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Structure and evolution of the Central Alps and their northern and southern foreland basins

*P. A. Ziegler *, S. M. Schmid *, A. Pfiffner ** & G. Schönborn ****

* Geological-Paleontological Institute,
University of Basel, Bernoullistr. 32,
CH-4056 Basel, Switzerland

** Geological Institute,
University of Bern, Baltzerstr. 1,
CH-3012 Bern, Switzerland

*** Insitut de Géologie,
Universite de Neuchâtel, rue E. Argand 11,
CH-2000 Neuchâtel, Switzerland

ABSTRACT

A combined geological and deep reflection- and refraction-seismic profile crossing the Central Alps helps to unravel the crustal structure of this classical orogenic belt which had been the focus of pioneering geologists since he middle of the 18th century. New insights were gained by integrating the stratigraphic, structural, geochronologic and metamorphic record of the Alpine nappe systems and of the northern and southern foreland basins with new geophysical data on the deep structure of the Alps.

The Central Alps developed in response to Middle and Late Cretaceous dextral oblique partial or complete closure of oceanic basins, which had opened during Middle Jurassic to Early Cretaceous times, and to Paleogene orthogonal full-scale collision of the Apulian block with the European craton. Neogene continued convergence, accompanied by dextral transpression, resulted in thrust-propagation into the forelands and partial destruction of the flexural northern and southern foreland basins.

Across the Central Alps, Cenozoic N-S plate convergence amounting to 500 to 550 km was accompanied by subduction of substantial amounts of continental and oceanic lithospheric material. Following Paleogene collision of the Alpine orogenic wedge with the little attenuated northern foreland, Neogene back-thrusting governed the evolution of its southern parts. Imbrication of the northern and southern foreland crust, resulting in uplift of basement cored external massifs, is a consequence of continued post-collisional crustal shortening and lithospheric overthickening.

The Molasse Basin was displaced together with the Jura Mountain fold-and-thrust belt which represents the northernmost external unit of the Central-Alpine orogen. The Molasse Basin is a remnant of a fore-arc foreland basin. The thin-skinned external South-Alpine thrust belt scooped out an Early Mesozoic rift-induced basin, causing partial destruction of the southern, conjugate retro-arc foreland basin.

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This article includes 1 enclosure.

INTRODUCTION

This paper discusses the structure and evolution of the Central Alps on the basis of a regional geological-geophysical cross section which extends from the Molasse Basin of Eastern Switzerland into the Po Basin near the city of Milano. Supporting structural cross-sections are provided for the eastern and central parts of the Swiss Molasse Basin and the southern margin of the Southern Alps.

The geotransect, given in Enclosure 1, integrates surface and sub-surface geological data with refraction-seismic and deep reflection-seismic data. Geophysical data were acquired in the context of the Swiss National Research Project 20 (NFP-20; Pfiffner et al., 1988, 1996) and during the recording of the European Geotraverse (Blundell et al., 1992). This transect crosses the Central Alps where the external massifs plunge axially to the east-northeast and straddles the western erosional margin of the Austoalpine nappes (Fig. 1). This permits axial projection into the plane of the section of major structural units, including the basement-involving Aar and Gotthard massifs, the supra-crustal Helvetic and Penninic nappes and the orogenic lid, formed by the Austoalpine nappes. Correspondingly, this profile gives also a possible reconstruction for the eroded parts of the Alpine orogen (Schmid et al., 1996a and 1996b).

The Central Alps developed in response to Cretaceous and Cenozoic convergence of Africa-Arabia and cratonic Europe. This involved progressive closure of three oceanic basins which had opened during the Mesozoic break-up of Pangea and the development of the Tethys (Fig. 2). The oldest of these oceanic basins is the Hallstatt-Meliata Ocean which opened during the Middle Triassic along the eastern margin of the continental Apulia terrane (Italo-Dinarid Block); this ocean may have formed part of the Hellenic-Dinarid basin, referred to also as the Vardar Ocean. The second oceanic basin is the South Penninic (Piemont-Ligurian) Ocean which opened during the Middle Jurassic between Apulia and the continental Briançonnais domain. The third oceanic basin is the North Penninic (Valais) Trough which opened during the Early Cretaceous, thus separating the Briançonnais terrane from the Helvetic Shelf; the latter formed the southern continental margin of cratonic Europe.

In Enclosure 1, different signatures are given for continental basement complexes which are attributed to the proximal and distal parts of the European margin, the Middle Penninic Briançonnais terrane and the Austoalpine and South Alpine parts of Apulia. Ophiolitic sequences, corresponding to the floor of the former North Penninic Valais and the South Penninic-Piemont-Ligurian ocean, are highlighted in black. The Hallstatt-Meliata ocean is not involved in the area of the Central Alps, although its Late Jurassic closure did play a significant role in the evolution of the Austroalpine nappes (Stampfli et al., 1991; Froitzheim et al., 1996)

Enclosure 1 illustrates clearly that during the the Alpine orogeny the European and the Apulian margins were intensely deformed and that these deformations were not restricted to their sedimentary cover but involved large-scale imbrications of the basement which propagated far into the foreland. The autochthonous basement of the Molasse Basin extends only some 20 km beneath the external units of the Alps and rises to the surface in the imbricated Aar Massif. The Oligocene to Miocene synorogenic clastic wedge of the Molasse Basin attains a thickness of some 4000 m and is underlain by a relatively thin sequence of Mesozoic shelf series. Late Miocene and Pliocene compressional deformation of the Jura Mountains, attributed to in-sequence thrust propagation into the foreland, caused uplift and erosion of the western and central parts of the Molasse Basin (Laubscher, 1974; see also Philippe et al. and Roure and Colletta, this volume). Exploration for hydrocarbons in the Swiss Molasse Basins has yielded only oil and gas shows and one very small gas accumulation (Brink et al., 1992). In contrast, the southern margin of the Central Alps is characterized by a relatively wide, thin-skinned foreland fold-and-thrust belt involving a thick, southward tapering wedge of Mesozoic and Paleogene series overlain by synorogenic clastics (Cassano et al., 1986). To the north, this thin-skinned thrust belt gives way to a system of major basement imbrications such as the Orobic and Mezzoldo (Colitignone unit) blocks (Laubscher, 1985; Schönborn, 1992; Roeder and Lindsay, 1992). The discovery of major hydrocarbon accu-

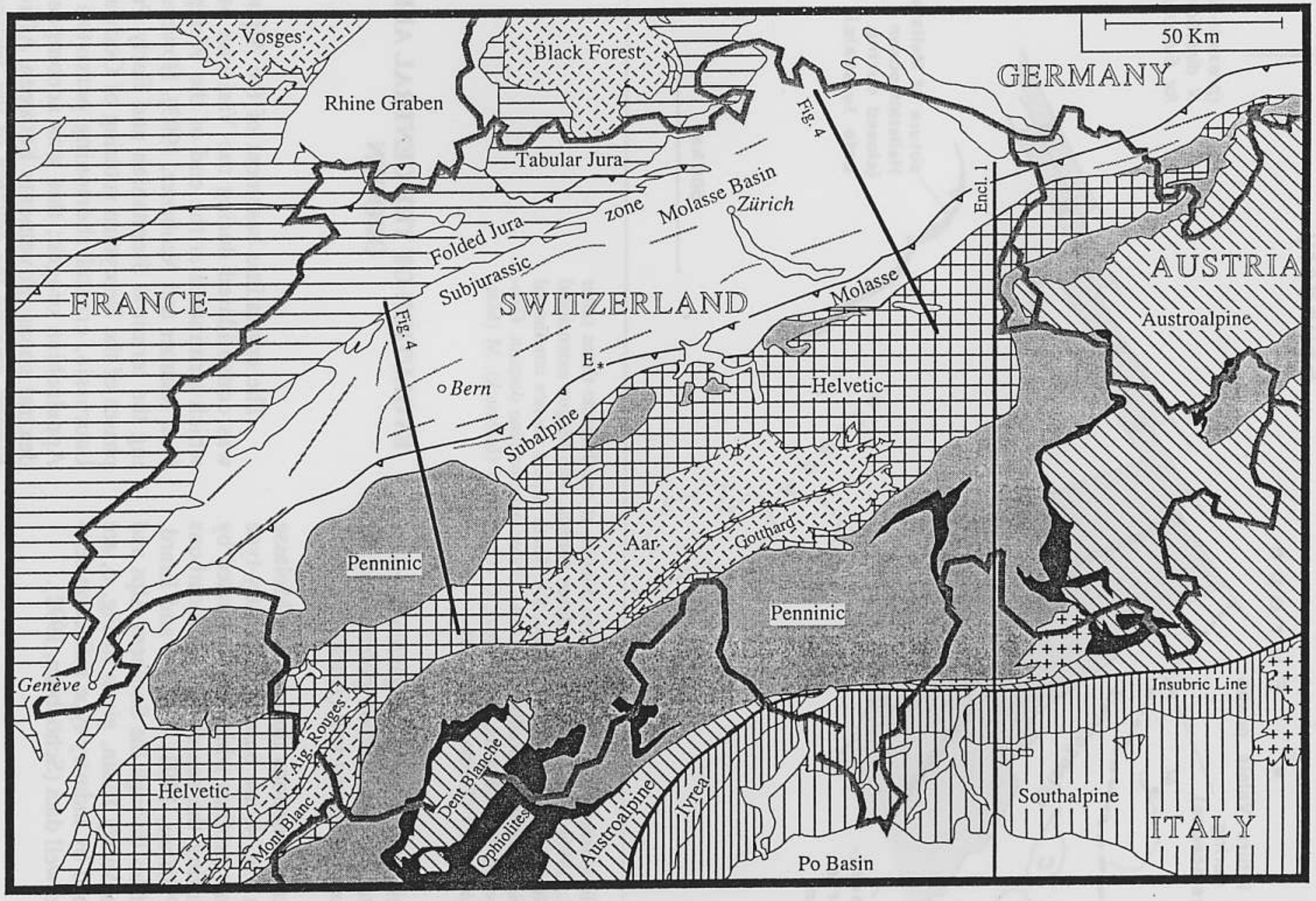


FIG. 1. Tectonic map of the Swiss Alps, showing major structural units and traces of cross-sections given in Fig. 4 and Encl. 1. Gray lines in Molasse Basin: major anticlines. E: Entlebuch gas accumulation. +: Tertiary intrusions. Narrow and wide spaced pattern in South-Alpine domain corresponds to crystalline basement and Mesozoic sediments, respectively.

