**Zeitschrift:** Eclogae Geologicae Helvetiae
**Herausgeber:** Schweizerische Geologische Gesellschaft
**Band:** 89 (1996)
**Heft:** 1

**Artikel:** Structure of the northern Maggia and Lebendun Nappes, Central Alps, Switzerland
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**DOI:** https://doi.org/10.5169/seals-167910

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Eclogae geol. Helv. 89/1:461–504 (1996)

0012-9402/96/010461-43 $1.50 + 0.20/0
Birkhäuser Verlag, Basel

# Structure of the northern Maggia and Lebendun Nappes, Central Alps, Switzerland

DJORDJE GRUJIC & NEIL S. MANCKTELOW

*Key words:* Central Alps, deformation, metamorphism, fold superposition

## ABSTRACT

In the Basòdino-Cristallina-Campolungo area, five deformation phases are distinguishable on the basis of overprinting criteria observable over a broad range of scales, from regional to microscopic. The first phase, related to initial thrust and nappe development, is preserved as recumbent tight to isoclinal folds with cores of pre-Triassic basement surrounded by a discontinuous envelope of dolomitic marbles and quartzites.

During the second phase, the nappe pile was refolded into major recumbent isoclinal folds. These folds show a strong penetrative axial planar schistosity and a marked elongation lineation, which is parallel to small scale fold hinges. Several major $D_2$ folds can be followed over long distances (> 50 km), and were mapped by earlier workers as distinct fold nappes (e.g. the "Antigorio nappe", whose antiformal core is a $D_2$ fold). The regional pattern of Mesozoic-cored synforms (e.g. Teggiolo, Campolungo, Piora and Molare) and intervening basement-cored antiforms is mainly due to large-scale $D_2$ folds.

The third phase structures developed obliquely to the trend of earlier structures and to the Penninic zone as a whole. Third phase folds are more open and have a characteristic chevron or corrugated style, with much lower limb to hinge ratios than folds of the first two deformation phases. A new crenulation cleavage is variably developed parallel to the axial planes of $D_3$ folds, particularly in more micaceous lithologies. In the northern Maggia area, amphibolite facies metamorphic conditions were reached after $D_2$ and maintained through $D_3$. Superposition of second and third phase folds resulted in Types 1, 2 and 3 interference patterns on all scales. Third phase folds have much greater regional importance than has been previously realised: the main structures related to this deformation phase are the Campo Tencia synform and the Maggia Steep Zone.

Fourth phase folds represent the backfolds of the Northern Steep Zone, which locally reactivated and modified existing third phase structures (e.g. the Basòdino fold). The "northern steep zone" represents the steep to overturned northern limb of a broad, regional fourth phase synform (from west to east known as the Berisal, Basòdino and Chièra synforms) with a nearly horizontal fold axis and shallow to moderately NW-dipping axial plane. The regional interference between $D_3$ and $D_4$ folds resulted in the overall double dome structure of the Lepontine Alps (i.e. the Simplon and Ticino culminations) as marked by the regional attitude of the main schistosity (i.e. $S_2$).

Fifth phase structures are coaxial with $F_4$ and locally developed within the steep zone as kinklike folds with nearly horizontal axial planes. They reflect a late vertical shortening, most likely related to orogenic collapse during continued Alpine convergence. Possibly coeval late minor fault, joint and quartz vein development demonstrates late stretching parallel to the Alpine trend (i.e. SW-NE), consistent with the Neogene development of the low-angle normal Simplon and Brenner Fault Zones.

## ZUSAMMENFASSUNG

Im Gebiet von Basòdino-Cristallina-Campolungo können fünf Verformungsphasen unterschieden werden. Die Überprägungsstrukturen lassen sich vom regionalen bis in den mikroskopischen Bereich hinein beobachten.

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Die erste Phase gehört zu den Anfängen der Decken- und Überschiebungsbildung. Davon erhalten sind liegende, enge bis isoklinale Falten mit prä-Trias Grundgebirge im Kern, welches von einem diskontinuierlichen Mantel aus dolomitischem Marmor und Quarziten umgeben ist.

Während der zweiten Phase wurde der Deckenstapel in grosse liegende Isoklinalfalten wiederverfaltet. Diese Falten zeigen eine starke durchdringende Achsenebenenschieferung und ein ausgeprägtes Streckungslinear parallel zu kleinen Faltenscharnieren. Einige grosse $D_2$-Falten können über weite Distanzen verfolgt werden (> 50 km) und wurden in früheren Arbeiten als einzelne Decken kartiert (z.B. die «Antigorio-Decke», der Kern dieser Antiform ist eine $D_2$-Falte). Das regionale Muster von Synformen mit Mesozoikum im Kern (z.B. Teggiolo, Campolungo, Piora und Molare) und dazwischenliegenden Antiformen mit Grundgebirgs-Kern ist grösstenteils eine Folge dieser grossen $D_2$-Falten.

Die Strukturen der dritten Phase entwickelten sich sowohl schief zu den früheren Strukturen als auch zu der Penninischen Zone als Ganzes. Die Falten dieser dritten Phase sind offener, mit einem charakteristischen Stil von Chevron- oder gewellten Falten. Das Verhältnis unterer Schenkel zu Scharnier ist viel kleiner als bei den Falten der ersten zwei Verformungsphasen. Speziell in glimmerreichen Lithologien ist eine neue, veränderliche Runzelschieferung parallel zur Achsenebene der $D_3$-Falten entwickelt. Die Überprägung der zweiten und dritten Phase ergab Interferenzstrukturen vom Typ 1, 2 und 3 jeglicher Grösse. Die Falten der dritten Phase haben eine viel grössere regionale Bedeutung als bisher angenommen wurde: die Hauptstrukturen die zu dieser Verformungsphase gehören sind die Campo Tencia Synform und die Maggia-Steilzone.

Die Falten der vierten Phase sind die Rückfaltung der nördlichen Steilzone und eine lokale Reaktivierung und Veränderung der Strukturen der dritten Phase (z.B. die Basòdino-Falte). Die nördliche Steilzone ist der steile bis überkippte Nordschenkel einer breiten, regionalen Synform der vierten Phase (von W nach E genannt Berisal-, Basòdino- und Chièra-Synform) mit einer beinahe horizontalen Faltenachse und flach bis mässig nach NW einfallender Faltenachsenebene. Die regionale Überprägung von $D_3$- und $D_4$-Falten ergibt die doppelte Dom-Form der Lepontinischen Alpen (z.B. die Simplon und Tessin Kulminationen), wie sie durch das regionale Verhalten der Hauptschieferung (z.B. $S_2$) angezeigt wird.

Die Strukturen der fünften Phase liegen koaxial zu $F_4$ und sind lokal innerhalb der Steilzone als kinkähnliche Falten mit fast horizontaler Faltenachsenebene entwickelt. Sie widerspiegeln eine späte vertikale Verkürzung. Diese steht wahrscheinlich in Beziehung mit Gebirgskollaps während andauernder alpiner Konvergenz. Die Entwicklung von wahrscheinlich zeitgleichen späten kleinen Falten, Klüften und Quarzadern zeigt eine späte Streckung parallel zu den Alpen an (d.h. SW-NE). Diese ist in Übereinstimmung mit der Entwicklung von flachen Abschiebungen im Neogen, der Simplon- und Brenner-Bruchzone.

## I. Introduction

In the Basòdino-Cristallina-Campolungo area (Fig. 1), several regional-scale Alpine structures of different generations meet to produce a complicated fold interference pattern outlined by the lithological boundaries and dominant schistosity. Unravelling the deformation history in this area is critical to establishing a relative chronology for the development of these major structures in the Central Alps and thus to understanding the tectonic history of the Alps as a whole. This paper discusses in detail the overprinting relationships developed in the Basòdino-Cristallina-Campolungo area. From these field observations, the style, orientation, and relation to metamorphic mineral growth of various fold "phases" (i.e. geometrically distinct fold and/or fabric forming events as part of a continuous, though probably pulsating, deformation history) can be established with some certainty. Correlation of individual folds on a regional scale is also attempted, but with a corresponding decrease in the degree of certainty, particularly for the earlier deformation phases that are strongly overprinted and refolded by later events. A tentative correlation is also attempted with adjacent areas. On the scale of the whole Penninic zone, older deformational events are better preserved in the structurally higher units (e.g. the Suretta and Tambo nappes to the east, cf. Schreurs 1993, Baudin et al. 1993), whereas younger events are more strongly developed in the core of the broad Lepontine meta-

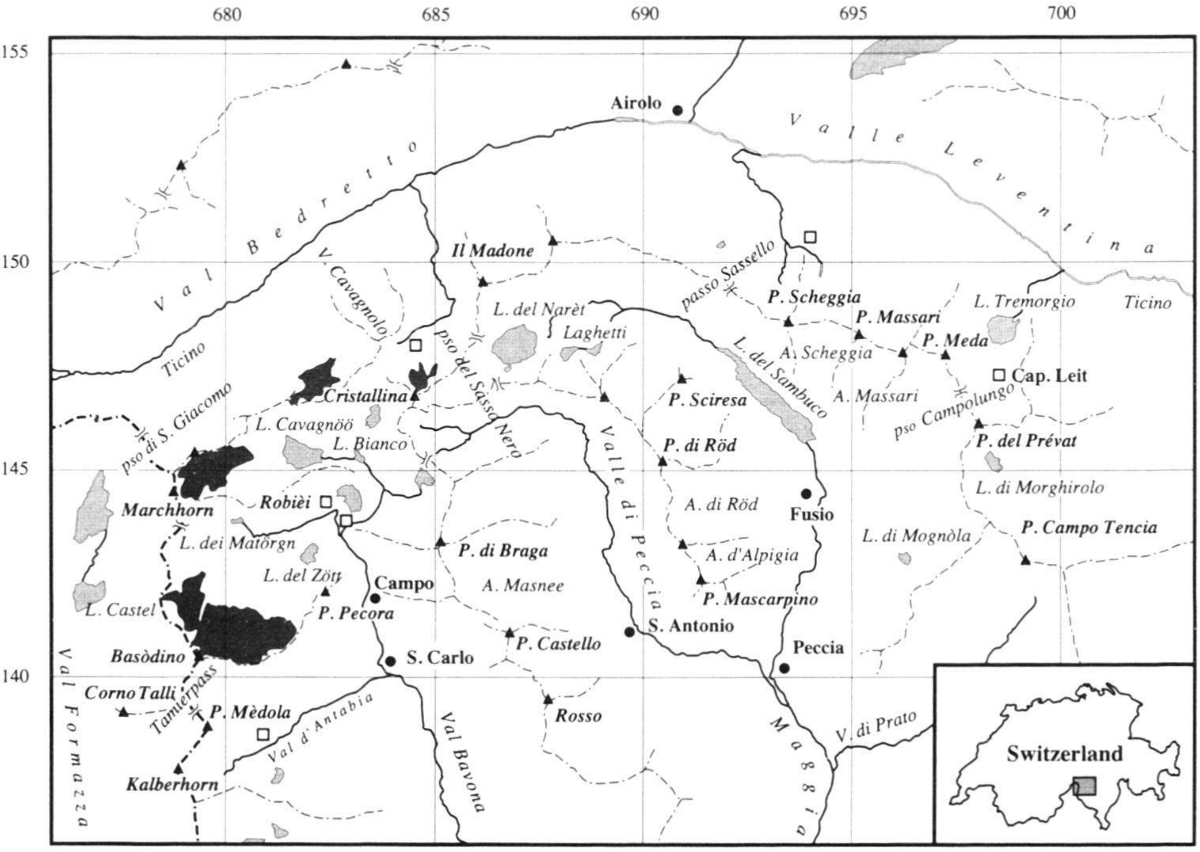



Fig. 1. Topographic sketch map of the study area with the main localities mentioned in the text indicated. Full lines: rivers, dashed lines: ridges; light-grey shaded areas: lakes; dark-grey shaded areas: glaciers; circles: villages; triangles: peaks; squares: mountain huts. Coordinate system is from the Swiss national topographic map grid.

morphic dome, which provides a window to deeper structural units. This reflects the gradual inward cooling of the thermal dome during continued deformation (Fox 1975).

## *1.1 Methods of correlation and structural analysis*

The structural analysis of multiply deformed areas makes use of several tools for distinguishing and correlating structures assigned to different phases (for reviews see Hobbs et al. 1976, Williams 1985). These techniques have important limitations, however, and must be applied critically in regional studies. For example, folds from each phase of deformation often show characteristic profile geometries within the same lithology, but this style may also vary regionally dependent on lithology, pre-existing deformation geometry (e.g. the orientation and style of earlier folds), intensity of deformation and metamorphic grade. Structures formed during each deformation phase may also have specific orientations and superposition of structures of different generations will therefore result in characteristic interference patterns. However, fold orientation can also be strongly influenced by the orientation of already existing planar and linear anisotropies (e.g. Watkinson & Cobbold 1981), and the shape of earlier folds may in part determine the type of refolding geometry (e.g. Grujic 1993). The local outcrop-scale fold interference patterns does not, therefore, always mimic the regional-scale pattern (e.g. Ghosh et al. 1993). In many cases, the final geometry cannot be related to the effect of a single specific deformation phase alone, but rather to the summed effect of several events. In this case, the final fold shapes on all scales represent finite strain structures developed as the result of sequential deformation (e.g. Grujic 1992). Finally, not all rock types necessarily record all the deformation phases; for example, in the current study, all five deformation phases can generally be recognised in metapelites, whereas the granitic gneisses often show only one composite planar and linear fabric, which is difficult to assign to a distinct deformational event. The current study employs a combination of both regional mapping and more detailed investigations in selected parts of the region with good outcrop continuity (e.g. Pl. 1). The interpretation of the observations was performed by an interactive, trial-and-error analysis of maps and outcrops, with an emphasis on internal consistency.

