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Multistage accretion and exhumation of the continental crust (Ivrea crustal section, Italy and Switzerland)

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Abstract. The Ivrea crustal section exposes in map view all levels of the southern Alpine continental crust, from ultramafic, mafic, and felsic granulite facies rocks of the deep crust (Ivrea-Verbano Zone), through medium-grade basement rocks (Strona-Ceneri Zone and Val Colla Zone), to unmetamorphosed Permo-Mesozoic sediments. The oldest part of the crustal section is preserved in the medium-grade basement units, which are interpreted to be the overprinted remains of an Ordovician (440-480 Ma) magmatic arc or forearc complex. During Variscan subduction this arc was tectonically underplated by a Carboniferous accretion-subduction complex (320-355 Ma) containing metasediments and slivers of Rheic oceanic crust presently found in the Ivrea-Verbano Zone. During the late stages of Variscan convergence (290-320 Ma), lithospheric delamination triggered magmatic underplating and lead to polyphase deformation under amphibolite to granulite facies conditions. This was broadly coeval with extensional exhumation and erosion of the Variscan-overprinted Ordovician crust presently exposed in the Strona-Ceneri and Val Colla Zones. Post-Variscan transtensional tectonics (270-290 Ma) were associated with renewed magmatic underplating, mylonitic shearing, and incipient exhumation of the lower crust in the Ivrea-Verbano Zone. This coincided with the formation of elongate basins filled with volcanoclastic sediments in the upper crust. Early Mesozoic, Tethyan rifting of the southern Alpine crust (180-230 Ma) reduced crustal thickness to 10 km or less. In the lower crust, most of this thinning was accommodated by granulite to retrograde greenschist facies mylonitic shearing. The lower crust was exhumed along a large, noncoaxial mylonitic shear zone that was linked to asymmetrical rift basins in the upper crust. The composite structure resulting from this complex evolution is probably typical of thinned, late Variscan continental crust on the passive margins of western Europe. Alpine faulting and folding (20-50 Ma) fragmented the crustal section. The originally deepest levels of the crustal section in the Ivrea-Verbano Zone as well as some segments of the basement-cover contact were steepened, whereas other parts of the crustal section, particularly the Strona-Ceneri Zone, underwent only minor to moderate Alpine rotation.

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1. Introduction

Continental crust is generally considered to form at convergent plate margins, where sediments accrete above subduction zones and then are deformed, metamorphosed, and sometimes melted during continental collision [*Dewey and Bird*, 1970]. Yet coherent cross sections of exposed continental crust [*Fountain and Salisbury*, 1981] reveal that crust also forms in other tectonic environments, including divergent settings within and along plate boundaries [*Percival et al.*, 1992]. In particular, magmatic underplating associated with asthenospheric upwelling and lithospheric attenuation is thought to be an important mechanism in forming and transforming the continental crust [*Furlong and Fountain*, 1986; *Fountain*, 1989; *Asmerom et al.*, 1990]. Lithospheric attenuation has also been proposed as a mechanism for exhuming coherent tracts of deep continental crust and upper mantle [*Wernicke*, 1990]. This paper examines the relative roles of accretion, magmatism, and attenuation in the formation and exhumation of the southern Alpine crust. Do these processes affect all levels of the crust similarly or do some of these processes act selectively on certain levels of the crust? How are these processes related to the regional tectonic framework?

The Ivrea crustal section at the western end of the southern Alps (Figure 1) is an excellent place to seek answers to these questions. This crustal section reveals different levels of the continental crust, from granulite facies metasediments and mafic and ultramafic intrusive rocks of the Ivrea-Verbano Zone in the northwest, through amphibolite facies metasediments and granitoids of the Strona-Ceneri Zone and Val Colla Zone, to unmetamorphosed upper Carboniferous, Permian, and Mesozoic sediments in the south and southeast (Figure 1). The general coincidence of these changes in metamorphic grade with density and seismic velocity gradients across the crustal section has lead to its interpretation as an upended section of continental crust [*Mehnert*, 1975; *Fountain*, 1976] that formed part of the rifted, Apulian margin in early Mesozoic time [*Zingg et al.*, 1990]. However, a consensus on the Paleozoic evolution of the Ivrea crustal section has proved elusive so far.

Debate centers on the ages of pre-Mesozoic sedimentation and regional metamorphism and especially on the relationship of the latter to magmatism in the crustal section (reviews by *Zingg et al.* [1990], *Gebauer* [1993], and*Schmid* [1993]). The metasediments are interpreted to have accreted in Proterozoic to early Paleozoic time [*Gebauer*, 1993] before experiencing regional metamorphism, variously dated as Ordovician [*Hunziker and Zingg*, 1980] or late Carboniferous [*Boriani et al.*, 1990; *Boriani and Villa*, 1997] in both the Ivrea-Verbano Zone and the Strona-Ceneri Zone. Other workers favor an

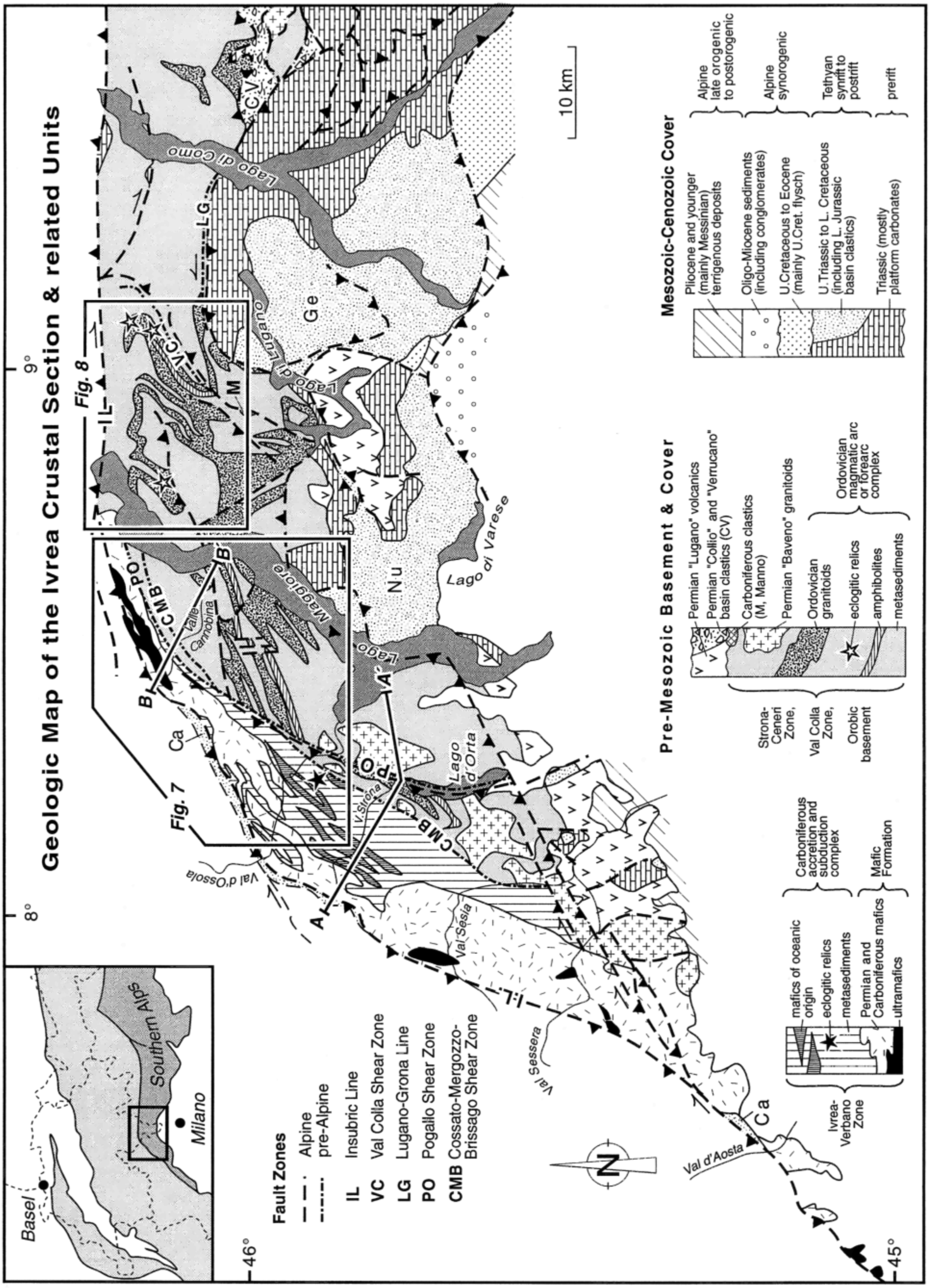

Geologic Map of the Ivrea Crustal Section & related Units
Fig. 7
Fig. 8
10 km
8°
9°
46°
45°
Basel
Milano
Southern Alps
Fault Zones
Alpine
pre-Alpine
IL Insubric Line
VC Val Colla Shear Zone
LG Lugano-Grona Line
PO Pogallo Shear Zone
CMB Cossato-Mergozzo-Brissago Shear Zone
Lago Maggiore
Lago di Como
Lago di Lugano
Lago di Varese
Lago d'Orta
Valle Cannobina
Val d'Ossola
V. Strona
Val Sesia
Val Sessera
Val d'Aosta
Ca
Ge
Nu
CV
M
A
A'
B
B'
Pre-Mesozoic Basement & Cover
Permian "Lugano" volcanics
Permian "Collio" and "Verrucano" basin clastics (CV)
Carboniferous clastics (M, Manno)
Permian "Baveno" granitoids
Ordovician granitoids
eclogitic relics
amphibolites
metasediments
Ordovician magmatic arc or forearc complex
Strona-Ceneri Zone, Val Colla Zone, Orobic basement
mafics of oceanic origin
eclogitic relics
metasediments
Permian and Carboniferous mafics
ultramafics
Carboniferous accretion and subduction complex
Mafic Formation
Ivrea-Verbano Zone
Mesozoic-Cenozoic Cover
Pliocene and younger (mainly Messinian) terrigenous deposits
Oligo-Miocene sediments (including conglomerates)
U.Cretaceous to Eocene (mainly U.Cret. flysch)
U.Triassic to L. Cretaceous (including L. Jurassic basin clastics)
Triassic (mostly platform carbonates)
Alpine late orogenic to postorogenic
Alpine synorogenic
Tethyan synrift to postrift
prerift

Figure 1.

Early Permian age for this metamorphism, attributing it to the intrusion of mafic melts in the Ivrea-Verbano Zone [*Pin*, 1986; *Fountain*, 1989; *Teufel and Schärer*, 1989]. Clearly, insight into deep crustal processes can only be gained if these discrepancies are reconciled.

The controversies above stem partly from the contrasting approaches and interpretations of specialists working in different parts of the crustal section. They also reflect the inherent difficulty of correlating tectonothermal events across a lithologically and structurally heterogeneous exposure of crust that occupied different depths during its evolution. A given tectonothermal event is recorded differently in different parts of the section. Conversely, different levels of the crust experienced similar deformational and metamorphic conditions at various times during exhumation. Added to this problem are the complex, Alpine emplacement tectonics, which in our case dismembered and selectively reoriented parts of the crustal section.

A prime goal of this paper is therefore to present a tectonic model of the Ivrea crustal section that is based on a first attempt to correlate structures, metamorphic mineral assemblages, and magmatic rocks across the entire section, from its base to its unmetamorphic cover. To this end, we synthesize new and existing structural, petrological, geochronological and paleomagnetic data. In section 2, we present the salient arguments and overprinting relationships used to relate pre-Alpine structures and metamorphism within the crustal section. Structural and paleomagnetic information in section 3 constrain differential rotations of parts of the section during Alpine emplacement tectonics and allow us to reconstruct the original orientation of pre-Alpine structures. The tectonic model of the Ivrea crustal section presented in section 4 serves as a vehicle for a discussion of deep-seated processes involved in the formation and exhumation of the southern Alpine continental crust. We conclude in section 5 by showing how consideration of these processes might inspire more realistic geophysical models of the continental crust.

2. Correlation of Pre-Alpine Events in Different Crustal Levels

Figure 2 summarizes the available age constraints on tectonometamorphic phases in the Ivrea-Verbano Zone, the Strona-Ceneri Zone, and adjacent units. The pre-Alpine phases are numbered sequentially for each unit. To help distinguish tectonometamorphic phases with identical numbers in different units, all phases are also named after their type localities within the two outlined areas in Figure 1. The criteria for determining the kinematics and age of the phases within these areas are discussed in sections 2.1-2.4. Note that identically numbered phases in different units are neither temporal nor kinematic equivalents. This reflects the contrasting Paleozoic histories of the Ivrea-Verbano and Strona-Ceneri Zones, as well as the fact that different levels of the crust reacted differently to the same crustal-scale events.

2.1. Ordovician Events

2.1.1. Sedimentation, accretion, and high-pressure metamorphism. A first stage of crustal accretion is restricted to the Strona-Ceneri and Val Colla Zones. It is marked by at least one phase of deformation (D1, Cannobio Phase) and by the intercalation of micaschist, banded amphibolite, and fine-grained gneiss containing quartz-rich bands and calc-silicate nodules. Very locally, these rocks preserve sedimentary features (compositional banding, graded bedding, cross-bedding) [*Origoni Giobbi et al.*, 1982; *Zurbriggen et al.*, 1998] and contain altered mafic and ultramafic lenses, some of which bear relict eclogite facies assemblages (open stars in Figure 1) [*Bächlin*, 1937; *Spicher*, 1940; *Borghi*, 1988]. These high-pressure relics reequilibrated partially under amphibolite to greenschist facies conditions [*Zurbriggen et al.*, 1997]. The trace element characteristics of the garnet amphibolites indicate that they originally comprised tholeiitic, ocean floor basalt [*Buletti*, 1983]. The imbrication of such mid-ocean ridge basalt type (MORB-type), eclogitic amphibolites with former pelites, greywackes, and carbonates is diagnostic of an accretionary sedimentary wedge, possibly containing older passive margin lithologies, that incorporated both obducted and exhumed, metamorphosed fragments of oceanic crust [*Giobbi et al.*, 1995].

Figure 3a shows that the clockwise pressure-temperature (P-T) path of the eclogites ends with nearly isothermal decompression prior to the onset of D2, Ceneri Phase deformation and metamorphism. During D1 most metasediments underwent prograde amphibolite facies metamorphism at a minimum depth of 15 km [*Zurbriggen*, 1996]. The absolute age of accretion and subduction is unknown but must predate Ordovician granitoids in the Strona-Ceneri Zone, because the imbricated rocks described above occur as xenoliths within these granitoids (Figure 4a).

