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Ivrea Zone and Adjacent Southern Alpine Basement

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Abstract

The available literature is critically assessed and existing controversies are emphasized. Based on a synthesis of published ideas the extended discussion proposes the following evolutionary scheme (compare sketches in Fig. 3): (1) an impressive volume of Proterozoic metasediments in the Ivrea zone and Serie dei Laghi has first been juxtaposed during accretionary wedge formation and underplating above a subducted Ivrea oceanic crust during a Late Proterozoic to Early Palaeozoic event ("Cadomian" or Caledonian). (2) A high geotherm was established by Ordovician times (460–480 Ma) as evidenced by anatexis in paragneisses of the Ivrea zone and granitic intrusion associated with granitization of adjacent metasediments in the Serie dei Laghi. This time marks the onset of a long-lasting history of deep burial under elevated temperatures for both Ivrea zone and Serie dei Laghi. (3) Variscan orogeny at around 320 Ma led to crustal thickening and decoupling between lower crust (Ivrea zone) and intermediate crustal levels (Serie dei Laghi). Large parts of the Serie dei Laghi were exhumed during Variscan orogeny, thereby preserving pressure-dominated Variscan mineral assemblages while the Ivrea zone remained in a lower crustal environment resulting in widespread re-equilibration of mineral assembleges to moderate pressures. (4) An important Late Palaeozoic magmatic event of Permian age is unrelated to Variscan orogeny since it post-dates re-establishment of normal crustal thickness. Synchronous magmatic activity is documented at all crustal levels from the still granulite facies metamorphic crust-mantle transition to the sedimentary cover and is best explained in the context of intracontinental wrench tectonics. (5) Crustal thinning associated with passive continental margin formation in the Early Mesozoic leads to considerable uplift of the Ivrea zone and cooling to temperatures below 300 °C. (6) Late Oligocene to Early Miocene deformation is responsible for the final exposure of a vertical section through attenuated continental crust.

1 Introduction

Recently a number of review-type articles have been published about the area concerned. For details and extensive references the reader is referred to these articles (i.e. Zingg 1983, 1990; Boriani et al. 1990a,b; Zingg et al. 1990). This contribution merely offers a brief overview introducing the reader who is unfamiliar with the area. The discussion will focus on selected points of interest with special emphasis on controversies and still open questions.

2 Geological Setting

It is best to start with the present setting of the Ivrea zone and adjacent basement units (Serie dei Laghi in the sense of Boriani et al. 1990a) within the framework of the Alpine orogeny since earlier tectonic settings are largely overprinted and, consequently, much more difficult to reconstruct.

The area concerned (Fig. 1) is located at the W end of a basement high within the Southern Alps (i.e. that part of the Alpine chain located to the SE and S of the Alpine Insubric line). This basement high closely follows the trend of the Insubric line: further to the E it runs parallel to the trend of the E-W-striking Tonale line, a segment of the Insubric line, E of Locarno (Orobic basement), in order to swing into a NNE-SSW-strike further to the W (Ivrea zone and Serie dei Laghi), again roughly parallel to the Canavese line (western segment of the Insubric line). Thus, there seems to be an intimate relationship between the Insubric line and this Southern Alpine basement high, both in terms of its location and structural trend. It is widely accepted that the section through the Ivrea zone (lower crust) and Serie dei Laghi (upper crust) offers a unique cross section through the Southern Alpine crust (Fig. 2). This implies that later tectonic movements are responsible for exposing such a crustal section at the earth's surface. But age, kinematics and geometry of these tectonic movements are

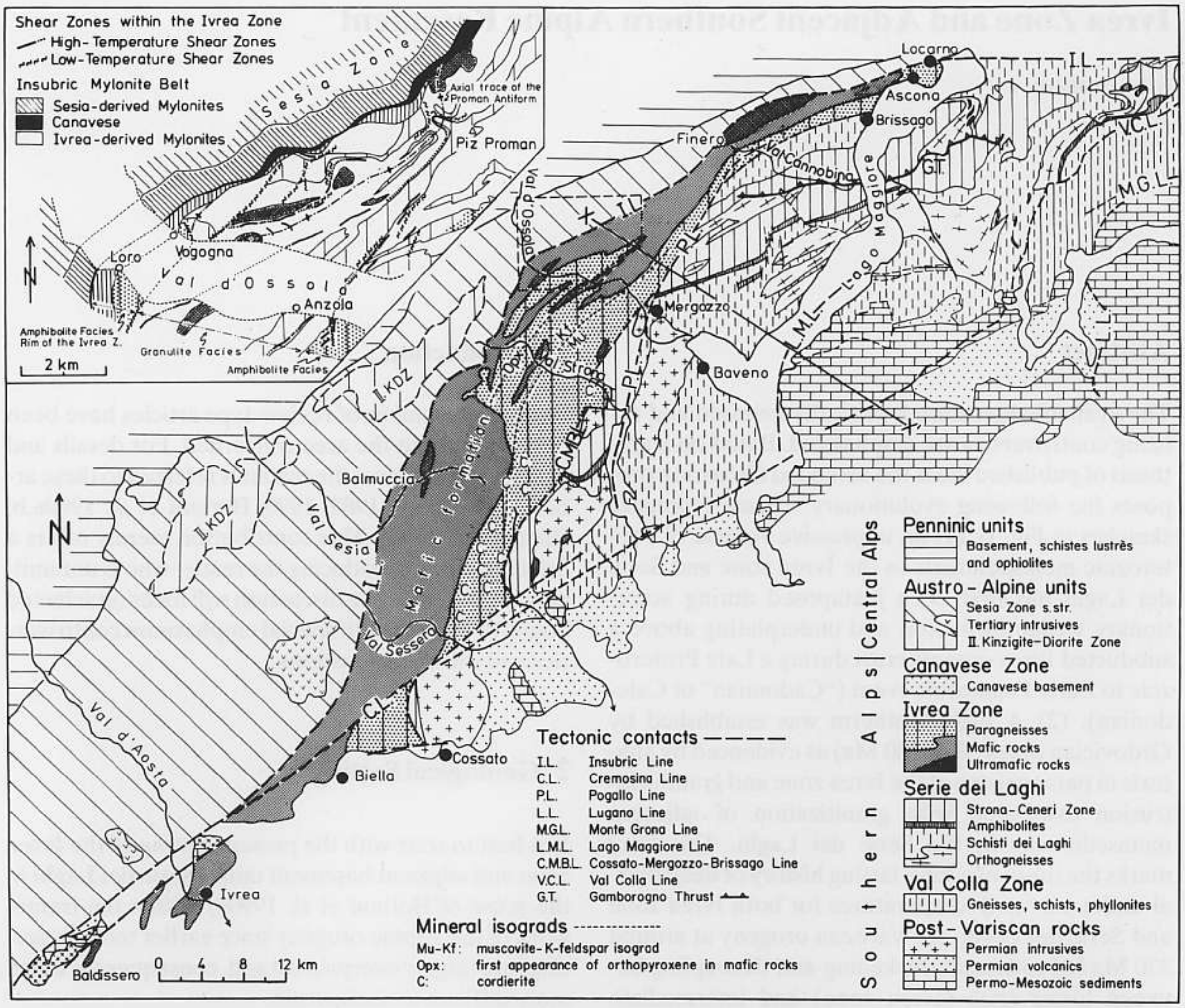

Fig. 1. Map of Ivrea zone and adjacent Southern Alpine basement (after Boriani et al. 1990a,b; Reinhard 1964; Zingg et al. 1990). *X-X'* Location of profile in Fig. 2A; **inset** detailed geological map of the northwestern rim of the Ivrea zone in the Val d'Ossola. (After Schmid 1967; Brodie and Rutter 1987; Schmid et al. 1987)

still a matter of debate: simple Alpine tilting as depicted in Fig. 2 (Handy 1987; Zingg et al. 1990), local tilting associated with ramp anticlines of Alpine age (Schumacher 1990) or preservation of Variscan and Late Palaeozoic structures with Alpine movements of only minor importance (Vai and Cocozza 1986; Boriani et al. 1990a,b) have been proposed.