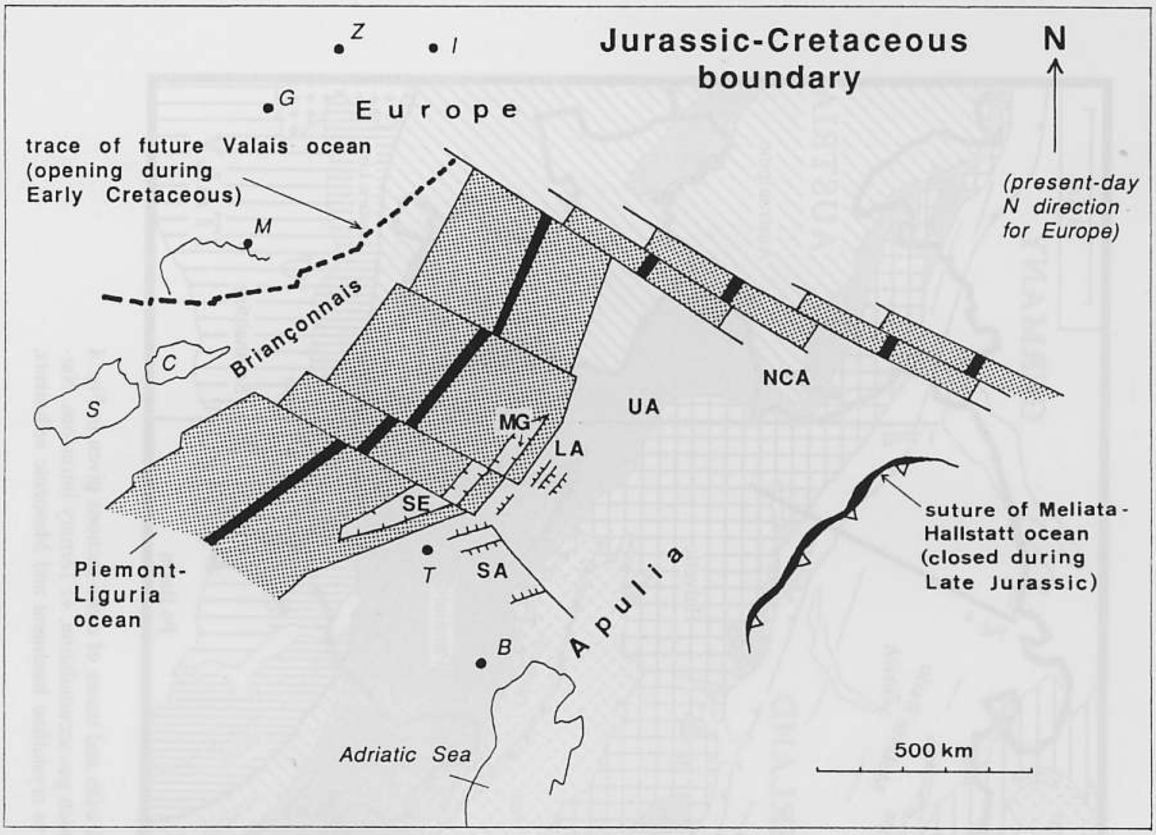


FIG. 2. Palinspastic sketch map of Alpine domain at end-Jurassic times (after Schmid et al., 1996b). LA: Lower Austroalpine domain, MG-Magua extensional allochthon, NCA: Northern Calcareous Alps, SA: South Alpine passice continental margin, SE-Sesia extensional allochthon, UA: Upper Austroalpine domain. Geographic reference: B (Bologna), C (Corsica), G (Geneva), I (Insbruck), M (Marseilles), S (Sardinia), T (Torino), Z (Zürich).

mulations, such as the Malossa gas/condensate field, testifies to the hydrocarbon potential of the South-Alpine external thrust belt (Anelli et al., this volume).

The two cross-sections through the Molasse Basin, given in Fig. 4, are based on industry-type reflection-seismic profiles which are calibrated by wells drilled during the search for hydrocarbons (Stäuble and Pfiffner, 1991; Pfiffner and Erard, 1996). The profiles through the Southern Alps and the adjacent Po Valley Basin, given in Fig. 6, are partly constrained by industry-type reflection-seismic profiles and well data (Schönborn, 1992).

EVOLUTION OF THE CENTRAL ALPINE OROGEN

The crystalline basement of the Alpine area was consolidated during the Variscan orogeny which terminated at the end of the Westphalian (von Raumer and Neubauer, 1993). However, during the terminal Stephanian and Early Permian phases of the Hercynian suturing of Godwana and Laurussia, crustal shortening persisted in the Appalachian orogen; this was accompanied by dextral shear movements between Africa and Europe, causing the collapse of the Variscan orogen and the subsidence of a system of wrench-induced troughs in which thick continental clastics accumulated. Following the Early Permian assembly of Pangea, a fundamental plate boundary reorganization underlies the development of the Tethys and Arctic-North Atlantic rift systems (Ziegler, 1990).

Opening of The Alpine Tethys Segment

During Late Permian and Triassic times, the Tethys rift systems propagated westward and interferred in the North Atlantic domaine with the southward propagating Arctic-North Atlantic rift system. In the East Alpine-Carpathian-Dinarid domain, rifting activity culminated in the intra-Triassic opening of a first system of oceanic basins, namely the Hallstatt-Meliata and Vardar oceans; these were possibly connected (Fig. 2). Following Middle Jurassic development of a discrete transform-divergent plate boundary between Gondwana and Laurasia, progressive opening of the Central Atlantic was accompanied by a sinistral transtensional translation of Africa-Arabia relative to Europe. This led to the opening of a second oceanic basin in the Alpine domain, the Liguria-Piemont-South Penninic oceanic basin, resulting in the isolation of the Apulian (Italo-Dinarid) microcontionent. Opening of the Ligurian-South Penninic Ocean went hand in hand with the gradual closure of the earlier formed Vardar and Hallstatt-Meliata oceans (Fig. 2). Latest Jurassic-earliest Cretaceous collision of the Apulia terrane with the eastern margins of the Vardar and Hallstatt-Meliata oceans and continued sinistral translation between Europe and Africa entailed the onset of counter-clockwise rotation of Apulia. This sequence of events indicates that opening of the Ligurian-South Penninic Ocean was neither spacially nor kinematically related to the opening of the Hallstatt-Meliata and Vardar oceans (Ziegler, 1988, 1990; Dercourt et al., 1993).

Early Cretaceous gradual opening of the North Atlantic and couter-clockwise rotation of Apulia were accompanied by the transtensional opening of a third oceanic basin in the Alpine domain, the North Penninic Valais Trough. The trace along which this youngest oceanic basin opened is shown in Figure 2, giving a latest Jurassic-earliest Cretaceous palinspastic sketch map of the Alpine region. Opening of the Valais Trough entailed separation of the continental Briançonnais terrane from Europe. It is questionalble whether the Briançonnais terrane formed part of the larger Iberian terrane, as postulated by Stampfli (1993), who visualizes a kinematic link between the opening of the Bay of Biscay and the Valais Trough. In this respect, data presente by Vially and Trémolières (this volume) suggest that the Corsica-Sardinia block remained attached to Europe during the Cretaceous opening of the Bay of Biscay and that the suture between Europe and Iberia projects from the Pyrenees to the south of Sardinia (after palinspastic restoration of the Corsica -Sardinia block; see also Ziegler, 1988). The eastern continuation of the Valais Trough is probably found within or near the northern margin of the earlier formed Piemont-Liguria Ocean (Rhenodanubian flysch and Upper Schieferhülle of the Tauern window, Outer Carpathian flysch belt). Correspondingly, the Briançonnais terrane is essentially confined to the Central and Western Alps. Relative movements between the European and Africa-Arabian continents and intervening microplates or terranes, leading to the opening and closing of oceanic basins in the Alpine domain, is discussed in greater detail by Stampfli (1993), Stampfli and Marchant (1996), Froitzheim et al. (1996) and Schmid et al. (1996a and 1996b).

Cretaceous Orogeny

Induced by the Cretaceous counter-clockwise rotation of Apulia, mass transport along its northwestern margin, facing the South Penninic-Piemont-Ligurian Ocean, was directed westwards. In the area of the Austroalpine units of Austria, closure of the Hallstatt-Meliata Ocean had occurred during a first stage in the Early Cretaceous (Neubauer, 1994). During the Cenomanian to early Turonian second stage of the Cretaceous orogeny, a dextral thrust wedge propagated westwards into the Central Alpine domain (see Schmid et al., 1996a and 1996b for a discussion of constraints on timing of orogenic activity along our transect). Subduction processes during both stages are indicated by the occurrence of Cretaceous-aged HP/LT eclogites which must be related to the activation of subduction zones along the former Meliata Ocean as well as along the northwestern margin of Apulia (Froitzheim et al., 1996). Late Cretaceous west-vergent imbrications and penetrative deformations, partly associated with metamorphism, are also observed in the Western Alps (France, Italy) and in the Eastern Alps (Austroalpine nappes), as discussed by Polino et al. (1990), Ring et al. (1989) and Froitzheim et al. (1994). The Austroalpine nappes were emplaced as thin allochthonous flakes onto the South Penninic ophiolites. This Late Cretaceous orogenic activity was accompanied by the shedding of clastics into the gradually closing South Penninic Trough. The Insubric Line marks the boundary between Austroalpine nappes, which are characterized by Cretaceous metamorphism, and the South Alpine domain which lacks such an overprint (Laubscher, 1991). However, in the South-Alpine domain, there is also good evidence for a Late Cretaceous first stage activation of the south-verging, basement involving Orobic and Gallinera foreland thrusts (Schönborn, 1992). These rising ramp anticlines acted as the source of the Turonian to Campanian flysch series which were deposited in the Lombardian Basin, located to the South of the South-Alpine domain (Bichsel and Häring, 1981; Bersezio and Fornaciari, 1987; Wildi, 1988; Bernoulli and Winkler, 1990).

