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Structural geometry, lower crustal magmatic underplating and lithospheric stretching in the Ivrea–Verbano zone, northern Italy

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Abstract—The Ivrea–Verbano zone is believed to represent an up-ended cross-section through the lower continental crust as it existed at the end of the Hercynian orogeny in the Southern Alps. Structurally-oriented geological mapping has been carried out in the central and northern parts of the Ivrea–Verbano zone, a region some 30 km along strike.

The geology of the southern half of the zone is dominated by a large basic–ultrabasic complex (the Mafic Formation), which is in contact with a strongly banded metasedimentary + metabasic sequence to the north. Particular attention was paid to: (a) the structural relationship between the rocks of the Mafic Formation and their envelope of high-grade metasedimentary and metabasic rocks; (b) the geometrical configuration throughout the Ivrea–Verbano zone of high-temperature shear zones, which accommodated post-Hercynian crustal extension; and (c) the geometry of late, low-temperature faulting, the effects of which have been removed in order to produce a restoration of the structure as it existed during the post-Hercynian extensional phase.

The intrusion of large volumes of basic magma (*ca* 50% of the outcrop area) to form the rocks of the Mafic Formation appears to be coeval with the onset of extension (*ca* 280 Ma). The main basic body has a laccolithic form, which was originally more than 10 km thick. Overfolding developed at the northern margin of the laccolith and is interpreted in terms of the gravitational collapse of the hot, immediately subsolidus or partially molten body, incorporating its envelope of hot metasediments into a large, originally recumbent fold. A geometrical association with a high-temperature, low-angle fault zone suggests that faulting was subsequently localized by the several km of uplift associated with the laccolithic intrusion. The Ivrea–Verbano zone may therefore demonstrate at least one particular geometry of lower crustal magmatic underplating, which may aid in the interpretation of present-day deep seismic profiles. It also demonstrates the geometry of a network of conjugate, high-temperature, low-angle shear zones in a well-layered lower crustal section.

INTRODUCTION

The Ivrea–Verbano (I–V) zone is widely held to represent a section through the lower continental crust, uplifted and tilted to a presently near-vertical attitude during the Alpine orogeny (e.g. Zingg *et al.* 1990). It lies directly above the gravity high which characterizes the internal arc of the Alps (Vecchia 1968). This, together with seismic data (Giese *et al.* 1982), suggests that the rocks of the I–V zone are connected to a slice or slices of lithospheric mantle which dip(s) to the south-east, joining with the present-day Moho beneath the Po basin. Rock types comprise granulite and amphibolite facies metasediments and a large proportion of metabasic rocks. The relative proportions of the rock types, their metamorphic state and their geochemistry accord well with models of lower continental crustal composition inferred from xenolith studies (e.g. Voshage *et al.* 1990, Wilshire 1990). The rocks yield a cluster of radiometric ages indicative of late-Palaeozoic high-grade metamorphism and igneous activity, with cooling extending through the Lower Mesozoic era (e.g. Bürgi & Klötzli 1990, Voshage *et al.* 1990). This section may therefore be indicative of the nature of the lower continental crust over the large area of Europe which was involved in the Hercynian orogeny and subsequent Mesozoic tectonism. As one of the few regions of exposed rocks of likely lower crustal provenance, it is potentially a valuable aid to the interpretation of deep seismic reflection profiles and other, less direct, methods of probing the contemporary lower continental crust.

Although the region has been subjected to intensive geochemical and petrological study (e.g. Schmid 1967, Rivalenti *et al.* 1975, 1981, 1984, Boriani *et al.* 1977, 1982, Garuti *et al.* 1980, Zingg 1980, 1983, Sills & Tarney 1984, Vorshage *et al.* 1987, 1980), with the exception of the work of Schmid (1967), Steck & Tièche (1976), Kruhl & Voll (1978), Boudier *et al.* (1984), Brodie & Rutter (1987) and Sinigoi *et al.* (1991) (on small parts of the region) almost no attention has been given to the structural geometry of the I–V zone. In this paper we describe the structure of a substantial section of the higher grade part of the Ivrea–Verbano zone, the region extending from the Sesia valley in the south to the northern side of the Valle d'Ossola (Fig. 1). Before describing the results of the new work, a brief summary of the geology of the region is given below.

SUMMARY OF REGIONAL GEOLOGY

The Ivrea–Verbano zone outcrops over a distance of some 80 km along the inner arc of the Western Alps. It is about 12 km wide at the middle of the outcrop. It is bounded to the northwest by the Insubric fault zone, which separates it from the Alps proper, where Mesozoic rocks have suffered Alpine metamorphism. To the southeast the I–V zone is in contact with the Serie dei Laghi, a group of amphibolite grade metasedimentary and metaigneous rocks of Lower Palaeozoic age (Boriani *et al.* 1990b), together with intrusive granitic bodies,

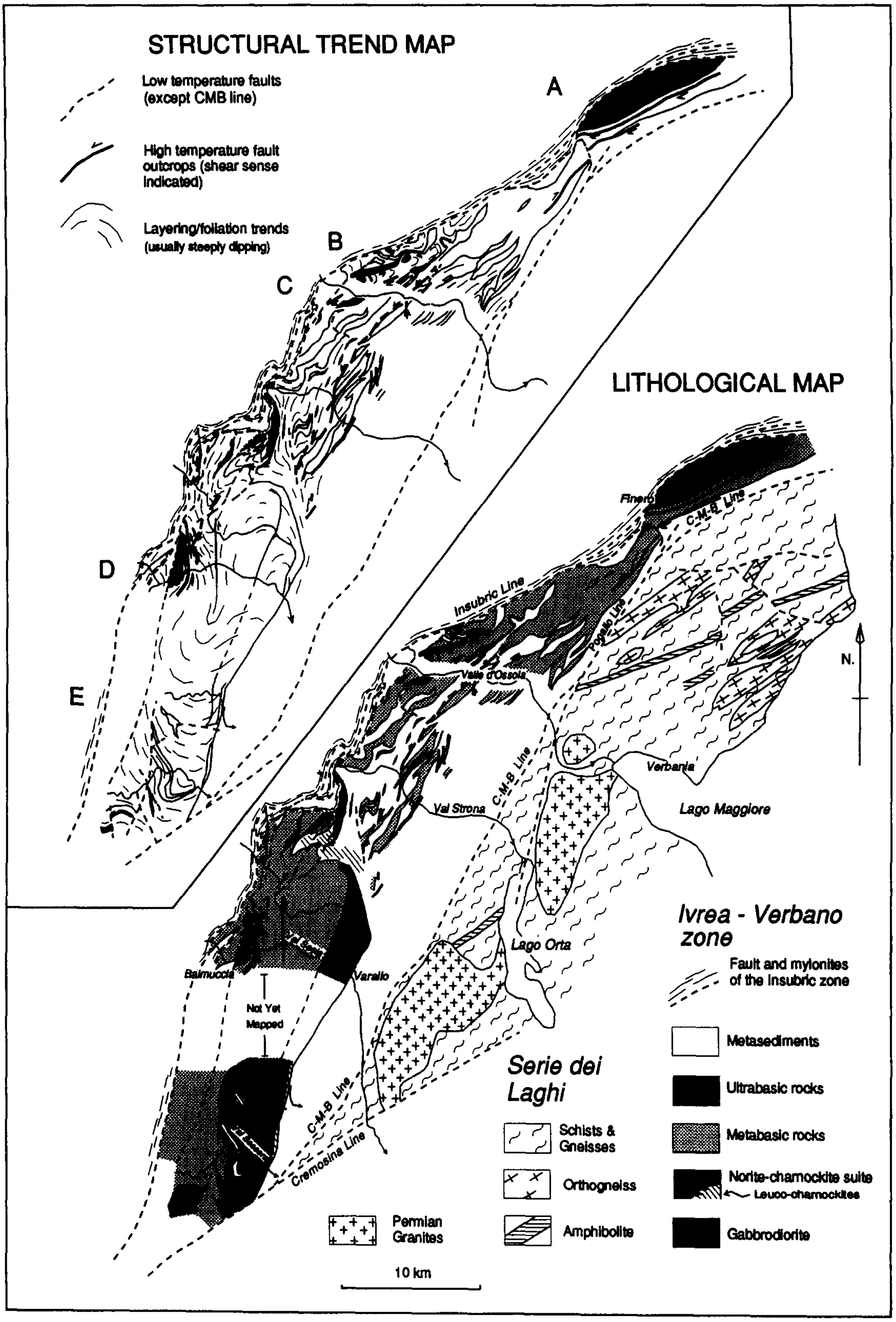
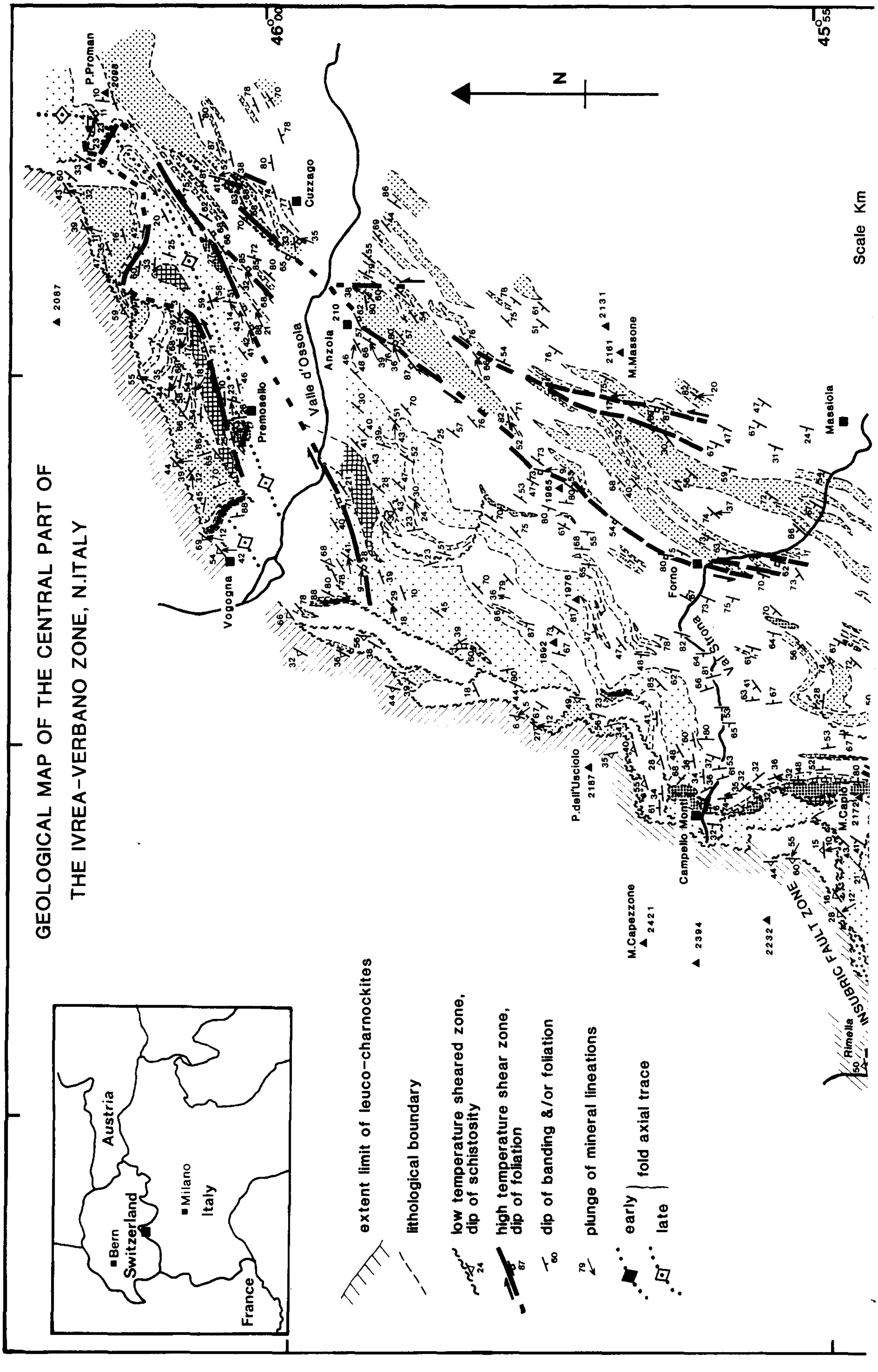


