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The structure, age and kinematics of the Pogallo Fault Zone; Southern Alps, northwestern Italy

By MARK R. HANDY[1])

ABSTRACT

The Pogallo Fault Zone is a km-wide ductile shear zone within paragneisses of the southern part of the Ivrea Zone. The Pogallo Line comprises the SE margin of the Pogallo Ductile Fault Zone (PDFZ) and forms part of the mutual boundary between the Ivrea and Strona–Ceneri basement units. Metamorphic and microfabric trends within the southern Ivrea Zone lead to the interpretation of the PDFZ as an inclined, deep crustal shear zone, with originally deeper parts of the zone presently exposed in the northeast than in the southwest. Structural relations and a correlation of estimated temperatures in the Pogallo tectonites with the radiometrically derived cooling history of the Ivrea and Strona–Ceneri Zones indicate that the Pogallo Ductile Fault Zone was active during the Late Triassic to the Early to Middle Jurassic. Sense of shear indicators reveal that the Pogallo deformation involved an oblique-sinistral shear in present-day coordinates (i.e. the Ivrea Zone was uplifted and displaced to the southwest with respect to the Strona–Ceneri Zone). When the Ivrea–Strona–Ceneri basement-section is restored to its pre-Alpine orientation, the Pogallo Ductile Fault Zone becomes a moderate to low angle, SE-dipping oblique-extensional fault that accommodated E–W directed extension. This is consistent with stratigraphic evidence in the Southern Alps of rapid differential subsidence associated with E–W attenuation of the upper crust beginning in the Late Triassic to Early Jurassic.

ZUSAMMENFASSUNG

Die Pogallo Linie trennt die Ivrea Zone von der Strona–Ceneri Zone und bildet den Südost-Rand einer ca. 1 km breiten Bewegungszone innerhalb der südlichen Ivrea Zone, der sogenannten «Pogallo ductile fault zone» (PDFZ). Die Foliation der PDFZ ist subparallel zu den kristalloblastischen Planarstrukturen der Ivrea Zone, schneidet jedoch die Schieferung und Stoffbänderung der Strona–Ceneri Zone diskordant ab. Gegen Nordosten verschwindet die strukturelle Diskordanz zwischen der Ivrea und der Strona–Ceneri Zone und damit auch die Pogallo Linie.

Gefüge und synkinematischer Metamorphosegrad der PDFZ zeigen eine systematische Entwicklung sowohl im Streichen wie auch senkrecht zur Bewegungszone. Die Deformation begann unter retrograder Amphibolitfazies auf einer Breite von ca. 1 km und konzentrierte sich zunehmend auf den Südost-Rand der PDFZ, wo schliesslich grünschieferfazielle Mylonite und Kataklasite der Pogallo Linie gebildet wurden. Höher temperierte Deformations-Gefüge im NE (mittlere Amphibolitfazies) als im SW (Amphibolit- bis Grünschieferfazies) deuten auf die primär tiefere strukturelle Lage des nordöstlichen Teils der PDFZ hin.

Die Pogallo Deformation überprägt permo-karbonische Granodiorite und Granite, die an der Grenze zwischen Ivrea und Strona–Ceneri Zone auftreten und ist somit jünger als diese. Aus dem Vergleich der abgeschätzten Temperaturen der Pogallo Deformation und der mit radiometrischen Daten belegten Abkühlungsgeschichte ergibt sich ein spät-triadisches bis früh- bis mitteljurassisches Alter der Pogallo-Bewegungszone.

Bezogen auf die heutigen Koordinaten, zeigen Strukturen der Pogallo-Tektonite eine Hebung gekoppelt mit einer SW-Versetzung des Nordblocks (Ivrea-Block) relativ zum Südblock (Strona–Ceneri-Block). Durch eine Rotation aller gefüglichen Elemente in ihrer ursprünglichen prä-alpinen Lage, wird die PDFZ zu einem mässig bis flach gegen SE einfallenden Extensionsbruch mit E–W gerichteter Extension. Die Interpretation der Pogallo

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Bewegungszone als frühmesozoische Dehnungsstruktur im Grenzbereich der mittleren und tiefen Kruste stimmt mit stratigraphischen Evidenzen in den Südalpen überein. Im frühen Jura bilden sich NNE streichende Becken und Schwellen aus, im Zusammenhang mit der Öffnung der Tethys.

RIASSUNTO

La Zona della faglia di Pogallo è un'area di scorrimento duttile large 1 km che convolge paragneiss affioranti nella parte meridionale della Zona di Ivrea. La linea di Pogallo comprende il margine Sud-Orientale della Zona della Faglia Duttile di Pogallo (PDFZ) e constituisce una parte del contatto tra l'Unità del basamento di Ivrea de l'Unità del basamento di Strona–Ceneri. In base al tipo di metamorfismo (sintettonico) e alle caratteristiche strutturali della parte meridionale della Zona di Ivrea, la PDFZ può essere interpretata come un zona di scorrimento inclinata di derivazione crostale profonda, le cui parti originarimente più profonde affiorano attualmente nel settore NE.

Relazioni strutturali e correlazioni tra i valori di temperatura stimati nelle tettoniti di Pogallo con dati radiometricamente attenuti, relativi all'evoluzione termica (raffredamento) della Zone di Ivrea e Strona–Ceneri indicano che l'attività della PDFZ puo essere collocata in un lassi di tempo fra il Triassico Superiore e Giurassico Inferiore. Indicatori della direzione della scorrimento rivelano che la deformazione di Pogallo è riconducibile ad uno scorrimento obliquo sinistro in riferimento ad un sistema di coordinate attuali (un fatti la Zona di Ivrea ha subito un sollevamento e una dislocazione in direzione SW rispetto alla Zona die Strona–Ceneri). Se si ricostruisce la sezione del Basamento Ivrea–Strona–Ceneri in base alla sua orientazione originaria, precedente alla deformazione Alpina ne risulta che la PDFZ diventa una faglia normale con asse di distensione E–W che imerge verso SE con un angulo moderato. Questo è in accordo con i dati stratigrafici relativi alle Alpi Meridionali, i quali testimoniano una rapida subsidenza differenziale associata ad un assottigliamento della crosta superiore iniziato nel Triassico Superiore–Giurassico Inferiore.

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Introduction

The Pogallo Line forms part of the boundary between two major lithotectonic units of the Southern Alpine basement: the Ivrea Zone in the NW and the Strona–Ceneri Zone in the SE (Plate). Together, these basement units are generally regarded as a section through the pre-Alpine metamorphosed, intermediate to lower continental crust.

Early descriptions of the contact between the Ivrea and Strona–Ceneri Zones in the lower Val d'Ossola revealed the presence of a wide variety of tectonites, ranging from cataclasites, low- to medium-grade mylonites (PEYRONEL PAGLIANI & BORIANI 1962) and penetrative ductile deformation in Late Paleozoic intrusives (HUTTENLOCHER 1950; SCHILLING 1957). Subsequent mapping showed that these tectonites (now known to comprise the Pogallo Line) extend along the Ivrea–Strona–Ceneri contact from the lower Val d'Ossola through the Val Grande as far northeast as Monte Piota, between the upper reaches of the Val Pogallo and the Val Cannobina (Plate; BORIANI 1970a, 1971; BORIANI & SACCHI 1973).

The Pogallo Line has been the object of several tectonic interpretations:

(1) According to BORIANI & SACCHI (1973) and BORIANI et al. (1977), the Pogallo Line is a Late Variscan transcurrent fault that was active during the intrusion of the Late Paleozoic Baveno granites. The emplacement of pre-granitic, dioritic intrusives along the Ivrea–Strona–Ceneri contact was thought to be concomitant with the activity of an older tectonic line, the Cossato–Mergozzo–Brissago Line (CMB Line), which is purportedly truncated by the Pogallo Line. More recently, BORIANI & SACCHI (1985) propose that activity of the Pogallo and CMB Lines pre-dates both the dioritic and granitic intrusives.

In this study, the Pogallo Line was found to form part of a ca. 1 km wide ductile fault zone (the Pogallo Ductile Fault Zone, or PDFZ) within paragneisses comprising the southern part of the Ivrea Zone. The Pogallo deformation affects, and thus, clearly post-dates Late Paleozoic intrusives cropping out in the lower Val d'Ossola.

(2) KÖPPEL (1974) relates movements along the Ivrea–Strona–Ceneri contact to Variscan uplift and overthrust of the mantle (i.e. to the emplacement of the geophysical «Ivrea Body»). ZINGG (1983) notes the attainment of low (300° ± 50 °C) temperatures in the Ivrea Zone during the Early Jurassic and speculates that greenschist facies mylonites of the Pogallo Line may be related either to Early Mesozoic rifting (in this context, see FERRARA & INNOCENTI 1974, and LAUBSCHER & BERNOULLI 1982) or to Alpine tectonic events. The contrasting pre-Alpine thermal evolutions of the Ivrea and Strona–Ceneri Zones and the preservation of Mesozoic extensional structures in the Southern Alps lead HODGES & FOUNTAIN (1984) to propose that the Pogallo Line is a Late Triassic to Early Jurassic, low-angle normal fault with up to 15 km of stratigraphic throw.

The structural and metamorphic relationships presented here indicate that the Pogallo Fault Zone accommodated oblique, E–W directed extension during the Late Triassic to Early to Middle Jurassic. The present map-view of the Pogallo Fault Zone resulted from rotation of the Ivrea–Strona–Ceneri basement-section during Early Mesozoic crustal thinning and again during Tertiary Insubric backfolding and strike-slip faulting (S. M. SCHMID et al. 1987).

This article summarizes the main results of detailed structural investigation along the Pogallo Line and in the adjacent Ivrea and Strona–Ceneri Zones of the Verbano area, north of the Lago Maggiore (Fig. 1). Emphasis is placed on establishing the age, conditions and kinematics of the Pogallo deformation. A more comprehensive report (HANDY 1986) on the structural and metamorphic history of the area, as well as on the use of quartz microfabrics in determining the conditions of deformation in the Pogallo Fault Zone is available on request from the author. The final section is an attempt to integrate

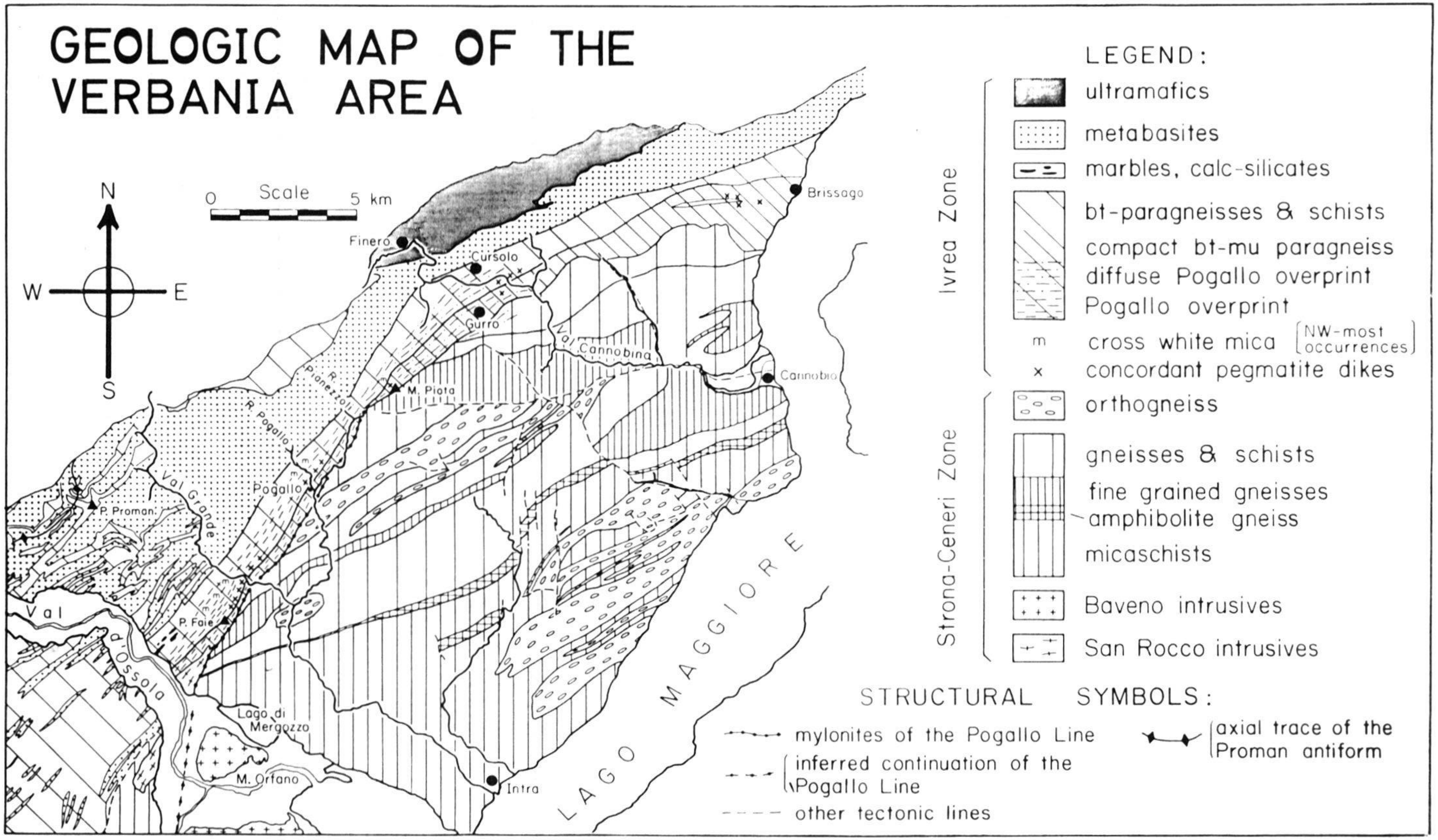


Fig. 1. Geologic map of the Verbania area; Map constructed using own data and the following maps: HERMANN (1937), Geologische Generalkarte der Schweiz (1955); R. SCHMID (1967), BORIANI et al. (1977).

the local structural information with the general geological evolution of the Southern Alps.

2. Geologic setting

The Ivrea and Strona–Ceneri basement-units are widely considered to represent a section of the intermediate to lower Southern Alpine continental crust, with progressively deeper structural levels exposed towards the NW (review in ZINGG 1983). This view is based on extensive geophysical investigation (e.g. GRGES 1968; FOUNTAIN 1976) as well as on lithologic and metamorphic trends in the two zones.

The NW portion of the Ivrea Zone contains metabasic rocks and ultrabasic lenses while the SE part of the zone (i.e. the part containing the Pogallo Fault Zone) consists of paragneisses with subordinate intercalations of amphibolite and marble (Plate).

The Strona–Ceneri Zone is comprised primarily of paragneisses, schists and tonalitic to granitic orthogneisses. Both basement units are separated from outcrops of Permo-Mesozoic sedimentary cover to the south by the Cremosina Line (Plate).

Regional metamorphic studies in the Ivrea Zone indicate a metamorphic gradient perpendicular to the strike of the Zone, with middle amphibolite facies in the SE increasing to granulite facies conditions in the NW (PEYRONEL PAGLIANI & BORIANI 1967; R. SCHMID 1967). BORIANI et al. (1977) note a similar, albeit more poorly documented metamorphic gradient across the Strona–Ceneri Zone from lower amphibolite facies in the SE to mid-amphibolite facies in the NW, adjacent to the Ivrea Zone.

The ages obtained for this regional metamorphism depend on the isotopic system employed, the size of the sample taken, and on the assumptions made about the systems diffusional characteristics (For a discussion of current interpretations in the literature, see ZINGG 1983). Peak metamorphic conditions in both the Ivrea and the Strona–Ceneri Zones occurred during the Paleozoic (Rb-Sr whole-rock ages, HUNZIKER & ZINGG 1980; BORIANI et al. 1982/83). The successively later closure of different mineral isotopic systems (U-Pb monazite, Rb-Sr and K-Ar muscovite) is interpreted to document cooling into the Early Jurassic, when Rb-Sr and K-Ar biotite systems in the Ivrea Zone and parts of the Strona–Ceneri Zone reached their ca. 300 °C closing temperature (HUNZIKER 1974, KÖPPEL 1974, HUNZIKER & ZINGG 1980). In contrast to whole-rock ages on large samples, radiometric mineral ages vary with location in the basement-section: Monazite and mica-ages are younger in the Ivrea Zone than in the Strona–Ceneri Zone. Particularly striking in this regard is the distribution of biotite ages (Plate): Early to Middle Jurassic ages prevail in the Ivrea Zone and the northern part of the Strona–Ceneri Zone, but increase from Permo-Triassic to Carboniferous towards the SE within the Strona–Ceneri Zone (MCDOWELL 1970). Interestingly, the change from Permo-Triassic to Early Jurassic biotite ages coincides with the Pogallo Line in the Val d'Ossola region, but occurs within the northern Strona–Ceneri Zone further to the NE in the Brissago region (Plate).

This study reveals that the jump in radiometric ages across the Pogallo Line corresponds to contrasting microfabric-development in the southern Ivrea and northern Strona–Ceneri Zones. The implications that this transition in microfabrics and radiometric mineral ages has for dating the movements of the Pogallo Fault Zone are addressed in the last section.

