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Alpine and pre-Alpine tectonics in the Central Orobic Alps (Southern Alps)

By P. FANNY MILANO¹⁾, GIORGIO PENNACCHIONI²⁾ and M. IOLE SPALLA³⁾

ABSTRACT

A sequence of regional deformation episodes is described in the Permian cover and in the metamorphic basement of a portion of the Southern Alps, southeast of Sondrio (Valtellina).

The earliest episode is contemporaneous with low to medium grade metamorphism in the basement; the second episode occurs during low temperature greenschist-facies retrogradation in the basement; these two synmetamorphic regional deformation episodes in the basement are pre-Alpine (probably of Variscan age) and predate the deposition of Permian sediments. Cover and basement are deformed together during a third tectonic episode of post-Triassic age, unrelated to regional metamorphic reactivation, and associated with nappe emplacement and regional folding, that took place at shallow levels of the Southalpine margin during Alpine time.

RIASSUNTO

Viene descritta una sequenza di episodi deformativi che coinvolgono la copertura permiana e il basamento metamorfico in una porzione delle Alpi Meridionali compresa tra la Linea del Porcile e la Valle Armisa (Alpi Orobiche a sudest di Sondrio).

Il primo episodio è contemporaneo, nel basamento, con il metamorfismo di medio-basso grado e il secondo coincide con la retrocessione in facies scisti verdi di bassa temperatura; queste due deformazioni regionali sinmetamorfiche che interessano il basamento sono pre-alpine e precedenti alla deposizione dei sedimenti permiani.

La copertura e il basamento sono coinvolti insieme da una fase deformativa di età post-triassica (terza fase) che non è associata a una riattivazione metamorfica regionale. La terza fase è responsabile dell'impilamento delle falde e del piegamento regionale che avviene a livelli crostali superficiali nel margine sudalpino durante l'orogenesi alpina.

Introduction

This paper deals with the tectono-metamorphic characteristics of a sector of the central part of the Orobic Basement, northern Italy. The studied area, outlined in Figure 1, is located southeast of Sondrio on the southern slope of the Valtellina, between the Orobic and the Porcile tectonic lines (GAETANI & JADOUL 1979; CASTELLARIN & SARTORI 1983). This portion of basement has been mapped together with an adjacent part of the Permo-Carboniferous cover sequences (Collio Formation) along the Seriana

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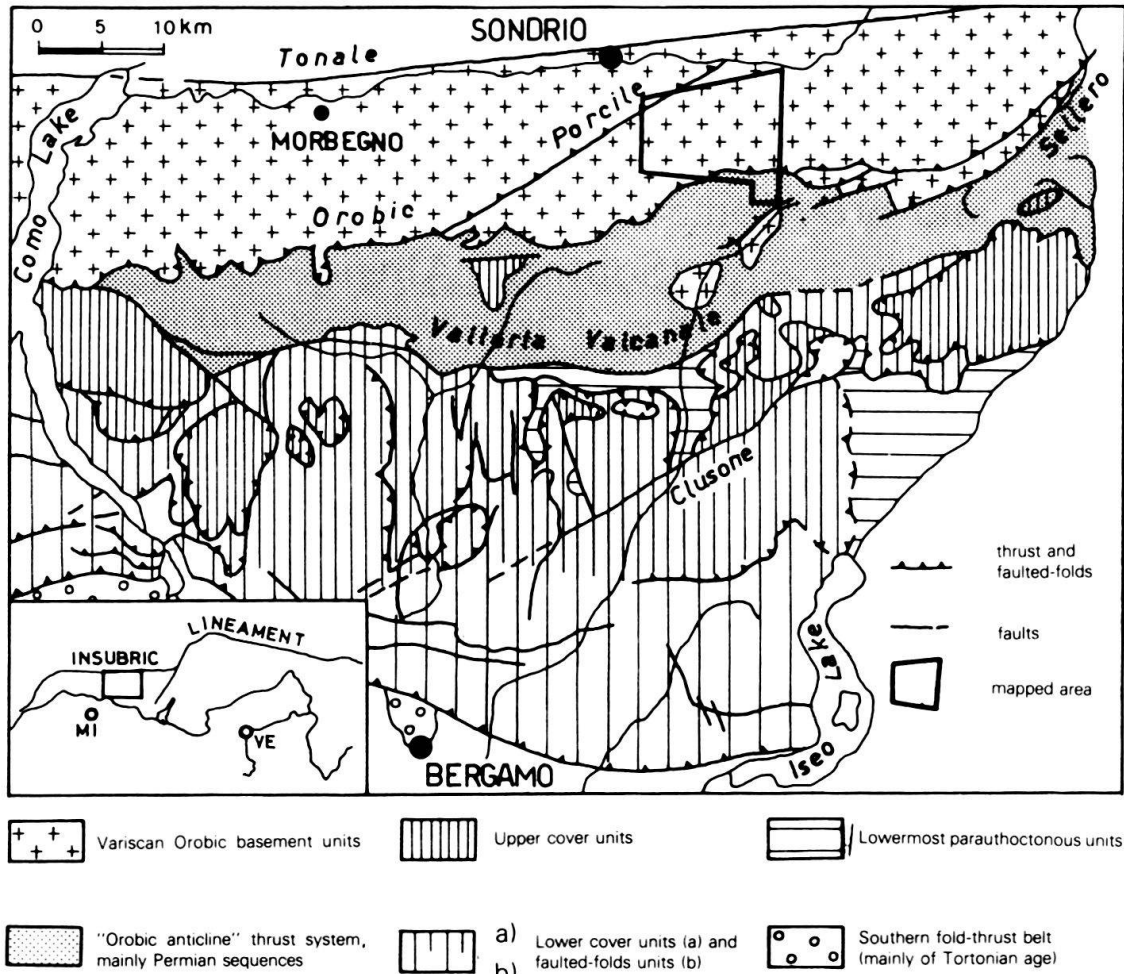


Fig. 1. Tectonic sketch map of the Orobic-Bergamasc portion of the Southern Alps between lakes Como and Iseo, simplified from GAETANI & JADOU (1979), JADOU & ROSSI (1982), CASTELLARIN & SARTORI (1983).

Valley (Bergamasc Alps), with the aim of distinguishing between the Alpine and pre-Alpine deformation within the basement through comparison with the tectonic features imprinted in the cover sequences.

We shall principally summarize the data obtained from the micro- and meso-structural analysis of some selected test areas, which forms the basis for a more extensive tectonic synthesis. Some of these results have already been discussed in CASSINIS et al. (1986).

Geologic setting

The Orobic-Bergamasc Alps occupy the Southern Alpine domain between Lake Como and Valcamonica. To the north, they are separated from the Austroalpine and Penninic domains by the Insubric (Tonale) Line. The northern section of the Orobic-Bergamasc Alps consists of a metamorphic basement of probable Variscan age whereas the southern section is dominated by the Permo-Mesozoic covers; both are involved in the Alpine thrust system (DE SITTER 1963; GAETANI & JADOU 1979; LAUBSCHER 1985) verging south onto the recent deposits of the Po plain.