Fig. 1. Lithological and structural trend maps of the Ivrea–Verbano zone. The lithological map shows the regional setting of the zone, separated from the inner arc of the Alpine chain by the Insubric tectonic line and from the Serie dei Laghi by the Cossato–Mergozzo–Brissago (C–M–B) line, an early tectonic discontinuity, which is in turn partially excised by the Pogallo fault (Lower Mesozoic). Data from the east of the C–M–B line are after Boriani *et al.* (1990b). On the structural trend map the present study deals with the section from B to D. High-temperature shear zones are shown only where exposed. No interpolation is given. The region around E is drawn from Sinigoi *et al.* (1991). Structural trends between D and E have been interpolated. The eastern part of area B draws on the work of Schmid (1967) and around A from Schmid *et al.* (1987).


GEOLOGICAL MAP OF THE CENTRAL PART OF
THE IVREA-VERBANO ZONE, N.ITALY
46°00'
45°55'
N
Scale Km
P.Proman
2088
2087
Cuzzago
Premosello
Vogogna
Valle d'Ossola
Anzola
210
M.Massone
2161
2131
Massiola
Forno
Strona
1965
1976
1892
P.dell'Usciolo
2187
Campello Monti
M.Capio
2172
M.Capezzone
2421
2394
2232
INSUBRIC FAULT ZONE
Rimella
Austria
Switzerland
Bern
Milano
Italy
France
extent limit of leuco-charnockites
lithological boundary
low temperature sheared zone, dip of schistosity
high temperature shear zone, dip of foliation
dip of banding &/or foliation
plunge of mineral lineations
early
late
fold axial trace

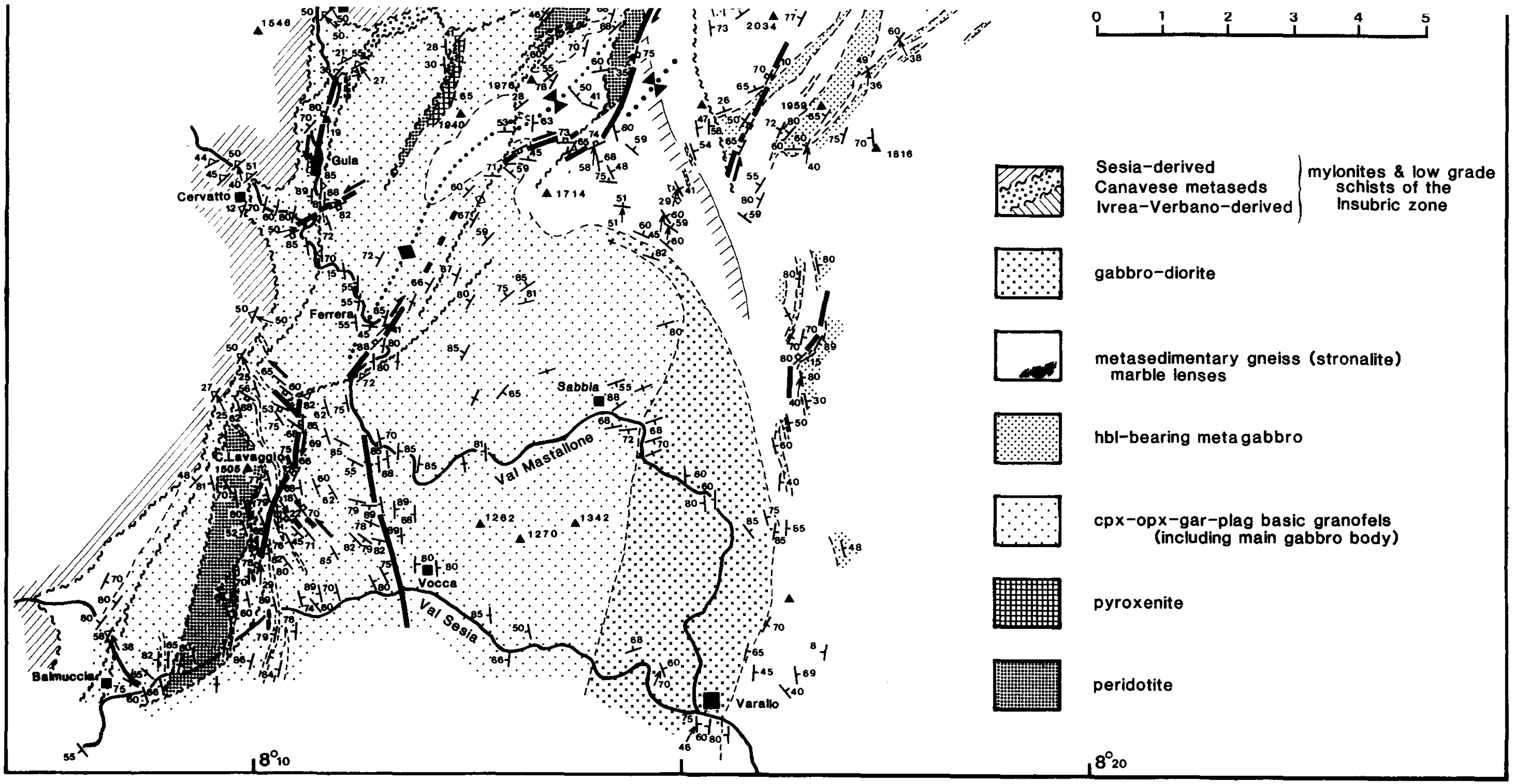


Fig. 2. Geological map of the region studied, with location map inset at the top left. Other than the peridotite bodies of Balmuccia and Premosello, and some of the thinner metabasic sheets (many of which are included within the ornamentation shown as metasedimentary gneiss), all other ultrabasic and metabasic rocks are thought to comprise the intrusive 'Mafic Formation'.

along the Cossato–Mergozzo–Brissago (C–M–B) line, a pre-metamorphic tectonic contact (Boriani *et al.* 1977, 1990a,b). This contact is displaced by a younger, extensional mylonitic fault zone, the Pogallo line (Handy 1987) (Fig. 1).

