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The kinematics of movements along the Insubric Line and the emplacement of the Ivrea Zone

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Abstract

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The Insubric Line west of Locarno is characterized by a 1 km thick greenschist facies mylonite belt. East of Locarno, these mylonites are overprinted by a discrete brittle fault. The mylonites are derived from basement units of the Central Alps (Sesia Zone) and the Southern Alps (Ivrea Zone) as well as from the Permo-Mesozoic cover of the Southern Alps (Canavese). Sense of shear criteria indicate that the mylonites accommodated backthrusting followed by dextral strike-slip motion.

Mylonitization during backthrusting was synchronous with backfolding of the Central Alpine nappes under higher metamorphic conditions. A horizontal temperature gradient resulted from the rapid juxtaposition of the warm Central Alpine block against the cold Southern Alpine block. Mylonites formed during the later dextral strike-slip event are related to large transcurrent displacements in the Central Alps deduced from regional kinematic considerations. Thus, both mylonitization events are contemporaneous with deformation to the north and south of the Insubric Line (Insubric phase) extensively modifying the pre-Insubric crustal configuration of the Alps. The Insubric phase post-dates the Bergell intrusion (30 m.y.).

The emplacement of the geophysical Ivrea body is a combined effect of vertical uplift due to E–W directed crustal thinning during the Early Jurassic and underplating by continental crust associated with Late Cretaceous compression. A deep crustal normal fault (Pogallo Line), subsequently rotated during Tertiary Alpine orogenesis, separates deeper parts of the Southern Alpine crust (Ivrea Zone) from intermediate crustal levels (Strona–Ceneri Zone). The rigid Ivrea body localized large strains within the Insubric mylonite belt and is responsible for the present curvature of the Insubric Line.

Introduction

The Insubric Line is a major Alpine lineament which is curved in map-view within the studied area (Figs. 1 and 2). This lineament marks the boundary between the Central Alps, consisting of intricately refolded basement nappes (Milnes, 1974), and the Southern Alps with S-vergent thrusts (Laubscher, 1985). At the same time, it also forms the southern limit of Alpine metamorphism. Thus, the Insubric Line accommodated a component of post-early Oligocene vertical uplift on the order of 10 to 20 km, juxtaposing the pre-Alpine-metamorphosed basement of the Southern Alps and its unmetamorphosed cover with the Alpine metamorphic Central Alps (Niggli and Zwart, 1973; Frey et al., 1974). In addition dextral strike-slip movements along the Insubric

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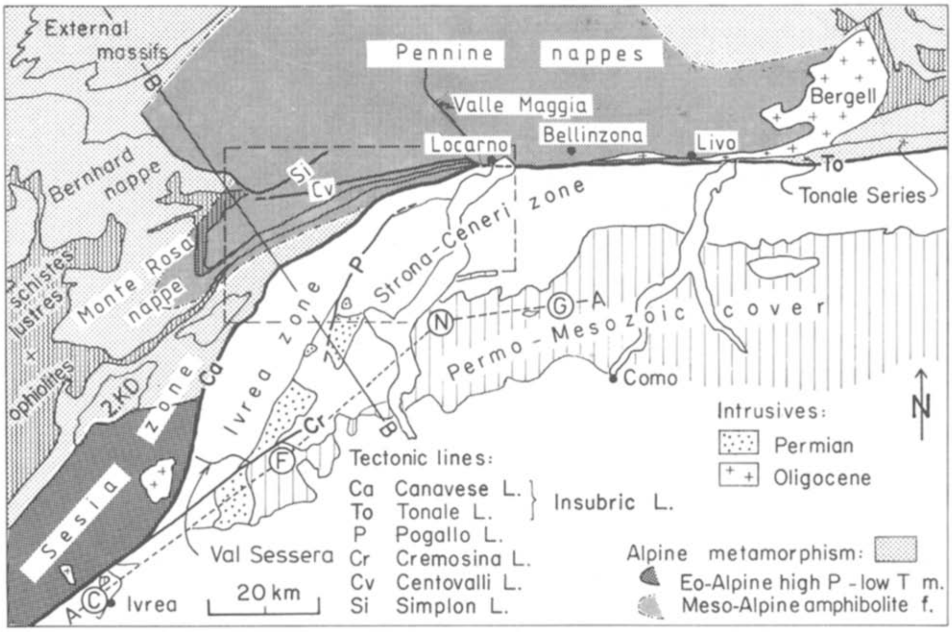

Fig. 1. Geological sketch map of the western part of the Insubric Line. *AA*—trace of profile in Fig. 8. *C*—Canavese; *F*—M. Fenera; *N*—M. Nudo; *G*—Generoso. *BB*—trace of profile in Fig. 10.

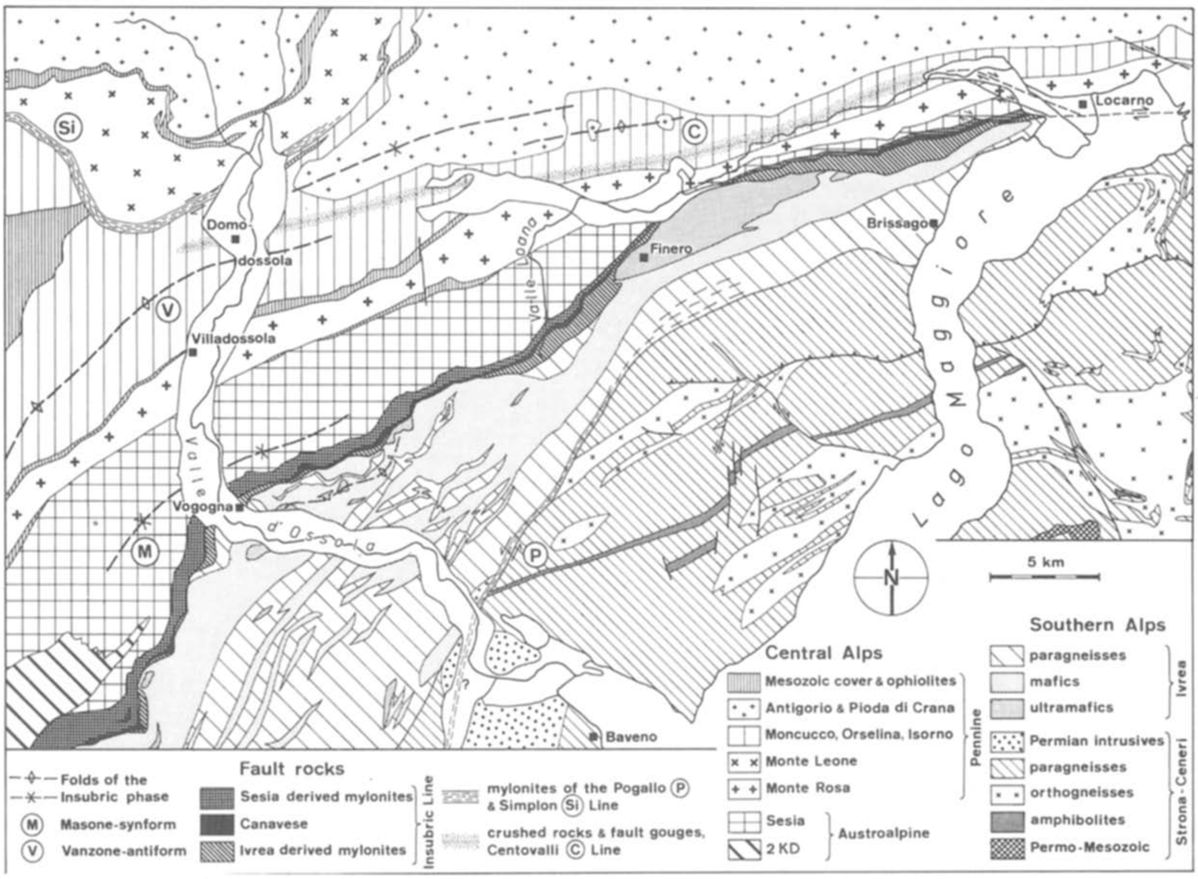

Fig. 2. Geological map of the investigated area.

Line are required from large scale kinematic analyses (Laubscher, 1971).

From west to east the Insubric Line consists of the following segments: Canavese Line (this study), Tonale Line, Giudicarie Line, Pustertal Line and Gailtal Line. This boundary region between the Central and Southern Alps is marked by faults of variable importance and by a mylonite belt of up to 1 km thickness, at least along the Canavese and Tonale lines (Figs. 1 and 2). These mylonites dip to the N and NW and constitute the southernmost part of the "Southern Steep Belt" (Milnes, 1974) classically referred to as the "Root Zone". Lenses of weakly metamorphosed Permo-Mesozoic sediments of Southern Alpine affinity (the Canavese sediments) are preserved within basement-derived mylonites.

