade regional metamorphism in relaxed or thermally perturbated conditions, anatectic processes, post-nappe deformation, flysch deposition, and syn-orogenic igneous activity (350–320 Ma). In the Late Carboniferous, the collapsed Variscan belt was sealed by clastic deposits (Variscan unconformity) and intruded by post-orogenic plutons.

Permian-Mesozoic evolution

Variscan plate convergence ended around the Carboniferous-Permian boundary, when transcurrent and transtensive tectonics became dominant on the scale of the Eurasian plate. Asthenospheric upwelling, thermal perturbation and lithosphere attenuation marked the Early 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 an upper plate) and widespread igneous activity from asthenospheric sources. In the Austroalpine and Southalpine basement, igneous activity began with underplating of Early Permian gabbro batholiths, emplaced below and within rising segments of attenuated continental crust, and then recrystallizing under granulitic conditions. The heated crustal roof generated anatectic melts which partly migrated to upper crustal levels. This cycle is 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 in the Southern Alps, and was produced by extensional partial melting of previously enriched mantle sources (Variscan subduction). From the Late Triassic, continental rifting between Adria (Africa) and Europa generated the Alpine Tethys, a deep-water seaway marked first by listric faults, half-grabens and syn-rift deposits. Rifting ended in the Middle Jurassic 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 the evolution of oceanic crust from the Middle Bathonian onwards, coeval with the oldest occurrences in the Central Atlantic. The Austroalpine-Southalpine domains became the distal and proximal parts of the Adriatic continental passive margin, opposite the European margin formed by the Penninic and Helvetic-Dauphinois domains. The Adriatic margin is well recorded by the sedimentary successions in the Northern Calcareous Alps and the less deformed Southern Alps; the European margin by the Prealpine klippen, the metamorphic Briançonnais cover, and the better preserved Helvetic-Dauphinois sedimentary sequences.

Continental rifting was generated by simple shear mechanisms, probably with Europa as the 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 an exhumed and altered peridotitic basement (e.g., Aosta, Malenco and Platta areas) may be envisaged. This hypothesis is corroborated by ophicarbonate breccias and continental detritus deposited on top of mantle serpentinites, recalling modern exposures along ocean-continent transitions (Manatschal and Bernoulli, 1999). In this view, coherent continental remnants of the extremely thinned extensional upper plate may have been lost within the Tethyan ocean, as isolated allochthons and potential sources for the Austroalpine and Penninic continental nappes presently inserted between ophiolitic units. As previously seen, other ophiolitic units recall either fragments of normal oceanic lithosphere, or tectonic slices and olistoliths of oceanic suites inside dominantly turbiditic and other mass-flow deposits.

Restoration of the Tethyan ocean is a long and intriguing problem, mainly due to the occurrence in the central Alps of multiple ophiolitic units within the collisional zone. Indeed, the complex multilayer of the Alps may represent two or more oceanic branches, or may be merely the ultimate result of orogenic dispersal by polyphase folding and transposition. The Piedmont zone is the largest ophiolite in the Alps. It extends over most of the western Alps and reappears beyond the Ossola-Ticino 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 external Penninic domain from the north-western (Valais zone, Ossola-Ticino) to the central Alps (Grisons) and Engadine window. By classic kinematic inversion of the nappe stack, these ophiolitic units are thought to be derived, respectively, from the Piedmont (South-Penninic) ocean and a northern basin (North-Penninic), supposedly separated by the Briançonnais microcontinent. Alternative reconstructions include a single Jurassic ocean with ribbon continents and/or variously-sized extensional allochthons, or a younger development of the North-Penninic basin, supposedly opening during the closure of the Piedmont ocean.

Alpine orogeny

The Alpine orogeny began in the eastern Austroalpine and finally involved, step by step, 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 is tentatively related to the closure of a western branch of the Triassic Vardar ocean, possibly extending into the eastern Austroalpine domain through the Carpathians (Meliata ophiolite) 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 documented and the axial trend of the Triassic ocean (oblique 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 the 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 proximal European margin, clearly recorded by the eclogitic to blueschist facies 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 syn-collisional subduction and accretion. Wedge dynamics are enigmatic and are interpreted by: i) accretion of delaminated fragments of lithospheric microcontinents separated by oceanic channels; ii) tectonic erosion of the Adriatic active margin, inferred from the debated Cretaceous age of the subduction metamorphism also in the internal Penninic continental nappes; iii) accretion, by tectonic underplating, of originally thin crustal fragments resulting from an extensional upper plate (asymmetric rifting). In any case, exhumation of the high-P Penninic nappes was assisted by periodic extension in the wedge suprastructure, associated with nappe underplating at depth and active plate contraction.

From the late or latest Eocene (in differing areas), the cool, subduction-related regime was replaced by relaxed and perturbated thermal conditions. Indeed, the subduction complex was exhumed to shallower structural levels and overprinted by a Barrovian metamorphism of Late Eocene-Early Oligocene age (called Mesoalpine), characterized by a thermal gradient of 35 to 50°C/km (Frey et al., 1999). Soon after, a post-collisional magmatic cycle developed and was rapidly exhausted during the Oligocene (32–30 Ma). It is widely recorded along the Periadriatic fault system, from the lower Aosta valley to the eastern edge of the Alps (Bigi et al., 1990). Older magmatic products (42–38 Ma) only occur in the southern part of the Adamello batholith. The Periadriatic magmatism is represented by calc-alkaline to ultrapotassic plutons and dykes, which cut the northern part of the Southern Alps and the inner part of the Austroalpine-Penninic wedge. These bodies were generated by partial melting of lithospheric mantle sources previously modified during the Cretaceous-Eocene subduction. Generation and ascent of Periadriatic melts to upper crustal reservoirs were linked 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 in the Late Oligocene, when renewed collisional shortening disactivated the magmatic sources. Continuing plate convergence progressed externally, mainly through bilateral frontal accretion, coupled with vertical and horizontal extrusion and cooling of the Austroalpine-Penninic wedge. Indeed, segments of the foreland were accreted in front of the collisional wedge, as shown by the Helvetic basement slices and décollement cover nappes, displaced over the sinking Molasse foredeep. An opposite-vergent thrust-and-fold belt developed in the Southalpine upper crust, mainly generated by indentation of the Adria mid-lower lithosphere moving against the rear of the wedge. In the meantime, the overthickened Austroalpine-Penninic nappe stack underwent orogen-parallel tectonic denudation along low-angle detachments (e.g., Ratschbacher et al., 1991). Seismicity, GPS measurements and foreland subsidence give evidence of still active Adria/Europe convergence, with extensional and/or contractional tectonics in different sectors of the belt.

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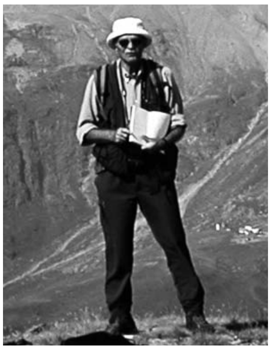
Giorgio V. Dal Piaz*, full professor of geology in the Faculty of Sciences of the University of Padova, Italy, was born in 1935 and his research activity focuses on field survey, tectonics, subduction metamorphism and hard rock geology in the Alps.*



Andrea Bistacchi *is PhD in Earth Sciences (University of Padova) and his work concentrates on post-nappe ductile to brittle tectonics in the Alps.*

Matteo Massironi *is PhD in Space Science and Technology and Lecturer of geological mapping in the University of Padova. He mainly works on remote sensing and tectonics in the Alps.*