Within the I–V zone, the oldest rocks comprise metasedimentary schists and gneisses interlayered with metabasic rocks on a scale of tens to hundreds of metres. Layering and foliation are commonly steeply dipping and strike parallel to the general trend of the zone (Fig. 2). A mineral elongation lineation is commonly developed, plunging about 35° to the northeast. Sills & Tarney (1984) inferred these rocks to have accumulated in an island arc setting, perhaps during early Palaeozoic times. Near the northwestern border of the Ivrea–Verbano zone, three peridotitic bodies crop out, at Balmuccia, Premosello (Valle d'Ossola) and Finero, that are inferred to have formed part of the (solid) upper mantle (Rivalenti *et al.* 1981, Boudier *et al.* 1984). Adjacent to these units, a group of intrusive metabasic rocks locally dominates the outcrop. This complex (called the Mafic Formation in the south of the region, Rivalenti *et al.* 1975, 1981, 1984) comprises several sill-like bodies, up to several 100 m in thickness in the north, but increasing in thickness in the region of Val Mastallone to almost 10 km. Primary igneous textures are sometimes preserved in the southern part of the outcrop of the Mafic Formation, but complete textural re-equilibration under metamorphic conditions has occurred in the north.

The rocks of the Mafic Formation show clear evidence that they comprise a composite of layered basic intrusions (Rivalenti *et al.* 1975, Garuti *et al.* 1980). They become less basic away from the mantle peridotite bodies, but locally differentiation has occurred to produce cumulate ultrabasic lenses (Rivalenti *et al.* 1981). the internal layering sometimes shows magmatic–sedimentary features, such as slump folding and cross-stratification. The southeastern margin of the complex is gabbrodioritic and shows evidence (structural and geochemical) of contamination with country rock. The country rocks themselves are extensively migmatized. These facts point to the complex having been intruded into originally flat-lying, lower crustal country rocks, immediately above the Moho. It has been argued (Voshage *et al.* 1990) that the age of intrusion of the Mafic complex is *ca* 280 Ma, approximately coeval with the intrusion of the Permian granites of the Serie dei Laghi Hunziker & Zingg 1980, Boriani *et al.* 1990b). Although various authors had argued that this activity took place in an extensional tectonic setting (e.g. Hodges & Fountain 1984), Brodie & Rutter (1987) showed that originally E–W extension of the regional banding occurred through displacements on high-temperature, post-metamorphic mylonitic fault zones lying at a low angle to the banding. Hodges & Fountain (1984) argued that the Pogallo fault was a low-angle extensional fault, active before the rocks were tilted into their present subvertical attitude. Schmid *et al.* (1987) proposed a model for the emplacement of the I–V zone into its present subvertical position adjacent to the Insubric line during Alpine orogenesis. It has, however, been argued alternatively that the I–V zone had already been tilted into a vertical attitude by Permian times (e.g. Boriani *et al.* 1990a).

There is a general increase in metamorphic grade northwestwards across the I–V zone, from upper amphibolite to granulite facies (see review by Zingg *et al.* 1990). Throughout the I–V zone, the metasedimentary schists and gneisses are Al-enriched (in contrast to the rocks of the adjacent Serie dei Laghi), which has led to the suggestion that they are restites resulting from the removal of a granitic partial melt (Schmid & Wood 1976, Schmid 1978). The intrusion of the enormous volume of the Mafic Formation may have led to the highest temperature metamorphic and textural equilibration of the rocks of the I–V zone (Schmid 1967), together with partial melting to provide the material for the Permian granites and acid volcanics (Fountain 1989, Sinigoi *et al.* 1991).

METHODS EMPLOYED IN THIS STUDY

Geological mapping was carried out on a scale of 1:10,000 or locally at larger scale. A primary aim was to obtain a fairly uniform coverage of orientation data, so that the planar and linear structures could be represented with a reasonable degree of confidence. Some 1500 orientation data were collected, and the selected data shown on Fig. 2 give a fair idea of the coverage obtained. Microstructural study of oriented samples has also been carried out, using optical and electron petrographic methods.

Special attention was given to the location of, and distinction between, low- and high-temperature faults. The term 'fault' is used in the sense of a planar zone of highly localized deformation. Typically, high-temperature fault zones (also loosely called 'shear zones') are characterized by intense intracrystalline plastic deformation and dynamic recrystallization. In this region they are generally isochemical and do not involve metamorphic retrogression (e.g. Brodie 1981, Brodie & Rutter 1985). Low-temperature faults are characterized by intense cataclastic (involving fracturing) deformation. In this region they can also show low metamorphic grade retrogressive changes, typically involving hydration in the greenschist facies, with the additional possibility of creep deformation involving limited plasticity and/or diffusive transfer processes. Viewed from a distance, or on the scale of a geologic map, there is often no difference between the geometric effects of low- and high-temperature faulting.

It was hoped that deflections of the direction field of planar structures would aid in locating faulting. This proved true in some instances. In many cases aligned tracts or networks of associated fault zones could be distinguished on the basis of common orientation and movement picture between different exposures. This allowed the simplified network of conjugate, low-angle, high-temperature ultramylonitic fault zones sketched on Figs. 1 and 2 to be inferred.

From thin section observations it was clear that grain-shape fabrics in the rocks could have formed either earlier or later than the high-grade metamorphic equilibration that affected the whole region (Figs. 3, 4 and 5). From grain shapes observed in hand specimen it was often (but not always) possible to distinguish these two fabric types in the field. Intense, post-metamorphic plastic strain was generally localized into high-temperature fault zones, hence the fabric type proved a useful mapping aid.

DESCRIPTION OF THE GEOLOGICAL MAP AND HISTORY

The regional setting of the area mapped is shown in Fig. 1. The more detailed map of the area studied is shown in Fig. 2, with emphasis being given to lithological variations and foliation–banding orientations. A schematic E–W cross-section through the region is shown in Fig. 6. The main features of the structural geology of the region are described below, in chronological order of their development.

The geometry of the rocks of the Mafic Formation

In the southern part of the area the Mafic Formation (here excluding the Balmuccia peridotite massif) is easily defined. It forms a body almost 10 km thick. The original base of the complex lies to the northwest. Rivalenti *et al.* (1984) recognized a number of divisions within the sequence. At the base is a 'Layered Series', some 600 m thick, which could be further subdivided with a more pyroxenitic lower part. Within the well-layered basic units, discontinuous ultrabasic sheets (dunites and pyroxenites) occur, which may indicate differentiation from successive intrusive sheets. Several thin septa of metasedimentary gneiss have been included near the base. The 'Layered Series' is overlain by a more homogeneous 'Main Gabbro'. The uppermost 2 km of this body is again heterogeneous through the incorporation of largely digested xenoliths and it has a more gabbrodioritic composition. The basic complex is overlain by 1 km or more of migmatized country rocks. The metabasic rocks show varying degrees of development of metamorphic garnet. Where garnet is subordinate, the rock in the field is scarcely different from an igneous gabbro. However, in the lower parts of the complex in particular, garnet, in large (1 or 2 cm diameter) clusters may form up to 20 modal per cent of the rock.

Northwards from the vicinity of Gula, the Mafic complex is markedly thinner, and forms a series of thick (hundreds of metres) sills, almost everywhere concordant with the host-rock banding. The petrographic character of the metabasic rocks in the granulite facies is always of a 2-pyroxene–garnet–plagioclase granofels. Thus in the field in the northern part of the mapped area it becomes impossible to distinguish with certainty the intrusive metabasics which form part of the Mafic Formation, from metabasics which formed part of the original country rock pile. Although it appears possible to make the distinction on the basis of trace-element geochemistry (Sills & Tarney 1984), in Figs. 1 and 2 these rocks have had to be described using metamorphic nomenclature, except where the original character is indisputable.

In the northern part of the mapped area the intrusive nature of metabasic rock units can be inferred from occasional cross-cutting relationships. Thin (a few cm) basic dykes occur (infrequently) cutting banding in ultrabasic, basic and country rocks throughout the region. At La Balma, some 3 km southeast of Campello Monti, a well-layered basic sheet some 150 m thick lies on top of an ultrabasic level. At the upper contact with metasediments, dykes branch from the basic rock and penetrate the metasediments (shown schematically in Fig. 8b). On the north side of the Strona valley, some 1 km east of Campello Monti, a substantial change of structural level of the contact of a basic sheet can be inferred. Over a distance of *ca* 1.5 km, the local E–W trend of the southern boundary of the basic body lies almost normal to the regional trend of the layering in the country rocks. However, immediately adjacent to the contact the country rock layering swings sharply into concordance.