2.1.2. Magmatism and regional metamorphism. Large volumes of granitic melts in the Strona-Ceneri Zone (Figure 1) intruded the accretionary wedge sequence described in section 2.1.1 sometime within the time span of 430-510 Ma (Figure 2, discussion below), although most such granitoids range in age from 440 to 480 Ma. These granitoid bodies are inferred to have intruded during D2, because they have high ratios, because their contacts are parallel to the main S2 schistosity in the Strona-Ceneri Zone and because large, euhedral feldspar phenocrysts in some granitoid bodies define a magmatic shape-preferred orientation that is coplanar with S2 [*Zurbriggen et al.*, 1997].

Figure 1. Map of western part of southern Alps. Box in small inset map shows location of large map within the Alpine chain (shaded); dashed lines indicate national boundaries. Traces of transects A-A' and B-B' are shown in Figure 5. Framed areas are shown in detail in Figures 7 and 8. Abbreviations of basins are as follows: Ca, Canavese; Ge, Generoso; Nu, Nudo; CV, Collio-Verrucano. Map is modified from *Bigi et al.* [1983], *Handy and Zingg* [1991], *Hermann* [1937], and *Schumacher et al.* [1997].

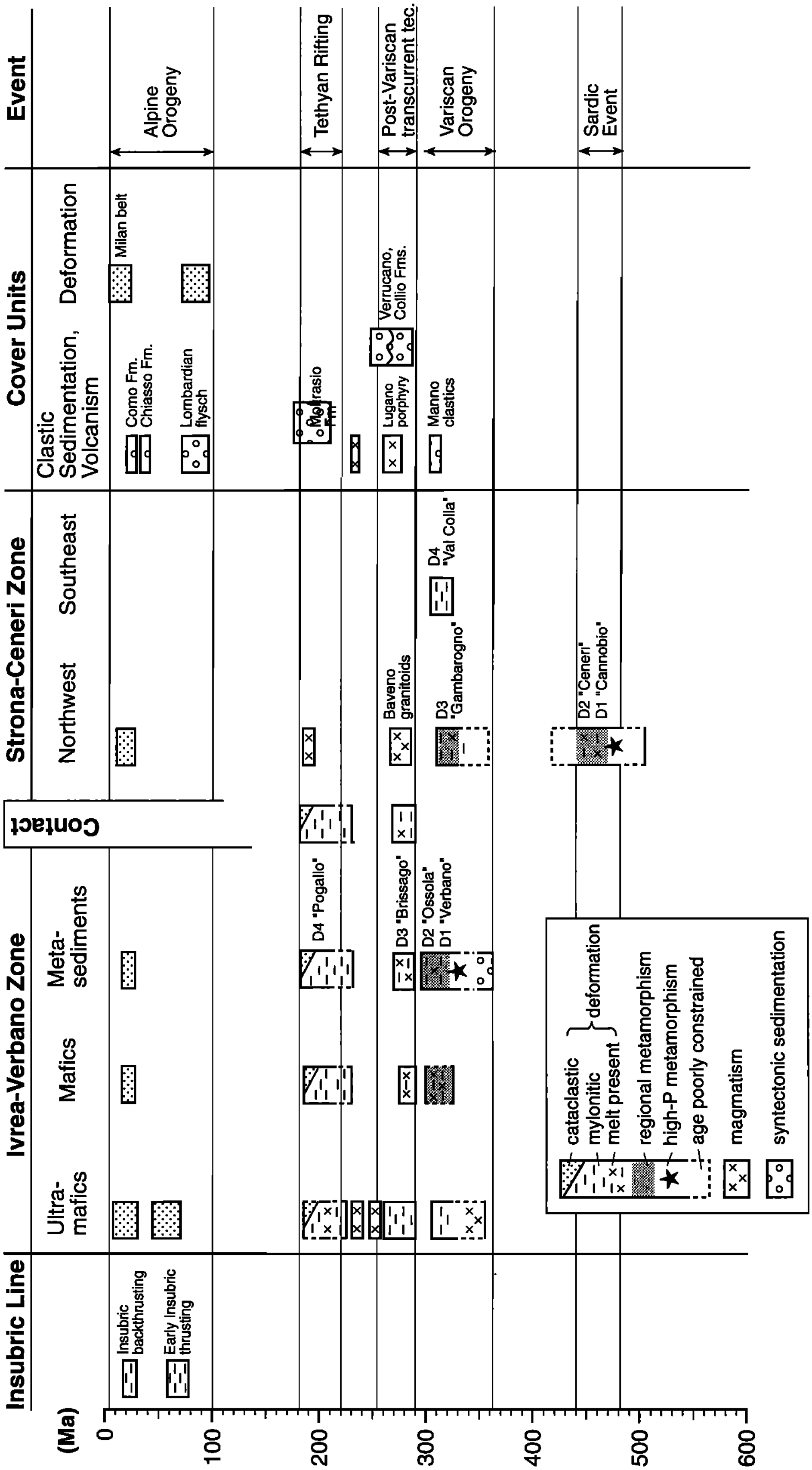


Figure 2. Ages of deformation, magmatism, and syntectonic sedimentation in basement units of the southern Alps, their sedimentary cover, and along the Insubric Line. Age criteria are discussed and cited in the text. Additional references used in Figure 2 but not cited in the text include the following: *Bernoulli et al.* [1993], *Brodie et al.* [1989], *Hofmann et al.* [1992], *Hunziker and Zingg* [1982], *Jäger et al.* [1967], *Lu et al.* [1994, 1997], *Miller and Jäger* [1968], *Schönborn* [1992], *Stähle et al.* [1986], *Wagner and Reimer* [1972], *Wright and Shervais* [1980], and *Zingg et al.* [1976]. Fm., Formation.

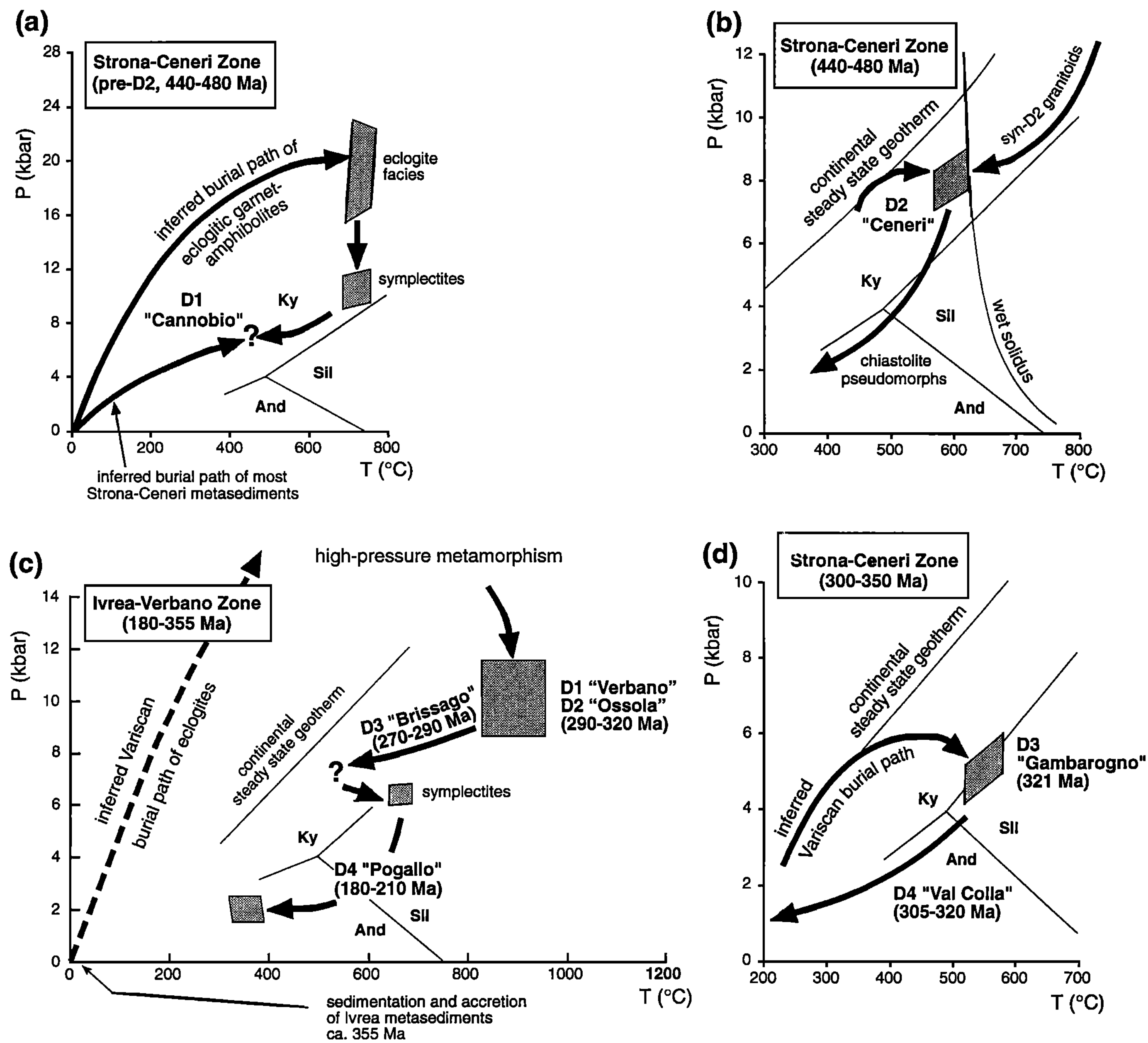


Figure 3. Pressure-temperature (P-T) paths for rocks in the Ivrea-Verbano and Strona-Ceneri Zones: (a) Ordovician paths of metasediments and eclogitic amphibolites in the Strona-Ceneri Zone simplified from *Borghi* [1988] and *Zurbriggen et al.* [1997]; (b) Ordovician paths of metasediments and granitoids in the Strona-Ceneri Zone from Zurbriggen et al.; (c) early Carboniferous to Jurassic paths of metasediments in the granulite facies part of the Ivrea-Verbano Zone synthesized from own data and that of *Franz et al.* [1994, 1996], *Handy* [1986], *Henk et al.* [1997], *Lu* [1994], *von Quadt et al.* [1992], and *Vogler* [1992]; (d) early Carboniferous to early Mesozoic paths of rocks in the Strona-Ceneri Zone from own unpublished thermobarometric data. Continental steady state geotherm is from *Peacock* [1989].

The intrusion of the granitoids was probably coeval with regional, amphibolite facies metamorphism in the Strona-Ceneri Zone, as evidenced by severe Pb loss in the U-Pb systems in zircon and monazite from both granitoids and metasediments of the Strona-Ceneri Zone at about 430-490 Ma [*Pidgeon et al.*, 1970; *Köppel and Grünenfelder*, 1971; *Köppel*, 1974; *Ragettli*, 1993]. The U-Pb and Pb-Pb systematics of staurolite oriented within the S2 foliation of metasediments in the Strona-Ceneri Zone suggest that this staurolite grew in Ordovician time and lost Pb during a later (D3, Variscan) thermal overprint (minimum 385±6 Ma $^{206}Pb/^{238}U$ staurolite age in the work of *Romer and Franz*

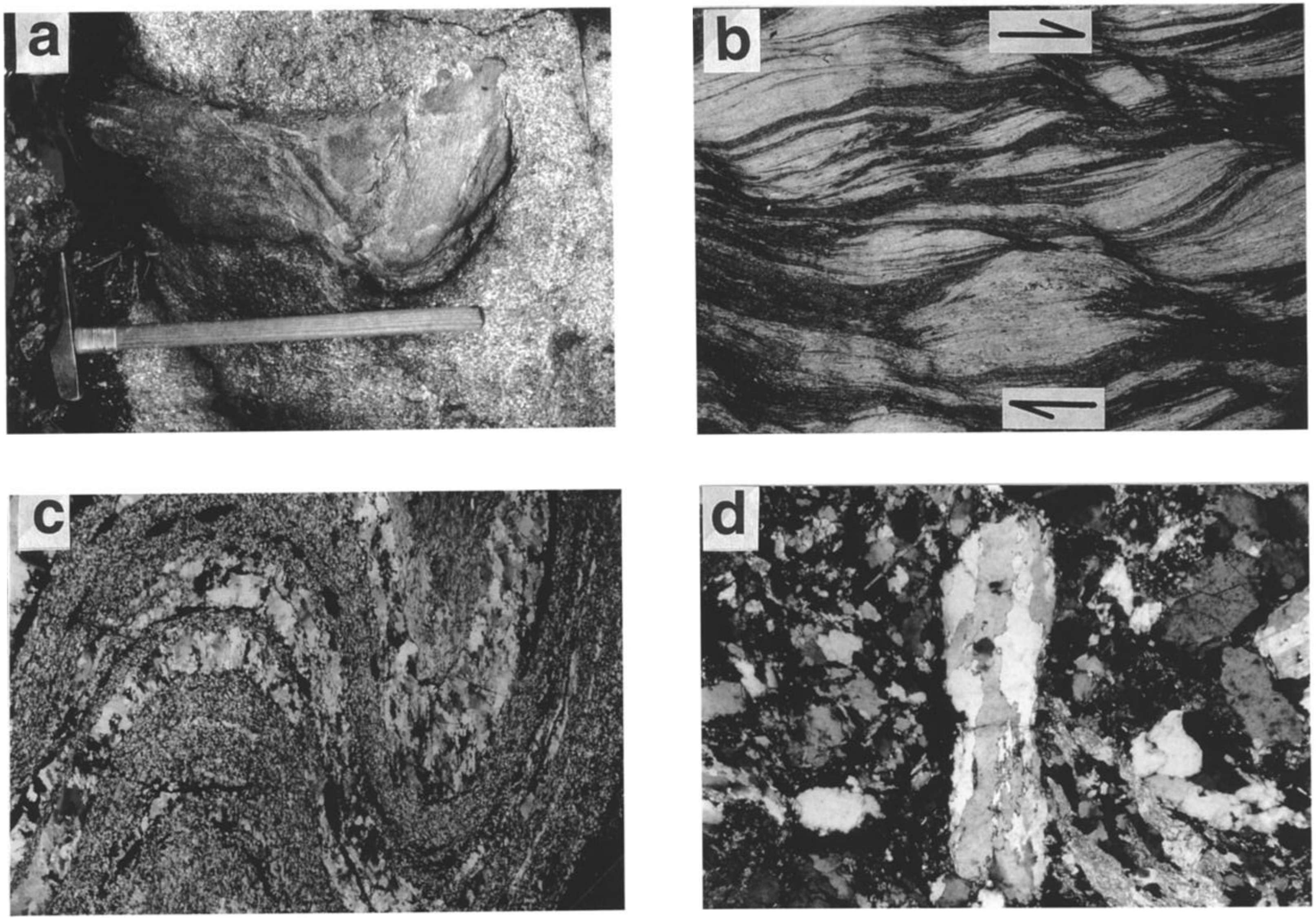


Figure 4. Key structural relationships in the Strona-Ceneri Zone: (a) xenolith of foliated (S1) metasediment within weakly foliated (S2) Ordovician granitoid; (b) shear bands in Val Colla mylonite with half arrows indicating top-to-SW shear sense as viewed in the XZ fabric plane, with crossed polarizers, frame length of 225 mm; (c) F3, Gamborogno Phase fold overprinted by D4 mylonitic deformation in the Val Colla Shear Zone; Note the shape-preferred orientation of dynamically recrystallized quartz grains, with crossed polarizers, frame length of 275 mm; (d) component of Val Colla mylonite with dynamically recrystallized quartz grains embedded in unmetamorphosed Westphalian conglomerate, with crossed polarizers, frame length of 6.8 mm.