Paleogene Orogeny

In conjunction with the Late Cretaceous and Paleogene step-wise opening of the Arctic-North Atlantic, sinistral motions between Europe and Africa decreased during the latest Cretaceous and Paleogene; with this the rotational movement of Apulia decreased gradually and westward mass transport along its northern margin came to an end. However, in connection with the progressive break-up of Gondwana, Africa-Arabia commenced to converge during the Senonian with Europe in a counter-clockwise rotational mode; this motion persisted during Cenozoic times (Ziegler, 1988, 1990) and controlled the collisional and post-collisional phases of Alpine orogeny.

During the late Senonian, the Austroalpine nappe stack was affected by tensional tectonics. This so-called Ducan-Ela extensional phase is viewed by Froitzheim et al. (1994) as reflecting the gravitational collapse of an overthickened orogenic wedge upon relaxation of the stress systems controlling its development. Exhumation and cooling of the Austroalpine units during the Ducan-Ela phase had severe implications for the subsequent evolution of the Central Alps. During the Cenozoic orogenic phases, the Austroalpine units remained largely undeformed and acted as a relatively rigid orogenic lid (in the sense of Laubscher, 1984), floating on viscously deforming Penninic units.

In our transect, the South Penninic Ocean was not closed before the end of the Cretaceous. The evolving orogen, which during the Late Cretaceous had been confined to the southeastern margin of the Piemont-Liguria Ocean and the Austroalpine-South-Alpine domain, collided in the Central Alpine region during the Paleocene with the southern margin of the Middle Penninic Briançonnais terrane (Figs. 3a and 3b; for timing constraints see Schmid et al., 1996a). However, in the Western Alps, collision of the evolving orogen with the Briançonnais terrane did not occur before the Oligocene, as evident by ophiolitic nappes overriding late Eocene pelagic series (Barféty et al., 1992).

During the Senonian, and particularly during the Paleocene, the European Alpine foreland was subjected to horizontal compressional stresses which gave rise to important intra-plate deformations, including the upthrusting of basement blocks and the inversion of Mesozoic tensional basins as far North as Denmark and the Central North Sea (Ziegler, 1990; Ziegler et al., 1995). In the area of the Central Alps, large parts of the Helvetic Shelf were uplifted at the end of the Cretaceous and subjected to erosion; this is confirmed by latest Cretaceous and Paleocene fission-track data from the Black Forest area (Wagner and van den Houte, 1992). Regional uplift and large radius deformation of the Helvetic Shelf caused the removal of much of its previously deposited Cretaceous cover and truncation and karstification of the Jurassic platform carbonates particularly in the area of the Jura Mountains, the Molasse Basin and the North Helvetic domain (Trümpy, 1980). Although the Paleocene deformation of the Helvetic Shelf of Switzerland was not as intense as further to the East in the area of the Bohemian Massif and the southward adjacent Austrian Molasse Basin (Zimmer and Wessely, this volume), its positive deflection must be related to compressional stresses which were exerted on the Alpine foreland in response to its collisional coupling with the evolving orogen (Ziegler, 1990; Ziegler et al., 1995). However, as by the end of the Cretaceous the Alpine orogenic front was still located along the southern margin of the Briançonnais terrane, it must be assumed that the lithosphere of the Valais Trough had sufficient strength to permit the transmission of large stresses through it and into the European foreland.

Along our transect, subduction of the Briançonnais microcontinent had commenced during the Paleocene and by the early Eocene this terrane was completely subducted together with the oceanic parts of the Valais Tough (Schmid et al., 1996b; Figs. 3a and 3b). By early Eocene times, the southern margin of the European foreland, corresponding to the Adula nappe, started to be overridden by the advancing more internal nappe systems of the Central Alps; subsequently it was subducted to great depth, as indicated by a Tertiary aged eclogite facies metamorphism (Figs. 3c and 3d; for timing of eclogite facies metamorphism in the Alps see Froitzheim et al., 1996). By late Eocene time, the Austroalpine and North Penninic nappes had advanced into the area of the future Gotthard massif which corresponds to the crystalline substratum of the future Helvetic cover-nappes (Fig. 3c). This led to the progressive flexural subsidence of the Helvetic Shelf under the load of the advancing orogenic lid, resulting in the development of a classical flexural foreland basin. By late Eocene time, marine transgressions had advanced northwards across the truncated Mesozoic strata to the southern margin of the present day Molasse Basin (Pfiffner, 1986; Lihou, 1995). Flexural subsidence of this foreland basin was accompanied by the development of an array of relatively small, essentially basin-parallel normal faults (Herb, 1965, 1992). Synsedimentary faulting is indicated by rapid lateral facies and thickness changes of Eocene sediments, containing large slump blocks of carbonates (Menkveld-Gfeller, 1995); this points to a considerable, fault-related relief in the Helvetic facies domain. During the Eocene-Oligocene phases of nappe emplacement onto the European foreland, the latter was apparently mechanically decoupled from the orogen, as there is no evidence for contemporaneous intraplate compressional deformations.

Detachment of the sedimentary cover of the Gotthard massif, resulting in the development of the Helvetic nappes, commenced during the late Eocene; by early Oligocene time, the Helvetic nappes, together with the overlying North Penninic and Austroalpine nappes, had advanced into the area of the future Aar massif (Figs. 3c and 3d). During the Paleocene and Eocene phases of the Alpine orogeny, substantial parts of the crust of the Briançonnais, the North-Penninic realm and the distal parts of the European foreland were subducted. However, the entire upper crustal volume of the more proximal and less attenuated part of the European crust (Gotthard and Lucomagno-Leventina units) was accreted to the orogenic wedge during the Oligocene and later phases. Resulting post-Eocene excessive thickening of the orogenic wedge implies that, following the main collisional event, only lower crustal material was subducted. Overthickening of the orogenic wedge was accompanied by south-directed back-folding north of, and back-thrusting along, the Insubric Line, causing rapid exhumation of the formerly deeply buried supra-crustal units in the Penninic (Lepontine) area during the Oligocene, as well as by thrust propagation into the northern foreland crust, resulting in step-wise imbrication of the Gotthard and Aar massifs and detachment of the Helvetic cover-nappes. In the Southern Alps, late Oligocene dextral transpressive movements along the Insubric Line induced in the area of the Lago Maggiore restraining bend East-West directed compressional deformations (Figs. 3e and 3f; Schumacher et al., 1996).

Oligocene post-collisional overthickening of the Alpine orogenic wedge was associated with the onset of northwestward movement of the rigid Adriatic indenter, south of the Periadriatic line (Schmid et al., 1989). This indenter is composed of stacked Apulian and European lower crustal and mantle material at its western end (Ivrea Zone and Ivrea geophysical body, Fig. 3e). In map view this indentation is associated with dextral strike slip