## 2. Previous work

The structure of the Penninic zone has been studied for more than a century. Gerlach (1869, p. 120 and table 2) recognised a large recumbent fold structure in the Antigorio gneiss and ascribed a Triassic age to marbles on the boundary between basement rocks and "Bündnerschiefer" calc-schists. Even the earliest workers intimated what later became well accepted, namely that in this zone pre-Triassic basement and their Mesozoic cover rocks are interleaved in a complex manner as a result of the Alpine orogeny. The basement units together with their presumed autochthonous cover were termed "nappes" and named according to type localities (Schmidt & Preiswerk 1908, Argand 1911, Staub 1924, Heim 1919–1922). These nappes were defined as northward closing fold anticlines, characterised by cores of pre-Triassic basement with envelopes of calcareous Mesozoic cover rocks in tight synclines. Preiswerk (1918) produced the first 1 : 50 000 geological map of the frontal part of the Maggia nappe. This work concentrated on petrographical and lithological subdivision of the rock units and outlined the major structures in the region. In the period between the two world wars, most work was concentrated on very detailed descriptions of the stratigraphy, local geology and petrography of the area, the results of which were summarised in Niggli et al. (1936). From 1940 onwards, E. Wenk and his students (Burckhard 1942, Hasler 1949, Buchmann 1953, Günthert 1954, Keller 1968) undertook a detailed remapping of the area, and established the basis for a mineralogic and petrographic understanding. From this work resulted the 1 : 25 000 geological maps *Basòdino* (Burckhard & Günthert 1957), *Val Bedretto* (Hafner et al. 1975) and *P. Campo Tencia* (Keller et al. 1980). Beginning around 1960, a third period of research involving detailed structural and metamorphic analysis of the Lower Penninic nappes was carried out in a series of Ph.D. and Masters theses from Imperial College in London (Higgins 1964, Chadwick 1965, Cobbold 1969, Mounteney 1969, Sibbald 1971, Thakur 1971, Hall 1972), and from the University of Basle (Chatterjee 1961, Milnes 1964). These studies established the concept of *fold phases* or *deformation phases* and the relative timing relations of polyphase deformation and metamorphism. An important new result from this period of research was the recognition that some of the classic basement nappes were actually regional second phase recumbent folds refolding earlier nappe structures (Milnes 1974a, b). More recently, a series of Ph.D. theses and diploma

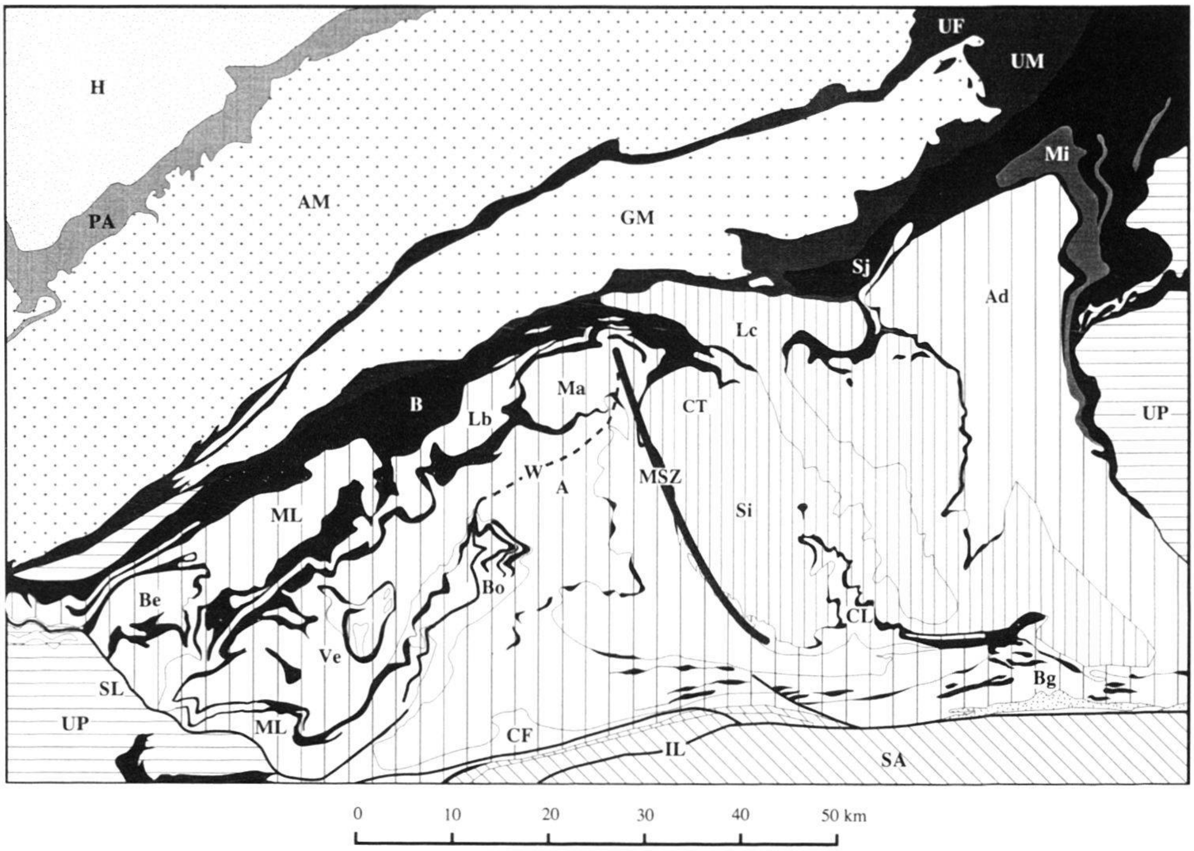



Fig. 2. The lower Penninic (Lepontine) nappes and external massifs ot the Central Swiss Alps. After: Keller (1968), Milnes (1974a) and Spicher (1980). Legend:

| | |
|---|---|
| AM | Aar massif |
| B | Bündnerschiefer |
| Bg | Bergell tonalite |
| H | Helvetic nappes |
| PA | Parautochthonous Mesozoic |
| SA | Southern Alps |
| UF | Garvera-Urseren-Furka zone |
| UM | Ultrahelvetic Malm |
| UP | Upper Penninic |

Subpenninic:

| | |
|---|---|
| GM | Gotthard massif |
| Lc | Lucomagno nappe |
| Si | Simano nappe |
| CT | Campo Tencia nappe |

Lower Penninic:

| | |
|---|---|
| A | Antigorio nappe |
| Ad | Adula nappe |
| Be | Berisal series |
| Bo | Bosco series |
| CL | Cima Lunga Lappen |
| CF | Centovalli Fault |
| IL | Insubric Line |
| Lb | Lebendun nappe |
| Ma | Maggia nappe |
| Mi | Misox zone |
| ML | Monte Leone nappe |
| MSZ | Maggia Steep Zone |
| Sj | Soja nappe |
| SL | Simplon Line |
| Ve | Verampio window |
| W | Wandfluhhorn fold |

studies from the ETH Zürich (Huber 1981, Simpson 1981, Huber-Aleffi 1982, Klaper 1985, Greco 1984, Oppizzi 1984, Aebischer 1985, Bleiker 1989, Zimmermann 1989, Berchtold 1990, Hohl 1990, Rüffer 1990, Stoll 1990, Grujic 1992) revealed more details of the polyphase nature of the Alpine deformation history. They also involved more process-oriented studies on strain determination, shear zone mechanisms, and the geometry and mechanism of superposed folding.

## 3. Regional geology

The Penninic zone lies structurally south and above the external massifs (Aar, Gotthard) and the Helvetic cover nappes, made up of Mesozoic and Tertiary shelf sediments from the southern continental margin of paleo-Europe, and north and below the Austroalpine zone, which contains Mesozoic and Tertiary sediments and basement from the northern continental margin of Apulia (Trümpy 1960). The Penninic zone can be subdivided into a lower and an upper part (Milnes 1974a). The Lower Penninic zone consists of the Simplon nappes (Antigorio, Lebendun, Monte Leone, Maggia and their structural equivalents) to the west and the Adula nappe complex to the east (Fig. 2). These nappes are generally characterised by intense Alpine deformation and metamorphism of upper greenschist to upper amphibolite grade (Trommsdorff 1966, Niggli 1970). The Upper Penninic zone (Monte Rosa and Bernhard nappes and Brig-Sion-Courmayeur zone to the west, and Suretta, Tambo and Schams nappes to the east) on the other hand, contains large basement remnants with a generally less intense Alpine metamorphic overprint. Paleogeographically, with respect to the Mesozoic cover, this distinction corresponds to units originally north (Lower Pennine ≈ Ultrahelvetic) and south (Upper Pennine = Briançonnais) of the Valais trough (Brig-Sion-Courmayeur and Misox zones).

In the west, the Lower-Upper Penninic boundary has been obscured by the Simplon Fault Zone, which is a southwest dipping normal fault (Mancktelow 1985, 1990); to the east, the boundary is marked by the Misox zone. Below the Lower Penninic zone, a Subpenninic complex which includes the Gotthard massif, Lucomagno, Leventina and Simano units, has been distinguished (Milnes 1974a; Infrapenninic in Trümpy 1980).

## 4. Deformation history

### *4.1 Summary of deformation phases – the Campolungo Area*

The Campolungo area has long been famous for its spectacularly exposed fold structures in the Mesozoic dolomitic marbles and marls and provides an excellent location to study the overprinting effects of all five deformation phases (Fig. 3). The area was mapped in careful detail by Bianconi (1971) and although he published accurate profiles and field sketches of the structures, there was no attempt made at that time to distinguish the relative age of overprinting folds.

The most obvious effect of the first phase $D_1$ is that the whole sequence north of Passo Campolungo is now overturned due to the position of the Campolungo area on the upper limb of a regional $F_1$ syncline (the downward facing syncline SSE of P. del Prévat on Fig. 3a) and the younger fold structures are therefore downward facing (stratigraphy in Fig. 3b). $D_1$ also developed a strong foliation $S_1$ both in the basement and in the overlying metasedimentary cover units. The dominant regional schistosity $S_2$ is a crenulation cleavage, with $S_1$ clearly preserved in the microlithons, and the spectacular macroscopic $F_2$ structures fold an existing $S_1$ foliation around their hinges. The near isoclinal, similar style of these $F_2$ folds indicates that the dolomite was fully ductile during folding, consis-

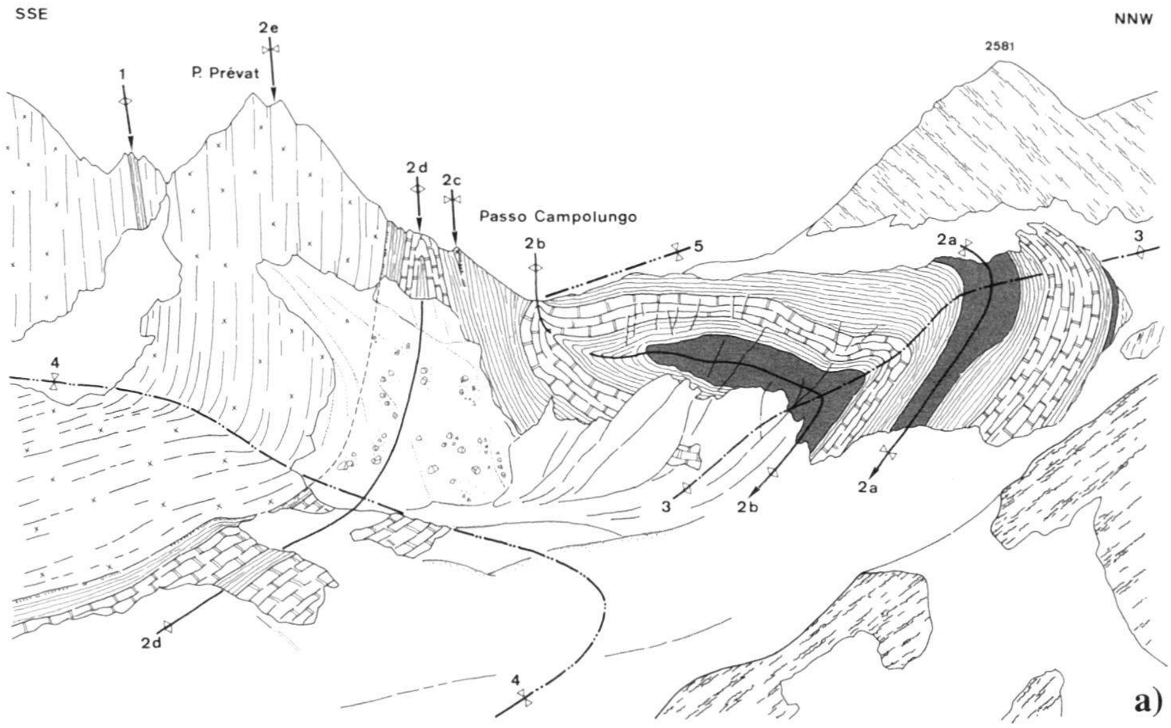



Fig. 3a. The Passo Campolungo area with its spectacularly exposed fold structures in the Mesozoic dolomitic marbles and marls provides an excellent example of the overprinting effects of all five deformation phases. Numbers 1, 2, 3, 4, and 5 on the fold axial plane traces indicate $F_1$, $F_2$, $F_3$, $F_4$ and $F_5$ folds respectively. The facing directions are indicated by arrows. The downward-facing antiform immediately SSE of P. del Prévat is an $F_1$ structure, as can be demonstrated from the crosscutting relationship of both $S_2$ and small-scale $F_2$ folds. This major $F_1$ syncline separates the Maggia nappe on the upper limb from the Campo Tencia nappe on the lower limb. The $F_2$ folds are second order structures to the main Campolungo synform (**CL** on Plate 3) and the $F_3$ is a second order fold to the main Campo Tencia synform (**CT** on Plate 4). The steeply SW-dipping axial plane to $F_3$ folds and crenulations is almost perpendicular to the shallowly to moderately N to NNE-dipping axial plane of the broad $F_4$ fold and to the shallowly S to SSE-dipping axial plane of the minor $F_5$ folds. Regionally, the $F_4$ synform corresponds to the Chièra backfold (**Ch** on Plate 5). The $S_4$ axial surface is almost parallel to the topography to the south of Campolungo, and its trace in map view is complex.

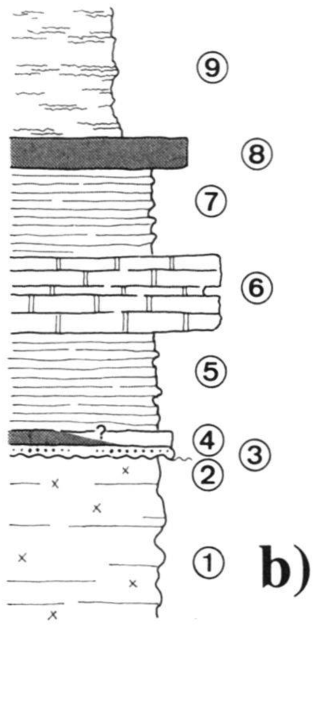



Fig. 3b. Lithological legend to Fig. 3a. 1: Pre-Alpine crystalline basement (ortho- and paragneisses); 2: more pelitic (common garnet-kyanite-staurolite-tourmaline-bearing schists) and quartzitic units, with quartz-pebble conglomerates (?) – possibly Permo-Carboniferous; 3: white to buff-coloured quartzite (basal Triassic?); 4: phlogopite-dolomite marble grading laterally into rauhwacke; 5: grey laminated dolomitic marble; 6: massive sugary white dolomitic marble; 7: grey laminated dolomitic marble; 8: rauhwacke; 9: calcareous micaschists ("Bündnerschiefer" *s.l.*).