[1998]). Indeed, thermobarometric studies on D2 and D3 mineral assemblages in the Strona-Ceneri Zone indicate that temperatures reached 500°-600°C during both tectonometamorphic phases (Figures 3b and 3d).

We note that our interpretation of the mineral ages in the Strona-Ceneri Zone in terms of separate Ordovician and Carboniferous (Variscan) metamorphic events with roughly equal thermal peaks contradicts *Boriani et al.'s* [1990] interpretation of a solely Variscan peak of regional metamorphism based on mid-Carboniferous K-Ar and Ar-Ar hornblende [*McDowell*, 1970; *Boriani and Villa*, 1997] and Rb-Sr white mica ages [*Boriani et al.*, 1983]. The structural setting of the hornblende and white mica dated in these studies is not clear (growth during D2 or D3?), however. The fact that U-Pb zircon and monazite systems in the granitoids of the Strona-Ceneri Zone were not reset in Carboniferous time may reflect the paucity of volatiles in the Variscan crust owing to Ordovician metamorphism and anatexis.

The Ordovician granitoids comprise both S-type, tonalitic to granodioritic gneisses and subordinate, mantle-derived, hornblende-bearing tonalitic gneisses. *Zurbriggen et al.* [1997] propose that the formation of the peraluminous, S-type granitoids involved the melting of substantial volumes of metapelite and/or metagreywacke at high-pressure, granulite facies conditions (10-14 kbar, 800°-900°C) in deeper levels of the crust originally underlying the Strona-Ceneri Zone in Ordovician time. The schists and fine-grained gneisses presently exposed in the Strona-Ceneri Zone may represent the shallower, compositional equivalents of these anatectic metasediments. The granitoid melt path in Figure 3b shows that these melts rose to the 8 kbar, D2 Ordovician isobar presently exposed at the surface in the Strona-Ceneri Zone. Pre-Carboniferous, D3-deformed augengneisses ("Gneiss Chiari") in the Val Colla Zone and Orobic basement are interpreted as volcanic or subvolcanic equivalents of the Ordovician granitoids [*Zurbriggen et al.*, 1997].

2.1.3. Deformation. Unfortunately, structural information regarding early Paleozoic tectonics in the Strona-Ceneri Zone is limited. Xenoliths in the Ordovician granitoids contain at least one preintrusive, amphibolite facies schistosity (S1, Figure 4a) parallel to the axial plane of isoclinal F1 folds. In most rocks the S2 schistosity of the Strona-Ceneri and Val Colla Zones completely transposes S1, obliterating the original S1 orientation and precluding kinematic reconstructions of D1 tectonics. Similarly, the kinematics of D2, Ceneri Phase deformation are masked by strong Variscan (D3, Gambarogno Phase) and Alpine structural overprints. The main S2 schistosity in the Strona-Ceneri Zone is characterized by mylonitic microstructures that were extensively annealed under D2 and/or D3, amphibolite facies conditions [*Handy and Zingg*, 1991, Figure 5c].

An Ordovician age for the D2, Ceneri Phase is inferred from the aforementioned parallelism of S2 with magmatic foliation in some granitoids. White micas aligned parallel to S2 have Si values that are consistent with the thermobarometrically derived 8 kbar pressure estimate for D2 metamorphism (Figure 3b). This pressure clearly exceeds the 4-5 kbar values obtained for D3, Gambarogno Phase assemblages in the same area (L. Franz et al., manuscript in preparation, 1999). If one assumes a crustal density of 2.8 g/cm^3, the 3-4 kbar difference in pressure estimates on D2 and D3 assemblages indicates that the Strona-Ceneri Zone underwent at least 9-12 km of exhumation before the baric peak of Carboniferous, D3 metamorphism. Most of this exhumation is inferred to have occurred already in Ordovician time, because pseudomorphs of D2 chiastolites that are transformed to kyanite and deformed during D3 (Figure 3b; see also *Zurbriggen et al.* [1997]) document post-D2 decompression prior to prograde D3 metamorphism.

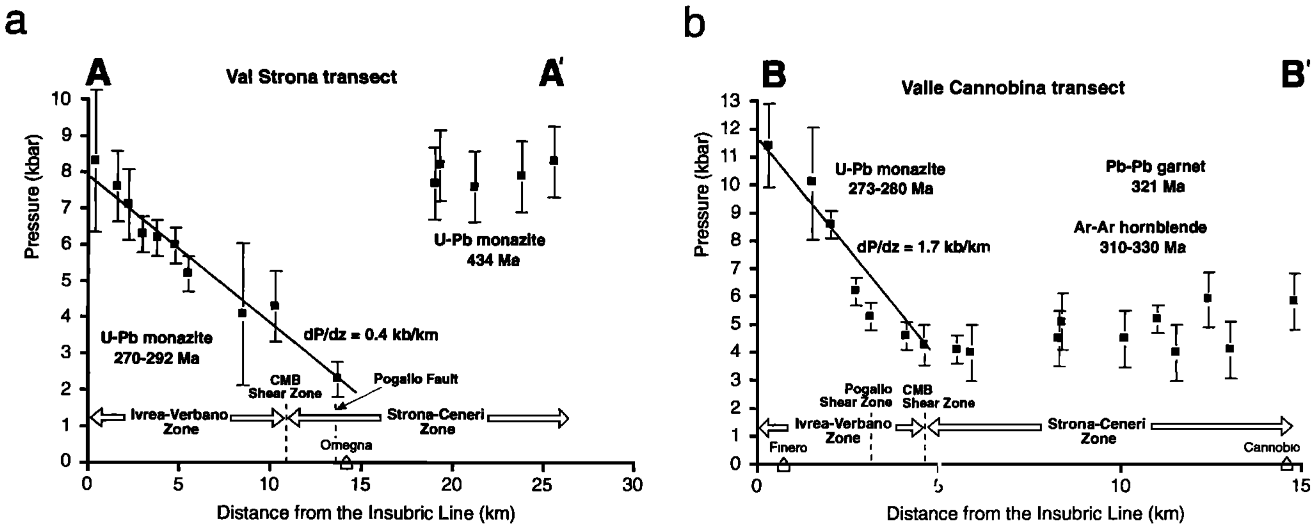


Figure 5. Metamorphic pressures across the Ivrea crustal section: (a) Val Strona transect (A-A') and (b) Valle Cannobina transect (B-B'). Trace of transects is shown in Figure 1. The U-Pb monazite ages and metamorphic pressures for Figure 5a are taken from *Henk et al.* [1997], and those for Figure 5b are taken from own data and *Franz et al.* [1994, 1996]. The Ar-Ar hornblende ages are from *Boriani and Villa* [1997], and the Pb-Pb garnet age is from *Zurbriggen et al.* [1998]. CMB, Cossato-Mergozzo-Brissago Shear Zone.

2.2. Carboniferous Events

2.2.1. Sedimentation and accretion. The deformed and metamorphosed remains of a second accretionary complex are preserved in the Ivrea-Verbano Zone (Figure 1). This complex is a highly deformed sequence of semipelitic gneiss and schist (so-called kinzigites) locally containing calc-silicate bands. The sequence alternates with amphibolite layers that show trace element characteristics of both normal MORB and enriched tholeiitic or alkalic MORB (type 1 mafic rocks of *Zingg et al.* [1990], *Sills and Tarney* [1984], and *Mazzucchelli and Siena* [1986]). There is no evidence for pre-existing continental basement underlying this complex. In fact, the accretionary complex probably formed above oceanic crust, represented by the amphibolite layers with MORB chemistry. The complex is overprinted by amphibolite to granulite facies, regional metamorphism and deformation in the Ivrea-Verbano Zone, and it is intruded by gabbroic and dioritic rocks of the Mafic Formation (Figure 1).

Up to now, accretion of the Ivrea metasediments is generally regarded to have occurred in early Paleozoic time [*Sills and Tarney*, 1984; *Zingg et al.*, 1990; *Zingg*, 1990; *Schmid*, 1993] on the basis of 480-700 Ma Sr model ages from Ivrea metasediments that are interpreted as sedimentation ages [*Hunziker and Zingg*, 1980]. However, we believe that sedimentation and accretion of the Ivrea metasediments is much younger for the following reasons:

1. The Ivrea-Verbano and Strona-Ceneri Zones comprise different lithologies with contrasting metamorphic histories. In particular, metasediments in the Ivrea-Verbano Zone differ both mineralogically and compositionally from those in the Strona-Ceneri Zone, even at comparable metamorphic grade. Unlike the Strona-Ceneri Zone, the Ivrea-Verbano Zone yields no mineral ages older than Carboniferous [*Zingg*, 1990]. This suggests that the two basement units underwent different Paleozoic evolutions,

2. The Ordovician Sr model ages are based on the extrapolation of a 478 ± 20 Ma, Rb-Sr whole rock isochron that may not be geologically relevant, given the differences cited above. *Hunziker and Zingg* [1980] obtained this isochron from a mixture of Ivrea metasediments, Strona-Ceneri metasediments, and Ordovician granitoids of the Strona-Ceneri Zone. They interpreted this mixed source isochron as the common age of regional metamorphism in the two zones. The Sr model ages of Hunziker and Zingg therefore overestimate the age of sedimentation.

In fact, there is compelling evidence that sedimentation and accretion of the Ivrea metasediments occurred in Early Carboniferous time: *Vavra et al.* [1996] found that the oldest cores of zircons in Ivrea metasediments yield a concordant, 355 ± 6 Ma U-Pb sensitive high-resolution ion microprobe (SHRIMP) age and have a prismatic morphology that is diagnostic of calk-alkaline magmatism. The occurrence of these zircons in both anatectic and metapelitic layers of the Ivrea schists reflects the admixture of the zircons in a sedimentary environment [*Vavra et al.*, 1996], indicating that the protolith was deposited in a volcanic setting in early Carboniferous time. Both metasediments and amphibolite layers of MORB affinity experienced 290-320 Ma regional metamorphism in the Ivrea-Verbano Zone (see dating of regional metamorphism in section 2.2.3). Thus accretion of the Ivrea metasediments at an active margin must have occurred sometime between 320 and 355 Ma.

2.2.2. High-pressure metamorphism. High-pressure metamorphism documenting the subduction of crustal and upper mantle rocks is manifest locally by eclogitic amphibolites [*Boriani and Peyronel Pagliani*, 1968] and kelyphitic peridotites [*Lensch and Rost*, 1972] in the Ivrea-Verbano Zone. These retrogressed high-pressure rocks occur along the southeastern border of the Ivrea-Verbano Zone (solid star in Figure 1), where they are imbricated with metasediments and amphibolites of MORB affinity. Other relics of pressure-dominated metamorphism, also arrayed along the southeastern margin of the Ivrea-Verbano Zone, include kyanites that are overgrown by sillimanite in metasediments [*Bertolani*, 1959; *Capedri*, 1971; *Boriani and Sacchi*, 1973; *Handy*, 1986]. None of these high-pressure assemblages has been dated yet. However, the high-temperature overgrowth textures of these assemblages indicate that pressure-dominated metamorphism preceded temperature-dominated, amphibolite to granulite facies, regional metamorphism (Figure 2 and section 2.2.3). The distribution of the high-pressure relics at and near the tectonic contact between the Ivrea-Verbano and Strona-Ceneri Zones suggests that this contact was originally a Variscan suture, as discussed in section 2.2.3. Suturing must have occurred sometime after the accretion of the Ivrea metasediments but before the onset of regional metamorphism in the Ivrea-Verbano Zone.

2.2.3. Regional metamorphism and magmatism in the Ivrea-Verbano Zone. Regional metamorphism in the Ivrea-Verbano Zone serves as an important time marker for magmatism and deformation. This Barrovian-type metamorphism increases from amphibolite facies along the tectonic contact with the Strona-Ceneri Zone to granulite facies along the Insubric Line (Figure 1). Thermobarometers record an increase of peak pressure with regional metamorphism from southeast to northwest across the Ivrea-Verbano Zone, as shown in Figures 5a and 5b, respectively, for the Val Strona and Valle Cannobina transects (lines A-A' and B-B' in Figure 1). Crustal thickness at the time of regional metamorphism was at least 30-40 km, as estimated from the peak pressures (8.5-11.5 kbar) recorded by granulite facies assemblages (Figures 3c and 6) [*Zingg*, 1983; *Henk et al.*, 1997] and an assumed, average crustal density of 2.8 g/cm^3.