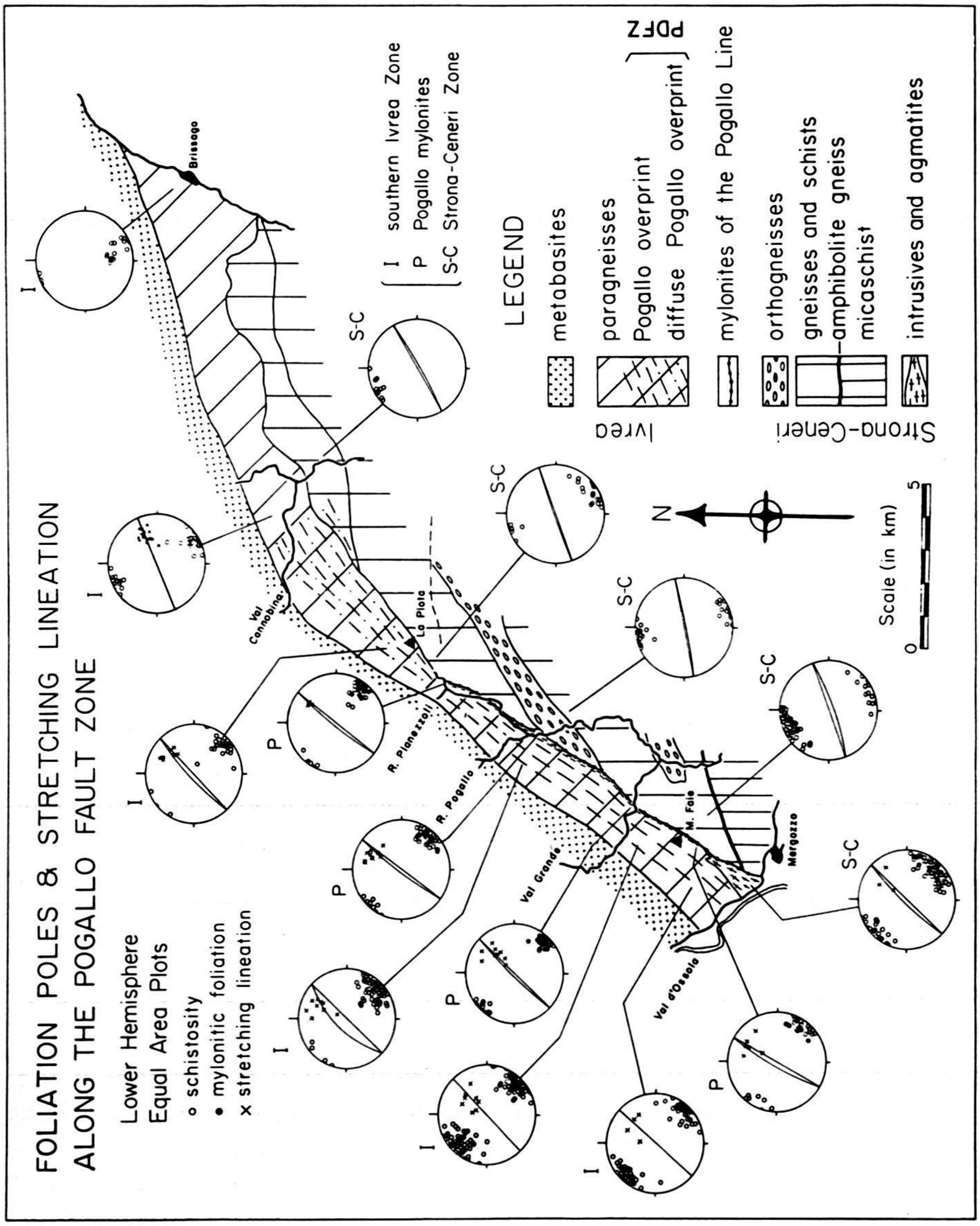


Fig. 2. Foliation poles and stretching lineations along the Pogallo Fault Zone.

3. Mesostructures

3.1 General structural relationships

General mesostructural relations along the Pogallo Fault Zone are shown in Figure 2 and depicted schematically in Figure 3. Schistosity in the Ivrea Zone trends NE–SW and dips subvertically. This orientation is subparallel to the mylonitic foliation of the Pogallo Line, but discordant to the foliation in those parts of the Strona–Ceneri Zone adjacent to the Pogallo Line (Fig. 1 and 2). The Strona–Ceneri schistosity trends ENE–WSW and generally dips subvertically to steeply to the SE. All structures (i.e. folds and foliation) in the Strona–Ceneri Zone are truncated by, and therefore predate, the Pogallo Line.

In the region from the Val d'Ossola to the Val Pogallo, the regional angular discordance between the Ivrea and Strona–Ceneri schistosities is approximately 30° and coincides with the Pogallo Line. This discordance decreases to about 10–15° to the east of Pogallo in the R. Pianezzoli. East of the R. Pianezzoli, the transition in the orientation of the schistosity from the Strona–Ceneri to the Ivrea Zones is gradational and the contact between the two Zones is no longer marked by the Pogallo Line (Fig. 2). From SW to NE, the Ivrea schistosity acquires a more ENE–WSW orientation. In both the Ivrea and the Strona–Ceneri Zones, compositional banding is usually parallel to the schistosity, although local discordances sometimes occur.

The schistosity in the Pogallo Ductile Fault Zone (PDFZ) is generally coplanar with the pre-Pogallo foliation outside of the PDFZ in the southern part of the Ivrea Zone. Thus, the relative age of the Ivrea schistosity in various parts of the Zone cannot be determined from geometric criteria alone. Microfabric and metamorphic studies (next section) are necessary to distinguish those parts of the Ivrea Zone that are strongly overprinted by the Pogallo deformation from areas further to the north which are only affected locally and/or to a limited extent by this deformation.

3.2 Pre-Pogallo Structures

Pre-Pogallo structures in the Ivrea and Strona–Ceneri Zones constrain the deformational history of the area, especially when considered in the context of the microfabrics (next section) and radiometric mineral ages in the literature. These structures will be mentioned only briefly here, since they are thoroughly described in HANDY (1986).

3.2.1 Ivrea Zone

Pre-Pogallo folds (F1b in Fig. 3) in rocks of the southern Ivrea Zone that are unaffected by the Pogallo deformation are open to close (with an interlimb angle of 30–80°) and have half-amplitudes on the cm, meter, and tens-of-meters scales (Fig. 4a). Their fold axes generally plunge moderately to shallowly to the NE, parallel to a well-defined intersection lineation (L1b). This lineation, ubiquitous in the rocks of the southern Ivrea Zone, is formed by the intersection of the dominant pre-Pogallo schistosity (S1a) with the folds' axial plane schistosity (S1b).

The pre-Pogallo age of these folds is based on: (1) their association with partly equilibrated amphibolite facies microfabrics which are progressively overprinted to the

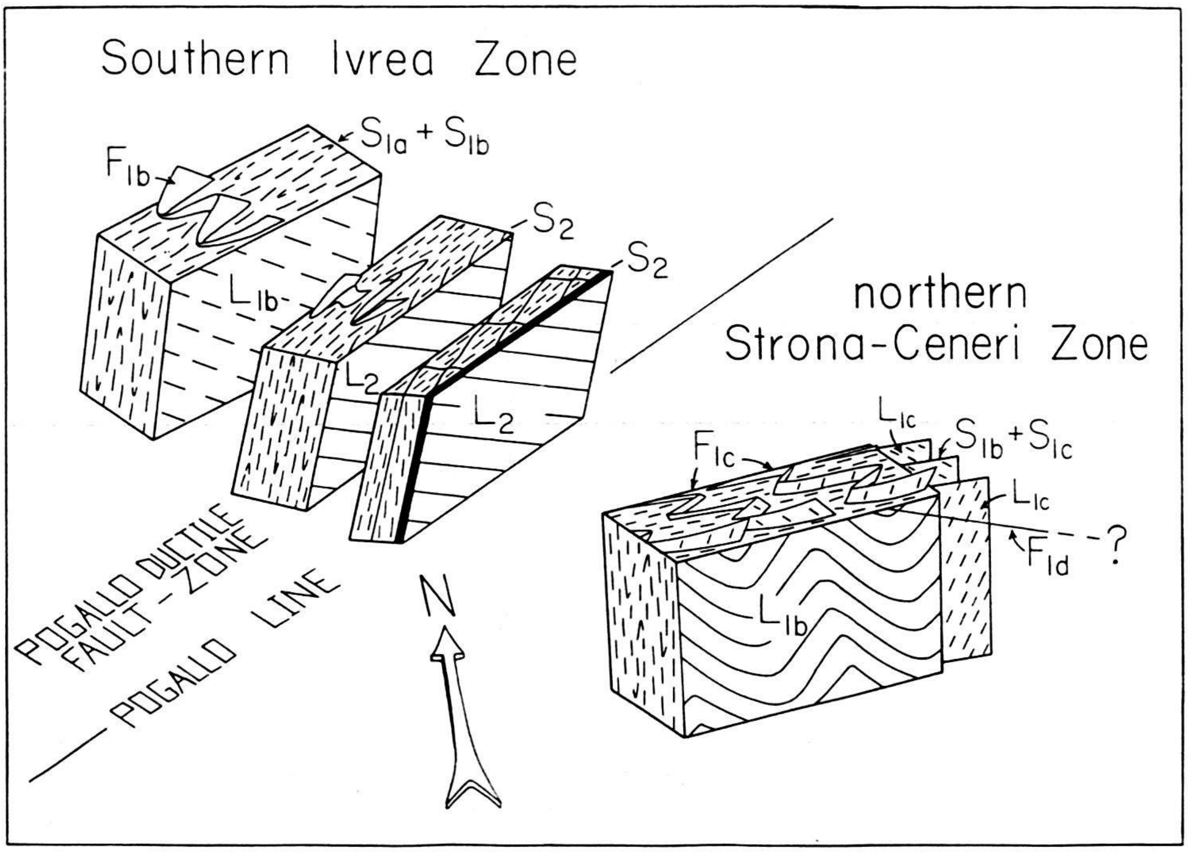


Fig. 3. Schematic diagram of the geometric relations among the pre-Pogallo and Pogallo structures in the Ivrea and Strona–Ceneri Zones of the Val d'Ossola–Val Pogallo area.

Ivrea Zone: F1b folds are associated with axial plane cleavage, S1b, and intersection lineation, L1b. They affect the pre-Pogallo foliation, S1a. S2 foliation and L2 stretching lineation form in the PDFZ and deform the earlier structures listed above. At the Pogallo Line, S2 is overprinted by conjugate ductile shear zones and mylonitic foliation (shown in black).

Strona–Ceneri Zone: Early folds, F1c, associated with axial plane schistosity, S1c, affect older foliation, S1b, and stretching lineation, L1b. Folding of L1b lineations and varied trend and plunge of F1c folds and L1c lineations is attributed to similar folds, F1d, whose axes are at low to moderate angles to the dominant S1b and S1c foliation. All structures are pre-Pogallo age (see text).

SE by the Pogallo deformation (Fig. 8 a, b, and c); (2) the growth of undeformed cross-laths of muscovite in the hinges and limbs of the folds; these laths are clearly affected by the Pogallo deformation (Fig. 8 b); (3) the truncation of the folds by shear bands related to the Pogallo deformation in the southernmost parts of the Ivrea Zone (Fig. 4 b).

Similar folds in the southern part of the Ivrea Zone have also been described by Walter (1950) and Papageorgakis (1961). They are probably related to a large NE-plunging antiform (südliche Gewölbe) mapped by R. Schmid (1967) in the southern part of the Ivrea Zone just to the north of the area treated here.

3.2.2 Strona–Ceneri Zone

At least two phases of folding (termed F1c and F1d in Figure 3) in the Strona–Ceneri Zone preceded the Pogallo deformation. The later F1d folds are inferred from the folded lineations (L1b) on S1b schistosity surfaces and from the varied NE to SW plunge of the F1c folds. Both folding events occurred prior to amphibolite facies anneal (inter-

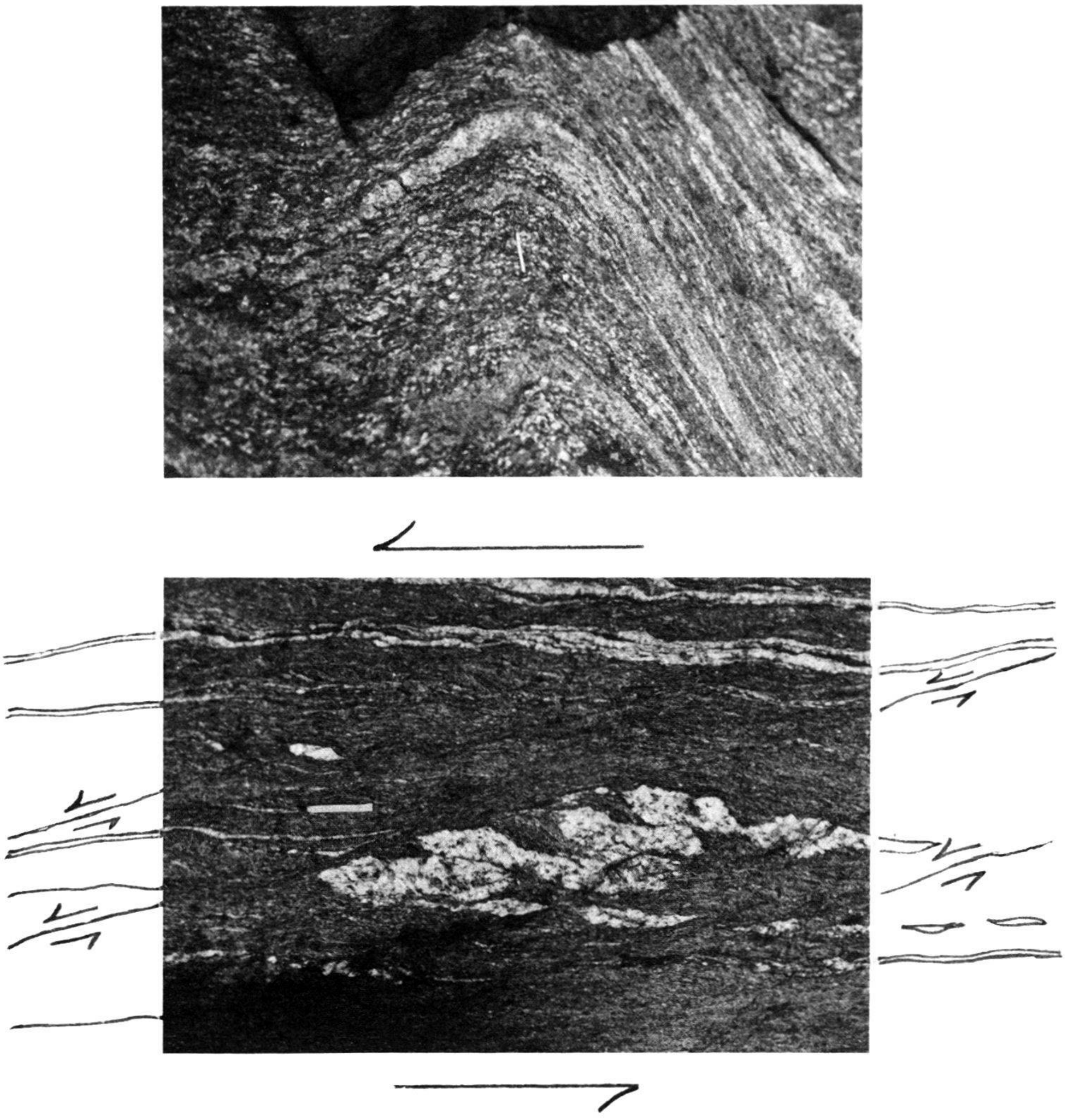


Fig. 4. a) Pre-Pogallo fold in a part of the southern Ivrea Zone unaffected by the Pogallo deformation; Match used for scale is 3.5 cm long.
b) Deformed pre-Pogallo fold in the Pogallo Ductile Fault Zone; Sinistral shear bands related to the Pogallo deformation truncate the schistosity and the pre-Pogallo folds. Arrows above and below the picture indicate the bulk sense of shear. Match for scale is 3.5 cm long.

kinematic phase 2–3 of Boriani 1970 a) recorded in the microstructures of the Strona–Ceneri Zone.

Permo-Triassic and Variscan biotite cooling ages in the Strona–Ceneri Zone (McDowell 1970; Hunziker 1974) and the occurrence of these tectonites as agmatized blocks in the Permo-Carboniferous intrusives of the lower Val d'Ossola (Handy 1986) place upper age limits on the deformation and post-tectonic anneal in the Strona–Ceneri Zone. This deformation and metamorphism probably occurred during the Variscan orogeny.

3.3 The Pogallo Ductile Fault Zone

The Pogallo Ductile Fault Zone (PDFZ) is an approximately 1 km wide band of ductily overprinted paragneisses and schists ("kinzigites" in the classical literature) occupying the southern margin of the Ivrea Zone (Fig. 1). The Pogallo Line forms the southeastern margin of this ductile fault zone. As noted above, the general concordancy of the foliations inside and outside the PDFZ necessitates the examination of microfabrics to delimit the areal extent of the fault zone.

Stretching lineations (L2 in Fig. 3) observed on the schistosity surfaces (S2) of quartz-rich tectonites in the PDFZ plunge consistently to the NE, parallel to the stretching lineations in the mylonites of the Pogallo Line (Fig. 2). In general, the intensity of the deformational and metamorphic overprint increases from NW to SE across the PDFZ, i.e. towards the Pogallo Line. The Pogallo deformation affects both the style and the orientation of the pre-Pogallo folds in the southern Ivrea Zone: Pre-Pogallo folds in the southernmost Ivrea Zone affected by the Pogallo deformation are much tighter than several hundred meters to the north, outside of the PDFZ (compare Figures 4a and b). Often, the folds are isoclinal and have been severely boudinaged. Where the deformation in the PDFZ is most intense, the pre-Pogallo folds are transected and displaced by shear bands (Fig. 4b). Sinistral shear bands are more common than the dextral variety. They also have the same orientation as the sinistral mylonitic shear zones developed along the Pogallo Line. The shear bands are interpreted as local instabilities associated with strain-softening during the late stages of ductile deformation in the PDFZ (Gapais & White 1982). They developed after a critical amount of strain, above which the rock was incapable of accommodating, homogeneously and under the prevailing conditions, the bulk deformation.

3.4 The Pogallo Line

The Pogallo Line forms the structural boundary between the Ivrea and Strona–Ceneri Zones from the Val d'Ossola to the upper R. Pianezzoli. A prominent morphological lineament marks the Pogallo Line from Piz Faie in the lower eastern Val d'Ossola to Monte Piota between the R. Pianezzoli and the western Val Cannobina (Fig. 1). The Line contains greenschist facies mylonites, discrete-ductile lower greenschist facies ultramylonites, pseudotachylites and other brittle tectonites.

Viewed on the outcrop scale, the Pogallo Line is a multifarious structure which changes character along its length. The Line is best developed in the Val Grande area, where two mylonite belts (ca. 6–8 m wide) active under greenschist facies conditions overprint ductile tectonites deformed under lower amphibolite to upper greenschist facies conditions (see block-diagram in Figure 5). The northerly belt is separated from the Ivrea gneisses and schists to the north by a relatively shallow-dipping lid of pegmatitic gneiss. The southern mylonitic belt is the dominant structural feature of the Pogallo Line in the Val Grande. Late deformation involving creep at low temperatures was concentrated into this band. A thin, 10 cm wide ultramylonitic band in the middle of this mylonite belt is marked by a prominent fault-scarp some 1 to 3 m high (Fig. 6). The fault-scarp marks the limited movements at the Pogallo Line which occurred below the transition from deformation dominated by dislocation- and diffusion-creep to deformation involving brittle fracture and flow (see section 4.2).

