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Large-scale folding in the upper part of the Ivrea-Verbano zone, NW Italy

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Abstract

New geological mapping has led to a new interpretation of the large-scale superimposed folding in the upper part of the Ivrea-Verbano zone, Italian Alps. The region is widely held to represent an upended section through lower continental crust of northern Italy. The dominant fold structure, extending some 40 km along strike, is the Massone tight to isoclinal antiform, with a hinge line strongly curved through 115°. This folds pre-existing large-scale folds that formed during regional migmatization, probably during the Hercynian orogeny, to form a type-2 interference geometry. The region then suffered post-orogenic mafic magmatic underplating and other magmatism, accompanied by crustal stretching, with contact metamorphism and migmatization causing the imposition of the final pattern of metamorphic isograds. The Ivrea-Verbano zone was brought into contact with the overlying metamorphic rocks of the Serie dei Laghi on a major shear zone. Sub-solidus stretching continued though displacements on low-angle, high-temperature shear zones. Most of the Ivrea-Verbano zone was finally tilted to the vertical and emplaced into its present position after the Mesozoic era and probably during Alpine orogenesis, forming the vertical limb of a crustal-scale double kink.

Keywords: Ivrea-Verbano; Lower crustal structure; Superimposed folding; Western Alps

1. Introduction

The Ivrea-Verbano (I-V) zone provides one of the most spectacular sections through rocks of lower crustal provenance upended and brought passively to the surface during Alpine orogenesis. The region outcrops in N.W. Italy and S. Switzerland, in the inner arc of the Western Alps (Fig. 1). On account of its relative accessibility and because it represents an almost complete, post-Hercynian crustal section, it has been subjected to a substantial amount of structural, petrological, geochemical and petrophysical study by geoscientists during the past few decades (e.g. Schmid, 1967; Bertolani, 1969; Zingg, 1980; Rivalenti et al., 1981; Sills and Tarney, 1984; Bürgi and Klötzli, 1990; Handy and Zingg, 1991; Quick et al., 1992, 1994, 1995; Schnetger, 1994; Henk et al., 1997; Barboza et al., 1999; Snoke et al., 1999; Barboza and Bergantz, 2000). Together with the metamorphic and igneous rocks of the adjacent Serie dei Laghi (SdL), that collectively form the Massiccio dei Laghi (Boriani et al., 1990a, 1990b), the rocks of the region record Palaeozoic accretion, metamorphic and magmatic processes, the effects of the Hercynian orogeny, post-orogenic magmatic underplating and associated lithospheric stretching and thinning, Mesozoic extension and effects associated with the position of the region in Alpine tectonism (e.g. Handy et al., 1999). The assembly of the rocks in their relative stacking order close to what we see today probably dates from Permian time, so that it is possible to construct a crustal cross-section that might be taken as a model for a magmatically underplated and extended crustal section (e.g. Rutter et al., 1993; Schnetger, 1994; Quick et al., 1994; Henk et al., 1997). Rutter

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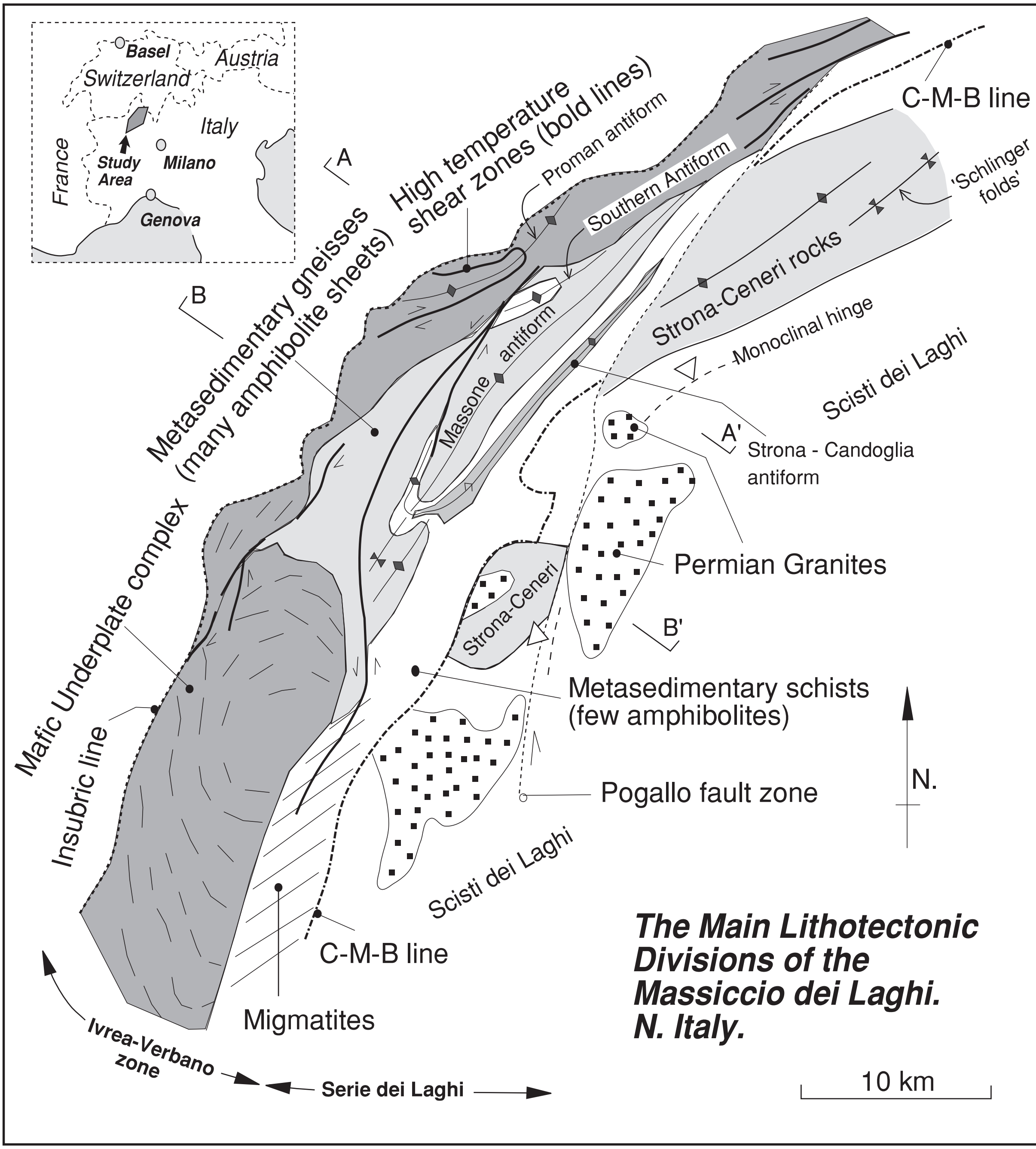

Fig. 1. Sketch map showing the main lithotectonic divisions of the Massiccio dei Laghi. A–A′ and B–B′ indicate the positions of the Valle d'Ossola and Val Strona sections through the region shown in Figs. 9 and 3, respectively. C-M-B line = the Cossato-Mergozzo-Brissago line, the tectonic contact between the Ivrea-Verbano and Serie dei Laghi terrains. Inset map shows the location of the Massicio dei Laghi in northern Italy.

et al. (1999) and Khazanehdari et al. (2000) constructed a forward reflection seismic model based on this section as an aid to the interpretation of contemporary reflection seismic profiles of the lower continental crust.

Previous work on the structure of the I-V zone has focused on geometry of the rocks forming the structurally lower igneous units and higher-grade (granulite and upper amphibolite facies) metamorphic rocks, in which schistosity defined by oriented micas is poorly developed or absent (Schmid, 1967; Zingg, 1980; Brodie and Rutter, 1987; Sinigoi et al., 1991; Quick et al., 1992, 1994, 1995, 2003; Rutter et al., 1993; Snoke et al., 1999). The present study presents new geological mapping in the more schistose rocks of the structurally higher part of the complex, that outcrop adjacent to the SdL lying to the south-east. This has revealed the occurrence of large-scale superposed folds forming a complex interference pattern, that now allow a more complete tectonostratigraphic history of the region to be assembled.

2. Geological setting and summary of previous work

The principal geologic units of the region are shown in Fig. 1. The Massiccio dei Laghi is composed almost entirely of pre-Mesozoic rocks, bounded to the north-west and separated from the Alpine metamorphic belt by the Insubric line. The latter comprises a thick belt of mylonitic rocks dipping about 45° to the northwest (Schmid et al., 1987). Alpine metamorphism has had only a minimal effect on the rocks of the Massiccio dei Laghi, principally in the 4 or 5 km adjacent to the Insubric shear zone, and is manifested particularly as retrograde (greenschist facies) metamorphism in association with folding and fault zones that sometimes display evidence of frictional melting. The Massif itself comprises the I-V zone, lying to the north and west, separated from the SdL, lying to the south and east, by the C-M-B (Cossato-Mergozzo-Brissago) tectonic line (Boriani et al., 1990a, 1990b). The latter is a major vertical tectonic discontinuity of Permian age (Boriani and Villa, 1997; Mulch et al., 2002). The SdL is subdivided into the Strona-Ceneri zone, a varied group of psammitic and some pelitic schists and gneisses, that are separated from a monotonous metapelitic unit, the Scisti dei Laghi, by a prominent amphibolite horizon (Figs. 1 and 2) (Boriani et al., 1990a, 1990b). The SdL is intruded by a suite of Permian granites (Graniti dei Laghi) (Fig. 1) that are completely untectonized and lie close to their original intrusive