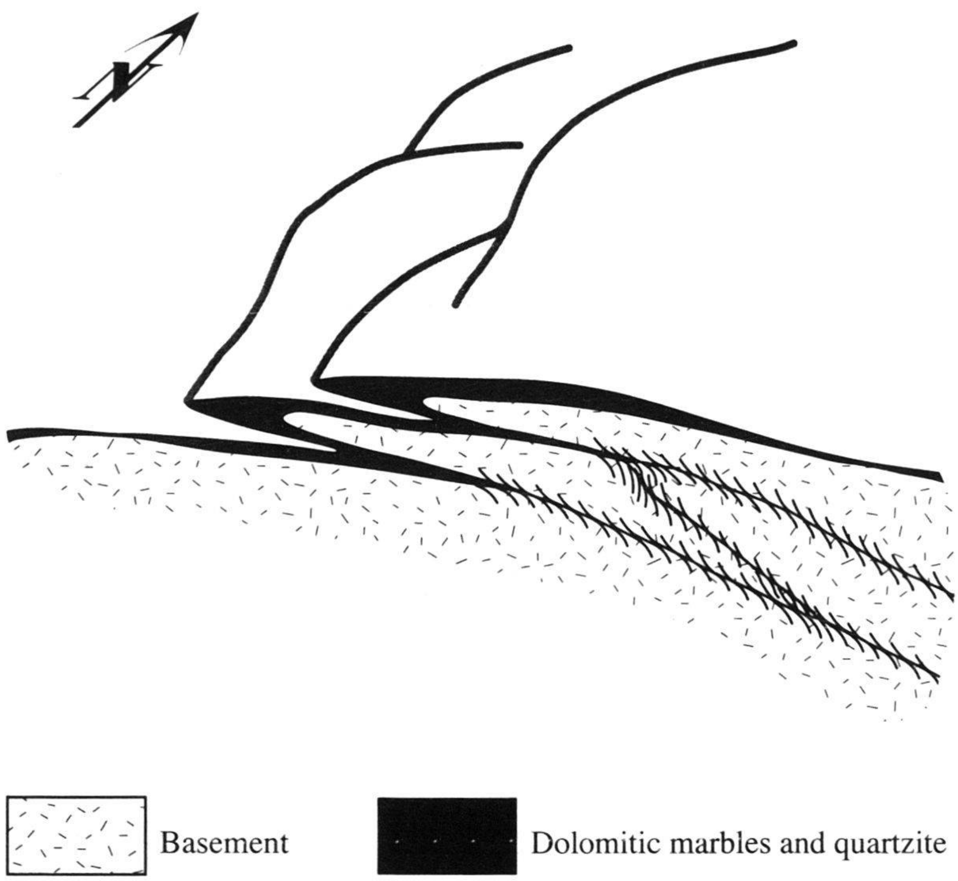



Fig. 4. Schematic regional geometry of first phase folds showing their possible orientation and high noncylindricity.

tent with the attainment of amphibolite facies metamorphic conditions already prior to or during $D_2$. Map-scale interference patterns between $F_1$ and $F_2$ developed in bedding in the region immediately north of P. Meda (Bianconi 1971, figs. 33 and 36) demonstrate that these two fold phases were not coaxial. The trend of $F_2$ fold axes in this area strikes approximately E-W, whereas $F_1$ must be oriented more SW-NE to explain the observed oblique Type 2 interference pattern. The $F_2$ folds are facing down and to the north-northwest, whereas the facing of $F_1$ folds is changing as a function of position within $F_2$ folds. The tight $F_2$ folds are themselves overprinted by a more open $F_3$ structure (the $F_3$ antiform of Fig. 3), which develops a new transverse steeply-dipping $S_3$ crenulation cleavage striking approximately NW-SE. The whole fold sequence is then folded about the $F_4$ Chièra synform, whose axial plane strikes ca. E-W and dips around 30° to the north (Fig. 3). Above and to the north of this axial plane the foliation is generally steep (the "northern steep belt" of Milnes 1974b, e.g. P. del Prévat), below and to the south the main foliation is generally flat-lying. $F_3$ folds are refolded, so that the $F_3$ antiform of Fig. 3 on the upper steep limb of the Chièra synform is, on the more extensive flat-lying southern limb of this $F_4$ structure, actually a smaller-scale synform in the broad hinge of the regional $F_3$

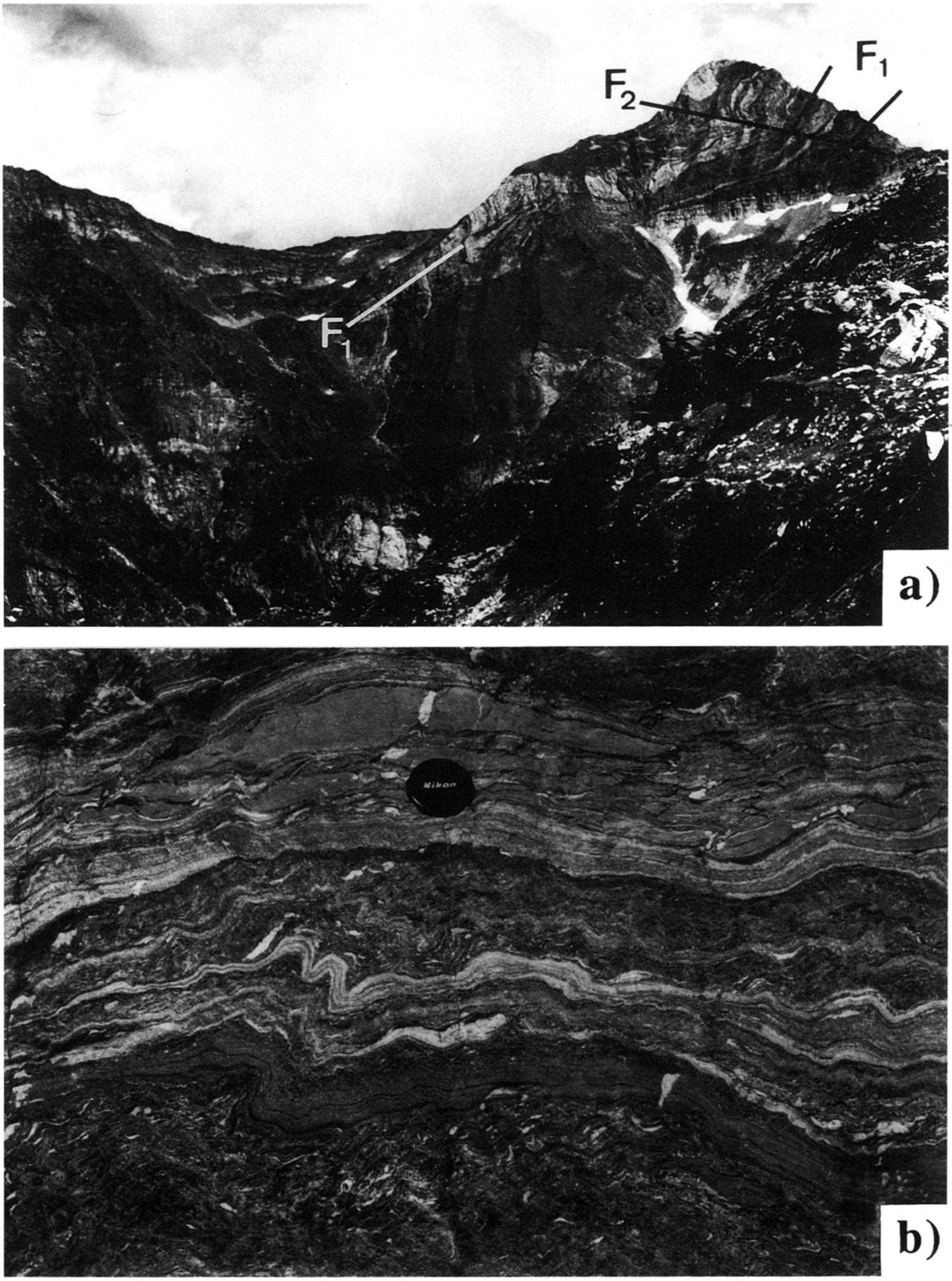



Fig. 5. Photographs of first phase folds: (a) Tight first phase fold with dolomitic marbles in the core, surrounded by amphibolites. Western cliffs of P. Castello, view to the northeast from Val d'Antabia; (b) first phase isoclinal folds in Mesozoic meta-sediments, northwest ridge of Cristallina (684.050/146.925). First phase folds are overprinted by second phase folds.

Campo Tencia synform. The small scale $F_3$ crenulation folds and the parallel intersection lineation are also folded: in the south, they are shallowly plunging but are rotated around the Chièra synform into moderately to steeply north-plunging orientations in the northern steep zone (Fig. 9b, e.g. Berchtold 1990). As the fold axes and axial planes of third and fourth phases are nearly orthogonal in the Campolungo area, they produce a Type 1 – dome and basin interference pattern (Ramsay 1967) that does not affect significantly the attitude of the third phase axial planes. Within the northern steep zone, kink-like chevron $F_5$ folds with shallowly south-dipping axial planes corrugate the main $S_2$ foliation on a scale from crenulations to open folds with wavelengths of 100's of metres (Fig. 3), but do not develop any new axial plane cleavage.

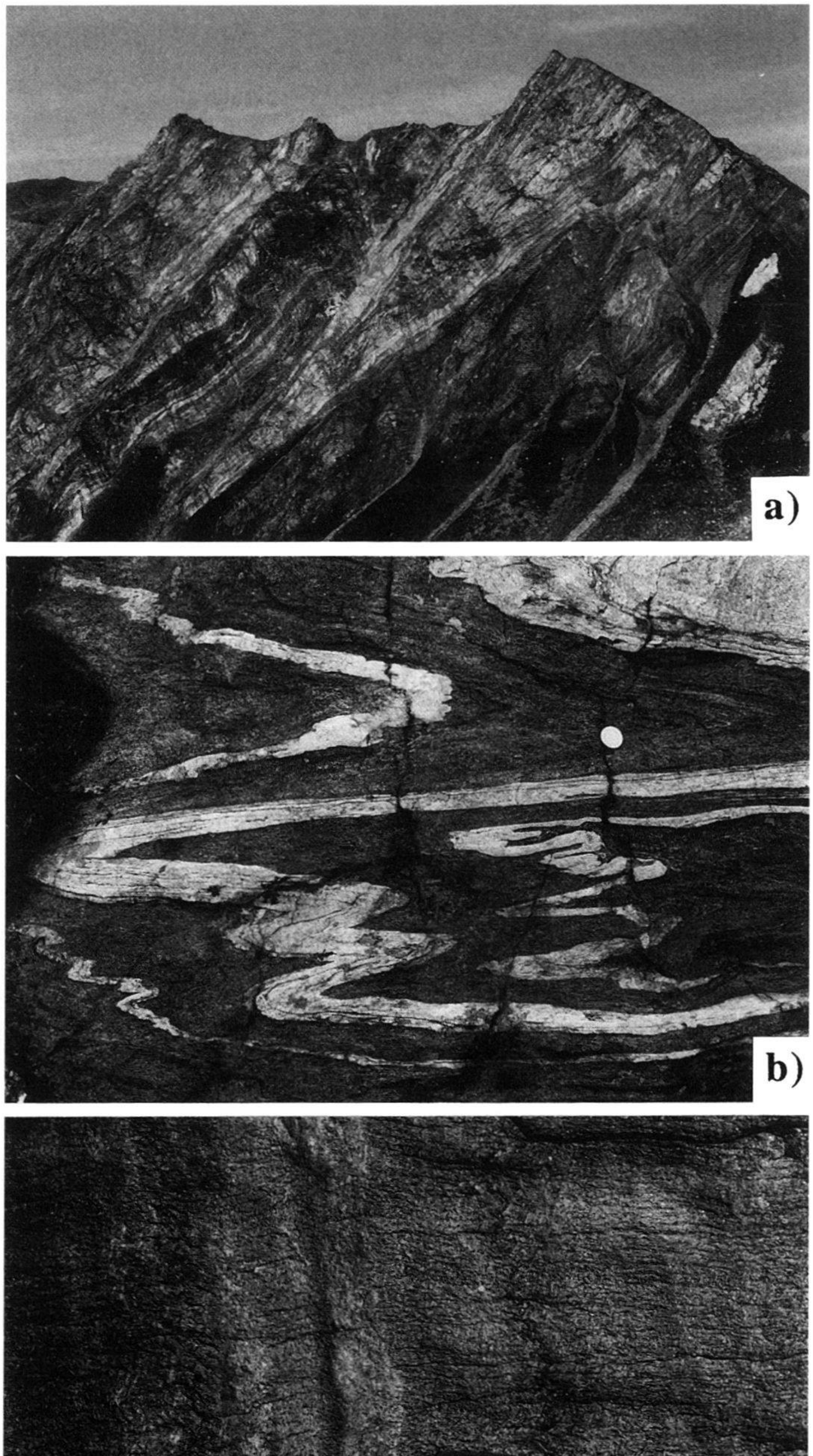
### *4.2 Deformation phase $D_1$*

Details of the geometry and kinematics of the first phase of Alpine deformation are difficult to decipher due to subsequent overprinting. Major first phase structures are preserved as large recumbent isoclinal folds with cores of pre-Triassic basement (metamorphic complexes, granitic intrusions and Permo-Carboniferous sediments) surrounded by a more or less unbroken, although often highly stretched, envelope of dolomitic marbles and quartzites (Fig. 4), which are generally attributed a Triassic age (Bianconi 1965). The first phase thus appears to be related to initial thick-skinned fold-nappe development and the repetition of basement and cover units (e.g. Ayrton & Ramsay 1974). In some cases, the overturned limbs of these nappes structures have been eliminated by more discrete thrusting.

Mesoscopic first phase folds are tight to isoclinal and layers show extreme thickening in the fold hinges relative to the limbs (Fig. 5). The first Alpine cleavage can only be measured in areas where the later tectonic overprint is weak, such as in Val d'Antabia and Campolungo. Fold hinges, although rarely observed, are often very irregular in orientation. On the northwest ridge of Cristallina there are good examples of tight, upward facing antiforms with basement cores. In the orthogneisses, the first phase deformation produced a penetrative $L$ fabric, which is locally accompanied by a planar fabric within shear zones (Simpson 1981).

The existence of major regional $F_1$ folds can be established by changes in facing direction along the axial planes of younger $F_2$ folds. In the pre-Hercynian paragneisses, it is difficult to interpret pre-$D_2$ folds, since it is often impossible to determine if these are Alpine or pre-Alpine. Despite these limitations, the regional and outcrop (e.g. around P. Meda) Type 2 fold interference geometry between $F_1$ and $F_2$ structures testifies to an initially significant angle between $F_1$ and $F_2$ folds and suggests an original northeast to north-northeast strike of hinges and a westward to northwest facing of $F_1$ folds. A similar

Fig. 6. Photographs of second phase structures: (a) Basement-cover rock relationship between Il Madone and Passo del Narét seen from the Cristallina SAC hut. The clearly downward closing synforms of granitic gneisses are second phase folds (synformal anticlines) superposed on the main Maggia nappe; (b) second phase folds in banded hornblende-biotite gneisses on Pianca, east of Lago Bianco (683.675/145.400); (c) Moderately developed second phase crenulation cleavage at high angle to first phase (?) schistosity. Antigorio nappe in Piatto Crois (687.975/140.565).


a)
b)
c)

interpretation of the earliest Alpine folds in the Upper Penninic nappes of eastern Switzerland was proposed by Baudin et al. (1993) and Schreurs (1993).