Towards the Po plain the Serie dei Laghi (and the rest of the Southern Alpine basement further to the E) are unconformably overlain by Upper Carboniferous to Lower Permian volcanoclastic and volcanic series, Permo-Carboniferous terrigenous sediments, and, eventually the Mesozoic series. The latter characterize the present-day area of the Southern Alps as a passive continental margin setting at the WNW edge of the Apulia (or Adria) microcontinent (Weissert and Bernoulli 1985) which formed during Late Triassic to Early Jurassic. Needless to say that stretching caused by passive continental margin formation is expected to leave a thermal and deformational imprint on the basement underlying the sediments and recently this has been directly documented in an area further to the E (Bertotti 1990, 1991), where basement-cover relationships are better preserved than in our area of interest. Another area of Permo-Mesozoic cover rocks (Canavese sediments) belongs to the very distal part of this passive continental margin and follows the Insubric line. Since these sediments are intensely mylonitized, forming part of the Insubric mylonite belt (Schmid et al. 1987), their exact position with respect to the adjecent Ivrea zone is obscured. In the area of the Canavese *s. str.*, i. e. near the town of Ivrea where stratigraphic basement-cover contacts are better preserved, Biino and Com-

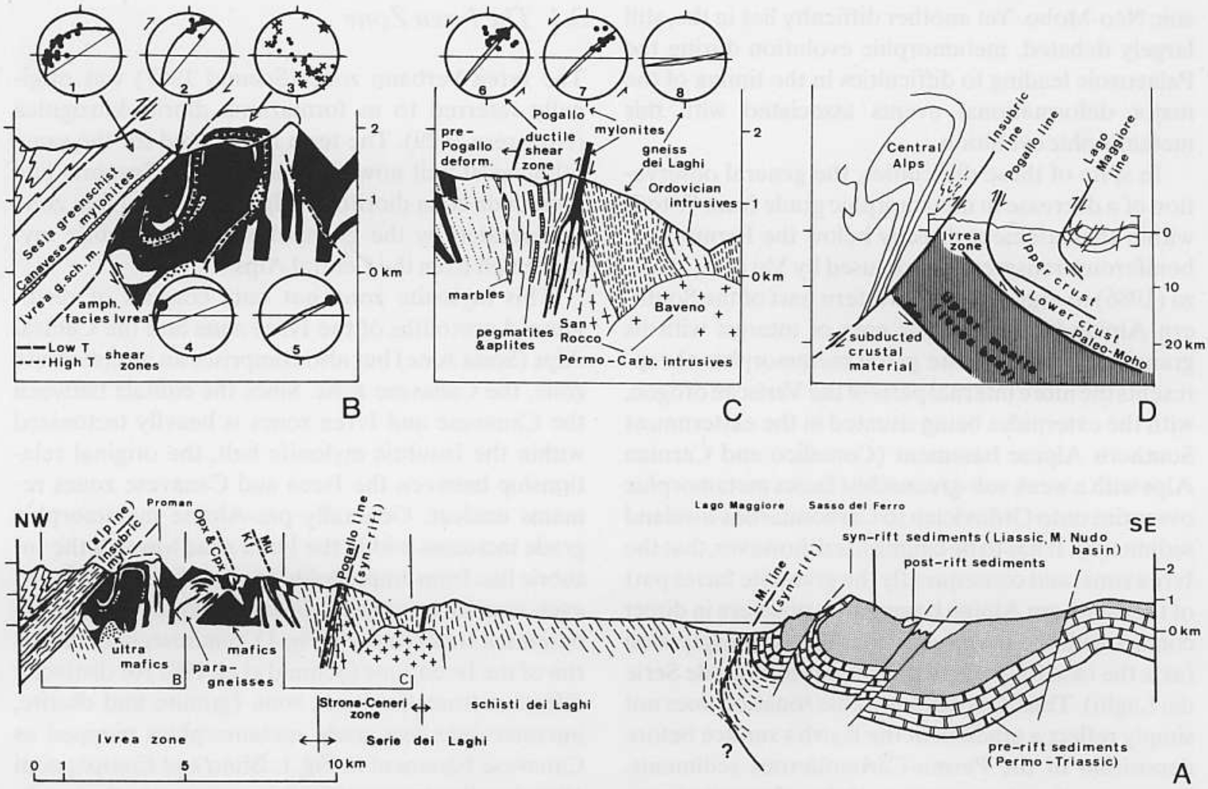

Fig. 2A–D. Cross-section along trace indicated in Fig. 1 (after Zingg et al. 1990). **A** General cross-section; **B** details of the Proman antiform and adjacent areas. All sterographic projections are lower hemisphere and indicate the average foliation and stretching lineations *(dots)* of the Insubric mylonites (*projections 1* and *2* from Schmid et al. 1987); measurements from the Proman antiform (*projection 3: dots* foliations poles; *crosses* slickenside lineations; *star* fold axis orientation from Zingg et al. 1990), average orientation of foliation and stretching lineation within the high-temperature shear zones (*projections 4 and 5*, from Brodie and Rutter 1987); **C** details of the area around the Pogallo ductile fault zone (*projection 6* indicates average foliation and lineation orientation within the Pogallo ductile fault zone; *projection 7* refers to the mylonites at the Pogallo line: *projection 8* give the average orientation of foliation in the Strona-Ceneri zone; *projections 6–8* from Handy 1987); **D** sketch illustrating the position of the profile depicted in Fig. 3A within a larger context

pagnioni (1989) report evidence that the Canavese sediments were deposited onto a low-grade Variscan basement, the "Canavese basement", which is in tectonic contact with the Ivrea zone.

Geophysically, the Ivrea zone is considered to represent the surface expression of a much larger high-density body (the Ivrea body) leading to a huge NNE-SSW-striking anomaly at the inner arc of the Western Alps. The original suggestion of a single ESE-dipping slice of mantle material (Berckhemer 1968), underplated by crustal material of lower density has recently been modified in the sense that this mantle slice associated with the Ivrea zone is only the most internal of several wedges of mantle and lower crustal material (Rey et al. 1990). However, mantle material directly underlying the Ivrea zone, together with the ESE-dipping subsurface continuation of the Ivrea lower crustal material is still considered to be the main cause of the observed gravity anomaly (see Figs. 8, 9, 11 in Rey et al. 1990). If these model sections, satisfying the gravity and magnetic anomalies in an admittedly non-unique way, are taken at face value they would argue for simple large-scale tilting of a crustal section into a near-vertical attitude.

Because the Ivrea zone and the Serie dei Laghi have been affected by tectonism, both related to Alpine orogeny and passive continental margin formation, a reconstruction of the pre-Alpine geological setting (Variscan and/or Caledonian) is very difficult. This difficulty is agravated by the fact that the Ivrea zone represents a lower crustal level during Palaeozoic orogeny. In analogy to the findings of Eisbacher et al. (1989) in the Schwarzwald-Vosges area, lower crustal levels are expected to ignore basically the main convergent tectonic boundaries due to detachment of the upper crust during convergence and due to late Hercynian overprint associated with the rise of granitic plutons and the formation of a Late Palaeozoic Neo-Moho. Yet another difficulty lies in the, still largely debated, metamorphic evolution during the Palaeozoic leading to difficulties in the timing of the major deformational events associated with this metamorphic evolution.

In spite of these difficulties, the general observation of a decrease in metamorphic grade from W to E within the basement directly below the Permo-Carboniferous transgression was used by Vai and Cocozza (1986) to argue that the western part of the Southern Alpine basement (our area of interest with its granulite to amphibolite grade metamorphism) represents the more internal parts of the Variscan orogen, with the externides being situated in the easternmost Southern Alpine basement (Comelico and Carnian Alps with a weak sub-greenschist facies metamorphic overprint onto Ordovician to Carboniferous foreland sediments). It has to be emphasized, however, that the Ivrea zone, and consequently the granulite facies part of the Southern Alpine basement is nowhere in direct contact with the Permo-Carboniferous transgression (as is the case for parts of the amphibolite grade Serie dei Laghi). Thus, this metamorphic zonation does not simply reflect a gradient at the Earth's surface before deposition of the Permo-Carboniferous sediments. Consequently, a large portion of the exhumation process, particularly in our area of interest, may well postdate the Variscan orogeny and has to be the product of passive continental margin formation and/or Alpine tectonics. Furthermore, the observation of low-grade metamorphism within the Canavese basement in the westernmost parts of the Southern Alpine basement mentioned already (Biino and Compagnoni 1989) argues against a simple metamorphic gradient below the Permo-Carboniferous transgression from W to E. Additional difficulties arise from the observation of pre-Permo-Carboniferous greenschist retrogradation of higher grade metamorphism in the basement of the Orobic Alps (Milano et al. 1988) and the Serie dei Laghi (Borghi 1987). Evidence for an even younger (Permo-Mesozoic) metamorphic overprint affecting parts of the Orobic basement is given by Siletto et al. (this Vol).