Several isotopic systems have been used in attempts to determine the age of this regional metamorphism [*Zingg et al.*, 1990], but the U-Pb monazite system has proved to be the most reliable so far, because the ages it yields can be readily interpreted in a petrogenetic context. Monazites aligned parallel to the main, S1 schistosity in amphibolite facies metasediments and mafics in the southeastern part of the Ivrea-Verbano Zone yield 290-310 Ma U-Pb ages [*Köppel and Grünenfelder*, 1978/1979; *Henk et al.*, 1997]. This is corroborated by 296 ± 12 Ma U-Pb SHRIMP ages on zircon overgrowths from anatectic leucosomes in Ivrea metapelites [*Vavra et al.*, 1996]. We interpret the monazite ages to date the regional metamorphism, because the peak temperatures attained in the amphibolite facies rocks (550°-600°C [*Zingg*, 1983, and references therein]) did not exceed the estimated 600° ± 50°C closure temperature of the U-Pb system in deformed monazite [*Smith and Barreiro*, 1990]. Peak conditions in the granulite facies part of the Ivrea-Verbano

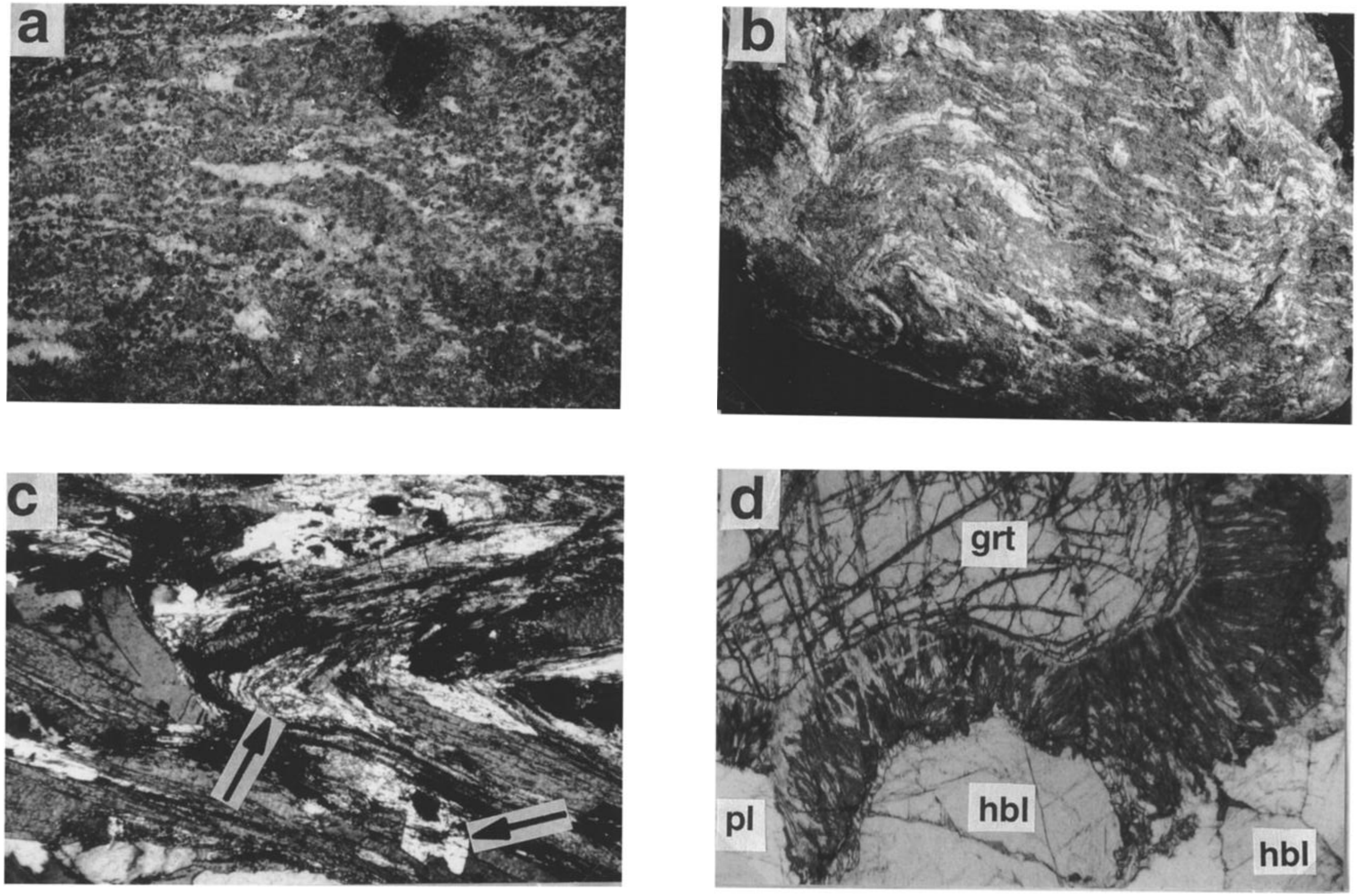


Figure 6. Key structural and metamorphic relationships in the Ivrea-Verbano Zone: (a) euhedral garnets that overgrow S1 and leucosomes in metasediment, with frame length of approximately 20 cm; (b) F2 folds that deform S1 containing leucosomes, with frame length of approximately 50 cm; (c) cross white mica (arrows) that overgrows fibrolite deformed by F2 fold in metasediment, with crossed polarizers, frame length of 2 mm; (d) garnet and hornblende rimmed by symplectites of orthopyroxene, spinel (hercynite) and anorthitic plagioclase in a hornblende-gabbro that underwent prograde metamorphism during D4. Abbreviations are as follows: grt, garnet; hbl, hornblende; pl, anorthitic plagioclase. Frame length is 1 cm.

Zone were attained some 5-10 Myr earlier (i.e., 300-320 Ma) according to the thermal modeling of *Henk et al.* [1997]. The range of U-Pb monazite ages (270-290 Ma) along the two transects of the Ivrea-Verbano Zone in Figure 5 is interpreted either to reflect cooling after regional metamorphism [*Henk et al.*, 1997] or to reflect fluid circulation after the thermal peak of this metamorphism [*Vavra et al.*, 1996]. The youngest, circa 270 Ma ages from the granulite facies part of the Ivrea-Verbano Zone therefore postdate this thermal peak by approximately 20-40 Myr.

When assessing the role of magmatic underplating and its relationship to regional metamorphism, it is important to remember that the Mafic Formation is a composite of three, differently aged suites of mantle-derived intrusive rock [*Zingg et al.*, 1990]. Most of the Mafic Formation comprises large gabbroic bodies and banded mafic rocks interlayered with ultramafics (type 2 and type 3 mafic rocks of *Zingg et al.* [1990], respectively). These rocks intruded the Ivrea metasediments but equilibrated at the conditions of regional metamorphism [*Zingg*, 1980]. The intrusive age of these mafic rocks is poorly constrained in the absence of isotopic age work on their relict magmatic minerals. If the intrusion of these mafic rocks triggered regional metamorphism as is indicated by the field relations cited above, then their crystallization must have only just preceded the attainment of peak temperatures in granulite facies metasediments at the base of the Ivrea-Verbano Zone some 300-320 Myr ago.

The youngest suite of mafic rocks comprises gabbro-diorites (type 4 mafic rocks of *Zingg et al.* [1990]) within the southeastern part of the Mafic Formation (Val Sesia in Figure 1). These rocks contain fresh magmatic structures [*Rivalenti et al.*, 1975] and magmatic zircons that yield concordant 285 Ma U-Pb ages [*Pin*, 1986]. Granodioritic to tonalitic intrusive breccias forming the rim of these mafic intrusions yield 274 Ma, Rb-Sr whole rock ages [*Bürgi and Klötzli*, 1990]. The intrusive contacts of these rocks are discordant to and truncate the regional metamorphic isograds [*Zingg*, 1980, 1983]. The relationships discussed above indicate at least two mafic, magmatic underplating events in the Ivrea-Verbano Zone: a massive, late Carboniferous pulse that triggered regional metamorphism and a smaller, Early Permian pulse that postdated, and was therefore unrelated to, the peak of regional metamorphism.

2.2.4. Deformation in the Ivrea-Verbano Zone. The structural and radiometric age constraints on metamorphism and magmatism help bracket the age of deformation in the Ivrea-Verbano Zone. At least two generations of nearly coaxial, isoclinal to tight folds (D1, Verbano Phase, and D2, Ossola Phase) developed in the Ivrea metasediments and pre-Permian mafic rocks of the Mafic Formation. The S1 axial planar foliation in the paragneisses is overgrown by high-grade minerals (e.g., euhedral garnet in Figure 6a), indicating that it developed prior to or during regional metamorphism. F2 folds clearly deform and therefore postdate leucosomes related to initial anatexis and regional metamorphism in the Ivrea-Verbano Zone (Figure 6b). However, the microstructures of rocks with F2 folds were annealed under regional metamorphic conditions [*Handy and Zingg*, 1991, Figure 5b] and overgrown by cross white micas (Figure 6c).

Taken together, these observations indicate that both D1 and D2 deformations in the Ivrea-Verbano Zone are broadly coeval with late Carboniferous regional metamorphism. Unfortunately, the kinematics of these deformations are ambiguous, because F1 and F2 folds were highly susceptible to reorientation during D3 and D4 deformations in the Ivrea-Verbano Zone.

2.2.5. Deformation and regional metamorphism in the Strona-Ceneri Zone. Across the crustal section in the Strona-Ceneri Zone the main Carboniferous structures include kilometer-scale folds (D3, Gambarogno Phase) and the Val Colla Shear Zone (D4, Val Colla Phase, Figure 2). The F3 folds have moderate to steep axes and axial planes and deform the main S2 schistosity in the Strona-Ceneri Zone (stereoplots labeled Gi in Figure 7 and Ga in Figure 8a). D3 folding was locally accompanied by the intrusion of tonalitic dikes derived from the anatexis of metasediments underlying the present erosional surface of the Strona-Ceneri Zone [*Zurbriggen et al.*, 1998]. By dating magmatic garnets in these dikes, *Zurbriggen et al.* [1998] determined that the F3 folds formed about 321 Myr ago under prograde, amphibolite facies conditions (Figure 3d). The peak temperatures of this metamorphism (500°-600°C) outlasted folding, as is inferred from the polygonization of micas and amphibole grains around F3 folds [*Zurbriggen*, 1996, Figure 4-10]. F3 folds rarely have an axial planar schistosity, except at the northwestern and southeastern limits of the Strona-Ceneri Zone where they are overprinted by mylonites of the Cossato-Mergozzo-Brissago (CMB) and Val Colla Shear Zones, respectively (Figure 1). The formation of the folds at or slightly before the thermal peak of D3 metamorphism together with the lack of vergence of these folds on the kilometer-scale suggests that they formed during subhorizontal shortening of a moderately to steeply dipping, S2 schistosity prior to exhumation during D4.

D4, Val Colla Phase mylonitic deformation affects the southeastern margin of the Strona-Ceneri Zone and the adjacent Val Colla Zone (Figure 1). There a 5 km thick zone of retrograde, amphibolite to greenschist facies mylonites, the Val Colla Shear Zone (labeled VC in Figures 1 and 8a), overprints the gradational lithological contact between these units. Kinematic indicators in these mylonites (Figure 4b) are consistent with top-to-the-south to -southwest displacement of the overlying Val Colla Zone with respect to the Strona-Ceneri Zone (Figure 8a). Extensional exhumation and cooling of the Strona-Ceneri Zone during Val Colla shearing is inferred from the successive closure of K-Ar hornblende and biotite systems in the footwall of the Val Colla Shear Zone (Figure 8b). Correlating the temperatures of mylonitization in the Val Colla Shear Zone (300°-500°C [*Janott*, 1996]) with the radiometrically derived temperature-time curve for this part of the Strona-Ceneri Zone in Figure 8b constrains Val Colla Phase shearing to have occurred sometime between 330 and 305 Ma.

A maximum age of 320 Ma for D4 extension is consistent with field relations which indicate that the Val Colla mylonites overprint F3, Gambarogno Phase folds in the Strona-Ceneri Zone. In the footwall of the Val Colla Shear Zone the axial planes and axes of F3 folds are reoriented to be coplanar and parallel to the foliation and stretching lineations

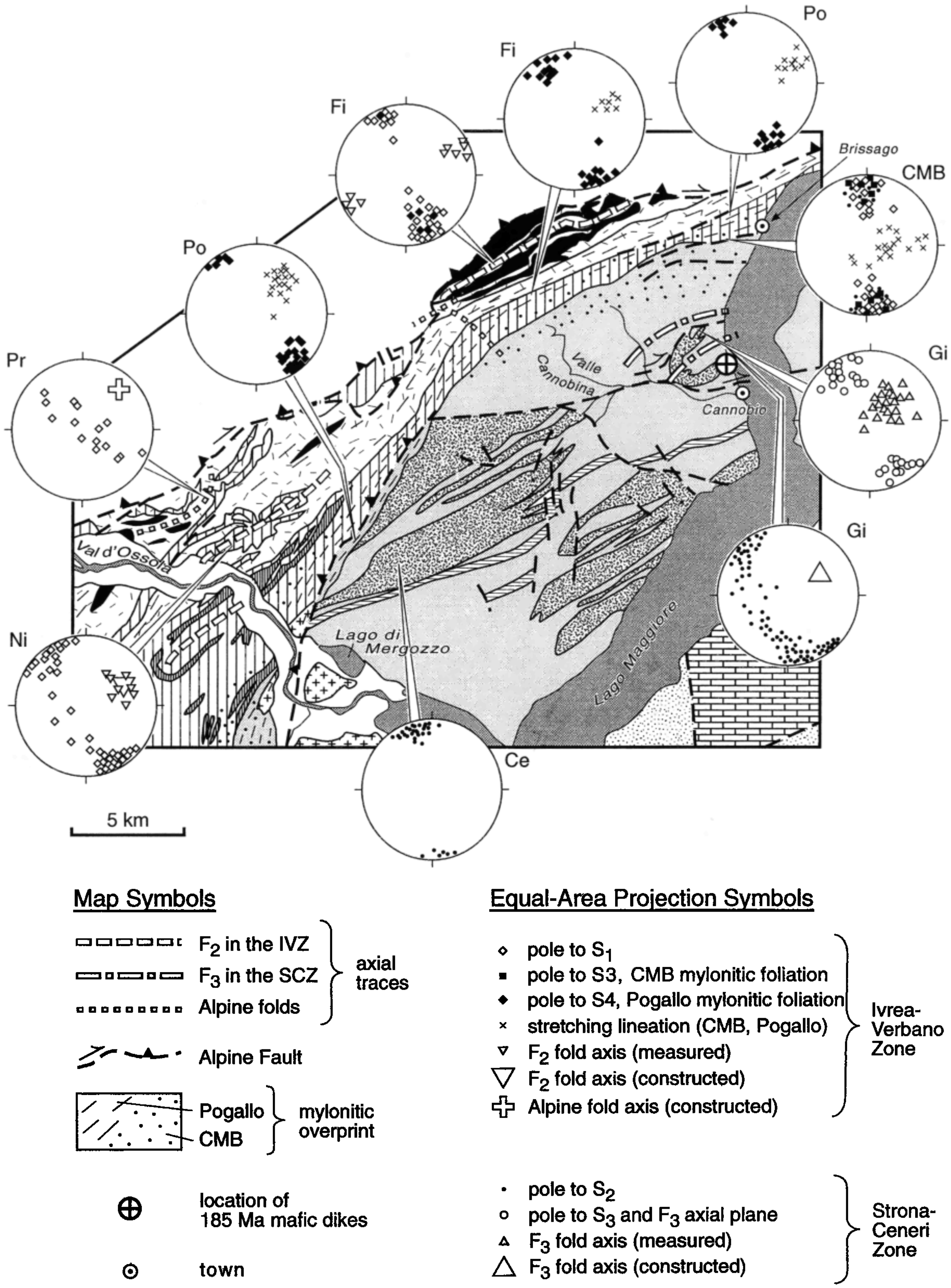
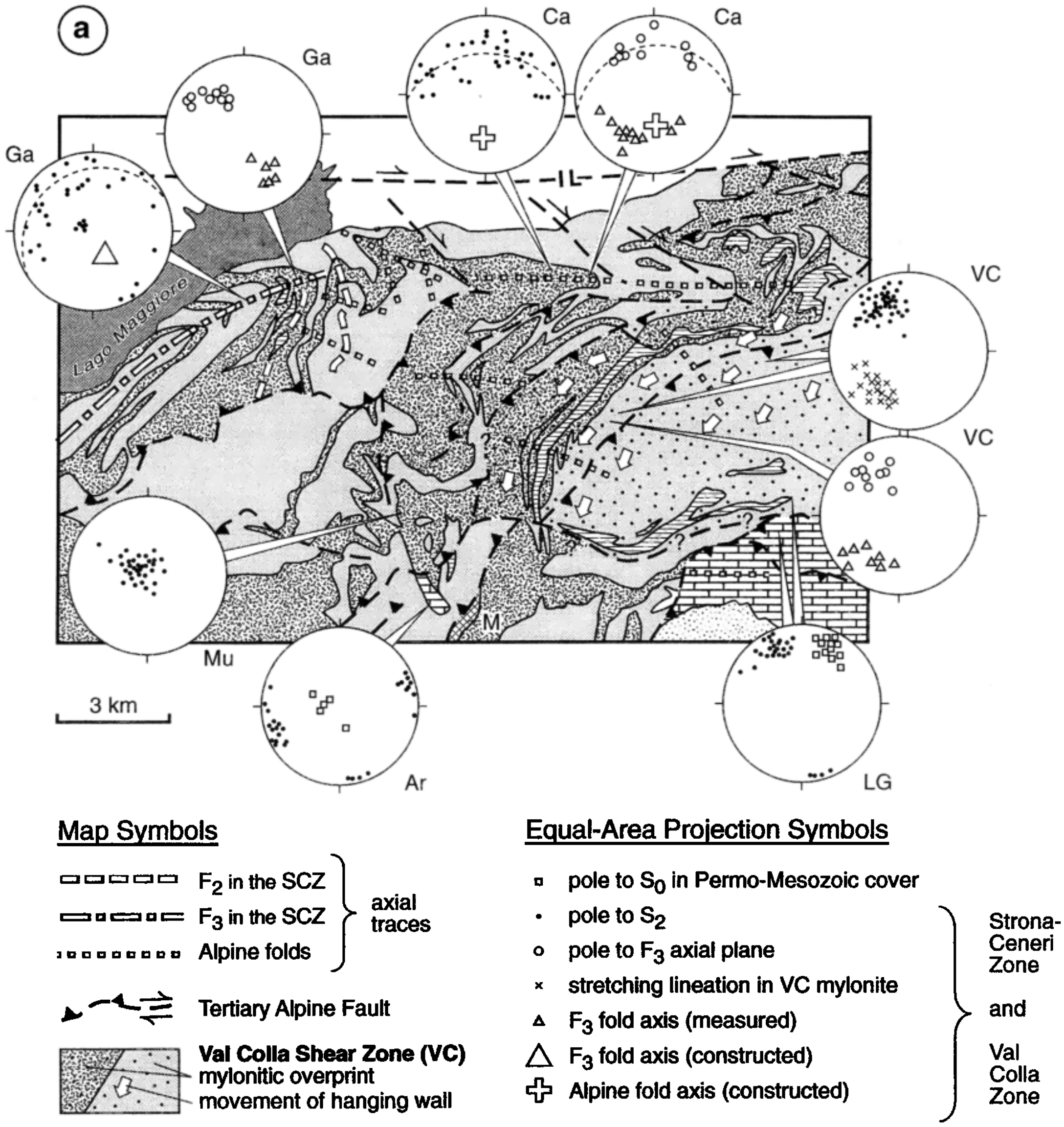