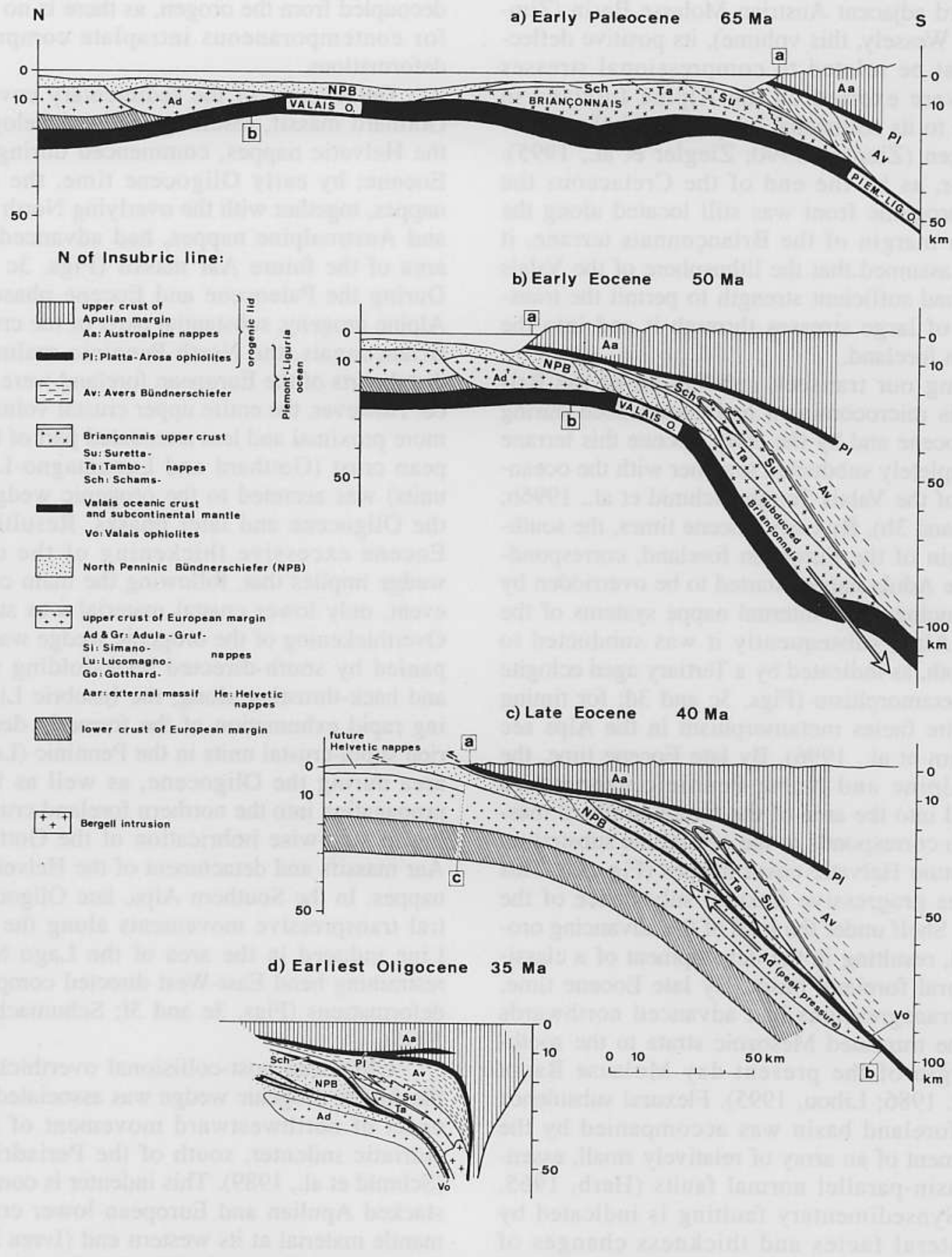
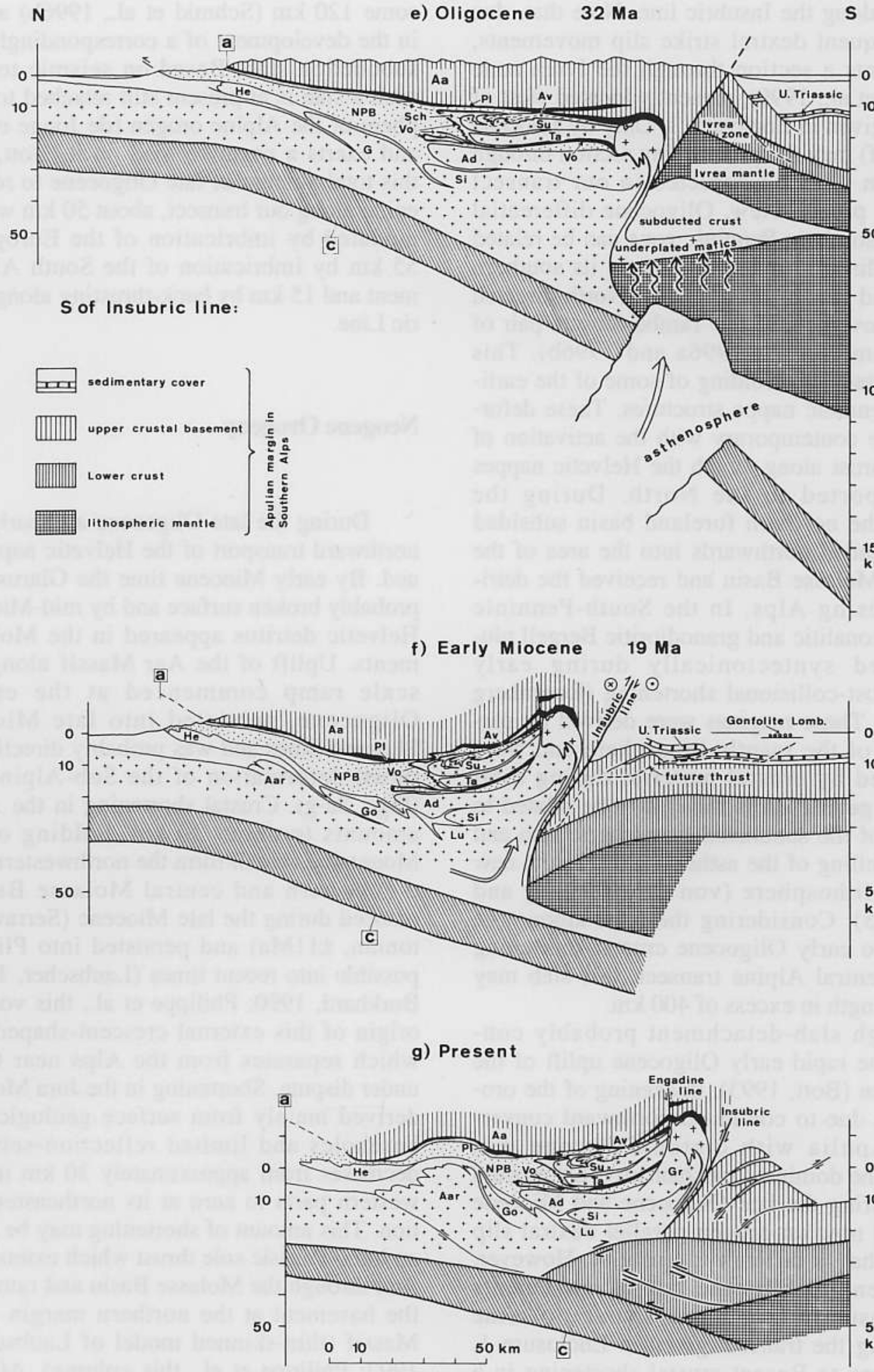


FIG. 3. Retro-deformed cross-sections through the Central Alps showing step-wise evolution of the Alpine orogen (after Schmid et al., 1996b).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sedimentary cover
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Lower crust
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Apulian margin Southern Alps
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movements along the Insubric line. Note that, due to the subsequent dextral strike slip movements, Fig. 3e depicts a section through the Ivrea zone (after Zingg et al., 1990), presently located west of the transect given in Enclosure 1. Only by Miocene times (Fig. 3f) may the present-day section through the Southern Alps be depicted in our transect (Fig. 3f). In profile view, Oligocene differential uplift of the southern Penninic zone can be related to upwards directed material flow in its southern steep belt and its deflection into a North-directed horizontal movement of the Tambo-Suretta pair of nappes (Schmid et al., 1996a and 1996b). This induced spectacular refolding of some of the earlier formed Penninic nappe structures. These deformations were contemporary with the activation of the Glarus thrust along which the Helvetic nappes were transported to the North. During the Oligocene, the northern foreland basin subsided rapidly, expanded northwards into the area of the present-day Molasse Basin and received the detritus of the rising Alps. In the South-Penninic domain, the tonalitic and granodioritic Bergell pluton intruded syntectonically during early Oligocene post-collisional shortening (Rosenberg et al., 1995). These magmas were derived by partial melting of the mantle lithosphere and were contaminated by crustal material during their ascent; their generation is thought to be related to detachment of the subducted lithospheric slab and ensuing upwelling of the asthenosphere to the new base of the lithosphere (von Blankenburg and Davies, 1995). Considering the total amount of Cretaceous to early Oligocene crustal shortening along our Central Alpine transect, this slab may have had a length in excess of 400 km.

Although slab-detachment probably contributed to the rapid early Oligocene uplift of the Alpine orogen (Bott, 1993), thickening of the orogenic wedge due to continued northward convergence of Apulia with cratonic Europe was presumably the dominant mechanism. This process continued during the late Oligocene and Miocene but included now an orogen parallel dextral slip component that is difficult to quantify. However, late Oligocene to Miocene lateral movements along the Insubric Line alone amount to some 50 km. Along the transect given in Enclosure 1, late Oligocene to Recent crustal shortening in a North-South direction is estimated to amount to some 120 km (Schmid et al., 1996b) and resulted in the development of a correspondingly long new subduction slab. Based on seismic tomography, such a slab is at present still attached to the lithosphere of the Alpine orogen (de Jonge et al., 1993) and exerts a negative load on it (Bott, 1993). Of this total amount of late Oligocene to recent shortening along our transect, about 50 km were accommodated by imbrication of the European crust, 55 km by imbrication of the South Alpine basement and 15 km by back-thrusting along the Insubric Line.

Neogene Orogeny

During the late Oligocene and early Miocene, northward transport of the Helvetic nappes continued. By early Miocene time the Glarus thrust had probably broken surface and by mid-Miocene time, Helvetic detritus appeared in the Molasse sediments. Uplift of the Aar Massif along a crustal scale ramp commenced at the end of the Oligocene, persisted into late Miocene and Pliocene times and was probably directly linked to thrust deformation of the Sub-Alpine Molasse (Figs. 3e-g). Crustal shortening in the Aar Massif amounts to about 20 km. Folding of the Jura Mountains, which form the northwestern margin of the western and central Molasse Basin, commenced during the late Miocene (Serravallian/Tortonian, ±11Ma) and persisted into Pliocene and possible into recent times (Laubscher, 1987, 1992; Burkhard, 1990; Philippe et al., this volume). The origin of this external crescent-shaped fold belt, which separates from the Alps near Geneva, is under dispute. Shortening in the Jura Mountains, as derived mainly from surface geological criteria, boreholes and limited reflection-seismic data, decreases from approximately 30 km in its southwestern parts to zero at its northeastern termination. This amount of shortening may be taken up at an intra-Triassic sole thrust which extends from the Jura through the Molasse Basin and ramps down to the basement at the northern margin of the Aar Massif (thin-skinned model of Laubscher, 1961, 1992; Philippe et al., this volume). Alternatively, shortening may be transferred to an intracrustal a sole thrust, incorporating Permo-Carboniferous sediments and the upper parts of the crystalline basement, which extends from the the Jura Mountains through the area of the Molasse Basin beneath the Aar Massif (thick-skinned model; Ziegler, 1982, 1990; Pfiffner and Erard, 1996; Pfiffner, 1995). Burkhard (1990) notes that shortening in the Sub-Alpine Molasse increases northeastwards as shortening in the Jura Mountains decreases in the same direction. He postulates a 7o clock-wise rotation of the Mesozoic and Cenozoic sediments of the Molasse Basin above a basal detachment horizon and along a system of wrench faults. Folding of the Jura Mountains entailed uplift and partial destruction of the Molasse Basin. The degree of uplift of this basin increases towards the southwest as shortening in the Jura Mountains increases. According to both the thin-skinned and the thick-skinned model, the Molasse Basin and the Jura fold-and-thrust belt form part of a major allochthon which represents the most external element of the Central Alpine orogen.