The structural setting of the Orobic Alps has been interpreted by Dutch authors (DE SITTER & DE SITTER-KOOMANS 1949; DE SITTER 1963; DE JONG 1967) as the result of surficial gravity tectonics. This interpretation was questioned by GAETANI & JADOU (1979) and by CASTELLARIN (1979), who invoked significant crustal shortening and the dominance of compressive tectonics. This view point has been supported recently by BRACK (1981, 1983, 1984) and LAUBSCHER (1985), who worked at the eastern and western margins of the Orobic Alps respectively and adopted kinematic models based on material balance considerations and the concept of thin-skinned tectonics; they propose a total shortening of about 40 km across the north-south section of the Orobic nappe belt.

The metamorphic basement is composed of two main lithological units, derived from psammitic to pelitic sequences of possible Lower Paleozoic age (MOTTANA et al. 1985). The former corresponds to the Morbegno Gneisses of the literature (CORNELIUS 1916), which are principally exposed in the western sector of the Orobic-Bergamasca Alps (Fig. 1). The latter includes the "Edolo Micaschists" and the "Ambria Phyllites" of the previous authors (SALOMON 1901, DOZY 1933). Several bodies of granitic gneiss are associated with these lithologies: they derive from the metamorphic reworking of intrusives of probable late Caledonian age (Pizzo Meriggio Gneiss and Gneiss Chiari) and from other less defined protoliths (locally called Cima Fraitina, Palone di Sopressà, Forno d'Allione and Monte Pedena Gneisses; BELTRAMI et al. 1971; BONSIGNORE et al. 1971). Minor metabasites, metagabbros, marbles and some deformed late-Variscan granitoids also occur.

The deciphered metamorphic evolution in the crystalline basement units of the western portion of the Orobic Alps (Monte Legnone Gneisses, Dervio-Olgiasca Zone, Monte Muggio and Morbegno Gneisses) shows two pre-Alpine events, with medium-grade mineral assemblages of intermediate pressure (BOCCHIO et al. 1980; CRESPI et al. 1980; MOTTANA 1963; MOTTANA et al. 1985), followed by a variably pervasive reequilibration under low temperature greenschist-facies conditions (CASSINIS et al. 1986). The radiometric ages obtained by MOTTANA et al. (1985) are consistent with two pre-Alpine events, though the proposed fitting of absolute ages to the metamorphic events may seem conjectural. The earlier event is interpreted to occur around 430 to 350 my, and the younger at 220 my (MOTTANA et al. 1985). Alpine stilpnomelane growth marks the final uplifting.

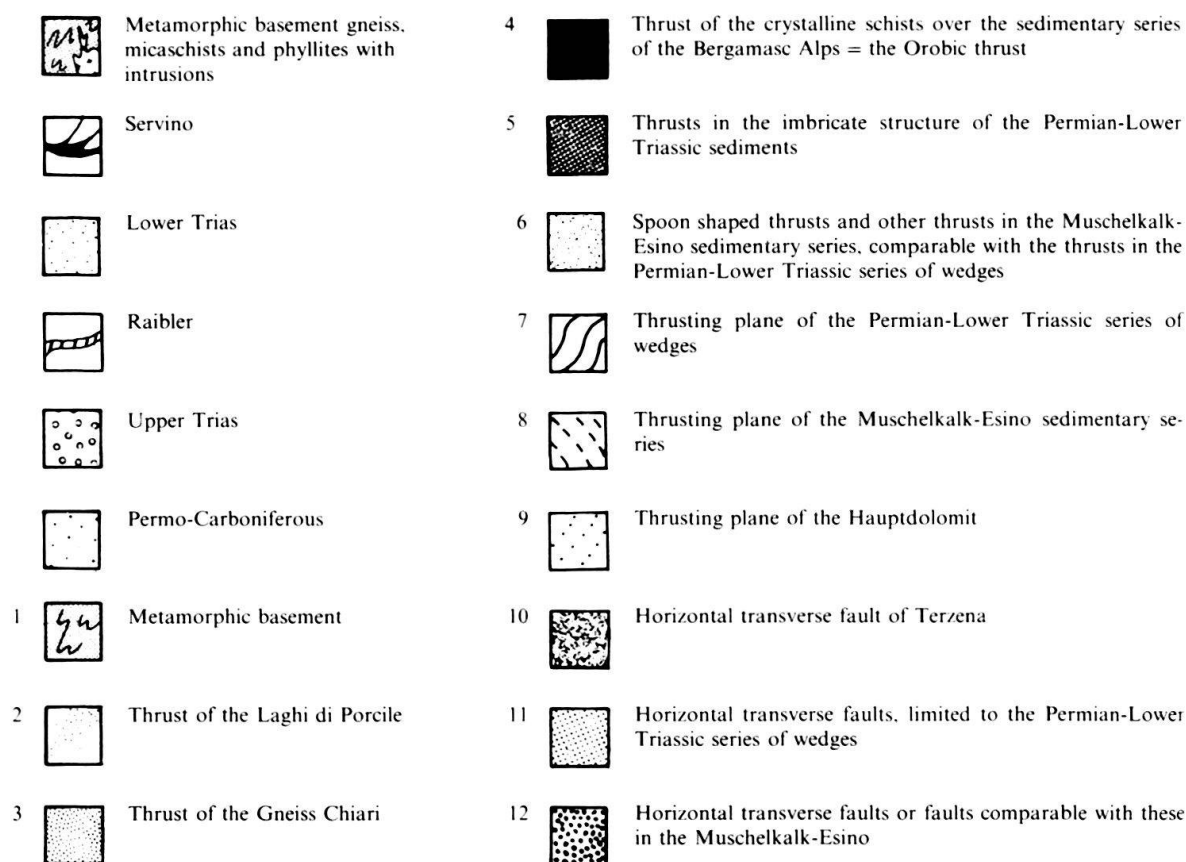
The regional distribution of pre-Alpine mineral assemblages must, however, be evaluated taking the translational alpine tectonics of the basement (WENNEKERS 1932) into consideration (Fig. 2).

An attempt to introduce new objective geological data for defining pre-Alpine and Alpine metamorphic and tectonic events is made here, starting from structural field evidence.

Structural observations

The structural study of this sector of the Orobic basement aims to describe the relationships between regional deformational events and metamorphic evolution using structural mapping and the reconstruction of the detailed geometric setting of the lithologic units and fabric elements in some test areas (TURNER & WEISS 1963; RAMSAY

Fig. 2. Idealized cross section and block diagram (tectonogram) of the Bergamasc Alps reported from WENNEKERS (1932) (here redrawn).



1967; HOBBS et al. 1976; HUBER et al. 1980). Form surface maps have been compiled for regions displaying superposed folds and foliations. Most of the mesostructural work was performed in a deglaciated valley near Bocchette di Santo Stefano (Sheet 19.III.N. W.; I. G. M.)⁴).