In general, the basic rocks which are inferred to be intrusive possess simple structures. They are texturally fairly homogeneous (equigranular or inequigranular granoblastic), and show banding and grain-shape fabric to varying degrees. Evidence of a complex folding history is generally absent. In contrast, the heterogeneously banded metasedimentary gneisses often show evidence of pre-metamorphic small-scale isoclinal folding, and give the impression of a longer and more complex history (Zingg *et al.* 1990). However, caution is required in drawing conclusions from this observation, for the metasediments have clearly suffered disruption associated with the migmatization apparently arising from the intrusion of the basic rocks.

The large-scale fold structure of the Mafic Formation

About 2–4 km north of Val Mastallone, the contact of the Mafic Formation with the country rocks is concordant and defines a large-scale pair of folds, plunging steeply to the northeast. The antiform, draped around the northeastward pointing lobe of the main metagabbro body, swings through a circular arc but the synform (to the west) is isoclinal (Figs. 1 and 2 and block diagram Fig. 7). In the country rocks the fold pair rapidly loses amplitude towards the northeast. Within the Mafic Formation the banding and foliation follow the form of the fold pair. Southwestwards along the axial trace of the synform in the basic rocks, the fold plunge steepens and passes through the vertical, so that by the vicinity of Ferrera, it plunges steeply to the southwest (i.e. is antiformal). Further south, on the ridge to the east of

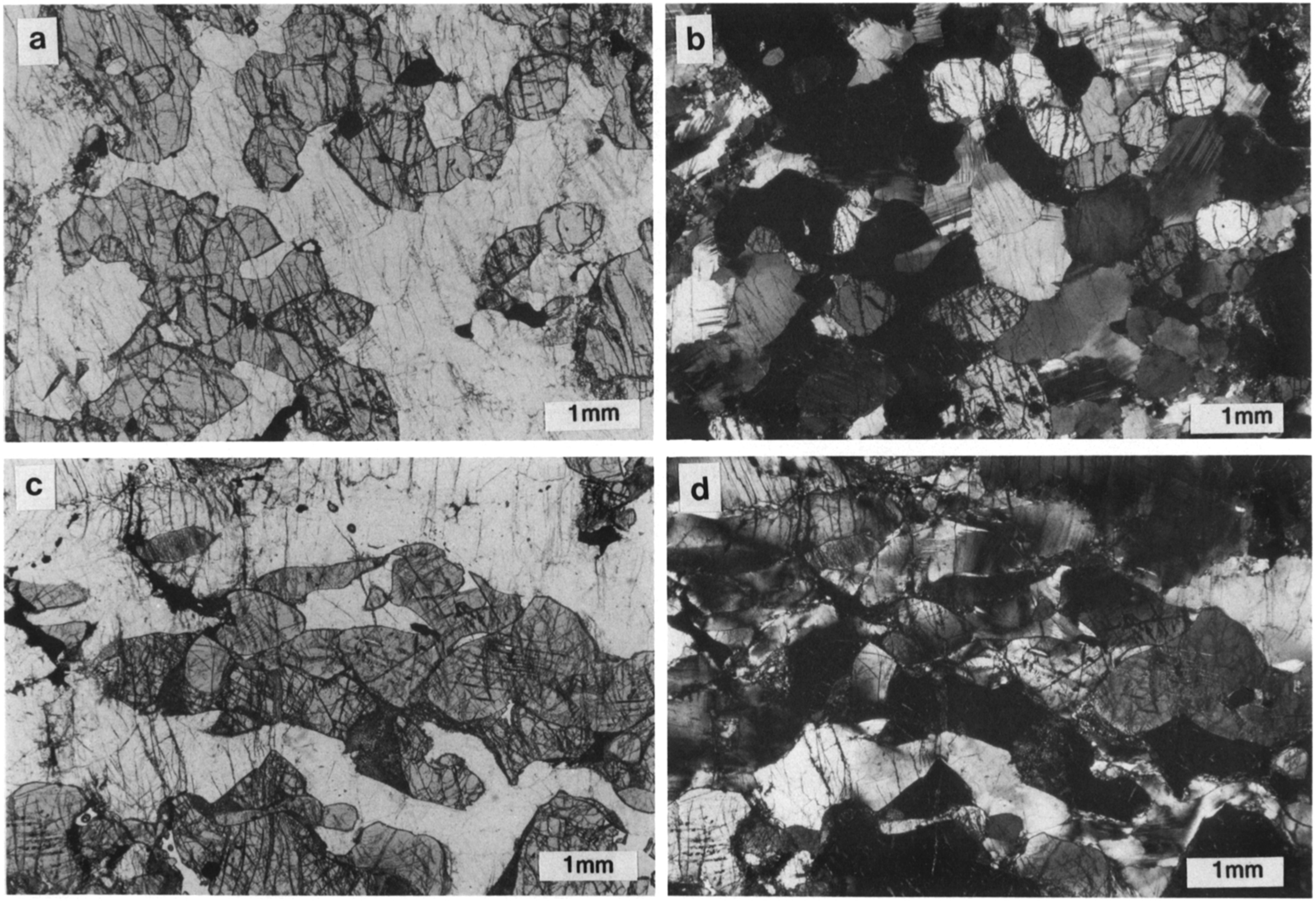


Fig. 3. (a) Isotropic granoblastic microstructure of typical basic granofels (plagioclase, garnet, pyroxene: plane polarized light); (b) crossed polars view of the same field. (c) Mafic granofels showing *typical pre-metamorphic* shape fabric revealed by elongate clusters of pyroxene and feldspar grains (plane polarized light). There is a slight overprint by later, intracrystalline plastic strain, as revealed by optical strain features in the plagioclase in (d) (crossed polars, same field). The superimposed plastic strain is insufficient to account for the shape fabric as perceived in hand specimen.

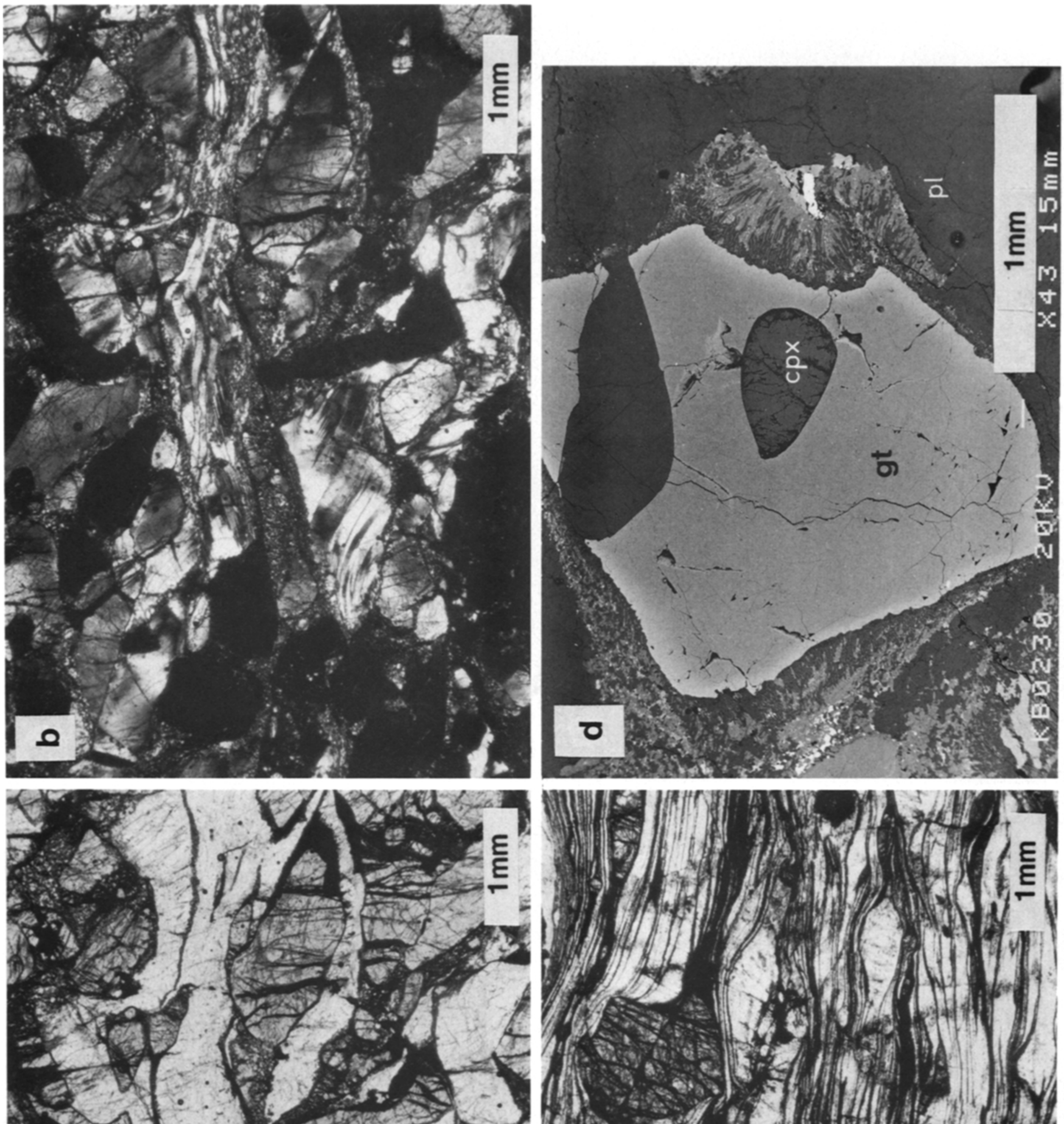


Fig. 4.