3 Lithological Units and Contacts Between These Units

It is customary to subdivide the basement rocks of the western part of the Southern Alpine basement into major lithological units, often refered to as "zones". Contacts between these zones may be gradual or marked by major faults.

3.1 The Ivrea Zone

The Ivrea-Verbano zone (Schmid 1967) was originally referred to as formazione diorito-kinzigitica (Novarese 1929). The term is still used for the same lithological unit now situated N of the Insubric line ("seconda zona diorito-kinzigitica"). The Ivrea zone is separated by the greenschist facies Insubric mylonite belt from the Central Alps.

This mylonite zone not only consists of retrogressed protoliths of the Ivrea zone and the Central Alps (Sesia zone) but also comprises an intermediate zone, the Canavese zone. Since the contact between the Canavese and Ivrea zones is heavily tectonized within the Insubric mylonite belt, the original relationship between the Ivrea and Canavese zones remains unclear. Generally pre-Alpine metamorphic grade increases within the Ivrea zone towards the Insubric line from amphibolite to granulite grade. However, heavily tectonized slivers of amphibolite grade basement rocks (inset in Fig. 1), reminiscent of the SE rim of the Ivrea zone (Schmid et al. 1987) or distinctly different from the Ivrea zone (granite and diorite, intrusive into low-grade metamorphics mapped as Canavese basement in Fig. 1, Biino and Compagnoni 1989) locally reappear within or adjacent to the Insubric mylonite zone. This Canavese basement is associated with the Canavese Permo-Mesozoic cover. These Canavese cover rocks only underwent low grade metamorphism of Alpine age (Zingg and Hunziker 1990). Thus, highly attenuated remnants of the South Alpine upper crustal levels reappear in the immediate vicinity of the Insubric line. It is difficult to decide as to how much of this attenuation had already occurred during crustal thinning during the Early Mesozoic and how much is due to Alpine movements along the Insubric line. Traditionally, the Canavese zone was interpreted as representing an independent palaeogeographic and tectonic unit (Argand 1910) forming the root of Austro-Alpine nappes. However, the close affinities of the Permo-Mesozoic Canavese cover with the distal part of the passive continental margin in the Southern Alps argues for the hypothesis that the Canavese zone simply represents a remnant of upper crustal levels originally overlying the Ivrea zone. Zingg et al. (1990) suggested that the overall structure of the Ivrea zone may be viewed as that of a huge asymmetric antiform of Late Alpine age (whose core is only locally preserved, Proman antiform in the Val d'Ossola, Fig. 2) with a highly attenuated NW limb (Canavese zone) and a much wider SE limb (the main part of the Ivrea zone) with its well-known transition from granulite facies metamorphism near the core to amphibolite facies conditions further to the SE.

The Ivrea zone is predominantly made up of paragneisses (referred to as kinzigites in the amphibolite grade part and stronalites in the granulite facies part) and mafic rocks. Thin marble horizons and pegmatitic dykes concentrate along the SE margin of the Ivrea zone and, more sporadically, near the Insubric line. Peridotites occur as isolated lenses predominantly within the NW part of the Ivrea zone, in the vicinity of the Insubric line, with the exception of one peridotite body at the southern border of the Ivrea zone (Boriani and Peyronel Pagliani 1968), associated with eclogitic amphibolites.

The ultramafic rocks include peridotites *s. l.* and pyroxenites. Spinel peridotites and lherzolites are predominant in the Baldissero and Balmuccia bodies (Lensch 1971; Shervais 1979; Rivalenti et al. 1981). The Finero body contains phlogopite and hornblende peridotite resulting from crustal contamination (Hunziker and Zingg 1982). The layered group adjacent to the Balmuccia body is made up of spinel-bearing dunite and harzburgite interlayered with gabbro and norite (Rivalenti et al. 1981). In the Balmuccia region Sm-Nd data suggest an event of crust formation about 600 Ma ago (Voshage et al. 1987). However, younger ages (Ordovician and/or Late Palaeozoic) for deep-seated intrusions and partial melting within the layered complex are very likely (see discussion in Voshage et al. 1987). Evidence for a Late Palaeozoic event (about 270 Ma) is particularly compelling (mafic and ultramafic dykes in the Balmuccia peridotite and phlogopite metasomatism associated with crustal contamination in the Finero complex, Voshage et al. 1987, 1988). In a later publication Voshage et al. (1990) no longer believe that there is any basis for the above mentioned 600 Ma event published in earlier publications (Voshage et al. 1987, 1988). Instead they propose magmatic underplating at 270 Ma to be responsible for the formation of the entire Mafic complex in Val Sesia.

Three types of mafic rocks experienced regional metamorphism and deformation of Palaeozoic age (predating the 270 Ma magmatic event, but more precise dating is still a matter for debate): (1) mafic rocks of oceanic origin, alternating with paragneiss (Sills and Tarney 1984), (2) large bodies of the "Anzola gabbro" type, and (3) parts of the banded mafic rocks within the granulite facies part of the Ivrea zone such as those within the layered complex mentioned already. It has to be emphasized, however, that a fourth type preserved magmatic features: the diorite rim of the Mafic formation in Val Sesia with orthopyroxene of magmatic origin (Zingg 1980). This rim yields ages of 286 Ma (Pin 1986) and Bürgi and Klötzli (1990) obtain similar ages (274 Ma) for anatectic paragneisses in the contact aureole of the Mafic formation. These particular anatectic melts related to the contact aureole of the Mafic formation define an important time-marker in that they (and consequently also the intrusion of the Mafic formation) postdate deformation associated with regional metamorphism.

Amongst the paragneisses, sillimanite bearing metapelites (kinzigites and stronalites) are predominant. Within the eastern part of the Ivrea zone, the mineral isograd zonation runs parallel to the predominant strike (NW-SE to NNW-SSE) in order to run discordantly across compositional banding in the vicinity of the Mafic formation (particularly well documented by the muscovite-K-feldspar isograd, Zingg 1980). Widespread occurrences of cordierite and andalusite within the metapelites adjacent to the Mafic formation suggest final equilibration at lower pressures as compared with the NE part of the Ivrea zone (Zingg 1980). This suggests that a former zonation into granulite and amphibolite regional metamorphism running parallel to the major structures in the Ivrea zone was later overprinted in the SW part of the Ivrea zone. This overprint is most probably associated with the thermal event due to the intrusion of at least parts of the Mafic formation at around 270 Ma.

The marble horizons concentrating along the SE rim of the Ivrea zone are in immediate neighbourhood to amphibolite horizons, interbedded with paragneisses whose chemistry indicates mid-oceanic basalt origin (Sills and Tarney 1984). The accretionary wedge scenario proposed by Sills and Tarney (1984) is very attractive also for explaining: (1) the lack of a granitic basement underlying metapelites and marbles, and (2) the occurrence of high-P relics such as eclogitic amphibolites (Boriani and Peyronel Pagliani 1968; Buletti 1983; Borghi 1987, 1988; Boriani et al. 1990b) and kelyphitic peridotites (Lensch and Rost 1972) found both within Ivrea zone and Serie dei Laghi. Concerning the age of accretionary wedge formation, it can only be said that it post-dates the Early Proterozoic age of the upper intercept of the zircon discordia (Köppel 1974) obtained for the paragneisses and pre-dates Ordovician granites found in the Serie dei Laghi (Boriani et al. 1990a).

Structurally, the Ivrea zone is characterized by the steep attitude of compositional banding and main foliation. E-plunging stretching lineations are of remarkably constant orientation. The structural section published by Schmid (1967) is still the only complete section available through the Ivrea zone (his profile has been incorporated into the profile depicted in Fig. 2). At least two phases of folding are contemporaneous with Palaeozoic amphibolite to granulite grade metamorphism (Kruhl and Voll 1976; Steck and

Tièche 1976). A prominent antiform next to the Insubric line (Proman antiform) formed under greenschist facies conditions and is of Alpine age (Schmid et al. 1987). Handy and Zingg (1991) subdivide the tectonometamorphic evolution into three episodes: Episode 1 includes large-scale magmatism and regional metamorphism, responsible for the general compositional and metamorphic zonation presently observed and characterized by annealed microstructures in all lithologies. Crustal attenuation during the Late Palaeozoic (transtension) and Early Mesozoic rifting lead to episode 2 deformation, resulting in localized shear under variable metamorphic conditions indicated by the synkinematic overprint of previously annealed microstructures. Episode 3 structures are related to polyphase Alpine transpressional tectonics.