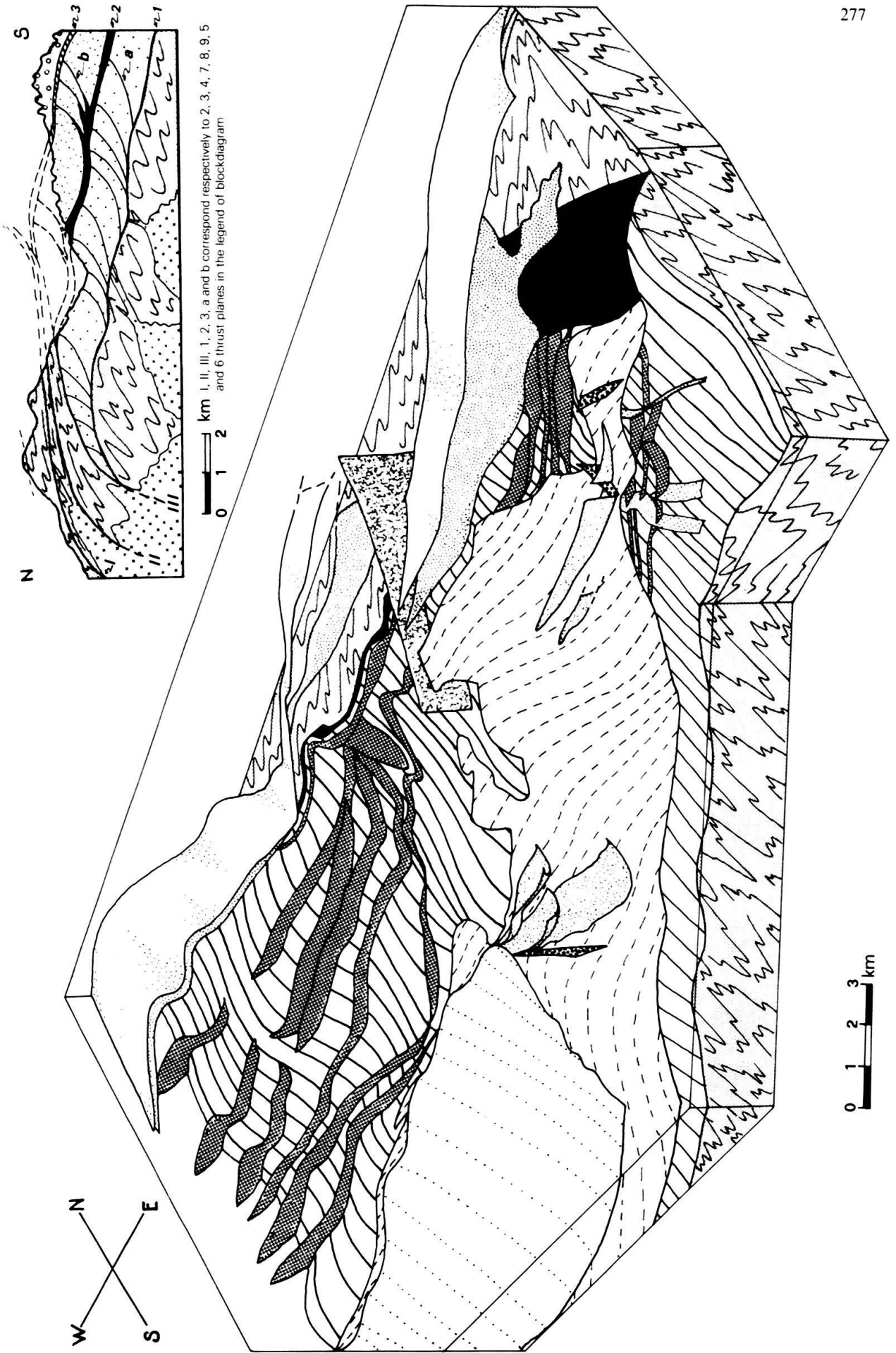
The degree of exposure is good, and in the “Edolo Micaschists”, quartzitic intercalations are frequent and represent useful spatial markers. The form surface map compiled for this area (original 1:500 or greater scale) is redrawn schematically in Figure 3.

Meso-scale structures

In the basement, four generations of superposed structures (folds and foliations) can be distinguished on the basis of overprinting criteria. The morphology of the fold sets (F1–F4) can be summarized as follows:

- F1 fold structures are small-scale rootless folds; they are revealed by superposition or by the inconsistent sense of asymmetry of minor folds on the F2 fold limbs. A pervasive axial plane foliation, mostly of crenulation cleavage type, is associated

⁴) Topographical names refer to the maps at 1:25,000 scale issued by the Istituto Geografico Militare, Florence, Italy.