Complicated structures at the southern border of the Maggia nappe (between P. Castello and P. Mascarpino), with many interleaved basement/cover bands, are interpreted here as a series of isoclinal first folds (Fig. 5a). A band of marble surrounded by amphibolites on the western cliff of P. Mascarpino (Buchmann 1953, Tafel 10) is the core of an $F_1$ fold closing upwards and to the south. Isolated dolomite horizons within the Bündnerschiefer could be interpreted as cores of isoclinal first Alpine folds. This is suggested by the symmetry of the lithologies found on either side of some of these dolomite bands (Klaper 1985). Similarly, the dolomite bands enveloped by gneisses of the Lebendun and Maggia nappe could be interpreted as synclinal isoclinal fold cores of this first phase (Higgins 1964, fig. 82). The infolding of paragneisses into the sheared orthogneisses in the region of Pizzo Sciresa may also have occurred during this earliest Alpine deformation event (Simpson 1981).

### *4.3 Deformation phase $D_2$*

#### 4.3.1 General characteristics

The second deformation phase affected the already formed nappe pile and produced major recumbent, isoclinal folds (the event designated by Milnes 1974a as the *main Alpine folding*). It is these large regional recumbent folds which led to the concept of "fold nappes" in the Simplon Alps (e.g. the "Antigorio Nappe", see Milnes 1964). These folds show a strong penetrative axial plane schistosity, and a marked elongation lineation, which is parallel to small scale fold hinges.

#### 4.3.2 Cleavage

Regionally, the $S_2$ schistosity is the dominant planar fabric and thus the fabric most commonly measured and presented on plots of the "main Alpine schistosity" (e.g. Wenk 1955). In the limbs of second phase folds, the second phase cleavage is usually effectively parallel to $S_0$ and/or $S_1$. However, in the hinges of some large second phase folds the second phase cleavage can be very weak or absent (e.g. in the core of the Lebendun synform in Valle di Antabia). In such places, the only penetrative cleavage, $S_1$, may be mistaken for $S_2$ (Fig. 6c).

The second phase schistosity is marked by syn-tectonic growth of muscovite, biotite, epidote, zoisite, clinozoisite, staurolite, kyanite and quartz in schists and gneisses and hornblende in amphibolites. In some places, tourmaline, rutile and ilmenite are found distributed in the plane of the main schistosity suggesting that they are pre- to syn-tectonic relative to the second deformation phase. In Bündnerschiefer micaschists, syn-tectonic garnets with spiralled inclusion fabrics are also observed (Mounteney 1969, Berchtold 1990). In some calcareous schists of the Bedretto and Teggiolo zones, quartz and calcite lenses have developed parallel to the main schistosity. These lenses were interpreted as probable early metamorphic segregations (Higgins 1964). The main schistosity is marked by strong flattening of conglomerate pebbles in psephites of the Lebendun nappe (Huber-Aleffi 1982) and flattening of xenoliths in late Hercynian granitic to dioritic intrusive rocks (Simpson 1981). In these Hercynian orthogneisses, the predominant deformation mechanism was one of heterogeneous simple shear, leading to the development of banded and foliated orthogneisses anastomosing around less foliated blocks (Ramsay & Allison 1979, Simpson 1981). The new schistosity in the orthogneisses is defined by platy biotite and quartz grain aggregates.

The orientation of the main schistosity is presented on the trend map of Plate 2. The trend lines are based on over 10,000 individual measurements compiled from our own measurements covering the whole area and from all previous published and unpublished data where an attribution to $S_2$ could be well established. The map presents the interpolated trajectory of the dominant $S_2$ strike integrated from field measurements, and not the intersection line of the $S_2$ surface with topography. The measurements were, however, obviously taken at different altitudes in this region of strong relief, and the implicit vertical projection of data points onto a common plane is a source of potential error. However, since there is no common projection direction, due to the complex non-coaxial overprinting by later structures, there is no better alternative. Assuming that the second phase schistosity was coplanar (which from field observation is a reasonable assumption to within 15–20°), this schistosity can be used as a reference plane for later folding. It can be seen from Plate 2 that the complicated regional picture must be a result of at least two additional superposed folding phases, which are discussed below.

### 4.3.3 Lineation

Second generation folds often show a stretching lineation parallel to fold axes (e.g. Milnes 1968, Simpson 1981). This lineation is marked by elongate quartz and feldspar crystals and aggregates, parallel to the minor fold hinges. The mineral lineation is accompanied by a parallel rodding and pervasive intersection lineation structure. In the granitic gneisses the lineation is usually weak, but in the hinge regions of large folds a rod-like fabric can develop parallel to $L_2$. In the Basòdino-Cristallina area, the second phase lineation generally plunges at a moderate angle to the northeast; in the eastern part of the study area it has an approximately east-west trend with varying plunge. Still further to the east and southeast, the observations of Wenk (1955, Tafel I) suggest that this lineation parallel to the regional $F_2$ fold axes may swing into a more south-southeasterly direction, comparable to the $F_2$ fold orientation reported from the Tambo (Baudin et al. 1993) and Suretta (Schreurs 1993) nappes further east.

### 4.3.4 Fold style

The second phase folds are generally tight with narrow, rounded hinges, although the curvature of the hinges depends strongly on lithology. This effect can also be observed on a map scale. For example, the antiformal infolds of Bündnerschiefer into the Lebendun and Maggia gneisses around Robièi are angular, while the corresponding infolds of gneisses into the Bündnerschiefer are rounded, more open structures. This results in an overall lobate-cuspate structure reflecting important bulk shortening (which could be a direct consequence of the Type 2 fold interference between $F_1$ and $F_2$ folds, cf. Grujic 1993). Amphibolite layers in banded gneisses are often boudinaged in the limbs and folded in the hinges of second phase folds. The second phase cleavage shows alternating convergent/divergent fan forms on both the regional and hand-specimen scale. Orientation

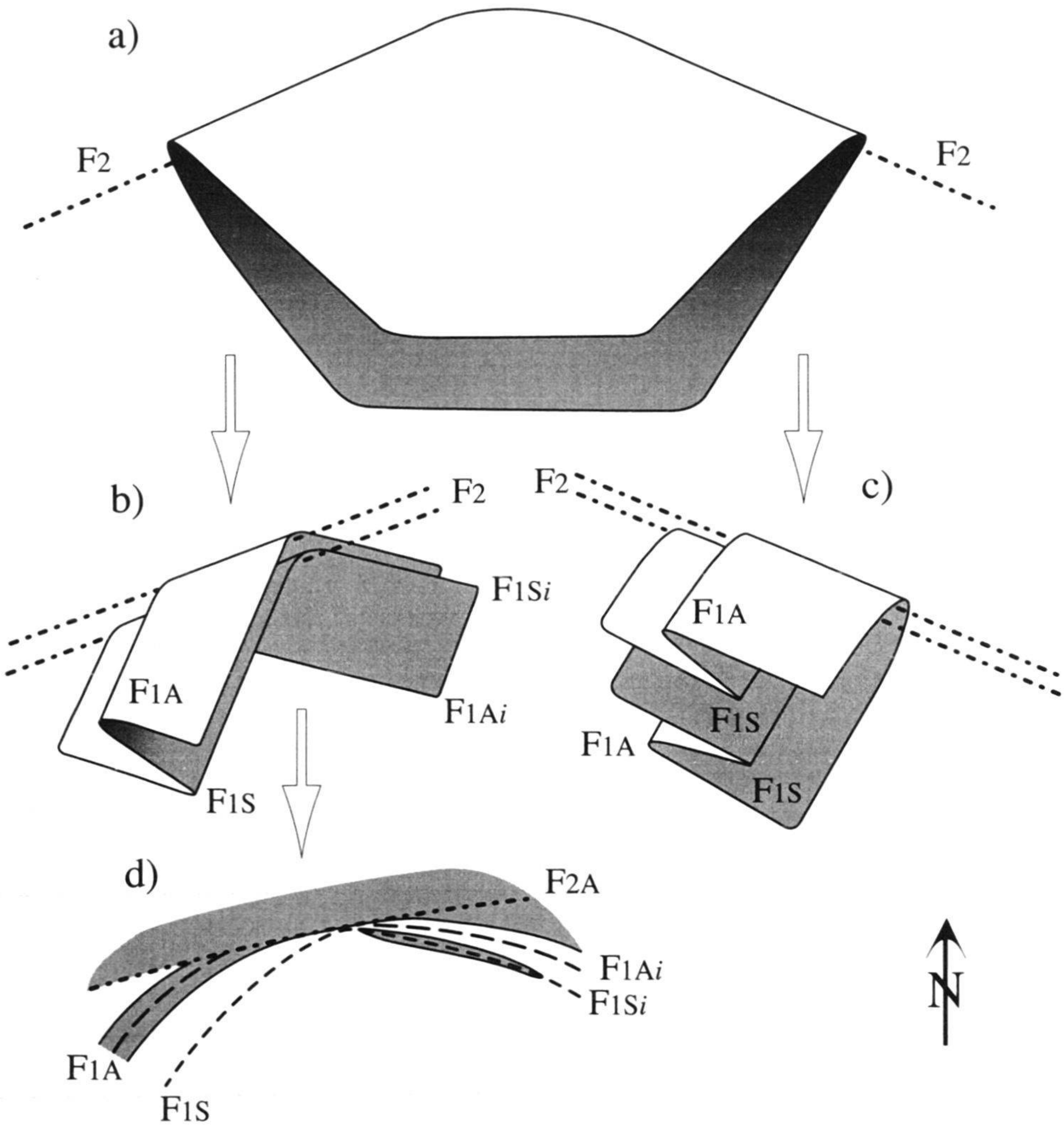



Fig. 7. Schematic regional geometry of second phase structures. a) generalised shape of major second phase antiform with bent hinge; b) oblique Type 2 interference pattern with first phase folds in the western part; c) orthogonal Type 2 interference pattern with first phase folds in the eastern part; d) map view of the structure presented in subfigure b. The facing direction of first phase folds changes across the axial plane of the second phase fold.

analysis of axial plane cleavage ($S_2$) in the Sciresa synform (Pl. 3), for example, shows that this cleavage is not parallel in the two limbs of the synform, but is distributed in a divergent manner, with an angle of ~15° between the cleavage on the two limbs.

### 4.3.5 Major fold structures

A large number of major second phase folds has been recognised in the Lebendun nappe (Higgins 1964, Huber-Aleffi 1982, Bleiker 1989), Maggia nappe (Simpson 1981, Rüffer 1990), Campo Tencia nappe (Berchtold 1990), in cover rocks of the Teggiolo zone (Greco 1984, Oppizzi 1984) and in the Campolungo area (Bianconi 1971) (Table). The axial traces of the principal folds are shown on the map in Plate 3.

From the Simplon Line west of the study area until the P. Castello – Cristallina area, the strike of the second phase structures is very constant at ~ 055°. East of Valle di Peccia, the strike of major $F_2$ folds changes progressively into an E-W orientation (Pl. 3). The variable interference patterns with both earlier and later folds indicate an original hinge curvature of the major $F_2$ fold (Fig. 7a). In the western area (Cristallina – P. di Braga), an oblique Type 2 to Type 3 interference pattern with first phase folds is observed from outcrop to map scale (Fig. 7b). In the eastern part (Campolungo), this interference pattern is oblique to orthogonal Type 2 (Fig. 7c). An oblique Type 2 interference pattern could also be an explanation for the change in facing direction of first phase folds and the resulting map pattern of the Maggia nappe in the Cristallina area (Fig. 7d).

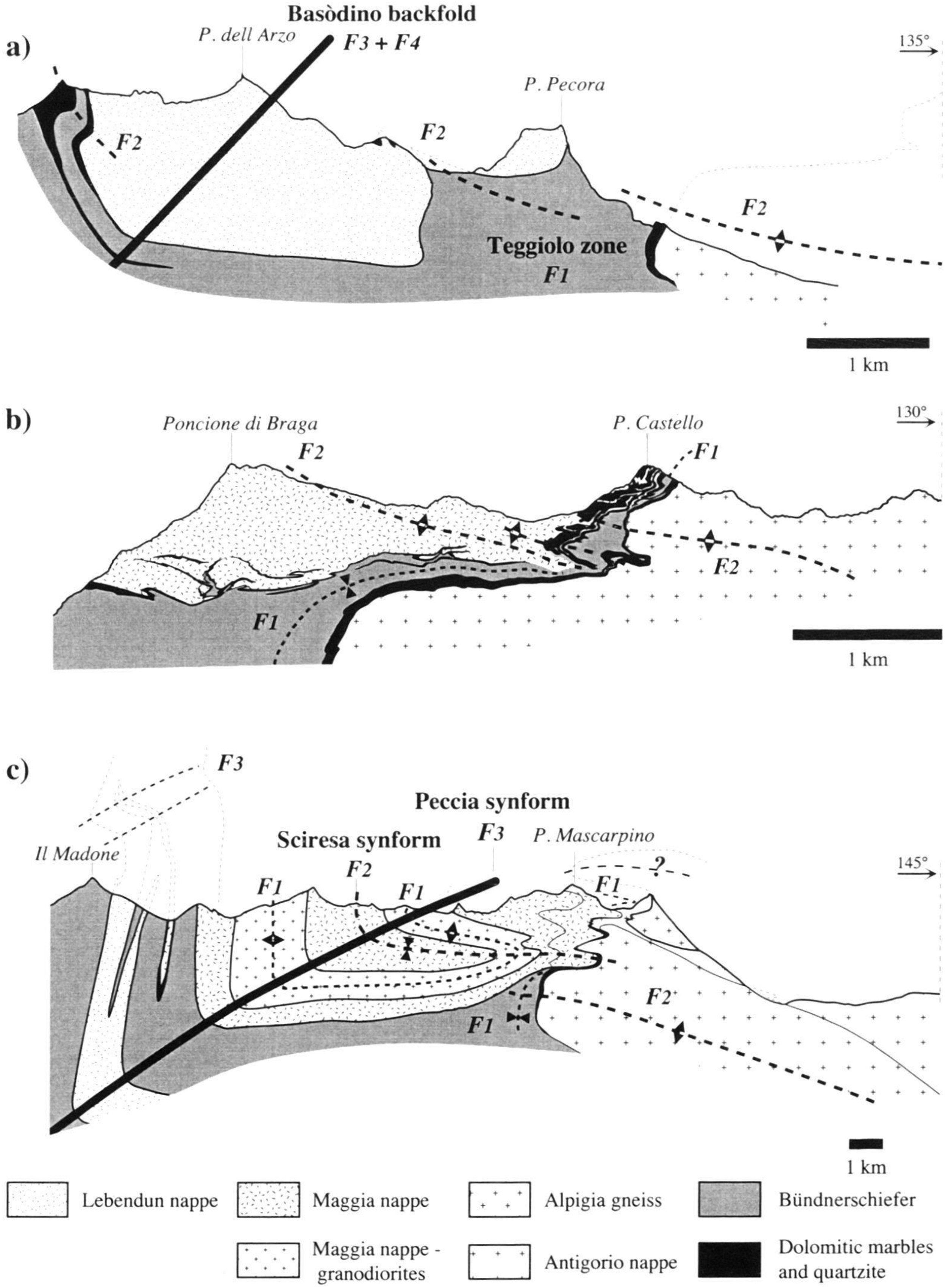
Immediately west of the study area, a large south-closing recumbent fold has been recognised in the area around Lago Castel (Schmidt & Preiswerk 1908, pl. II/2). The cover rocks in the fold core are surrounded by psammitic and psephitic gneisses of the Lebendun nappe (Greco 1984). On the basis of a postulated stratigraphic succession (Friz 1963, Joos 1969), Milnes (1974a) interpreted this structure as the main synclinal structure affecting the Lebendun nappe and termed it the *Lebendun fold*. The axial plane trace can be followed towards the northeast, into the Cristallina area, where it cannot be traced further. Towards the south, the axial trace of the Lebendun synform was traced east of the Tamierpass and through the cover rocks separating the Antigorio and Maggia nappes (Milnes op. cit.). This interpretation implies that the axial plane of the Lebendun synform has been folded into a late-Alpine, south-closing synform (see Milnes 1974a, pl. II, cross-section 1). As we will see later, field observations suggest that such a late-Alpine synform does not exist in the Basòdino region. In the Lebendun nappe in the region of Pizzo Pecora, another large late-phase fold had been identified by previous authors. The large fold between Pizzo Pecora and Basòdino has a common, gently dipping limb with the Basòdino synform (a mainly $D_3$ structure, see below) and a steep southern limb. Higgins (1964, fig. 57 and 66) suggested that the large fold at Pizzo Pecora is a "phase 3" antiform with axial plane dipping northwards. Huber-Aleffi (1982, pl. II) interpreted the steeply dipping schistosity at Pizzo Pecora as forming a limb of a third phase synform separated from the Basòdino synform by a very open antiform. Field data from this study do not support either of these models. The steeply north-dipping schistosity between Pizzo Pecora and Basòdino and on cliffs south of them is $S_1$ (which is here nearly parallel to the primary layering $S_0$). The $D_2$ axial plane cleavage (i.e. regionally the main schistosity $S_2$) is only very weakly developed and dips gently to the northeast. The flat $S_2$ orientation can be best observed in the northeastern cliff of Pizzo Mèdola in Val d'Antabia. The steepening of the lithological boundaries between L. del Zött and Pizzo Pecora is, therefore, a major second phase fold hinge – the Lebendun synform of Milnes (1974a).