Pressure and temperature estimates scatter enormously. For the granulite facies part pressure estimates vary between 6.5 and 9 kb (Sills 1984) while temperature estimates are between 750 and 950 °C (see also references and discussions in Zingg 1983 and Zingg et al. 1990). For the amphibolite facies part pressures around 5–6 kb and temperatures between 550 and 750 °C are reported. Sills (1984) reports a substantial pressure gradient across strike within the granulite facies part (around 0.5 kb/km) suggesting tectonic thinning after equilibration.

The large scatter in P-T estimates is not surprising given the long-lasting tectono-metamorphic evolution of the Ivrea zone. These estimates are often taken to indicate the P-T conditions of the main event of regional metamorphism during episode 1 of Handy and Zingg (1991). However, as already emphasized by Handy and Zingg (1991) this episode 1 is certainly not a single event, given the ongoing controversy over its age, discussed later. Reequilibrations are also expected during the Late Palaeozoic magmatic event (around 270 Ma) associated with initial exhumation in a transtensional environment (episode 2 of Handy and Zingg 1991).

3.2 The Serie dei Laghi

Terminology concerning the basement between Ivrea zone and the main part of the Permo-Triassic cover of the Southern Alps is confusing. Italian workers collectively refer to this basement as Serie dei Laghi (Boriani et al. 1990b) while Swiss authors (Schmid 1967; Zingg 1983) use the term Strona-Ceneri zone (here referred to as Strona-Ceneri zone *s. l.*). According to Boriani et al. (1990b), the Serie dei Laghi can be further subdivided into the Schisti dei Laghi and the Strona-Ceneri zone in his sense (here referred to as Strona-Ceneri zone *s. str.*, identical to the older term "gneiss dei Laghi").

The Serie dei Laghi predominantly consists of amphibolite grade metasediments, intruded by metagranite bodies of Ordovician age (466 Ma, Boriani et al. 1982/83), and plutonic rocks belonging to the Late Palaeozoic (285–275 Ma) magmatic cycle (a suite of small stocks and dyke swarms of predominantly basaltic composition, the "appinites" of Boriani et al. 1990a, and epiplutonic Permian granite intrusions, known as "Graniti dei Laghi" or "Baveno-M. Orfano suite"). The subdivision of pre-Ordovician metasediments into Schisti dei Laghi and Strona-Ceneri zone *s. str.* is based on several arguments (Boriani et al. 1990b):

1. The metasediments within the Schisti dei Laghi are predominantly pelitic. They correspond to the "schiefrige Biotit-Plagioklasgneise" and "Giumello-Gneise" of Reinhard (1964). Meta-sediments of the Strona-Ceneri zone *s. str.* are predominantly arenaceous, sometimes with abundant clay matrix. According to Boriani et al. (1990b), older metasandstones (Cenerigneiss of Reinhard 1964, containing small boudins of hornfels and calc-silicates), are followed by "gneiss minuti" ("Hornfelsgneis" of Reinhard 1964), interpreted as clay-rich metasiltites and finer-grained metasandstones. The metasediments within the Strona-Ceneri zone *s. str.* still preserve sedimentary structures in spite of later granitization interpreted to be coeval with the Ordovician intrusions.
2. In many places, a continuous amphibolite horizon defines an important marker horizon between the two subunits (Fig. 1). Boriani et al. (1990b) interpret this horizon in terms of a stratigraphic intercalation of metasedimentary origin (coarse-grained basaltic tuffites). However, amphibolites are not restricted to this main horizon but are also found within the Schisti dei Laghi of the Gamborogno area where they contain eclogite facies relics (Borghi 1988). Furthermore, this marker horizon contains peridotite lenses near the eastern termination of the Serie dei Laghi adjacent to the Val Colla line (Reinhard 1964).
3. The Schisti dei Laghi are interpreted to be polymetamorphic, still recording a pre-Ordovician phase of high-grade metamorphism, whereas the Strona-Ceneri zone *s. str.* is supposedly still unmetamorphic at the time of intrusion of the Ordovician granites.

The subdivision based on criteria 1 and 2 is *probably* justified. The evidence of a single (Variscan) regional metamorphic event in the Strona-Ceneri zone *s. str.*, however, is not very convincing and based on: (1) the interpretation of Al-silicate nodules within metasediments to have formed during contact metamorphism (Bigioggero and Boriani 1975); (2) the view that granitization of the Strona-Ceneri country rocks, due to the Ordovician intrusion, apparently argues for the absence of metamorphism within these country rocks (Boriani et al. 1990b); (3) the assumption that the amphibolites mentioned form a stratigraphic marker horizon, and (4) structural arguments indicating that the dominant D1 schistosity of post-Ordovician age transposes an earlier schistosity in the Serie dei Laghi whereas it transposes sedimentary bedding in the Strona-Ceneri zone *s. str.* Should this interpretation be correct, it would have severe consequences for unravelling Variscan tectonics since the Schisti dei Laghi would represent an older basement complex with respect to the cover of the Strona-Ceneri zone *s. str.* (Borghi 1987).

Structurally, compositional layering and main foliation of the Serie dei Laghi remain in a subvertical orientation, W of Lago Maggiore. The general strike (WSW-ENE), however, is distinctly discordant to that of the Ivrea zone over a considerable distance along the Pogallo fault discussed later. Along the Val d'Ossola section, depicted in Fig. 2, the Strona Ceneri zone *s. str.* is directly juxtaposed with the Ivrea zone, followed by the Schisti dei Laghi further to the S. Hence, the "younging" direction would be towards the N, if the Schisti dei Laghi are, indeed, older. This would imply that the lower crustal section across the Ivrea zone was overlain by an inverted mid- and upper crustal section represented by the Serie dei Laghi after removing later tilting of the entire section. Further complications with the concept of the Serie dei Laghi representing an older basement, arise from the fact that the Serie dei Laghi reappear in direct contact with the Ivrea zone, in an area further to the NE (Val Cannobina) according to Boriani et al. (1990b). This area is characterized by later folding of the main foliation around subvertical E plunging axes ("Schlingen") continuing into the Gamborogno area east of Lago Maggiore (Reinhard 1964; Borghi 1989). This folding around subvertical axes is interpreted to be the result of Late Palaeozoic strike-slip tectonics by Boriani at al. (1990a). However, if verticalization of the main schistosity is attributed to Alpine tilting (Schmid et al. 1987) the attitude of the fold axes would have been subhorizontal at the time of their formation. The stretching lineations within the Serie dei Laghi exhibit considerable scatter (Borghi 1989) probably due to this same large-scale refolding event.

The Ordovician granites provide a time marker not available in the Ivrea zone. The age of sedimentation of the Schisti dei Laghi is most probably Proterozoic or early Palaeozoic, given high-P relics pre-dating the Ordovician granites. The age of regional metamorphism coeval with the formation of the main foliation is constrained to be post-Ordovician in the Serie dei Laghi according to Boriani et al. (1990b). Relics of a pre-Ordovician phase of high-pressure metamorphism are found within the Schisti dei Laghi in the Gamborogno area where Borghi (1988) estimates pressures between 15 and 20 kb and temperatures > 700 °C. Widespread occurrences of kyanite document relatively high pressures for the main post-Ordovician metamorphism as well. During this Variscan event there appears to be little spatial variation in metamorphic grade except near the contact with the Ivrea zone where sillimanite appears. Sillimanite grows post-kinematically indicating that the thermal peak (600–650 °C) followed the baric peak (6–8 kb; P-T estimates according to Borghi 1988 and Boriani et al. 1990b). Borghi (1987, 1988) reports a second greenschist metamorphic and deformational overprint related to exhumation but pre-dating Late Palaeozoic magmatism (Boriani et al. 1990b). This observation supports interpretations based on the cooling age concept indicating that the Serie dei Laghi represent a higher structural level, that cooled earlier than the Ivrea zone, which still occupies a deep crustal level during the Late Palaeozoic (anatexis related to the Late Palaeozoic intrusion of parts of the main Mafic formation). This is important since Boriani et al. (1990a) cast serious doubts on the cooling age concept and its tectonic consequences, discussed later.