Southwest of Locarno (Fig. 2), the basement of the Southern Alps consists of deep and intermediate crust (Ivrea and Strona–Ceneri zones, respectively) which underwent amphibolite to granulite facies metamorphism during the Paleozoic (e.g. Zingg, 1983). The Ivrea Zone is related to a large geophysical anomaly, the Ivrea body, with the Moho discontinuity rising from a depth of 30 km beneath the Po plain to close to the surface near the Insubric Line (Berckhemer, 1968). Since the Insubric Line approximately marks the northern boundary of this large geophysical anomaly, the emplacement of the Ivrea body was related to movements along the Insubric Line by Laubscher (1970). To the south, the Ivrea Zone is bounded by another mylonite zone, the Pogallo Line (Boriani and Sacchi, 1973), which truncates the E–W trending structures of the Strona–Ceneri Zone (Fig. 2).

This contribution summarizes the main results of detailed mapping and petrological and microstructural investigations. We focus on the following topics: (1) the nature and tectonic position of the source rocks (protoliths) which were mylonitized; (2) the kinematics of movements within the mylonites deduced from the microstructures; (3) the relation in time and space between mylonitization and internal deformation within the country rocks; and (4) possible relationships between movements within the mylonite belts and the emplacement of the Ivrea body.

The protoliths of the Insubric mylonites

In the classical view (Gansser, 1968) the Insubric Line is a discrete fault separating typical Ivrea rocks with prealpine structures in the south from: (1) a belt of schists and metasediments referred to as the Canavese Zone (Argand, 1910) or as the "Schisti di Fobello e Rimella" (e.g. Sacchi, 1977); and (2) the Sesia Zone further to the north. Ahrendt (1980) still refers to the Insubric Line as a discrete fault but places it within the mylonite belt, north of the Canavese sediments. However, brittle faulting is only moderately developed west of Locarno (Canavese Line), in contrast to the sector east of Locarno (Tonale Line).

Our investigations placed great emphasis on studying progressive mylonitization in order to gain information about the rock units which now form the mylonite belt. From south to north, the mylonites mapped out in Fig. 2 are: (1) mylonites derived from the basement of the Southern Alps (Ivrea-derived mylonites); (2) mylonitized Permo-Mesozoic cover rocks (Canavese); and (3) mylonites derived from the Sesia Zone, an Austroalpine unit of the Central Alps (Sesia-derived mylonites). This sequence can be traced from the Valle d'Ossola to Locarno (Fig. 2), even though imbrication and/or isoclinal folding locally affect these units.

Ivrea-derived mylonites

Petrological studies across the Ivrea Zone from southeast to northwest revealed the following sequence: (1) the main part of the Ivrea Zone with a Paleozoic metamorphism grading from the amphibolite to the granulite facies towards the northwest; (2) Paleozoic amphibolite facies paragneisses, amphibolites and impure marbles forming the northwesternmost rim of the Ivrea Zone; (3) greenschist facies mylonites and phyllonites of alpine age, containing amphibolite facies mineral relics. The contact between (2) and (3) is gradational. The progressive mylonitization of Ivrea rocks is well documented in sections near Loro (Valle d'Ossola) and in the Valle Loana.

In the paragneisses the mylonitic foliation develops progressively with the break-down of the assemblage qtz–plag–ga–bi ± sill ± mu ± Kf to qtz–ab–cl.zo–white mica–chl–sphene. These mylonites are associated with sheared amphibolites (plag-brown hbl ± cpx ± bi → ab–act–chl–cl.zo.–sphene) and impure marbles with relics of diopside and actinolite. In general, source rocks of granitic composition are absent. In the easternmost sector near Locarno, however, intimate relationships between foliated meta-granites and Ivrea-paragneisses can be observed despite the mylonitization, suggesting that these granitic rocks formed part of the Ivrea Zone. Tonalitic intrusions in the northwest rim of the Ivrea Zone are better preserved southwest of the studied area in the Val Sessera. Pegmatites, similar to those in the southern amphibolite facies part of the Ivrea Zone near the Pogallo Line, are widespread within the Ivrea-paragneisses and their mylonitic derivatives in the Valle Loana section.

What has usually been referred to as the Insubric Line is the relatively sharp fabric boundary between these mylonitic Ivrea rocks and the mafics and paragneisses of the Ivrea Zone with the well preserved pre-Alpine fabrics to the south. This fabric boundary reflects the rheological contrast between mafic-rich parts of the Ivrea Zone which are much more resistant to mylonitization and greenschist retrogression than the paragneiss-rich rim of the Ivrea Zone.

Canavese meta-sediments

Most sequences of Canavese meta-sediments are dismembered and often imbricated with or folded into the Ivrea-derived mylonites. They comprise quartz-mica-rich clastic sediments (Permo-Triassic), dolomites (Triassic), and dark calc-schists and silicious limestones (lower Jurassic ?). The dolomites are well preserved in boudins, whereas all other lithologies are mylonitized. The Canavese limestones and mylonitized Ivrea-marbles may resemble each other in the field, but in thin-section the latter commonly show calc-silicate minerals as relics of the prealpine metamorphism. The Canavese meta-sediments exhibit Alpine greenschist facies metamorphism only, in contrast to the plurifacial metamorphism of the Austroalpine Sesia Zone. Therefore, these metasediments are considered to represent the cover of the Southern Alps. Alternatively, but less probably they could represent the Austroalpine cover which was detached and thrusted onto the Southern Alpine domain during the Cretaceous (eo-Alpine) phase.

The best profiles are found in the Valle Loana (Southwest of Finero) where clastic sediments containing quartz-porphyritic detritus typical of the Verrucano and Servino formations grade into stromatolitic dolomites with occasional clastic intercalations (Permo-Triassic). These Canavese meta-sediments are imbricated with Ivrea-derived mylonites. However, the Early Mesozoic mica ages from adjacent Ivrea paragneisses (J.C. Hunziker, pers. commun., 1985) preclude a direct basement–cover relation.

Sesia-derived mylonites

The bulk of the Sesia-derived mylonites is derived from granitic gneisses, but mylonitized biotite schists and few amphibolites occur as well. In addition, mylonitized porphyritic dikes restricted in occurrence to the southernmost Sesia zone (Reinhard, 1966) form a key lithology in mapping and dating the Sesia-derived mylonites. Within the Sesia gneisses away from the mylonite belt, these dikes are weakly deformed and cross-cut the older pre-mylonitic foliation. Towards the south, however, they are progressively mylonitized along the Insubric Line. It is very likely that these dikes are associated with the Oligocene magmatic activity found elsewhere along the Insubric Line (Bergell, Biella, Traversella intrusives).

In general, the Sesia-derived mylonites are found north of the northernmost outcrops of the Canavese meta-sediments and are rarely imbricated with the latter. The northern boundary of the mylonite belt is diffuse and the mylonites grade into isoclinally folded Sesia gneisses.

The metamorphic conditions of mylonitization along the Insubric Line

During mylonitization, the Canavese meta-sediments were metamorphosed under lower greenschist facies conditions all along the Insubric Line (Zingg et al., 1976). About the same grade of metamorphism accompanies mylonitization of the Ivrea paragneisses. In mylonites of pelitic composition quartz + chlorite but not biotite are stable. In the paragneisses, quartz is more ductile than all other minerals. However, the break-down of the amphibolite facies assemblage under greenschist facies conditions leads to a reversal in competence. Quartz then forms microboudins, augen and lenses in the fine-grained mica-rich mylonitic matrix (Zingg, 1982). The retrograde overprint is always syn-mylonitic and it appears that work softening is reaction-enhanced.

Within Sesia-derived mylonites of granitic composition a flow-induced segregation of quartz-rich laminae and geometrical softening within these laminae are regarded as the principal mechanisms of work softening. Biotite, muscovite and feldspar form relatively unaltered porphyroclasts in a fine-grained matrix of white mica–green biotite–ab–qtz–cl.zo–sphene. In mylonitized pelitic schists of the Sesia Zone biotite alters to chlorite. Thus, the metamorphic conditions are comparable to those found within the Ivrea-derived mylonites. Similar metamorphic conditions throughout the mylonite belt are also suggested indirectly by the similar quartz microstructures: Quartz dynamically recrystallizes to a grain size of between 10 and 30 μm, a range of grain sizes commonly found in greenschist facies terranes.

These synmylonitic metamorphic conditions produce a retrograde overprint with respect to the mesoalpine (Lepontine) isograds within the Sesia Zone. Thus, mylonitization post-dates the peak of metamorphism.

The kinematics of movements within the Insubric mylonite belt

The Insubric Line within the studied area

Nearly all of the lithologies found whithin the mylonite belt have a very clear L-S fabric. Isolated hinges of isoclinal folds with axial planes and fold axes parallel to the mylonitic foliation and the stretching lineation, respectively, are found occasionally. A post-mylonitic crenulation is only locally developed, mainly in the eastern sector of Fig. 2. We correlate this crenulation with a large scale fold at the western termination of the Finero complex described by Kruhl and Voll (1976) and Steck and Tièche (1976). The consistent asymmetry of the crenulation indicates a synform to the north.