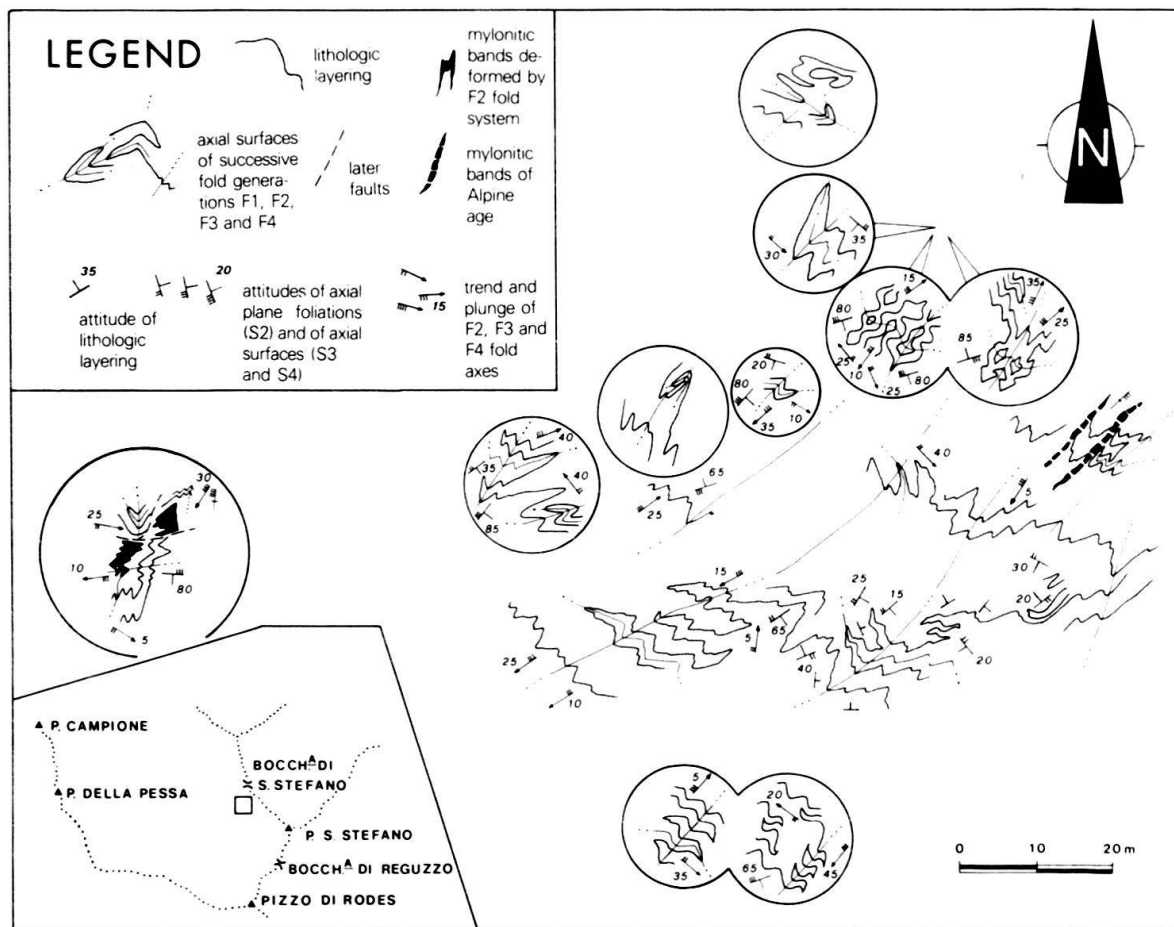


Fig. 3. Fold interference patterns in the "Edolo Micaschists", with interlayered quartzites, at Bocchetta di Santo Stefano. The orientation of mesoscopic fabric elements shows that fold axes of the earlier two phases (F1 and F2) are nearly coaxial; their interference patterns are of type 3 (RAMSAY 1967). F2 and F3 folds have axial surfaces nearly perpendicular and interference patterns of type 2.

with this structure, possibly implying the existence of a still earlier foliation-forming deformation event. F1 fold systems can be rarely reconstructed over more than a few meters; however some km-scale F1 structures do exist and contribute to the overall architecture of this basement sector (see the inset of Fig. 12).

- F2 fold structures are tight to isoclinal folds, specially marked by swarms of quartzite layers or by Pizzo Meriggio Gneiss; a differentiated, crenulation cleavage type foliation is developed in the mica-rich levels of the "Edolo Micaschists", while the F2 schistosity is less prominent in the interlayered quartzites. Frequently a pervasive mineral-stretching lineation is preserved at a low angle to F2 fold axes; this lineation predates F2. The axial plane surfaces are subhorizontal to moderately inclined, due to orientation by the F3 deformation. The F2 axes trend is frequently around north-south.
- F3 fold structures generally have a typical chevron geometry in the quartzites, grading into a kink-type in the more micaceous levels; the fold morphology is strictly dependent on the lithological association and relative layer thickness. Conjugate

kink band sets and box folds are often observed. This accounts for a dispersion of about 60° for the F3 fold axes. The variation in strike of the axial surface is controlled by the original attitude of layering and schistosity, due to the preexisting fabrics. Axial plane surfaces are generally subvertical or steeply dipping to north or south (conjugate folds).

The Permo-Carboniferous cover sequences of the Collio Formation, outcropping in the southern sector, is consistently deformed by fold sets which are in continuity with the F3 basement folds; for the latter an Alpine age is therefore deduced. F1 and F2 deformation patterns of the basement do not occur in the Permo-Carboniferous cover; their age may be implied to be pre-Alpine. In the sedimentary cover a regional slaty cleavage is associated with the F3 folds. This cleavage is defined in thin section by a planar fabric of the white micas, mostly driven by pressure solution. Axial plane-related mylonitic zones and faults commonly develop both in the basement and in the cover, and are therefore associated with this folding. Triassic sediments (Carniola di Bovegno) are pinched within the mylonitic zones of the basement (Passo di Portorella). These features are interpreted to be related to stages of Alpine thrusting and polyphase nappe formation in the Southalpine domain. A considerable internal strain took place in the prisms between the thrust planes, as demonstrated by intense folding.



Fig. 4. Fracture cleavage in quartzites of the "Edolo Micaschists" representing the latest Alpine deformation fabric (F4). The cleavage planes may locally be sealed by quartz and/or siderite and pressure solution of quartz and micas may be observed microscopically (Bocchetta di Santo Stefano).

Two groups of andesite dykes are present. One of these predates F3 fold structures that are cut by the second group. The intrusion of the second group of dykes is probably related to Tertiary calcalkaline magmatic activity developed along the Periadriatic lineament.

- F4 structures are locally discontinuous and are revealed by a regular waving of the preexisting fabrics, associated with a centimeter-spaced fracture cleavage (Fig. 4); the axial plane orientation trends roughly around NE–SW with a subvertical dip.

The geometric relationships and the relative chronology between the four fold groups occurring within the basement are indicated by consistent types of interference patterns at the outcrop scale.

The F1 and F2 folds generally show overprinting patterns of type 3 of RAMSAY (1967) (Fig. 5).

Type 2 interference patterns, or more rarely type 3, occur due to superposition of F3 folds on the older phases (Fig. 6, 7, 8). Type 3 patterns occur where the third phase axial trend shows the largest deviation from the predominant east–west trend (Fig. 9).

We therefore deduce that the two pre-Alpine fold sets are approximately coaxial, but with a large angle between the axial surfaces. In contrast the angle between the F3 and F2 axes range from 90° to 40° , and the axial surfaces are roughly perpendicular.

The block diagram of Figure 10 summarizes schematically the three-dimensional geometry of the polyphase structure (F1 + F2 + F3).



Fig. 5



Fig. 6



Fig. 7



Fig. 8



Fig. 9

Fig. 5, 6, 7, 8, 9. Types of interference patterns in the quartzites of the "Edolo Micaschists" at Bocchetta di Santo Stefano. 5 = type 3 of RAMSAY (1967) formed by F2 and F1 folds; 6 = type 2 pattern formed by F3 and F2 folds, on a topographic surface at 90° from the former, in the same outcrop; 7, 8 = type 2 pattern formed by F3 and F2 or F1 folds; 9 = type 3 pattern formed by F3 and F2 folds.