The major regional antiform, which may form a fold pair with the Lebendun synform is the Antigorio antiform, often referred to as the Antigorio "Stirnfalte" or frontal fold. Situated structurally below the Lebendun synform, the front of the Antigorio nappe outcrops in Val Bavona near Campo (Huber et al. 1980, plate). The general shape of the Antigorio nappe has been recognised for more than a century (Gerlach 1869, Profil I) and was the subject of many interpretations (e.g. Gerlach 1869, Lugeon 1903, Schmidt & Preiswerk 1908, pl II/5–13, Heim 1921–22). The most recent interpretation by Milnes (1973, 1974a) and Greco (1984) suggests that this structure is an isoclinal, north-closing antiform refolding an earlier nappe structure. The common limb of the Lebendun synform and Antigorio antiform *s.s.* is relatively short. So also is the common limb of the Lebendun synform and the immediately overlying Lebendun antiform (Pl. 3). This gives the whole structure the geometry of a huge *M*-shaped hinge of a major north-closing $F_2$ antiform – the Antigorio fold *s.l.* (Fig. 8). Part of this hinge can be seen on the western slope of P. Mascarpino (Buchmann 1953, Tafel 10, Huber 1981, fig. 58) as an antiform-synform pair refolding a band of marble (which is itself an isoclinal first phase fold core). Towards the west, the crest of the Antigorio nappe can be followed over 50 km until the Simplon Line, although its hinge outcrops only locally (e.g. in Val Formazza, Preiswerk 1917, fig. 2).

The major south-closing synform separating the Maggia nappe from the Campo Tencia nappe in the Campolungo region was already recognised by Preiswerk (1918). The western part of the Campolungo synform, the Fusio-Mogno synform, has been mapped by Berchtold (1990). He constructed detailed cross-sections and based on the interpretation of the stratigraphic succession demonstrated that the structure is indeed a syncline. The current complex outcrop pattern of the Campolungo synform reflects the varying effects of all five deformation phases but is predominantly a combination of $D_1$ and $D_2$ structures. In the area roughly west of Passo Campolungo, the second phase lineation plunges ENE, while east of Passo Campolungo the same lineation plunges WSW (Fig. 9a). Accordingly, the western closure of the synform at Mogno can be connected to the eastern closure near Gribbio in Valle Leventina (as suggested by Preiswerk 1918), allowing construction of the overall regional trace of the Campolungo synform, and demonstrating a regional Type 2 interference pattern between $D_2$ and $D_3$ folds.

A number of higher-order $F_2$ folds in the Lebendun nappe and Basòdino-Robièi region can be discerned from the geological map (e.g. Burckhard & Günthert 1957, Higgins 1964). These folds transgress nappe boundaries, and can be traced from the Lebendun into the Maggia nappe. The Caralina synform, outlined by outcrops of calcareous rocks, is the best exposed. In detail, the Caralina synform is made up of a series of parasitic synforms and antiforms with steeply dipping northern limbs ($S_0$ and $S_1$), showing an overall southwest vergence (Bleiker 1989). This $F_2$ fold vergence indicates that the Basòdino summit belongs to the upper, northeast limb of the Lebendun synform. The intense folding of the marble horizons in this upper inverted limb of the Lebendun synform has been described in detail by Higgins (1964, p. 124–132).

Fig. 8. Schematic cross-section of the front of the Antigorio antiform: (a) Cross-section in P. Pecora – P. dell' Arzo region; (b) Valle di Peccia (Val Bavona) region. After Huber et al. (1980); (c) P. Mascarpino – Il Madone region. Locations of the cross-sections indicated in Plate 2 (**1–3**).


a)
Basòdino backfold
F3 + F4
P. dell Arzo
P. Pecora
135°
F2
F2
F2
Teggiolo zone
F1
1 km
b)
Poncione di Braga
P. Castello
130°
F2
F1
F2
F1
1 km
c)
F3
Peccia synform
Sciresa synform
F3
P. Mascarpino
Il Madone
145°
F1
F2
F1
F1
?
F2
F1
1 km
Lebendun nappe
Maggia nappe
Alpigia gneiss
Bündnerschiefer
Maggia nappe - granodiorites
Antigorio nappe
Dolomitic marbles and quartzite

The Sciresa synform is the main synform observed within the Maggia nappe (Simpson 1981). In the P. Sciresa region, this is a northeast-plunging, upright, tight synform, marked by a band of paragneisses flanked by sheared orthogneisses. On the eastern wall of Valle di Peccia, the Sciresa synform is folded by a south-closing third phase fold, the Peccia fold (Pl. 4). In this region the axial plane of the Sciresa synform can be traced through a hinge marked by diorites (originally taken as the closure of a third phase fold by Simpson, op. cit.). Further south, the axial trace can be followed into the cliffs north of Sant' Antonio in the Valle di Peccia. The closure is there marked by a sudden bend in the marbles on the border between the Maggia and Antigorio nappes. The hinge of the antiformal counterpart above the Sciresa synform can be followed into Alpe di Röd where it has been mapped by Stoll (1990) – in his interpretation as a third phase structure. Further to the east, the antiform is refolded by a north-closing structure considered by Stoll (op. cit.) to be a fourth phase fold. In the present interpretation, this antiform is considered to be the southern continuation of the Peccia fold (i.e. a third phase structure, see below). The lower limb of the Sciresa synform forms the common limb with the Antigorio antiform. This relation between the Antigorio antiform and Sciresa synform in Valle di Peccia suggests that the Sciresa synform is equivalent to the Lebendun synform in the Basòdino region. Furthermore, this correlation implies that the second phase antiform at Alpe di Röd and the second phase antiform in the Lebendun nappe (the "Lebendun antiform", Pl. 3) may be the same structure.

Another good example of a second phase structure in the Maggia nappe is the Massari synform (Pl. 3). This is a second order synform within the major Maggia antiform. The Massari synform is tight with pinched-in cover rocks, in contrast to the broad, rounded Maggia antiform hinge with basement rocks in its core.

In the Campo Tencia nappe, few unambiguous second phase folds can be traced. The best example is the Lareccio antiform (Keller 1968). The Lareccio fold is a second-order antiform on the lower, inverted limb of a major antiform. This major antiform is the Simano nappe, with Verzasca gneisses in the core flanked by Campo Tencia micaschists and paragneisses forming an outer core region. Other second phase folds in the Campo Tencia nappe are suggested by the distribution of micaschist and paragneisses (Keller 1968), but their clarification awaits further work.

### *4.4 Deformation phase $D_3$*

#### 4.4.1 General characteristics

The third phase structures have developed obliquely to the trend of earlier structures and to the Penninic zone as a whole. In the southern part of the study area (Pl. 4), third phase folds strike north-south (Campo Tencia), but this strike changes progressively toward the north into a northwest-southeast (Peccia synform) and eventually a northeast-southwest orientation. In the southeastern part of Pennine Alps, the most plausible counterpart of $D_3$ structures in the Maggia area, namely the Cresem antiform (Kopp 1923), again has an east-west strike resulting in a regional Z-shaped trace to the $D_3$ axial planes.

Third phase folds are often associated with a crenulation of older minerals such as mica, amphibole, staurolite and kyanite. In schists and mica-rich gneisses a new, domainal, axial plane parallel schistosity is developed ($S_3$). It is marked by newly developed biotite,

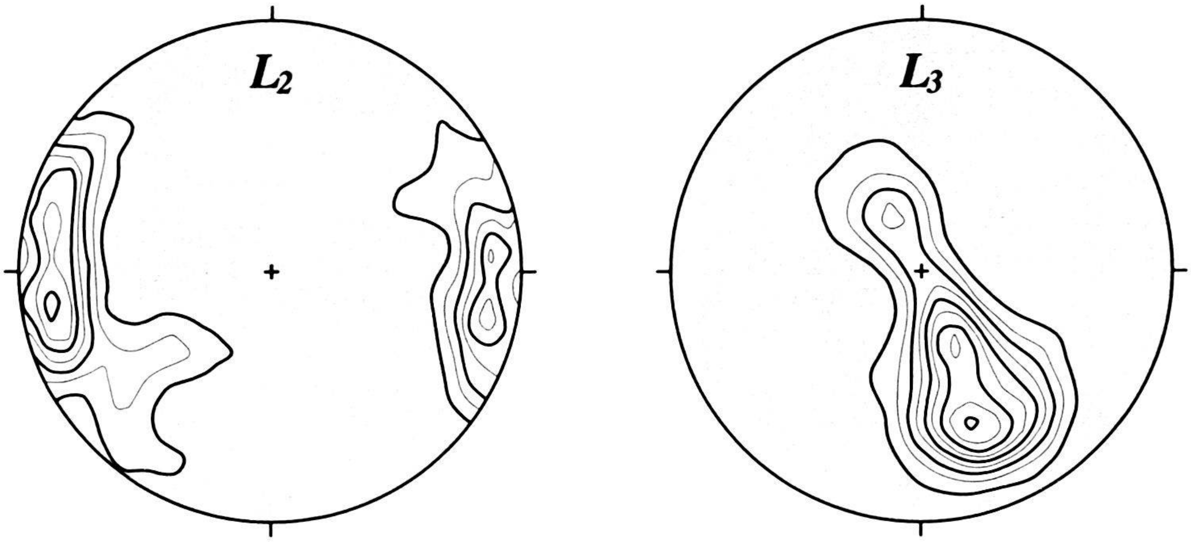



Fig. 9. Stereograms of lineation in Campolungo region: (a) second phase lineation, 189 data, contoured at 1 2 3 ... 7 times uniform; (b) third phase lineation, 381 data, contoured at 1 2 3 ... 9 times uniform. Compiled from: Aebischer (1985), Berchtold (1990), Rüffer (1990), and own data.

white mica and phlogopite (in marbles). In pelitic gneisses, the crenulation cleavage is overgrown by helicitic-poikiloblastic plagioclase, garnet, kyanite, staurolite, zoisite and clinozoisite, and in marbles by tremolite and scapolite (Table). These observations are in agreement with observations of previous authors (Klaper 1980, 1982, 1985, Berchtold 1990, Hohl 1990, Rüffer 1990 and Stoll 1990) which indicate that porphyroblast growth began during $D_2$, was most extensive between $D_2$ and $D_3$, but outlasted the third deformation phase. Undulose extinction of post-$D_3$ staurolite, kyanite and mica indicates additional subsequent deformation.

Elongate biotite flakes give rise to a third phase mineral lineation ($L_3$), which is parallel to the small-scale third phase fold axes. As a result, it is often possible to distinguish two differently oriented lineations on a single $S_2$ main schistosity surface: a biotite lineation $L_3$ and a stretching lineation $L_2$. The lineation changes its plunge from a low angle in the south to a moderate to steep plunge in the northeast (Fig. 9b), as a result of the $D_4$ Chièra synform. The orientation of the third phase fold axes is determined both by later overprinting and upon the pre-$D_3$ inclination of surfaces on which the $D_3$ structures developed. Variation of axial direction is to some extent inherited from the variability of layering and schistosity arising from previous fold events. In small structurally homogeneous areas, $L_3$ is generally parallel to the pole of the great circle defined by the main schistosity pole distribution. This demonstrates that most mesoscopic scale refolding of $S_2$ can be related to $D_3$, consistent with the observation that important $D_4$ folding is generally of regional rather than of outcrop scale. There are, however, exceptions in areas with strong later phase overprint (e.g. Campolungo), where the great circle distribution of main schistosity poles is related to the fourth and fifth phases of deformation.