The poles to the foliation and the stretching lineations from within the mylonite belt only, avoiding crenulated areas, are plotted in Fig. 3 and reveal the following features:

(1) The foliation is parallel to the map-scale trend of the Insubric Line. It swings from a near E–W strike with a dip of 70° to the north near Locarno into a NE–SW-strike with a shallower dip (40°–60°) towards the Valle d'Ossola.

(2) Although there is considerable scatter in the trend of the lineations within any of the given localities, there is a distinct difference in the average orientation of the lineations between the Sesia-derived and Ivrea-derived mylonites all along the mylonite belt. The Sesia-derived mylonites exhibit a down-dip plunging lineation with a tendency for westerly pitches in some areas. The lineation within the Ivrea-derived mylonites is subhorizontal in the east and pitches to the north and northeast in the west. Often, the change in the orientation of the lineations coincides with the boundary between the two protoliths.

The systematic changes in the orientation of foliation and lineation along strike of the Insubric Line are incompatible with ideal simple shear at a regional scale. However, there is ample evidence to suggest that deformation on the local scale occurred along a rotational strain path. Quartz *c*-axis fabrics are predominantly of the asymmetric single girdle type and indicate a deformation path close to ideal simple shear (Schmid and Casey, 1986). Furthermore, different sense of shear indicators gave very consistent results.

Various methods for determining the sense of movement within sheared rocks have been established (Simpson and Schmid, 1983; Lister and Snoke, 1984). In this study the most reliable indicators of shearing sense were: (1) the quartz *c*-axis fabrics (determined by X-ray texture goniometry in some cases, but usually by inserting a gypsum plate in order to assess quickly the asymmetry of the *c*-axis single girdle pattern in a thin-section cut perpendicular to *Y*); (2) the obliquity of the

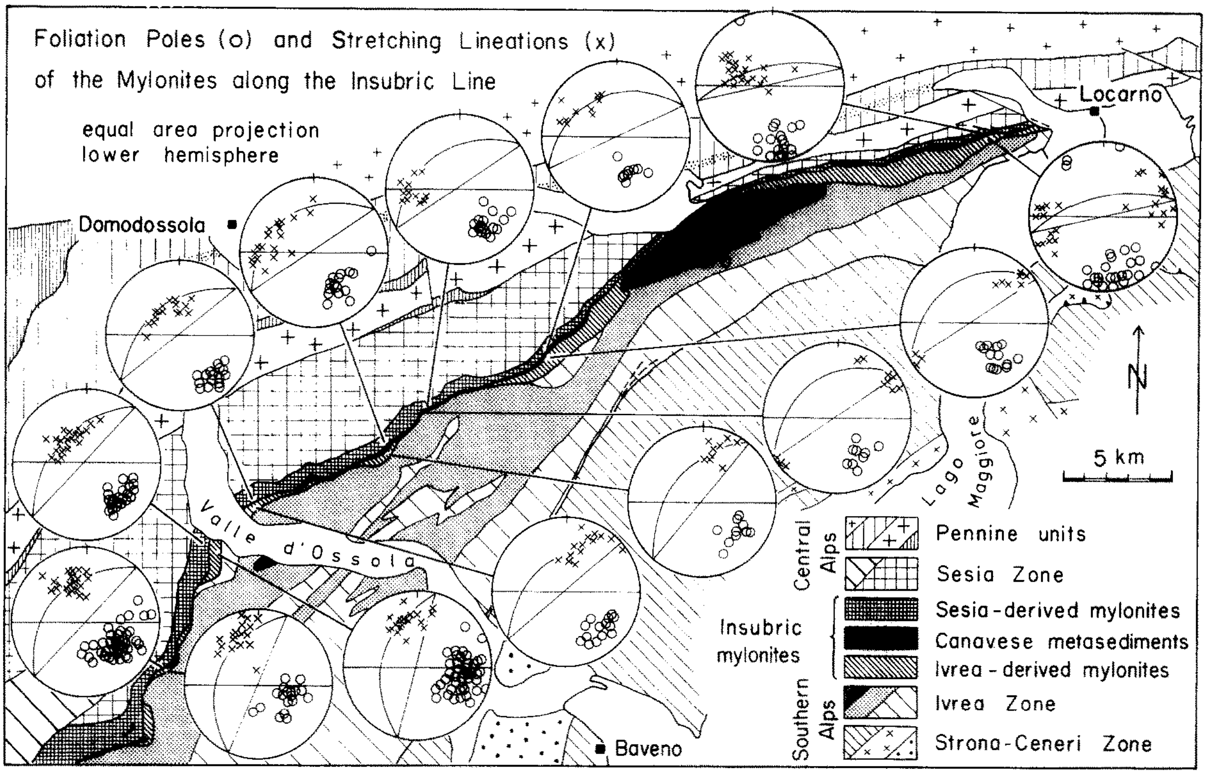

Fig. 3. The orientation of mylonitic foliation and stretching lineation of the Insubric mylonites north and south of the Canavese metasediments.

long axes of recrystallized grains and subgrains with respect to the mylonitic foliation; and, (3) the orientation of shear bands which are abundant in the mica-rich mylonites.

From these indicators it was inferred that the Sesia-derived mylonites accommodated a thrusting of the Central Alps over the Southern Alps coupled with a minor dextral strike-slip component along the eastern portion of the studied area where the lineations depart from a down-dip orientation (backthrusting event). For the Ivrea-derived mylonites a horizontal, dextral strike-slip motion is indicated for the eastern sector (strike-slip event). In the southwest this dextral strike-slip motion is coupled with a vertical component associated with a relative downthrow of the Central Alps. Thus, in the southwest a vertical component of opposite sign is recorded within Sesia-derived mylonites (thrust motion) to that within the Ivrea-derived mylonites (normal fault motion). Since the strike-slip components occurred along a

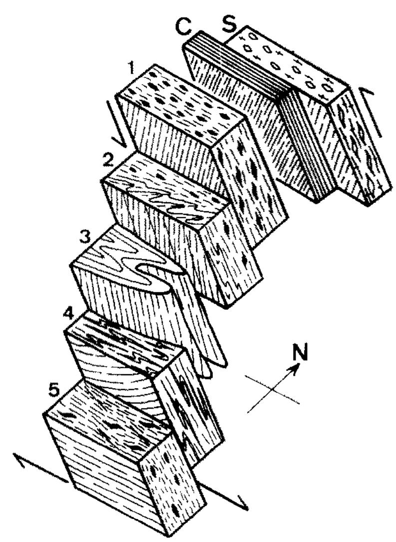

Fig. 4. Overprinting relationships in the Locarno area, indicating an overprint of earlier formed mylonites related to backthrusting and preserved within Sesia-derived mylonites (*S*) and Canavese metasediments (*C*). This overprint (domains *1*–*5*, see text) is related to the strike-slip event and affects the Ivrea-derived mylonites.

curved surface the country rocks outside the mylonite belt had to deform simultaneously as described in a later section. Furthermore, if the average direction of the lineation is taken to approximate the movement direction, the relative motion between the Central Alps and the Southern Alps must have been associated with relative rotations of the two blocks around an axis normal to the mylonitic foliation during the strike-slip event.

It is likely that these movements represent different events. Surprisingly, in most localities the change from one lineation regime to the other is very abrupt and coincides with the location of the Canavese meta-sediments. Consequently, overprinting relationships are rare.

Figure 4, however, depicts such overprinting relationships found in the Locarno area. As usual, the Sesia-derived mylonites record the backthrusting event. Domains *1–5* in Fig. 4 illustrate overprinting relationships south of the main body of Canavese meta-sediments in that area and within Ivrea-derived mylonites intercalated with minor slices of Canavese meta-sediments. Domain 1 shows that the northern rim of the Ivrea-derived mylonites has been affected by the backthrusting event as well. Domain 2 contains incipient crenulations that overprint the backthrusting mylonites. These crenulations dip steeply and show a dextral vergence. Within domain 3, the folds in the mylonites become isoclinal with axes nearly parallel to the pre-existing stretching lineation. These isoclinal folds become tighter (stage 4) and the fold axes rotate into a subhorizontal orientation, attaining parallelism with the stretching lineation related to the strike-slip event (domain *5*). Thus, we interpret the development in domains 2–5 in terms of a progressive shearing overprint during the later strike-slip event.

The same overprint sketched in Fig. 4, domain 2, was also found in the Valle d'Ossola area, but this time within the southernmost few meters of Sesia-derived mylonites. Thus, both the older backthrusting and the younger strike-slip event affected the Ivrea- and the Sesia-derived mylonites to a certain extent.