Cima Lavaggio, the fold core passes into a sharp fault (see foliation trends on Figs. 1 and 2). The fault contact was not seen, but it could be located to within a few metres from the sharp discordance of the foliation. Further south again, in Val Sesia, the fold–fault contact is no longer apparent. The layering appears always to trend N–S along the Sesia Valley section, but from the foregoing there is an implied inversion of the 'stratigraphy' some 400 m west of Vocca.

In addition to the definition of the above structures by the compositional banding, they are also defined by a (generally) weak grain-shape foliation (Figs. 3c & d), which is almost everywhere parallel to the compositional banding. This is interpreted to be a magmatic or immediately subsolidus foliation, because it is overprinted by the granulite facies microstructural equilibration. No optical intragranular strain features are preserved. Under the microscope it is easily distinguished from the grain shape fabric produced by superimposed high-temperature, solid-state flow (Figs. 4a & b) which becomes localized into plastic shear zones, some of which were clearly formed at granulite facies temperatures but overprint the earlier, high-temperature textural equilibration. The distinction can generally be made in the field. At moderate to high strains superposed plastic strain always affects feldspars first. Pinching of the feldspars by mafic phases can easily be seen with a hand lens, whereas the equilibrium grain boundary configurations in rocks possessing only the 'magmatic' fabric can also easily be recognized.

Within the main gabbro and the gabbrodioritic unit, compositional banding is rare, but the folded form mentioned above can be mapped using the 'magmatic' grain shape foliation. Within the gabbrodiorites, the foliation is often revealed by the preferred orientation of biotite crystals. From Fig. 2 it is clear that the foliation transects the lithological transition from the main gabbro to the gabbrodiorites.

Partial melting of the metasedimentary gneisses

In the southeast of the area mapped (e.g. around Varallo), the gabbrodiorites of the Mafic Formation lie in contact with highly migmatized and disrupted metasedimentary gneisses, 1 km or more in thickness. It is to be expected that the most extensive degree of partial melting of the country rocks would lie above the thickest part of the basic intrusive complex. It is noteworthy that the foliation trends in the metasediments to the north converge towards the migmatized region (Figs. 1 and 2) and this effect may arise partially from the thinning of the migmatized region through the extraction upwards and laterally of granitic melt.

In the wedge of metasedimentary gneisses drawn into the synformal fold core of the Mafic Formation and around the lobe of the antiform (2 or 3 km south of Mte. Capio), the country rocks are characterized by alternations of leucocratic, quartzofeldspathic gneiss with more garnet- and sillimanite-rich gneiss. The approximate extent of their development is shown in Fig. 2. Interbanding of the rock types takes place on a scale of 10 cm to more than 1 m. In the field, the leucocratic layers often display coarse, igneous textures, although in thin section grain-boundary configurations are typical of solid-state equilibration. These rocks are thought to correspond to the leucocratic charnockites described from the region of Val Sessera (Sinigoi *et al.* 1991), some 10 km south of the area mapped. Sinigoi *et al.* (1991) suggested that the leucocratic charnockites are crustal melts. This seems to be the most likely origin for the leucocratic gneisses of the mapped area, given their occurrence on the flanks of the thick basic intrusion (Figs. 1 and 2). They may have been injected laterally from the migmatites forming above the thickest part of the basic body. Their present morphology can perhaps best be described using the (now) rarely used term, *lit-par-lit* injection gneisses.

The high-grade metamorphic textural equilibration as an event marker

A striking feature of the I–V zone, at least in the high-grade part, was the attainment of a mineralogical and microstructural equilibration at the peak of metamorphism, under granulite facies conditions. The mineral assemblages produced have been described by various authors (e.g. Schmid 1967, Zingg 1980), but we wish to emphasize here the development in almost all rock types (the principal exceptions being the mantle peridotite bodies and some of the intrusive rocks), of a coarse-grained, equigranular or slightly inequigranular microstructure. Lack of optical intragranular strain features indicates that this occurred under low or even zero deviatoric stress conditions (Figs. 3a–d). Structural features of the rocks that are developed on the scale of many grains, however, such as gneissose and compositional banding, or lineations defined by oriented clusters of grains, were preserved during this event. This

Fig. 4. (a) & (b) (Plane polarized light and crossed polars, respectively). Considerable modification of the initial, pre-metamorphic shape fabric by superimposed plastic deformation and dynamic recrystallization of plagioclase in a basic granofels. The 'pinching' of the plagioclase grains by the less deformable mafic phases would be evident in hand specimen. This protomylonitic microstructure is typical of the margins of the high-temperature shear zones. (c) (Plane polarized light.) Typical microstructure of a high temperature metabasic mylonite, showing recrystallized feldspar grains drawn out into bands (white), with resistant garnet and pyroxene porphyroclasts being carried about passively in the flowing matrix. Left-lateral shear band features and asymmetric trails reveal sense of shear. (d) (Backscattered electron image.) Development of oriented symplectites at the relatively extended parts of a garnet grain where it is in contact with clinopyroxene grains (extension direction at a low angle to the long edge of the micrograph). The sample comes from the margin of a 15 m wide ultramylonitic shear zone north of Premosello village. The reaction took place within the granulite facies and records a pressure reduction of *ca* 300 MPa in the direction of extension. gt = garnet, pl = plagioclase, cpx = clinopyroxene. Products inside the symplectite are plagioclase (dark), orthopyroxene (medium grey), spinel (light grey) and Fe-oxide (white).

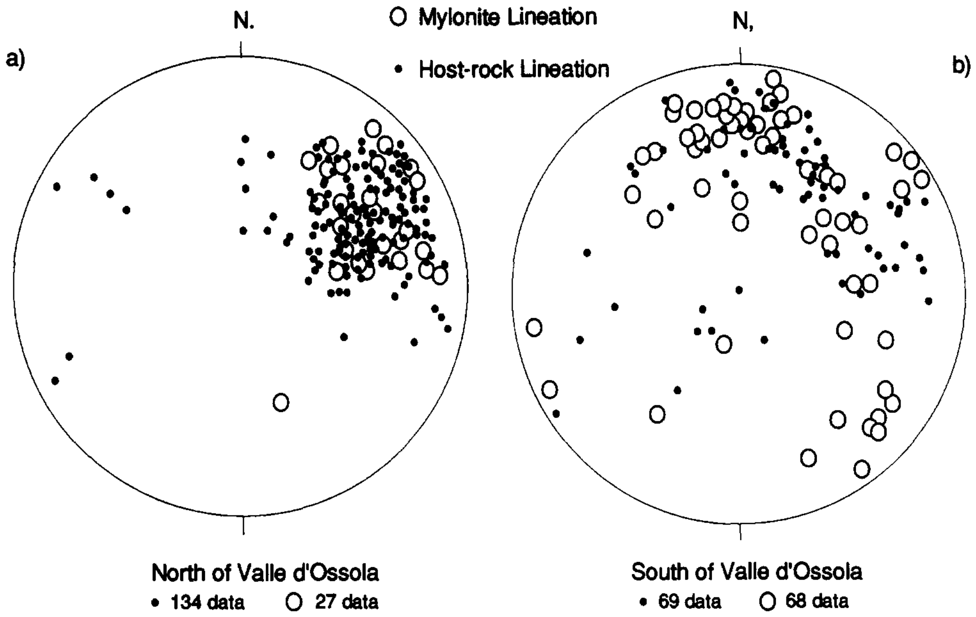


Fig. 5. Equal-area, lower-hemisphere projections showing the correspondence in orientation between plastic mylonite grain elongation lineations and earlier (pre-peak-metamorphism) linear features (best developed in the metasediments). This is interpreted to mean that the same extensional tectonic regime continued throughout the heating and cooling parts of the metamorphic cycle. There is more scatter of data in the region to the south of Valle d'Ossola owing to the deflection of foliations and mylonite belts around the basic intrusive complex.

textural equilibration forms an event marker, and it can be used to distinguish pre-equilibration events from later structural and microstructural histories.