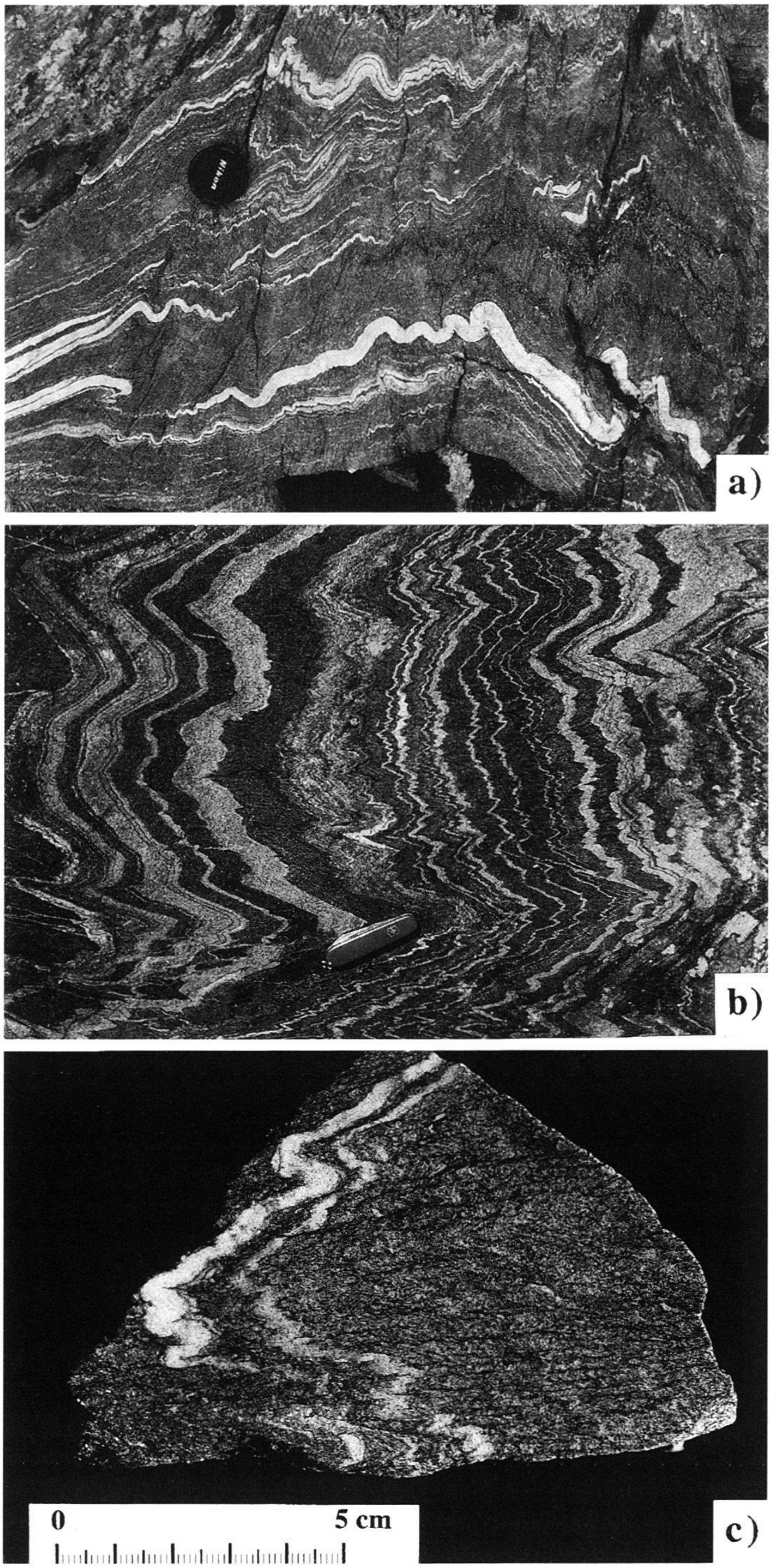
### 4.4.2 Fold style

The shape of third phase folds is strongly lithology dependent, suggesting that the folds initiated by buckling and that competence contrasts played a significant role in fold development. Compared to the second phase folds, the third phase folds have smaller arc-length/thickness ratios. This may reflect a general decrease in competence contrast between layers near the peak of amphibolite-facies metamorphism. However, it may also simply be an effect of the refolding geometry. $D_3$ cross-folding, developed oblique to the trend of earlier regional $F_2$ folds, should lead to Type 1 or Type 2 interference patterns, depending on the shape of the pre-existing $F_2$ folds (Grujic 1993). Because of the increased bending resistance due to the already corrugated shape of the layering, fold amplification rates are much lower and the amount of layer-parallel shortening much higher than for flat layers with the same matrix/layer competence contrast. It is to be expected that the wavelength to thickness ratio for $F_3$ folds will be consequently smaller. The significant layer parallel shortening will also modify $F_2$ (and $F_1$) folds towards a more similar shape (Grujic 1993), thereby increasing the arclength/thickness ratio. In making any interpretation about relative rheologies during deformation, it must be born in mind that the preserved shape of these earlier $F_1$ and $F_2$ folds may have been significantly modified during subsequent deformation.

Excellent examples of the control of competent layer thickness on $F_3$ fold wavelength can be found throughout the area (Fig. 10a). Dependent on the distance between adjacent competent layers, this leads to a polyharmonic to disharmonic fold style on all scales. This is an important observation for the regional correlation of $F_3$ folds – broad major structures can be followed for tens of kilometres, but in detail, individual fold hinges are often discontinuous along their axial plane reflecting the disharmonic fold style.

In banded gneisses and amphibolites, the layer thickness increases from limb to hinge, such that third phase folds show profile shapes near to similar fold geometry (Type 1C, Ramsay 1967). However, the approach to the similar fold model is not as close as in folds of earlier phases. The hinges of folds are often sharp, giving them a characteristic chevron style (Fig. 10b). In more mica-rich schists and gneisses, an $S_3$ crenulation cleavage is developed (Fig. 10c). In highly deformed areas, ductile shear zones offset the main schistosity parallel to the axial planes of third phase folds. These shear zones often show a concentration of leucosomes, although the temperature conditions during their development were insufficient for partial melting (T < 600 °C). Characteristically, these shear zones are located on the shorter limb of the parasitic folds. The sense of shear along the leucosome-bearing shear zones changes as a function of location around the higher-order fold and would seem to have no regional kinematic significance.

Fig. 10. Photographs of third phase folds: (a) Polyharmonic and disharmonic folds in quartzo-feldspathic bands illustrating the clear wavelength-thickness relation in buckle folds. Different styles of folds (ptygmatic to cuspate-lobate) are probably the result of different grain size in the competent layers. Banded hornblende-biotite gneisses at electricity pylon (686.125/146.725) on the Cristallina-Passo del Narèt ridge; (b) polyharmonic folds in banded hornblende-biotite gneisses. Alpe Scheggia (694.475/147.900); (c) axial plane cleavage marked by new biotite growth. Sasso del Corbo, lake at point 2398 m (685.700/146.950).


a)
b)
0
5 cm
c)

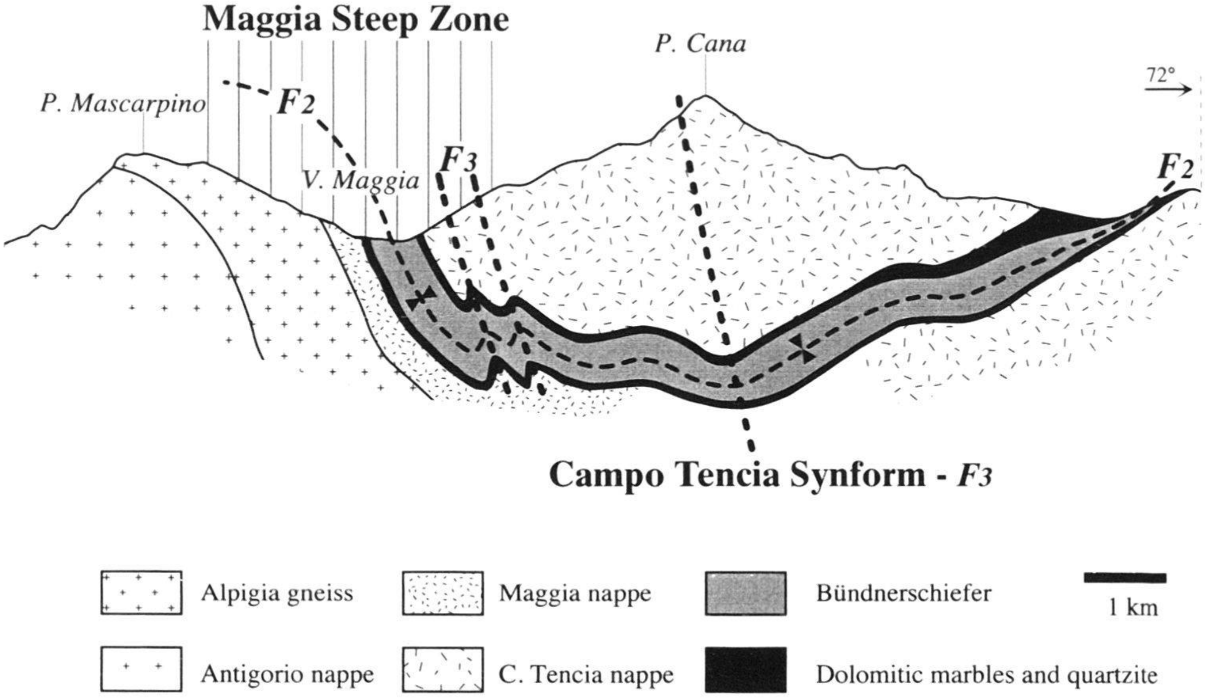



Fig. 11. Schematic east-west cross-section across the Maggia Steep Zone and Campo Tencia synform. Location of the cross-section is indicated on Plate 2 (**4**).

### 4.4.3 Major fold structures

The main third phase folds are an upright synform in the Campo Tencia area, a south-closing recumbent fold in Valle di Peccia, and the broad, inclined Basòdino synform. The Maggia Steep Zone is also interpreted as related to this generation of structures.

The Campo Tencia synform (Fig. 11, Pl. 4) was first mapped by Keller (1968), who defined it on the basis of changes in attitude of the main schistosity, but he did not differentiate successive generations of folds. The northwestern part of the Campo Tencia nappe was later remapped and the structures related to the Campo Tencia synform established as third phase structures (Berchtold 1990). The hinge zone of the main fold occupies the eastern part of the study area, with a width of about ten kilometres (Pl. 4). This important regional synform (Fig. 2, 11) separates the Lepontine structural dome into two sub-domes – the Simplon (or Toce) culmination to the west and the Ticino culmination to the east (cf. Merle et al. 1989, fig. 2). The Maggia "Querzone" (i.e. cross-zone, Preiswerk 1918) or Maggia Steep Zone represents the steep western limb of this regional $D_3$ synform (Fig. 11, 12), which may have been reactivated during subsequent deformation (see discussion below).

A south-closing recumbent fold in Valle di Peccia (Pl. 4) was first identified by Simpson (1981). She was the first to recognise a folding phase between the second folding phase, which produced regional tight recumbent folds with a related penetrative schistosity, and the backfolding phase which produced the northern steep belt. However, she attributed only local importance to this structure. The structure recognised by Simpson (op. cit.) is now interpreted as a composite one: the southern part of this structure is a second phase fold, namely the Sciresa synform (Pl. 3), which is refolded by a north-closing third phase fold.

The Basòdino fold and related structures are equivalent to the major "phase three" folds of Higgins (1964, fig. 66) and to the regional "backfolding" phase of Huber et al. (1980) but do not have the same regional significance (see discussion below and the correlation Table). In general, the Basòdino folds are characterised by steep to moderately dipping, SW-NE striking axial planes. Porphyroblast growth seems to be later (relative to deformation) in the Teggiolo than in the Bedretto zone (Higgins 1964). This implies that the peak of metamorphism in the Bedretto zone was attained after the second and before the third deformation phase, while further south in the Teggiolo zone it was coincident with the third deformation phase. Higgins (op. cit.) suggested that this indicates that the deformation was migrating from south to north through time, but it alternatively may reflect inward cooling of the Lepontine metamorphic dome (Fox 1975).

In the Lebendun nappe, the $D_3$ crenulation cleavage poles show a partial girdle distribution with two maxima; a steeper one related to the southern limb and a flatter one related to the northern limb of the Basòdino synform, reflecting the rather box-like form of this broad structure. Both geometrically and in relation to the mineral growth, this crenulation is very similar to the $D_3$ crenulation of the Peccia and Campo Tencia folds. In the Basòdino-Robièi area, two groups of crenulation cleavage are developed. Orientation is often the only criteria to distinguish between them. Crenulation cleavage with NW-SE strike fits geometrically to the third phase fold in Valle di Peccia, while the crenulation cleavage with E-W to NE-SW strike fits the Basòdino synform. Overprinting relations are observed, but very seldom. The crenulation cleavage of the Basòdino fold is itself overprinted by even younger folds.

The axial trace of the Basòdino synform has been constructed by joining the points of maximum curvature of the main schistosity (Pl. 4). Although the hinge is sharp and well defined, its trace is not a single line. As the result of the Type 3 interference pattern with second phase folds, the axial trace of the Basòdino synform is offset when crossing the axial traces of earlier folds and arranged in an "en echelon" manner (Ramsay 1967, p. 509). The full expression of the axial plane of the Basòdino synform is the result of the folding of four initially inclined sets of surfaces, namely the lithological layering ($S_0$ or $S_1$) and schistosity ($S_2$) on each of the $D_2$ fold limbs, which are not necessarily parallel. This phenomenon is well illustrated by the different position of the Basòdino synform axial trace in the schistosity to the one in the lithology (Pl. 4). The earlier lineation ($L_2$) shows a single maximum distribution indicating approximately coaxial refolding. In detail, however, when the orientation of the $L_2$ lineation from the two limbs of the Basòdino fold is analysed separately, it can be seen that the earlier lineation on the northern limb has a steeper plunge than that on the southern limb, and is generally not strictly parallel to $L_3$. This is confirmed by direct field observation. Immediately east of Lago Bianco the hinge of the Basòdino fold becomes much broader and more rounded as it passes into the Maggia nappe and it is more difficult to locate its axial trace on the map. In the area between Cristallina and L. del Narèt, the hinge zone is about 600 m wide and very complex, being composed of many parasitic *M* folds. Passing into the Maggia nappe the fold axis becomes slightly steeper. The earlier lineation is also steeper and is distributed in a similar manner to that seen in the Lebendun nappe. The crenulation cleavage has, at first, the