Figure 7. Structural map with contact of Ivrea-Verbano and Strona-Ceneri Zones. Lithological symbols and map location are given in Figure 1. Stereoplot abbreviations are as follows: Pr, Proman fold; Po, Pogallo Shear Zone; Fi, Finero complex; CMB, Cossato-Mergozzo-Brissago Shear Zone; Gi, Giove fold; Ni, Nibbio fold. Stereoplots are lower hemisphere equal-area projections. Map is based on own mapping and structural data and modification of maps by *Boriani et al.* [1977], *Handy* [1986, 1987], *Schmid* [1967], *Steck and Tièche* [1976], *Vogler* [1992], *Walter* [1950], and *Zurbriggen* [1996]. Structural data for Proman fold are taken from *Schmid et al.* [1987] and *Zingg et al.* [1990]. IVZ, Ivrea-Verbano Zone; SCZ, Strona-Ceneri Zone.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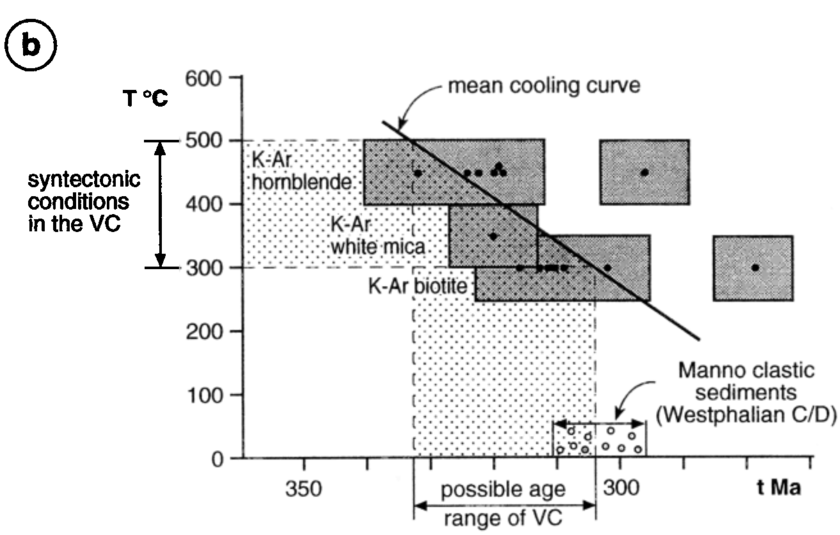
Map Symbols
F2 in the SCZ
F3 in the SCZ
Alpine folds
axial traces
Tertiary Alpine Fault
Val Colla Shear Zone (VC)
mylonitic overprint
movement of hanging wall
Equal-Area Projection Symbols
pole to S0 in Permo-Mesozoic cover
pole to S2
pole to F3 axial plane
stretching lineation in VC mylonite
F3 fold axis (measured)
F3 fold axis (constructed)
Alpine fold axis (constructed)
Strona-Ceneri Zone
and
Val Colla Zone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syntectonic conditions in the VC
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K-Ar hornblende
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K-Ar biotite
Manno clastic sediments (Westphalian C/D)
350
300
t Ma
possible age range of VC

Figure 8.

in the Val Colla mylonites, respectively (stereoplots marked VC in Figure 8a). The annealed, amphibolite facies microstructure typical of F3 folds in other parts of the Strona-Ceneri Zone is overprinted by mylonitic fabrics of the Val Colla Shear Zone (Figure 4c).

Conglomerates that unconformably overlie the Strona-Ceneri Zone at Manno (location marked M in Figures 1 and 8a) contain unmetamorphosed Westphalian plant remains [*Jongmans*, 1960] and components of Val Colla mylonite (Figure 4d). The Westphalian conglomerates also contain clasts of gneiss from the Val Colla and Strona-Ceneri Zones, indicating that these basement units were exposed to erosion by late Carboniferous time [*Graeter*, 1951; *Zingg*, 1983]. Independently of the radiometric data, these sediments place a minimum age limit of 305 Ma for the activity and exhumation of the Val Colla Shear Zone.

2.3. Early Permian Events

2.3.1. Deformation and magmatism in the Ivrea-Verbano Zone. Early Permian magmatism and deformation affected all levels of the Ivrea crustal section but in different ways. In the Ivrea-Verbano Zone the aforementioned intrusion of 285 Ma, gabbroic to gabbro-dioritic melts in parts of the Mafic Formation was contemporaneous with and transitional to localized mylonitic shearing and renewed anatexis of the contacting metasediments [*Rutter et al.*, 1993; *Quick et al.*, 1994]. Higher up in the crustal section along the contact between the Ivrea-Verbano and Strona-Ceneri Zones, mutually crosscutting relationships between anatectic, upper amphibolite facies mylonites of the CMB Shear Zone and 270-280 Ma, mafic and aplitic veins [*Pinarelli et al.*, 1988; *Mulch et al.*, 1999] document coeval mylonitization and Early Permian magmatism [*Handy and Streit*, 1999]. The vein geometry and mylonitic fabrics in the subvertically dipping CMB mylonites indicate a strong component of flattening normal to schistosity combined with a component of sinistral noncoaxial shear parallel to predominantly east-northeast plunging mineral stretching lineations (stereoplot marked CMB in Figure 7). Large-scale, D2, Ossola Phase folds in the Ivrea-Verbano Zone are acylindrical with steep axial planes and have axes aligned subparallel to this stretching lineation (stereoplot labeled Ni in Figure 7). This indicates that F2 folds may have been reoriented during D3 shearing, such that their axial planes became subparallel to the CMB mylonitic foliation [*Handy and Zingg*, 1991].

The pressure-temperature-time (P-T-t) path for the Ivrea-Verbano Zone in Figure 3c shows that the D3, Brissago Phase is associated with decompression and cooling from peak metamorphic conditions. The D3 decompression of 1.3 kbar in Figure 3c is obtained from element zonation patterns in garnets in local equilibrium with plagioclase and hornblende in garnet-bearing amphibolites of the Val Strona transect [*Henk et al.*, 1997]. This is a minimum estimate of D3 decompression, because a single thermobarometer can record only part of the exhumation. A much greater decompression of approximately 7 kbar to pressures of at most 3 kbar (not shown in Figure 3c) can be inferred from the occurrence of cordierite and andalusite in Ivrea metapelites that experienced contact metamorphism adjacent to Early Permian, gabbro-dioritic intrusions at the rim of the Mafic Formation in Val Sesia [*Zingg*, 1980].

Petrologic evidence for decompression during D3 is consistent with several independent lines of evidence for crustal attenuation in Early Permian time: (1) Discrepant temperature-time cooling curves for the adjacent parts of the Ivrea-Verbano and Strona-Ceneri Zones in the Val d'Ossola transect (Figure 1) indicate that at least 3 km of crust were excised from the crustal section along the CMB Shear Zone at about 280 Ma [*Handy*, 1987]. (2) The metamorphic pressure gradients across the Ivrea-Verbano Zone in Figure 5 are anomously high (0.4 kbar/km in Val Strona and 1.7 kbar/km in Valle Cannobina), suggesting heterogeneous stretching subparallel to the length of the Ivrea-Verbano Zone during and/or after Permian cooling through the 600° ± 50°C closure temperature for the U-Pb monazite system. On the basis of the high pressure gradient in the Val Strona transect, *Henk et al.* [1997] estimated that approximately 4 km of crust were thinned from the Ivrea-Verbano Zone in Permian time, although an early Mesozoic age for this thinning cannot be ruled out. We attribute the even higher metamorphic pressure gradient in the Valle Cannobina transect to later crustal extension during D4, Pogallo Phase deformation, as discussed in section 2.4. The lack of a break in metamorphic pressure gradients across the CMB Shear Zone (Figure 5) indicates that it accommodated little, if any, vertical throw after the thermobarometers equilibrated during regional metamorphism. Therefore the CMB Shear Zone was subhorizontal while active in Early Permian time. Today, Alpine faults truncate the southeastern end of the CMB Shear Zone (Figure 1), preventing us from tracing it into shallower levels of the Early Permian crust exposed at the basement-cover contact.

2.3.2. Structures in the Strona-Ceneri Zone and upper crustal units. Except for the CMB Shear Zone, all post-Carboniferous structures in the Strona-Ceneri Zone are brittle and therefore difficult to distinguish from later structures. The Strona-Ceneri Zone contains Early Permian granitoid bodies that cut the S2 schistosity (Baveno granitoids in Figure 1), and it is unconformably overlain by rhyolitic to andesitic, Permian Lugano volcanics [*Graeter*, 1951; *Hunziker*, 1974; *Stille and Buletti*, 1987]. The occurrence of miarolitic cavities

Figure 8. Structural relations and isotopic ages in the Strona-Ceneri Zone, Val Colla Zone, and cover units. (a) Structural map based on own data and modification of maps by *Reinhard* [1964], *Janott* [1996], *Bertotti* [1991], and *Schumacher et al.* [1997]. Lithological symbols and map location are given in Figure 1. Structural abbreviations are as follows: Ga, Gambarogno fold; Ca, Camoghè fold; VC, Val Colla Shear Zone; Ar, Arosio basement-cover contact; Mu, Mugena valley; LG, Lugano-Grona Line. Stereoplots are lower hemisphere equal-area projections. (b) Cooling curve for the Strona-Ceneri Zone in the footwall of the Val Colla Shear Zone; K-Ar isotopic ages are from *McDowell* [1970]. C/D, subseries of the Westphalian.

in these granites [*Köppel*, 1974] indicates that these intrusive bodies and the surrounding gneisses in the Strona-Ceneri Zone already occupied relatively shallow levels (approximately 10 km) when the granitoids were emplaced.

2.4. Early Mesozoic Events

Early Mesozoic deformation (Figure 2) is strongly partitioned within the crustal section and occurred under widely varied conditions in different crustal levels. In the originally deepest parts of the Ivrea-Verbano Zone, high-grade mylonites in anastomozing shear zones (D4, Pogallo Phase) overprint the regional metamorphic fabric in granulite facies paragneisses and mafic rocks [*Brodie and Rutter*, 1987; *Zingg et al.*, 1990]. This structural and metamorphic overprint is strongest in the narrow, northeastern segment of the Ivrea-Verbano Zone shown in Figure 7.

The mineral assemblages in some of these high-grade mylonites are diagnostic of a renewed increase in metamorphic grade from amphibolite to granulite facies conditions at the onset of D4 shearing. In Figure 6d, for example, the prograde reaction of garnet to symplectitic orthopyroxene, hercynite, and plagioclase in a garnet-hornblende gabbro indicates temperatures of at least 650°-700°C [*Spear*, 1995]. The contacting garnet and orthopyroxene in this rock are not in chemical equilibrium, indicating that subsequent cooling under static (i.e., stress-free) conditions must have been rapid. In general, however, high-grade mylonitization continued under retrograde, amphibolite facies conditions, as was already documented in several studies [*Handy and Zingg*, 1991, and references therein]. Retrograde mylonitization is concentrated in quartz-bearing rocks, especially along the part of the rim of the Ivrea-Verbano Zone in contact with the Strona-Ceneri Zone (dashed lines in Figure 7). This 1-3 km wide zone of retrograde mylonites defines the Pogallo Shear Zone (marked PO in Figure 1). The replacement of syn-tectonic sillimante by postkinematic andalusite in amphibolite facies, Pogallo mylonites near Brissago (Figure 7) documents D4 decompression and cooling. Retrograde, amphibolite to greenschist facies mylonites and cataclasites of the Pogallo Shear Zone overprint the CMB mylonites and associated Early Permian intrusive rocks [*Handy*, 1987]. Crossing the Ivrea-Verbano Zone across its strike from northwest to southeast, only 5 km separates the granulite facies mylonites from the cataclasites along the southern margin of the Pogallo Shear Zone. This small separation indicates an abnormally high D4, metamorphic field gradient of approximately 80°C/km. Southwest of the Val d'Ossola, the Pogallo Shear Zone is poorly exposed but appears to continue as a brittle fault within the Strona-Ceneri Zone (Figure 1).