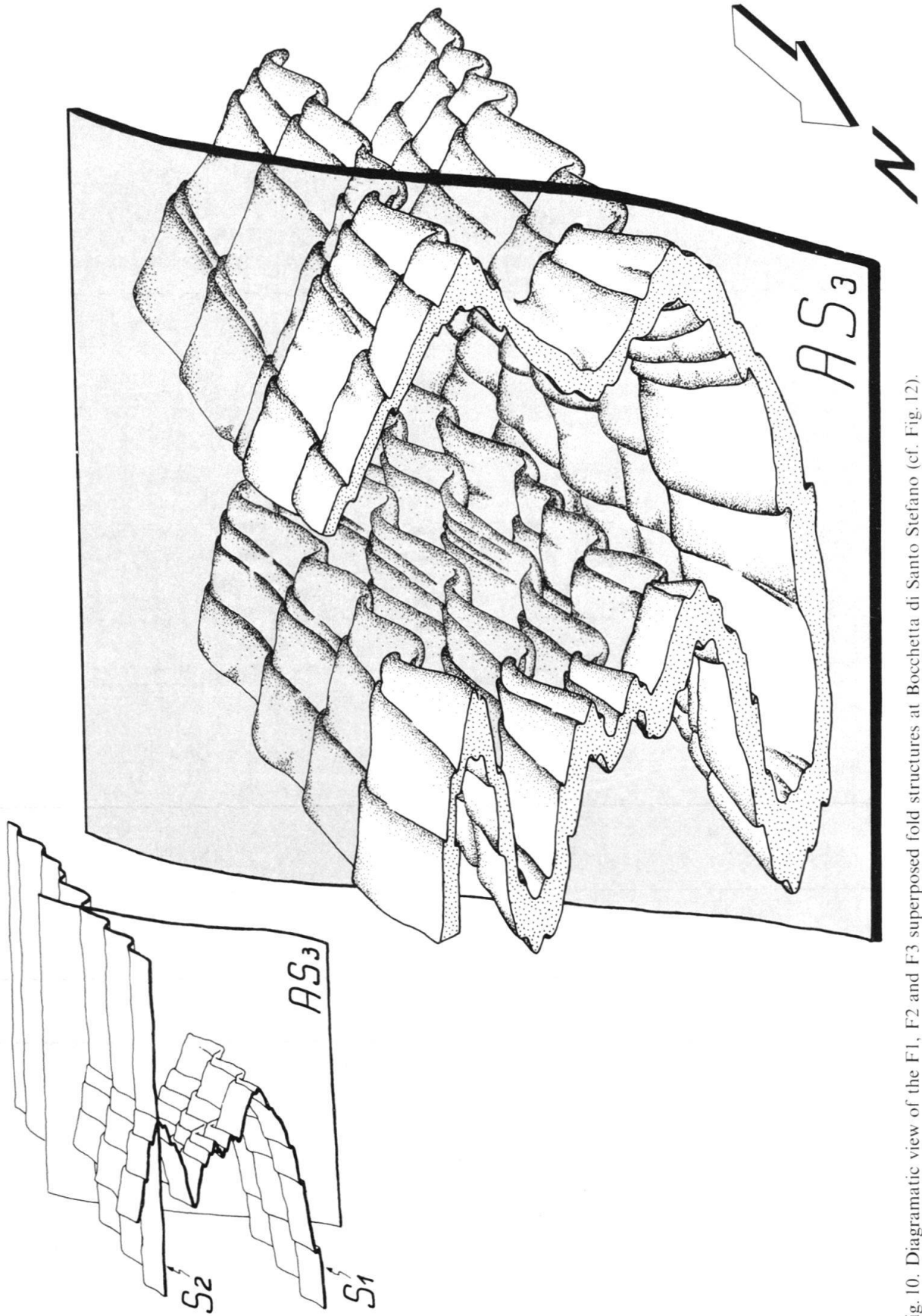


Fig. 10. Diagrammatic view of the F1, F2 and F3 superposed fold structures at Bocchetta di Santo Stefano (cf. Fig. 12).

Mylonite zones

Mylonites of two different ages are distinguished on micro- and mesostructural criteria. The more recent group exists both in the basement and in the Permo-Carboniferous cover and is associated with the F3 folding phase; it forms narrow discontinuous bands at a low angle to the F3 axial surfaces. These mylonitic bands contain sheath-like folds, which have never been found in the surrounding rocks. The Permo-Carboniferous cover is decoupled from the basement in varying degrees by mylonitic zones (décollement), which are associated with the F3 group of structures. They form



Fig. 11. Type 3 pattern of fold interference occurring on a mylonitic level in the "Edolo Micaschists" and predating F2 fold structures. The mylonite band is offset by later faults (Bocchetta di Santo Stefano).

at a low angle to the lithologic layering within the basal levels of the cover; the mylonitic bands located at the sole of the cover may be occasionally folded by the F3 folds. These mylonites generally lack significant recrystallization and cataclastic textures are common.

The earlier group occurs exclusively in the basement and consists of blastomylonites (Fig. 11). Discontinuous bands, up to several meters thick, are extensively folded by the F2 fold group. No clearcut evidence of F1 folds overprinting the mylonites of the basement was found. The mylonitic layering inside the bands is folded into sheath-like structures. These mylonites are impregnated by carbonates, making them quite distinctive in the field. Albitization of the country rock at the mylonite border is frequent, as it is in the lenticular lithologic remnants preserved within the zone.

Other types of mylonites, less continuous in the field and never affected by active blastomylonitic recrystallization, may represent traces of the surficial tectonic activity that ensured the opening of the Permo-Mesozoic basins.

Mega-scale structure

The lithological association of quartzite swarms and gneissic bands (Pizzo Meriggio Gneisses and Gneiss Chiari) with micaschists and paragneisses suggest a number of megascopic folds of complex shape (Fig. 12). These are observed in vertical views or in

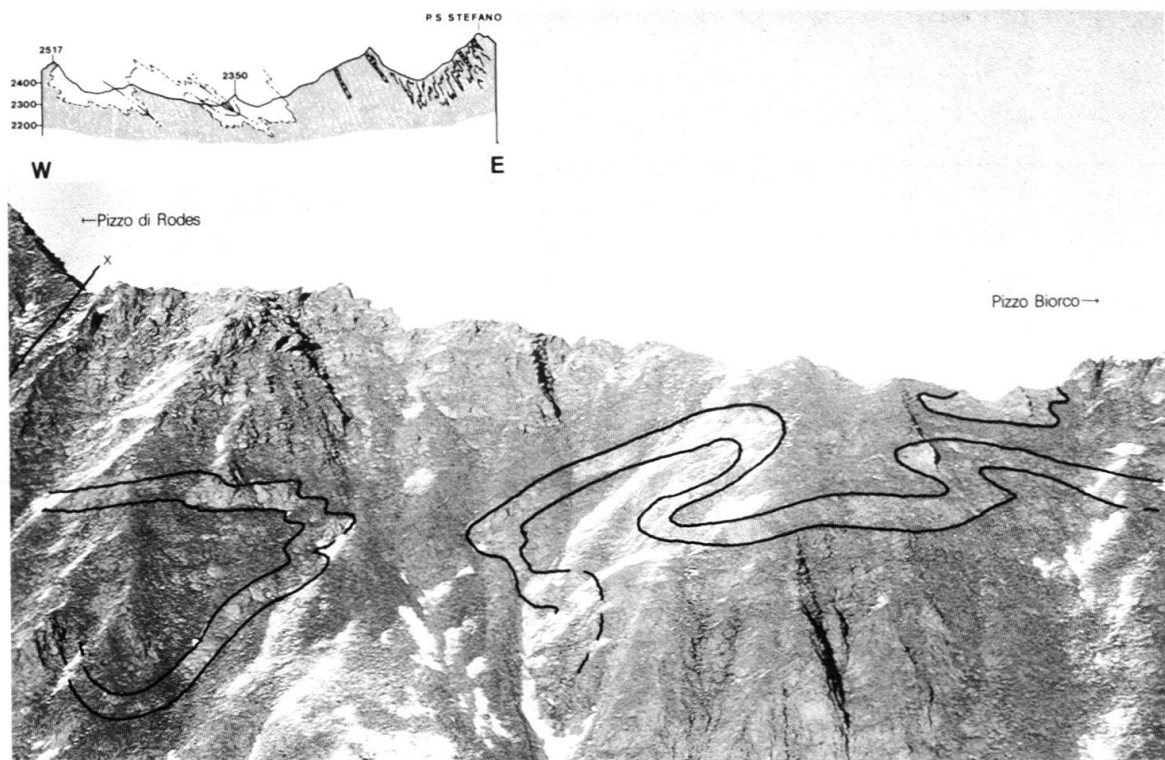


Fig. 12. Megascopic mushroom pattern in felsic levels within the Morbegno Gneisses on the Pizzo di Rodes–Pizzo Biorco ridge. The pattern represented in the photograph corresponds to a superposition of F2 on F1 folds, as in the inset, representing a northern section and corresponds to Figure 3 in CASSINIS et al. (1986).