Back-thrusting of the South Penninic nappes over the South Alpine domain along the Insubric Line persisted during the late Oligocene under a dextral transpressive scenario; however, by Miocene times, movements along the Insubric Line were purely dextral (Schmid et al., 1989; Figs. 3e-g). Pebbles and boulders of the Bergell pluton appeared during the latest Oligocene-earliest Miocene in the deeper water Lombardian foreland basin (Gonfolite Lombardia; Giger and Hurford, 1989). In most of the Southern Alps, Tertiary-aged thrusting did not resume before the mid-Burdigalian (Schönborn, 1992). The external, thin-skinned Lombardy thrust belt is sealed by the Messinian unconformity and is covered by up to 2.5 km of latest Miocene and Plio-Pleistocene, only slightly folded clastics. Uplift of the internal parts of the Southern Alps is related to the stacking upper crustal thrust sheets which were detached at a mid-crustal level. The corresponding lower crust and mantle lithosphere forms the Adriatic or Apulian wedge which interfaces with the south-dipping European lower crust beneath the Central Alps (Encl. 1 and Fig. 3g). The geometry of this wedge is, according to the resolution of the geophysical data available, only schematically outlined in Enclosure 1. In fact, this highly reflective wedge may have a more complicated internal structure (Hitz, 1995). However, for material balance reasons, imbrication of lower crustal material within this Adriatic wedge is a corollary of some 46 km Miocene-aged N-S shortening taking place within the South Alpine upper crustal fold- and thrustbelt (Schönborn, 1992; Schmid et al., 1996a and 1996b). Hence, shortening at upper crustal levels south of the Insubric line is kinematically linked to thickening within the Apulian wedge located beneath the southern part of the Central Alps. Formation of this Neogene wedge post-dates back-thrusting along the Insubric line and thrusting of the Helvetic nappes; however, it is contemporaneous with shortening in the external massifs and the Molasse-Jura allochthon (Laubscher, 1991).

The Central Alpine orogen is at present tectonically still active as evident by earthquake activity and an uplift rate of about 1 mm/year. Within the Central Alps, earthquake hypocentres are concentrated in the upper crust whereas in the Molasse Basin they are distributed over the entire crust. Focal mechanisms indicate that the crust of the Molasse Basin is affected by sinistral and dextral shear with the principal horizontal compressional stress trajectories trending NW-SE, compatible with the overall stress fied of Central Europe (Pavoni, 1990; Deichmann and Baer, 1990; Balling and Banda, 1992; Grünthal and Strohmeyer, 1994).

MOLASSE BASIN

The Swiss Molasse Basin is limited to the northwest by the Jura Mountains and to the southeast by the Alps (Fig. 1). Its sedimentary fill consists of a southeastward expanding, up to four kilometres thick wedge of Oligocene and Miocene sandstones, conglomerates and shales, derived from the Alpine orogen, which rests unconformably on truncated Mesozoic carbonates, shales and clastic rocks, ranging in thickness between 1.5 and 3 km. The latter overlay a Variscan basement complex and, more locally, several kilometres thick Permo-Carboniferous clastics contained in fault-bounded, wrench-induced troughs (Fig. 4, Encl. 1).

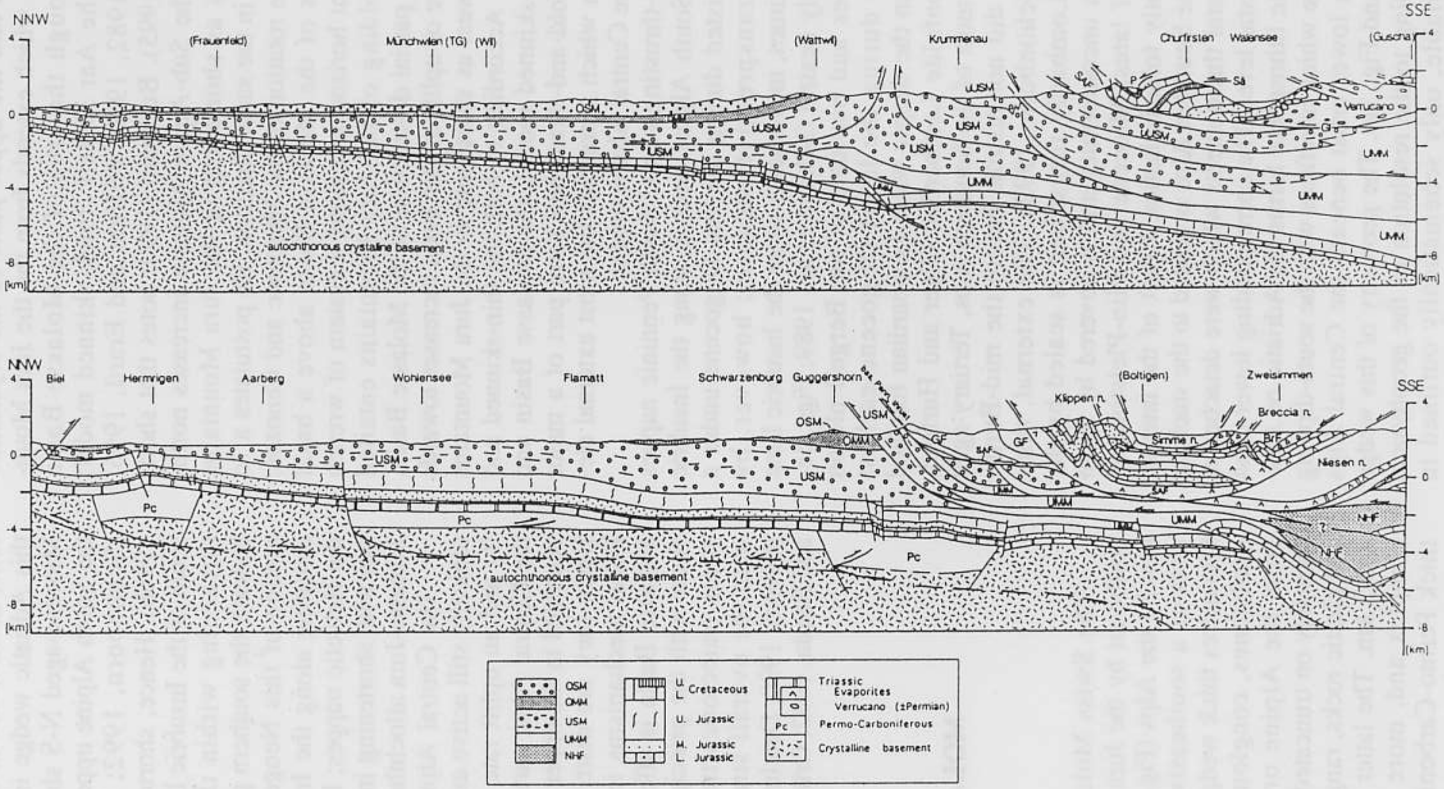

FIG. 4. Structural cross-sections through the eastern (top) and central (bottom) Molasse Basin (modified from Pfiffner and Erard, 1996). The basin fill is cut by numerous faults and thrust faults in the internal part, the Subalpine Molasse. The western cross-section shows fault-bounded Permo-Carboniferous basins, which were partly inverted; the top of the crystalline basement is shown to be allochthonous, in agreement with the Jura Mountains as a thick-skinned fold-and-thrust belt. OSM: Upper Freshwater Molasse, OMM: Upper Marine Molasse, USM: Lower Freshwater Molasse, UMM: Lower Marine Molasse; NHF: North-Helvetic Flysch, SAF: Sub-Alpine Flysch, P: Penninic nappes, GF: Gurnigel Flysch, Gl: Glarus thrust, Sä: Säntis thrust.

The Mesozoic evolution of the area occupied by the Swiss Molasse Basin was dominated by regional tensional stress regimes related to the break-up of the Late Palaeozoic Pangea. Its latest Cretaceous and Tertiary evolution was governed by the development of the Alpine orogen and the folding of the Jura Mountains. The Cenozoic Rhine-Rhône rift system influenced the evolution of the Molasse Basin only marginally (Trümpy, 1980; Ziegler 1990, 1994).

Basin Evolution

The crystalline basement underlying the Swiss Molasse Basin was consolidated during the Variscan orogeny which terminated at the end of the Westphalian. Stephanian-Autunian wrench-faulting gave rise to the subsidence of often narrow and deep fault-bounded troughs in which continental clastics, partly coal-bearing and containing lacustrine shales, accumulated. At the same time the Variscan fold belt was uplifted and deeply eroded. Late Permian, Triassic and Early Jurassic series transgressed, under a regional tensional setting, over this erosional surface from the Northeast and the Southwest and onlapped against the Alemannic High, coinciding partly with the area of the present Aar Massif. This led to the gradual establishment of a broad basin which occupied the area of the future Swiss and German Molasse Basin, extended northwestwards into the Paris Basin and was linked to the North with the Northwest European Basin (Ziegler, 1990; Bachmann et al., 1987). Following Mid-Jurassic crustal separation in the South-Penninic domain, the Alemannic High subsided and a wide carbonate and shale platform occupied during the Middle and Late Jurassic and the Cretaceous the Helvetic Shelf. This broad shelf occupied large parts of southern Germany and extended through the area of the future Swiss Molasse Basin into the Paris Basin. Early Cretaceous tectonic instability of this shelf, reflected by subsidence anomalies (Funk, 1985; Loup, 1992), can be related to the transtensional opening of the Valais Trough and to rifting activity in the North Sea and the Bay of Biscay. Palaeogeographic reconstructions suggest that the entire Helvetic Shelf was once covered by Late Cretaceous carbonate-dominated sediments. During the latest Cretaceous and Paleocene large parts of the Helvetic Shelf were uplifted and mildly deformed in response to compressional stresses exerted on it from the collision zone between the Alpine orogen and the Briançonnais block. This uplift, which reflects broad lithospheric buckling and smaller scale crustal deformations, caused the development of a regional unconformity, which in the area of the Molasse Basin cut deeply into the Cretaceous and Late Jurassic strata, causing karstification of carbonate rocks and leaching of Triassic salts, resulting in the development of salt pillows (Ziegler, 1990). Thrust-loading of the Helvetic Shelf commenced apparently during the Eocene, as evident by the gradual development of a foreland basin in the proximal parts of which syn-orogenic clastics accumulated in deeper waters whereas in its distal parts fluvio-deltaic sands, derived from the foreland, and shallow water carbonates were deposited. Progressive northward displacement of the basin axis was accompanied by overstepping of its northern margin and the development of a system of essentially basin-parallel normal faults (Herb, 1965, 1992; Menkveld-Gfeller, 1995). In the southernmost parts of the Molasse Basin, sedimentation commenced during the latest Eocene to earliest Oligocene, rapidly spread northward during the middle Oligocene and persisted under alternating shallow marine and continental conditions into early late Miocene times.