The microstructures above indicate a clockwise P-T exhumation path for the Ivrea-Verbano Zone during D4, Pogallo Phase deformation (Figure 3c). The Pogallo Shear Zone was active sometime between 180 and 230 Ma, as is constrained by correlating the temperature range of retrograde, syntectonic metamorphism in the Pogallo mylonites with the temperature-time cooling curves constructed from the successive closures of the Rb-Sr and K-Ar white mica and biotite systems from the Ivrea-Verbano Zone [*Handy*, 1987]. High-grade D4 mylonites have not been satisfactorily dated but were probably coeval with Pogallo mylonitization on the basis of the lack of strong annealing in D4 mylonites and the aforementioned, high D4, metamorphic field gradient across the Ivrea-Verbano Zone.

Kinematic indicators in the high-grade mylonites are ambiguous and indicate foliation-parallel stretching parallel to moderately northeast plunging mineral and stretching lineations (stereoplots marked Fi in Figure 7) [*Brodie and Rutter*, 1987]. The Pogallo mylonites, however, yield a sinistral sense of shear parallel to a similarly northeast plunging stretching lineation (stereoplots marked Po in Figure 7) [*Handy and Zingg*, 1991]. The significance of this kinematic framework for early Mesozoic tectonics in the southern Alps becomes clear only when the Ivrea-Verbano Zone is back-rotated into its pre-Tertiary orientation, as is discussed in section 3. The Pogallo mylonitic foliation then accommodated east-west directed crustal extension.

The structural evidence for lateral crustal extension in early Mesozoic time is consistent with the idea that the D4 mylonites attenuated the lower crust while exhuming the Ivrea-Verbano Zone from beneath the Strona-Ceneri Zone along the Pogallo Shear Zone [*Handy and Zingg*, 1991]. D4 thinning is most pronounced in the northeastern part of the Ivrea-Verbano Zone, where it telescoped the crustal section and caused the anomalously high metamorphic pressure gradient in the Valle Cannobina transect (Figure 5b).

In the upper crust, Pogallo Phase deformation involved brittle faulting along north-south trending normal faults. Such faults are ubiquitous in the southern Alps [*Winterer and Bosellini*, 1981] and bound asymmetrical basins (marked Nu and Ge in Figure 1) containing unmetamorphosed, Early to Middle Jurassic rift sediments [*Bernoulli*, 1964; *Bertotti et al.*, 1993]. This is best seen in map view along the Lugano-Grona Line (LG in Figures 1 and 8a) where cataclasites and mylonites that accommodated east-west extension along the verticalized basement-cover contact [*Bertotti*, 1991] form a low-angle discordance with tilted, Upper Triassic carbonates and Lower Jurassic clastics of the Generoso basin.

Only limited calc-alkaline to alkaline magmatism and metasomatism accompanied D4 deformation. Most of this activity is restricted to the Ivrea-Verbano Zone for the time span 200-230 Myr [*Stähle et al.*, 1990; *von Quadt et al.*, 1992; *Vavra et al.*, 1996], although 185 Ma mafic dikes also intruded the Strona-Ceneri Zone (see *Zurbriggen* [1996] and section 3). Minor volumes of mid-Triassic intrusive [*Sanders et al.*, 1996] and extrusive [*Hellmann and Lippolt*, 1981] rock in other middle to upper crustal units of the southern Alps are interpreted as harbingers of Late Triassic to Early Jurassic extension.

3. Alpine Tectonics

Any attempt to reconstruct the original structure of the Ivrea crustal section must begin by subtracting the effects of Alpine folding and faulting. These effects vary strongly with location in the crustal section. Figure 9 summarizes various criteria that serve as guides to the original orientation of pre-Alpine structures. Only the newest or most reliable of these are described below.

3.1. Pre-Tertiary Orientation of the Ivrea-Verbano Zone

In the Ivrea-Verbano Zone several independent observations indicate that compositional banding and the

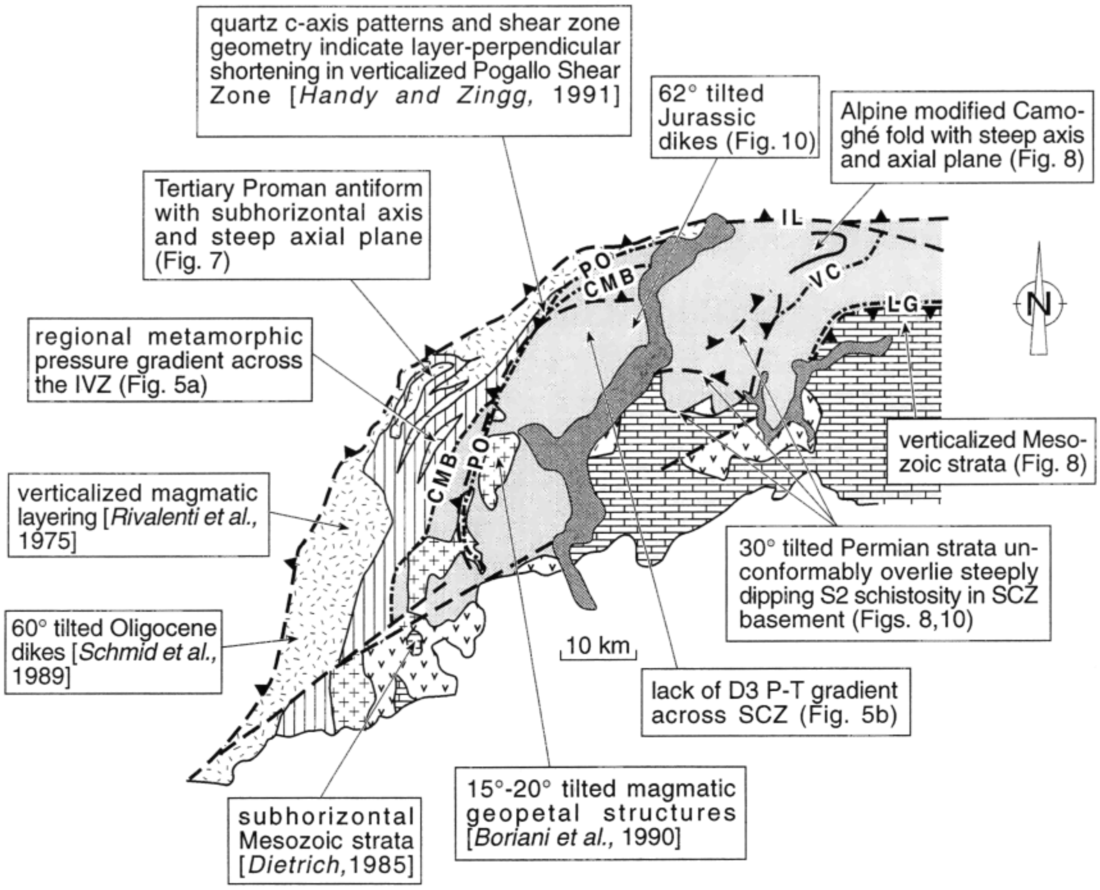

Figure 9. Criteria for determining pre-Tertiary orientation of basement and cover units in the Ivrea crustal section (see text for explanation).

main foliation (S1) was subhorizontal prior to Tertiary time:

1. Regional metamorphic pressure gradients from thermobarometry across the Ivrea-Verbano Zone (Figure 5) trend perpendicular to the strike of the S1 foliation. Except in the vicinity of Early Permian mafic intrusives, regional metamorphic isograds run parallel to this foliation and to the compositional banding [*Zingg*, 1980].

2. The pre-Alpine foliation adjacent to the Insubric Line is deformed by flexural slip folds with steep axial planes and gently plunging fold axes (Proman fold with stereoplot marked Pr in Figure 7; greenschist facies folds of *Kruhl and Voll* [1978/1979] and *Steck and Tièche* [1978/1979]). Folds with this attitude could only have formed if the pre-Alpine foliation was originally horizontal to moderately dipping. They are related to south to southeast directed, Tertiary shortening and backthrusting [*Schmid et al.*, 1987].

3. Natural remanent magnetization (NRM) directions from discordant dikes of inferred Oligocene age within the Ivrea-Verbano Zone along the southwestern part of the Insubric Line (Figure 9) indicate a 60° clockwise rotation (looking northeast about a horizontal axis) since early Tertiary time [*Schmid et al.*, 1989]. Back-rotating these dikes into concordance with the NRM direction for stable Europe indicates that the compositional banding and schistosity in the southwestern part of the Ivrea-Verbano Zone was moderately to gently inclined to the southeast.

4. Quartz *c* axis fabrics of the early Mesozoic, Pogallo Shear Zone indicate combined simple shear parallel to the shear zone boundary and shortening perpendicular to the steeply northwest dipping Pogallo mylonitic foliation [*Handy and Zingg*, 1991, Figure 8]. Shortening perpendicular to the Pogallo mylonitic foliation in the Ivrea-Verbano Zone is only compatible with east-west crustal extension documented by early Mesozoic sediments of the southern Alps if the Pogallo mylonites were gently to moderately dipping in Early Jurassic time.

3.2. Pre-Tertiary Orientation of the Strona-Ceneri Zone, Val Colla Zone, and Cover Units

In the Strona-Ceneri Zone the following arguments based on new structural and paleomagnetic information indicate that the main schistosity (S2) was moderately to steeply dipping already before Alpine deformation:

1. The large Camoghé fold in the northeastern part of the Strona-Ceneri Zone (marked Ca in Figure 8a) deforms S2. The Camoghé fold was originally an F3 fold like the Gambarogno fold to the southwest (marked Ga in Figure 8a), but on the basis of its box-shaped hinge and the abundance of brittle accommodation structures in its core, we believe that it tightened and became isoclinal in response to north-south directed, Tertiary Insubric thrusting under sub-greenschist-

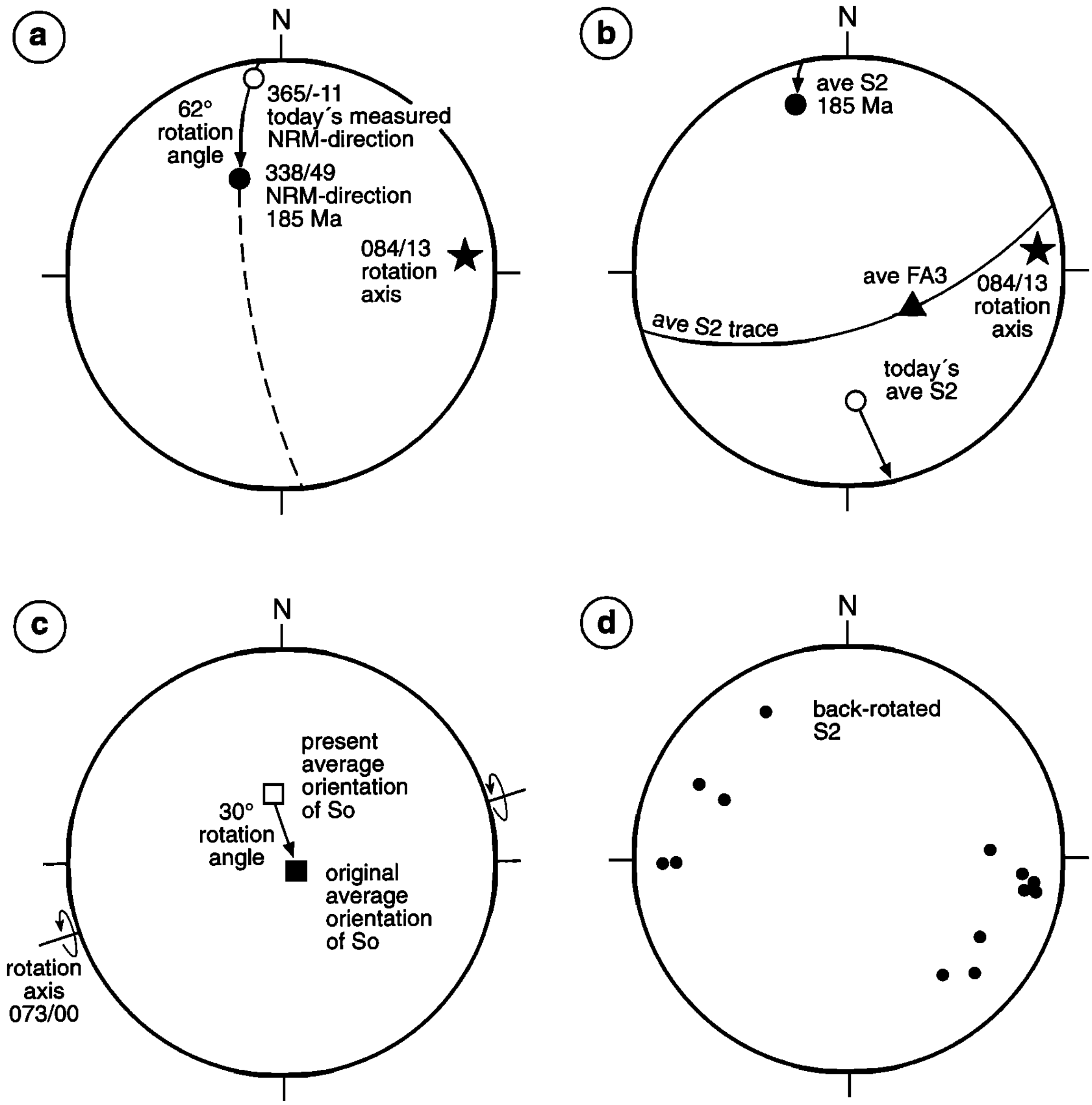

Figure 10. Present and back-rotated orientations of structures in the Strona-Ceneri Zone: (a) characteristic natural remanent magnetization (NRM) directions in 185 Ma mafic dikes from the Strona-Ceneri Zone (location in Figure 7); (b) back-rotated, pre-Jurassic orientations of S2 and F3 fold axis (FA3) in the Strona-Ceneri Zone; (c) back rotation of sedimentary bedding (So) in Permian strata unconformably overlying the Strona-Ceneri Zone; (d) back-rotated, Permian orientation of S2 in the Strona-Ceneri Zone beneath the Lower Permian unconformity. Stereoplots are lower hemisphere equal-area projections. See text for explanation.

facies conditions. The Camoghè fold is truncated by and therefore predates dextral Riedel faults associated with late Insubric, strike-slip faulting (Figure 8a). A 60°-70° dip for S2 and F3 fold axial planes in the Strona-Ceneri Zone prior to Insubric shortening and folding is inferred from the moderate attitude of the fold's axis and axial plane (Figure 8a).