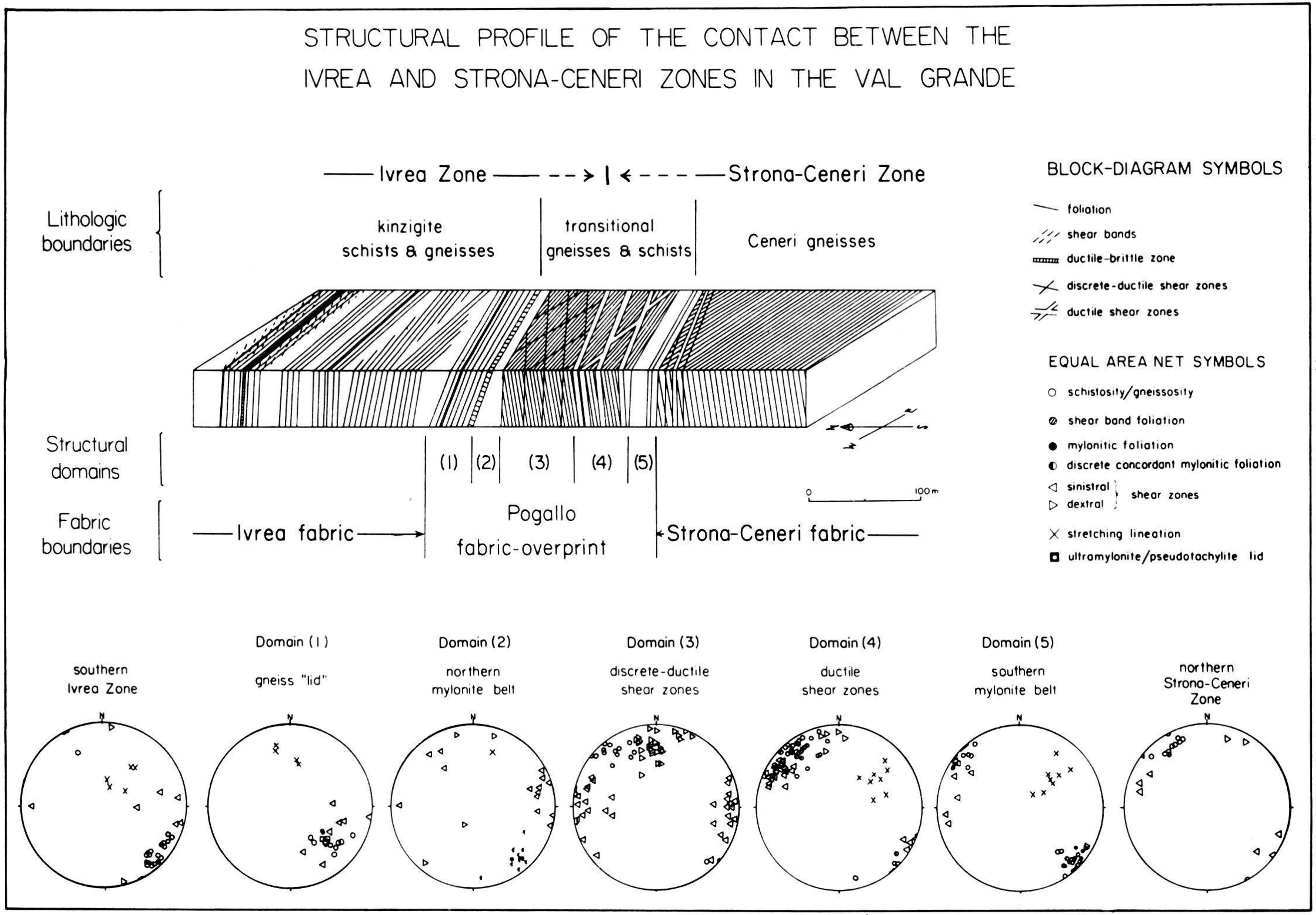


Fig. 5. Structural profile of the contact between the Ivrea and Strona–Ceneri Zones in the Val Grande streambed (see Figure 1 for location).

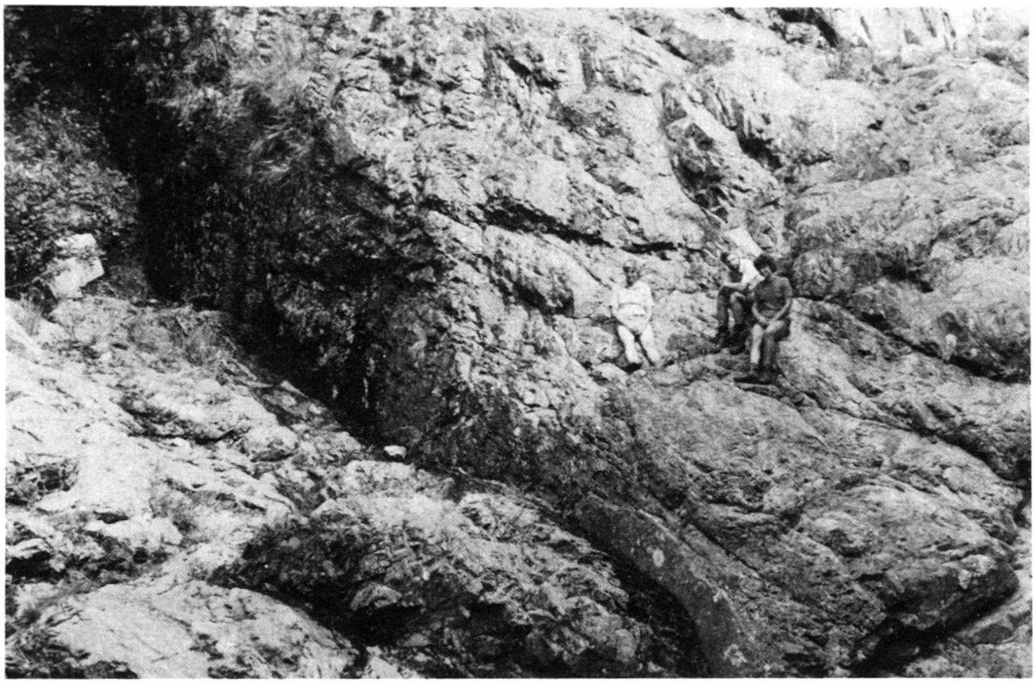


Fig. 6. A fault scarp marks a thin ultramylonitic band within the southern mylonite belt of the Pogallo Line in the Val Grande streambed.

The two greenschist facies mylonitic belts in the Val Grande are associated to the north and south with conjugate mylonitic and ultramylonitic shear zones (Fig. 5). The predominance of sinistral shear zones is consistent with the sinistral sense of shear determined from independent shearing criteria for the Pogallo Fault Zone as a whole (see section 4.4). However, the conjugate geometry of the ductile shear zones indicates that the deformation along the Pogallo Line superposed a component of pure shear on a simple sinistral shear.

In the Val Pogallo (Fig. 1), the tectonites comprising the Pogallo Line form a broader zone of deformation (300 m vs. ca. 200 m in the Val Grande profile) with concordant higher (amphibolite facies) and lower (amphibolite to greenschist facies) grade mylonites in the north and amphibolite to greenschist facies shear zones in the south. Even further to the NE, in the R. Pianezzoli, the Line appears to narrow to a band (ca. 50 m wide) of overlapping mid-amphibolite and greenschist facies shear zones before disappearing entirely in the western flank of Monte Piota (Fig. 1). All along the Pogallo Line, the Pogallo mylonites are concentrated at the Ivrea–Strona–Ceneri contact or occur just inside the northernmost rim of the Strona–Ceneri Zone.

The NE-ward disappearance of the Pogallo Line may reflect a transition from shear within relatively discrete mylonitic shear zones to more diffuse crystal-plastic flow under higher grade conditions within the PDFZ. This interpretation is consistent with microstructural and metamorphic trends in the PDFZ, indicating that originally deeper structural levels of the fault zone are presently exposed in the NE (section 4.2).

3.5 The Pogallo deformation in Late Paleozoic intrusives

Intrusive rocks at the contact between the Ivrea and Strona–Ceneri Zones crop out in a wedge-shaped area in the lower eastern part of the Val d'Ossola (Fig. 1, "San Rocco intrusives"). Structural and lithologic relations in these rocks are valuable in delimiting the age of the deformations in the Ivrea and Strona–Ceneri Zones. Two main types of intrusives are distinguished:

1. Granodiorites, diorites and granodioritic gneisses yield 290–310 my. U-Pb monazite ages (KÖPPEL & GRÜNENFELDER 1978/79). These are interpreted as ages of intrusion (KÖPPEL & GRÜNENFELDER 1975).
2. The San Rocco granitic gneiss, interpreted to be an inhomogeneously deformed relative of the Montorfano and Baveno granites due to their similar mineralogy, lithologic association and (in the case of the Montorfano granite) general appearance (SCHILLING 1957; GANDOLFI & PAGANELLI 1974). Intrusives of the Baveno suite yield Permian radiometric ages, interpreted to date the intrusion (e.g. KÖPPEL & GRÜNENFELDER 1978/79, HUNZIKER & ZINGG 1980).

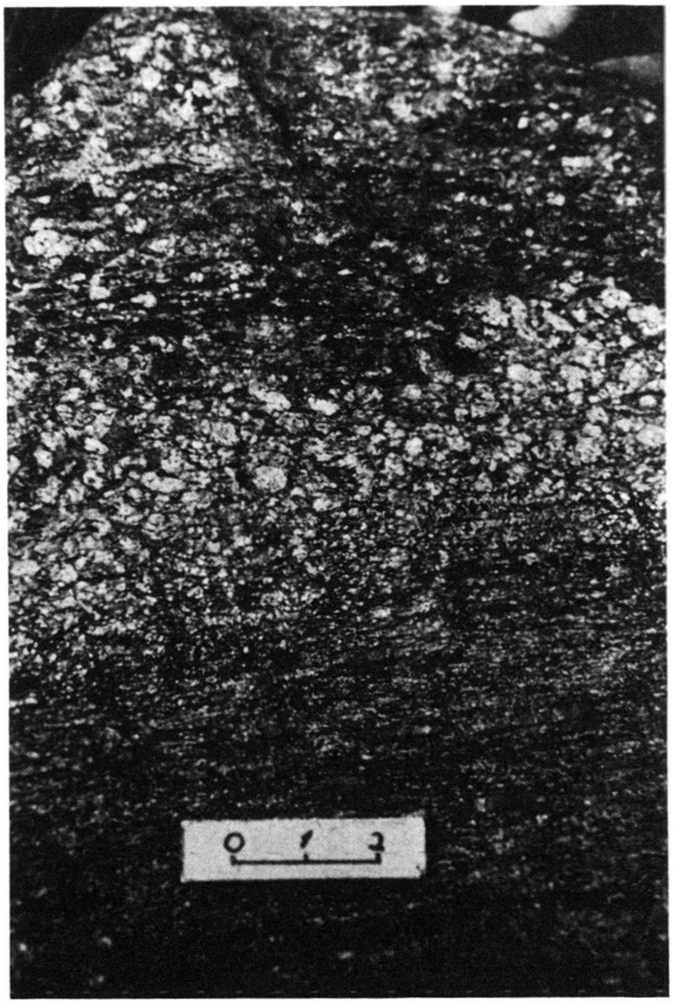
These intrusives are termed agmatites (i.e. intrusive breccias) since they contain angular to rounded blocks of Ivrea and Strona–Ceneri rocks and locally comprise a relatively small volume-proportion of the rocks cropping out in the wedge-shaped area described above. Similarly aged intrusive relationships have also been described on the SW side of the lower Val d'Ossola (BORIANI & PEYRONEL PAGLIANI 1968, see Fig. 1).

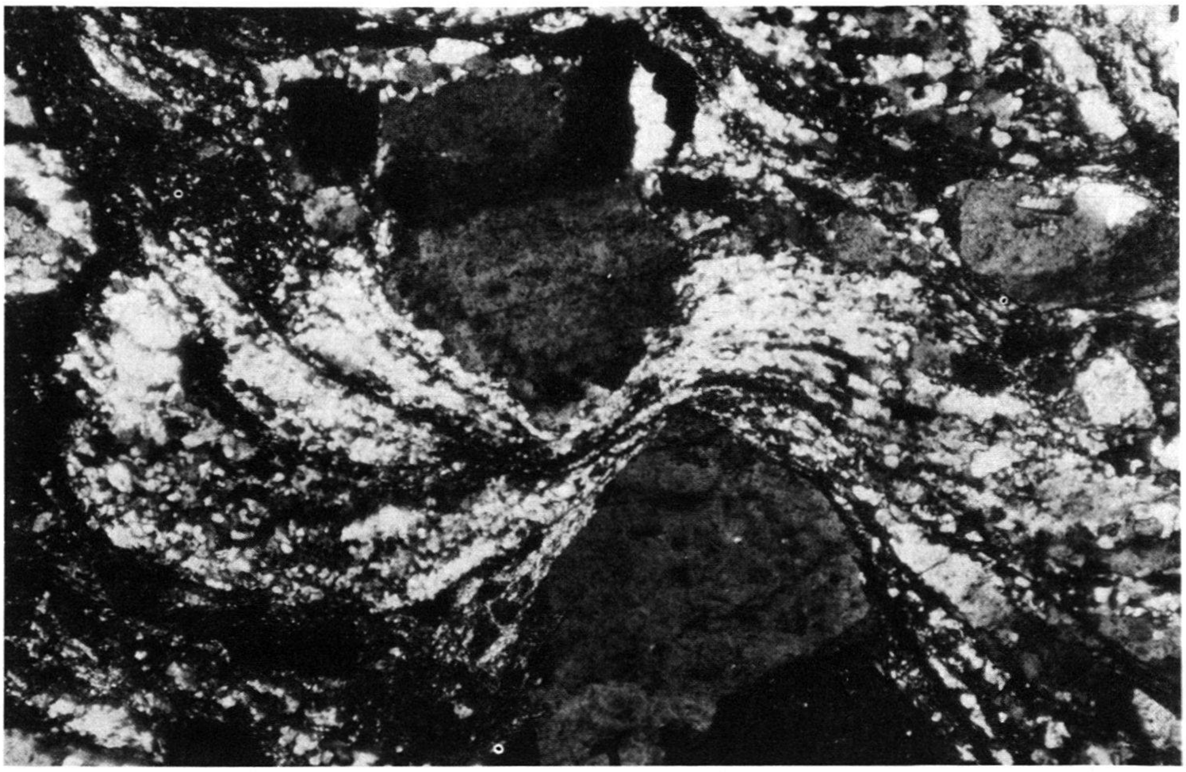
The trend and the character of the Pogallo Line alter in the vicinity of the San Rocco intrusives. On a local scale, this change is related to the rheological contrast between the intrusive rocks and the surrounding gneisses of the Ivrea and Strona–Ceneri Zones. Pogallo mylonites are found to affect both the intrusive rocks and the adjacent Strona–Ceneri gneisses. Sinistral shear zones skirt the southern margin of the intrusive body. The mylonitic foliation trends NNE–SSW and dips to the WNW, an orientation coincident with the Orta valley, but discordant to the Strona–Ceneri schistosity (Fig. 2 and Plate). Both granites and granodiorites range from massive (unfoliated) to schistose (Fig. 7a). This foliation is generally better developed towards the southern rim of the intrusive wedge and becomes locally mylonitic near the Pogallo Line. It is associated with dynamic deformational microfabrics identical to those formed during the Pogallo deformation (compare Fig. 7b, 8c, and 10a). Similar foliation and microfabrics have also been observed locally in granites and granodiorites to the west of the Val d'Ossola (SCHILLING 1957). These relationships indicate that the Pogallo event post-dated the Permo-Carboniferous and Permian intrusive activity.

3.6 Late to post-Pogallo brittle deformation

Brittle deformation in the area involved cataclasis, ultracataclasis and even the local formation of vein-type pseudotachylite (Plate 3.16 in HANDY 1986). If normal strain-rates are assumed, brittle deformation occurred after ca. 180 ma. According to biotite cooling ages, this is the approximate time that temperatures in the Ivrea Zone fell below the 250–350 °C conditions marking the transition from crystal-plastic to brittle deformation in quartzitic rocks (SIBSON 1977). Most brittle structures are thought to post-date the Pogallo deformation, although in some instances (e.g. section 3.4 above) brittle deformation occurred during the final stages of mylonitization along the Pogallo Line. Within the Pogallo tectonites, it is usually difficult to distinguish late Pogallo brittle deformation from the post-Pogallo brittle deformation which has reactivated Pogallo shear zones.

Fig. 7. a) Foliation associated with the Pogallo deformation in the San Rocco granite (lower eastern Val d'Ossola) is variably developed, ranging from gneissic (top and middle of picture) to mylonitic (bottom).
b) Dynamically recrystallized quartz flows around feldspar clasts in the granitic gneiss (shown in (a)) which was affected by the Pogallo deformation (x-nichols, 3.5 × 2.3 mm). Note the stress-dependent decrease of quartz grain-size in the high-strain, pinched area between the two feldspar clasts.





Predominantly N–S trending joints filled with low grade alteration products offset the Pogallo mylonites and are ubiquitous in the area. These joints may be of late Alpine age since similarly oriented joints in the northern part of the Ivrea Zone (R. SCHMID, 1967) and in the Sesia and Monte Rosa Zones also affect the Tertiary Insubric mylonites (B. REINHARD, 1966). Quite possibly, this jointing is related to late Alpine movements in the entire area.

4. Microfabrics

The term microfabric as used here refers to two microscale features of a deformed rock (VERNON 1976, p. 23): the *microstructure* (all aspects of the microscopic appearance of deformed minerals readily visible in an optical or electron microscope) and the *texture* (commonly termed "petrofabric" or "lattice preferred orientation"). This section pertains only to the microfabrics of paragneisses within the southern Ivrea Zone. Annealed pre-Pogallo microfabrics of the Strona–Ceneri Zone in this area have been treated elsewhere (e.g. BORIANI 1970 b; HANDY 1986).

4.1 Pre-Pogallo microfabrics

Pre-Pogallo microfabrics in paragneisses of the southern Ivrea Zone show little or no manifestation of the Pogallo deformation and are characterized by the mid-amphibolite facies mineral paragenesis: garnet–sillimanite ± staurolite – biotite – muscovite – plagioclase – quartz. The areas mapped lie just south of the muscovite-Kfeldspar isograd (PEYRONEL PAGLIANI & BORIANI 1967; R. SCHMID 1967). Quartz is coarse grained and has locally equilibrated grain boundaries (Fig. 8 a). Large laths of muscovite growing across this fabric yield 220 my. K–Ar ages (HUNZIKER 1974; interpreted as cooling ages) and are affected by the Pogallo deformation (Fig. 8 b). The inclusion of agmatized Ivrea rocks containing these microfabrics in the Permo-Carboniferous intrusives (section 3.5) places an upper age-limit on the pre-Pogallo deformation and anneal in the southern part of the Ivrea Zone.