The subvertically oriented contact between Serie dei Laghi and Ivrea zone is of tectonic nature along the Pogallo line which comprises the Pogallo ductile fault zone and a narrow fault zone associated with greenschist facies mylonites and cataclasites (Handy 1987). The kinematics of movement are those of oblique sinistral strike-slip in present-day coordinates. The synkinematic metamorphic gradient (increasing metamorphic grade across strike towards the Ivrea zone and along strike towards the NE) led Handy (1987) to confirm a hypothesis first published by Hodges and Fountain (1984), namely that of a tilted normal fault of Mesozoic age. The asymmetry of synkinematic metamorphic conditions precludes a strike-slip scenario and is typical for normal faults (see Mancktelow 1990, for a particularly well-documented Alpine example). The age is inferred from applying the cooling age concept and will be discussed later.

Boriani et al. (1990a) do not share this view and interpret the Pogallo fault as a strike-slip zone formed during the late Variscan but before intrusion of the appinites. This dating is at odds with the observation of tectonic overprint of Permian intrusions by tectonic activity along the Pogallo fault (Handy 1987). This alternative view results in an earlier age for verticalization of the Ivrea zone and Serie dei Laghi (Variscan as opposed to Alpine) and is incompatible with evidence from the cooling ages (Handy 1987), Alpine deformation in the Ivrea zone (Schmid et al. 1987) and palaeomagnetic evidence for post-Oligocene 60 ° rotation of the Ivrea zone (Schmid et al. 1989).

According to Boriani et al. (1990a) another fault zone is believed to be closely associated with the Pogallo fault, in terms of kinematics and time of formation: the "Cossato-Mergozzo-Brisago line" (CMB line). According to Boriani et al. (1990a), this "line" marks the transition between the Ivrea zone and Serie dei Laghi where the Pogallo fault breaks away from this lithological contact (SW of Val d'Ossola) and where the Pogallo fault no longer appears as a structural discontinuity (Val Cannobina) due to higher metamorphic conditions during fault movement (Handy 1987). The principal argument for the interpretation of both CMB line and Pogallo line in terms of a Late Variscan strike-slip zone is that the appinite suite is spatially and temporally associated with the CMB line, the appinites having intruded into transtensional segments of this vertically oriented fault zone. In view of the undisputable fact that the Pogallo fault deforms Permian intrusives (Handy 1987), the timing of the CMB and Pogallo lines as part of a late Variscan fault zone becomes very unlikely.

In the absence of modern structural studies along the CMB line it cannot yet be decided with certainty, when, and if at all, such a high-grade fault zone was active. The occurrence of (Early Palaeozoic?) high pressure relics at and to both sides of this "line", together with difficulties in delineating a clear lithological and/or structural boundary away from the Pogallo line (Val Cannobina, SW part of Val d'Ossola) argues for a common geological history of both the Ivrea zone and Serie dei Laghi for the final stages of crustal evolution, before the onset of fault movement along the Pogallo line. However, considerable detachment must have occurred between Ivrea zone and Serie dei Laghi during Variscan orogeny as discussed in the following discussion section.

Towards the E, the Serie dei Laghi are delimited by another fault zone, the Val Colla line, from the Val Colla zone. This fault zone is characterized by greenschist facies overprint of presumably Variscan age (Reinhard 1964) and its southern part was reactivated during Alpine orogeny according to Schumacher (1990). No major jump in Variscan metamorphic grade is observed across the Val Colla line. The kinematics of movement along the Cremosina line are still unknown. The map pattern (Fig. 1) suggests dextral transtensive movements during Alpine orogeny.

4 Discussion

4.1 Age and Geotectonic Setting of Pre-Late Palaeozoic Deformation and Metamorphism

A pre-Variscan event related to high-pressure metamorphism (only sporadically documented in Ivrea zone and Serie dei Laghi) and associated deformation (documented only in parts of the Serie dei Laghi) is interpreted to be responsible for pile up and juxtaposition of the various metasedimentary units which now occupy an impressive volume of rocks within Ivrea zone and Serie dei Laghi. At least parts of the mafic lithologies were incorporated during this event as well (mafics of oceanic origin, amphibolites with high-P relics). The age of intrusion of the Anzola-type gabbro and the mafics within the layered complex remains unknown. The pre-Ordovician age of this event is documented in the Serie dei Laghi. Accretionary wedge formation and underplating of a hypothetical continent above a subducted Ivrea oceanic crust is the most likely scenario for explaining the lack of an older granitic basement for the Ivrea zone and Serie dei Laghi metasediments (Fig. 3A). Supposing such a scenario to be correct any attempt at reconstructing a simple stratigraphic sequence for these metasediments would be bound to fail. The age of accretionary wedge formation can only be further constrained if the Sm-Nd data of around 600 Ma (Voshage et al. 1987, 1988, however, cf. another view in Voshage et al. 1990) are taken to date the earliest event of crust (more precisely oceanic crust accepting an accretionary wedge scenario) formation near the crust-mantle boundary in the Ivrea zone. In such a case Late Proterozoic to Early Palaeozoic ("Cadomian" or Caledonian) age is most likely. Radiometric dating of an Ordovician tectono-metamorphic event in anatectic paragneisses (478 Ma Rb-Sr whole rock isochron of Hunziker and Zingg 1980, however, cf. Pin 1990 for a reinterpretation) and contemporaneous intrusion of granites in the Serie dei Laghi indicate restauration of a high geotherm by Ordovician times (Fig. 3B). The age of intrusion of the Anzola-

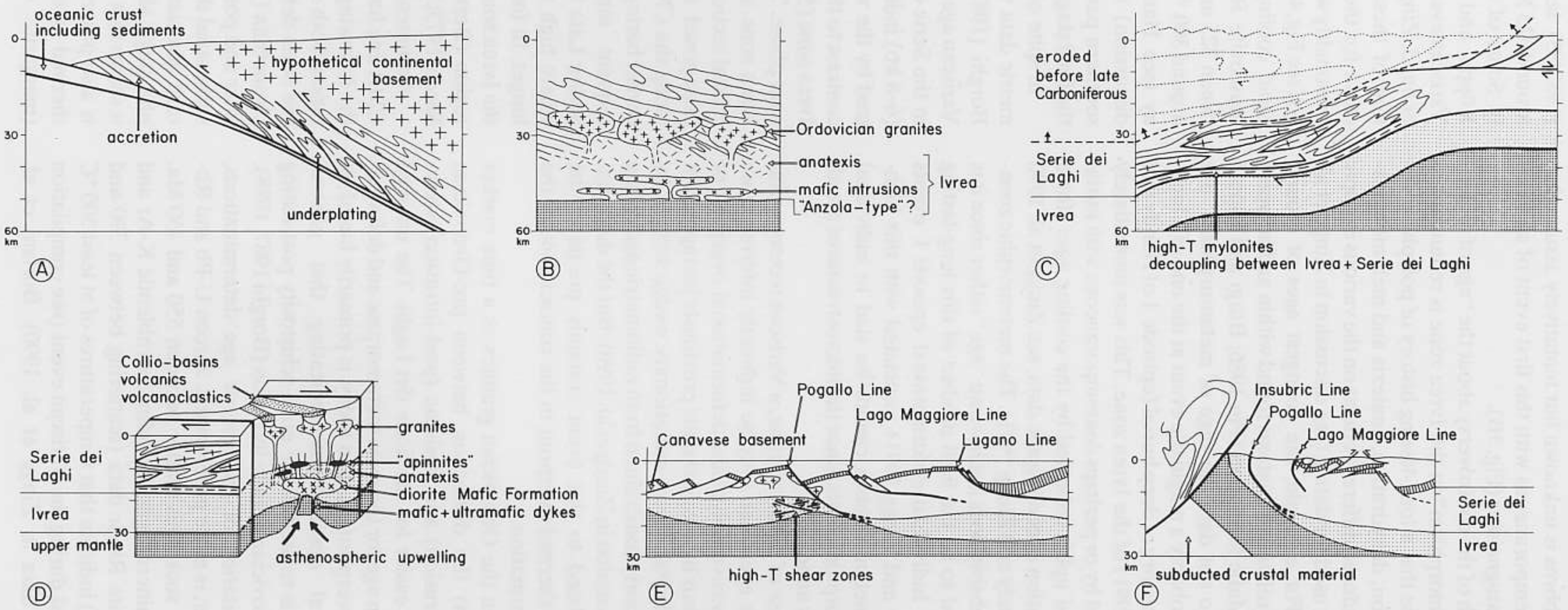

Fig. 3A–F. Largely speculative sketches illustrating the evolutionary scheme discussed in the text. All sketches have the same scaling (vertically and horizontally) and are very approximately viewed towards the N (W on the *left-hand side*). **A** Late Proterozoic or Early Palaeozoic; **B** Ordovician; **C** Variscan orogeny; **D** Late Palaeozoic (very Late Carboniferous – Early Permian) wrench tectonics and associated magmatic activity; **E** Early Mesozoic crustal attenuation; **F** Alpine (mainly Late Oligocene to Early Miocene) orogenic movements type gabbros is unknown but tentatively assumed to be contemporaneous with this first event of anatexis in the paragneisses (Fig. 3B).