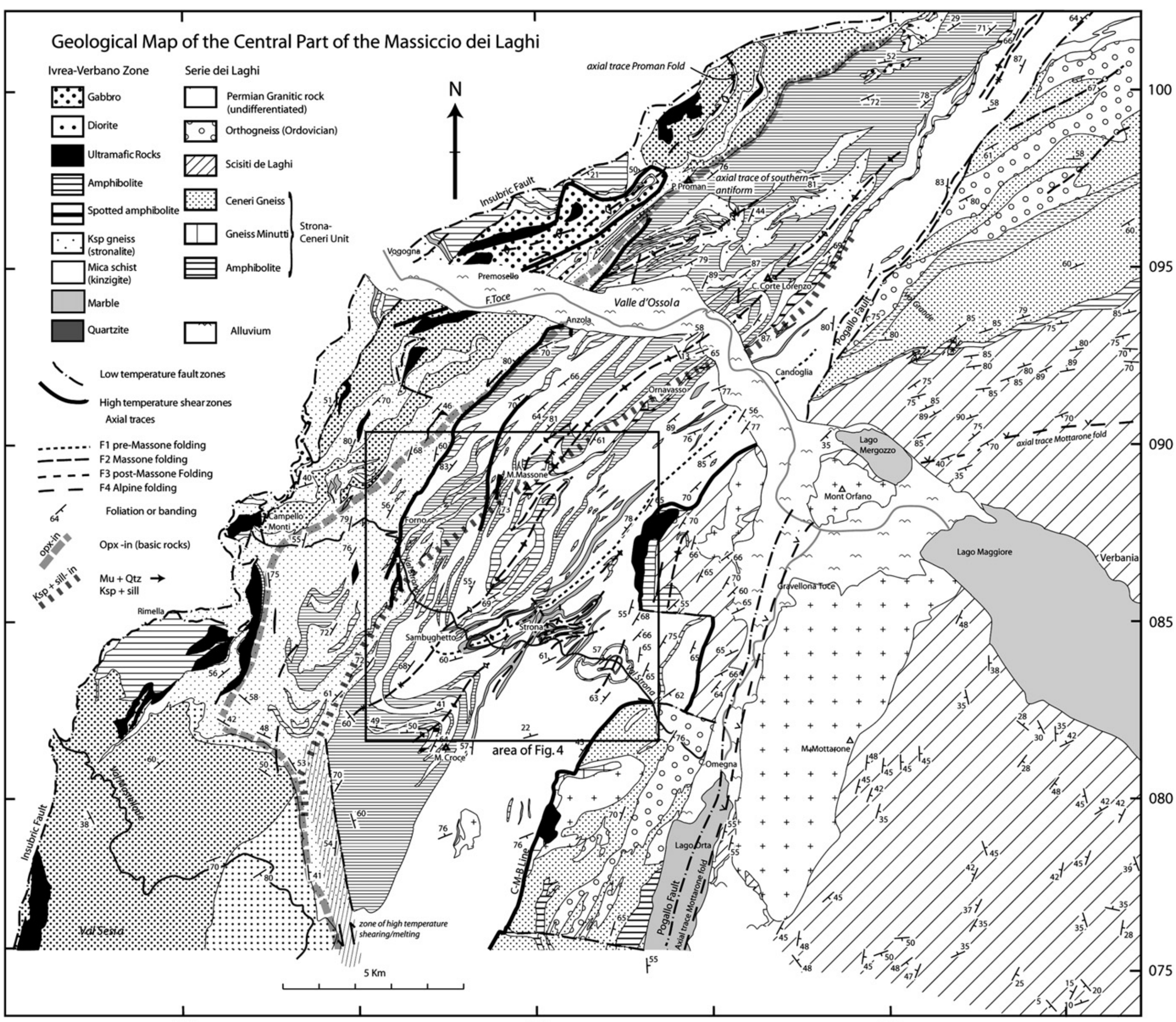

Fig. 2. Geological map of the central part of the I-V zone and the adjacent Serie dei Laghi. The central part of the map represents the results of new geological mapping, the north and western part is drawn from Rutter et al. (1993) and Evans (1995), the north from Schmid (1967), to the south from Snoke et al. (1999) and the Serie dei Laghi from the work of Boriani and Burlini (1994). In the south-east of the map note the change in dip of the main foliation on either side of the Mottarone granite pluton, from gently undulating in the south-east to near vertical to the north-west, in common with the near-vertical attitude of most of the rocks of the I-V zone. The positions shown of the main metamorphic isograds are based on Zingg (1980). Grid numbers correspond to the Swiss National (1963) Grid.

attitudes, as evidenced in the Mottarone pluton by the occurrence of large, oriented miarolitic cavities and petrographically distinct granitic units in the roof region (review by Boriani and Giobbi, 2004).

The metamorphic foliation and primary banding in the I-V zone lying west of the Lago Maggiore (Fig. 2) are generally steeply dipping and trend NE–SW, parallel to the Insubric line. The highest-grade (granulite facies), and by inference the originally deepest buried, metamorphic rocks of the region outcrop in the NW part of the Ivrea-Verbano zone. This is consistent with pressure estimates made from metamorphic mineral assemblages (Schmid and Wood, 1976; Zingg et al., 1990; Handy and Zingg, 1991; Henk et al., 1997). Fig. 3 shows profiles of synmetamorphic pressures and temperatures (after Henk et al., 1997; T. Hoyle, unpublished data, 1999, this laboratory) in the central part of the region. The presently implied steepness of the geobaric gradient across the (now vertical) I-V zone is probably attributable to the substantial stretching and thinning the region underwent during and after the Permian igneous activity (e.g. Brodie and Rutter, 1987; Handy and Zingg, 1991; Brodie, 1995), whereas the (older) constant pressures in the SdL correspond to a tract where the average dip of layering and schistosity is sub-horizontal or gently undulating. Extrapolation of the geobaric trend in the I-V zone indicates a pressure on the order of 200 MPa in the vicinity of the C-M-B line, which is consistent with the hypabyssal depth of emplacement of the SdL granites implied by the presence of miarolitic cavities and by the presence of retrogressive andalusite in the kinzigites S of Candoglia (Fig. 2).

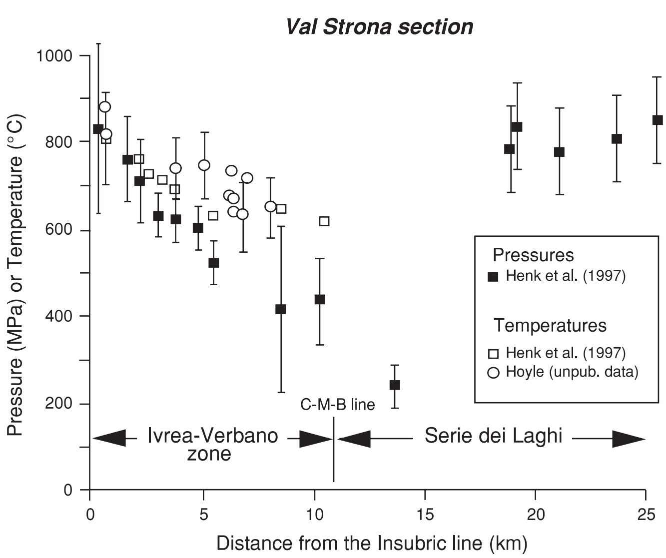

Fig. 3. Summary diagram showing paleotemperature and pressure estimates along the Val Strona transect (B–B′ on Fig. 1). Note the marked contrast between paleopressures in the Serie dei Laghi and the Ivrea-Verbano zone, and the way in which both pressure and temperature increase to the NW (inferred greater depths) in the Ivrea-Verbano zone. The steepness of the geobaric gradient is attributable to the Permian stretching and thinning the region has undergone. Unpublished thermometry data by Hoyle used the garnet–biotite geothermometer in pelites, and garnet–clinopyroxene (Ellis and Green, 1979) and amphibole–plagioclase (Blundy and Holland, 1990) in metabasic rocks.

The high temperature–high pressure part of the I-V zone also hosts a large, basic intrusive complex of Permian age (the ‘‘Mafic formation’’, Rivalenti et al., 1981; Zingg, 1983; Quick et al., 2003) in which primary igneous layering is well preserved. These observations led to the conclusion by most geologists that the northwestern part of the Massicio dei Laghi was tilted to the vertical after Permian time, probably as a result of Alpine tectonism. On the other hand, Boriani and Giobbi (2004) interpret the geology of the contact region between the I-V zone and the SdL in terms of that contact lying in a vertical attitude during the Permian igneous activity, with the rocks of the I-V zone being brought into contact with the SdL along a vertical trans-tensional shear zone (the C-M-B line) containing mylonitic rocks and which was decorated by mafic and granitic igneous rocks intruded contemporaneously with movement. This divergence of interpretations will be discussed further below.

Immediately west of the Lago Maggiore the attitude of the schistosity and banding changes from the predominantly steep dip of the I-V zone to the NW to a much lesser south-easterly dip on the SE side (Fig. 2). To the east of Lago Maggiore, fault-bounded sedimentary basins contain Permian volcanic and Triassic clastic sedimentary rocks, and early to mid-Jurassic sediments that record the onset of Tethyan rifting, and which lie with gently dipping contacts upon the underlying metamorphic rocks of the SdL (Handy et al., 1999; Boriani and Giobbi, 2004).

The present-day map view of the near-vertical part of the Massiccio dei Laghi to the west of Lago Maggiore therefore corresponds approximately to a cross-section of how the region would have appeared when it was in the lower and middle crust during the late Permian or Triassic period. The effects of Alpine faulting and folding on this part of the section can be easily removed. The rocks of the Massicio dei Laghi are truncated to the south of the area shown on Fig. 1 by another zone of Alpine faulting, the Cremosina line, and the Tertiary cover rocks of the Po-river basin.

2.1. The Ivrea-Verbano zone

The I-V zone (Fig. 1) is dominated in its lower metamorphic grade (south-eastern) part by a thick unit of variably migmatized metapelitic schists (garnet, biotite, plagioclase, quartz, sillimanite; ± muscovite), known in the European literature as the kinzigite formation, that forms a strikingly continuous and uniform tract about 3 or 4 km wide along the entire length of the outcrop of the Ivrea-Verbano zone. As metamorphic grade increases north-westward, the rock texture changes due to progressive replacement of muscovite (plus quartz) and biotite by K-feldspar and garnet (Schmid and Wood, 1976; Zingg, 1980), from schistose to a massively banded migmatitic gneiss, known locally as Stronalite. Locally associated with the kinzigite formation in the central part of the outcrop is a more heterogeneous group of metasediments, comprising marbles, quartzites and less phyllosilicate-rich paragneisses (Fig. 2). The higher-grade (more northwesterly outcropping) kinzigites are interlayered with bands of amphibolite from

1 to 200 m thick that have been interpreted as coeval mafic lavas or intrusives interlayered within an early (Palaeozoic) pelitic accretionary complex represented by the kinzigite formation (Sills and Tarney, 1984). These mafic rocks can be distinguished from younger, Permian intrusive mafic rocks on the basis of their rare-earth element patterns.

Towards the higher-grade (and potentially deeper) side of the I-V zone, increasing numbers and thicknesses of Permian mafic intrusive sheets occur, eventually dominating the outcrop pattern. They are commonly concordant with the lithologic banding in the host metasediments, but occasionally show cross-cutting relationships. These have distinctive rare-earth patterns compared to the older amphibolites interlayered with the kinzigites, but they cannot readily be distinguished in the field. The geology of the southern end of the Ivrea-Verbano zone is dominated by an intrusive layered mafic complex, some 10 km wide and extending along strike for some 40 km (Fig. 1). This 'Mafic formation' (Rivalenti et al., 1981; Zingg, 1983; Quick et al., 2003) is dated radiometrically (Pin, 1986) at about 280–295 Ma (Permian) and displays vertical primary igneous layering on its western side. Here the rocks were held at high temperatures in the sub-solidus regime sufficiently long for granular, metamorphic textures to develop, whereas the originally shallower, eastern side of the complex still displays igneous textures. The Mafic formation and the complex of thinner intrusive sheets extending further northeast along the outcrop represent an excellent example of lower crustal mafic underplating.

At various positions within the I-V zone, but particularly towards the western edge, sheet-form or lensoid ultramafic bodies outcrop. These include peridotites, dunites and pyroxenites. Quick et al. (1995) argue that none of these bodies are connected to a contiguous mass of ultrabasic rocks at depth. Although some of them are clearly of upper mantle origin (e.g. Boudier et al., 1984), they may have become detached and incorporated as tectonic slices into the kinzigite formation during a Palaeozoic accretionary process (Quick et al., 1995). Nevertheless, the proximity of the present outcrop of the I-V zone to the gravity high that represents the dense geophysical 'Ivrea body' at depth (Berkhemer, 1968) suggests that contiguous mantle rocks lie not very far beneath and to the NW of the presently exposed rocks of the I-V zone.

The development of the Permian intrusive complex was accompanied by heterogeneous regional stretching. Virtually every linear feature in the metamorphic rocks (elongation of mineral clusters, orientation of amphibole long axes, minor fold axes, rodding of quartzofeldspathic segregations, synmagmatic boudinage features in the contact migmatites and the intrusive rocks) was stretched in a direction plunging NE at about 30° (Rutter et al., 1993; Quick et al., 1992). Rocks of the NE part of the Ivrea-Verbano zone were most affected, as implied by the total convergence of lineations to a common orientation (Fig. 5), thinning of mappable geological units, and preservation of the apparently steepest geobaric gradient (Henk et al., 1997).