4.2 Pogallo microfabrics

Two microfabric-trends are discerned in the paragneisses affected by the PDFZ at the southern margin of the Ivrea Zone: 1. perpendicular to the strike of the Ivrea Zone, from NW to SE, Pogallo microfabrics progressively overprint the pre-Pogallo microfabrics towards the Pogallo Line; 2. parallel to the strike of the Zone, from SW to NE, the Pogallo overprinting fabrics show progressively higher grade metamorphic conditions.

Pogallo ductile faulting affects Ivrea microfabrics within about 1200 m (across strike) of the Pogallo Line. Quartz is dynamically recrystallized (Fig. 8 b–d) and the pre-Pogallo amphibolite facies minerals undergo syntectonic alteration (Fig. 9). The syntectonic metamorphic conditions in the Pogallo Ductile Fault Zone are lower amphibolite to upper greenschist facies in the Val d'Ossola – Val Grande region and mid-amphibolite facies in the Val Pogallo and to the NE. This SW to NE, strike-parallel trend is expressed in the behavior of quartz and biotite, as well as in the syntectonic mineral stabilities within the fault zone.

The dynamically recrystallized grain-size of quartz within the fault zone increases towards the NE as the dynamic recrystallization mechanism changes from predominantly

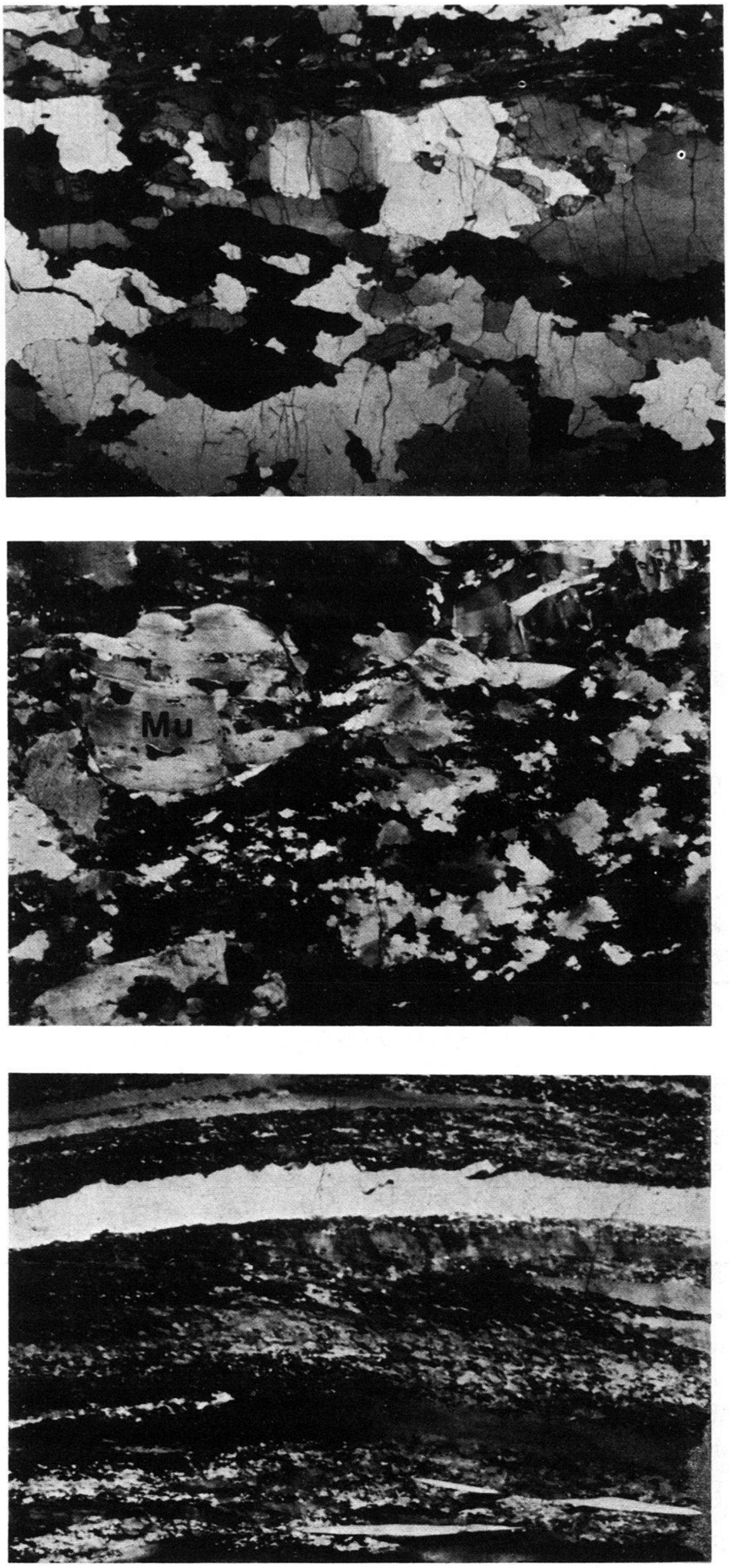


Fig. 8a, b, c

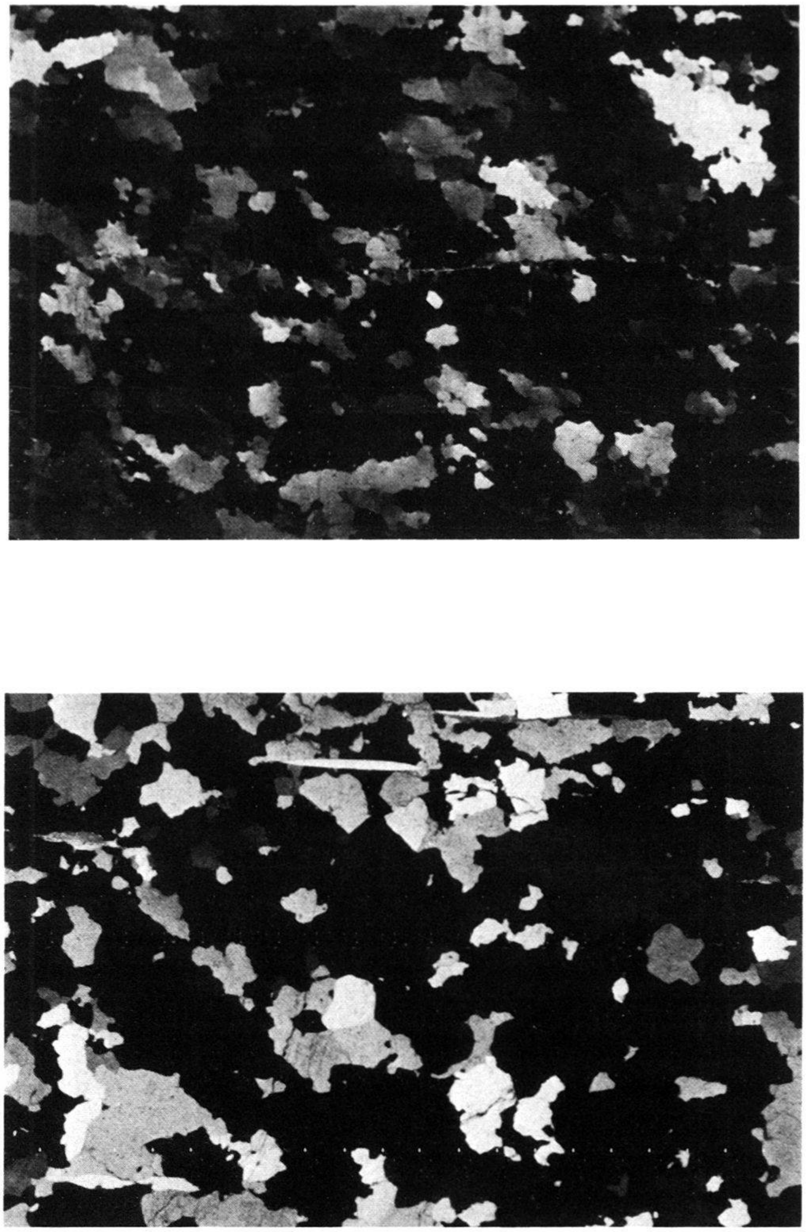


Fig. 8d, e

Fig. 8. a) Pre-Pogallo microfabric with large quartz grains unaffected by the Pogallo deformation (x-nichols, 11.3 × 7.5 mm).

b) Dynamically recrystallized quartz from the PDFZ, approximately 1 km NW of the Pogallo Line in the Val d'Ossola – Val Grande area. Dynamic recrystallization is concentrated at the boundaries of the larger, irregularly shaped quartz grains. Note the deformation of large white-mica grains (marked with an «Mu») (x-nichols, XZ fabric-plane; 11.3 × 7.5 mm).

c) Dynamically recrystallized quartz from the PDFZ, within 600 m of the Pogallo Line in the Val d'Ossola–Val Grande area. Original grains are deformed into elongate ribbons that appear to swim in a matrix of less viscous, dynamically recrystallized grains (x-nichols, XZ fabric-plane, 11.3 × 7.5 mm).

d) Dynamically recrystallized quartz from the PDFZ in the Val Cannobina area; Irregularly shaped grains show unstable (cuspate-lobate) grain boundaries typical of the grain boundary migration mechanism of recrystallization. Note the angle between lengths of quartz grains and the schistosity defined by the mica (x-nichols, XZ fabric-plane, 11.3 × 7.5 mm).

e) Deformational microfabric from the southern Ivrea Zone of the Brissago area on the Lago Maggiore. Lammellar and fish-shaped mica-clasts define the foliation (x-nichols, XZ fabric-plane, 11.3 × 7.5 mm).

"in situ" (subgrain rotation) to grain boundary migration (compare Fig. 8 b with Fig. 8 d and 8 e). Drury et al. (1985) have shown that dynamic recrystallization involving grain boundary migration occurs at higher homologous temperatures and yields larger grain-sizes for a given flow stress than does the subgrain-rotation mechanism. This marked microstructural change in quartz is accompanied by a textural change, with kinked c-axis girdles prevalent in the lower grade SW parts of the PDFZ replaced by point c-axis maxima in the higher grade NE part (Fig. 12 a and b). Mid-amphibolite facies deformational microfabrics in Ivrea and Strona–Ceneri rocks of the Brissago region (Fig. 1) retain evidence of noncoaxial flow (Fig. 8 e), suggesting that the PDFZ broadens towards the Lago Maggiore to affect both the southern part of the Ivrea Zone and the northern part of the Strona–Ceneri Zone.

From SW to NE, the color of syntectonic biotite changes from hazel or greenish-brown to dark-brown and reddish-brown. This contrasts with the uniformly reddish-brown color of pre-Pogallo biotite relics. Such a color distribution implies that higher grade syntectonic conditions prevailed in the NE parts of the PDFZ than in the SW, since the degree of redness in biotites (generally proportional to the Ti-content and Fe_2O_3/($FeO + Fe_2O_3$) ratio) tends to increase with increasing temperature and/or decreasing oxygen fugacity (Hayama 1959).

The syntectonic mineral assemblage in the SW parts of the PDFZ (Val d'Ossola – Val Grande area) is biotite-white mica-quartz, with relict clasts of plagioclase-garnet-sillimanite-staurolite metastable or unstable. Further to the NE (Val Pogallo – Val Cannobina area), all of the aforementioned minerals appear to coexist stably.

At the Pogallo Line (i.e. within the mylonitic shear zones) the amphibolite facies minerals in the tectonized gneisses of the Ivrea and Strona–Ceneri Zones recrystallize and/or alter to form a fine, foliated micaceous matrix (Fig. 10 a). In all areas, the mylonitic foliation is locally disrupted by narrow zones of brittle deformation (Fig. 10 b). The dynamically recrystallized grain size of quartz in the Val d'Ossola area averages 60 μm in the amphibolite facies tectonites of the PDFZ, but decreases to about 10 to 20 μm within

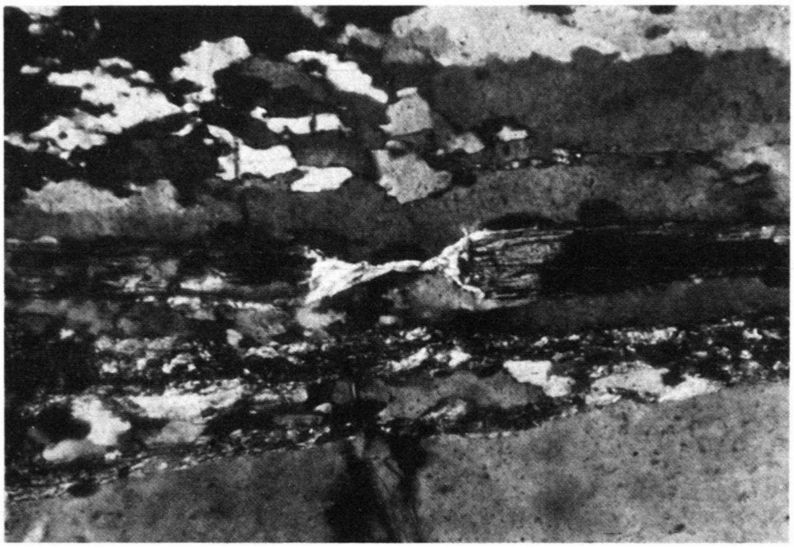


Fig. 9. Deformational microfabric of the PDFZ in the Val d'Ossola–Val Grande area. Syntectonically grown white mica appears in the pressure-shadow region between two boudinaged clasts of sillimanite (x-nichols, XZ fabric-plane, 0.8 × 0.5 mm).

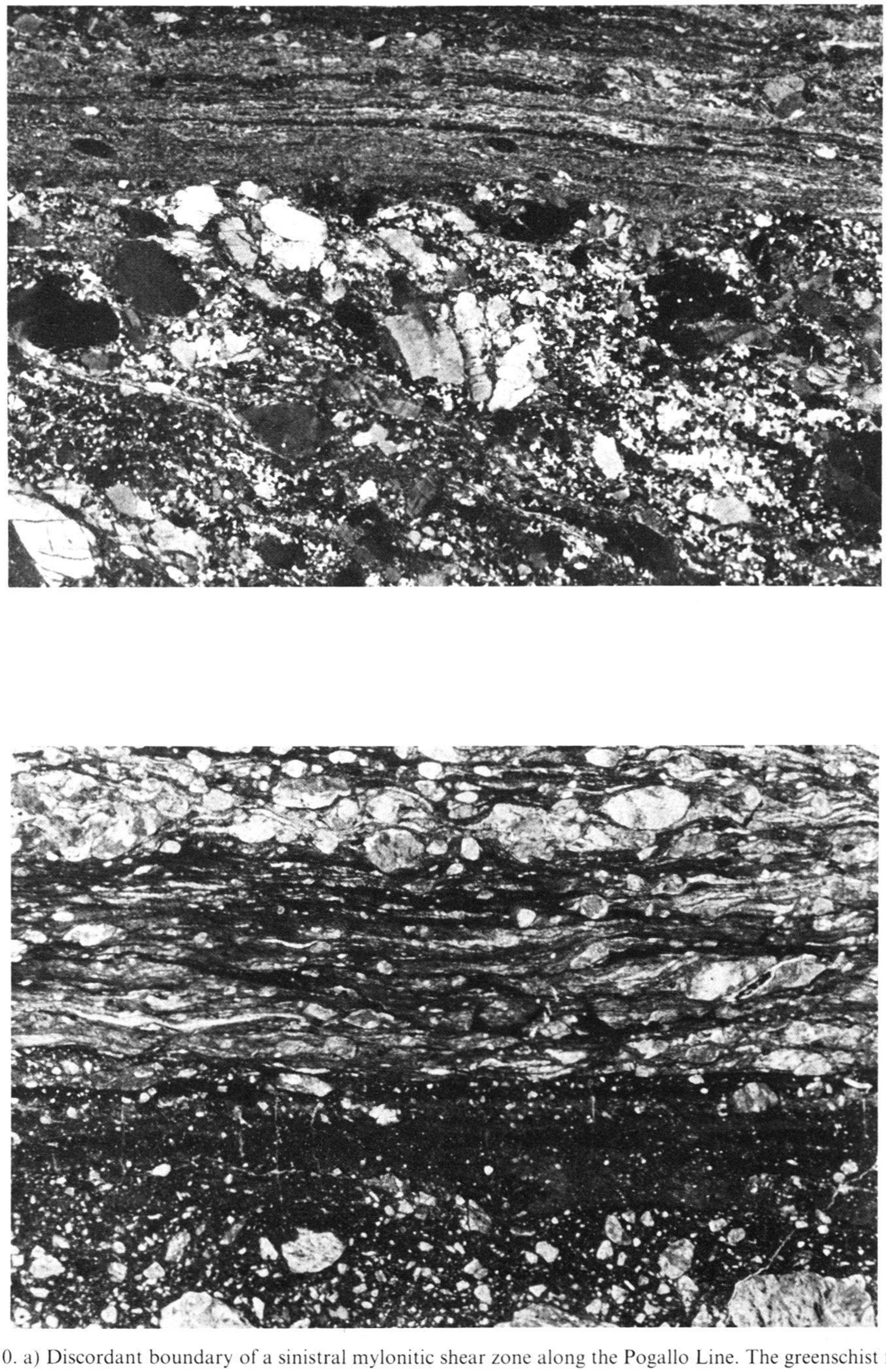


Fig. 10. a) Discordant boundary of a sinistral mylonitic shear zone along the Pogallo Line. The greenschist facies mylonitic foliation (top, parallel to print-length) overprints the deformed amphibolite facies foliation (x-nichols, XZ fabric-plane, 11.3 × 7.5 mm).

b) Microstructural transition from a mylonite (top) to an ultracataclasite (bottom) within a greenschist facies Pogallo shear zone (nichols at 45°, XZ fabric-plane, 11.3 × 7.5 mm).

the greenschist facies Pogallo shear zones. This is interpreted to reflect higher flow stresses (due to lower temperatures) and/or increased strain-rates in the Pogallo mylonites than in the PDFZ, based on the experimentally calibrated quartz piezometry in the literature (e.g. ORD 1981).

Mylonitization along the SW and central segments of the Pogallo Line occurred under hydrous greenschist facies conditions. Mylonitized para- and orthogneisses (derived from both the Ivrea and Strona–Ceneri Zones) have the syntectonic mineral assemblage quartz-white mica-clinozoisite-sodic plagioclase ± biotite ± chlorite. At least some of the chlorite is inferred to be a product of post-tectonic hydrothermal alteration. Mylonitized metabasites contain clinozoisite/epidote-chlorite-whitemica-quartz ± amphibole ± sodic plagioclase.