The Insubric Line outside the area of detailed investigations

Work in progress along the southwest continuation of the Insubric Line (Aebli, in prep.) indicates additional complications. Pre-Insubric mylonites which are cut by Tertiary andesitic dykes are found in the northwestern rim of the Ivrea Zone. A younger (Insubric) mylonitization event deforms these dykes and corresponds to the backthrusting event. Near the town of Ivrea, the boundary between the Ivrea and Sesia zones is overprinted by a late normal fault (Ahrendt, 1972).

East of Locarno the Insubric Line (Tonale Line) is characterized by an additional brittle overprint as the Centovalli Line merges with the Insubric Line. In the literature (e.g., Gansser, 1968; Fumasoli, 1974; Vogler and Voll, 1981; Lardelli, 1981) the Insubric (or Tonale) Line denoted the master fault associated with this brittle overprint. In the Locarno area the mylonites described above are offset by WNW–ESE-striking brittle faults (Fig. 2). These faults form synthetic Riedel shears and indicate continued dextral movements under brittle conditions. Further to the east, similar dextral Riedels are associated with a counterclockwise rotation of the pre-existing foliation affecting the tail of the Bergell intrusion (Fumasoli, 1974). In addition, the masterfault bounding the Riedels to the south contains slickensides that also indicate dextral movement. A pitch to the east (occasionally of up to 40° within subvertical slickensided surfaces) indicates a vertical component of movement under brittle conditions associated with a relative downthrow of the Central Alps. This vertical displacement dragged the Triassic cover of the Southern Alps from a shallow northward dip into near parallelism with the steeply north-dipping masterfault in the Livo area (Fig. 1, Fumasoli, 1974).

The further continuation of the Insubric Line south of the Tauern window (Puster- and Gailtal Line) seems to be characterized by a brittle event as well. Ahrendt (1980) pointed out that the jump in radiometric ages does not coincide with this brittle lineament but occurs further to the north. This indicates that the eastern continuation of the mylonite belt does not necessarily coincide everywhere with the trace of the brittle lineament usually referred to as the Insubric Line or the Periadriatic Lineament. It is also possible that the backthrusting and strike-slip movements are spacially separated in this region.

The mylonites related to the ductile events are found north of the masterfault (Heitzmann, 1975). They have a shallower northward dip and are truncated by the subvertical masterfault at their southern margin. These mylonites are part of the Tonale Series generally believed to be an Austroalpine unit (Fumasoli, 1974; Heitzmann, 1975; Lardelli, 1981).

The Tonale Series mylonites contain NW-dipping lineations in the area east of Bellinzona (Vogler and Voll, 1981) and horizontal lineations farther to the east (Wiedenbeck, 1986). We found the horizontal component of movement to be dextral at both these localities. The formation of these Tonale Series mylonites is possibly coeval with the ductile strike-slip event along the Canavese Line.

North of the Tonale Series Vogler and Voll (1981) describe NE-dipping lineations within the deformed tail of the Bergell batholith. We do not regard their arguments for a coaxial strain path within these Bergell intrusives to be conclusive. Rather, we suggest that the tail of the Bergell intrusion has been sheared during the backthrusting event. Both radiometric age determinations and sedimentological studies on Late Oligocene–Early Miocene conglomerates containing Bergell pebbles indicate substantial uplift of the Bergell intrusion (Wagner et al., 1977; Gunzenhauser, 1985). We correlate this uplift with the backthrusting event recorded in the Insubric mylonites.

The timing of movements along the Insubric Line

The relationships mentioned above suggest that backthrusting postdates the Bergell intrusion (30 m.y.) as well as possibly contemporaneous intrusions of porphyritic dykes found within the Sesia-derived mylonites west of Locarno. Recent radiometric profiling in the Valle Maggia cross section (north of Locarno) by Hurford (1986) allows us to date the backthrusting event even more precisely. For a region immediately north of the Insubric Line this author documents a period of rapid cooling (52–86°C/m.y.) between 23 and 19 m.y. A correlation of this rapid cooling with the backthrusting event is obvious, since the southern limit of the area affected by rapid cooling coincides with the Insubric mylonite belt. Because the onset of rapid cooling somewhat postdates the beginning of rapid uplift (Werner, 1980) 23 m.y. are a minimum age for the beginning of the backthrusting event. The younger strike-slip event continued well into at least the Late Miocene, a time when the temperatures dropped below the ductile–brittle transition. At present the Insubric Line is inactive.

Contemporaneous deformation outside the Insubric mylonite belt

Central Alps

The northern boundary of the mylonite belt is situated within the Austroalpine Sesia Zone. Its transitional character has been studied in detail in the Valle d'Ossola cross section (Fig. 5). Isolated hinges of synmylonitic folds become more open towards the northwest. At the same time the fold axes, initially parallel to the mylonitic stretching lineation, rotate into a horizontal orientation via an intermediate pitch to the east (Fig. 5). The northern boundary of the mylonites has been drawn rather arbitrarily in Figs. 2 and 5 so as to coincide with the departure of the orientation of the fold axes from the down-dip orientation typical for the Sesia-derived mylonites. Further to the northwest the pre-mylonitic schistosity is deformed by rather open, similar folds with nearly horizontal fold axes. These folds refold all the earlier higher temperature structures such as a mineral stretching lineation and earlier folds. Just 2 km north of Vogogna (Fig. 5), these folds are M-shaped and mark the hinge zone of a major synform (Masone synform, (Fig. 2) whose axial plane dips more steeply to the northwest (70°) than does the mylonite belt.

Contrary to an earlier interpretation by Johnson (1973), our observations strongly suggest the formation of this synform to be contemporaneous with the mylonites related to the backthrusting event. The progressive reorientation of these fold

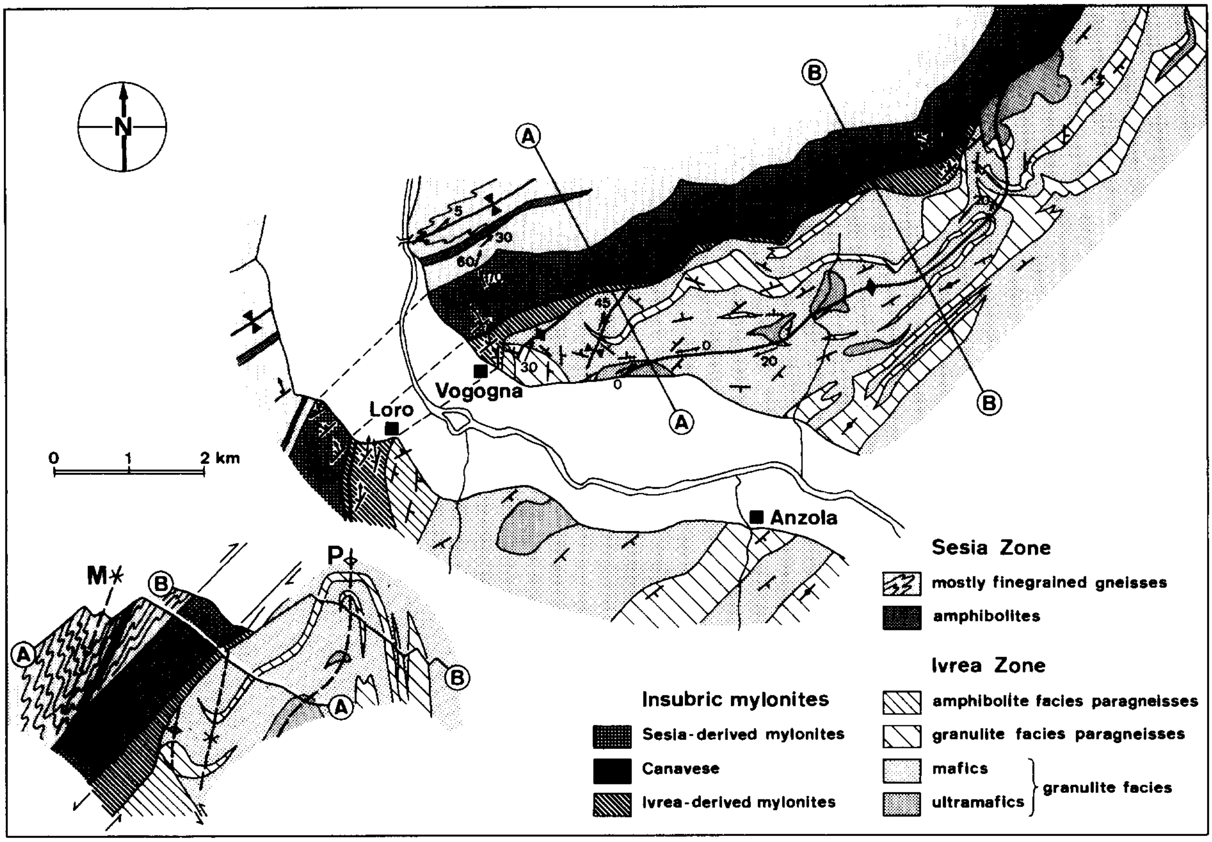

Fig. 5. Detailed map and cross section of the area near the Insubric Line in the Valle d'Ossola. *P*—Proman antiform; *M*—Masone synform.

axes and the absence of overprinting relationships indicate an increasing shear strain towards the southeast during the backthrusting event. The contemporaneity of the deformation is evidenced by the newly formed minerals found both in the mylonite matrix and in the axial plane cleavage of these folds: green biotite grows in pulled apart white micas and in fractured garnets; phengitic white micas are found in tails around large mica clasts. The increasing amount of retrograde overprint towards the southeast may be a function of increasing strain and/or decreasing temperature in a direction from N to S. A horizontal temperature gradient is to be expected during the emplacement of a relatively hot hangingwall (amphibolite facies grade within the northwest part of the Sesia Zone) over the relatively cool footwall (at most, lower greenschist facies conditions within the northernmost Ivrea Zone during the Alpine orogeny).