maps and cross sections (see inset of Fig. 12). Their orientation and shape mimic the set of small scale interference patterns shown by the superposition of the earliest two groups of folds of pre-Alpine age. The intrusive protoliths of the tabular bodies of Pizzo Meriggio Gneisses and Gneiss Chiari therefore predate these earlier folding phases.

Other prominent megastructures are related to the regional fold system occurring within the Permian cover, in association with mylonitic bands and folds. The prolongation of this fold system from the cover into the underlying metamorphic basement may be seen in the vertical geology; the foliation is geometrically related to these folds and is easily correlated with the F3 chevron folds in the basement. Faulting and formation of mylonitic zones during this phase, within the cover and at its sole, are multistage: F3 folds may deform duplications of the same lithostratigraphic levels and the intervening mylonites. Regional folding of the basement in each thrusting episode of the cover cannot be demonstrated. The F3 basement folds occur as conjugate sets of different orientation. Most probably the F3 tectonization of the metamorphic basement of Alpine age should not therefore be regarded as occurring over a relatively short span of time; the mylonites between basement and cover are locally folded by structures of F3 age.

Microstructural observations

In the previous section the pre-Alpine regional structural features of the metamorphic basement were distinguished by comparison with the structural character of the Permo-Carboniferous cover. The primary interest in the microstructural analysis has been to determine the relationships between mineral growth and deformation of the basement rocks during pre-Alpine time. Current analytical criteria are taken into account (FERGUSON & HARTE 1975; VERNON 1976, 1977, 1978; VERNON & POWELL 1976) by considering critically the range of processes that may give rise to the same microstructure. Relative ages of microstructural features such as cleavages and mineral layerings, are derived exclusively from regional field evidence.

Edolo Micaschists and Ambria Phyllites

These two rock definitions from the literature are compositionally equivalent; on petrographical ground the rock types traditionally called "Ambria Phyllites" may be considered more retrograded into low temperature greenschists facies than those called "Edolo Micaschists". The microscopic data are in accordance with those already gathered in the field; in the area considered here the two types are intermingled at the kilometer scale.

The two types are well foliated rocks, very often phyllitic, with interlayered quartzite swarms. They show a low grade metamorphic imprint (WINKLER 1979) with an assemblage of garnet, red-brown biotite and white mica. This assemblage may be followed locally by albite, chlorite, epidote and green biotite.

The mineralogical association – white mica, quartz, garnet, red-brown biotite (I), albite, chlorite, epidote, green biotite (II), carbonates, opaques, apatite, tourmaline and zircon – dominates in the more phyllitic types.

The earliest two regional deformation phases (F1 and F2, pre-Alpine) are associated with mineral growth and the development of foliations. The third phase (F3, Alpine) occurs without new mineral growth (Fig. 13); the mesoscopic kinking or gentle waving of the foliations is accompanied microscopically by grain boundary migration of preexisting grains. The last phase (F4), showing in the field a local fracture cleavage at a high angle to the pre-existing foliation, is associated with passive rotation and dissolution of phyllosilicates.

Garnet and red-brown biotite (I) generally predate the S2 foliation (Fig. 13/1). Biotite (I) shows dissolved boundaries (Fig. 13/2); its dimensional orientation is parallel and {001} is transversal to the S2 crenulation cleavage; chlorite grows within the {001} planes. The biotite is therefore considered to predate the S2 foliation (e.g. BELL 1979).

Moreover, biotite (I) and garnet grow in contact, with rational boundaries. This seems to suggest that low grade conditions were attained before the onset of S2.

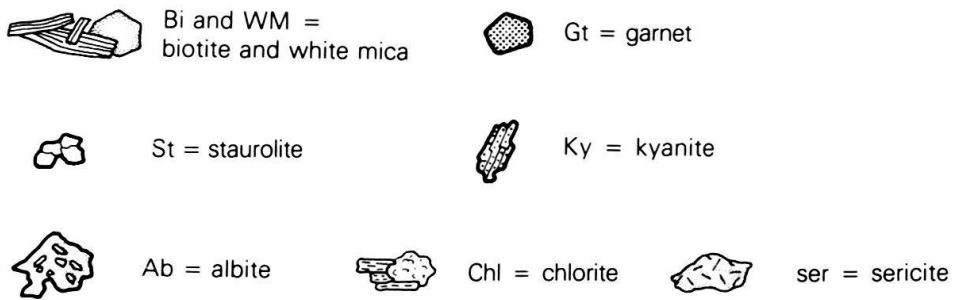
In the relict sites of the S1 mineral layering, within the S2 quartz-rich microlithons, the white mica grains recrystallized into very fine multigranular aggregates.

The metamorphic retrogradation is indicated by recrystallization of white mica in the S2 mica-rich films, by the growth of chlorite and albite, and more rarely of green biotite (II). Chlorite partially replaces garnet and biotite, and forms in the pressure shadows of garnet and within the new white mica layers of the S2 foliation. Albite overgrows the white mica grains aligned either in the S1 or in the S2 foliations. It is therefore postkinematic with respect to S2 and is locally deformed by F3 kink bands (Fig. 13/3). Green biotite (II) grows into openings along the {001} of the white micas.

Pizzo Meriggio Gneisses

Previous interpretations refer the origin of these augengneisses to porphyric intrusives (DOZY 1933) or to mylonites that underwent feldspatization (LIBORIO in MOTTANA 1963); these rocks are classical augengneisses with a variably pronounced