During the post-intrusive cooling history, continued stretching of the crust was accommodated by slip on localized, high-temperature shear zones which share the same regional movement picture as the more pervasive deformation in the earlier, higher temperature part of the history (Brodie and Rutter, 1987). Depressurization of the section is evidenced by the occurrence at the margins of high-temperature shear zones at the base of the crustal section (near the Insubric line) of oriented symplectites (Brodie, 1995), produced by the local breakdown of cpx + gar to opx + plag at intergranular interfaces oriented normal to the stretching direction, across which the interfacial normal stress was smallest. This down-pressure reaction in the granulite facies records the removal of 6–10 km of overburden (according to the assumed degree of non-hydrostatic loading) associated with movement on that shear zone and any contemporaneously active shear zones lying above. Restoring the section to an horizontal orientation of the layered mafic intrusion by rotation about the axial orientation of Alpine folds means that the Permian stretching deformation would have been oriented almost east–west (Rutter et al., 1993).

2.2. The Serie dei Laghi

The Ivrea-Verbano zone is in contact on its south-eastern margin with the Serie dei Laghi (Boriani et al., 1990a) (Figs. 1 and 2). The C-M-B line, which forms the main contact, is a poorly exposed, sub-vertical tract that sometimes displays 'annealed' mylonitic textures, but is often 'decorated' by coeval gabbrodioritic and other intrusive rocks of Permian age (Boriani and Giobbi, 2004) and at least some of the movement appears to have involved local migmatization. The C-M-B line is itself transected at a small angle by a younger mylonitic fault zone, the Pogallo fault, that has been interpreted as having been a low-angle extensional fault of Triassic or Jurassic age (Hodges and Fountain, 1984; Schmid et al., 1987; Zingg et al., 1990). However, it continues the same movement picture of the earlier, high-temperature, post-Mafic formation shear zones (Brodie and Rutter, 1987) that stretched the I-V zone. The rocks of the Serie dei Laghi were probably displaced into contact with the underlying Ivrea-Verbano zone rocks along a gently inclined C-M-B shear zone early in the post-Hercynian stretching event which culminated in the magmatic underplating. The rocks of the C-M-B line do not appear to be affected by any of the main folding events that affected the adjacent Ivrea-Verbano zone or the Serie dei Laghi.

The rocks of the Serie dei Laghi comprise a series of metasedimentary schists and gneisses (Scisti dei Laghi and the Strona-Ceneri unit, Boriani et al., 1990b) with minor amphibolite sheets that are cut by orthogneisses of Ordovician age (Fig. 2). The outcrops of the rocks of the Strona-Ceneri unit (Giobbi et al., 1997; Zurbriggen et al., 1997) comprise Cenerigneiss, Gneiss Minuti, and gneisses including amphibolites and ultramafic rocks that form a distinctive tract (Figs. 1 and 2), now separated into two parts by 14 km of left-lateral displacement on the Pogallo fault. The Strona-Ceneri unit comprises an early isoclinal fold core set in a 'matrix' of Scisti dei Laghi (Bächlin, 1937; Burlini, unpublished data). The SdL also hosts a number of isotropically textured, undeformed granitic intrusions of Permian (275−280 Ma) age (Boriani et al., 1995; Figs. 1 and 2) that range in diameter from 1 km to more than 10 km.

The metamorphic rocks of the SdL are folded at least twice on a range of scales but it is unclear whether any of the folding events can be geometrically directly correlated with folding events in the Ivrea-Verbano zone. All fold structures and their associated schistosities are cut by the Pogallo fault line, and apparently undeformed gabbrodioritic rocks of Permian age cut the C-M-B line also. Thus, it seems likely that the Permian stretching and magmatism come after all folding and foliation-producing events. Earliest folds and associated axial planar penetrative schistosity (S1) trend NE−SW, parallel to the general trend of the Strona-Ceneri unit outcrop. Ordovician orthogneisses and migmatized metasediments contain reoriented xenoliths of foliated rocks, yet the orthogneisses are themselves variably and sometimes intensely foliated. Thus, the foliation in orthogneisses is generally designated S2 (e.g. Borghi, 1989; Zurbriggen et al., 1998). Superposed, large-scale folds are developed that have steeply dipping axial planes (S3), that trend about 15° closer to N−S than the general trend of the Strona-Ceneri zone, and that fold the orthogneisses bodies and their foliation. This episode appears to include the kilometric scale, moderately NE plunging close to tight folds that have been termed ‘schlingenbau’ (Bächlin, 1937), and whose outcrops are traced in map view by the major lithologic units in the Strona-Ceneri zone (Boriani and Burlini, 1994). On the basis of cross-cutting relations between folds and minor intrusives that have been dated radiometrically, the schlingen folds are widely held to have formed during Hercynian igneous and metamorphic activity (Zurbriggen et al., 1997, 1998).

3. New geological mapping

In Figs. 2 and 4 we present the results of new geological mapping in the central and southeastern tract of the I-V zone, between Val Mastallone in the SW and to the NE of Valle d’Ossola, and extending to the SE across the C-M-B line. In Fig. 2 we have attempted to link this with the results of previously published mapping, mainly by Schmid (1967), Rutter et al. (1993), Boriani and Burlini (1994), Evans (1995) and Snoke et al. (1999). Most of the new work was carried out at a scale of 1:10 000, with work at larger scales as

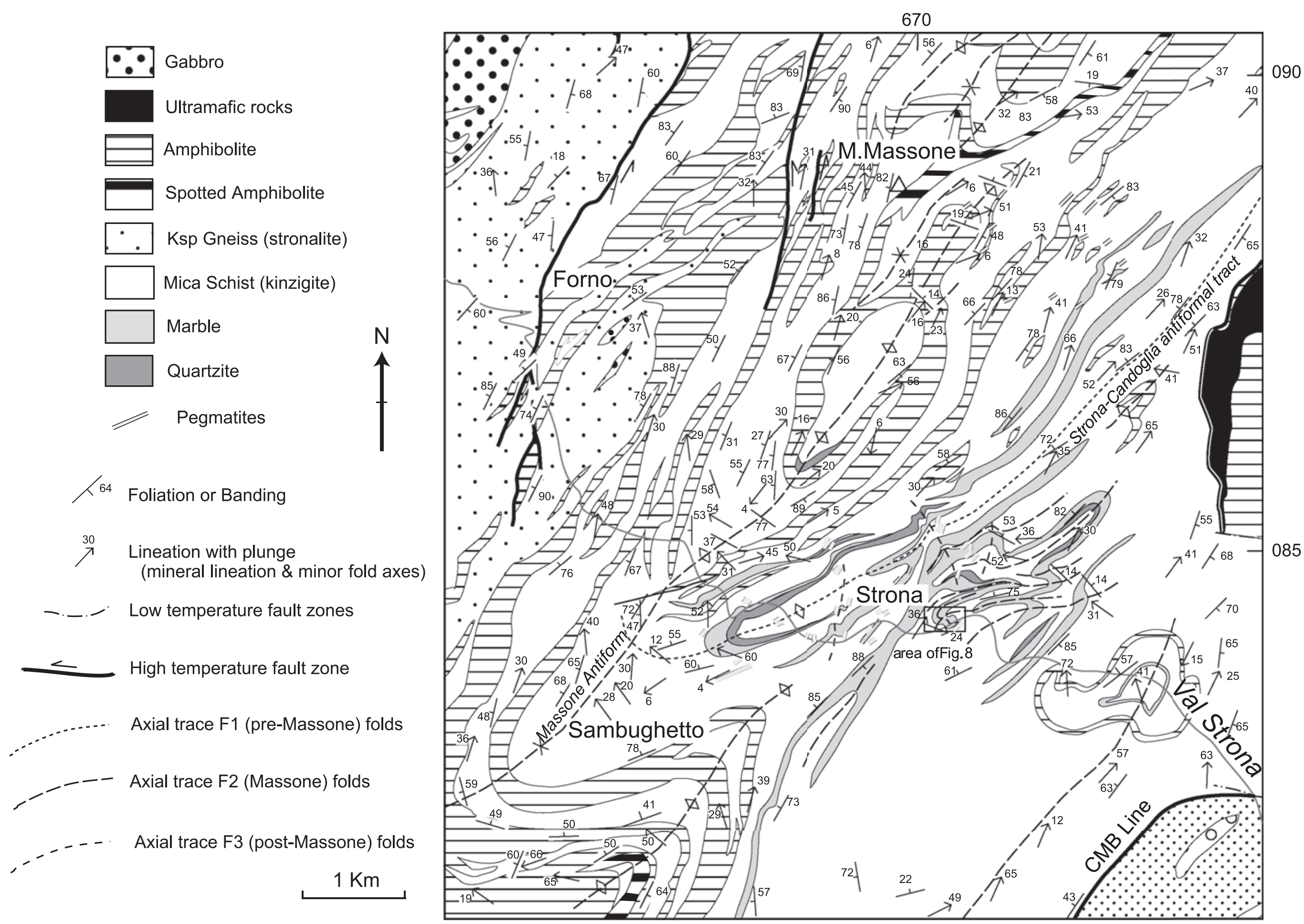

Fig. 4. Detail of the central part of Fig. 2, showing the relationships between the structure of the Massone folding and the earlier Strona-Candoglia antiformal syncline in Val Strona where they are particularly well displayed. Plunge arrows show how the early mineral lineations and fold axes are folded around the hinge of the Massone Antiform in the southern part of the map where the Massone Antiform plunges vertically. An enlarged map of the area to the east of Strona village (indicated) is shown in Fig. 8. The spotted amphibolite is distinctive through the occurrence of plagioclase rims around garnet prophyroblasts.

appropriate in areas of particular geological significance. The rock types encountered were as outlined in the above summary of previous work, but in this part of the I-V zone it became apparent that large-scale patterns of superposed folding exist and these are described below.

4. Major fold geometries

4.1. The Massone folding

The area shown in Fig. 2 lies in the central third of Fig. 1. The dominant structural feature of this area is a large, upright, near-isoclinal antiformal fold structure whose axial trace passes through the summit of M. Massone, on the watershed between Val Strona and Valle d'Ossola (Figs. 1, 2, 4 and 5). The fold structure, here called the Massone Antiform, is well defined by the outcrop pattern of alternating bands of metapelitic schists of the kinzigite formation with hornblende–plagioclase amphibolites that range up to ca. 200 m thickness. The fold can be traced for some 40 km along strike. It tightens progressively toward the NE. The axial orientation varies dramatically along strike, from plunging ca. 30° NE to the NE of Valle d'Ossola (Fig. 5), through horizontal in the vicinity of M. Massone, and progressively plunging more steeply southwestwards to the SW of M. Massone. The plunge becomes vertical in Val Strona, and further SW passes through the vertical until it plunges steeply to the NE between Val Strona and Val Mastallone (Fig. 2). In this area, it also opens somewhat and the axial trace intersects the margins of the Mafic formation near Val Mastallone. The strongly curved axis of the Massone Antiform gives it a sheath fold geometry (Figs. 2 and 5).