Much of the controversy about the "age of regional metamorphism" in the Ivrea zone is redundant in the sense that a long-lasting history of polyphase deformation, dehydration, anatexis and melt mobilization produced different effects on the various isotopic systems used for dating (see discussion in Zingg et al. 1990). For example, the youngest ages of around 270 Ma related to anatexis found within and adjacent to the Mafic formation (Pin 1986; Bürgi and Klötzli 1990) do not date the "age of metamorphism" but most probably a magmatic event at the end of a long-lasting history of deep burial (episode 1 of Handy and Zingg 1991) of the Ivrea zone. This was immediately followed by or perhaps contemporaneous with initial stages of uplift indicated by the cooling ages (for a compilation of cooling age data, see Zingg et al. 1990 and Handy and Zingg 1991). The metamorphic zonation probably does not have an "age" either since it is expected to be the final product of this long-lasting history. Individual deformational episode 1 events (Handy and Zingg 1991) associated with this high-grade metamorphism cannot be tied to individual metamorphic events, since the microstructures are all strongly annealed.

In case of the Ivrea zone, a Variscan tectonometamorphic event can only be indirectly inferred from the pervasive polyphase deformational overprint of the various lithological units previously juxtaposed in the Early Palaeozoic accretionary wedge setting. Its age is poorly constrained from radiometric age dating (see discussion in Zingg et al. 1990). But the deformation related to this event certainly pre-dates the 270 Ma thermal overprint in the contact zone of the Mafic formation.

Given the Ordovician granites as a time-marker (466 Ma) the distinction between pre-Ordovician (pre-intrusion) and Variscan (post-intrusion) structures is easier for the Serie dei Laghi. The inferred Variscan age for the main metamorphic and deformational overprint, as seen today, is primarily based on structural observations indicating that mineral growth is related to the main schistosity post-dating the Ordovician granite intrusion (Borghi 1987, 1988). Interpretation of radiometric age determinations, however, is more problematic. Zircon U-Pb and Rb-Sr total rock ages scatter between 550 and 450 Ma, while mineral ages, including hornblende K-Ar and muscovite Rb-Sr data (scattering between 390 and 260 Ma) indicate that temperatures of at least 500 °C persisted during the Variscan event (see compilation of age data in Zingg et al. 1990). Boriani et al. (1982/83) suggest that the muscovite Rb-Sr ages around 325 Ma date this Variscan event more precisely. Some of the monazite U-Pb ages (Köppel 1974; Köppel and Grünenfelder 1978/79) also indicate a Variscan event between 320 and 285 Ma. On the other hand, Zingg (1983) casts doubts on the interpretation of these ages as formation ages. The cooling curve for the southern part of the Serie dei Laghi is reasonably well established for the region S of Brissago (see Fig. 4b in Handy and Zingg 1991) and suggests rapid cooling immediately post-dating the 325 Ma muscovite Rb-Sr age. Since rapid exhumation between 325 and about 310 Ma (biotite ages closing at around 300 °C) is probably related to Variscan orogeny (see Handy and Zingg 1991 and the following discussion) the 325–310 Ma cooling period for the southern part of the Serie dei Laghi probably dates the final stages of Variscan orogeny.

In spite of these difficulties in interpreting radiometric data we regard the structural observations of Borghi (1987, 1988) as convincing evidence for a Variscan age of the main tectono-metamorphic event in the Serie dei Laghi. The relatively high pressures (6–8 kb) indicated for this Variscan event characterized by the widespread occurrence of kyanite are in contrast to those of the amphibolite facies part of the Ivrea zone (5–6 kb) where sillimanite is the predominant phase. Two interpretations are possible: (1) the Ivrea zone and Serie dei Laghi do not represent a crustal section during Variscan orogeny at all and are juxtaposed in late Variscan times by movements along the CMB line (Boriani et al. 1990a); or (2) an earlier baric peak was completely overprinted by subsequent temperature dominated metamorphism and/or Late Palaeozoic magmatism in the Ivrea zone where high temperature conditions persisted much longer. In fact, kyanite has also been reported from the Ivrea zone in the Val Sesia, Biella and Val Grande region (Bertolani 1959; Capedri 1971; Boriani and Sacchi 1973; Handy 1986).

Arguments against late Variscan activity along the CMB line have already been discussed. Additionally, the following argument favours the second interpretation: both sillimanite and kyanite are found within the Serie dei Laghi adjacent to the Ivrea zone in Val Cannobina (Boriani et al. 1977), sillimanite growing later and post-kinematically. Borghi (1988) reports a substantial decrease in pressure at constant temperature associated with this post-kinematic metamorphic stage, also found in the Gamborogno area. Thus, it seems that a later thermal overprint, albeit weaker, is also present in the Serie dei Laghi. However, this thermal overprint was closely followed by uplift (margarite coronas around kyanite reported by

Borghi (1988) and did not reach completion within the Serie dei Laghi.

Two additional features of the Variscan tectonometamorphic event in the Serie dei Laghi contrast with findings in the Ivrea zone: (1) the absence of a metamorphic zonation except near the contact with the Ivrea zone; and (2) the presence of greenschist facies deformational overprint pre-dating Late Palaeozoic magmatism. This suggests decoupling between the lower crust (Ivrea zone) and intermediate crustal levels (Serie dei Laghi) during the Variscan orogeny (Fig. 3C) rather than late Variscan juxtaposition along the CMB line. This decoupling could be held responsible for major differences in structural style between the Ivrea zone and Serie dei Laghi (see also Handy and Zingg 1991): large-scale Pre-Alpine folding leading to variable orientations of stretching lineations ("Schlingen" folds) is restricted to the Serie dei Laghi. Such large-scale folding and/or faulting, associated with crustal thickening and subsequent exhumation during the pre-Late Palaeozoic greenschist facies event of Borghi (1988), could be held responsible for the disruption of metamorphic gradients and early exhumation of large parts of the Serie dei Laghi. Due to the considerable lack of detailed structural investigations in the Serie dei Laghi, no more can be said with respect to the Variscan orogeny and its geotectonic setting.

It has to be emphasized, however, that the exhumation history of the SE part of the Serie dei Laghi definitely pre-dates that of the Ivrea zone and thus cannot be related to Late Palaeozoic or Mesozoic events discussed in the next section. In the SE part of the Serie dei Laghi, exhumation occurred during the closing stages of Variscan orogeny (325–310 Ma) and was accompanied by very substantial amounts of erosion (indicated in Fig. 3C) as documented by the Permo-Carboniferous transgression onto amphibolite grade basement. No direct signs of exhumation and cooling pre-dating Late Palaeozoic and Mesozoic events have been found in the Ivrea zone so far. The Ivrea lower crust is completely detached from higher crustal levels and remains in a regime of elevated temperatures. However, since the considerable amounts of erosion in the Serie dei Laghi suggest isostatic uplift of overthickened intermediate and upper crustal levels, isothermal uplift of the lower crust is to be expected. The pressure estimates of Sills (1984) for the lowermost granulite facies part (< 9 kb) indeed suggest that normal crustal thickness of around 30 km was reinstalled before final equilibration of the geobarometers. It is this isostatic and isothermal uplift which could lead to temperature-dominated overprint in the Ivrea zone, related to the re-installation of normal crustal thickness and strong annealing of microstructures.