The main phase of folding of the Jura Mountains spans late Miocene to Pliocene times (Laubscher, 1987, 1992; Kählin, 1993; Bollinger et al., 1993). At the same time the Molasse Basin was uplifted and its sedimentary fill subjected to erosion with the degree of uplift and erosion increasing towards the southwest in tandem with increasing shortening in the Jura Mountains. The seismicity of the Molasse Basin and of the Jura Mountains, as well as geodetic data indicate that crustal shortening is at present still active (Pavoni, 1990; Deichmann and Baer, 1990; Jouanne et al., 1995).

Basin Architecture

Figure 4 gives two reflection-seismically controlled cross-sections though the Swiss Molasse Basin; the eastern section crosses the basin to the east of the Jura Mountains whereas the western section extends from the folded Jura Mountains to the Alps. These sections show that the southeastern parts of the Molasse Basin were imbricated during the uplift of the Are Massif and are partly overridden by sedimentary nappes (Pfiffner and Erard, 1996). Moreover, they illustrate that the Mesozoic and basal Tertiary series of the Molasse Basin are cut by numerous normal faults, some of which were compressionally reactivated at a later stage. However, some normal and wrench faults appear to cut to the surface. Compressionally reactivated faults play an increasing important role in the central and western parts of the Molasse Basin. Some of these structures are related to partial inversion of Permo-Carboniferous troughs (Brink et al, 1992; Gorin et al., 1993; Pfiffner and Erard, 1996). Ramp anticlines, involving Mesozoic carbonates carried to surface by thrusts soling out in Triassic evaporites, play only a significant role to the southwest of Lake Geneva (Gorin et al., 1993; Philippe et al., this volume).

Small-scale extensional faults, cutting up from the basement through the Mesozoic series and dying out in the lower part of the Oligocene sediments, must be related to flexure of the foreland during its thrust-loaded subsidence. This type of faulting is well expressed in the German and Austrian Molasse Basin where reflection-seismic data, calibrated by numerous wells, permit dating of fault activity as ranging from early to late Oligocene with fault activity younging towards the north in conjunction with gradual northward displacement of the basin axis (Bachmann and Müller, 1992; Roeder and Bachmann, Wessely and Zimmer, this volume). On the other hand, faults cutting up from the basement through Mesozoic and Tertiary strata to the surface were presumably active during the main folding phase of the Jura Mountains or may even post-date it. Some of these faults probably form part of wrench systems which accommodated rotation of the Molasse Basin during the deformation of the Jura fold-and-thrust belt (Burkhard, 1990; Brink et al., 1992).

Based on recently released reflection-seismic data, Oligocene normal faults, which were not reactivated in later times, are also evident in the central and western parts of the Swiss Molasse Basin (Brink et al., 1992; Gorin et al., 1993; Pfiffner and Erard, 1996). This raises doubts about the applicability of the thin-skinned distant-push model, proposed by Laubscher (1961, 1974) (see Philippe et al., this volume) for the development of the Jura Mountains. However, it must be kept in mind, that for the French Jura Mountains an initial phase of thin-skinned thrusting, followed by a phase of basement-involving shortening is envisaged (Jouanne et al., 1995). Pfiffner and Erard (1996), following the earlier proposed model of Ziegler (1982, 1990), envisage that during the folding of the Jura Mountains compressional reactivation of Permo-Carboniferous troughs, underlying part of the Jura and the Molasse Basin, was accompanied by the development of an intra-crustal detachment along which the uppermost crust of the Molasse Basin, together with its sedimentary cover, was transported northwestwards. Pfiffner (1995), based on balanced cross-sections through the Jura Mountains, estimates that a minimum of about 2.5 km of crystalline basement and/or Permo-Carboniferous sediments, were incorporated into this thick-skinned detachment. However, the distribution of earthquake hypocentres in the North-Alpine foreland suggest that the whole crust underlyig the Molasse Basin is presently undergoing brittle deformation; moreover, focal mechanisms indicate that these deformations are controlled by northwest directed compressional stresses (Deichmann and Baer, 1990). In contrast to the thin-skinned model, the thick-skinned model accounts fully for the observed uplift of the Molasse Basin.

Decoupling of the Mesozoic and Cenozoic strata from their autochthonous basement has occurred in the French part of the Molasse Basin, is also evident in many parts of the Jura belt (Buxtorf, 1907, 1916; Guellec et al., 1990; Philippe et al., this volume) and has been confirmed by recently released reflection-seismic data from the central Jura (Sommaruga, 1995). The southeastward continuation of such detachments beneath the Molasse Basin and the occurrence of intra-basement thrusts below the Jura is at present debated. Sheared Triassic evaporites have also been encountered in a number of boreholes drilled in the east-central parts of the Molasse Basin, thus attesting to the activation of an intra-sedimentary decoupling layer (Jordan, 1992). On the other hand, locked normal faults suggest that basement involved rotation of the Molasse Basin may have contributed to the shortening observed in the Jura fold and thrust belt. The lack of access to the entire reflection-seismic data base, acquired by the Petroleum Industry in the Molasse Basin, impedes the evaluation of the relative contribution of thin- and thick-skinned deformations to the folding of the Jura Mountains.

Hydrocarbon Habitat

During the exploration for hydrocarbons in the Molasse Basin some 8500 km of reflection-seismic lines were recorded and 33 wells drilled, resulting in the discovery the very small Entlebuch gas accumulation (see Fig. 1; rec. res. 3.6 BCF gas; Lahusen, 1992; Brink et al., 1992; Gunzenhauser and Bodmer, 1993). However, as most of the wells yielded minor oil and gas shows, hydrocarbon charge does not appear to be the primary constraining factor in the hydrocarbon potential of the Molasse Basin.

Coals and lacustrine shales of the Permo-Carboniferous series, contained in wrench-induced, partly inverted troughs, provide non-predictable potential source-rocks; these have reached maturity in most of the area. Early Jurassic organic shales are generally mature for oil generation under the Molasse Basin and enter the gas window near the Alpine deformation front where they are less well developed. The basal Oligocene "Fischschiefer" (Sannoisian), the primary oil source-rock in the Bavarian and Austrian Molasse Basin, may occur only beneath the Alpine nappes where they have probably reached maturity. The Val de Travers tar deposit of the western Jura Mountains indicates that hydrocarbon generation and migration had occurred already prior to the deformation of the Jura fold and thrust belt.

Potential reservoirs are the Triassic Bunter sands and Muschelkalk dolomites which are sealed by salts. Rhaetian sands, sealed by Early Jurassic shales, are poorly developed. Karstified Jurassic carbonates, partly developed in a reefal facies, are only sealed by early Oligocene marine shales in the deepest parts of the basin where they host the Entlebuch gas accumulation. Elsewhere these carbonates are directly overlain by Oligocene sands and therefore are not sealed. The Oligo-Miocene Molasse series lack well defined reservoir-seal pairs.

Remaining prospects in the Molasse Basin are related to sub-salt Triassic reservoirs, charged by Permo-Carboniferous source-rocks, and to Mesozoic carbonates and sands, charged by Early Jurassic source-rocks and sealed by basal Oligocene marine shales. Triassic prospects in the northwestern parts of the basin are difficult to define by reflection seismic data. Similarly, in the southeastern-most parts of the basin, definition of Jurassic carbonate prospects is impeded by the complex overburden of the Alpine nappes and by topographic constraints. In view of these difficulties and past discouraging results, exploration activity in the Molasse Basin recently has been discontinued.

SOUTH-ALPINE THRUST BELT

The arcuate central South-Alpine thrust belt has a width of 80 km and is bounded to the North by the Insubric Line (Fig. 5). Its internal parts consist of stacked, basement-involving thrust sheets, whereas its external parts are characterized by thin-skinned thrust sheets which are detached from the basement at Triassic levels (Fig. 6; Roeder and Lindsey, 1992; Schönborn, 1992). The Po Plain hosts a remnant Oligo-Pliocene foreland basin which is underlain by a thick Paleogene and Mesozoic succession. The external parts of the South-Alpine thrust belt and the Po Basin have been extensively and successfully explored for hydrocarbons (Pieri and Groppi, 1981; Cassano et al., 1986; Anelli et al., this volume).