Although the Massone Antiform is near isoclinal, for example from M. Massone northeastwards, in profile section it does not appear to be strongly flattened, for example, as one might expect if the axis curvature was due to amplification by flattening or shearing of a fold with an originally less-curved hinge line (Fig. 6). The amphibolite sheets in particular do not appear to be thickened even two fold in the hinge region relative to the hinges. The metapelitic schist layers are usually thickened in the hinge region more than the amphibolites. This is inferred to mean that the layering regionally possessed a large degree of curvature prior to the Massone folding event, but the hinge curvature was probably also enhanced during the

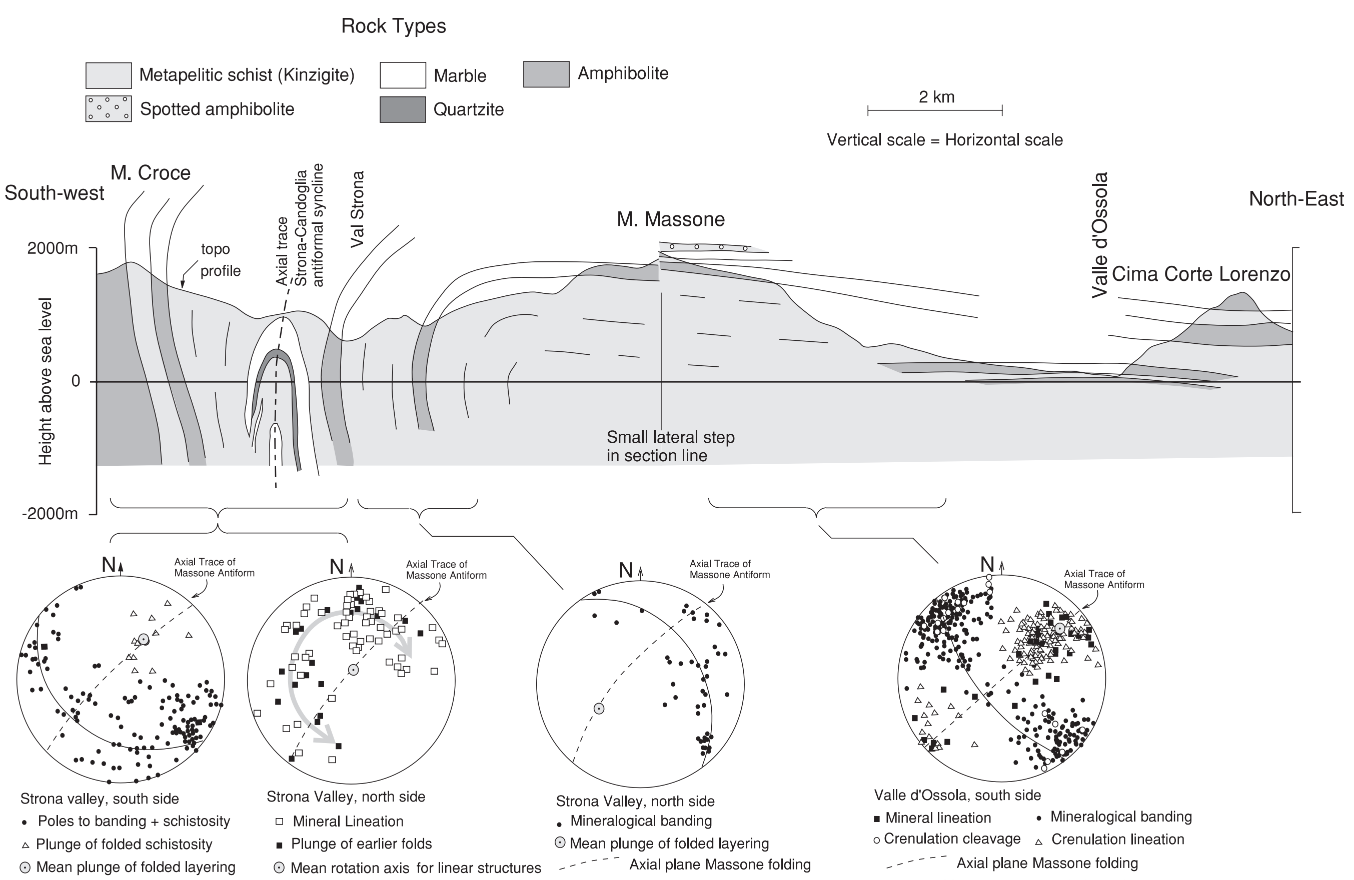

Fig. 5. Geological cross-section drawn parallel to the axial plane of the main Massone Antiform, showing the marked plunge culmination between M. Massone and Val Strona. The Massone folding refolds earlier major folds, principally the (locally steeply plunging) antiformal core of the Strona-Candoglia antiform, whose profile cuts across the axial plane of the Massone folding immediately SW of Strona valley. The equal-area, lower-hemisphere projections of data up to 2 km on either side of the Massone Antiform axial trace show how the attitude of layering and early schistosity changes along the axial zone of the Massone Antiform and how early fold axes and mineral lineations are folded about the hinge of the Massone Antiform where it is near vertical. The strong concentration of linear structures into a more gently NE plunging orientation towards the NE end of the section is typical of most of the northern I-V zone.

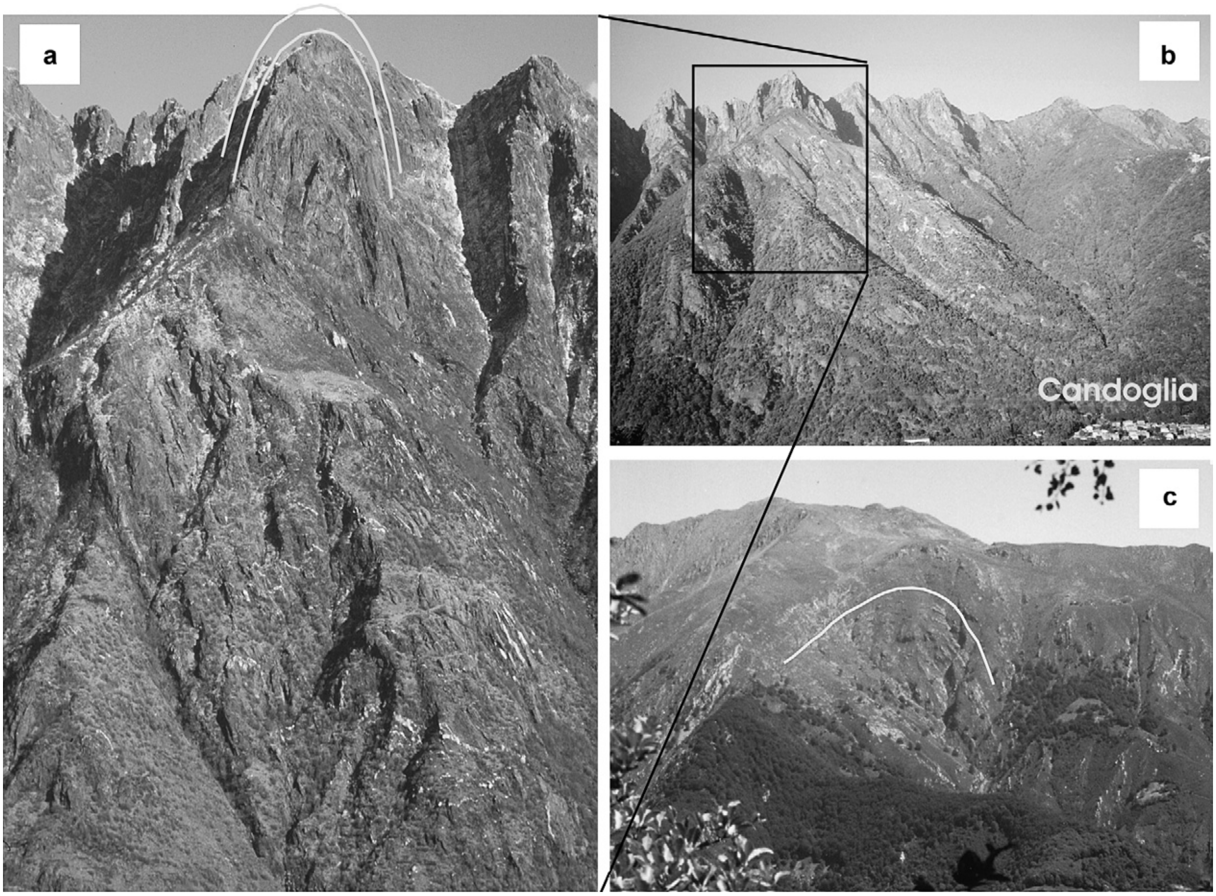

Fig. 6. Photographs of the Massone Antiform as it can be seen in the field. (a) The isoclinal closure at the summit of Cima Corte Lorenzo (Fig. 2), looking NW across the Valle d'Ossola (fold closure highlighted). Some of the swarm of small pegmatite bodies (Fig. 4) that cut the layering can just be distinguished. (b) Wider angle view including the same field of view as in (a), but showing the full 2 km relief of the Valle d'Ossola southern side, and how the fold structure becomes more open downwards. (c) View along the axis of the Massone Antiform on the north-eastern side of the Val Strona, from M. Croce (Fig. 2). The shape of the fold has been highlighted. Note the relatively small amount of thickening of the layers in the hinge region.

Permian regional NE–SW heterogeneous stretching (see Section 4.2 below).

The Massone folding resulted in a strongly developed crenulation cleavage of typically up to 6–10 mm wavelength (Fig. 7), particularly in the metapelitic rocks. It is therefore not the first fold event to have affected the region, and is here designated F2 in the sequence of superimposed folding described below. The metapelitic schists comprise mainly biotite, muscovite, plagioclase, sillimanite and garnet, with oriented fibrous sillimanite bundles spatially segregated into dilatational 'pressure shadows' in the hinges of the crenulation folds, and often seen in the field to form a distinctive mineral cluster lineation. Hence, we infer the crenulation cleavage to have formed under amphibolite facies conditions. NE of M. Massone, the crenulation cleavage can become so tight and pervasive that it is difficult in the field to recognize its crenulation character (Fig. 7). Coaxial minor folds sharing the same axial planar crenulation cleavage are generally close to tight, sometimes isoclinal, and range in wavelength from a few cm to 100 m (Figs. 4 and 7).

The metapelitic schists (kinzigites) of this part of the I-V zone are characteristically peraluminous and hence very rich in biotite and sillimanite, and generally are interlayered with, and occasionally crosscut by quartzofeldspathic lenses (leucosomes), up to 2 cm thick (Fig. 7), that are interpreted as the remnants of a granitoid melt that has been partially extracted from the schists. The schists throughout the I-V zone are also commonly cut by more substantial aplitic dykes and pegmatoid sheets of up to 1 to a few m in thickness (Figs. 4 and 8). They outcrop dominantly on the SE limb of the Massone Antiform. The leucosomes and at least some of the intrusive sheets are deformed and folded by the Massone folding event (Figs. 7 and 8) that produced the crenulation cleavage and hence are all likely to have been produced in the same migmatization event, but some intrusive sheets could have been produced later if they are seen to cut schistosity but are themselves not seen to be folded. Commonly such sheets lack an internal deformation fabric. Thus, the Massone folding is developed in rocks that had already suffered a regional migmatization event. The Massone folding is clearly the dominant structural feature of a major fraction of the I-V zone, so that there is a complete reversal of the structural facing of the rocks of the region across its axial trace (Fig. 9).