4.2 Age and Geotectonic Setting of Magmatism and Uplift During the Late Palaeozoic and Early Mesozoic

Diametrically opposed views have been proposed with regard to the Late Palaeozoic and Early Mesozoic evolution. One is that expressed by Boriani et al. (1990a,b) who emphasize the importance of transcurrent movements during the Late Palaeozoic (Permian) period. They invoke a subduction zone with oblique incidence along the CMB line connected with uplift of the Ivrea zone and emplacement of dioritic stocks and dykes in transtensional sectors, immediately followed by an Early Permian magmatic arc represented by the Graniti dei Laghi and related volcanics. Stille and Buletti (1987) even propose SE-directed subduction of Ivrea oceanic crust during Permian time, a scenario similar to that proposed in the previous Section for Early Palaeozoic times. They suggest that final closure of the Proto-Tethys did not occur before Permian times. These views are not only incompatible with the regional metamorphic evolution during the closing stages of Variscan orogeny discussed so far, but also with the large-scale scenario proposed by Ziegler (1986) indicating Westphalian-Early Stephanian (about 300 Ma) consolidation of the Variscan fold belt in Europe.

Another view assumes that no crustal thickening occurred since Early Permian times and that the present-day thickness of Ivrea zone and Serie dei Laghi in the Val d'Ossola profile allows for an estimate of the total crustal thickness of about 30 km for the Southern Alpine basement (sketched in Fig. 3D) before the onset of Late Palaeozoic events (Handy 1987). Thereby, the effects of Variscan orogeny and crustal thickening are not taken into consideration, i. e. it is tacitly inferred that a normal crustal thickness (30 km) was re-installed after the Variscan orogeny and before deposition of the Permo-Carboniferous cover about 300 Ma ago. These assumptions are reasonable in the light of the discussions of the previous chapter and the findings of Eisbacher et al. (1989) for the Schwarzwald-Vosges area. It is important to recall that estimates on the amount of crustal thinning during Late Palaeozoic and Early Mesozoic crustal attenuation (Handy 1987) rely on these assumptions, which are not unanimously accepted.

Deformations related to episode 2 deformation, in the sense of Handy and Zingg (1991), clearly post-date annealed microstructures for the high-temperature shear zones observed in many parts of the Ivrea zone, some of them forming under similar or even higher metamorphic conditions than those prevailing during episode 1. Brodie and Rutter (1987) inferred some 2 km of crustal thinning produced by an anastomosing network of mylonite zones and small-scale shear zones within the lowermost 5 km of the Ivrea zone adjacent to and within ultramafic bodies. They infer E-W-directed extension by restoring the stretching lineations into their pre-Alpine orientation. Handy (1987) estimated a total amount of crustal thinning of around 8–10 km produced by normal faulting along the contact between Ivrea zone and Serie dei Laghi at and in the vicinity of the Pogallo fault, again indicating E-W extension when restoring the Ivrea zone into a subhorizontal attitude. There, although extension initiated under peak metamorphic conditions, most of the movement occurred under retrograde conditions. Assuming an original custal thickness of 30 km, the total amount of stretching results in a stretching factor of $\beta = 1.5–1.7$.

Difficulties arise during attempts to date these extensional features more exactly within the large 270–180 Ma time interval indicated by the cooling ages in the Ivrea zone. Direct observational links between stretching and Late Palaeozoic magmatic activity have not been established yet. Brodie et al. (1989) date initiation of crustal thinning in the lowermost Ivrea crust at around 280 Ma, interpreting Ar-Ar data obtained from extensional shear zones to be cooling ages. This age closely corresponds to the age of intrusion of parts of the Mafic formation in Val Sesia. Thus the manifestations of Late Palaeozoic magmatic activity are contemporaneous with the initial stages of E-W-directed extension according to these authors.

It follows from this discussion that the initial phases of crustal attenuation may be Late Palaeozoic. Handy and Zingg (1991) proposed that these initial stretching stages reflect a tectonic regime which is distinctly different from passive continental margin formation in the Mesozoic. Based on the geometry of presently ENE-WSW-trending Collio-Verrucano basins they propose sinistral transtension of the Southern Alpine crust, coeval with Permian magmatism in all crustal levels, and compatible with the observed E-W stretching lineations in the high-temperature mylonites of Brodie and Rutter (1987). Handy and Zingg (1991) suggest that such local sinistral transtension would have to be conjugate with large-scale dextral shear between Africa and Europe (Arthaud and Matte 1977; Ziegler 1986).

Concerning the Pogallo fault, Handy (1987) estimates that about 3 km of crust was thinned at the Ivrea zone – Serie dei Laghi – contact sometime between Early Permian and Middle Triassic times, based on an interpretation of cooling ages adjacent to the Pogallo line. However, an additional 5–7 km have to be kinematically linked to a new tectonic scenario: the opening of the NNE–SSW–trending asymmetrical rifts formed during the Late Triassic to Early Jurassic (Bernoulli 1964; Bertotti 1990, 1991). The idea, that earlier crustal attenuation related to wrench tectonics was actually related to movements along the Pogallo fault zone, as seen today, is not compelling. The structural discordance across the greenschist facies mylonites and cataclasites at the southern margin of the Pogallo fault zone certainly formed during the Early Jurassic when temperature in the Ivrea zone fell to below 300 °C.

Late Palaeozoic magmatism is coeval at all crustal levels (Fig. 3D). The new data and observations of Bürgi and Klötzli (1990) lend additional support to the suggestion first proposed by Fountain (1986) that intrusion of the Mafic formation caused partial melting in deep crustal metasediments which in turn led to Permian plutonic and volcanic activity in higher crustal levels. Additionally, crustal contamination within phlogopite peridotites and intrusion of mafic and ultramafic dykes into the Balmuccia peridotite (Voshage et al. 1987, 1988) are contemporaneous with this event. This points to a deep seated origin of magmatic activity. Whole crustal failure due to Late Palaeozoic wrench tectonics (Ziegler 1986) could have allowed rapid magma ascent (Handy and Zingg 1991). Potentially, the Ivrea zone offers an unique opportunity to study the deep crustal manifestations of this, often underestimated, major tectonic and magmatic event. Since this event post-dates exhumation of the Serie dei Laghi and restauration of a normal crustal thickness after the Variscan orogeny, the term "Late Variscan" is misleading. In fact, Arthaud and Matte (1977) suggest that this wrench faulting event is independent of the previous evolution and forms a peculiar class of tectonic movement affecting the entire rigid crust.

Details on contemporaneous strain partitioning between lower crustal extension by anastomosing conjugate shear zones, localized shear along the Pogallo fault and faulting directly associated with basin formation (Fig. 3E) remain problematic, due to dating problems with regard to the high-temperature shear zones in the lower crust. However, we do not regard the arguments for Late Palaeozoic initiation of shear zone formation proposed by Brodie et al. (1989) as conclusive. According to Brodie and Rutter

(1987), the geometric characteristics of these conjugate shear zones suggest substantial shortening perpendicular to layering (i. e. in a vertical direction after retro-deformation of Alpine tilting). This type of strain is hardly compatible with wrench tectonics. Consequently, we favour an Early Mesozoic age for their formation (Fig. 3E). From large-scale considerations and from a sedimentological point of view (Bertotti 1990, 1991) it is more appropriate to separate clearly Late Palaeozoic wrench tectonics from the onset of crustal attenuatiuon during the Middle Triassic. In fact, a Middle Triassic magmatic event related to the initiation of rifting has recently been reported by Stähle at al. (1990) from the Ivrea zone.

4.3 Emplacement Tectonics During Alpine Orogeny

The cooling ages indicate that temperatures fell below 300 °C before the Middle Jurassic for the entire Southern Alpine basement section exposed today. Therefore, emplacement tectonics during the Alpine orogeny was only associated with moderate uplift and the temperatures prevailing during Alpine deformation did not allow for a penetrative structural overprint. Consequently, the Ivrea zone acted as a relatively rigid indenter during post-collisional transpressive movements, at a retraining bend of the Insubric line (Merle et al. 1989; Schmid et al. 1989).