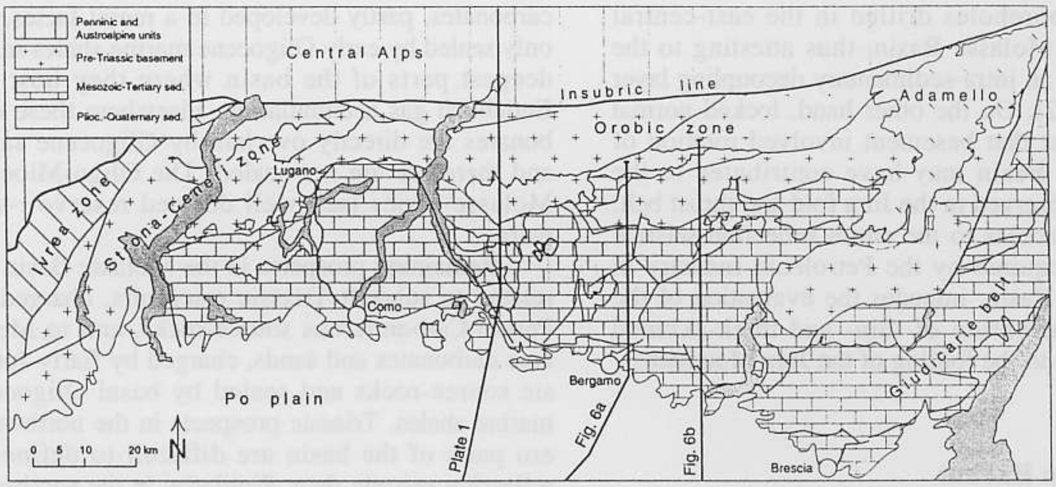

FIG. 5. Tectonic map of Lombardian fold-and-thrust belt, showing traces of cross-sections given in Fig. 6 and Encl. 1 (modified after Schönborn, 1992)

Basin Evolution

Following termination of the Variscan orogeny, the area of the Southern Alps was affected by wrench tectonics (Arthaud and Matte, 1977), controlling the accumulation of up to 1.5 km thick latest Westphalian to Early Permian continental clastics in SW-NE trending transtensional basins and a widespread intrusive and extrusive magmatism (Cassinis and Perotti, 1993). Late Permian continental clastics were deposited on a regional peneplane under tectonically quiescent conditions; these grade upwards into shallow marine Early Triassic sands, carbonates and evaporites (Asserto and Casati, 1966).

During the Middle Triassic, development of a complex pattern of carbonate platforms and intervening anoxic basins was accompanied by transtensional/transpressional tectonics and widespread volcanic activity, probably related to opening of the Hallstatt-Meliata Basin (Stampfli et al., 1990). Tectonic and volcanic activity persisted during the Carnian low-stand in sea-level during which terrigenous clastics were shed into basinal areas from the south (Brusca et al., 1981). By end-Carnian times, the South-Alpine domain was occupied by a uniform evaporitic platform, reflecting renewed tectonic quiescence.

However, rifting activity resumed during the deposition of the Norian Hauptdolomite, as evident by its lateral thickness changes describing the development of northerly trending platforms and intervening basins; amongst the latter, the Lombardy Basin is of special interest as its configuration controlled the geometry of the external South-Alpine thrust belt (Castellarin and Picotti, 1990). During the Rhaetian, up to 2500 m of black shales, capped by shallow water carbonates, were deposited in this basin under rising sea-level conditions (Gnaccolini, 1975); offsetting platforms were characterized by considerably thinner series. Rifting activity intensified during Early Jurassic times, as indicated by the accumulation of up to 4 km of hemipelagic carbonates in basinal areas, containing slump breccias derived from active fault-scarps, and of shallow water carbonates on platforms (Bernoulli, 1964). Erosion on some platforms reflects extensional footwall uplift (Gaetani, 1975). During the Toarcian and Middle Jurassic, rifting activity abated in the central South-Alpine domain and shifted westward towards the margin of the Piemont Trough. In the Lombardy Basin, which by now had subsided below the photic zone, carbonate turbidites, followed by the pelagic Rosso Ammonitico were deposited. The flanking platforms were drowned during the Callovian and Oxfordian. Late Bathonian crustal separation in the Piemont Basin was followed by regional subsidence of the South-Alpine domain in which Late Jurassic series are represented in basinal areas by radiolarites and on palaeo-highs by Rosso Ammonitico-type limestones (Winterer and Bosellini, 1981; Bertotti et al., 1993).

During the latest Jurassic and Neocomian, the area was covered by a blanket of coccolith limestones (Maiolica). After a short break during the early Aptian low-stand in sea-level, sedimentation resumed with the deposition of black shales, grading upwards into hemipelagic marly limestones (Scaglia). late Cenomanian onset of terrigenous flysch influx from northern sources, presumably reflects uplift and erosion of the internal South-Alpine domain to basement levels; this flysch cycle culminated during the early Senonian and lasted until Campanian times. During the late Campanian hemipelagic shaly carbonate deposition resumed (Scaglia) and lasted until late Eocene times (Bichsel and Häring, 1981; Bersezio and Fornaciari, 1987; Bernoulli and Winkler, 1990).

The turbiditic, partly conglomeratic "Gonfolite Lombardia" was derived from northern sources; this syn-orogenic succession ranges in age from late Oligocene to middle Miocene, attains thicknesses of up to 3500 m and shales out towards the south. It was deposited in a typical foreland basin. Deformation of the South-Alpine external thrust belt is Seravallian to Tortonian in age. All thrusts and folds are sealed by the Messinian unconformity which is related to an evaporation-induced draw-down of the Mediterranean sea-level. The up to 2.5 km thick Messinian and Plio-Pleistocene sedimentary fill of the Po Basin essentially post-dates the deformation of the Southern Alps and is affected by gentle folding only (Pieri and Groppi, 1981). Therefore, it can be regarded as the fill of the North-Appenine foreland basin (Gunzenhauser, 1985; Schönborn, 1992; Cassano et al., 1986).

Basin Architecture and Hydrocarbon Habitat

The arcuate geometry of the thin-skinned external thrust belt of the central Southern Alps was preconditioned by the configuration of the Mesozoic Lombardian Basin. The availability of Triassic detachment horizons and the rheological composition of the carbonate dominated Triassic and Jurassic series favoured the development of 10 to 20 km wide thrust sheets and in-sequence thrust propagation (Schönborn, 1992). Deformation of this thrust belt resulted in partial destruction of the Oligo-Miocene flexural foreland basin (Figs. 5 and 6).

Middle and Late Triassic basinal shales are oil-prone source-rocks (Bernasconi and Riva, 1993; Stefani and Burchell, 1993). Fractured, low porosity Late Triassic and Early Jurassic dolomites form the reservoir of the Malossa gas/condensate field which was drilled on a ramp-anticline. The Oligo-Miocene sandy Gonfolite Group contains reservoirs which are charged by hydrocarbons generated from Mesozoic source-rocks. The Pliocene series of the Po Valley contain biogenic gas (see Anelli et al., this volume).

CONCLUSIONS

The Central-Alpine orogenic wedge consists of a stack of nappes which involve continental and oceanic crustal and supra-crustal rocks. This wedge started to develop during Cretaceous oblique subduction of the Hallstatt-Meliata Ocean and of the southeastern parts of the South Penninic-Piemont-Liguria Ocean (Cretaceous orogeny). Final closure of the South Penninic Ocean and the partly oceanic Valais Trough is attributed to the Paleogene second orogenic cycle, post-dating the latest Cretaceous collapse of the Eoalpine orogen. The Cenozoic orogenic phases were governed by collision of the Apulian block with the European craton. Cumulative Tertiary-aged crustal convergence across the Central Alps amounts to some 550 km. Basement cored nappes typically involve only 5 to 10 km of continental crustal material. Moreover, only relatively small volumes of oceanic crustal material were incorporated into the Alpine orogenic wedge. Therefore, sizable volumes of lithospheric material, including oceanic and continental crust, were apparently subducted.

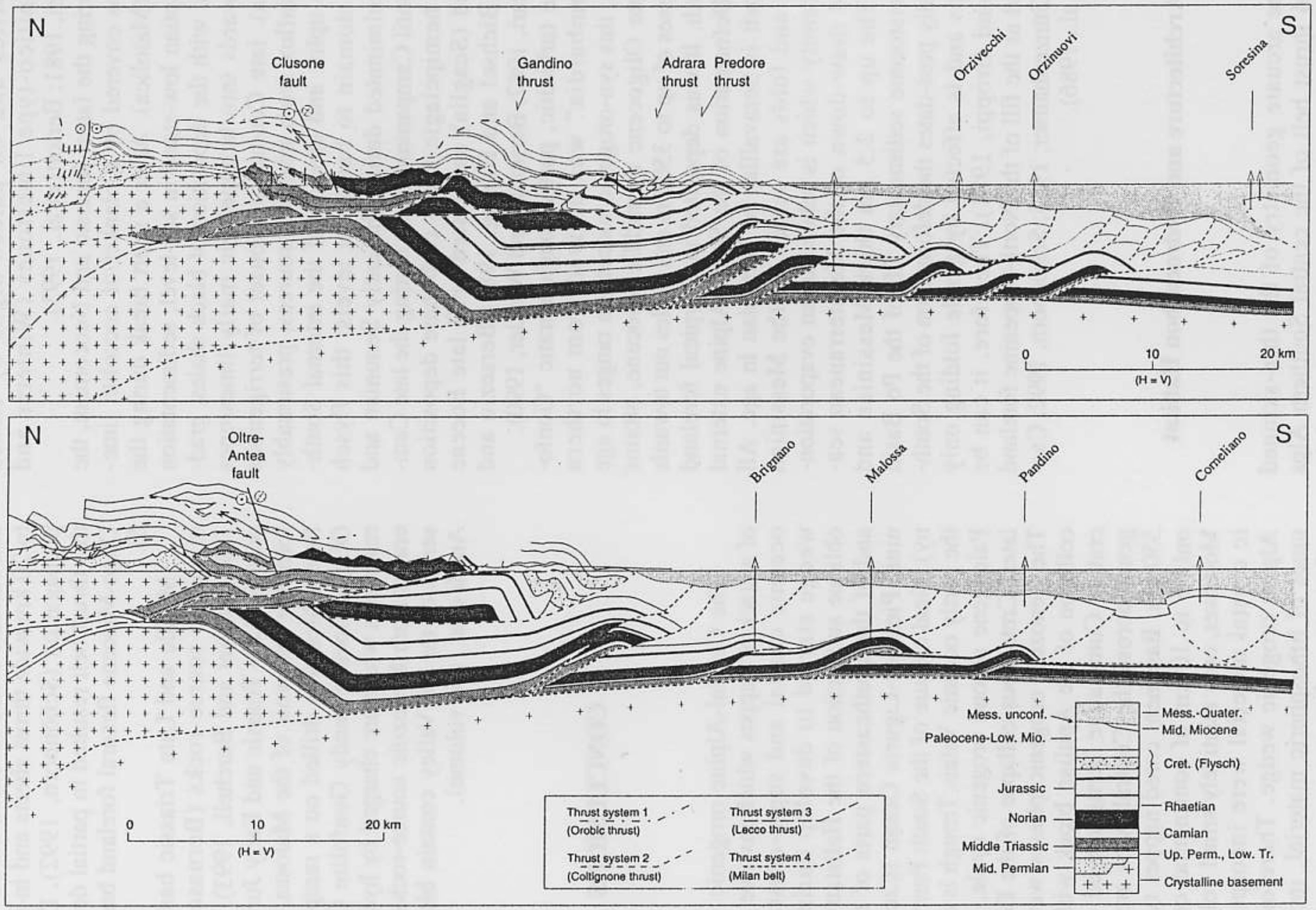

FIG. 6. Structural cross-sections through Lombardian thrust belt (modified after Schönborn, 1992), The pre-Messinian basin fill is affected by folding and thrusting. The crystalline basement is involved in the most internal units.