Post-peak-metamorphic structures

During the cooling which followed the late Palaeozoic thermal peak, the region was cut by localized zones of isochemical, isomineralic, high-temperature plastic deformation (Brodie 1981, Brodie & Rutter 1985, 1987) Figs. 4a & b). One of the main aims of the present study has been to discover the regional geometry of these shear zones and the pattern of displacements that they accommodate. Shear sense of the zones can generally be discovered from the geometry of rotated porphyroclasts, development of shear bands or from the rotation sense of the foliation as it develops at the margins of the shear zones.

The shear zones are best seen in the metabasic rocks, but they affect all rock types of the region. They are usually quite sharply bounded, foliated and lineated zones (Fig. 5) of intense strain, involving tectonic grain size reduction (to *ca* 10 μm) by dynamic recrystallization. In the granulite facies metabasic rocks the mafic phases, pyroxenes and garnets, are much more resistant to intracrystalline plastic deformation and are commonly carried about passively in a flowing matrix of fine-grained, recrystallized plagioclase (Fig. 4c). However, large orthopyroxene grains are often elongated through (100) slip, and orthopyroxene often forms a matrix phase dispersed between plagioclase grains. In the hornblende-bearing metabasic rocks limited plasticity and dynamic recrystallization of the amphibole has been observed. In the metasedimentary rocks, quartz and feldspar show intense grain-size reduction by dynamic recrystallization, whereas garnet and sillimanite are fractured and drawn-out in the mylonitic foliation.

In the few instances where pyroxenite bodies are cut by shear zones (e.g. near Premosello village, in Valle d'Ossola), intense plastic deformation and dynamic recrystallization of the pyroxene to less than 10 μm grain size was also seen. Under SEM examination, within these recrystallized zones a fine dispersion of plagioclase grains was noted. It is thought that such dispersed second phases in recrystallized shear zones are responsible for the preservation of very fine grain sizes even at the high temperatures of granulite facies metamorphism.

Few instances have been recorded of the formation of shear zones in the peridotite bodies, resulting in substantial recrystallization of olivine to grain sizes of only a few microns, but a good example is provided by the small mantle peridotite body lying to the west of Premosello (Rutter & Brodie 1988). The small recrystallized grain size implies deformation at 'low' (i.e. crustal, but under granulite facies conditions) temperatures and (initially) high stresses, probably as part of the movements which produced shear zones in the overlying metabasic rocks. These microstructural features are superimposed upon older, higher temperature, coarser grained deformation features, such as were described in detail by Boudier *et al.* (1984) from the Balmuccia peridotite massif.

The high-temperature shear zones range in thickness up to a maximum of a few tens of metres but are commonly less than 10 m. They are often bounded by wider protomylonitic zones of plastic deformation of the country rock. They commonly may develop in braided networks of several shear zone strands, for in some well exposed areas it is common to find several discrete mylonite bands, a few tens of metres apart, with the same movement sense (e.g. in the Strona river below Forno, Fig. 2). In many cases there is a strong tendency for the individual exposures bearing shear zones to line up in tracts in which the shear zones have the same movement geometry. This has been used to define, by interpolation, a conjugate network of high-temperature faults, at a low angle to the regional banding, which systematically accommodate an extension of the sequence parallel to the banding. This confirms further the pattern of behaviour observed by Brodie & Rutter (1987) in the area north of Valle d'Ossola. Thus this fault array would be expected to have caused thinning and cooling of the sequence when the layering was subhorizontal. Compared to the effects of displacements on these highly localized faults, pervasive ductile extension of the rocks in the post-peak-metamorphic period was relatively unimportant. To apply the overworked expression "the ductile lower crust" to these rocks would be a misnomer. Evidence for the high temperature (peak metamorphic and downwards) nature of this plastic deformation is summarized below.

Evidence for the high-temperature nature of the shear zones

(a) From a study of the mineral chemistry and microstructure of the metabasic shear zone exposed 500 m east of Anzola village, Brodie (1981) found that the dynamically recrystallized plagioclase was more calcic than the host feldspar, and that the recrystallized amphibole was more pargasitic than the host grains. Both trends are normally associated with a regional increase in metamorphic grade. In this extensional environment, however, these effects were attributed (Brodie & Rutter 1987) to depressurization together with the juxtaposition of the cooler rocks of the hanging wall against the hotter footwall rocks. Analyses showed that the deformation was isochemical. Brodie & Rutter (1985) described the development of delicate symplectic intergrowths of orthopyroxene + plagioclase from amphibole within the mylonite, implying that high temperatures (granulite facies) outlasted the deformation.

(b) In all of these mylonites the anhydrous, high-grade assemblages remained stable during dynamic recrystallization. In several cases the breakdown of garnet + clinopyroxene in the protolith to orthopyroxene + plagioclase in the matrix of the ultramylonite was observed, indicative of a decrease in pressure but within the granulite facies. In many cases the ultimate persistence of the high-grade mineralogy may only indicate that no water was added, and one would expect the shear zones to develop episodically over a range of pressure–temperature conditions. However, the consistently observed hot work microstructures of the plagioclase indicate that temperatures were high, on the order of 500°C at least (Brodie & Rutter 1985).

(c) From two protomylonites, at Rio del Ponte (on the north side of Valle d'Ossola, near Premosello, and on the eastern flank of Cima Lavaggio, *oriented* symplectites have been discovered, growing between parts of garnet–clinopyroxene interfaces subjected to extension. These show the formation of orthopyroxene carrying oriented 'rods' of plagioclase (Fig. 4d). Their formation is clearly related to the onset of the mylonitization, but it is a down-pressure reaction entirely within the granulite facies with an apparent pressure drop of *ca* 300 MPa in both cases. This represents the clearest evidence of shear zone formation in the granulite facies and suggests strongly that their motion accommodated crustal thinning. It seems unlikely that the entire 300 MPa represents differential stress but if, say, half of it represents overburden removal then the reaction event would correspond to crustal thinning of *ca* 6 km.

(d) From radiometric dating of hornblende from the Anzola mylonite (Brodie *et al.* 1990), the grains of different sizes appear to have closed on the regional cooling curve following the metamorphic peak at about 280 Ma. This suggests that the cooling and mylonitic shearing may be related.

Low-temperature faulting

The I–V zone is cut by numerous late, low-temperature faults, mostly trending sub-parallel to the regional strike. They become less frequent with increasing distance from the Insubric zone. They range from cataclastic faults accompanied by pseudotachylite lenses and veins, to foliated shear zones in which there has been hydrous retrogression of the original granulite or amphibolite facies mineral assemblage to greenschist (or lower) facies assemblages. In the latter case shear bands, cutting the initial foliation at a small angle, or growth-fibre lineations can reveal the direction and sense of displacement on these faults. In the I–V zone, these faults are most commonly down-to-the-northwest dip-slip faults, although occasionally the opposite sense was recorded (see Fig. 6).

The faults and mylonite zones that comprise the Insubric zone itself also form part of this set of structures. The Insubric zone is about 500 m thick, dips at *ca* 45° to the northwest, and generally cuts the more steeply dipping faults which affect the rocks of the underlying I–V zone. Overall, the Insubric fault zone uplifts high *P–T* rocks of the Sesia zone over the I–V zone and towards the southeast. Schmid *et al.* (1987) showed that in the section of the Insubric zone from Valle d'Ossola towards the northeast, the structurally higher mylonites incorporate lenses of Sesia zone-derived rocks which are overthrust onto I–V rocks. The structurally lower mylonites of the Insubric zone incorporate lenses of more-or-less cataclastically damaged and retrogressed rocks derived from the I–V zone, but these have a dominantly right-lateral plus down-to-the-northwest shear-sense. Schmid *et al.* (1987) deduced that the overthrusting of the Sesia units was generally earlier than the right-lateral plus normal-sense dip-slip movements. Lying sandwiched between the Sesia-derived and I–V-derived sheared rocks of the Insubric zone, highly sheared and mylonitized Mesozoic metasedimentary