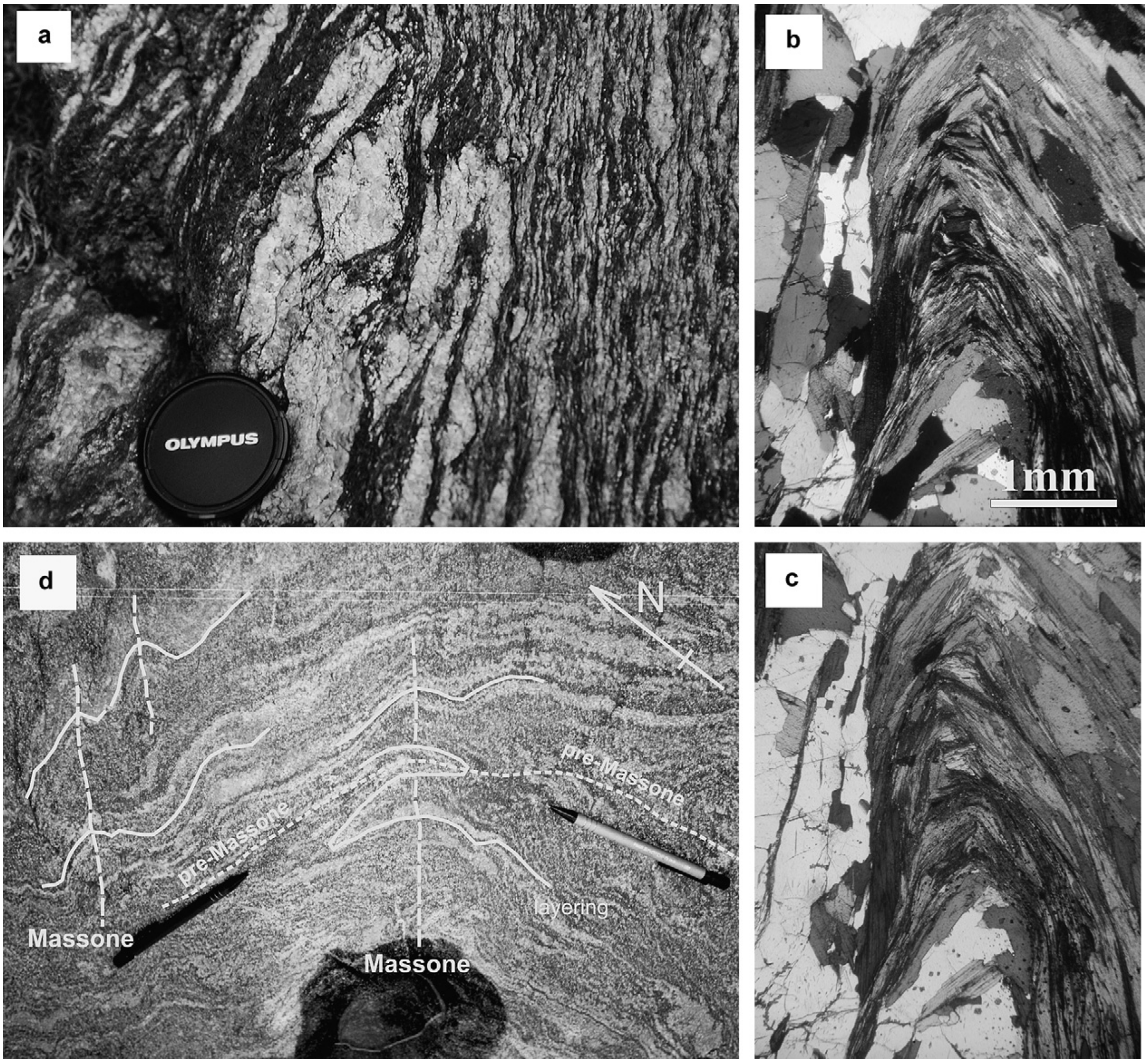

Fig. 7. (a) Intense crenulation cleavage axial planar to the folds of Massone age in migmatitic biotite–sillimanite schist (kinzigite Fm), showing isoclinal folding of leucosome (centre), Loc. Strona river near Strona village. (b and c) Localization of fibrous sillimanite growth into the dilatant hinge of a crenulation of early schistosity in biotite–sillimanite schist of the kinzigite Fm, implying growth of the sillimanite during crenulation. The crenulation cleavage is axial planar to the Massone Antiform. Locality: M. Massone summit (Figs. 2 and 4), crossed-polars (b) and plane-polarized light (c). (d) Vertical view onto small-scale interference of tight pre-Massone minor folds with NE-plunging Massone-age small-scale folds affecting banded amphibolite in the axial region of the Massone Antiform in Val Grande, some 5 km NE of Valle d'Ossola. Axial traces of the two sets of folds are highlighted.

4.2. Pre-Massone folding

That the axial planar structure of the Massone folding is a crenulation cleavage clearly indicates that there was an earlier schistosity producing event (F1). Small-scale, pre-Massone intrafolial folds of primary banding with an axial planar schistosity are not uncommon. Where the vertically plunging axial region of the Massone Antiform crosses the Val Strona, the geometric relations between pre-Massone structures and folds of Massone age are most clearly displayed. Fig. 5 shows equal area, lower hemisphere projections that illustrate these relations. The orientation of the steeply NW-dipping axial surface and the steeply plunging axis of the Massone Antiform are shown for reference. The axial planar schistosity of pre-Massone folds rotates about the Massone axial direction. Pre-existing mineral lineations that lie parallel to the axes of pre-Massone folds and early fold axes themselves are rotated in a small circle track around the hinge region of the Massone Antiform axis. In the Strona river valley some 100 m to the east of the village of Strona the geometric relations between Massone and pre-Massone small-scale structures are well-exposed, where pre-Massone isoclinal minor folds are folded around larger (100 m wavelength), moderately plunging Massone minor folds (Fig. 8). Fig. 7d shows small scale, locally type 3 (Ramsay, 1967) interference between Massone and pre-Massone folds exposed in the hinge region of the Massone Antiform in Val Grande, a valley that trends parallel to Valle d'Ossola but some 5 km further NE.

To the SE of the outcrop of the axial trace of the Massone Antiform, the axial zone of a major pre-Massone fold structure

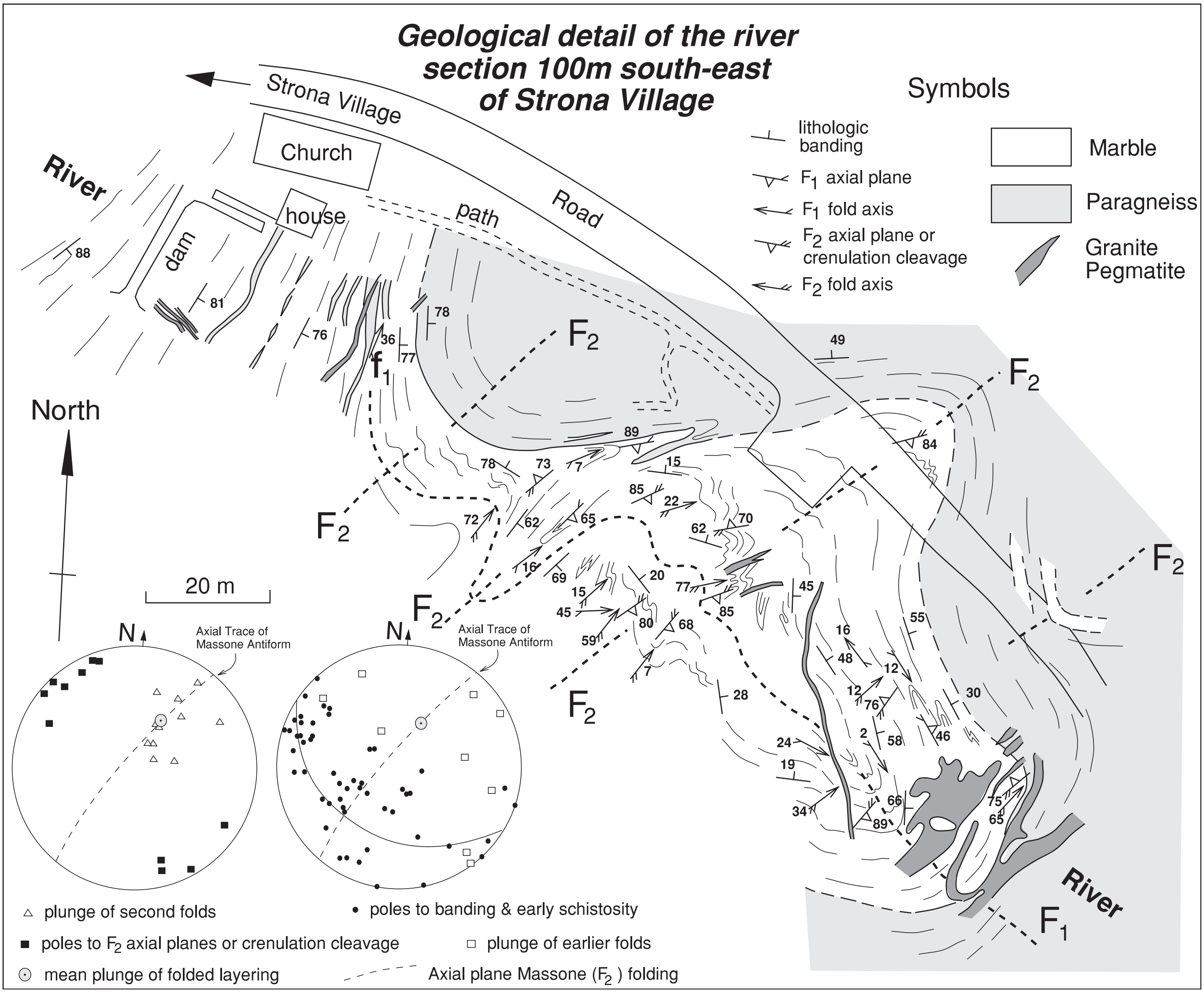

Fig. 8. Detailed map of the F1/F2 fold interference structures displayed in a short section of the Strona river about 100 m south-east of Strona Village (location shown on Fig. 4). Massone folds (F2) plunge moderately to the NW, folding an earlier schistosity and fold axes (F1). Small granite pegmatite bodies crosscut the earlier folds but are folded about axial planes of folds of Massone age.

outcrops (Figs. 2 and 3). This is represented by a tract of lithologically distinctive coarse-grained (5 mm) calcite marble bands that are up to 150 m thick, white quartzite (1 mm grain size) and up to 100 m thick, and paragneisses that are finer grained (1–2 mm) than the kinzigitic schists and poorer in biotite (although bands of the latter are not distinguished in Fig. 4). This metasedimentary association is inferred to represent originally a lithologic group of shallow water marine sediments (Baker, 1988), originally deposited stratigraphically on top of an emergent accretionary complex (Sills and Tarney, 1984) and now represented by the kinzigite–amphibolite association. In the Strona valley near Sambughetto (Fig. 4, where the thickened marble has been quarried), the hinge region of a large, steeply plunging (synclinal if the inferred age relations are correct) fold structure is exposed (Fig. 4). This F1 hinge zone can be seen to be folded around the hinge of the Massone Antiform core to the NW. The tract of marbles, quartzites and paragneisses that form the hinge region of this synclinal zone can be traced along strike to the NE across the Val Strona–Valle d'Ossola watershed, and across the Valle d'Ossola at Candoglia (Fig. 2) and into Val Grande. A tract of these metasediments also extends southwestwards into Val Sesia, which lies 2 km off the southern edge of Fig. 2. The marble bands are normally discontinuous as a result of large-scale, along-strike boudinage, but on the NE flank of Valle d'Ossola they are again thickened by Massone-age folding in an area that is quarried for decorative stone (Candoglia marble quarries, Fig. 2). We have termed this extensive, pre-Massone synclinal region the Strona-Candoglia fold (Fig. 4).