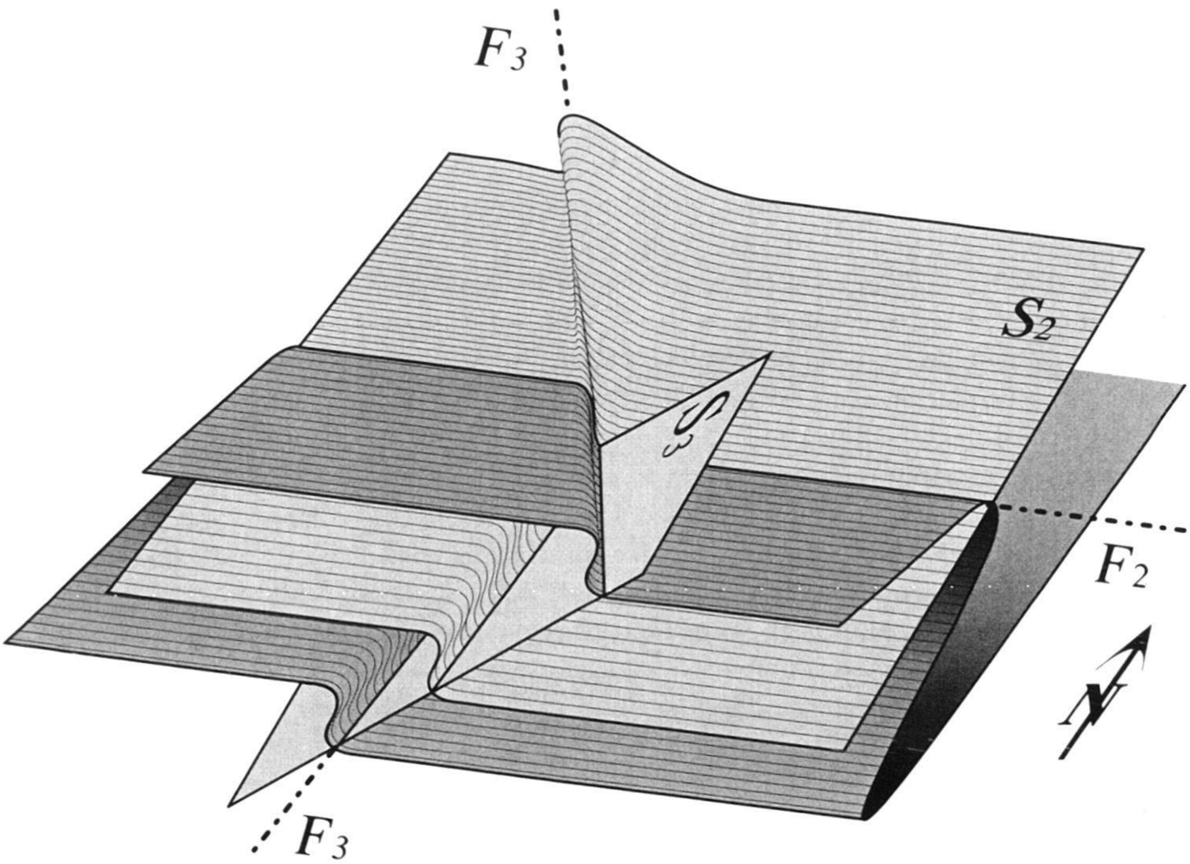



Fig. 12. Schematic regional geometry of third phase regional structures. The relation between the Peccia synform to the north and the Campo Tencia synform to the south is indicated; the western limb of the latter fold forms the Maggia Steep Zone. The general Type 2 interference pattern between second and third phase folds is also represented.

same orientation as on the southern limb in the Lebendun nappe, but then, east of Cristallina, it acquires a more easterly dip. Further to the east of the Passo del Sasso Nero, the Basòdino fold hinge was previously traced along the southern shore of L. del Narèt (Simpson 1981) and through Passo Sassello (Klaper 1985). However, the present work suggests that the Basòdino fold continues as the Peccia fold and as such passes through Valle di Peccia to Alpe di Röd. Further to the southeast its trace is uncertain.

The Peccia fold and the Maggia Steep Zone seem to be closely related. The two structures diverge around the village of Peccia itself; the Peccia fold becomes tighter toward NW while the Maggia Steep Zone dies out toward the NNW (Fig. 12). Due to this effect (and the original regional bend of the major $F_2$ fold hinge), the interference pattern between $F_2$ and $F_3$ folds is progressively more coaxial toward the northwest (the Cristallina area) while in the Campolungo area it is an orthogonal Type 2 interference pattern. The interaction has forced the Peccia fold to bend into a mechanically more favourable orientation, coaxial with the Antigorio fold.

## *4.5 Deformation phase $D_4$ ("backfolding")*

### 4.5.1 General characteristics

The $D_4$ large-scale fold structures in the area are represented by the Cristallina synform in the west and the Chièra synform in the east (Pl. 5). These are north-closing synforms with steep north limbs defining the *northern steep zone* (Milnes 1974b). The continuation of this major regional synform to the west is represented by the Berisal Synform (Steck 1984) and to the east by the Chièra Synform (Thakur 1973, Milnes 1976).

Fourth phase folds do not develop axial plane cleavage. It is therefore difficult to establish relative timing relationships to porphyroblast growth. Higgins (1964) suggested that some biotite, muscovite and quartz, and perhaps some staurolite, have still grown after the $D_4$ folding, but the evidence is not unequivocal. In the pelitic schists small-scale fourth phase folds are distorted around existing porphyroblasts, and muscovite is always bent or kinked as a result of the fourth phase folding. The fourth phase lineation is poorly developed and is represented only by the hinges of minor fourth phase folds.

### 4.5.2 Fold style

Mesoscopic fourth phase folds are generally noncylindrical and have low amplitude. They were also described by Higgins (1964) as "phase four" folds, but he did not relate them to any large scale structure. The fourth phase folds have axial planes dipping gently to moderately northward (~ 30–50°) and the angle of plunge of the fold axes is usually $\leq 30°$ toward the northeast. $F_4$ folds are best developed on the northern, steep limb of the Basòdino fold, while on the southern limb they are much less common. In the steep limb itself, the fourth phase folds can be traced eastward until L. del Narèt.

### 4.5.3 Major regional folds

Since Higgins (1964), the hinge zone between Lago Bianco and Marchhorn has been ascribed to backfolding (e.g. Milnes 1974a, Huber et al. 1980, Klaper 1985). Current field data suggest that the Basòdino synform is a third phase fold which has been significantly modified by the later backfolding (see discussion below). It was initiated during the same $D_3$ deformation phase as the Campo Tencia and Peccia folds, but its current shape also reflects an important $D_4$ overprint. The hinge zone of the major fourth phase synform is actually situated north of the Basòdino fold hinge and has not previously been mapped (Pl. 5). The hinge of this fold is rounded and approximately two kilometres wide. The northwest ridge of Cristallina, with practically vertical schistosity, forms the hinge of this fold (Fig. 13). This major fourth phase fold is therefore called the *Cristallina* synform. East of L. del Narèt, the main schistosity changes strike to E-W and becomes overturned (Pl. 2): this represents the upper, inverted limb of the Cristallina fold (Fig. 13).

The antiformal counterpart of the Basòdino synform is situated in Val d'Antabia. Its axial trace runs south of the Kalberhorn and along Val d'Antabia, parallel to the trace of the *Antabia fold* of Milnes (1974a) and the main third phase antiform of Greco (1984). It is interpreted here as a broad $D_4$ antiform whose axis corresponds to that of the Simplon subdome culmination (cf. Merle et al. 1989, fig. 2a and Klaper 1990, fig. 6). The axial trace of this antiform can be traced westward between P. Castello and Rosso. With much

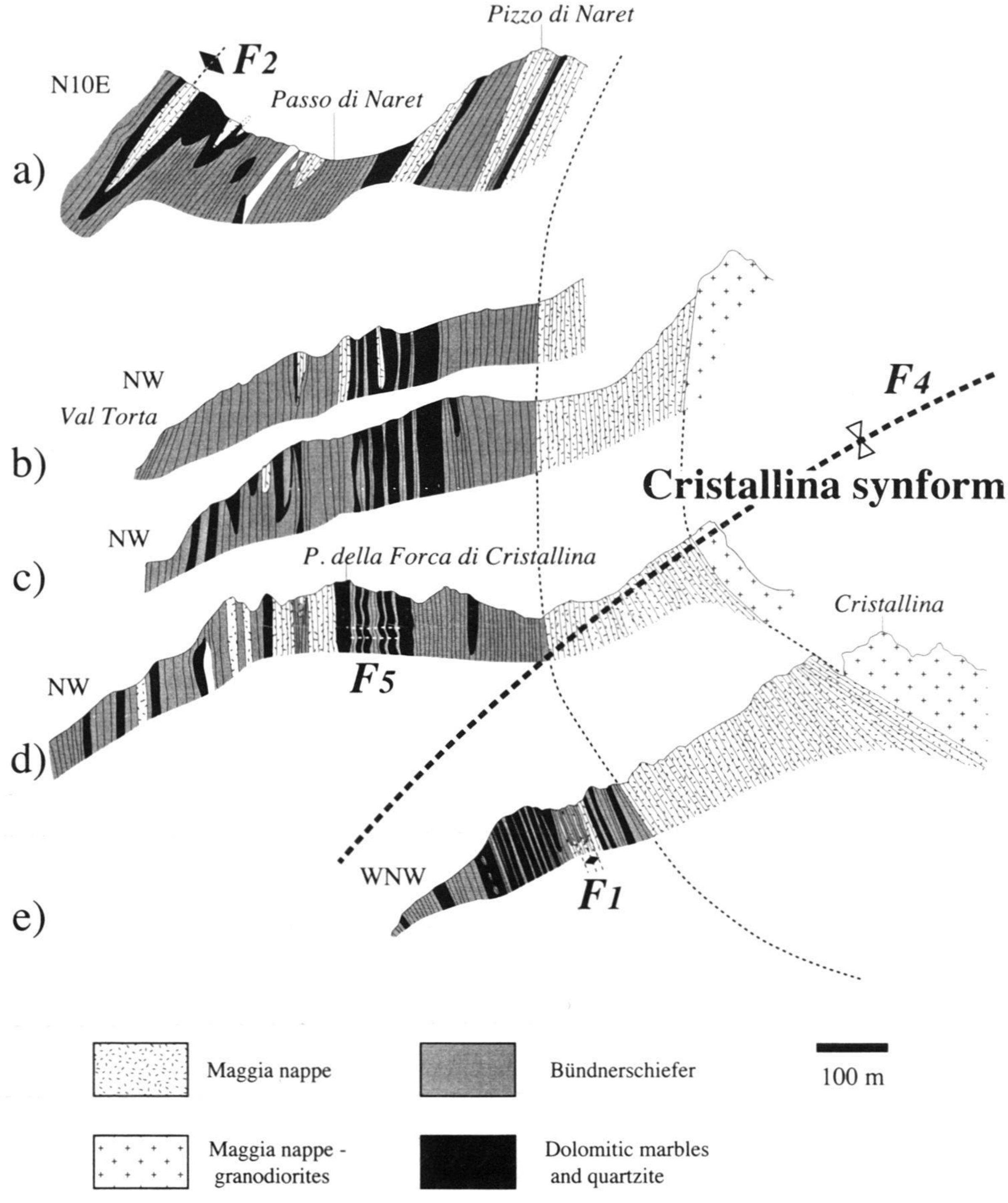



Fig. 13. Schematic cross-section in the Cristallina fold hinge region, based on the cross-sections of Günthert (1954). On (a) the downward-facing synforms of granitic basement rocks are $F_2$ synformal anticlines (cf. Fig. 6a). On (d) the minor open folds with flat-lying axial planes are $D_5$ structures (cf. Fig. 16a). On (d) and (e) there are several sheets of basement granitic gneisses separated by Bündnerschiefer; the basement occupies the cores of upward-facing $F_1$ anticlines. Locations of cross-sections (a)–(e) are indicated on Plate 2 (**5–9**).

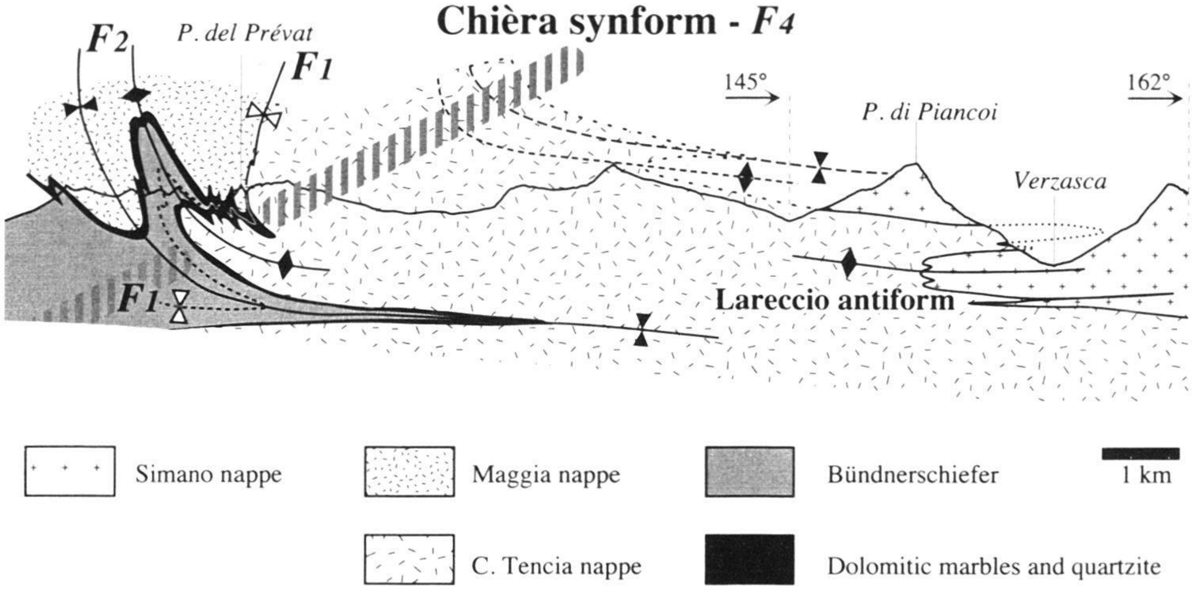



Fig. 14. Schematic cross-section parallel to the Campo Tencia fold axis. The $F_1$ fold is the major first phase syncline separating Maggia and Campo Tencia nappe. For details between P. del Prévat and Passo Campolungo see Fig. 3. The location of the cross-section is indicated on the Plate 2 (**10**).

less certainty, the structure can be followed across P. Campo Tencia as a very open antiform on the basis of changes in the orientation of the third phase lineation $L_3$.

The other major backfold in the area, which is basically the continuation of the Cristallina synform towards the east, is the Chièra synform, which is best seen in the L. Morghirolo-Campolungo region (Fig. 14). It was first recognised as a $D_4$ structure by Berchtold (1990) and Rüffer (1990). A north closing synform was identified by Preiswerk (1918) on his NW-SE cross-section, and a late E-W striking fold was also postulated by Keller (1968, p. 61). Our field observations suggest that the structure in the L. di Morghirolo-Campolungo region is a fourth phase synform with flat southern and steep northern limbs, which is the western continuation of the Chièra Synform mapped by Thakur (1973) and Milnes (1976) on the eastern side of the Valle Leventina.