At the NE-most end of the Pogallo Line (R. Pianezzoli), these greenschist facies mylonites occur together with amphibolite facies mylonites that show the same mineral stabilities as in the adjacent tectonites of the PDFZ. The higher grade mylonites are interpreted to have formed under higher temperature/less hydrous conditions at greater depths in the ductile fault zone. The SW–NE trend of increasing syntectonic metamorphic grade indicates that the fault zone was originally inclined, with the NE end of the PDFZ occupying deeper structural levels.

4.3 Quartz textures

Quartz textures are sensitive to the kinematic history and the physical conditions of flow in the crust. Only the representative types of quartz textures from the PDFZ are presented here. The textures in this study are interpreted in terms of the «easy glide» hypothesis (ETCHECOPAR 1977), which predicts a strain-dependent rotation of the active glide-system to an orientation nearly parallel to the shearing direction of the deformed aggregate (Fig. 11). This concept has been extended to textures formed in plane-strain as well as to the more general cases of flattening and constrictional strains (S. M. SCHMID & CASEY 1986).

Kinked, oblique, single-girdle c-axis patterns characterize amphibolite to greenschist facies tectonites in the SW part of the PDFZ (Fig. 12a). The girdles typically show a concentration of c-axes subparallel to the intermediate strain direction, Y. This maximum is stronger in the middle amphibolite facies tectonites further to the NE in the PDFZ (compare Fig. 12a and b). In contrast, greenschist facies mylonites at the Pogallo Line yield unkinked oblique c-axis girdles (Fig. 12c). The c-axes are more evenly distributed over the length of the girdle (i.e. from the periphery to the center of the pole-figure).

Unkinked, oblique single-girdle c-axis patterns such as occur in the Pogallo mylonites are diagnostic of simple shear conditions (e.g. BOUCHEZ 1978). Glide in these mylonites is inferred to have occurred on the m, r and/or z, and basal (0001) slip-planes in the ‹a› direction (S. M. SCHMID & CASEY 1986). The prevalence of kinked, single-girdle c-axis patterns in the PDFZ indicates that ductile faulting involved largely rotational strain. A component of coaxial strain inferred from the kink in the c-axis girdle patterns is confirmed by the oblate shape of quartz ribbon grains in the same tectonites (Fig. 5.03 in HANDY 1986). Glide in the quartz-rich tectonites of the PDFZ occurred predominantly on the first order prisms, m, and on the unit rhombs, r and/or z, in the ‹a› direction (complete texture-analysis in HANDY 1986). The low concentration of c-axes towards the

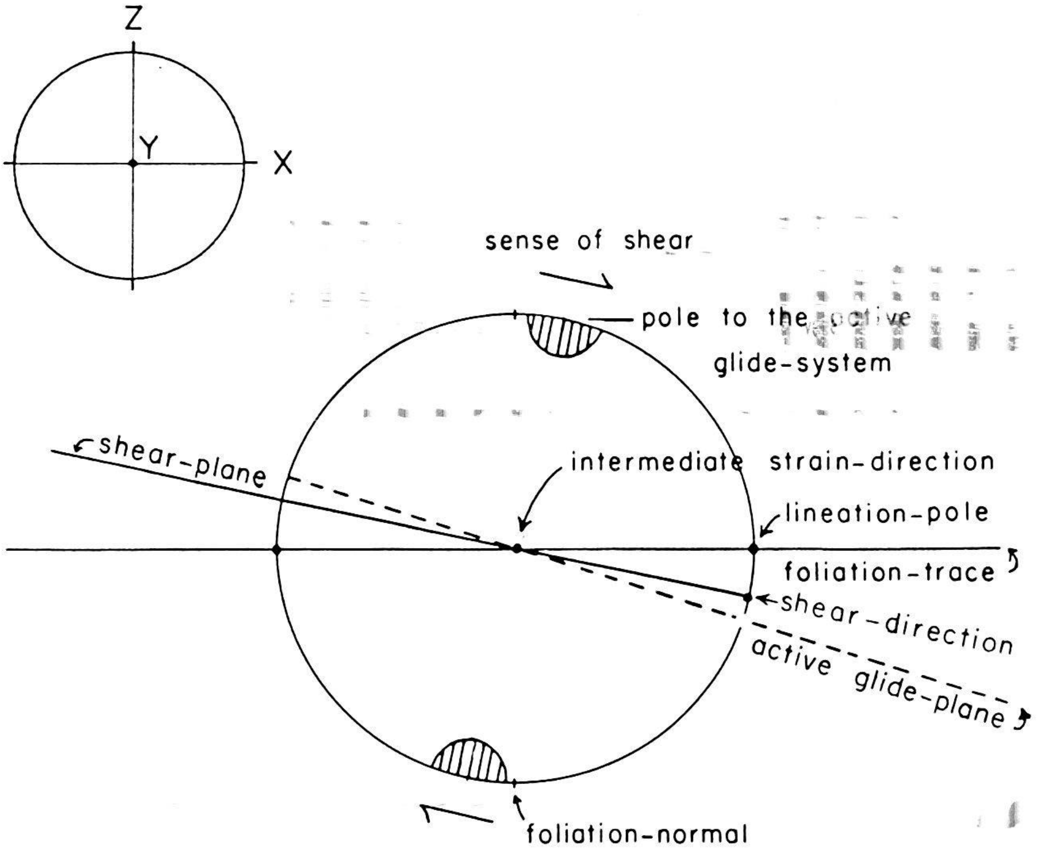


Fig. 11. Pole-figure showing the relationship of mesoscopic fabric-elements of the specimen (foliation-trace, foliation-normal, lineation-pole) to the active glide-plane, the shearing plane, and the shearing direction. The orientations of the principal strain-axes of the strain-ellipsoid with respect to the pole-figure coordinates are shown in the upper left corner.

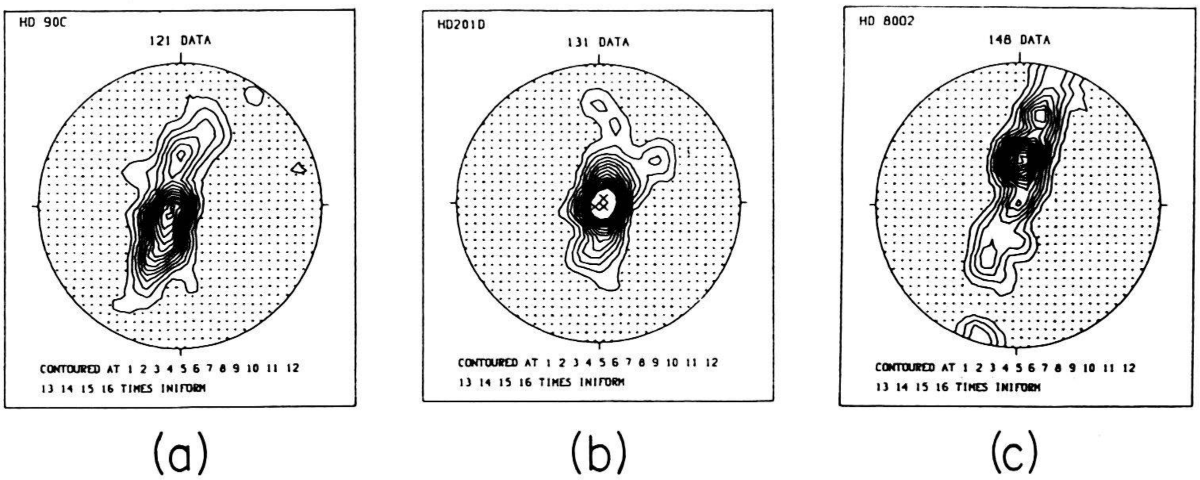


Fig. 12. Optically measured quartz c-axes: a) Kinked, oblique single-girdle quartz c-axis pattern from a lower amphibolite to upper greenschist facies L–S tectonite in the SW part of the PDFZ between the Val d'Ossola and the Val Grande.

b) Point-maximum quartz c-axis pattern from a mid-amphibolite facies L–S tectonite at the NE end of the Pogallo Line in the R. Pianezzoli.

c) Oblique single-girdle quartz c-axis pattern from a greenschist facies mylonitic shear zone at the Pogallo Line in the Val Grande.

edge of the c-axis pole-figures (i.e. normal to the inferred shear-plane) suggests that activity of the basal (0001)‹a› slip-system was weak. The NEward and NWward strengthening of the c-axis parallel Y-direction maxima indicates increased activity of the prism, m‹a›, system at the expense of slip on the unit rhomb‹a› and basal (0001)‹a› systems (e.g. WILSON 1975).

These textural trends correspond to the syntectonic metamorphic trends in the PDFZ: upper greenschist to lower amphibolite facies conditions in the SW grade to middle amphibolite facies conditions both across (to the NW) and along strike (to the NE). The correlation of increased relative activity of the m‹a› slip system with heightened syntectonic metamorphic conditions in the ductile fault zone is also consistent with the observed switch from basal to prism glide at higher temperatures in experimentally derived quartz textures (TULLIS et al. 1973).

4.4 Sense of shear

The microstructural criteria used in this study for determining the sense of shear in ductile tectonites are reviewed in SIMPSON & SCHMID (1983) and LISTER & SNOKE (1984). Only those tectonites with a clearly developed mineral-stretching lineation were chosen for analysis. A requirement for the determination of the shearing direction within a given thin section was the consistency of at least three microstructural criteria. The most reliable criteria were: 1. asymmetrical quartz c-axis texture-patterns; 2. the shape preferred orientation of dynamically recrystallized quartz grains; 3. the orientation of shear-bands with respect to the schistosity; 4. the orientation of fish-shaped mica clasts. The asymmetrical tails of feldspar, garnet and mica clasts usually confirmed the sense of shear determined with the other methods above. However, their use as shear-criteria was avoided here. Experimental studies (e.g. GOSH & RAMBERG 1976) have shown that both the rotational sense of the clast and the asymmetry of the clasts tails depend on a host of

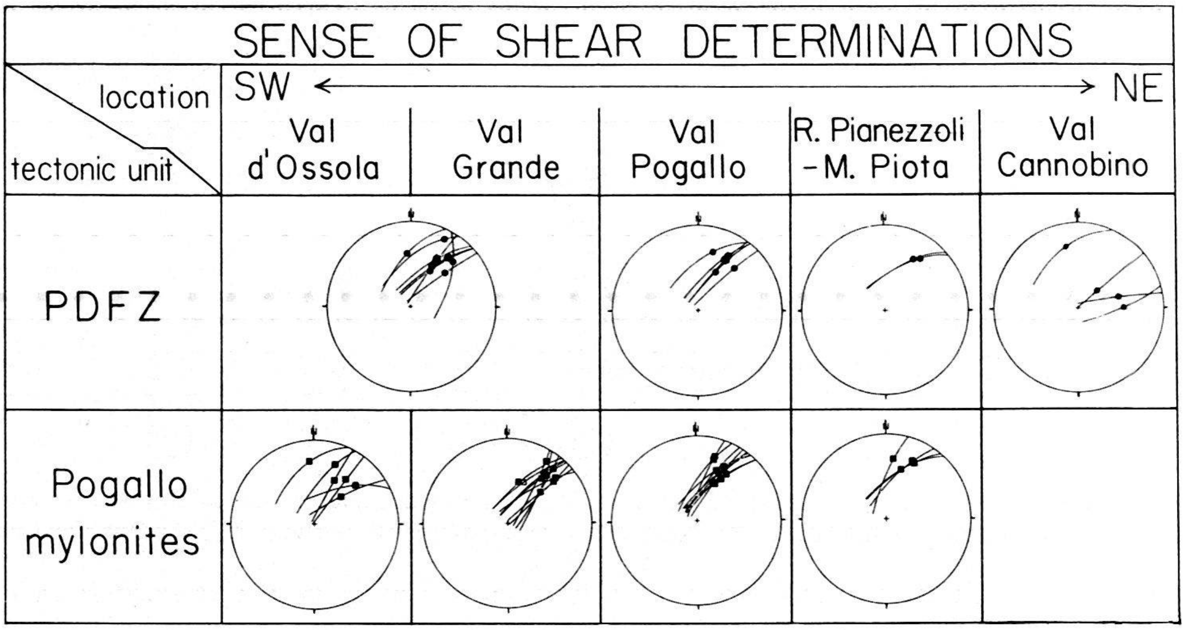


Fig. 13. Sense of shear determinations in the Pogallo Fault Zone; All equal-area plots are in the lower hemisphere. Solid symbols indicate Ivrea block uplifted with respect to the Strona–Ceneri block.

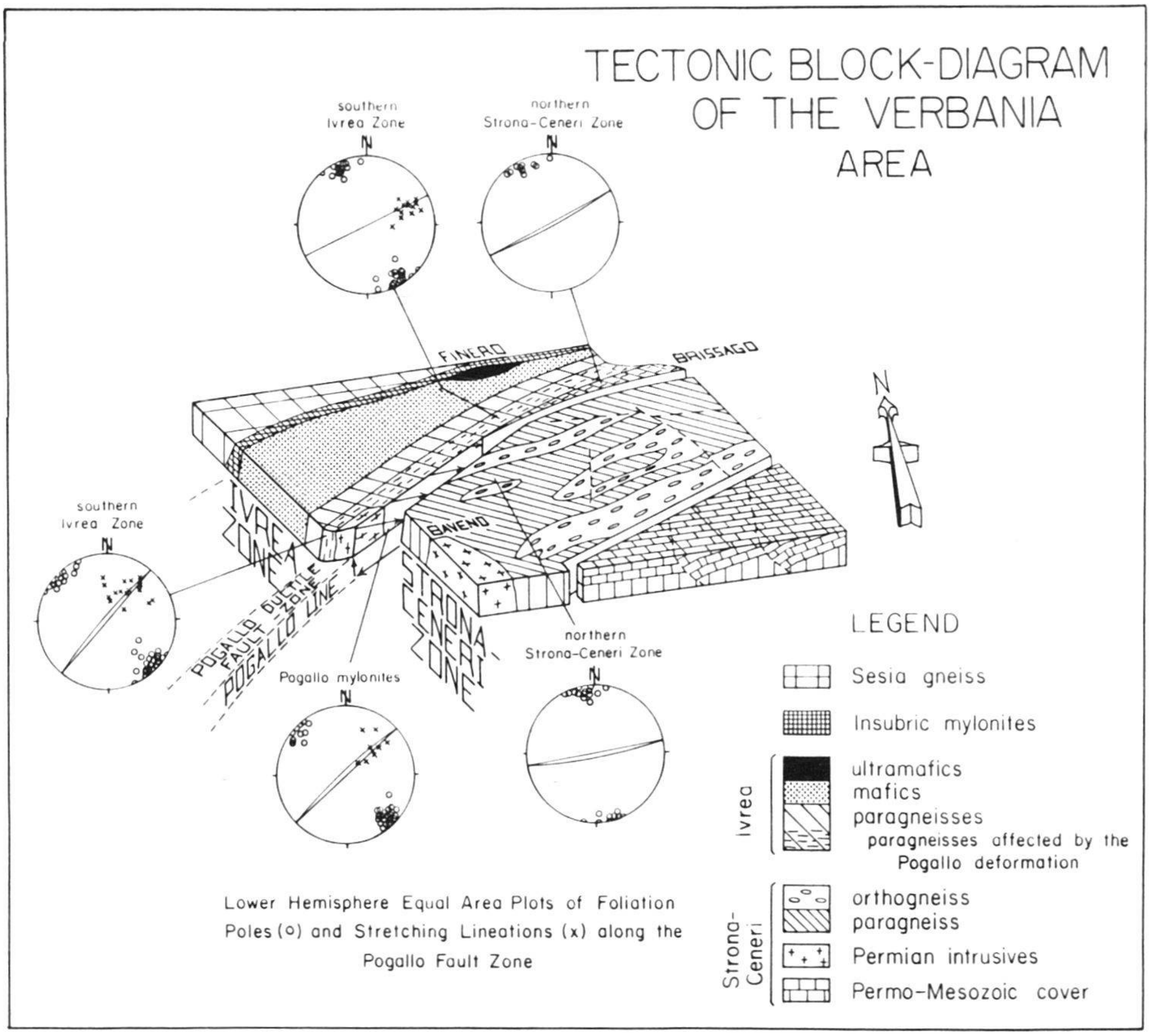


Fig. 14. Tectonic block-diagram of the Verbano area.

variables (e.g. dimensions and initial orientation of the clasts with respect to the less viscous matrix, viscosity-contrast between matrix and clast) which may only be approximated, but never all unequivocally determined in nature.

The results of all sense of shear determinations are summarized in the equal area plots of Figure 13. While there is some scatter in the lineation trends, the L–S tectonites in the PDFZ and along the Pogallo Line show a consistent oblique-sinistral sense of shear. That is, in present-day coordinates, the Ivrea Zone was uplifted and displaced to the SW with respect to the Strona–Ceneri Zone (block-diagram in Figure 14).

5. Synthesis, discussion and tectonic interpretation

5.1 The age of the Pogallo deformation

The Pogallo deformation affects and thus postdates Permo-Carboniferous granodiorites and granites related to the Permian Baveno intrusives. Moreover, the schistosity in the Pogallo Ductile Fault Zone and along the Pogallo Line clearly truncates Paleozoic structures in the Strona–Ceneri Zone.

Several lines of evidence indicate that the Pogallo ductile faulting is not of Tertiary (i.e. Alpine) age: 1. the Pogallo Line coincides with a jump in the radiometric ages from Permo-Triassic and Variscan in the northern Strona–Ceneri Zone to Early Jurassic in the Ivrea Zone. Moreover, no Tertiary mica ages are found in the Southern Alpine basement; 2. ductile deformation in the PDFZ occurred under conditions ranging from middle amphibolite to greenschist facies, conditions at or above the 300° ± 50 °C closing temperature of the K–Ar and Rb–Sr biotite systems yielding Early Jurassic ages in the Ivrea Zone; 3. the oblique sinistral movement-sense of the PDFZ contrasts sharply with the largely dextral movement-vector associated with Tertiary movements of the Insubric Line (Laubscher 1971; S. M. Schmid et al. 1987).

So far, the age of the Pogallo deformation is best constrained by correlating the estimated temperatures in the Pogallo tectonites with the radiometrically determined thermal history of the Ivrea zone (Fig. 15). Middle to lower amphibolite facies conditions in the PDFZ may have been attained as early as 230 my., during the Late Triassic, when the warm Ivrea block was juxtaposed against the cold part of the Strona–Ceneri block. If the ductile faulting was fast compared to the equilibration-rate of the isotherms in the warm, uplifting Ivrea Zone (i.e. across the PDFZ), then greenschist facies mylonitization along the Pogallo Line was roughly contemporaneous with the amphibolite facies deformation in the PDFZ. Certainly, the greenschist facies deformation along the Pogallo Line occurred no later than ca., 180 my. (Early to Middle Jurassic), the time when temperatures in the Ivrea Zone fell below the closing temperature of the isotopic systems in biotite.