Curiously, the supracrustal metasedimentary rocks forming the core of the Strona-Candoglia fold do not outcrop on the NW flank of the Massone Antiform (Figs. 2 and 4). Bearing in mind the steeply west-plunging major fold closure that outcrops at Sambughetto, this is not surprising, provided the fold

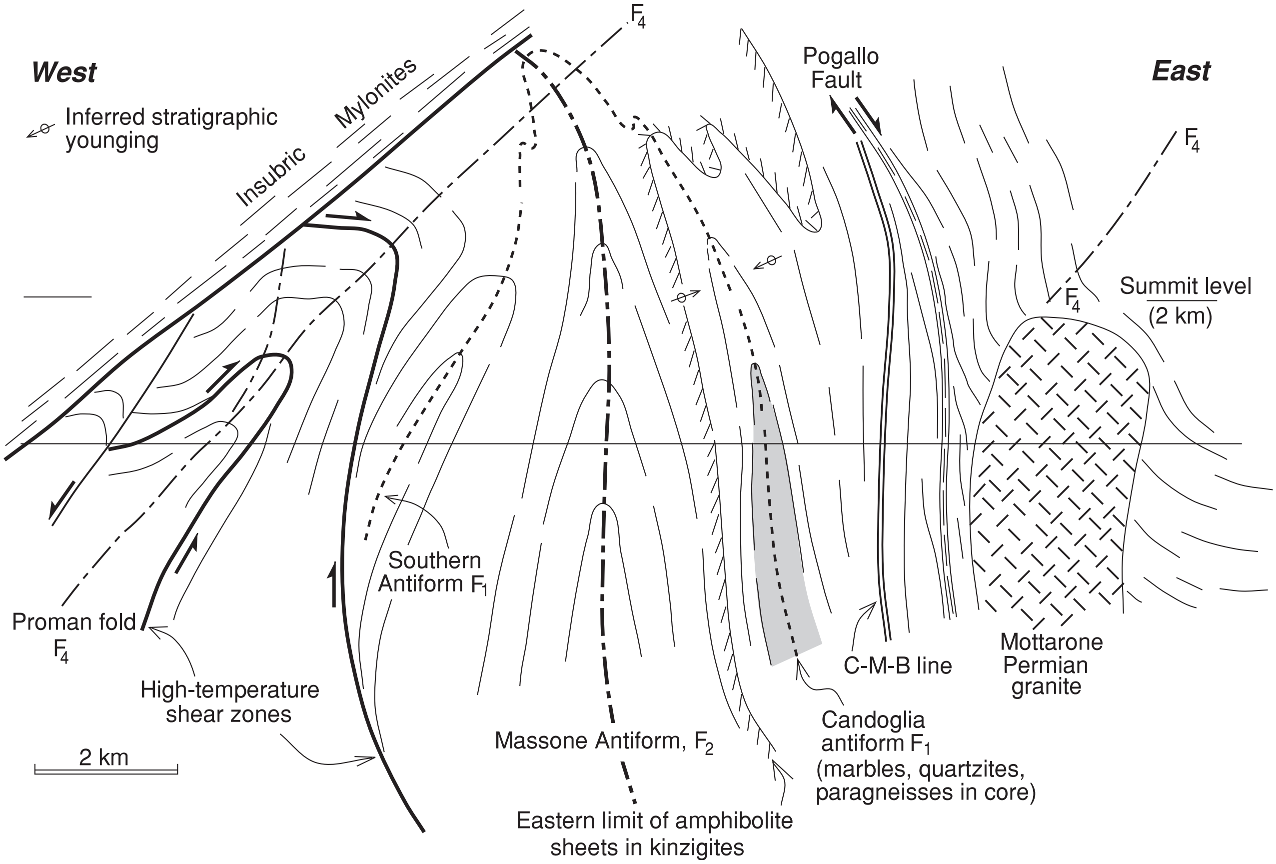

Fig. 9. Outline vertical cross-section parallel to the Valle d'Ossola (location on Fig. 1) to show the relationships between the main structural features. The I-V zone is bounded to the NW by the Insubric mylonite zone, and is in contact with the adjacent S. dei Laghi to the SE across the C-M-B line. Along the contact the S. dei Laghi rocks are near vertical, in common with most of I-V zone rocks, but swing around to a gentle SE dip in the vicinity of the Mottarone granite. The vertical I-V zone rocks are also folded back to the near-horizontal by the Proman fold (axial trace labelled F4), just beneath the Insubric mylonite belt, so that Alpine folding has generated a large monoclinal kink, with the I-V zone comprising most of the steep limb. The earlier, upright Massone Antiform structure also folds the earlier Strona-Candoglia fold core, the latter interpreted to be of equivalent age to the Southern Antiform (Schmid, 1967), which lies on the NW limb of the Massone Antiform.

closes upwards. Thus, for the extent of the fold lying to the NE of Sambughetto it must be antiformal (an antiformal syncline), with the hinge line that emerges from beneath the ground at Sambughetto curving around towards the horizontal as it extends north-eastward. Generally, in the I-V zone to the NE of Valle d'Ossola the regional banding and foliation gently converge and thin, and all linear structures, including fold axes, of all ages converge toward a 30° NE plunge (Fig. 5). This is inferred to be due to north-eastwardly increasing amounts of regional stretching produced during the late Permian crustal extension event (Brodie and Rutter, 1987; Rutter et al., 1993). This variation in the degree of Permian stretching explains why the obliquity between pre-Massone linear features and the hinge of the Massone Antiform is seen so much more clearly in Val Strona than further NE, and likely accounts for a significant part of the strong curvature of the Massone Antiform hinge line.

On the NW flank of the Massone Antiform, the migmatitic metapelitic rocks of the kinzigite formation still display the pre-Massone schistosity, although the transition between amphibolite and granulite facies metamorphism cuts slightly obliquely across the banding and schistosity. This transition is represented by the muscovite-out (Mu + Qtz = Ksp + Sill + water) isograd in the metapelitic rocks (Zingg, 1980) and is approximately parallel to the Massone Antiform axial zone between Val Strona and Valle d'Ossola (Fig. 2), but south of Val Strona and north of Valle d'Ossola the muscovite-out isograd appears to drift across the axial trace, rather than being folded about it.

The orthopyroxene-in isograd in the amphibolites (Zingg, 1980, Fig. 2) occurs slightly further NW, slightly to the SE of the Forno-Anzola high-temperature shear zone (Rutter et al., 1993 and Fig. 2). Both features obliquely transect the Massone Antiform axial surface trend. The prolongation of the Forno-Anzola high-temperature shear zone to the south cuts across the axial trace of the Massone Antiform and brings the former into coincidence with the zone of synmagmatic shearing described by Snoke et al. (1999) in the roof of the thick mafic body that dominates the SW end of the I-V zone (Fig. 1) These isograds and the high-temperature shear zones are not repeated on the SE side of the Massone Antiform and, although the angle of transection is small, it seems clear that the main Massone Antiform must be older than the age of imposition of these isograds and the formation of the shear zones.

For many years, following the work of Schmid and Wood (1976) and Zingg (1980) it had been supposed that all the high-grade metamorphism of the I-V zone was due to the hot intrusion of the rocks of the Mafic formation. It is already clear from the folding of migmatite leucosomes and metamorphic textures that the rocks of the I-V zone had suffered two episodes of large- and small-scale folding with or following regional migmatization in the upper amphibolite facies, probably during the Hercynian orogeny. The later (Permian) intrusion of the Mafic formation caused rather more localized (contact) granulite facies metamorphism and some remelting, and produced a final isograd pattern superimposed upon the earlier fold structures. Barboza et al. (1999) and Barboza and Bergantz (2000) presented mineralogical and textural evidence from the contact region near the roof of the mafic complex near Val Sesia that demonstrates the superposition of the two metamorphic events.

Even without the outcrop of the supracrustal metasediments being present on the NW flank of the Massone Antiform, we might reasonably expect the axial trace of the pre-Massone Strona-Candoglia fold core, or at least features associated with the same early folding event, to outcrop on the NW flank of the Massone Antiform. A large antiformal structure does indeed outcrop in amphibolites and stronalites (biotite-poor, garnet-rich, granulite facies metapelitic equivalent of the kinzigite formation) near Premosello, on the northern side of the Valle d'Ossola. This structure was termed the Southern Antiform by Schmid (1967), and we interpret it to correspond to the Strona-Candoglia structure on the SE side of the Massone Antiform. It will be recalled that NE of the Valle d'Ossola the Permian stretching has tended to pull all linear features into correspondence, but we infer that to the SW of the Valle d'Ossola the hinge line of the Southern Antiform swings around the axial plane of the Massone Antiform to join with the axial direction of the Strona-Candoglia fold at Sambughetto, forming a large-scale type 2 interference structure (Ramsay, 1967). The geometry envisaged is shown as a block diagram in Fig. 10. Note that there is no requirement for the pre-Massone folding to have everywhere possessed parallel axes. Indeed, the geometry proposed requires strongly curved axial directions to have existed. The intense flattening these folds have suffered would amplify any initial fold axial culminations and depressions. The Southern Antiform is itself truncated on the south side of the Valle d'Ossola by the Forno-Anzola high-temperature shear zone that was active during sub-solidus but high-temperature stretching that followed the intrusion of the Mafic formation.

4.3. Post-Massone folding

Locally developed, open to tight folds (F3), with wavelengths lying in the range 500 m and smaller are found with a second crenulation cleavage slightly oblique (more north–south) to the trend of the axial surface of the Massone folding (e.g. Fig. 4), but these do not seem to be associated with a major event. Rather than representing a spatially and temporally distinct folding event, these folds may have formed as part of the progressive deformation of the region as rocks became reoriented during the Massone folding. Alternatively, their formation might be related to movements on the C-M-B line, closer to which their frequency of occurrence increases, and the obliquity of their axial traces would be consistent

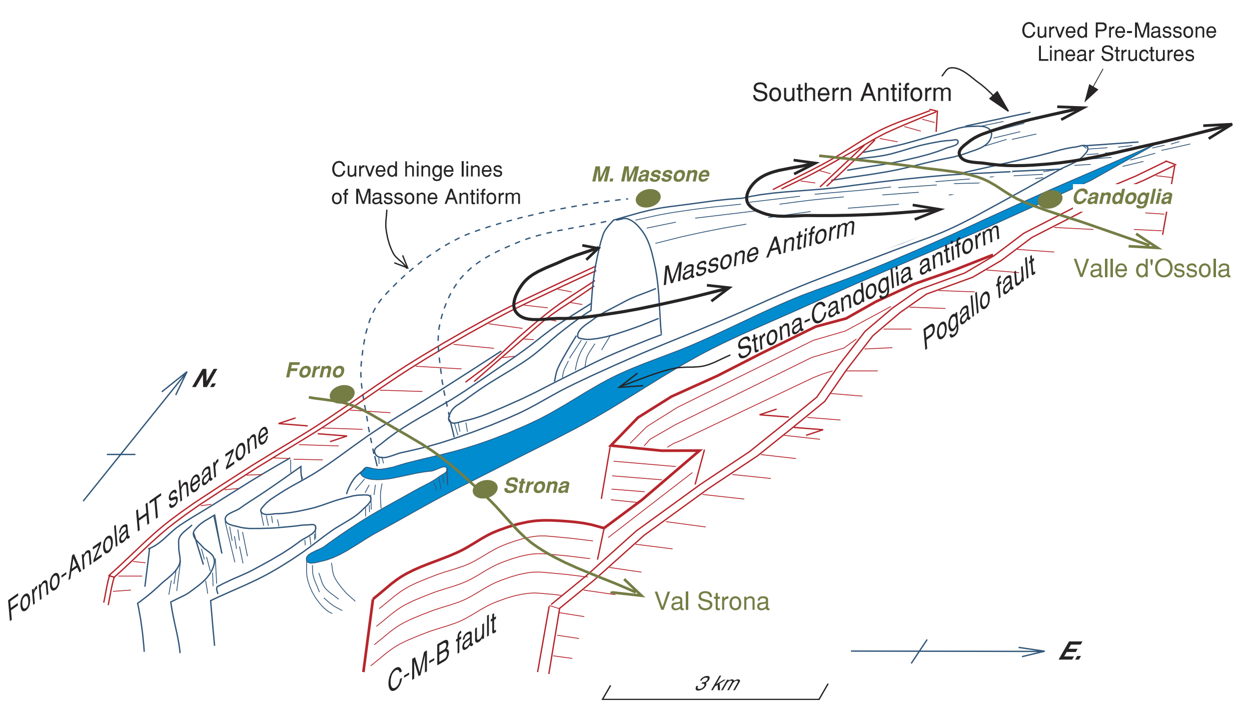

Fig. 10. Block diagram (looking north) to illustrate the three-dimensional geometry of the plunge culmination of the Massone Antiform and the earlier folds (the Southern Antiform and the Strona-Candoglia antiformal syncline), and the major fault surfaces. Pre-Massone mineral lineations and fold axes are curved around the Massone Antiform axial plane to form a type-2 interference geometry.

with a right-lateral sense of movement. Fault rocks of the C-M-B line are only rarely exposed, but this is the sense of movement implied by infrequently occurring shear band features.