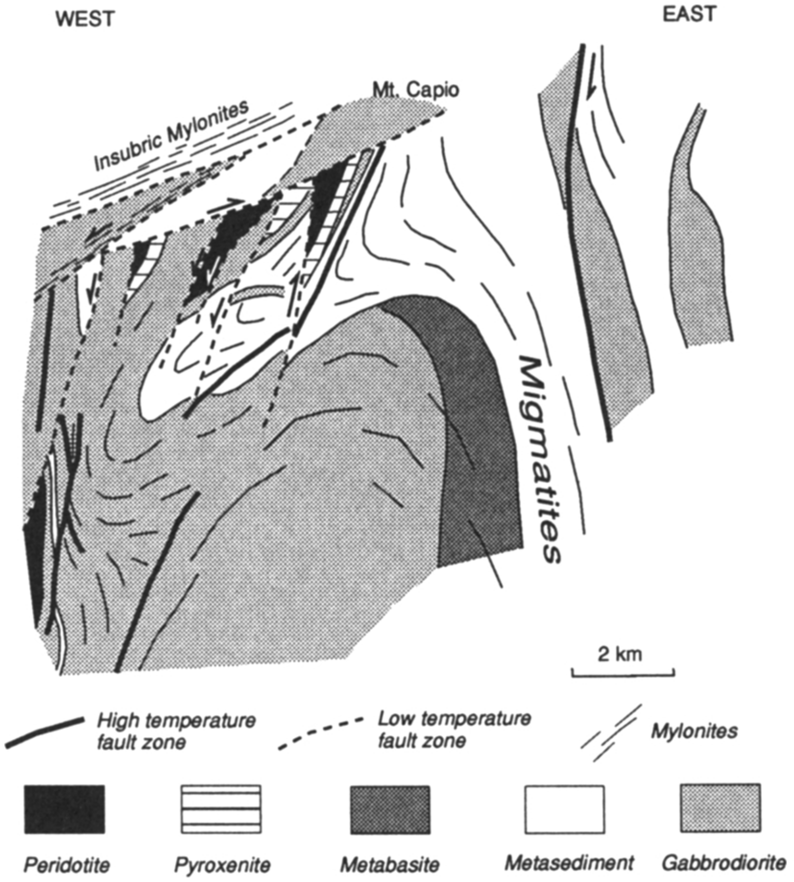


Fig. 6. Schematic E–W vertical cross-section through Mte. Capio, to show the inferred relationships between the steeply W-dipping low temperature faults and the overlying more gently dipping faults and mylonites of the Insubric zone. The steep faults are usually dip-slip, down-to-the-west and are truncated by the overlying fault slices. Structural relationships between the rocks of the I–V zone and the trends of banding–foliation are also illustrated below, projected onto the plane of the section.

rocks (Canavese metasediments) outcrop. Our observations and conclusions in these respects are broadly in accord with those of Schmid *et al.* (1987), made on rocks to the north and east of the Valle d'Ossola. These conclusions may also be extended to include the Insubric zone lying to the south and west from Valle d'Ossola (Fig. 2).

Where the steeply inclined faults cut the layering with a more gentle westerly dip than the layering, they are effectively contractional and can cause repetition of parts of the sequence. For example, the slice of dominantly metabasic rocks lying to the west of the Balmuccia mantle peridotite body is down-faulted from the eastern side of the peridotite, so that the peridotite itself would be repeated if it were not cut out by the more gently W-dipping Insubric fault zone. Also, the complex outcrop pattern of the ultrabasic bodies lying beneath the Mte. Capio thrust slice appears to be due to fault repetitions (Fig. 6). Although the high-grade, northwestern part of the I–V zone is dominated by metabasic rocks, substantial amounts of I–V zone metasedimentary gneiss lie in the fault-bounded lenses of the Insubric zone. It is inferred that in many cases these have been incorporated into this position through down-to-the-west fault displacements.

Late folding

Accommodation of displacements by folding a long time after the metamorphic peak in the I–V zone is uncommon, presumably reflecting the difficulty of plastic deformation in these rocks at low temperatures. Except in the well foliated rocks of the Insubric zone and in the amphibolite grade metasedimentary schists in the southeastern margin of the area we have studied so far, no late small-scale folds were seen. However, some large-scale folding of the regional banding occurs in the granulite grade rocks. At the northern end of the mapped area lies the Proman antiform (Schmid 1967, Brodie & Rutter 1987, Schmid *et al.* 1987) (Fig. 2). This is an isocline with some 3 km of exposed amplitude and a box-shaped profile. Its axial surface dips to the northwest at about 45° and its axis is horizontal. It is truncated at its western end by the Insubric zone. A lower amplitude complementary synform–antiform pair, also affected by faulting, lies to the northwest of the Proman fold. The layer-parallel slip necessary for the development of the Proman fold appears to have been accompanied by sliding along layer-parallel, retrogressive (greenschist grade) shear zones (Brodie & Rutter 1987, Schmid *et al.* 1987).

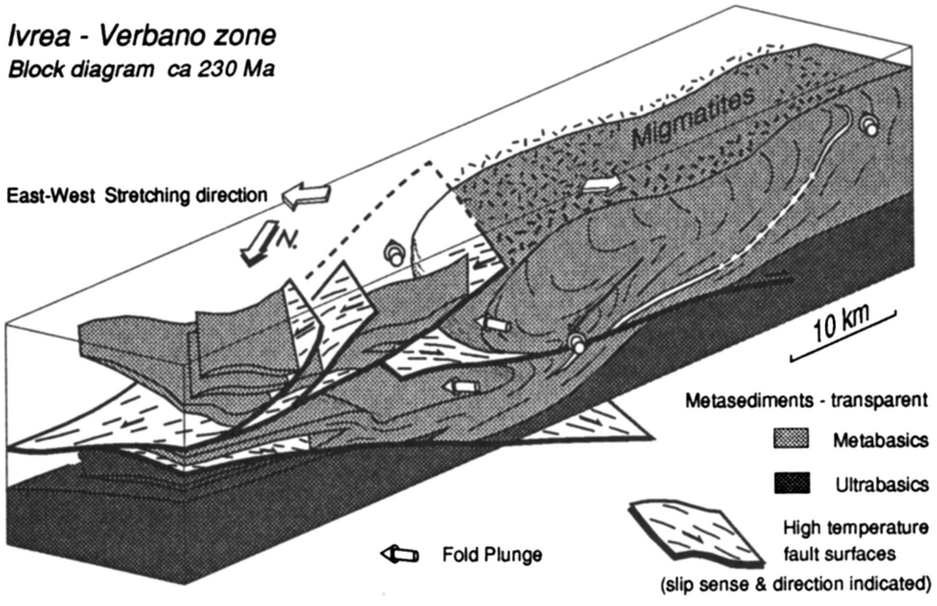


Fig. 7. Block diagram to illustrate schematically the three-dimensional structure of the Ivrea–Verbano zone as it existed at the end of the period of mafic intrusion and crustal extension (Triassic), before its tilting and emplacement into the inner arc of the Alpine orogen. The front right face of the sketch corresponds to the present-day land surface. Traces of compositional layering and foliation are shown on this surface.

Although the above folds are cut by late faults, both types of structure clearly formed under comparable physical conditions, probably during the emplacement of the I–V zone into its present subvertical attitude high in the continental crust (Schmid *et al.* 1987, Zingg *et al.* 1990, Handy & Zingg 1991).

INTERPRETATION OF GEOLOGICAL HISTORY

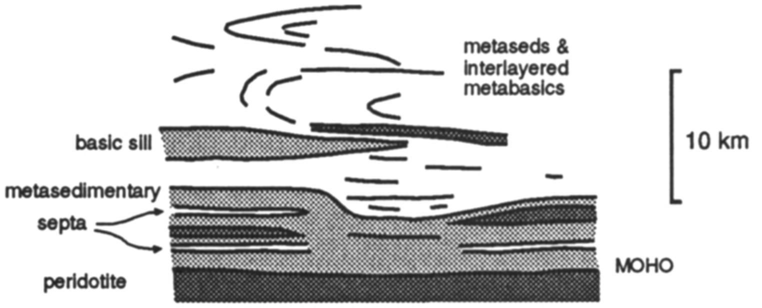
Our interpretation is based upon the geochronological studies which indicate that the intrusion of the rocks of the Mafic Formation occurred at about 280 Ma, some tens of millions of years after the peak of the Hercynian orogeny (Pin 1986, Voshage *et al.* 1990), and that this caused granulite facies metamorphism and large-scale migmatization of the previously deformed and metamorphosed country rocks. The final geometry is illustrated in Fig. 7 and the sequence of events envisaged in Fig. 8. Even before melting of the country rocks, it seems likely that the evolution of further metamorphic water plus the progression of a number of metamorphic reactions would have rendered the country rocks pervasively weak and ductile (Brodie & Rutter 1985). We have previously pointed out (Rutter & Brodie 1990) that there exists no firm basis for estimating the rheological characteristics of rocks in this state, and that experimentally determined constitutive laws for plastic flow are wholly inappropriate.

It is inferred that basic sills would have been sporadically injected into this weakened and ductile lower crust (Fig. 8a), parallel to the (subhorizontal) regional layering, under an overburden pressure of at least 900 MPa (Schmid & Wood 1976). It is not clear what was the overall tectonic environment, but it should be noted that the mineral elongation lineation developed in the country rocks prior to granulite facies equilibration was parallel to the stretching lineation eventually developed in the plastic deformation during the cooling part of the cycle (Fig. 5). The overall tectonic framework may therefore have been the same.