The following observations suggest that greenschist facies mylonitization along the Pogallo Line was contemporaneous with amphibolite facies deformation in the PDFZ: 1. the continuity of deformational microstructures from the L–S tectonites of the PDFZ into the mylonites of the Pogallo Line and the lack of statically recrystallized quartz fabrics in the PDFZ. This indicates that deformation within the PDFZ continued uninterrupted to temperatures of 300 °C or less, i.e. beneath the minimum temperature generally assumed for grain boundary equilibration in quartz; 2. the same distribution of

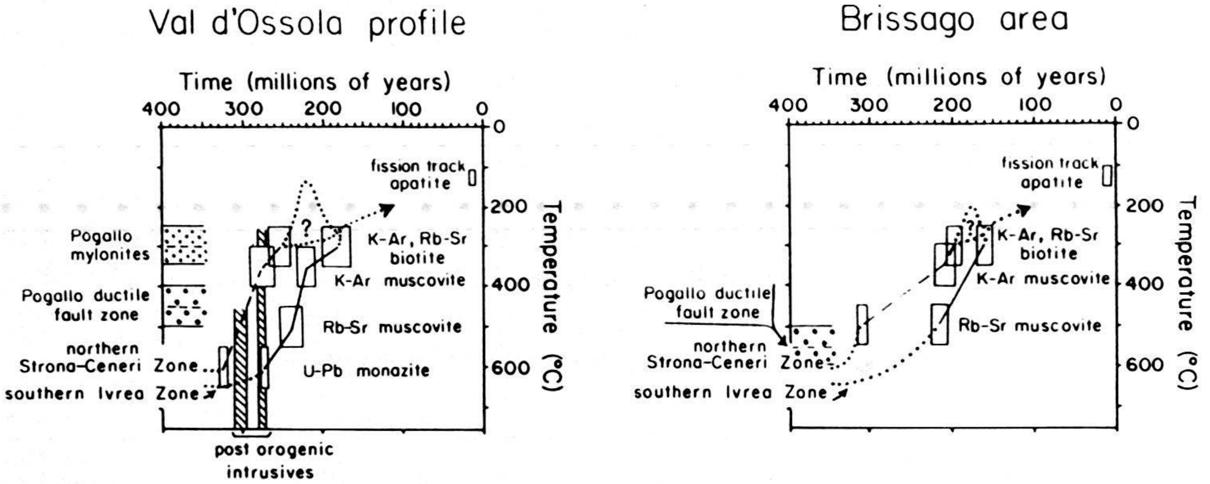


Fig. 15. Temperature-time curves for adjacent parts of the Ivrea and Strona–Ceneri Zones in the Val d'Ossola and Brissago areas plotted from radiometric ages in the literature: Jäger et al. (1967), McDowell & Schmid (1968), Miller & Jäger (1968), McDowell (1970); Wagner & Reimer (1972), Hunziker (1974), Köppel (1974), Köppel & Grünenfelder (1978/79).

syntectonic metamorphic conditions in the mylonites of the Pogallo Line as in tectonites of the PDFZ (viz. higher grade conditions in the NE); 3. the disappearance of the Pogallo Line towards the NE, with increasing structural depth in the originally inclined PDFZ; 4. the same orientation of stretching lineations and sense of shear in the Pogallo mylonites as in the L–S tectonites of the PDFZ.

Thus, the Pogallo deformation is inferred to have involved deformation within a progressively narrowing ductile fault zone sometime during the Late Triassic to the Early to Mid-Jurassic. The mylonites of the Pogallo Line document the movements in the PDFZ during and/or towards the end of this period. Cataclasites spatially and geometrically related to the Pogallo mylonites mark the limited movements along the Pogallo Line at or beneath the rheological transition from dislocation and grain-size sensitive creep to brittle fracture and flow.

5.2 Kinematics

5.2.1 Synthesis of pertinent geological information

The attitude of the PDFZ at its inception and hence, the kinematics of the Pogallo deformation during the Early Mesozoic, depend critically on both the extent and timing of changes in the orientation of the Ivrea–Strona–Ceneri basement section. Kinematic models of the Pogallo deformation must take into account the following local geological information:

1. The structural discordance between the Ivrea and Strona–Ceneri Zones coincides with the Pogallo Line, but decreases and eventually disappears towards the NE. Its disappearance coincides with the NE end of the mylonites marking the Pogallo Line.

2. The PDFZ was probably active at depths of between 10 and 15 km. The ca. 10 km upper depth limit is derived from the hydrous greenschist facies conditions (ca. 300 °C) in the mylonites along the Pogallo Line. A lower depth-estimate of roughly 15 km is consistent with the amphibolite facies conditions in the PDFZ. This estimate is also compatible with knowledge of the current thickness of the Ivrea Zone and the probable local thickness of the Southern Alpine crust during the Late Triassic – Early Jurassic (ca. 20 km; Fig. 18 b).

3. The map-view of the PDFZ is a slice some 30° oblique to the transport-direction in the ductile tectonites (see stretching lineation orientations in the PDFZ in Fig. 2 and 14). In effect, the map affords a section through what during the Early Mesozoic was an inclined ductile fault zone. Crude estimates of the apparent dip of the PDFZ (i.e. the dip in a direction parallel to the plane of today's erosional surface) can be made from the temperature range of syntectonically stable mineral parageneses in the fault zone: A temperature of approximately 450 °C seems reasonable for the lower amphibolite to upper greenschist facies deformation in the SW part of the PDFZ (Val d'Ossola – Val Grande region), while temperatures between 500° and a maximum of 650 °C are inferred for the mid-amphibolite facies, NE part of the PDFZ (Val Cannobina area; Fig. 4.05 c in Handy 1986). This brackets the estimated syntectonic temperature-differences along the PDFZ at between 50 and 200 °C. For an average geothermal gradient of 30 °C/km, this suggests a difference in depth between the NE and the SW parts of the PDFZ of from 2 to 7 km over a strike-parallel distance of ca. 10 km. The apparent dip of the PDFZ

calculated from these inferred depth differences ranges from 10 to 34°. Within this range, values closer to the 10° apparent dip-estimate are more plausible; the 34° higher apparent dip-estimate is based on the maximum temperature (650 °C) for the upper stability limit of staurolite relics in the deeper (NE) parts of the PDFZ.

It should be noted that for any of these apparent dip estimates, the actual or true dip of the fault zone was probably somewhat greater, since the regional geological evidence strongly suggests that the original dip-azimuth of the PDFZ was not coplanar with today's map-surface. Also, the estimated dips will vary with the assumed geothermal gradient; higher geothermal gradients will yield lower fault-dips, and vica-versa.

4. Displacement-estimates for the PDFZ range from 7 to 13 km in a direction parallel to the average plunge of the stretching lineations. The 7 km represents a minimum displacement-value and was calculated from the dimensions of quartz ribbon grains by assuming plane-strain simple shear (Fig. 5.02 in HANDY 1986). The 13 km estimate stems from a correction of BORIANI & SACCHI's (1973) 11 km strike-slip value for the 30° NEward plunge of the stretching lineations within the PDFZ. The authors' 11 km displacement is derived from the offset of an amphibolite band in the Strona–Ceneri Zone that is presumed to have been continuous prior to faulting (see Plate).

5. There is evidence that the Pogallo fault extends SWward of the Val d'Ossola. Previous workers (NOVARESE 1929; BORIANI & SACCHI 1973) propose a large transcurrent movement to account for a marked lithological discordance on opposite sides of the Val d'Orta. The variably well-developed foliation and dynamically recrystallized quartz microfabrics in granitic to granodioritic Permian intrusives west of the lower Val d'Ossola (SCHILLING 1957) suggest that a SW extension of the Pogallo Fault Zone affects both the southern Ivrea Zone and the northern Strona–Ceneri Zone. Early Jurassic biotite ages in the Strona–Ceneri Zone north of the Pogallo–Orta disturbance and west of the Val d'Ossola (Plate) support this hypothesis and indicate that this part of the Strona–Ceneri Zone underwent the same tectono-metamorphic history as did the southern Ivrea Zone.

6. NE of the area investigated, the distribution of Early Jurassic biotite ages both east and west of the Lago Maggiore indicate that the NE part of the Strona–Ceneri Zone underwent a similar thermal history as did the Ivrea Zone (Plate). This development may be linked to an eastward continuation of the PDFZ. Indeed, amphibolite facies deformational microfabrics in quartz-rich rocks of the Brissago area are interpreted as resulting from flow in deeper parts of the PDFZ.

Several lines of larger scale geological evidence indicate that the Ivrea–Strona–Ceneri basement-section containing the PDFZ occupies a much different orientation than it did during the Early Mesozoic, when the PDFZ was active:

1. Originally deeper crustal levels are presently exposed towards the NW within the basement-section, as noted in the brief review of the general geology at the beginning of this paper. Early Jurassic biotite cooling ages are younger towards the NW rim of the Ivrea Zone, recording movement to deeper levels of the 300° ± 50°C isotherm during cooling of the Ivrea Zone (J. C. Hunziker and A. Zingg, pers. comm.). This suggests that the Ivrea–Strona–Ceneri basement-section attained its present subvertical orientation only since the Early-Middle Jurassic.

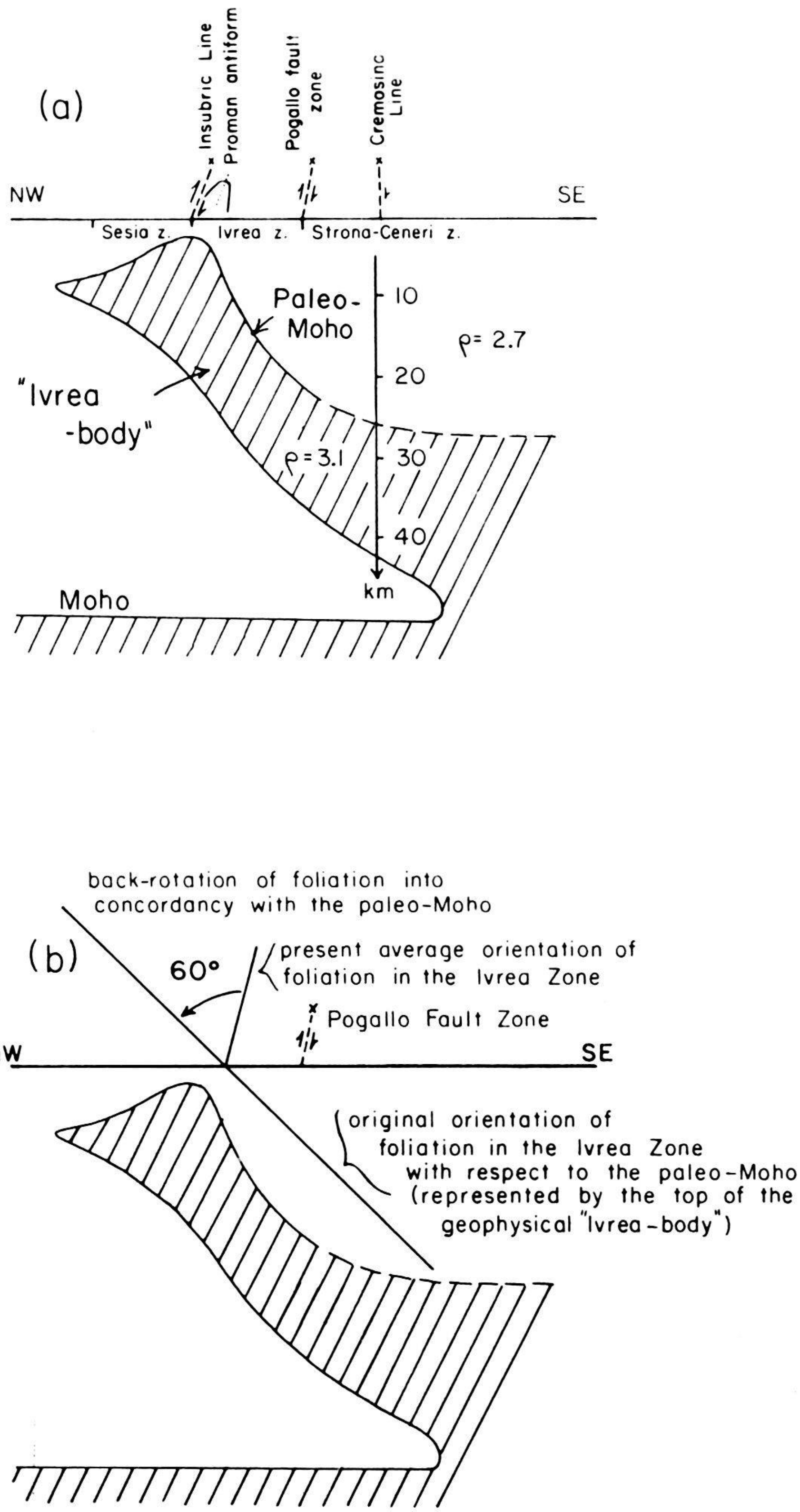


Fig. 16. a) «Bird's head» configuration of the SE-dipping geophysical Ivrea-Body in the Val d'Ossola profile, Verbania area (GRGES, 1968); Note the orientation of the geological features with respect to the Ivrea-Body.
b) Minimum rotational angle (60°) employed in this study to restore the subvertically to NW-dipping foliation of the Ivrea and Strona–Ceneri zones to their pre-Alpine, post-Early Mesozoic orientations. Maximum rotational angle of 85° (constrained by syntectonic metamorphic trends in the PDFZ) corresponds to lower angle orientations of the embryonic Ivrea-Body immediately following Early Mesozoic crustal extension (see text).

2. The geophysical "Ivrea Body" comprises a dipping (approximately 45° SE, Fig. 16a) seismic and gravimetric anomaly in the Verbano region (GRGES 1968). This is consistent with the aforementioned exposure of deeper structural levels towards the NW parts of the basement-section. Some workers relate the present configuration of the Ivrea Body mainly to Alpine compressional tectonics (LAUBSCHER 1971; HUNZIKER 1974; LAUBSCHER & BERNOULLI 1982). Paleozoic ages of emplacement (KÖPPEL 1974; HUNZIKER & ZINGG 1980) are considered less plausible due to: 1. the fit of the Ivrea Body to the Tertiary arc of the western Alps; 2. the purported magnitude of Alpine movements along the Iorio–Tonale–Canavese part of the Insubric Line; and 3. the potential dynamic problems associated with maintaining an isostatically unstable mass in the crust over longer periods of time (see discussion in ZINGG 1983). Based partly on results presented here, S. M. SCHMID et al. (1987) propose that the «bird's head» structure of the Ivrea Body resulted from a combination of Early Mesozoic crustal thinning and subsequent Alpine subduction and orogeny.

3. Folding of the Ivrea foliation under greenschist facies or lower conditions is observed in the northern part of the Ivrea Zone adjacent to the Insubric Line in the Val d'Ossola (Fig. 1, Proman Antiform; R. SCHMID 1967; S. M. SCHMID et al. 1987; BRODIE & RUTTER, 1987) and Finero areas (KRUHL & VOLL 1976; STECK & TIÈCHE 1976). These greenschist facies deformations must by younger than 180 my, given the thermal history of the Ivrea Zone (Temperature-time curves in Fig. 15). S. M. SCHMID et al. (1987) relate folding of the Proman Antiform to Tertiary backthrusting along the Insubric Line. The presence of these Alpine folds implies that the Ivrea foliation was not in its present subvertical position prior to folding.

4. Andesitic dikes in the NW part of the Ivrea Zone (Val Sessera, Plate) show mineralogical characteristics and NRM-directions (Natural Remnant Magnetization) similar to those of Tertiary andesites (31 ± 2 my, SCHEURING et al., 1974) in the SE part of the Sesia Zone (HELLER & SCHMID 1974). Taken qualitatively, the NRM data on these dikes suggest that at least some of the rotation of the Ivrea Zone has occurred since the Oligocene. HELLER & SCHMID (1974) postulate a 73° counterclockwise rotation (looking NE) about a NNE-oriented axis that corresponds to the strike of the andesites' bedding. The rotation brings the NRM-direction of the andesite into concordance with that of the Late-Oligocene Bergell intrusions, north of the Iorio–Tonale part of the Insubric Line. AEBLI (in prep.) employs a slightly smaller, ca. 60°, counterclockwise rotation to attain concordance between andesitic dikes in the Ivrea Zone and the Bergell intrusion.

5.2.2 Restoration of the PDFZ to its original orientation:

To restore the Ivrea–Strona–Ceneri basement-section to its pre-Alpine, post-Pogallo (i.e. post Early Jurassic) orientation, a 60 to 85° counterclockwise rotation (looking NE) about a NE–SW oriented axis was performed on the main fabric elements in the study area (Fig. 17a). The orientation of the rotational axis was chosen to be parallel to the average trend of the schistosity, the compositional banding, and the metamorphic isograds in the central part of the Ivrea Zone, i.e. that part of the Zone containing the PDFZ. The NE–SW trend of the rotational axis also coincides with the mean orientation of both the fold axis of the Proman Antiform (within the northern Ivrea Zone in the Val d'Ossola, Fig. 1) and the axis of the geophysical Ivrea Body in the Verbano area.

The rotational angles and the counterclockwise rotational sense are best understood from the regional geologic context. Following the reasoning in S. M. SCHMID et al. (1987), the geophysical Ivrea Body is believed to have attained its SE-dipping configuration as a combined result of Early Mesozoic crustal thinning and later Alpine compression (Fig. 8, 9, and 10 of S. M. SCHMID et al. 1987). The orientation of the Ivrea–Strona–Ceneri basement also changed during this time. However, the basement-section underwent important additional movements with respect to the underlying geophysical Ivrea Body. Two general kinematic stages are envisaged:

1. Early Mesozoic crustal attenuation may have induced a low-angle, generally eastward dip of the Moho and overlying lower crustal structures in the vicinity of the Southern Tethyan continental margin. A fragment of the pre-Alpine Moho is represented today by the E- to SE-dipping lid of the Ivrea Body (labelled "Paleo-Moho" in Figure 16a). Eoalpine (Late Cretaceous) crustal subduction lead to an embryonic version of the present Ivrea Body (Figure 9 in S. M. SCHMID et al., 1987). This compression probably also steepened the dip of the pre-Alpine Moho somewhat. Throughout this time, the orientation of the pre-Alpine foliation and structures (including the PDFZ) in the Ivrea Zone is assumed to have remained fairly constant with respect to the Ivrea Body (Figure 16b). Thus, the foliation in the Ivrea Zone had acquired a low to moderate SEward dip by the Early Tertiary.