Nevertheless, the pre-Alpine main foliation, including high-grade mylonite horizons related to Late Palaeozoic and Early Mesozoic exhumation were affected by flexural slip folding producing major antiforms immediately S of the Insubric line. Schmid et al. (1987) regard these antiforms as synchronous with backthrusting along the Insubric line during the Late Oligocene. The tilted cross-section through the Southern Alpine crust in the Val d'Ossola geometrically corresponds to the SE limb of the Proman antiform with granulite facies Ivrea zone in its core (Figs. 2 and 3F). Its NW limb is constituted by strongly mylonitized remnants of higher crustal levels (Canavese and amphibolite facies Ivrea zone). Extreme attenuation of the NW limb and lack of lateral continuity between individual antiforms along strike is due to later overprint by strike-slip movements along the Insubric line. Conflicting views exist on the metamorphic conditions associated with another antiform at Finero (greenschist facies conditions, according to Kruhl and Voll 1976 versus amphibolite facies conditions, reported by Steck and Tièche 1976). The eastern plunge of yet another antiform (undoubtedly formed under greenschist facies conditions) of inferred Alpine age near Ascona (Schmid unpubl. results) is reponsible for the eastern termination of the Ivrea zone which is interpreted to be at much greater depth (around 20 km) along the NFP 20 southern traverse (Bernoulli et al. 1990). On the other hand, tilting due to large-scale folding seems to persist towards the SW and into the ECORS profile (Rey et al. 1990). The basement-cover contact, under the cover of the Po plain, is gently SE dipping along the ECORS profile (Roure et al. 1990), indicating a hinge zone between the verticalized Ivrea cross-section and this gently dipping basement-cover contact. During the Late Oligocene to Early Miocene, i.e. contemporaneous with verticalization due to folding, this basement-cover contact was shortened by minor thrusting (Roure et al. 1990).

East of Lago Maggiore, the Alpine deformation is more complex and appears to be characterized by a network of thrusts (e.g. the Gamborogno thrust mapped in Fig. 1) and transfer zones forming in response to an interference between E-W and N-S compression during several phases of Alpine overprint (Schumacher 1990). Thus, the basement high, E of Lago Maggiore, cannot be uniquely related to tilting of a cross section through the Southern Alpine basement. Even further to the E (Grignia section, Laubscher 1985) it may be entirely related to ramp antiforms forming during S-vergent thrusting.

Only a limited amount of fission track data are presently available for radiometrically dating Alpine emplacement tectonics (Hurford 1986; Hurford et al. 1989; Bürgi and Klötzli 1990). According to the apatite fission track data tilting of the Ivrea zone and vertical components of relative movement along the Insubric line are older than 12 Ma. The zircon data exhibit a large scatter, possibly due to rejuvenation near the Insubric line. However, the age of 64 Ma reported by Bürgi and Klötzli points to a pre-Oligocene phase of uplift, predating verticalization during the Late Oligocene. Earlier events are also indicated by K-Ar mineral ages found within the Canavese sediments along the SW part of the Insubric line (Zingg and Hunziker 1990), a segment of the Insubric line where pre-Oligocene mylonites are preserved (Schmid et al. 1989).

Late Cretaceeous and/or Palaeocene orogeny affected a large part of the Southern Alpine basement, presently exposed in the Central Alps (Sesia zone, including the "seconda zona diorito kinzigitica", Dal Piaz this Vol). Schmid et al. (1987) speculated that the density inversion at the base of the Ivrea geophysical body is due to underplating by a SE-dipping continuation of the Sesia zone during this early Alpine event.

Brack (1981) documented pre-Late Eocene deformation near the Adamello intrusion, a compressional phase held responsible for much of the thrusting E of Lago Maggiore by Schumacher (1990). Zingg and Hunziker (1990) report Cretaceous mica ages in the Canavese sediments at the SW end of the Insubric line. No structures related to this early phase of Alpine tectonics have been documented so far in the Ivrea zone.

Other phases of Alpine overprint are postulated for the cover of the Southern Alps (Late Eocene to Early Miocene and Late Miocene thrusting, Bernoulli et al. 1989). However, their effect is not documented west of Lago Maggiore where large-scale tilting of the SE limb of the Proman antiform during the Late Oligocene and Early Miocene is held responsible for exposure of this unique cross section through the entire crust (Fig. 3F).

4.4 Do Ivrea Zone and Serie dei Laghi Expose a Typical Cross-Section Through Continental Crust?

It was argued that the major effect of Alpine orogeny was large-scale tilting in the absence of a penetrative overprint and/or major thrusting along the Val d'Ossola section. Supposing this interpretation to be correct (for opposing views see Boriani et al. 1990a,b) a cross-section through pre-Alpine crust is indeed exposed. However, does this cross-section expose a typical section through continental crust in general, a Palaeozoic orogen, or, alternatively thinned continental crust in a passive continental margin environment?

It is hoped that the previous discussions made it clear that this section is the result of a long-lasting complex evolution. It began with accretion of thick packages of metasediments and mafic intrusions above a subducting oceanic lithosphere and below an old continental basement, not preserved within the area of interest, followed by a long-lasting period of consolidation in a lower crustal environment and partial exhumation due to Late Palaeozoic and Early Mesozoic extension tectonics. In this sense, the presently exposed section is a composite of an evolution which is particular for this zone. Therefore, it can certainly not provide a universally valid "type section" of continental crust. Very likely the search after a "type section" is a fruitless enterprise, anyway, in the sense thast it would reflect a highly immobilistic view of crustal evolution.

In regard to the Variscan orogeny, the potential advantage of having an exposed crustal section is counteracted by the disadvantage that higher crustal levels are not preserved, due to substantial amounts of erosion, before deposition of the Permo-Carboniferous onto amphibolite grade rocks. Consequently, only deeper crustal levels of this orogen are exposed. A comparison of P-T conditions between the Ivrea zone and Serie dei Laghi suggests that P-T-conditions did not equilibrate at the same time within these units which were decoupled during orogeny. Hence, the present metamorphic zonation does not reflect the P-T conditions at a particular instant of time during Palaeozoic orogeny. This is most dramatically exemplified by the contemporaneity between granulite facies conditions in the Ivrea zone and transgression of the Permo-Carboniferous cover onto amphibolite grade Serie dei Laghi. The most important consequences of the interpreations regarding Variscan orogeny are: (1) decoupling between lower und intermediate crust during Variscan orogeny; and (2) re-equilibration to normal crustal thickness during the late stages of Variscan orogeny.

The most direct insight offered in this cross section relates to the Late Palaeozoic magmatic activity (Fig. 3D) and to extensional tectonics during the Early Mesozoic (Fig. 3E) which affected a piece of continental crust which re-equilibrated to normal thickness before the onset of both these events. The section offers a unique opportunity to study contemporaneous magmatic activity associated with Late Palaeozoic wrench tectonics at all crustal levels, an opportunity which largely remains unexploited by magmatic petrologists so far. Due to dating problems, it cannot be excluded that this Late Palaeozoic magmatic activity is contemporaneous with the initiation of crustal thinning in the Ivrea zone and along the NE part of the contact between Ivrea zone and Serie dei Laghi.

Attempts to reconstruct the geometry and kinematics of crustal attenuation during the Early Mesozoic have been made (Brodie and Rutter 1987; Handy 1987; Schmid et al. 1987; Bertotti 1990, 1991; see Fig. 3E) and suggest that each crustal level had its own particular style for acommodating extension: listric or domino-type faults in upper crustal levels, localized faulting (Pogallo fault) at mid-crustal levels, and extension of the lower crust by a network of conjugate shear zones. However, these reconstructions assume contemporaneous stretching during the Early Mesozoic at all crustal levels.

Seismologists early recognized the potential offered by this Southern Alpine cross-section for interpreting seismic properties of the crust, in particular of the highly reflective lower crust (e. g. Fountain 1976). Recently, this cross-section has been sampled for laboratory studies on seismic wave velocities (e. g. Burke and Fountain 1990). These studies confirm the view that Ivrea zone and Serie dei Laghi represent an excellent example of attenuated continental crust.

The reconstruction of the evolutionary scheme as depicted in Fig. 3 is admittedly speculative, in particular regarding the stages pre-dating Mesozoic extension. Nevertheless, such a reconstruction was attempted with the main purpose of stimulating further research directed towards solving fascinating problem-oriented questions. The final stages of the evolution (Fig. 3E,F) and, in particular, the Alpine age of tilting of a crustal section are much better constrained by the available data. Concluding, we firmly believe that Ivrea zone and Serie dei Laghi offer a unique opportunity to study a section through attenuated continental crust and to further investigate deep crustal manifestations of pre-Alpine orogeny.

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