The northwestern part of the Sesia Zone is generally characterized by the steeply NW-dipping foliation typical for the Southern Steep Belt (a more appropriate term for the Root Zone proposed by Milnes, 1974), although this schistosity is still deformed by parasitic folds related to the synform described above. The contact with the Monte Rosa Zone further to the north is still part of the NW-dipping Root Zone. It is the spectacular south-facing backfold of the Vanzone antiform (e.g. Milnes et al., 1981) which brings the overturned nappe pile in the south into a recumbant orientation west of the Valle d'Ossola. This relatively open Vanzone antiform tightens in an easterly direction and its axial trace can only be followed with difficulty across the Val d'Ossola (Milnes et al., 1981).

The Vanzone antiform postdates the peak of the mesoalpine (Lepontine) thermal event (Laduron and Merlyn, 1974; Laduron, 1974) and represents the latest large scale structure of the area (Klein, 1978; Milnes et al., 1981). We correlate it with the aforementioned Masone synform within the Sesia Zone. In doing so, we propose that the backfolding, the formation of the Southern Steep Belt and the mylonitization along the Insubric Line are all contemporaneous. The observation of higher metamorphic grades synchronous with this backfolding does not contradict this proposition since horizontal temperature gradients must have prevailed during this backthrusting event. This late Alpine event (we attribute it to the Insubric Phase following Argand, 1916) is characterized by very intensive shearing under greenschist facies conditions within the mylonite belt and by substantial flattening perpendicular to the axial planes of the backfolds which formed during this same shearing but under higher metamorphic conditions.

It is more difficult to assess the regional extent of the late Insubric strike-slip event. Dextral shearing throughout the Alpine cross section has been postulated by Steck (1984). A dextral overprint is very obvious within the highly sheared Monte Rosa Zone in the Valle d'Ossola. In addition to high-tempered dextral shearing, oblique boudinage and folding under low grade conditions (chlorite + quartz in the boudin necks) is observed in the northern margin of the Monte Rosa Zone (stream section in the center of the village of Villadossola). Thus, part of the dextral shearing within the Southern Steep Belt occurred after the peak of the mesoalpine metamorphism and may be assigned to the Insubric phase.

On a large scale the decrease in width of the Sesia and Monte Rosa zones towards the east to a total thickness of just over 2.5 km (Fig. 2) is highly suggestive of such a late dextral overprint. The previously described, eastward tightening of the Vanzone antiform may also be due to this overprint. Furthermore, the curved trace of the Insubric Line necessitates the accommodational strains outside of the mylonite belt during the Insubric strike-slip event.

The ductile movements along the Simplon fault farther to the north (Fig. 2) are geometrically unconnected with the Centovalli Line (Mancktelow, 1985). Based on the radiometric dating of Wagner et al. (1977), Mancktelow constrained these movements to have taken place between 19 and 6 m.y. ago. Thus, the Simplon mylonites are likely to post-date the Insubric backthrusting event.

Southern Alps

The rocks of the Ivrea Zone south of the fabric boundary lack a penetrative alpine overprint. This observation on a micro- and mesoscale may easily lead to the premature conclusion that there is virtually no alpine deformation of the Ivrea Zone. The following observations along the Valle d'Ossola traverse forced us to abandon this view.

The northernmost Ivrea Zone is dominated by a large antiform (Proman antiform, Fig. 5; Schmid, 1967). This antiform refolds all the earlier structures including pre-Alpine high-temperature mylonites. There are no parasitic folds related to this antiform . The earlier foliation is bent in a kink-like manner near the hinge zone and these zones of rather abrupt change in dip are associated with a strong brittle overprint characterized by discrete shearing along a network of slickensided shear planes. All around the fold the foliation planes are slickensided. Measurements on both orientation and sense of movement along the slickensides are compatible with flexural slip folding.

Based on the knowledge about the thermal history of the Ivrea Zone (Hunziker, 1974; Köppel, 1974) these deformations under low temperature conditions must be post-Permian, and an Alpine age is inferred. In the northeast the axial trace of the Proman antiform is cut by the Insubric Line (Fig. 5). Towards the west the same trace bends from a SW–NE strike into an E–W-strike. Thus, the fold is non-cylindrical and no continuation is found south of the Valle d'Ossola. In the west another pair of smaller NE-plunging syn- and antiforms are also truncated by the Insubric Line (Fig. 5). We interpret these structures to have formed during the Insubric backthrusting event and to have been cut off during the strike-slip event.

Both compositional banding and foliation are steeply inclined south of the folds described above

(Schmid, 1967). In a geometric sense, the Southern Steep Belt of the Central Alps extends further into the Ivrea Zone. The strike of the main foliation and associated pre-Alpine isoclinal folds swing from a NNE–SSW-direction in the southwest into an ENE–WSW-strike in the northeast, lending the Ivrea Zone an arcuate shape (Fig. 2). Paleomagnetic data of Heller and Schmid (1974) combined with radiometric ages indicate that this bending is post-Variscan. We propose that this change of orientation resulted from large scale drag during the Insubric strike-slip event. In the following chapter we will discuss additional Alpine rotations of the Ivrea structures around a subhorizontal axis, i.e. rotations associated with the backthrusting event.

The deformation along the Pogallo Line

Between the Valle d'Ossola and the eastern side of the Valle Pogallo to the northeast, the contact between the Ivrea Zone and the Strona–Ceneri Zone is tectonic (Boriani and Sacchi, 1973). This tectonic contact is expressed morphologically by the Pogallo Line, a steeply NW-dipping, variably thick band of ductile and subordinate brittle tectonites (Fig. 2). This same contact appears gradational further to the northeast, towards the Lago Maggiore. South of the Valle d'Ossola the Pogallo Line assumes a N–S trend (Fig. 2; Boriani and Sacchi, 1973).

Northeast of the Valle d'Ossola the Pogallo Line juxtaposes basement rocks of contrasting