Fig. 13. Synthetic assemblage of some of microstructurally significant relationships between mineral blastesis and the three deformational phases (F1, F2 and F3). The various porphyroblasts are from different thin sections of "Edolo Micaschists" and Morbegno Gneisses. They are represented together for the sake of clearness. Relative scale is approximately retained. 1 = Prevalence of chlorite along the S2 foliation planes and chloritization of relict biotite, bent within the microlithon arcs. Garnet abuts and is replaced against the S2 planes. 2 = Single relict grain of red-brown biotite dimensionally elongated along the S2 foliation. The latter is chlorite-rich. The {001} planes of biotite are non parallel and form a 60° angle with the S2 foliation; its margins are lobate due to dissolution; chloritization proceeds in the biotite grains along openings in the {001} planes. Other biotite grains with the {001} parallel to the S2 chlorite films are not corroded. 3 = Kinked albite grain overgrowing the S2 foliations, marked by aligned grains of rectangular quartz and by phyllosilicates. Kinking orientation is consistent with the F3 deformation. 4 = Semi-inclusion of red-brown biotite within garnet ("moulded structure"); the overall state of the moulded biotite grain is rational. 5 = Microshear zone, parallel to S2, crosscutting staurolite porphyroblast. Along the shear zone white mica replaced staurolite. 6 = Microboudinage of staurolite in S2 foliation; the "neck zones" are filled by white micas. 7 = Large porphyroblast of staurolite including euhedral, smaller sized, garnet; both are replaced almost completely by white mica and chlorite. Staurolite growth terminated after that of the included garnet. S2 foliation crosscuts staurolite; chlorite and white mica grow along S2 microshear in the porphyroblast. 8 = Porphyroblasts of staurolite pseudomorphically replaced by white mica, which seem to have overgrown S1. 9 = Kyanite transverse to the S1 foliation. Replacement products (white mica) flow in the S2 foliation.



mineral layering and K-feldspar porphyroclasts. Their microstructural evolution is compatible with that of the "Ambria Phyllites" (or "Edolo Micaschists").

Their mineralogical association is: quartz, microcline, albite, white mica, garnet, red-brown biotite (I), chlorite, green biotite (II), apatite, tourmaline and opaques. Chessboard albite often pseudomorphically replaces microcline. The occurrence of the later mineral and of relictic intrusive textures and mesoscopic xenoliths (southwest slope of the P.ta della Pessa, 2180 m) supports an intrusive origin for these rocks.

In the Pizzo Meriggio Gneisses the assemblage garnet, biotite (I) and white mica, prelates the second deformation phase; garnet and biotite show the same microstructural relationships as in the "Edolo Micaschists".

The retrogradation is marked by the appearance of green biotite and chlorite, and by the recrystallization of white mica, during the onset of the S2 crenulation cleavage; albite postdates the S2 foliation and is deformed by F3 structures. Chlorite and green biotite (II) are located in the identical microstructural position as in the "Edolo Micaschists".

Dispersions of tourmaline with a microstructure predating F3 and related in the field to mylonitic bands indicate episodes of fluid introduction during the pre-Alpine history of the basement; they are locally present in the northern Venina Valley.

Amphibolites

The structure of these rocks is foliated or mylonitic and their mineralogical composition suggests an origin from Fe-gabbros.

Two amphibole generations occur (I and II), together with garnet, red-brown biotite, white mica, quartz, zoisite/clinozoisite, albite, chlorite, carbonates, apatite, rutile, titanite and opaques. Albite may be rimmed by oligoclase.

These metagabbros do not readily reproduce the same deformation sequence recorded in the other rocks, thus preventing an equivalent microstructural study. Their metamorphic evolution, however, shows even in this case a late episode of retrogradation.

Relics of brown hornblende, probably magmatic, are replaced by amphibole (I) (pargasitic). The latter is kinked and microboudinaged and may be extensively replaced by chlorite and white mica. Amphibole (I) and its pseudomorphically replaced sites maintain a preferred orientation. Amphibole (II) (Fe-actinolite) is dimensionally smaller and oriented transverse to amphibole (I), from which it may nucleate; it is microboudinaged and crossed by microshear zones. The growth of chlorite, white mica and amphibole (II) seems to be contemporaneous.

Garnet occurs in porphyroblasts or in small granular seams, and is replaced by chlorite.

Biotite often postdates amphibole (I) and is, in turn, replaced by chlorite.

Clinozoisite, amphibole (II), albite and chlorite are dominant in the retrograded types; in these cases opaques replace rutile and sphene.

Other types of amphibolites were locally observed in the field, as small pods within the previously described metagabbros; the mineralogical association zoisite, tremolite, Mg-chlorite, albite and sphene might suggest an origin from Mg-gabbros.

Blastomylonites

Under the microscope these units display a recrystallization of minerals of the low grade assemblage (namely of garnet and biotite). The protoliths were probably rocks of phyllitic composition.

Further stages of mineral growth took place in these mylonites during the low pressure greenschist reequilibration. Albite-oligoclase, white mica, chlorite, quartz, carbonates and opaques overprint the mylonitic texture.

Morbegno Gneisses

These rocks are banded paragneisses with the mineral association: quartz, white mica, albite/oligoclase, garnet, red-brown biotite (I), staurolite, kyanite, chlorite, green biotite (II), rutile and opaques.

The microstructural setting of these rocks was investigated in a test area that was mapped in detail, and is located west of the test area of the "Ambria Phyllites" near Pizzo dello Scoltador (Val Venina). The mesostructure is coherent with the succession of deformational events recorded in the phyllites and Pizzo Meriggio Gneisses.

A major difference of the Morbegno Gneisses from the lithologies of the "Scisti di Edolo" and "Ambria Phyllites" is the occurrence of kyanite-, staurolite- and garnet-bearing assemblages, proving that they underwent medium grade metamorphism, interkinematic to the F1-F2 deformation phases.

The relationships between garnet and biotite can be interpreted either as a contemporaneous growth or as a growth of biotite later than garnet. Moulded types of structures were actually observed (see Fig. 2 in VERNON 1977), that may suggest a coexistence or a later growth of the semi-included phase (Fig. 13/4). In other cases porphyroblastic garnets occur, with large biotites in their pressure shadows.

Biotite is oriented parallel to S₂ and forms intergrowths with the white mica; in the S₁ relict microlithons polygonal arcs of biotite are still preserved. In some cases biotite is located within the pressure shadows of staurolite. The former is aligned dimensionally parallel to S₂, but with a transverse crystallographic orientation; chlorite grows along {001} of biotite and the chlorite laths are oriented parallel to S₂. Staurolite is often crossed by microshear zones, with growth of white mica + chlorite, positioned parallel to S₂ (Fig. 13/5).

The occurrence of small-sized garnet inside the staurolite grains apparently suggests that the staurolite growth postdates that of garnet; staurolite and garnet may also have grown contemporaneously in competition (VERNON 1978). It is, however, probable that staurolite terminated its growth after the included garnets.

The relationships between staurolite and the S₂ foliation are relatively clear and suggest that staurolite predates the F₂ deformation phase. This pattern is later overprinted by F₃ deformation (Fig. 13/6-7).

Less clearcut are the relationships between the S₁ foliation and staurolite growth. In one case an S₁, marked by white micas, seems to be overgrown by staurolite (Fig. 13/8). This pattern cannot, however, be considered to be diagnostic, since staurolite is completely replaced by sericite and the sericitization obliterates a possible internal foliation of the porphyroblasts.