2. NRM directions from discordant, 185 Ma mafic dikes in the northern part of the Strona-Ceneri Zone (circled cross in Figur 7; Ar-Ar hornblende ages by *Zurbriggen* [1996]) indicate that there, D2 and D3 structures underwent a post-Jurassic, clockwise rotation of 62° looking down a rotation axis oriented 084°/13° (Figure 10a). When back-rotated, the S2 schistosity in the northern part of the Strona-Ceneri Zone acquires a 70°, pre-Jurassic dip (Figure 10b), and F3 fold axes acquire the same orientation as that in southern parts of the Strona-Ceneri Zone.

3. The high-angle erosional unconformity between S2 schistosity in the southern part of the Strona-Ceneri Zone and subhorizontal bedding in the overlying Permian sediments (steroplot marked Ar in Figure 8a; stereoplot in Figure 10c) indicates that S2 was inclined 60°-80° at the time of sedimentation (Figure 10d).

4. The lack of D3 thermobarometric gradients across the northwestern part of the Strona-Ceneri Zone (Figure 5) indicates that the 4-5 kbar, D3 isobar is roughly parallel to the present erosional surface and that D2 and D3 structures in this part of the Strona-Ceneri Zone (stereoplots marked Gi in Figure 7) had attained their steep orientation prior to the equilibration of the thermobarometers in Carboniferous time.

The evidence in the Ivrea-Verbano Zone for originally subhorizontal foliations and regional metamorphic isobars indicates that large parts of the Ivrea-Verbano Zone were rotated some 60°-80° into a subvertical attitude with respect to the already moderately to steeply dipping, intermediate crustal units to the south. Most of this differential rotation was probably accommodated by numerous steep faults that transect the northwestern part of the Strona-Ceneri Zone [*Zurbriggen*, 1996] and overprint parts of the Pogallo Shear Zone [*Handy and Zingg*, 1991], but the kinematics of this faulting have yet to be worked out in detail.

The K-Ar mica ages along the Insubric Line [*Zingg and Hunziker*, 1990] and fission track ages from zircons and apatites within the Ivrea-Verbano and Strona-Ceneri Zones [*Hurford et al.*, 1989; *Hunziker et al.*, 1992] indicate that

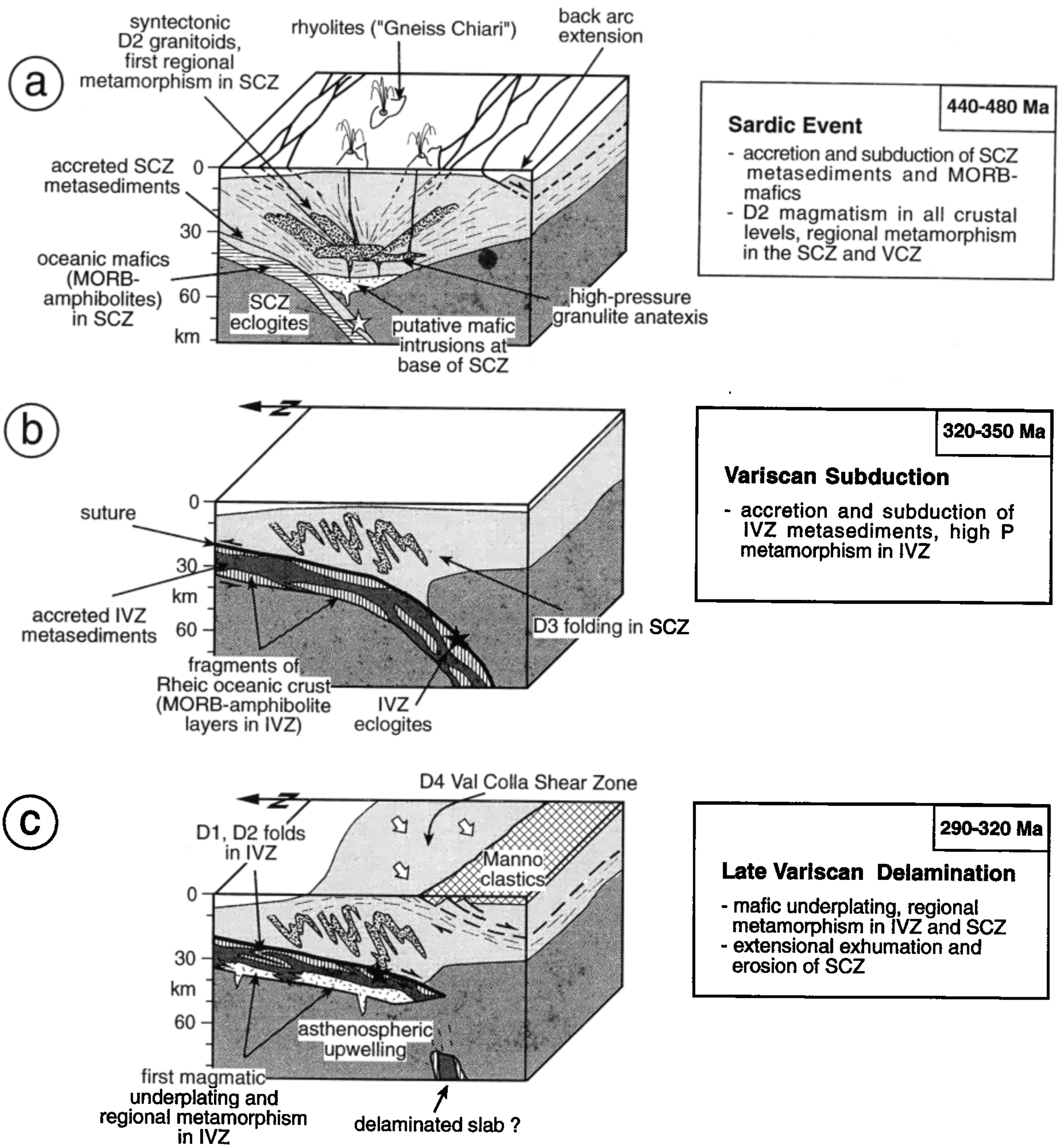

Figure 11. Evolution of the Ivrea crustal section described in text: (a) Sardic event, (b) Variscan subduction, (c) late Variscan delamination, (d) Permian transtension, (e) Tethyan rifting, and (f) Alpine emplacement. Abbreviations are as follows: IVZ, Ivrea-Verbano Zone; SCZ, Strona-Ceneri Zone; VCZ, Val Colla Zone.

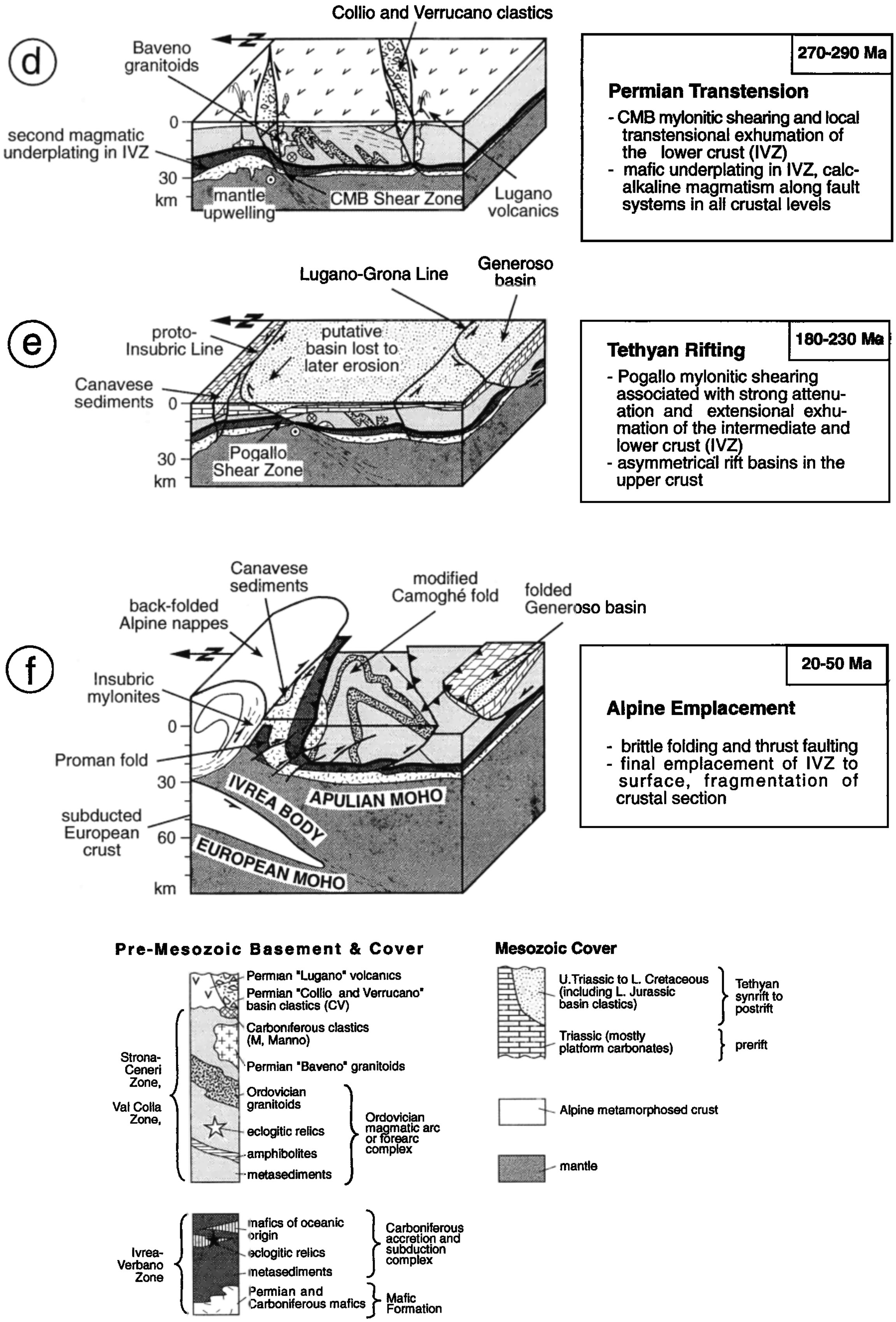

Figure 11. (continued)

northern parts of the crustal section including the Ivrea-Verbano Zone were exhumed in Late Cretaceous time and finally emplaced in early Tertiary to Mid-Tertiary time (Figure 2). In the southern part of the crustal section the basement-sediment contact is segmented into fault-bounded blocks with orientations varying from subvertical to horizontal (stereoplots marked Mu and Ar in Figure 8a). This complex local structure reflects the interference of north-south trending, early Mesozoic normal faults with both north and south directed Alpine folding and faulting [*Bertotti*, 1991]. The Alpine faulting is mid-Tertiary to late Tertiary on the basis of seismic and borehole information in the sedimentary cover to the south [*Bernoulli et al.*, 1989; *Schumacher et al.*, 1997].

4. A Model for the Evolution of the Southern Alpine Lithosphere

The evolution depicted in Figure 11 derives from the successive retrodeformation of Alpine and pre-Alpine structures. We emphasize that uncertainties in the local kinematics of Alpine deformation render any such reconstruction qualitative at best. In particular, the pre-Variscan structure of the crust is conjectural, based as it is on interpretations of thermobarometric and geochemical data in the context of actualistic models of crustal subduction and accretion.

4.1. Sardic Arc Tectonics

We envisage two possible scenarios for the pre-Variscan evolution of the southern Alps, depending on the ages of the eclogites and the D1, Cannobio Phase in the Strona-Ceneri Zone: (1) Subduction, high-pressure metamorphism, and exhumation (D1) are closely related in space and time to D2, Ceneri Phase deformation and magmatism in an Ordovician forearc or magmatic arc located at or near the northern margin of Gondwanaland (Figure 11a). (2) D1 occurred much earlier, during Cadomian orogenesis (520-580 Ma) and is unrelated to D2. We favor the first scenario (Figure 11a) because in pre-Alpine basement units of the Alps that are similar to the Strona-Ceneri Zone (e.g., the Gotthard Massif), eclogite facies metamorphism, felsic magmatism, and high-temperature metamorphism occurred within the relatively short span of 440-470 Ma [*Oberli et al.*, 1994]. Alternative scenarios involving rifting [*Ziegler*, 1990] are unlikely given the paucity of mantle-derived intrusives and the minimum crustal thickness of 35-50 km estimated above for the generation of S-type granitoids in the Strona-Ceneri Zone.

A magmatic arc setting has also been proposed to explain the felsic, subalkaline character of Early to Middle Ordovician magmatic suites in southern Sardinia [*Carmignani et al.*, 1994] and in the Central Iberian Zone of central Spain [*Valverde-Vaquero and Dunning*, 1999]. Relating these Ordovician events with those in the southern Alps, though speculative, is consistent with paleogeographic reconstructions locating the southern Variscides (including Alpine basement units) along the peri-Gondwanan margin of the Iapetus Ocean in mid-Ordovician time [*von Raumer*, 1998]. We therefore adopt the term "Sardic event" to refer to Ordovician tectonometamorphism in the southern Alps. This term is more appropriate than the term "Caledonian" for Ordovician events in units which, like most pre-Variscan basement of the Alps at that time, occupied the opposite (Gondwanan) side of the Iapetus Ocean to the Caledonides of Scotland and Scandinavia [*Ziegler*, 1990; *Torsvik et al.*, 1996].

The thickened Ordovician crust shown in Figure 11a was modified prior to the onset of Variscan accretion and subduction, as is evidenced by the aforementioned post-D2, pre-D3 decompression of 3-4 kbar and cooling of 200°C in the Strona-Ceneri Zone. The nature and exact timing of this modification are unconstrained but we speculate that the modification may be related to the breakup of the northern margin of Gondwana [*Ziegler*, 1990; *von Raumer*, 1998], possibly behind the retreating subduction zone and magmatic arc illustrated in Figure 11a.

4.2. Variscan Convergent Tectonics

Variscan accretion and subduction are shown in Figure 11b. Slivers of oceanic crust and upper mantle were subducted to depths consistent with eclogite facies metamorphism, as preserved in MORB-mafic layers along the southeastern margin of the Ivrea-Verbano Zone. These oceanic fragments of subducted, pre-Variscan mafic crust are interpreted as remnants of the Rheic Ocean between Avalonia and Gondwana. Tectonic underplating of imbricated Ivrea metasediments and MORB-mafic layers to the Ordovician crust in the Strona-Ceneri Zone was sited along a predecessor to the CMB Shear Zone (suture in Figure 11b). Relics of prograde, pressure-dominated amphibolite facies metamorphism in the Ivrea metasediments testify to this accretion and underplating along the crustal roof of the subduction zone. In the overlying Strona-Ceneri Zone, D3, Gambarogno Phase folds formed during subhorizontal shortening of the steeply dipping, Ordovician S2 foliation (Figure 11b).