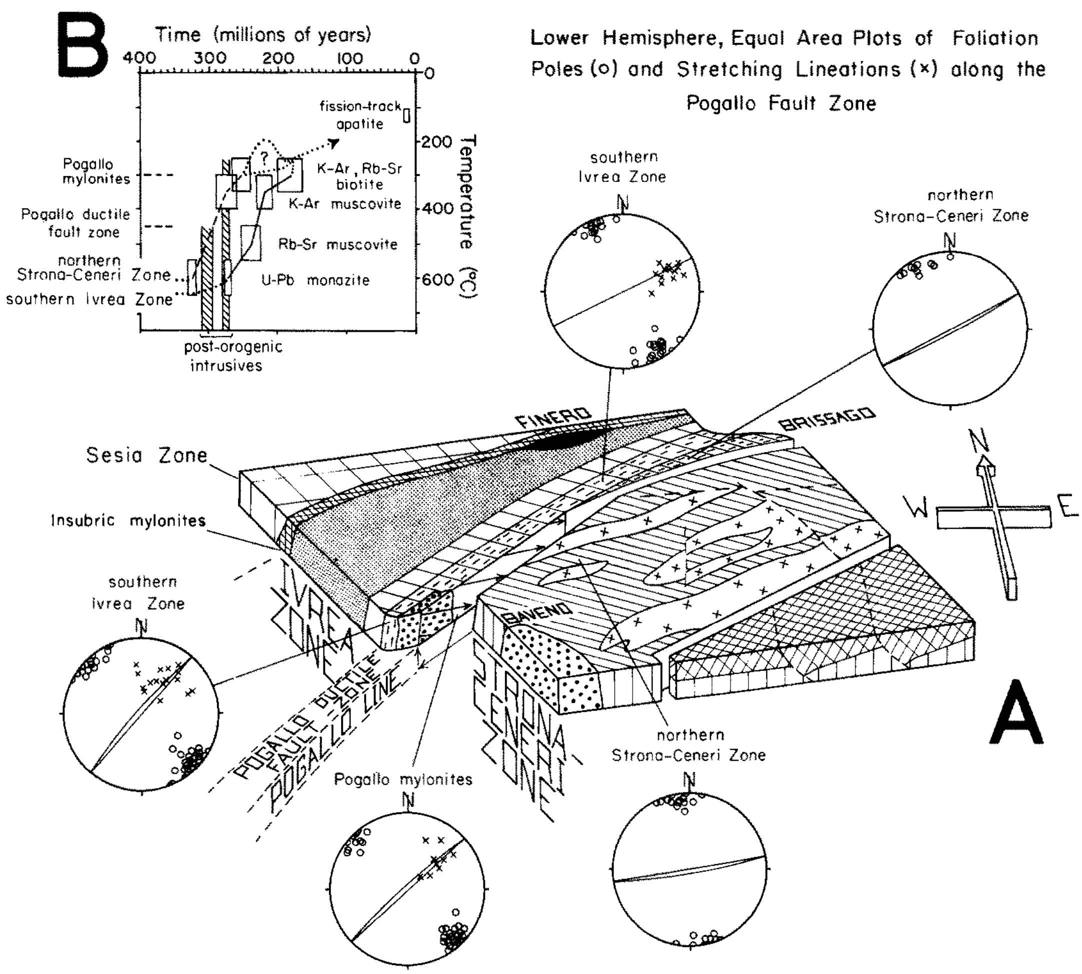

Fig. 6. Schematic block diagram of structural relations in the Southern Alpine basement section of the area studied. The post-Variscan time–temperature curves for the Ivrea and Strona–Ceneri zones are constructed from the radiometric dates in the literature (Mc Dowell and Schmid, 1968; McDowell, 1970; Hunziker, 1974; Köppel, 1974; Köppel and Grünenfelder, 1978/79).

lithology and tectonometamorphic history. The southernmost Ivrea Zone consists of biotite-rich paragneisses intercalated with pegmatites and amphibolite gneisses. The Strona–Ceneri Zone contains ortho- and paragneisses which were intruded by Permo-Carboniferous granites to diorites. While both the southern part of the Ivrea zone and the Strona–Ceneri Zone attained peak conditions of the middle amphibolite facies during the Paleozoic, isotopic mineral ages indicate that the two zones have undergone separate cooling histories (Fig. 6b). Biotite ages generally jump from the late Variscan to the Liassic in the vicinity of the Pogallo Line (McDowell, 1970; Hunziker, 1974).

Structural development and metamorphic conditions

The mylonitic foliation of the Pogallo Line is subparallel to the foliation in the southern Ivrea Zone but oblique to the regional trend of the Strona–Ceneri foliation (Figs. 2 and 6). This marked structural discordance is related to contrasting structural and microfabric developments between the two zones.

Gneisses and schistosity-concordant (pre-Pogallo) mylonites of the Strona–Ceneri Zone were folded and subsequently annealed under middle amphibolite facies conditions (e.g. figs. 7 and 8 in Boriani, 1970). They occur as xenoliths within intrusives of the Baveno suite, indicating that deformation and anneal of the Strona–Ceneri Zone predate Permo-Carboniferous magmatism. The activity along the Pogallo Line, however, postdates this magmatism.

Ductile deformation under amphibolite to greenschist facies conditions related to the Pogallo event has affected the southernmost rim of the Ivrea Zone. These deformational fabrics overprint and, therefore, postdate the tempered fabrics associated with the Paleozoic, middle amphibolite facies metamorphism of the southern part of the Ivrea Zone. In general, two microfabric trends are observed within the Ivrea Zone adjacent to the Pogallo Line: (1) The deformational and retrograde Pogallo overprint increases towards the Pogallo Line normal to the strike, i.e. from northwest to southeast; (2) parallel to the strike of the zone the overprinting fabrics become progressively higher tempered in a direction towards the northeast. Further to the northeast, towards the Lago Maggiore, the Pogallo overprint becomes diffuse and the northern Strona–Ceneri Zone contains deformed microfabrics similar to those found within the tectonized Ivrea paragneisses to the north.

The microfabrics trend across strike, i.e. towards the Pogallo Line, is interpreted as a time and strain-dependent sequence of structural development within a 1-km wide ductile shear zone affecting the southern Ivrea zone (Handy, 1985). Deformation within the main body of this shear zone occurred under lower amphibolite facies conditions. The greenschist facies mylonites of the Pogallo Line mark the southeastern contact of this same shear zone with that part of the Strona–Ceneri Zone which is unaffected by the Pogallo event.

The higher temperature fabrics in the northeast as well as the northeastward disappearance of the sharp structural discordance between the Ivrea and Strona–Ceneri zones suggests that deeper portions of this fault zone are exposed in the northeast than in the southwest. Ostensibly, the pronounced microstructural and metamorphic discontinuity in the Valle d'Ossola region wanes towards the northeast as this ductile shear zone broadens to affect both the Ivrea and Strona–Ceneri blocks.

Kinematics of movement

An oblique sinistral sense of movement was determined from oriented thin sections for both the mylonites along the Pogallo Line and the tectonites within the southern margin of the Ivrea Zone. That is, in present-day coordinates, the Ivrea block was uplifted and displaced to the southwest along the subvertical Pogallo shear zone relative to the Strona–Ceneri block (see block diagram, Fig. 6).

There are reasons to believe that the Pogallo shear zone did not form in its present subvertical orientation: (1) Mafic and ultramafic lithologies metamorphosed during the Paleozoic under granulite facies conditions predominate in the northwest part of the Ivrea Zone while paragneisses prevalent in the southeast part underwent mid- to upper amphibolite facies metamorphism. Boriani et al. (1977) report a similar southeast to northwest trend of increasing metamorphic grade across the Strona–Ceneri Zone. Thus, the basement section containing the Pogallo Line represents a tilted section through the lower to intermediate Southern Alpine crust, with progressively deeper structural levels exposed towards the northwest. (2) The folding of the Ivrea foliation about the Alpine age Proman antiform indicates that prior to folding, the foliation was not in its present subvertical orientation. (3) The "birdhead" configuration of the mantle–crust boundary (Berckhemer, 1968; Fig. 10) features a steeply inclined Moho in the Ivrea Zone region.

We chose a NE–SW oriented rotation axis in order to back-rotate the Southern Alpine crust by 60° in a counterclockwise sense as viewed towards the northeast (Fig 7). The choice of the sense and amount of rotation is compatible with the minimum rotation-angle required to bring the northwest parts of the basement complex to their originally deeper structural levels. The orientation of the rotation axis was chosen to be roughly parallel to the average trend of the schistosity, compositional banding and metamorphic isograds within the Ivrea Zone. This rotation axis also

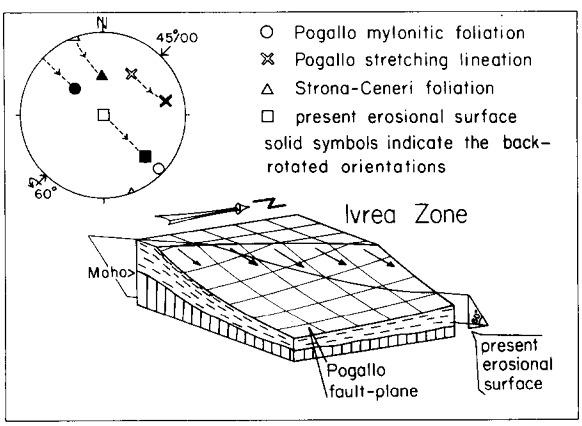

Fig. 7. Block diagram of the restored crustal section. Rotations of the fabric elements by 60° about a 45°/00 axis is depicted. Arrows on block diagram show the inferred transport direction of the Strona–Ceneri block with respect to the Ivrea block. The Strona–Ceneri block has been removed to reveal the Pogallo fault plane.

coincides with the mean orientation of the fold axis of the Proman antiform. At least part of this rotation is interpreted to be related to the Alpine age Insubric backfolding event. It should be noted, however, that both the amount of rotation and the orientation of the rotation axis are not well constrained.