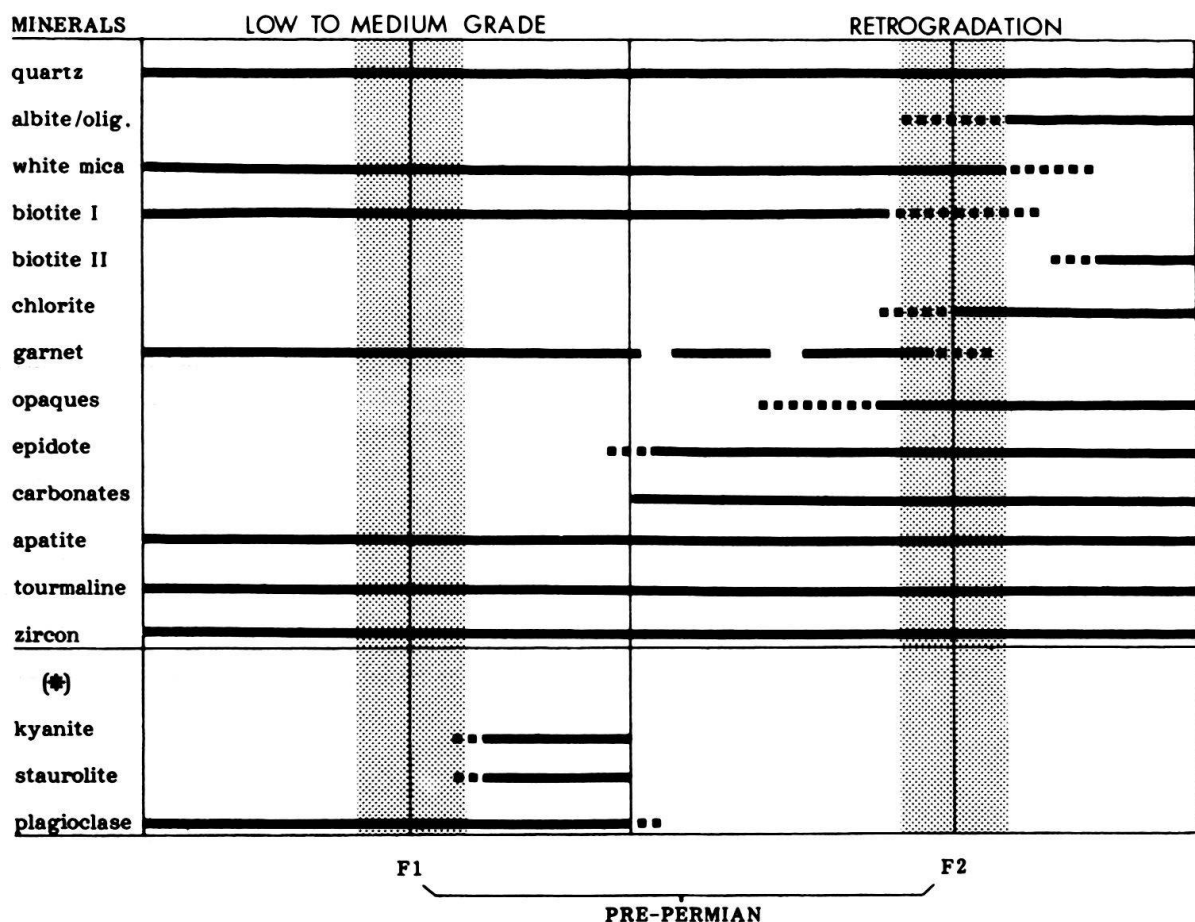
Kyanite appears to have formed before S2 and is located transverse to S1 in the relictic microlithons (Fig. 13/9); the replacement overgrowths of the prevailing white mica flow into the S2 mineral layering.

No other microstructures were observed in which the relationships between kyanite and the other medium grade minerals could be elucidated.

The occurrence of plagioclase may be noted, including myrmekitic quartz and with deformation twins; it appears to be texturally earlier than the porphyroblastic albite, developing at the expenses of white micas of the F2 foliation.

Discussion of the microstructural observations

A coherent scheme of textural evolution can be determined in the various lithologies of the sector of the Orobic Alps between the Armisa and Livrio valleys and the Orobic and Porcile tectonic lines. A synoptic scheme of the mineral growth and deformation relationships is presented for the paragneisses and phyllites in Figure 14.



(*) phases present only in Morbegno Gneisses

Fig. 14. "Edolo Micaschists" and Morbegno Gneisses.

The occurrence of staurolite and kyanite in local areas of the Morbegno Gneisses may be explained by the bulk compositional difference of some paragneisses with respect to others (HOSCHEK 1967) or, more probably, to a local change in the P–T conditions. The kyanite-staurolite association is indicative of $P > 4.5$ kb (e.g. HOLDAWAY 1971; RICHARDSON et al. 1969) and $T > 530^\circ\text{C}$.

The microstructural study, which integrates a previous more general work on this area (CASSINIS et al. 1986), indicates the interkinematic growth of kyanite and most probably also of staurolite between the two oldest regional deformation events of pre-Alpine age.

The assemblages grown during medium grade conditions invariably predate the structural features generated by the F2 deformation phase.

Garnet and biotite relationships are interpreted as partly contemporaneous; those between staurolite and biotite show that the latter grew continuously till the pre-F2 metamorphic stage. Only garnet continues growing, in some cases, during F2 deformation.

Retrogradation under low temperature greenschist facies conditions is contemporaneous with the F2 deformation phase. A further mineral growth stage of albite and white micas exists; the latter are oriented in the S2 foliation. Chlorite nucleates within the openings along the {001} planes of biotite and white micas and in intergrowth with newly-formed sericite as replacements of garnet.

The F3 deformation phase is not associated with any detectable metamorphic reactivation of the microstructure.

Concluding remarks

Two main periods of deformation are recorded in this region of the Orobic Alps. The earliest is confined to the basement and is subdivided into two episodes (F1 and F2); F1 takes place at deep crustal levels compatible with regional metamorphism (climax conditions are $P > 4.5$ kb and $T > 530^\circ\text{C}$). Greenschist retrogradation is coeval with the F2 episode. The more recent episode F3 (locally followed by F4) corresponds to a non-metamorphic and near-surface tectonic reactivation of basement slices into a thrust system involving the Permo-Carboniferous cover, in the studied area. Local stratigraphy of the sector considered here indicates a post-Triassic age as a maximum dating; the regional extension of the thrust grid shows pinching of Triassic horizons within mylonitic zones (Passo di Portorella); the F3 episode of deformation can be therefore indicated as Alpine.

Pre-Alpine low to medium grade metamorphism takes place with the F1 regional folding and terminates before F2 deformation.

The greenschist retrogradation occurs during F2 deformation of the basement and predates the deposition of the Permian sequences.

The Alpine thrust deformation of coupled sheets (Fig. 2) of basement and covers is non-metamorphic; the associated mylonitic zones are not affected by granular scale recrystallization.

Pre-Alpine mylonitic zones exist in the basement and are affected by low grade metamorphism and F2 regional folding with associated retrogradation.

The existence of two metamorphic events and three main tectonic episodes in this part of the Orobic Alps, and the ability to demonstrate their interrelationships suggests caution when elaborating regional information on metamorphic assemblages and fitting them into zonal distributions without considering regional pre-Alpine deformation and Alpine thrusting. F2 deformation as regional mega-folds and pre-F2 mylonites may be responsible for a basic redistribution of preexisting metamorphic patterns.

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