A Triassic to Early Jurassic rifting cycle preceded Mid-Jurassic opening of the South-Penninic oceanic basin. The North-Penninic Valais Trough subsided in response to Early Cretaceous sinistral translatory movements between Europe and Apulia which accompanied the gradual opening of the Atlantic Ocean. The Alpine orogenic cycle consists of a pre-collisional Cretaceous compressional phase, characterized by a westward directed mass transport, and a Cenozoic collisional phase, marked by northwards and southwards directed mass transport. The controlling factor is seen in the motion of the Africa-Arabia plate relative to the Eurasian plate and their interaction with the intervening Apulian microplate. During the Cenozoic collisional phase, southward directed back-folding and -thrusting, playing a significant role in the architecture of the Central-Alpine orogen, commenced upon incorporation of little attenuated northern foreland crust into the orogenic wedge.

Latest Cretaceous-Paleocene uplift of the northern Alpine foreland is thought to be the expression of compressional stresses which were projected from the orogenic wedge into the foreland, prior to its collision with the Helvetic passive margin, inducing broad lithospheric deflections. This suggests that the lithosphere of the Valais Trough had sufficient strength to permit transmission of large stresses into the European foreland.

The Central Alpine transect illustrates that post-collisional convergence, resulting in substantial lithospheric overthickening, was accompanied by thrusts propagating into the foreland crust, causing its imbrication and the uplift of basement-cored external massifs. Such external massifs, carried by thrusts soling out at mid-crustal levels, occur both on the European and the Apulian margin of the Central-Alpine orogen. Their uplift, combined with the development of the Lombardian and the Molasse-Jura nappe systems, resulted in partial destruction of flexural foreland basins which had developed during earlier phases of nappe obduction. In the context of the overall kinematics of the Alpine orogen, with the European plate dipping south beneath the orogenic wedge, the Molasse Basin evolved as a pro-wedge (in the sense of Willet et al., 1993) or a fore-arc foreland basin (in the sense of Ziegler, 1990), whereas the conjugate South-Alpine Lombardy basin evolved as a retro-wedge or "retro-arc" foreland basin (Willet et al., 1993; Ziegler, 1990, see also Doglioni, 1993). Both basins were partly destroyed by subsequent incorporation into the orogen. Thrust faults propagating into the forelands caused uplift of these basins and partial erosion of their sedimentary fill.

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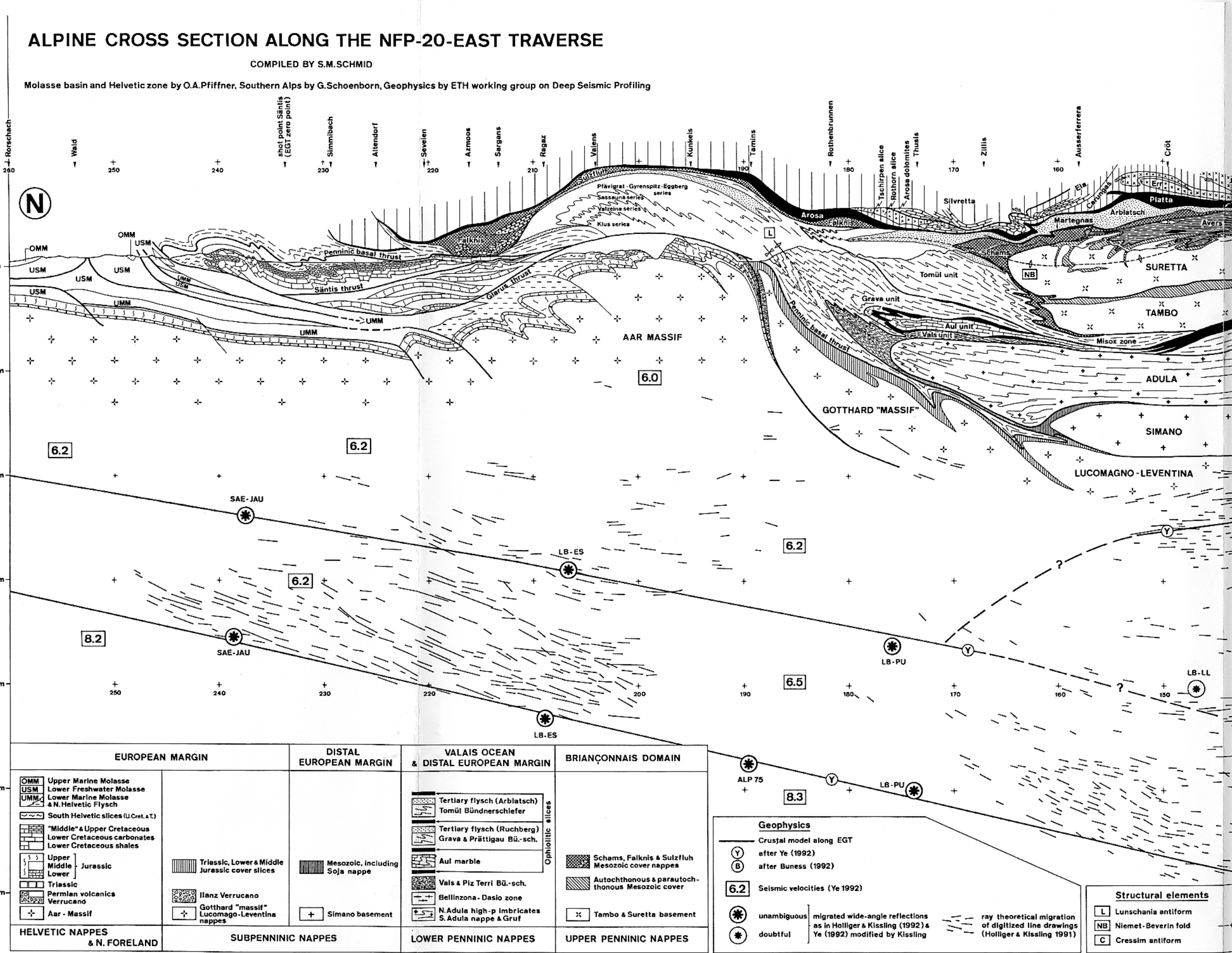
Enclosure

Encl. 1. Alpine cross-section along the NFP-20-East traverse, integrating geological and geophysical data (from Schmid et al., 1996b).



Enclosure 1

ZIEGLER, P. A., SCHMID, S. M., PFIFFNER, A. & SCHÖNBORN, G., 1996. — Structure and evolution of the Central Alps and their northern and southern foreland basins. *In*: ZIEGLER, P. A. & HORVÁTH, F. (eds), Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands. *Mém. Mus. natn. Hist. nat.*, **170**: 211-233 + Enclosure 1. Paris ISBN: 2-85653-507-0.

G THE NFP-20-EAST TRAVERSE

S.M.SCHMID

G.Schoenborn, Geophysics by ETH working group on Deep Seismic Profiling

Corvatsch-Bernina
Margna-Sella
Engadine line
Alp Sovrana
Cima di Lago
Piuro
Tonale series
Insubric line
Insubric mylonites
Margna
fault
Turba normal
Chiavenna oph.
Gruf
Bellinzona-Dascio
Cima del Cortese
Rocca di Baiedo
Pizzo d'Erna
Gerola
Olgiate
Seregna
Cernusco
Pobbiano
San Donato M.
Lacchiarella
Battuda
S
Orobic thrust
Coltignone thrust
Lecco thrust (out of sequence)
Milan thrust
Mesozoic
C
LM
PG
PL
MM
0 km
10 km
20 km
30 km
40 km
50 km
60 km
6.1
6.2
6.5
6.6
8.0
8.3
LB-LL
LB-VE
SUDALP 77
Y
B
?
140
130
120
110
100
90
80
70
60
Axial trace of major post-nappe folds
PIEMONT-LIGURIA OCEAN & DISTAL APULIAN MARGIN
Margna Sella nappes ("Ultrapenninic", Austroalpine affinities)
Avers Bündnerschiefer
Ophiolitic slices (Avers, Lizun, Forno, Malenco, Platta)
PENNINIC-AUSTROALPINE SUTURE ZONE
Novate granite post Bergell
Granodiorite
Tonalite
Bergell intrusion (30-32 MA)
TERTIARY INTRUSIONS
APULIAN MARGIN
Upper Austroalpine nappes
Lower Austroalpine nappes
Lower Austroalpine basement
AUSTROALPINE NAPPES
Upper Cretaceous flysch (C), Paleogene (PG), Lower Miocene (LM), Middle Miocene (MM), Pliocene (PL)
Maiolica
Rhaethian conchodon carbonates
Rhaethian, Jurassic & Lower Cretaceous
Dolomia Principale (Norian)
Carnian
Middle Triassic carbonates
Permian & Lower Triassic clastics
South-Alpine upper crust
SOUTHERN ALPS
Tertiary basins
External massifs
Undeformed Mesozoic of the European foreland
Jura, Helvetic nappes
Penninic nappes
Austroalpine nappes
S.Alps, Dinarides
Profile trace
EGT - profile & shotpoints A to E
ZÜRICH
MILANO
APENNINES
A
B
C
D
E