Huppert & Sparks (1988) compared the different patterns of behaviour expected for basic magmas injected in the form of dykes and sills. From dykes, only limited heat transfer to the country rocks can take place by conduction. From sills, the possibility exists of more efficient heat transport through melting of the cover with convective transfer, tending also to reduce the apparent geothermal gradient which might be inferred from the metamorphic mineralogy. Above the thick part of the Mafic Formation in the I–V zone large-scale migmatization has occurred, but in the region (between Sabbia and Mte. Capio) where the Mafic Formation thins, the amount of migmatization becomes less, and the sequence may even have been thickened locally through the segregation of melt as leucocratic layers as described above. It has previously been suggested that granitic liquids extracted from the I–V zone may have provided a source for the Permian (275 Ma) granites of the Serie dei Laghi (Pin 1986, Voshage *et al.* 1990) and Permian volcanics. The gabbrodiorites of the upper part of the Mafic Formation may also have been the source of the compositionally and mineralogically similar gabbrodiorite sheets of the contact region between the I–V zone and the Serie dei Laghi (Boriani *et al.* 1990a).

Whilst the country rocks were initially relatively cool and strong, with a sub-horizontal planar anisotropy, sill injection would have been a favoured mode of intrusion. The high density of basic magma under pressure favours pooling in the lower crust (Herzberg *et al.* 1983), but pressure would have had to be sufficient to lift the overburden. With continued softening of the host rocks we may envisage an event whereby lateral propagation of a sill becomes arrested by 'blunting' of the crack tip, or perhaps a freezing of basic magma in the crack tip region, so that laccolithic inflation of the sill begins, with stretching of the roof region (Fig. 8b). The laccolith would have inflated to more than 10 km high relative to the surrounding upper levels of basic intrusions. Uplift of the surface may have driven erosion sufficiently to expose metamorphic rocks, but may have been limited to some degree by volcanic extrusions, near-surface extensional faulting and the stretching and thinning of the roof of the intrusion.

At the base of the laccolith the overburden pressure would have been *ca* 30 MPa higher than at the same depth outside it. This was apparently sufficient to drive the deformation of the carapace of hot, weak country rocks to allow a gravitational collapse of the side and interior of the laccolith, producing the large, lobe-shaped protrusion of the main gabbro and the underlying isoclinal, recumbent fold. It is inferred that within the gabbro body a gently E-dipping detachment fault developed in the synclinal axial plane region, carrying the main lobe of gabbro over the layered series. This flow is inferred to have been magmatic or immediately



a. Stage One - Sill Injection

b. Stage Two - Laccolithic Inflation

c. Stage Three - Laccolith Collapse and Fault Formation

Fig. 8. Schematic illustration of the inferred sequence of events affecting the lower crustal I–V section through Permo-Triassic time, presented as a sequence of E–W vertical cross-sections (parallel to the regional extension direction after restoration to the horizontal through rotation about an axis parallel to the axis of the Proman antiform). (a) *Stage* 1. Injection of basic and ultrabasic sills into metasediments and metavolcanics which suffered amphibolite facies metamorphism and deformation during the Hercynian orogeny. The temperature of the overlying metapelitic schists rises and local melting begins (*ca* 280 Ma). (b) *Stage* 2. Against a background of regional ductile extension, one of the sills begins to inflate into a laccolith, following softening of the country rocks associated with heating, prograde metamorphic reactions and partial melting. The extra heating causes large-scale migmatization of the cover over the thickest parts of the laccolith. Melt is removed upwards to cause Permian acid volcanism and granitic intrusions in the mid-crust, and sideways as granitic sills. Contamination of the upper part of the laccolith by mixing with country rocks occurs. Some of this melt is removed to form mid-crustal intrusions. Under the stresses arising from lateral density contrasts, the upper part of the laccolith begins to collapse eastwards and northwards (i.e. the displacements are not entirely in the section plane), enveloping part of the carapace of cover rocks in the recumbent fold (*ca* 270 Ma). (c) *Stage* 3. Under subsolidus but still granulite facies conditions, metamorphic mineralogical and microstructural equilibration occurs. Continued regional stretching is accommodated through the formation of localized, high-temperature mylonitic shear zones in conjugate arrays (*ca* 230 Ma), causing depressurization and cooling of the sequence to about 300°C by mid Triassic time.

subsolidus, folding the primary layering and the magmatic grain-shape fabric which developed during the inflationary phase. The non-coaxial character of the folding of the metagabbro body suggests that some of the displacements were out of the plane containing the stretching direction. At the end of this stage the metamorphic mineralogical and textural equilibration would have been largely complete.

In the Val Sessera–Val Strona di Postua region of the outcrop of the Mafic Formation, some 10 km south of the area mapped, Sinigoi *et al.* (1991) described a large, apparently steeply plunging fold which affects sheeted igneous rocks and an included septum of metasedimentary gneiss (possibly the continuation of the gneiss band overlying the Balmuccia peridotite). The trends of folded layering are shown on Fig. 1 (area E), together with a suggested interpolation to the Val Sesia region. It seems most likely that the Val Sessera fold represents a continuation of the initially recumbent synclinal structure which affects the northern part of the Mafic Formation, with the axial region of this fold in the intervening region being replaced by a fault within the magma body.

The next event to affect the rocks of the I–V zone was the formation of the isochemical, high-temperature, plastic shear zones (Fig. 8c). These formed low-angle conjugate networks and systematically extended the sequence. They would have brought about depressurization and the cooling which is recorded in the mineral ages from the region (Bürgi & Klötzli 1990). Symplectite-forming reactions in two shear zones record *ca* 6–12 km of overburden removal, depending on the magnitude of deviatoric stress and the extent of new sedimentation at the surface. No unambiguous offsets of markers are known, but a possible offset of 7 km (2 km vertical) and 1 km can be estimated for the Anzola and Cima Lavaggio ridge shear zones, respectively. Over the length of section studied, and given the observed apparent frequency of occurrence of shear zones, these estimates mean that stretches on the order of × 1.3 may have been accommodated by movements of such shear zones.

The tract of shear zone outcrops which passes through Anzola and Forno can be traced for more than 20 km (Figs. 1 and 2). Their outcrop position suggests that they may have been so localized to allow partial collapse of the cover from the flanks of the laccolith of the Mafic Formation, and hence that in extensional terrains in some cases the formation of basin bounding faults may be localized by step-wise changes in the 'topography' of lower crustal basic intrusive bodies (e.g. Brodie *et al.* 1992).

It would be expected that for post-metamorphic stretching by isochemical plastic deformation, laboratory-determined constitutive flow laws would be most applicable to the description of the mechanical behaviour. This would be true if the stretching was by homogeneous ductile flow to a strain of less than × 1.5. However, the strain is highly localized and the lower crust during this event was *not* homogeneously ductile. The flow properties which are relevant are those of the highly grain-refined mylonites within the shear zones, the rheological characteristics of which have yet to be properly studied by means of laboratory experiments (the general question of the rheology of rocks under lower crustal conditions is reviewed by Rutter & Brodie 1992). From the surface, the fact that the stretching was accommodated on conjugate faults would be indistinguishable from the effects of homogeneous symmetric stretching.

The direction of stretching during this phase is given by the orientation of the mineral elongation lineation in the high-temperature mylonites (Fig. 2). Coincidence of this with the earlier, pre-metamorphic-equilibration mineral lineations in the gneisses (Fig. 5) suggests that this was a continuation of a previously established regional stretching direction. Restoring the region to the horizontal by rotation about a horizontal axis parallel to the overall trend of the I–V zone (also parallel to the axis of the Proman antiform, a fold believed to have formed during emplacement of the I–V zone), the original stretching direction (relative to northern Italian lithosphere) was approximately E–W. This also corresponds to the local extension direction on Permo-Triassic basins (Winterer & Bosellini 1981).

Schmid *et al.* (1987) discussed the emplacement of the I–V zone into its present upended position in the inner arc of the Alpine orogen and related it to the Insubric backthrusting. We do not propose any significant modification of the sequence of events that they proposed. They suggest that the Pogallo extensional fault was active during Triassic–Lower Jurassic time, leading to the lower part of the I–V zone being within 10 km of the surface as a result of Jurassic crustal extension. Curiously, both the Mesozoic and late Palaeozoic extension directions were coincident, but Zingg *et al.* (1990) suggest that despite this, the late Palaeozoic extension occurred within a Permian transtensional tectonic framework, independent of the early Jurassic Tethyan rifting. The crustal section thinned to the west where Mesozoic sediments, now juxtaposed against I–V zone rocks in the Insubric zone, were probably deposited directly upon formerly lower crustal rocks. It is possible that even in the late Palaeozoic era the Moho dipped gently towards the east, for the general sense of vergence of the large-scale fold structures within the Mafic Formation was towards the east, and petrologic evidence suggests that equilibration occurred at slightly higher pressures in the northeast of the I–V zone than the southwest (Zingg *et al.* 1990).

Finally, it will be recalled that the steeply dipping, low-temperature faults of the northwestern part of the I–V zone are generally truncated by the Insubric zone (Figs. 2 and 6). These steep faults have a dominantly down-to-the-west sense of displacement. It is suggested therefore that they developed during the phase of rotation of the I–V lithospheric slab to the vertical, as a means of accommodating extension of the outer arc of the flexure.

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