The most important post-Massone folding is exemplified by the Proman antiform (Schmid, 1967; Brodie and Rutter, 1987), here designated F4 in the sequence of folding events. This is a major fold structure with a box-fold geometry in profile section (Fig. 9) that folds all pre-existing lithologic banding, foliations and linear structures, and also the high-temperature shear zones that formed during crustal extension following the intrusion of the Mafic formation (Brodie and Rutter, 1987). It outcrops immediately beneath the Insubric mylonite belt with an horizontal axis. Its 45° NW-dipping axial plane passes through the village of Premosello, in the Valle d'Ossola (Fig. 2). The bending of the layering in high-grade gneisses appears to have been accommodated through the formation of layer-parallel shear zones in which there has been retrogression to greenschist facies assemblages, together with local faulting which can include frictional melt development (Brodie and Rutter, 1987; Rutter et al., 1993).

A second major manifestation of post-Massone folding is represented by the kink-like reorientation of the regional schistosity from its dominantly vertical attitude in the I-V zone and in the Strona-Ceneri zone of the SdL (Figs. 1 and 2), to the gently undulating attitude of the schistosity that dominates from the western side of the Mottarone granite pluton toward the SE. Thus, the vertical attitude of the I-V zone and the Strona-Ceneri rocks should be considered as 'abnormal' and the near-horizontal or gently folded attitude of basement schistosity and cover rocks to the east of Lago Maggiore as 'normal'. In this way, the I-V zone can be seen as outcropping on the steep limb of a crustal-scale kink structure, with the Proman antiform marking the transition to the normal attitude in the NW, and the 'Mottarone' kink forming the transition to the normal attitude to the SE. This large-scale kink geometry (Fig. 9) was previously pointed out and illustrated by Handy et al. (1999). Fig. 2 shows new orientation data in the region of the Mottarone pluton that demonstrate the kink geometry. The bending of the rocks of the I-V zone and SdL is largely coincident with the Mottarone pluton. The bending is inferred to have been localized by the presence of the line of granitic intrusions, whose deep roots may have acted as hinge for the bending, thus leaving the granites in largely their original attitudes. The substantial swing in strike (and trend of the Mottarone kink) in this part of the SdL from near N–S to the south to NE–SW to the north-west (Fig. 2) is likely due to some combination of the regional curvature of the inner arc of the Western Alps plus the effects of rotation of the trend of the SdL due to displacements on the Pogallo fault.

Fig. 9 shows a vertical cross-section along the line of the Valle d'Ossola that illustrates many of the features of the structure of the region as described above. Beneath the NW-dipping greenschist mylonitic belt of the Insubric zone, the double kink structure of the I-V zone formed by the Proman antiform and the Mottarone kink is apparent, with the I-V zone forming the abnormal limb. The axial surface of the Proman fold is cut by the slightly steeper-dipping Insubric fault zone, but is otherwise of similar attitude (Fig. 9). Regarding the Insubric fault in broad terms as a backthrust that accommodates the uplift of the core of the Western Alps against the N.W. Italian basement, the overall geometry is consistent with the double kink being a large backfold produced during Alpine compression and uplift, although it is recognized that the sequence of movements along the Insubric zone are more complex than the final disposition of major geological units implies (Schmid et al., 1987).

Fig. 9 shows that the Proman structure folds the high-temperature shear zones of Permian age. The dominant structure in the central part of the cross-section is the Massone Antiform, whose axial trace is partially folded around the Proman antiform. On either limb of the Massone Antiform are seen, respectively, the Southern antiform and the Strona-Candoglia antiformal syncline. These structures are cut by the high-temperature shear zones. The pre-Massone folds are shown with a common axial surface linked over the Massone Antiform, although there may not be such direct linkage of their axial planes. In the NW limb of the Strona-Candoglia fold is shown the southeasternmost limit of the occurrence of amphibolite sheets in the kinzigite formation. This is inferred to represent a stratigraphic upper limit to their occurrence. A curious feature of the Valle d'Ossola cross-section is the occurrence of four large antiformal structures adjacent to each other. The proposed model explains how this can develop.

5. Discussion and geological history

The new data on the large-scale structural geometry of the upper part of the I-V zone, together with previously published work, allow us to assemble an outline geological history of the region. This is summarized in Fig. 11.

The age of the earliest events in the I-V zone and the pressures and temperatures to which the rocks were exposed are obscured by the effects of the thermal overprint caused by the intrusion of the mafic complex during the early Permian (Henk et al., 1997). Only the structural, geochemical and stratigraphic relationships provide insight into this period. From the lithologies seen and their geochemistry, the I-V zone is held to be assembled from an accretionary volcano-sedimentary complex containing original basic layers of MORB affinity (Sills and Tarney, 1984). Quick et al. (1995) argued that most of the ultramafic bodies of mantle origin seen within the I-V zone are tectonically incorporated slices, but at some imprecisely known depth beneath the present outcrop of the Insubric mylonites the I-V zone rocks probably make contact with continuous upper mantle, represented by the gravity anomaly of the geophysical 'Ivrea Body' (Berkhemer, 1968). Finally, the assemblage of marbles, quartzites and fine-grained paragneisses of the Strona-Candoglia tract is interpreted here to represent the remains of a supracrustal

Tectonic Environment	Event	Associated Small-Scale Structures	Associated Major Structures
Hercynian Orogeny or earlier.	Pre-Massone folding (F_1).	Mineral stretching lineation, axial planar schistosity. Early folds, migmatization and regional metamorphism.	Strona-Candoglia syncline. Southern Antiform.
	Massone folding (F_2).	Axial-planar crenulation fabric. Folding of leucosomes and granitoid sheets.	Massone Antiform.
	Post-Massone folding (F_3).	Open, chevron-style coarse crenulation. Axial-planar crenulation fabric.	No obvious large-scale structures.
Post-orogenic extension. (Permo-Triassic)	Intrusion of Mafic Formation. Ductile stretching.	Contact metamorphism and migmatization.	Mafic Formation. C-M-B line shearing and igneous activity.
	Regional subsolidus stretching.	Linear features aligned where strain is highest. High temperature shear zones.	High-temperature shear zone formation. Pogallo faulting.
Alpine Orogenesis.	Alpine backthrusting on Insubric Line and associated folding (F_4) and faulting.	Brittle faults bearing greenschist assemblages. Some with frictional melting. Increasing frequency towards Insubric line.	Regional-scale monoclinal structure forms - Proman fold and folding about Serie dei Laghi granites.

Fig. 11. Summary (time sequence top to bottom) of the tectonic events and associated small and large-scale structures produced in the Ivrea-Verbano zone.

unit deposited stratigraphically on top of the rocks of the accretionary complex.

The earliest clear folding events that can be recognized were the pre-Massone folds represented by small-scale folds with a penetrative axial-planar schistosity, early large-scale folds such as the Southern Antiform, and folds in the marbles and quartzites of the Strona-Candoglia tract, interpreted here to form an antiformal syncline within the kinzigite formation.

The Massone folding is clearly superimposed upon the above events because earlier tectonic lineations, minor fold axes and the earlier schistosity are folded around the Massone Antiform, which possesses an axial planar crenulation cleavage. The Massone Antiform and associated minor folding developed under high amphibolite facies conditions as evidenced by the localized growth of fibrous sillimanite in crenulation hinges. It was also preceded by widespread migmatization of the metapelitic rocks of the kinzigite formation, because leucosomes, pegmatoid and aplitic sheets are folded by the Massone folds. We suspect that these folding events were produced during the Hercynian orogeny, with the fold structures in a recumbent attitude.

During Permian times, after the Massone folding, the region was subjected to large-scale injection by basic magma, producing the 10 km thick Mafic formation of the southern I-V zone and thinner, though still substantial injections extending to the NE. This was responsible for contact metamorphism and migmatization, producing the present pattern of metamorphic isograds and high-temperature leucocharnokite sheets (Rutter et al., 1993) from local remelting of the metapelites. The disposition of metamorphic isograds (Fig. 2), a geobaric gradient of increasing depth to the NW (Fig. 3), and the pattern of layering produced in the main mafic intrusive complex

(Rivalenti et al., 1981; Rutter et al., 1993; Quick et al., 1994), strongly suggests that the rocks lay in a horizontal attitude at the time of the mafic injections, which means we can refer to these events as an example of mafic underplating of continental crust. Underplating took place accompanied by pervasive east–west stretching and concomitant thinning (Brodie and Rutter, 1987; Rutter et al., 1993; Quick et al., 1994) with many rocks under hypersolidus conditions. As rocks cooled, the stretching and thinning continued to be accommodated by slip on high-temperature shear zones, accounting for the present-day steep paleo-geothermobaric gradient (e.g. Henk et al., 1997) and further emphasizing the curvature of the Massone Antiform hinge line within its axial plane. The superimposition of underplating, contact metamorphism and stretching on the earlier Massone folding is evidenced by the cross-cutting of the Massone axial trace by the edge of the Mafic formation, the metamorphic isograds and high-temperature shear zones.

Closely associated in time to the mafic underplating events was the displacement along the C-M-B line, leading to mechanical juxtaposition of the I-V zone against the SdL, with the latter's radically different petrological, structural and metamorphic history (Boriani and Giobbi, 2004). The mylonitic contact zone, by inference gently dipping at this time on account of its similar orientation to the igneous layering of the Mafic formation and orthogonal attitude with respect to the metamorphic gradient in the I-V zone, became extensively decorated with intrusive gabbrodioritic (appinites) and granitoid rocks, most of which are not deformed. Syntectonic migmatization in this tract suggests there was marked mechanical detachment between the I-V and SdL units at the time. Broadly coevally the granitic plutons of the SdL were emplaced, possibly before movements on the C-M-B line had ceased. It is not clear what were the spatial relationships between the I-V zone and the SdL when these Permian igneous rocks were emplaced—it may not have been as we see them now because the contrasts in the geology of the I-V zone and the SdL probably imply a total lateral displacement of several tens of km and possibly some relative vertical displacement. Boriani and Giobbi (2004) review the petrological and geochemical evidence for the mixed crust/mantle origins of these magmas.

The post-magmatic history of the region begins with the displacements on the Pogallo fault (Handy and Zingg, 1991), interpreted by Hodges and Fountain (1984) to have been a low-angle extensional fault. The east–west extension it accommodates would have continued that which occurred on the deeper, high-temperature shear zones of the I-V zone, but developing later (Triassic to early Jurassic, Zingg et al., 1990), and presaging Jurassic continental rifting.

Finally, during the Alpine orogenesis, the displacements of the core of the Alpine orogen upwards against the northwestern Italian crust formed a large monoclinal kink, in which the I-V zone was for the most part tilted to the vertical against the Insubric fault zone, with one kink hinge being localized to form the Proman fold (Fig. 9). At the SE edge of the I-V zone the regional schistosity was rotated about the Permian granites of the SdL, with the granite bodies, exemplified by the Mottarone pluton, themselves resisting rotation as relatively rigid, passive inclusions in a deforming schistose matrix. Boriani and Giobbi (2004) appealed to the minimal tilting of the Permian granites to argue that the I-V zone was vertical during Permian time, when these plutons were emplaced, but the recognition of the double kink structure of the I-V zone and interpretation presented here are consistent with the I-V zone having been tilted to the vertical as late as during Alpine orogenesis.