After this rotation, the foliation in the Pogallo tectonites dips shallowly to the east-southeast while the stretching lineations plunge to the east-northeast. The Strona–Ceneri foliation and compositional banding assume a moderately south-dipping orientation. In this reconstruction (see block diagram, Fig. 7), the Pogallo Line becomes a low angle extensional fault separating the Ivrea Zone (footwall) from the overlying Strona–Ceneri Zone (hanging wall) as already proposed by Hodges and Fountain (1984). This kinematic framework is compatible with the previously described structural and metamorphic trends across and along strike: A strong greenschist facies overprint associated with mylonitization and a clear structural discordance between mylonites and Strona–Ceneri Zone characterizes the cooler southeastern margin of this Pogallo shear zone. Deformation within the northwestern part of this shear zone and within the entire shear zone further to the northeast occurred at higher temperatures as the warmer Ivrea block moved up and to the southwest. The fault trace observed today does not reflect the true fault-geometry, but some slice oblique to the transport direction. The curvilinear trend of the Pogallo shear zone seen on a large scale map (Fig. 2) is due partly to Alpine bending of the Ivrea Zone, most probably during the Insubric strike-slip event. In addition, a primary listric geometry may be inferred from the aforementioned distribution of microfabrics and Liassic biotite ages within the northern Strona–Ceneri Zone in the Lago Maggiore region.

The timing of the Pogallo deformation

The Pogallo deformation deforms, and, thus, postdates Permo-Carboniferous (295–310 m.y. U–Pb monazite, Köppel and Grünenfelder, 1978/79) dioritic agmatites in the lower Valle d'Ossola. In addition, the southern branch of the

Pogallo Line, the Pogallo–Lake Orta fault, displaces an amphibolite horizon and granites of the Permian Baveno suite according to Boriani and Sacchi (1973). Temperature–time curves constructed from radiometric mineral ages for the southern Ivrea and northern Strona–Ceneri zones in the Valle d'Ossola region indicate that the two zones followed independent post-Variscan cooling paths (Fig. 6). A comparison of these curves with a temperature estimate of about 450°C for the ductile tectonites in the southernmost Ivrea Zone suggests that the kilometer-wide Pogallo shear zone may have been active as early as 230 m.y., during the Triassic. The occurrence of brittle tectonites within the greenschist facies mylonites along the Pogallo Line indicates that the final stages of deformation occurred at, most probably below, the 300°C isotherm (Sibson, 1977). At this temperature, the isotopic biotite system closed in the Ivrea Zone approximately 180 m.y. ago.

Discussion of the main results in the framework of the tectonic evolution of the Alps

The emplacement of the Ivrea Zone to shallow crustal levels as a result of crustal thinning

The interpretation of the Pogallo Line as a NNE–SSW-striking low angle extensional fault fits well into the paleogeographical evolution of the Southern Alps as a passive continental margin during the Jurassic. The cooling history of the Southern Alpine basement indicates that crustal attenuation initiated sometime during the Triassic. However, substantial E–W directed stretching, associated with differential subsidence started rather abruptly during the Early Jurassic (Bernoulli, 1964). In Fig. 8 we interpreted the findings of Kälin and Trümpy (1977) in terms of rotational planar faults (Wernicke and Burchfiel, 1982) which become listric at depth as they diffuse into a broader zone of cataclasites. The stretch recorded from the adopted fault geometry corresponds to 25% extension in the case of the two faults west of the Mt. Nudo and Generoso basins (Fig. 8). Assuming plane strain conditions and an original thickness of 30 km for the crust this would result in a final crustal thickness of 24 km.

Since the sedimentary cover further to the west is only fragmentarily preserved, no direct estimates of stretching can be made for the Southern Alpine crust west of Lago Maggiore. However, the cooling history of the Ivrea zone representing the deepest portions of the crust which carried these sediments suggests a substantial stretch. Temperatures of about 300°C at 180 m.y. ago for the Ivrea Zone (Hunziker, 1974), i.e. the lowermost crust, suggest that the entire crust was thinned down to around 10 km or less in case of a large geothermal gradient (Laubscher and Bernoulli, 1982). In Fig.

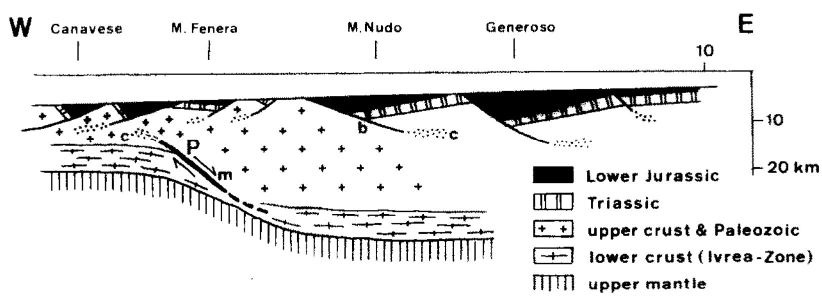

Fig. 8. Reconstruction of an E–W-section through the crust of the passive continental margin formed during the lower Jurassic within the Southern Alps (trace *AA* in Fig. 1). Crustal thicknesses are reconstructed on the basis of the thickness of Liassic sediments after Kälin and Trümpy (1977), assuming a geometry of rotational planar faults and an original thickness of the continental crust of 30 km in case of the area east of the Pogallo Line. The thickness of the continental crust further to the west is based on the thermal history of the Ivrea Zone, the fault geometry adopted for the Canavese sediments is that proposed by Bally et al. (1981), and compatible with the amount of crustal thinning inferred from the thermal history of the Ivrea Zone. According to this reconstruction the deep crustal Pogallo fault and the faults affecting the sediments above the Pogallo fault operated in opposite and conjugate senses. This leads to the hypothesis that there is an intermediate crustal level with diffuse cataclastic flow separating brittle near-surface faults from a deep crustal fault such as the Pogallo Line. *P*—Pogallo Line; *b*—brittle extensional faults; *c*—diffuse zone of cataclasis; *m*—mylonites.

8 we sketched the Pogallo fault as a deep crustal ductile fault zone. The mylonites grade into more diffuse crystal plastic deformation downwards and into a wider zone of cataclasites upwards. Near-surface brittle faulting and lower crustal ductile faulting are interpreted to be separated by a zone of cataclasis at about 4–8 km depth. According to the interpretation given in Fig. 8, the Pogallo fault indicates a rather rapid increase in the amount of stretching towards the west, resulting in an east-southeast sloping Moho discontinuity.

The presence of a large volume of mantle material at a shallow depth before the onset of orogenesis has severe consequences. The rheological behaviour of olivine is such that ductile deformation by intracrystalline plasticity would lead to unrealistically high flow stresses at temperatures of less than 600°C and at a geological strain rate (Post, 1977; Schmid, 1982). Since the crust of the Southern Alps remained relatively unaffected by subduction and orogenesis, that part of the volume of mantle material which forms the geophysical Ivrea body must have acted as a rigid stress guide during orogenesis.

The following results, emerging from the study of the Insubric mylonites, may also be interpreted in terms of pre-Alpine crustal thinning: (1) the recognition of a northernmost rim of amphibolite facies Ivrea rocks, that were mylonitized during the Insubric Phase, and (2) the presence of Canavese metasediments within the Insubric mylonites, representing the cover of the Southern Alps. Both these lithologies represent shallow levels of the Southern Alpine crust which were juxtaposed with deep crustal material further to the south, i.e. the granulite facies Ivrea Zone before the onset of backthrusting. This juxtaposition is situated southeast of the Insubric Line and it may well be the result of movements along another extensional fault which affected the northwestern rim of the Ivrea Zone, synchroneous with the movements along the Pogallo Line. Alternatively, this juxtaposition may be related to the tectonic processes leading to the density inversion along the southeast sloping plane at the base of the Ivrea body discussed in the following chapter (Fig. 9).

The main compressional phases during the Cretaceous and the Eocene

So far we have discussed evidence for a prealpine emplacement of the Ivrea rocks in a shal-

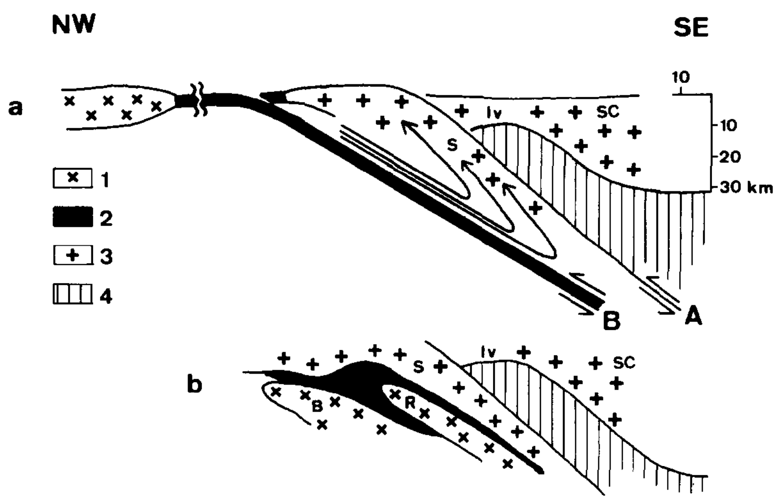

Fig. 9. Early eo-Alpine subduction (*A*) led to the density inversion at the base of the Ivrea geophysical body. Later eo-Alpine underplating along the main suture zone of the Alps (*B*) was associated with the exposure of the Sesia high pressure rocks due to a complex flow pattern indicated by arrows and adopted from Cowan and Silling (1978). b. Reconstruction of the final collisional stage before the onset of the Insubric phase. Legend: *1* = Crust of the northern continental margin (*B*—Bernhard nappe; *R*—Mt. Rosa nappe); *2* = oceanic crust of the Piemontese trough; *3* = southern continental margin (*S*—Sesia Zone; *Iv*—Ivrea Zone; *SC*—Strona-Ceneri Zone); *4* = upper mantle material, defining the Ivrea geophysical anomaly below the Ivrea Zone.

lower crustal level. For a better understanding of the evolution of the Ivrea body and the effects of the Insubric events, we need to briefly consider the major events of compressional tectonics in the Alps: the eo-Alpine and meso-Alpine events (Trümpy, 1973).