The direction of Variscan subduction in the southern Alps is poorly constrained. *Vai and Cocozza* [1986] proposed west directed subduction on the basis of the assumption that the Ivrea-Verbano Zone was verticalized and emplaced in the core of the Variscan orogen, where it was supposedly flanked to the east by more external units with westward increasing Variscan metamorphic grade (Orobic basement, Val Colla and Strona-Ceneri Zones in Figure 1). However, the abundant evidence for an Alpine rather than Variscan emplacement age of the Ivrea-Verbano Zone refutes this hypothesis [*Zingg et al.*, 1990; *Schmid*, 1993]. According to the orientational criteria discussed in section 4.1, back-rotating the Ivrea-Verbano Zone into its pre-Alpine attitude yields a southeastward dip of the Ivrea-Verbano - Strona-Ceneri contact. This is consistent with a southeast dipping Variscan subduction zone, as drawn in Figure 11b.

Figure 11c depicts a late stage of Variscan convergence during the time span 290-320 Ma. We speculate that events in the Ivrea crustal section during this time (Figure 2) were triggered by some kind of lithospheric delamination, for example, slab break-off [*von Blanckenburg and Davies*, 1995], that lead to asthenosheric upwelling, mantle anatexis, and advection of heat into the thickened crust. A similar mechanism has been proposed to explain late Carboniferous magmatism and regional metamorphism in other parts of the Variscan orogen, such as the Moldanubian domain in the

Vosges and Schwarzwald of France and southern Germany [*Eisbacher et al.*, 1989]. Isostatic rebound of the delaminated Variscan crust may have been partly responsible for the exhumation and overprinting of Variscan high-pressure rocks presently exposed in the southern part of the Ivrea-Verbano Zone (Figure 11c). Lithospheric delamination also provides a plausible explanation for the general simultaneity of regional metamorphic deformation in the Ivrea-Verbano Zone and extensional unroofing of the Strona-Ceneri Zone. The latter lead to the subaerial erosion of basement into intramontane basins filled with Manno clastic sediments (Figure 11c). These events preceded peneplainization of the southern Alpine basement, as is marked by the Lower Permian erosional unconformity at the top of the Strona-Ceneri Zone [*Graeter*, 1951]. We note that presently observed differences in the style and orientation of late Carboniferous structures in the Ivrea-Verbano and Strona-Ceneri Zones reflect the fact that these two basement units originally occupied different levels of the Variscan crust and were juxtaposed much later during early Mesozoic extensional shearing along the Pogallo Shear Zone (see section 4.4).

4.3. Early Permian Transtensional Tectonics

Figure 11d shows the southern Alpine crust during Early Permian, oblique-slip tectonics and magmatism. Sinistral transtension in the western part of the southern Alps is inferred from kinematic restoration of the steeply dipping CMB mylonites in the Ivrea-Verbano Zone to their subhorizontal, pre-Alpine attitude [*Handy and Zingg*, 1991]. We propose that the CMB Shear Zone steepened upward to merge with oblique-slip faults which bound elongate, Permian basins in the intermediate to upper crust (Figure 11d). Today, these faults are marked by ENE-WSW trending facies boundaries in Lower Permian basinal sediments overlying the Strona-Ceneri Zone [*Kälin and Trümpy*, 1977] and the Orobic basement [*Cassinis et al.*, 1986]. Pronounced, north-south variations in facies and thickness of the Permian, Collio, and Verrucano formations in the southern Alps (marked CV in Figure 1) are diagnostic of strong subsidence within narrow, fault-bounded basins [*Schönborn and Schumacher*, 1994]. This evidence for localized subsidence in the upper crust is consistent with exhumation of the lower crust in the Ivrea-Verbano Zone.

The Early Permian crustal section was approximately 30 km thick, as is inferred from the 600° ± 50°C closure temperature of the U-Pb monazites that yield 270-280 Ma ages at the base of the crustal section in the Ivrea-Verbano Zone [*Henk et al.*, 1997] and the assumption of a moderate to high geothermal gradient (20°-30°C/km) at this time [*Handy*, 1987]. Magmatic underplating of mantle-derived, mafic melts probably played an important role in maintaining this thickness where parts of the lower crust, like the Ivrea-Verbano Zone, were locally stretched and exhumed during transtensional mylonitic shearing (Figure 11d). The concentration of syn-mylonitic mafic veins and granitoids along the CMB Shear Zone suggests that this shear zone channeled mantle- and crust-derived melts upward from deep to shallow crustal levels. The Baveno intrusives adjacent to the CMB Shear Zone and the Lugano volcanics discordantly overlying the Strona-Ceneri basement (Figure 1) represent such middle to upper crustal magmatic rocks. Although Early Permian magmatism affected all levels of the Ivrea crustal section, its obvious effects (renewed metamorphism and anatexis) were restricted to parts of the lower crust in the vicinity of post-regional-metamorphic, mafic intrusives.

We emphasize that Early Permian magmatism and oblique-slip tectonics are temporally and kinematically distinct from Variscan convergent tectonics. This fact has been overlooked or even obscured in the literature by misleading use of the term "late Variscan" or "late Hercynian" for Early Permian events. As shown above, Early Permian intrusives and structures overprint truly late Variscan features in the Ivrea crustal section. These overprinting relationships are clearly incompatible with the idea, inspired by geophysical and petrological models [*Furlong and Fountain*, 1986; *Huppert and Sparks*, 1988], that Early Permian mafic intrusions within parts of the Mafic Formation affected amphibolite to granulite facies, regional metamorphism and anatexis in the entire Ivrea-Verbano Zone [*Fountain*, 1989; *Voshage et al.*, 1990].

Handy and Zingg [1991] proposed that Early Permian sinistral transtension in the southern Alps was conjugate to dextral strike-slip shearing across Europe within an overall regime of post-Variscan, right-lateral strike slip between Gondwana and Laurussia, linking convergence in the Uralides and the Appalachians [*Arthaud and Matte*, 1975; *Ziegler*, 1990]. Alternatively, transtension in the southern Alps was related to oblique spreading behind an eastwardly retreating convergent margin in the western Paleotethys [*Stampfli*, 1996]. Whatever its cause, oblique-slip tectonics ended in Early Triassic time with the transition from clastic sedimentation to carbonate precipitation on gradually and differentially subsiding, marine platforms [*Winterer and Bosellini*, 1981]. This subsidence continued into Middle Triassic time, when it was complicated by strike-slip tectonics [*Bertotti et al.*, 1993]. Structures related to this event are abundant farther to the east in the Dolomites [*Doglioni*, 1984] but have not yet been identified in the Ivrea crustal section.

4.4. Tethyan Rifting

Figure 11e shows the Ivrea crustal section toward the end of Pogallo Phase deformation in Early to Middle Jurassic time. The Pogallo Shear Zone itself is depicted as a moderate- to low-angle, oblique-normal fault that accommodated noncoaxial, east-west directed, extensional exhumation of the Ivrea-Verbano Zone to depths of 10 km or less. This kinematic reconstruction is based on a backrotation of the D4, Pogallo mylonitic foliation and stretching lineations into their pre-Alpine orientations, as discussed by *Handy* [1987] and in section 3. The rift basin and upper crustal normal faults that were linked to the Pogallo Shear Zone at depth have been lost to Tertiary erosion but probably had a geometry similar to that of the Monte Nudo and Generoso basins presently exposed in the southern part of the crustal section (Figures 1 and 11e). The putative basin may have been bounded to the north by an east-west trending, early Mesozoic predecessor of the Insubric Line (proto-Insubric Line in Figure 11e), whose former existence is inferred from the highly deformed "Canavese" sediments preserved locally along the Insubric Line (marked Ca in Figure 1). In the southwestern part of the Ivrea-Verbano Zone these sediments represent a very condensed, early Mesozoic passive margin facies [*Bertotti et al.*, 1993] and rest in tectonic contact with relics of their granitoid basement and with late Carboniferous, granulite facies mafic rocks of the Ivrea-Verbano Zone [*Biino et al.*, 1988]. The juxtaposition of attenuated rocks from such disparate levels of the Ivrea crustal section may be due to early Mesozoic thinning [*Handy and Zingg*, 1991].

The kinematics of early Mesozoic deformation in the Ivrea crustal section are consistent with widespread evidence in the Alps for east-west directed crustal extension within a sinistral pull-apart margin at the northwestern corner of the Apulian promontory of Africa in Early to Middle Jurassic time [*Weissert and Bernoulli*, 1985]. Given the location of the Ivrea crustal section in the distal parts of the Apulian continental margin, Pogallo Phase extensional exhumation of the lower crust probably occurred during the advanced stages of rifting, when necking of the distended margin was accommodated by conjugate faulting and highly noncoaxial shearing in the upper and lower crust, respectively [*Handy*, 1987; *Bertotti et al.*, 1993].

4.5. Alpine Emplacement Tectonics

Figure 11f depicts the Ivrea crustal section in late Tertiary time, after it had been modified by Tertiary, Insubric faulting and brittle folding. Some of the faults that transect the crustal section are reactivated structures that helped to accommodate differential rotation of crustal blocks. For example, brittle reactivation of parts of the Pogallo Shear Zone accommodated differential rotation of the Ivrea-Verbano Zone into its present, subvertical attitude (Figure 11f). Similarly, reactivation of the Lugano-Grona Line accommodated folding and verticalization of the northern part of the early Mesozoic Generoso basin (Figure 11f).

Early Alpine tectonics are not shown in Figure 11, because of the difficulty of determining the precise age of Alpine faults within the basement units of the Ivrea crustal section. The lack of fission track analyses in traverses across such faults and the complexity of Tertiary tectonics render Late Cretaceous reconstructions south of the Insubric Line [*Schumacher et al.*, 1997] highly speculative.

5. Implications for Crustal Processes and Seismic Imaging of the Crust

The evolution outlined above has several interesting implications, first for the processes which formed the continental crust in western Europe and second for the interpretation of seismic profiles of such crust. The southern Alpine crust has a composite structure, comprising an older intermediate crust sandwiched between much younger segments of the lower and upper crust. This kind of structural zonation appears to be a general characteristic of continental crust in western Europe [*Costa and Rey*, 1993], although the age range of early deformation and metamorphism in the Strona-Ceneri Zone (440-480 Ma) is somewhat older than that of the earliest events in some other exposed Variscan basement terrains (e.g., Massif Central, Eo-Variscan phase of *Ledru et al.* [1994]). In the case of the Ivrea crustal section this zonation results primarily from Variscan suturing of a Carboniferous accretion-subduction complex in the Ivrea-Verbano Zone to an Ordovician magmatic arc in the Strona-Ceneri and Val Colla Zones.

This structural zonation only partly corresponds to the distribution of metamorphic facies and isotopic ages observed today in the crustal section. This discrepancy is testimony to the three ways in which deformation, metamorphism, and magmatism selectively modified different levels of the crust at different times:

1. Main elements of the Sardic magmatic arc and Variscan accretion-subduction complex that make up the Ivrea crustal section were modified or lost, probably during the late stages of Variscan convergence. The Ordovician lower crust that originally underlay the Strona-Ceneri Zone was delaminated, whereas the Ordovician upper crust was lost to extensional and erosional denudation. In contrast, the intermediate crust represented by the Strona-Ceneri Zone survived despite overprinting by Variscan folds and amphibolite facies metamorphism.

2. Early Permian magmatic underplating and transtensional shearing locally overprinted late Variscan structures and regional metamorphism that had already modified the Variscan lower crust (Ivrea-Verbano Zone) during the main pulse of late Carboniferous magmatic underplating. Permian magmatism lead to a further reconstitution of the crust and reequilibration of the petrological crust-mantle boundary at approximately 30 km. This is the average depth of continental crust beneath large parts of western central Europe, i.e., crust that was unaffected by rifting or the Alpine orogeny [*Ansorge et al.*, 1992].

3. Low-angle normal faulting associated with early Mesozoic, Tethyan rifting excised at least 10-20 km of mostly intermediate to lower crust from the section. Together with Early Permian transtensional shearing, early Mesozoic extension sheared out up to two thirds of the late Variscan crust while juxtaposing pieces of this crust that originally occupied different lateral positions. The Strona-Ceneri Zone is therefore the lateral equivalent of intermediate crust that once overlay the Ivrea-Verbano Zone and has since been faulted out and/or eroded.

The late Paleozoic exhumation of the Ivrea crustal section is polyphase and corresponds closely to that outlined by *Burg et al.* [1994] for continental crust across western Europe: Late Variscan (Westphalian) extensional unroofing of the intermediate crustal Strona-Ceneri Zone yielded to post-Variscan (Early Permian) transtensional exhumation of the deep crustal Ivrea-Verbano Zone. Most exhumation of the deep crust occurred during Early Jurassic rifting, however, and was accommodated along the continentward-dipping Pogallo Shear Zone. The southern Alpine crust is therefore typical of thinned, late Variscan continental crust within Tethyan and Atlantic passive margins.

The crustal evolution of the southern Alps has several implications for the interpretation of seismic reflection profiles of "Variscan" crust in western Europe: Seismic reflectivity of the lower crust can be attributed to the subhorizontal geometry of flattened and sheared, late Variscan mafic intrusives and Carboniferous metasediments [Figure 3.10 by *Ansorge et al.*, 1992, and references therein]. In contrast, the relative seismic transparence of the intermediate crust probably stems from the moderate to steep attitude of Sardic and Variscan structures. Reflectivity of the upper crust is due to Early Permian and early Mesozoic faults and basins.

Finally, we note that the Ivrea crustal section is transected by numerous Alpine faults and was not uniformly steepened during Tertiary, Insubric tectonics. Only the originally deepest levels of the section in the Ivrea-Verbano Zone and some shallow parts of the section along the basement-cover contact are presently verticalized. Other parts, particularly the Strona-Ceneri Zone, underwent only minor to moderate Alpine rotation [*Boriani et al.*, 1990] and have an erosional surface that is generally parallel to the late Carboniferous, metamorphic isobars. Unfortunately, some geophysical models that have used the Ivrea crustal section to simulate the seismic reflective properties of continental crust are implicitly or explicitly based on the assumption that a uniform, en bloc Alpine rotation affected all the basement units, including the Strona-Ceneri Zone [*Burke and Fountain*, 1990; *Holliger and Levander*, 1994; *Rutter et al.*, 1999]. Future modeling will no doubt take into account the abundant evidence for varied, differential rotations within the Ivrea crustal section.

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