2. Mid- to Late Tertiary (Meso- and Neoalpine) compression modified the configuration of the Ivrea Body and affected the attitude of the Ivrea–Strona–Ceneri foliation. Folding of the Proman Antiform is correlated with SE-directed Insubric backthrusting and is interpreted to indicate that the Ivrea and Strona–Ceneri structures north of the Lago Maggiore (Plate) were rotated clockwise (Looking NE) with respect to the now more steeply dipping Ivrea Body (Fig. 16b; Fig. 5 in SCHMID et al. 1987). In effect, transpressive Insubric tectonics increased the SEward dip of the Ivrea Body and lead to a detachment of the Ivrea–Strona–Ceneri crustal section from its lower crustal – upper mantle edifice.

The regional kinematic framework outlined above is constrained by the local geological relations in the following way: The 60° minimum counterclockwise rotation angle that restores the basement-section represents the acute angle between the current, ca. 45° SE-dip of the Ivrea Body and the 70–80° NW-dip of both the axial plane of the Proman Antiform and the Ivrea schistosity (Fig. 16a and b). This choice of rotation is compatible with the minimum rotational angle required to bring the NW parts of the basement-complex to their originally deeper structural level. Further, the rotational sense and general rotational angle are the same as proposed for the Tertiary andesitic dikes in the northern Ivrea Zone of the Val Sessera (AEBLI, in prep.). The implication is that 60° of a probably larger (up to 85°, see below) rotation of the Ivrea–Strona–Ceneri basement-section has occurred since the Oligocene intrusion of the andesitic dikes.

Obviously, lower primary (i.e. pre-Alpine, post-Pogallo) dips of the geophysical Ivrea Body necessitate rotational angles greater than 60°. A maximum rotational angle of ca. 85° is constrained by the ca. 10° minimum apparent dip of the PDFZ inferred from syntectonic metamorphic trends in the fault zone. Such a rotational angle brings the Ivrea foliation into a subhorizontal position, in accord with evidence that compositional banding in the Ivrea Zone lay subhorizontally during the Paleozoic (viz. magmatic flow

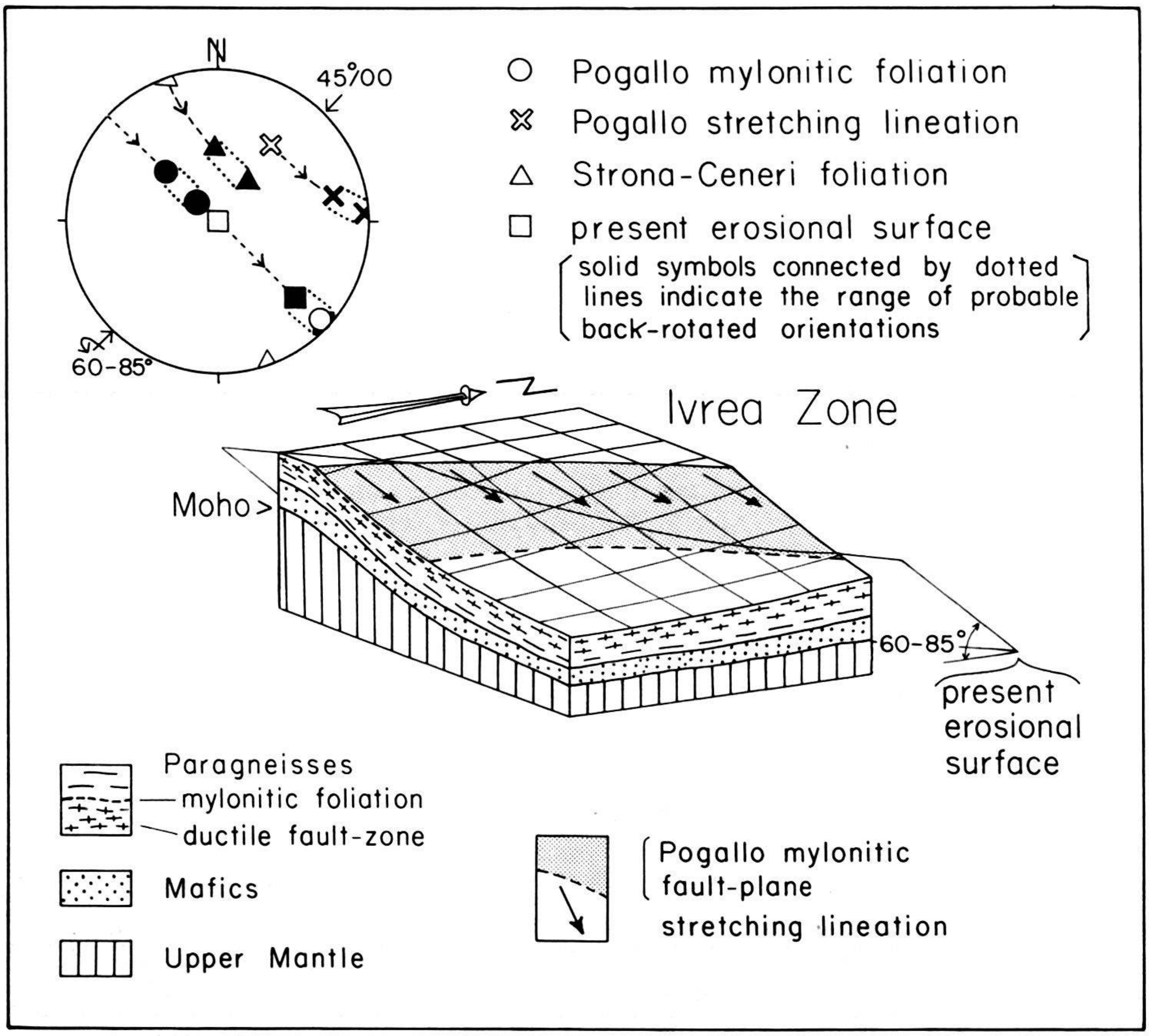


Fig. 17. a) Equal area net showing the main fabric-elements in their present orientation (open symbols) and their range of possible back-rotated, Early Mesozoic orientations (solid symbols). Horizontal rotational axis, N45E, and rotational angle, 60–85° counterclockwise looking NE, are labelled at the edge of the equal area net.
b) Block-diagram of the Early Mesozoic configuration of the Ivrea–Strona–Ceneri basement-section resulting from the back-rotation shown in (a). The Strona–Ceneri block has been removed to expose the Pogallo Fault Zone (viewed from the SE). Arrows on the fault-plane indicate the motion of the Strona–Ceneri block with respect to the Ivrea block during the Pogallo deformation. For reference, the present erosional surface is shown in the back-rotated coordinates.

structures in mafic rocks of the Ivrea Zone; RIVALENTI et al. 1975). However, there is no a priori reason to assume that the pre-Alpine Ivrea foliation was also subhorizontal at the onset of the Pogallo deformation in the Early Mesozoic. In fact, Paleozoic (Caledonian and/or Variscan?) tectonics certainly had a significant influence on the orientation of the foliation and compositional layering in the Southern Alpine basement (e.g. pre-Pogallo folds in the Ivrea and Strona–Ceneri Zones, section 3.2).

A 60–85° counterclockwise (looking NE) rotation of the main fabric elements in the Verbano area results in a SE-dipping Pogallo tectonite foliation that contains a stretching lineation plunging to the east (Fig. 17b). The Ivrea foliation remains parallel to that of the Pogallo tectonites while the Strona–Ceneri foliation assumes a moderately south- to

SW-dipping orientation. In the rotated coordinates, the shear in the Pogallo tectonites involves E–W directed extension.

It should be emphasized that the amount of rotation used to restore the Pogallo Fault Zone to its pre-Alpine orientation is poorly constrained and is based largely on evidence accrued in the Ivrea–Strona–Ceneri basement. Nevertheless, the prediction of Late Triassic to Early Jurassic E–W directed extension in the Southern Alpine basement fits very well with the stratigraphic evidence in the Southern Alps of rapid subsidence and E–W crustal extension during the Early Jurassic (e.g. BERNOULLI 1964; GAETANI 1975).

5.2.3 Mesozoic geometry and kinematics of the PDFZ: model and implications

The Pogallo Ductile Fault Zone is interpreted as a low- to moderate-angle, SE-dipping extensional fault in the intermediate to deep portions of the Southern Alpine crust, similar to the configuration proposed by HODGES & FOUNTAIN (1984). The Pogallo Line forms at the top of the PDFZ and separates the Ivrea Zone (footwall) from the Strona–Ceneri Zone (hanging wall) (Fig. 17b). At the structurally lower end of the Pogallo Line, the mylonites splay downward into a zone of diffuse, crystal-plastic deformation (linked with the disappearance of the Pogallo Line), while at the opposite end, they grade upward into a broad zone of cataclasis (corresponding to the Pogallo–Orta disturbance, Plate).

This kinematic framework is consistent with the structural and syntectonic metamorphic trends observed today across and along strike of the southern Ivrea Zone: Deformation within the NW part of the PDFZ and within the entire NE part of the PDFZ occurred at higher temperatures as the warm Ivrea crustal block moved up and to the SW relative to the Strona–Ceneri Zone. Greenschist facies mylonitization and a marked structural discordance between the two basement-units characterize the cool SE margin of the PDFZ.

Two explanations are offered for the angular discordance across the Ivrea–Strona–Ceneri contact: 1. the discordance is a pre-Mesozoic feature and is unrelated to Pogallo faulting. The presence of an angular discordance between the two zones in part of the basement-section to the NW of the Pogallo–Orta fault (Plate) could be attributed to an older, pre-Pogallo disturbance (e.g. the Cossato–Mergozzo–Brissago Line of BORIANI & SACCHI 1973) affecting the entire length of the Ivrea–Strona–Ceneri contact; 2. the discordance is attributed to relative rotation of the Ivrea or Strona–Ceneri Zones during Early Mesozoic Pogallo ductile faulting. It is conceivable that there are other Early Mesozoic disturbances similar to the PDFZ that affected various parts of the Ivrea–Strona–Ceneri contact (e.g. the aforementioned discordance NW of the Pogallo–Orta Fault).

The pre-Pogallo age metamorphism in the rocks of the Ivrea and Strona–Ceneri Zones juxtaposed along the PDFZ occurred under approximately the same mid-amphibolite facies conditions (HANDY 1986). This lack of a pre-Pogallo metamorphic discordance across the fault zone is interpreted to reflect the low angle orientation of the PDFZ during the Early Mesozoic (section 5.2.1). A consequence of the low angle geometry is that large horizontal displacements may be accommodated without requiring a significant amount of vertical (i.e. stratigraphic) throw.

5.3 Estimates of crustal thinning

The temperature–time cooling curves derived from the various mineral-isotopic systems for the SE rim of the Ivrea Zone and the northern Strona–Ceneri Zone juxtaposed along the Pogallo Line (Fig. 15) may be used to estimate changes in the depth of the two Zones and the amount of crustal thinning associated with the Pogallo deformation. The values of crustal depth, thickness and thinning of the Ivrea and Strona–Ceneri Zones shown in Figure 18 depend strongly on the geothermal gradient as well as on the interpretation of the radiometric mineral ages as cooling ages. While the estimates in Figure 18 were made for geothermal gradients ranging form 25 to 35 °C/km, for the sake

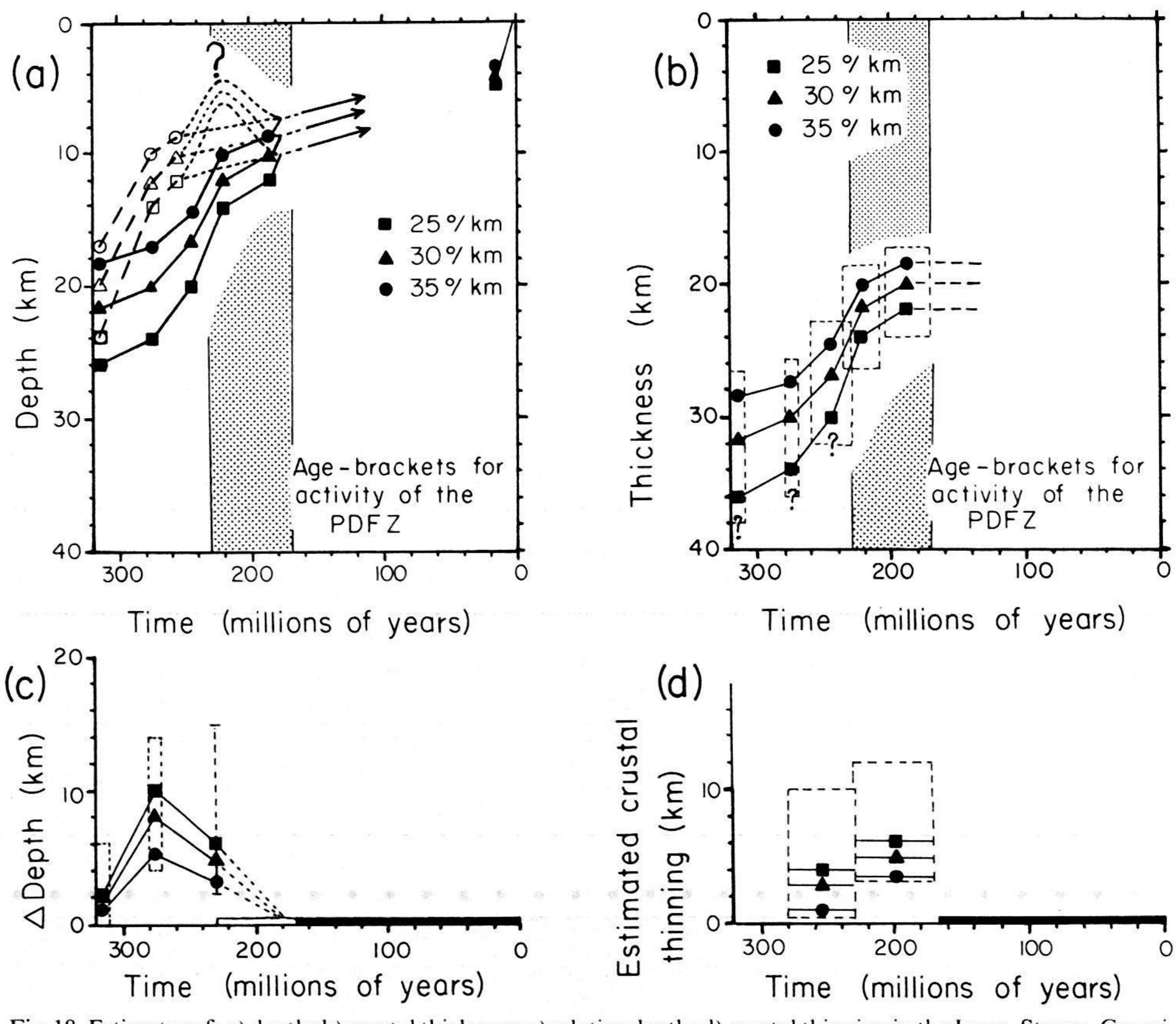


Fig. 18. Estimates of: a) depth; b) crustal thickness; c) relative depth; d) crustal thinning in the Ivrea–Strona-Ceneri basement-section NW of the Lago Maggiore; estimates based on radiometric ages and present crustal thicknesses in the Val d'Ossola profile. Values are calculated for geothermal gradients of 25°/km (squares), 30°/km (triangles), and 35°/km (circles). Boxes in b–d indicate error associated with blocking-temperature estimates of the various radiometric age systems. In a), solid and dashed lines are the depth-time trajectories for the southern Ivrea Zone and the northern Strona–Ceneri Zone, respectively. Radiometric ages from adjacent parts of the Ivrea and Strona–Ceneri Zones in the Val d'Ossola region are taken from: McDowell & Schmid (1968); Hunziker, (1974); Köppel (1974); Köppel & Grünenfelder (1978/79). In estimating the amount of thinning in the basement-section, it is tacitly assumed that no crustal thickening has occurred since the Early Permian.

brevity, values cited in the text below are for an average geothermal gradient of 30 °C/km. Obviously, variations in the geothermal gradient with time affect these estimates.

The greatest discrepancy in depth between the two Zones existed prior to, and during, the Early Permian ($\geq$ 270 my) when the southern Ivrea Zone was at a depth of about 20 km, while the presently adjacent northern part of the Strona–Ceneri Zone lay at around 12 km (Fig. 18 a and c). The total thickness of the basement-section at this time was about 30 km (Fig. 18 b). By the Late Triassic (ca. 230 my), prior to or during the earliest activity of the Pogallo Fault Zone, the difference in level between the two basement units had been reduced to at least 50 km (Fig. 18 c), with the southern Ivrea and northern Strona–Ceneri Zones at depths of about 15 km and at most 10 km, respectively (Fig. 18 a). This implies that not more than 3 km of crust were thinned between the Early Permian and the Late Triassic along the present contact between the two Zones (Fig. 18 d). Possibly, the pre-Pogallo deformational fabrics in the southern Ivrea Zone (Fig. 8 a, section 4.1) are relics of such an earlier period of extension.

The southern Ivrea Zone attained a depth of just 10 km sometime during the Early to Middle Jurassic, according to 220–160 my. biotite ages (Plate, Fig. 15 and 18 a). The cooling history of the Strona–Ceneri Zone after the Permo-Triassic is poorly constrained in the Val d'Ossola area due to the lack of radiometric age data from isotopic systems with closing temperatures between 300 and 100 °C. However, in light of the record of extensional tectonics preserved in the Lower Jurassic sediments of the Southern Alps, it seems plausible to assume that the Strona–Ceneri Zone presently adjacent to the Pogallo Line had attained the same crustal level as the southern Ivrea Zone by at least the Early Jurassic (Fig. 18 a and c). Thus, Pogallo ductile faulting during the Late Triassic to the Early to Middle Jurassic was responsible for the thinning of about 5 km of crust from the Ivrea–Strona–Ceneri basement-section. By the end of crustal thinning in the Jurassic, the total thickness of the basement-section had been reduced to approximately 20 km (Fig. 18 b).

It should be noted again that these estimates of crustal thinning pertain only to the present-day contact between the Ivrea and Strona–Ceneri Zones in the Val d'Ossola area. The actual amount of crust thinned from the basement section is probably greater, since extensional faulting also affected lower crustal levels of the Ivrea Zone (BRODIE & RUTTER, 1987; A. Zingg, pers. comm.). Indeed, high temperature, upper amphibolite facies mylonites from various localities in the Ivrea Zone (Brissago area: WALTER 1950; Finero area: KRUHL & VOLL 1976; STECK & TIÈCHE 1976; BRODIE 1980; Val d'Ossola area: R. SCHMID 1967; BRODIE 1981) may be related to (episodic?) crustal attenuation during the Permian and Early Mesozoic (HANDY 1986).