Parts of the Sesia Zone southwest of our area of investigation (Fig. 1) underwent high pressure–low temperature metamorphism during the collisional eo-Alpine event (Compagnoni et al., 1977). The Sesia Zone represents a slice of continental crust belonging to the Austroalpine unit. This slice was in turn part of the Adriatic promontory or micro-continent together with the Southern Alpine crust. The eoalpine high pressure–low temperature metamorphism is found in the Sesia Zone (sensu stricto) and in the southeast rim of the 2. zona dioritica–kinzigitica (2.KD in Fig. 1). The 2.KD as part of the Sesia Zone shows a close lithological affinity with the Ivrea Zone and underwent the same thermal evolution until Cretaceous time. Thus, like the Ivrea Zone, the 2.KD represents deeper continental crust, but was affected by deformation and metamorphism during the eo-Alpine collisional event.

We propose that the density inversion at the base of the geophysical Ivrea body marks the site of early eoalpine subduction of the Sesia Zone (Fig. 9a). The Sesia Zone represents the former continuation of the stretched continental margin to the northwest of the present-day Ivrea Zone. Thus, the present configuration of the Ivrea body is essentially the result of Liassic crustal thinning followed by Cretaceous underplating. This interpretation contrasts with the view that the Ivrea body was obducted during the Insubric phase (Laubscher, 1970; Laubscher and Bernoulli, 1982). The subduction of the Sesia Zone was followed by further eo-Alpine subduction of oceanic crust along the major suture of the Alps, i.e. the remnants of the Piemontese trough (Fig. 9a). The Ivrea body may have acted as a rigid buttress during continued subduction west of the Sesia Zone. Thus, models of complex flow patterns within the accretionary wedge such as "corner flow" (Cowan and Silling, 1978) are very attractive as possible modes of exposure of the high pressure terranes of the Sesia Zone.

No manifestations of subduction were found within the Insubric mylonites of the investigated area. The kinematics of this eoalpine phase call for a SE-dipping fault. This fault cannot be identical with the Insubric Line southwest of our area of investigation which marks the southern boundary of the high pressure metamorphism of the Sesia Zone.

In Fig. 9b the effects of the Insubric backfolding and backthrusting event have been removed to reveal the situation after the mesoalpine phase. Continued SE-directed subduction of the northern continental margin along the Piemontese suture zone lead to a secondary imbrication (or isoclinal

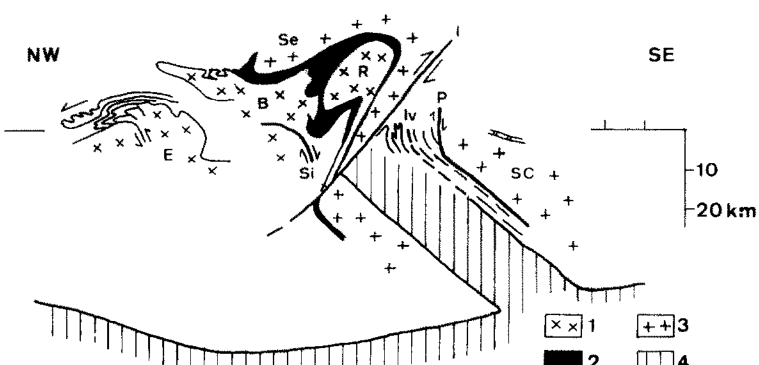

Fig. 10. Present-day cross section through the Alps (trace BB in Fig. 1). An attempt was made to integrate the shape of the Ivrea geophysical anomaly (gravity model of Kissling, 1980) with the surface geology. Legend: 1 = crust of the northern continental margin (*E*—external massifs; *B*—Bernhard nappe; *R*—Monte Rosa nappe); *2* = oceanic crust and sediments of the former Piemontese trough; *3* = southern continental margin (*Se*—Sesia–Dent Blanche nappe; *Iv*—Ivrea Zone; *SC*—Strona–Ceneri Zone); 4 = Upper mantle. *I*-Insubric Line; *P*—Pogallo Line; *Si*—Simplon Line.

folding) of the Mt. Rosa and Bernhard nappes (post-f_1-situation of Klein, 1978). The Sesia- and Dent Blanche nappes override the northern continental margin and the remnants of the Piemontese ocean.

The oceanic suture dips to the southeast and must continue below the Ivrea anomaly to a considerable depth (Fig. 10). The Insubric Line is definitely not the site of a suture in the sense of Dewey and Bird (1970) but a younger intracontinental fault zone.

The Insubric phase

We have shown that both the earlier backthrusting and the later strike-slip movements are not restricted to the Insubric mylonite belt but affect tectonic units away from the Insubric Line. Following Argand (1916), we use the term Insubric phase for these post-Eocene deformations which substantially modified the Alpine edifice (Fig. 10).

A clear subdivision of the Insubric phase into those two separate events may only hold for the Insubric mylonites within the studied area (Fig. 2). Both the magnitude and the orientation of the movement vector related to the backthrusting event probably did not remain constant along strike. The concentric shape of the isograds associated with Lepontine metamorphism (Niggli and Zwart, 1973) indicates that the amount of vertical displacement of the Central Alps diminishes from a maximum around Locarno both to the east and the southwest. In case of the later strike-slip event, the movement vector changes its orientation even within the area of investigation (Fig. 3). It produces the rather unexpected transformation of a dextral strike-slip motion found near Locarno into a strike-slip motion which is combined with a normal fault component in the Valle d'Ossola. However, this complex movement pattern during this second Insubric event may be of local significance only and due to strain compatibility problems arising from flow around the rigid Ivrea body.

Considering the Insubric overprint within the Central and Southern Alps on a larger scale, it is more appropriate to characterize both of these events as resulting from a continuous transpressive strike-slip motion along the Tonale Line with an increasing component of backthrusting as the Insubric Line swings into a NE–SW-strike (Canavese Line). The arcuate shape of the Insubric Line is interpreted to be predetermined by the existence of the Ivrea body which acted as a rigid buttress during the Insubric phase. The Insubric Line follows the NNE–SSW-strike of this anomaly southwest of the area investigated (Fig. 1) and starts to partly transsect and partly bend the Ivrea structures as it swings into an E–W-strike (Fig. 2). The northern boundary of the Ivrea body is identical with the projection of the Insubric Line down to a depth of at least 10 km (Kissling, 1980). This cut-off possibly follows an earlier E–W-trending zone of weakness related to a Jurassic transform fault since no continuation of the Ivrea geophysical anomaly is found north of the Insubric Line.

The arcuate shape of the Insubric Line is related to the arc of the Western Alps in general. The locatin of the arc of the Western Alps is predetermined by the paleogeographic configuration during the Mesozoic. According to recent paleogeographic reconstructions (Weissert and Bernoulli, 1985) the Piemontese ocean strikes aproximately N–S relative to present-day coordinates, i.e. parallel to the Ivrea body and the Liassic basins within the Southern Alps. Its northern continuation is offset by E–W striking transform faults.

Unfortunately, we are unable to ascertain the magnitude of dextral movements of the Central Alps with respect to the Adriatic microplate. It is clear, however, that a large component of the 300 km postulated by Laubscher (1971) has been accommodated by strains outside of the mylonite belt.

Several reasons have been proposed to explain the major change in tectonic transport direction associated with backfolding (Argand, 1916; Roeder, 1972; Laubscher, 1983). When considering possible mechanisms for the backfolding during the Insubric phase, it is important to realize that the Insubric backfolding and backthrusting event started at around 23–30 m.y. ago, i.e. contemporaneously with major components of folding and/or thrusting of the Helvetic units to the north

(Trümpy, 1969; Schmid, 1975; Milnes and Pfiffner, 1980). This indicates that subduction and/or crustal thickening cannot keep pace with the imposed rate of plate convergence. Consequently, the mobile crust of the Central Alps seeks to escape upwards and laterally onto the foreland, thereby inducing N-directed thrusting within the Helvetic nappes and S-vergent transport within large portions of the Central and Southern Alps (Fig. 10).

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