6. Conclusions

New mapping in the central part of the Massicio dei Laghi has revealed a system of large-scale superimposed folds in the structurally higher part of the I-V zone. The dominant feature is the Massone Antiform, an upright fold structure that extends some 40 km NE–SW, with a prominent plunge culmination. The axial direction curves through an angle of 115° within the axial plane. The structure folds metapelitic and metabasic rocks that had previously undergone large-scale folding with high-grade metamorphism and migmatization. A Massone axial planar crenulation cleavage deforms preexisting schistosity and lineations associated with the earlier large-scale folding to produce type two fold interference geometries.

After the Massone folding, the complex suffered mafic magmatic underplating, with high-grade contact metamorphism and migmatization, during Permian crustal extension and crustal thinning, first pervasively with the involvement of melts and later focused onto high-temperature shear zones. These features are superposed on the Massone folding and likely modified its shape. The I-V zone was brought into contact with the SdL by slip on the C-M-B structure, a major low-angle fault, at about the same time that the post-tectonic granites of the SdL were emplaced, together with decoration of the C-M-B line with gabbrodioritic and small granitoid bodies.

Finally, in association with the emplacement of the Massicio dei Laghi in the inner arc of the Western Alps, the I-V zone and the northwesternmost rocks of the SdL were tilted to the vertical as the steep limb of a large monoclinal kink structure, which finally became truncated by later movements on the Insubric fault system.

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References

Bächlin, R., 1937. Geologie und petrographie des M. Tamaro-Gebeites (südliches Tessin). Schweizerisches Mineralogische und Petrographische Mitteilungen 17, 1–79.

Baker, A.J., 1988. Stable isotope evidence for limited fluid infiltration of deep crustal rocks from the Ivrea zone, Italy. Geology 16, 492–495.

Barboza, S.A., Bergantz, G.W., Brown, M., 1999. Regional granulite facies metamorphism in the Ivrea zone: is the mafic complex the smoking gun or a red herring? Geology 27, 447–450.

Barboza, S.A., Bergantz, G.W., 2000. Metamorphism and anatexis in the mafic complex contact aureole, Ivrea zone, northern Italy. Journal of Petrology 41, 1307–1327.

Berkhemer, H., 1968. Topographie des ''Ivrea-Korpers'', abgeleitet aus seismischen und gravimetrischen daten. Schweizerisches Mineralogische und Petrographische Mitteilungen 48, 235–246.

Bertolani, M., 1969. La petrografia delle Valle Strona (Alpi Occidentale Italiane). Schweizerisches Mineralogische und Petrographische Mitteilungen 49, 314–328.

Blundy, J.D., Holland, T.J.B., 1990. Calcic amphibole equilibria and a new amphibole–plagioclase geothermometer. Contributions to Mineralogy and Petrology 104, 208–224.

Borghi, A., 1989. L'evoluzione metamorfico-strutturale del settore nord-orientale della Serie dei Laghi. (Alpi Meridionali). PhD thesis, Iniv. Torino, Italy, 187 pp.

Boriani, A., Burlini, L., Sacchi, R., 1990a. The Cossato-Mergozzo-Brissago line (Southern Alps, Italy) and its relationships with late Hercynian magmatic and metamorphic events. Tectonophysics 182, 91–102.

Boriani, A., Origoni Giobbi, E., Borghi, A., Caironi, V., 1990b. The evolution of the 'Serie dei Laghi' (Strona-Ceneri and Scisti dei Laghi): the upper component of the Ivrea-Verbano crustal section; Southern Alps, North Italy and Ticino, Switzerland. Tectonophysics 182, 103–118.

Boriani, A., Burlini, L., 1994. Carta Geologica della Valle Cannobina. CNR, Milano.

Boriani, A., Giobbi Origoni, E., Pinarelli, L., 1995. Palaeozoic evolution of southern Alpine crust (northern Italy) as indicated by contrasting granitoid suites. Lithos 35, 47–63.

Boriani, A., Villa, I., 1997. Geochronology of regional metamorphism in the Ivrea-Verbano zone and Serie dei Laghi, Italian Alps. Schweitzerisches Mineralogische und Petrologisches Mitteilung 77, 381–401.

Boriani, A., Giobbi, E., 2004. Does the basement of western southern Alps display a tilted section through the continental crust? A review and discussion. Periodico di Mineralogia 73, 5–22.

Brodie, K.H., 1995. The development of oriented symplectites during deformation. Journal of Metamorphic Geology 13, 499–508.

Brodie, K.H., Rutter, E.H., 1987. Deep crustal extensional faulting in the Ivrea zone of northern Italy. Tectonophysics 140, 193–212.

Boudier, F., Jackson, M., Nicolas, A., 1984. Structural study of the Balmuccia Massif (Western Alps): a transition from mantle to lower crust. Geologie en Mijnbouw 63, 179–188.

Bürgi, A., Klötzli, U., 1990. New data on the evolutionary history of the Ivrea zone (N. Italy). Bulletin of the Swiss Association for Petroleum Geology and Engineering 56, 49–70.

Ellis, D.J., Green, D.H., 1979. An experimental study of the effect of Ca upon garnet–clinopyroxene Fe–Mg exchange equilibria. Contributions to Mineralogy and Petrology 71, 13–22.

Evans, P., 1995. Structural geometry of parts of the Ivrea-Verbano zone, northern Italy. PhD thesis, University of Manchester.

Giobbi, E., Zappone, A., Boriani, A., Bocchio, R., Morten, L., 1997. Relics of pre-Alpine ophiolites in the Serie dei Laghi (Western Southern Alps). Schweizerisches Mineralogische und Petrographische Mitteilungen 77, 197–207.

Handy, M.R., Franz, L., Heller, F., Janott, B., Zurbriggen, R., 1999. Multistage exhumation and accretion of the continental crust (Ivrea crustal section, Italy and Switzerland). Tectonics 18, 1154–1177.

Handy, M.R., Zingg, A., 1991. The tectonic and rheologic evolution of an attenuated cross-section of the continental crust: Ivrea crustal section, southern Alps, northwestern Italy and southern Switzerland. Geological Society of America Bulletin 103, 236–253.

Hodges, K., Fountain, D.M., 1984. The Pogallo line, south Alps, northern Italy: an intermediate crustal level, low-angle normal fault? Geology 12, 151–155.

Henk, A., Franz, L., Teufel, S., Oncken, O., 1997. Magmatic underplating, extension, and crustal reequilibration: insights from a cross section through the Ivrea zone and Strona-Ceneri zone, Northern Italy. Journal of Geology 105, 367–377.

Khazanehdari, J., Rutter, E.H., Brodie, K.H., 2000. High pressure/temperature seismic velocity structure of the mid- and lower-crustal rocks of the Ivrea-Verbano zone and Serie dei Laghi, N.W. Italy. Journal of Geophysical Research 105, 13843–13858.

Mulch, A., Rosenau, M.R., Dörr, W., Handy, M.R., 2002. The age and structure of dikes along the tectonic contact of the Ivrea-Verbano and Strona-Ceneri Zones (southern Alps, Northern Italy, Switzerland). Schweizerisches Mineralogische und Petrographische Mitteilungen 82, 55–76.

Pin, C., 1986. Datation U-Pb sur zircons à 285 Ma du complexe gabbro-dioritique du Val SesiaVal Mastallone étage tardi-hercynien du métamorphism granulitique de la zone Ivrea-Verbano (Italie). Comptes Rendu de l'Académie des Sciences Paris 303, 827–830.

Quick, J., Sinigoi, S., Negrini, L., Demarchi, G., Mayer, A., 1992. Synmagmatic deformation in the underplated igneous complex of the Ivrea-Verbano zone. Geology 20, 613–616.

Quick, J., Sinigoi, S., Mayer, A., 1994. Emplacement dynamics of a large mafic intrusion in the lower crust, Ivrea-Verbano zone, N. Italy. Journal of Geophysical Research 99, 21559–21573.

Quick, J., Sinigoi, S., Mayer, A., 1995. Emplacement of mantle peridotite in the lower continental crust, Ivrea-Verbano zone, N. Italy. Geology 23, 739–742.

Quick, J.E., Sinigoi, S., Snoke, A.W., Kalakay, T.J., Mayer, A., Peressini, G., 2003. Geologic map of the southern Ivrea-Verbano zone, Northwestern Italy. Geologic Investigations Series Map I-2776, U.S. Geological Survey, U.S. Government Printing Office.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York, 568 pp.

Rivalenti, G., Garuti, G., Rossi, A., Siena, F., Sinigoi, S., 1981. Existence of different peridotite types and of a layered igneous complex in the Ivrea zone of the western Alps. Journal of Petrology 22, 127–153.

Rutter, E.H., Brodie, K.H., Evans, P., 1993. Structural geometry, lower crustal magmatic underplating and lithospheric stretching in the Ivrea-Verbano zone, N. Italy. Journal of Structural Geology 15, 647–662.

Rutter, E.H., Khazanehdari, J., Brodie, K.H., Blundell, D., Waltham, D., 1999. Synthetic seismic reflection profile through the Ivrea-Verbano zone—Serie dei Laghi continental crustal section, northwestern Italy. Geology 27, 79–82.

Schmid, R., Wood, B.J., 1976. Phase relationships in granulite metapelites from the Ivrea-Verbano zone (N. Italy). Contributions to Mineralogy and Petrology 54, 255–279.

Schmid, R., 1967. Zur petrographie und strukur der zone Ivrea-Verbano zwischen Valle d'Ossola und Valle Grande. Schweizerische Mineralogische und Petrographische Mitteilungen 47, 935–1117.

Schmid, S.M., Zingg, A., Handy, M.R., 1987. The kinematics of movements along the Insubric Line and the emplacement of the Ivrea zone. Journal of Structural Geology 135, 47–66.

Schnetger, B., 1994. Partial melting during the evolution of the amphibilite to granulite facies gneisses of the Ivrea zone, northern Italy. Chemical Geology 113, 71–101.

Sills, J.D., Tarney, J., 1984. Petrogenesis and tectonic significance of amphibolites interlayered with metasedimentary gneisses in the Ivrea zone, S. Alps, N. Italy. Tectonophysics 107, 187–206.

Sinigoi, S., Antonini, P., Demarchi, G., Longinelli, A., Mazzuchelli, M., Negrini, L., Rivalenti, G., 1991. Interactions of mantle and crustal magmas in the southern part of the Ivrea zone (Italy). Contributions to Mineralogy and Petrology 108, 385–395.

Snoke, A.W., Kalakay, T.J., Quick, J.E., Sinigoi, S., 1999. Development of a deep crustal shear zone in response to tectonic intrusion of mafic magma into the lower crust, Ivrea-Verbano zone, Italy. Earth and Planetary Science Letters 166, 31–45.

Zingg, A., 1980. Regional metamorphism of the Ivrea zone (S. Alps, N. Italy): field and microscopic investigations. Schweizerische Mineralogische und Petrographische Mitteilungen 60, 153−179.

Zingg, A., 1983. The Ivrea & Strona-Ceneri zones (Southern Alps, Ticino & N, Italy)—a review. Schweizerische Mineralogische und Petrographische Mitteilungen 63, 361−392.

Zingg, A., Handy, M.R., Hunziker, J.C., Schmid, S.M., 1990. Tectonometamorphic history of the Ivrea zone and its relationship to the crustal evolution of the Southern Alps. Tectonophysics 182, 169−192.

Zurbriggen, R., Franz, L., Handy, M.R., 1997. Pre-Variscan deformation, metamorphism and magmatism in the Strona-Ceneri zone (southern Alps of northern Italy and southern Switzerland). Schweizerische Mineralogische und Petrographische Mitteilungen 77, 361−380.

Zurbriggen, R., Kamber, B.S., Handy, M.R., Nägler, T.F., 1998. Dating synmagmatic folds: a case study of schlingen structures in the Strona-Ceneri zone (Southern Alps, northern Italy). Journal of Metamorphic Geology 16, 403−414.