5.4 Implications for Alpine tectonics in the Verbano area

The considerations involved in establishing the kinematics of Pogallo ductile faulting bear numerous implications for Alpine tectonics in this corner of the Southern Alps. A 60 to 85° rotation has been proposed to restore the part of the Ivrea–Strona–Ceneri basement NW of the Lago Maggiore to its original pre-Alpine orientation. Yet south of the Lago Maggiore, the orientation of the Permo-Mesozoic sediments that overlie the Strona–Ceneri Zone does not suggest such a large regional tilt, despite some locally intensive, generally S-vergent Alpine folding and faulting (e.g. VAN HOUTEN 1929; Plate 7

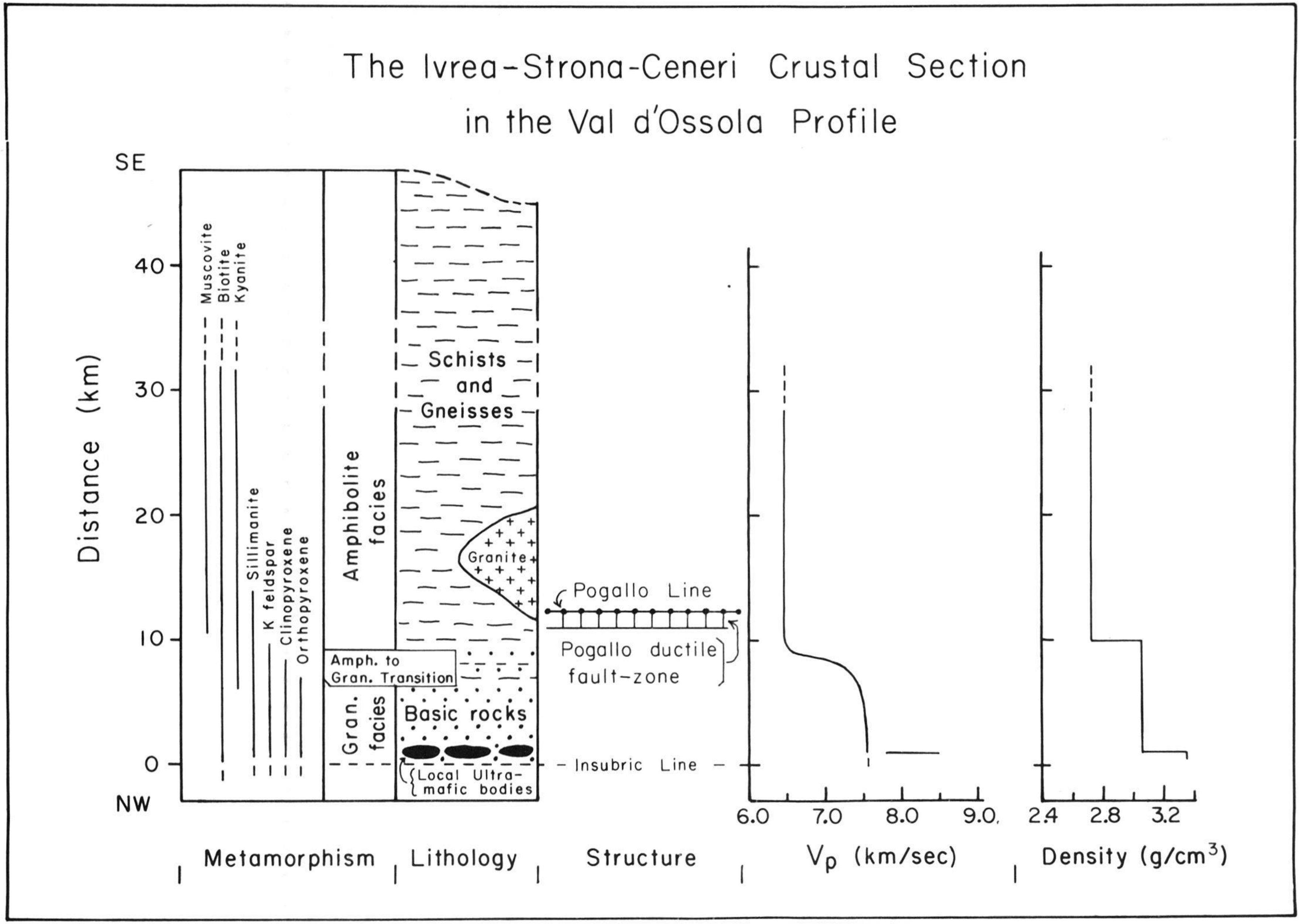


Fig. 19. Comparative profiles of pre-Pogallo metamorphism, lithology, structure, seismic velocity, and density in the Ivrea–Strona–Ceneri basement-section (modified after FOUNTAIN 1976). The Insubric Line truncates the lower end of the section and serves as a reference line for distance plotted on the vertical axis. Stability ranges of key metamorphic minerals are taken from R. SCHMID (1967), PEYRONEL PAGLIANI & BORIANI (1967), ZINGG (1980) and this study. Seismic velocities and densities from FOUNTAIN (1976) were measured at confining pressures between 6 and 10 kb.

of KÄLIN & TRÜMPY 1977). This discrepancy implies the presence of one or more faults or folds in the basement which acted as a major hinge between the rotated basement-section in the NW and the un- or less-rotated section in the south and SE. It is both tempting and convenient to place a large NE–SW striking hinge-zone within the Lago Maggiore. Possibly, such a «Lago Maggiore hinge zone» (not to be confused with the N–S trending «Lago Maggiore fault» of BERNOULLI 1964!) is related to the NE–SW trending Cremosina–Val Cuvia fault-system further to the SE (KÄLIN & TRÜMPY 1977). Indeed, the locally severely disturbed contact between the Strona–Ceneri basement and its Permo-Mesozoic sedimentary cover (e.g. Fig. 5 in NOVARESE 1929; GRAETER 1951) may be a manifestation of faulting related to hinge movements. The apparent lack of evidence for NE and SW continuations of the purported Lago Maggiore hinge-fault may be due to subsequent offset along N–S oriented faults (common in the Verbano area, see the Plate and Fig. 1) or reflect the lack of careful structural mapping in the region. In the absence of conclusive field evidence, such a hinge-fault remains conjectural but necessary.

5.5 Implications for geophysical characteristics of the deep continental crust in the Southern Alps

Comparison of the distribution of PDFZ microfabrics with seismic velocities and densities of the Ivrea and Strona–Ceneri Zone rocks measured in the laboratory (FOUNTAIN 1976) indicates that the Pogallo Ductile Fault Zone is rooted just above the transition in seismic velocities and densities from intermediate to lower crustal values (Fig. 19). This intracrustal geophysical boundary may represent the Conrad discontinuity and corresponds with the transition from Paleozoic amphibolite to granulite facies metamorphism in the Ivrea Zone (Fig. 19; FOUNTAIN 1976). The results of this study suggest that under the deformational conditions of the Pogallo ductile faulting during the Early Mesozoic, large-scale extensional detachment in the Southern Alpine basement occurred preferentially within the warm, relatively hydrous base of the intermediate crust. This is in agreement with experimentally determined rheological properties of basement rocks undergoing dislocation creep: the creep-strength of the relatively hydrous quartzitic rocks comprising the intermediate crust is much lower than that of the feldspar-, amphibole-, pyroxene-, or olivine-rich rocks predominating in the lower crust (e.g. CARTER 1976).

Deep seismic reflective profiling of the continental crust often reveals a tripartite crustal configuration: an intermediate crustal level showing few seismic reflectors separates a reflective, faulted upper crust from a lower crust containing subhorizontal to low-angle reflectors (reviews in BARAZANGI & BROWN 1986). Much debate centers on the possibility that some lower crustal seismic reflectors represent mylonitic shear zones such as the PDFZ. The km-wide PDFZ consists predominantly of quartz-rich tectonites. Although their mineralogy and density is similar to that of the surrounding rocks in the Ivrea and Strona–Ceneri Zones, the strong crystallographic preferred orientation of quartz in these tectonites could produce a seismic anisotropy of as much as 11% (JONES & NUR 1982). The seismic reflectivity might be further enhanced by the infiltration of fluids into the ductile fault zone. The former presence of such fluids in the PDFZ is inferred from retrograde syntectonic, hydrous mineral reactions of pre-Pogallo mineral parageneses (section 4.2). In an experimental study, FOUNTAIN et al. (1984) demonstrate that the physical characteristics of mylonitic zones such as the Pogallo Line (i.e. strong structural anisotropy, retrograde mineralogy, relatively continuous and planar geometry of shear zone networks) can produce seismic reflectors provided that the signal-to-noise ratios are sufficiently high. Given what is now known about the structure and history of the PDFZ, this area provides an excellent opportunity to test some of these hypotheses in the field.

6. Conclusions

The Pogallo Fault Zone is interpreted as a low to moderate angle, oblique-extensional ductile fault active sometime during the Late Triassic to the Early to Middle Jurassic. The evidence of E–W directed extension accommodated within this crustal-scale shear zone is compatible with abundant stratigraphic evidence in the Southern Alps of rapid differential subsidence coupled with E–W crustal attenuation beginning in the Liassic. Such large-scale, Early Mesozoic crustal extension was related to the development of a passive continental margin at the southern margin of the Mesozoic Tethyan ocean (BALLY et al. 1981; WINTERER & BOSELLINI 1981). The Pogallo ductile faulting is therefore directly involved in the Early Mesozoic attenuation of lower curstal levels, bringing the originally intermediate to lower continental crust of the Southern Alps (represented by the Ivrea–

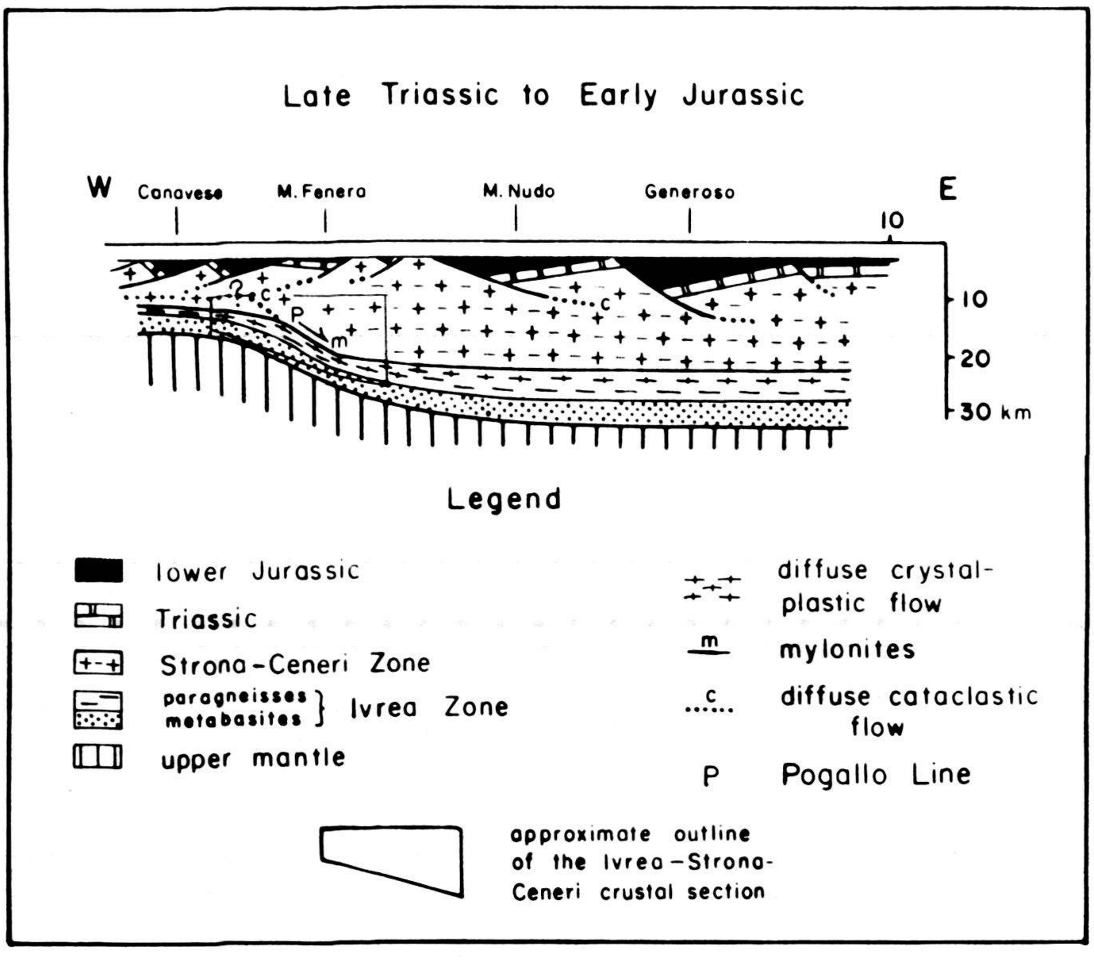


Fig. 20. Schematic palinspastic reconstruction of the Southern Alpine crust as it might have appeared during the Late Triassic to Early Jurassic (slightly modified from Figure 8 of S. M. SCHMID et al. (1987)).

Strona–Ceneri crustal section) to relatively shallow levels (ca. 10 km) and low ambient temperatures. Later, Eoalpine subduction and Tertiary movements associated with transpressional Insubric faulting further rotated the Ivrea–Strona–Ceneri basement-section to its present subvertical orientation (S. M. SCHMID et al. 1987). The present-day map-view of the Verbano area includes a slice through the Pogallo Ductile Fault Zone which is oblique to the transport-direction.

The analysis of microstructures and quartz textures preserved in the PDFZ indicates that extension of lower crustal levels can be accommodated within broad, dipping ductile zones of predominantly simple shear. Such ductile style of deformation involving crystal-plastic flow contrasts with the discrete, brittle deformation typical of extensional faulting in the upper 8 to 10 km of the continental crust.

Seen on the scale of the continental crust, dipping ductile fault zones may be common in narrow domains of oceanward «necking» of the continental crust inferred from deep crustal seismic profiling of passive continental margins (e.g. MONTADERT et al. 1979). A highly conceptual profile of the attenuated Southern Alpine continental margin during the Early Jurassic appears in Figure 20. The PDFZ is depicted as part of a system of ductile flow at the base of the crustal neck and is antithetically oriented with respect to relatively discrete brittle extensional faults in the overlying upper crust.

The emphasis of this paper on evidence of Late Triassic – Early Jurassic extension in the Southern Alpine basement (a topic in vogue at the time of this writing) will hopefully not obscure the fact that the Ivrea and Strona–Ceneri Zones have undergone a very complex Paleozoic, Mesozoic and Tertiary tectono-metamorphic history. Several events have left their imprint, but distinguishing among them is often problematical. Moreover, much of the Southern Alpine basement has not yet been mapped structurally. It is hoped that careful structural and petrological work combined with selective radiometric dating, preferably using a variety of isotopic systems in and around the tectonites, will further help to relate small-scale structures to the regional tectonic evolution of the Southern Alps.

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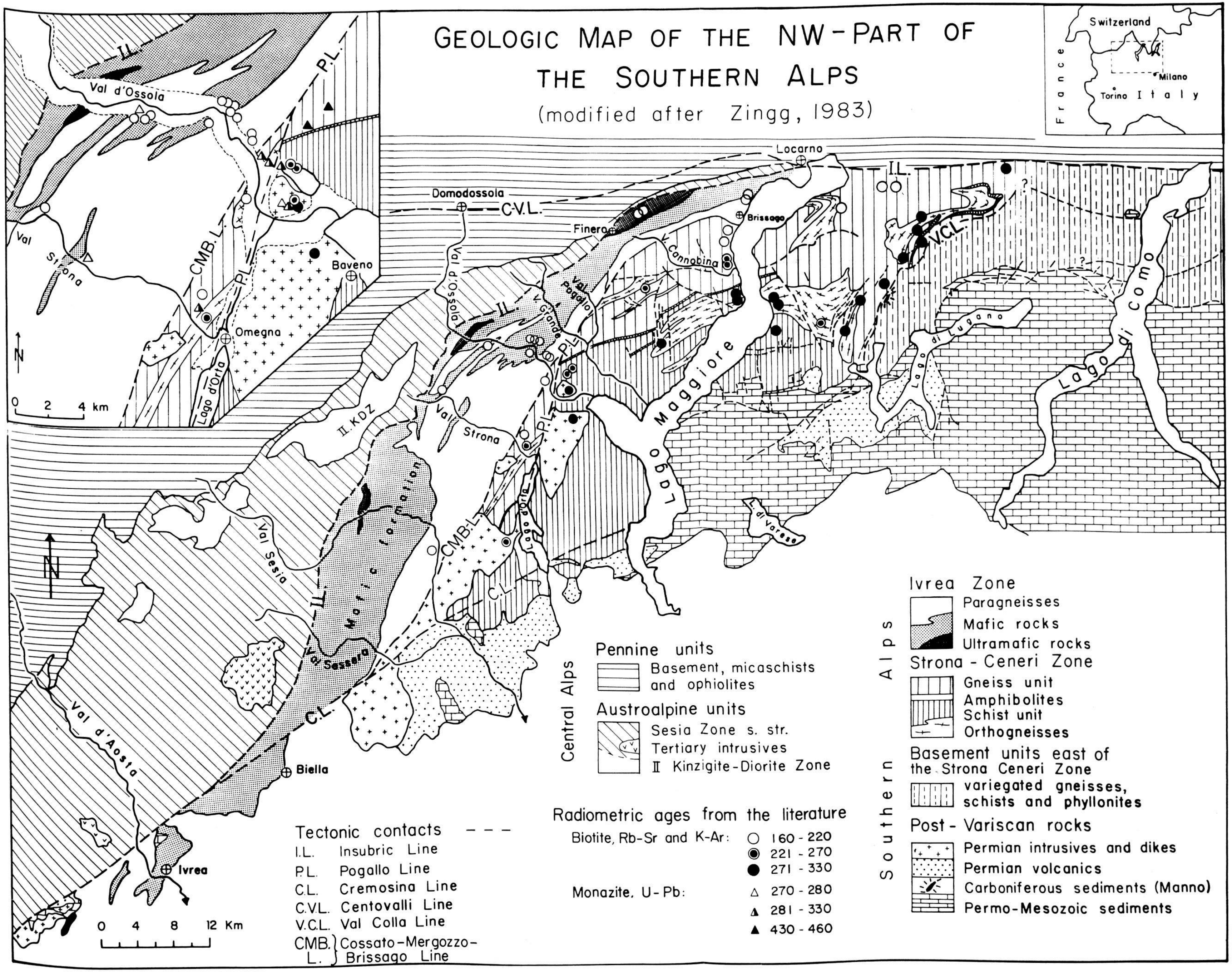

Generalized geologic map of the NW-part of the Southern Alps (adapted from Plate I of ZINGG (1983) with minor modifications).