The structure of the Chièra syncline is more complex than the Cristallina syncline because the different phase folds in this region are not coaxial. It is easiest to locate the synform based on the attitude of the third phase fold axes: south of L. di Morghirolo the third phase lineation plunges at a low angle toward the south-southeast, whereas north of L. di Morghirolo it is subvertical (Fig. 9b, 15). Small scale structures related to the Chièra synform are very scarce. In the gneisses, the fourth phase folds are open and angular, in schists and mica-rich gneisses they are present as a crenulation. Folds refolding the third phase folds are non-cylindrical, do not develop axial plane cleavage and have a broad scatter in orientation. The axial planes of fourth phase folds have a shallow to moderate dip toward N to NNE, with fold axes trending NE-SW. The third phase and fourth phase crenulations are, therefore, perpendicular, as are their fold hinges. In some outcrops in mica-rich rocks both crenulations occur, giving rise to shallow dome and basin undulations of the main schistosity reflecting the regional Type 1 fold interference pattern. As a

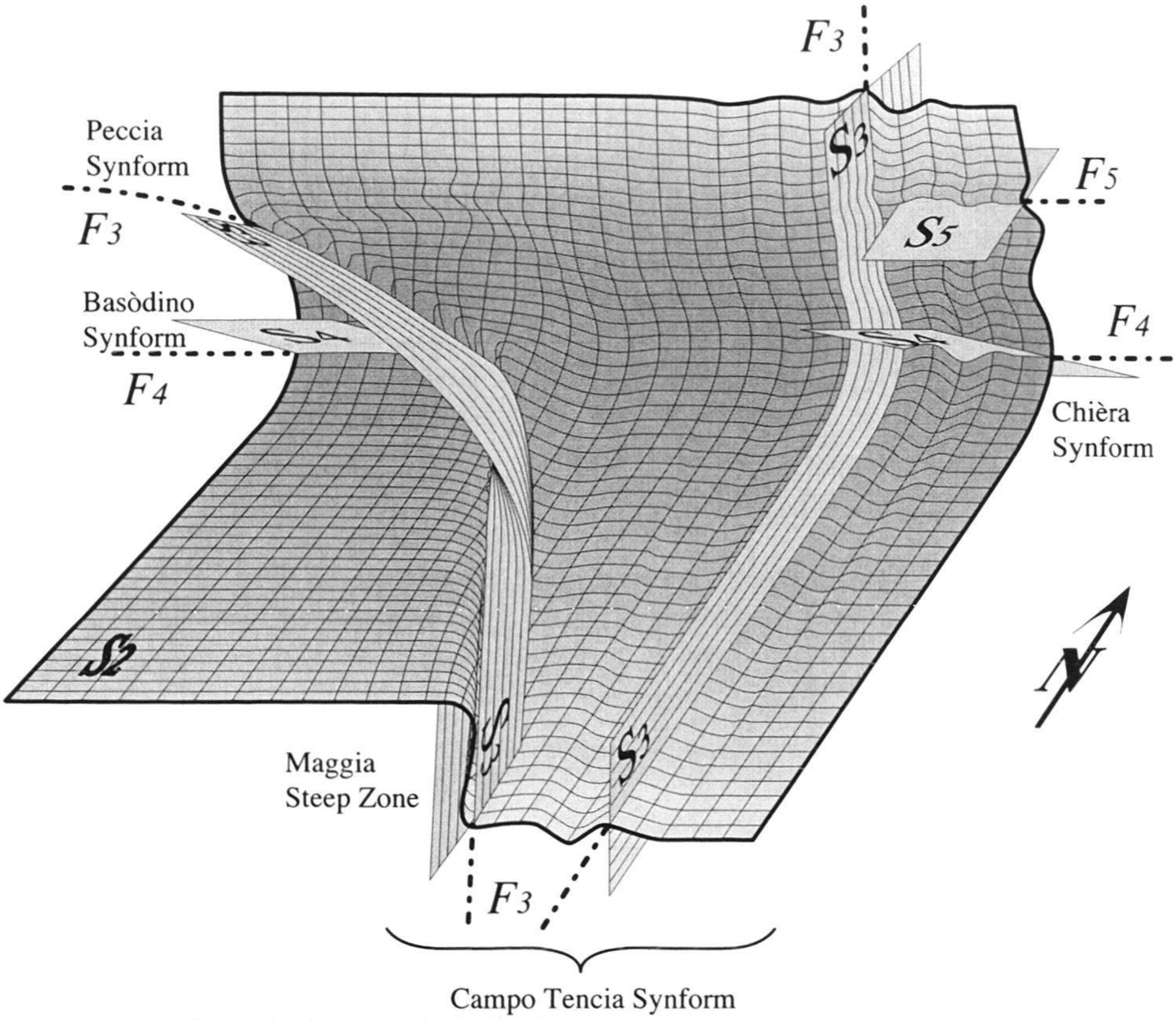



Fig. 15. Schematic regional geometry of fourth phase regional structures. For simplicity, only the relation of backfolds to the third phase structures is represented. In the east the folds of third and fourth phases are orthogonal while to the west they are nearly coaxial. Fifth phase structures ($S_5$) occur only in the steep limb of the backfolds.

consequence of this interference the axial planes of third phase folds are not significantly affected by the backfolding. In shape, orientation, and relation to mineral growth the fourth phase folds of the Chièra synform resemble the fourth phase folds of the Cristallina synform. The shallow northerly dip of the Chièra synform axial surface results in the complex map pattern of its trace around Lago Tremorgio. Moreover, this is the geometrical reason why, west of the Valle Leventina, the axial trace must go through the Campolungo area and not straight through upper Val Sambuco to the L. del Narèt (cf. Klaper 1980).

### 4.6 *Deformation phase $D_5$*

Fifth phase folds are similar in style (i.e. generally angular or kinky) and coaxial with $F_4$, but with a more flat-lying axial plane, which often dips gently to the south or south-east (that is in the opposite direction to $S_4$). A new axial plane cleavage is usually not devel-

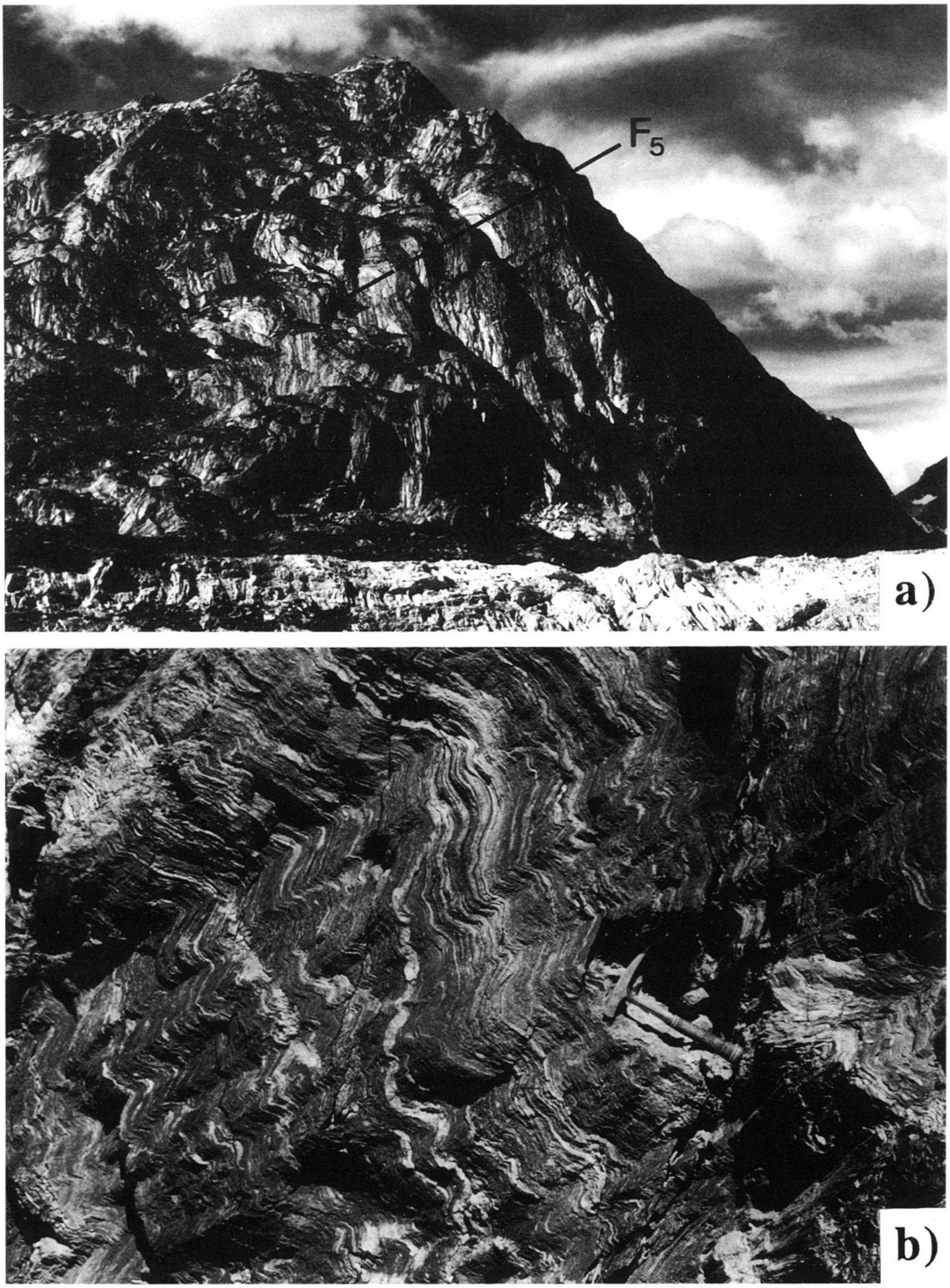



Fig. 16. Photographs of fifth phase folds: (a) The ridge east of Cima di Lago, view to the north; (b) Outcrop NW of Lago Bianco (682.625/145.700). Axial planes with moderate dip to the NE.

oped. Good examples of $F_5$ folds can be observed immediately north of Lago Sfundau (Fig. 16) and in the region of P. Meda north of Campolungo. $F_5$ folds have only been observed where the dominant regional foliation $S_2$ was already steeply oriented, in particular in the northern steep zone corresponding to the steep limb of the $F_4$ Cristallina-Chièra synform. The orientation of these structures suggests a late near-vertical shortening (e.g. Froitzheim 1992).

## 6. Major regional structures and their relation to the superposed folding

### *6.1 Nappes*

Preiswerk (1918) and Schmidt & Preiswerk (1908) demonstrated the presence of persistent, although locally discontinuous, Triassic marble bands separating a generally noncalcareous basement from the calcareous schists of the Bündnerschiefer. The tight, pinched-in synforms of Mesozoic rocks between north-closing lobes of crystalline basement were used to separate the crystalline cores into a series of nappes. Much later, Milnes (1974a) showed that the original nappe structures have been overprinted by regional-scale isoclinal folds (his "post-nappe" folds). These large superposed folds dominate the structure of the Lepontine Alps. The largest of them is the Antigorio "nappe" – a north closing $F_2$ antiform. Care should be taken in interpreting folds with cover rocks in their core, since such geometry can occur in various folding phases. For example, the cover zone on the western cliff of P. Mascarpino is an antiformal $F_1$ syncline refolded around the hinge of the $F_2$ Antigorio antiform. Similarly, the complicated structure at P. Castello consists of tight $F_1$ folds folded around major $F_2$ *S*-shaped folds (Fig. 5a). The Teggiolo zone separating the Antigorio and Lebendun nappe in the Val d'Antabia is also a first phase structure situated in the hinge of the major Lebendun $F_2$ synform. The "nappe structure" of the Penninic Alps is, therefore, the result of superposed $F_1$ and $F_2$ structures and, as the superposition of these structures is often not coaxial, lateral correlation of these "nappes" is meaningless.

Ambiguous is the structural position of the Maggia nappe vs. the Campo Tencia/Simano nappe. The major $F_1$ syncline at P. del Prévat has Maggia nappe on its upper limb and Campo Tencia nappe on the lower limb. The whole structure is on the upper limb of a major $F_2$ fold – the Campolungo synform (Fig. 14). If only the latter structure is taken into consideration, the Maggia Nappe would be in a structurally lower position than the Campo Tencia nappe.

The tectono-stratigraphic position of the Lebendun nappe remains controversial. The metaconglomerates are generally considered to be of Permo-Carboniferous age (e.g. Higgins 1964, Joos 1969), but its position relative to the Antigorio and Monte Leone nappes has led to one unorthodox model in which the Lebendun meta-conglomerates are considered to be Mesozoic flysch-like sediments deposited upon the Bündnerschiefer (Rodgers & Bearth 1960). Field data from this study support the more traditional view that the Lebendun nappe was tectonically emplaced upon the Bündnerschiefer during the west- to northwest-directed $D_1$. The $F_2$ (and $F_1$) folds affect the Maggia and Lebendun nappes in a completely analogous manner, which, together with certain lithological similarities (such as the presence of conglomeratic rocks in both units), suggests that they have undergone similar tectonic histories.

### 6.2 *Maggia Steep Zone*

The Maggia Steep Zone is defined by the attitude of the main schistosity $S_2$ as a steeply dipping, north to north-northwest trending transverse belt, which extends 40 kilometres from the northern end of Lago del Sambuco south towards the Insubric Line (Fig. 2). It was first noted by Preiswerk (1918, 1921) and named the Maggia Querzone because of its ("anomalous") trend oblique to the whole Penninic zone.

In the south of the study area, the eastern limit of the Maggia Steep Zone runs from the Monte Zucchero to the Larecc, where it parallels the axial plane trace of the Larreccio fold (Keller 1968). This major antiform, overturned towards the west, has been directly connected to the Maggia Steep Zone (Merle & Le Gal 1988), its western steep to overturned limb representing the steep zone. The Larreccio fold is interpreted here as a north closing $F_2$ antiform lying within the western, steep limb of the third phase Campo Tencia synform (Fig. 14 and Pl. 3). An east-west cross section shows, therefore, an asymmetric $F_3$ fold with a short steep limb (Maggia Steep Zone), broad synform (Campo Tencia synform) (Fig. 11) and related gentle antiform (Ticino culmination). Toward the north, the eastern limit of the steep zone crosses the Val di Prato near the village of Schièd, passes through the Lago di Mognòla and can be followed until Pizzo Scheggia and Passo Sassello. In this section, the crenulation cleavage related to the Campo Tencia synform ($S_3$) is parallel to the Maggia Steep Zone. This cleavage is more strongly developed in this region and eventually overprints the main schistosity in such a way that the two structures are almost indistinguishable in the field. This effect is well seen on the maps of the main schistosity (Pl. 2) as a zone of discordant schistosity in the region of Alpe Massari and Alpe Scheggia.

The western limit of the Maggia Steep Zone is best defined in the region between the northern end of Val Sambuco (Grasso di Dentro) and Alpe d'Alpigia. There, all the structural elements already developed are rotated into the steep zone. The main schistosity seems to be folded about a north-northeast trending, southeast-dipping axial plane (Simpson 1981, figs. 3.18 and 3.23). This bend is associated with metric scale folds and crenulation cleavage having the same characteristics as the third deformation phase cleavage. The intensity of development of the cleavage coincident with the steep zone seems to increase towards the east. This phenomenon can be seen on the southern slopes of Pizzo Mascarpino. The second phase fold hinges and stretching lineation are also rotated to become parallel with the strike of the steep zone, as observed around Lago Sambuco (Simpson 1981) and farther to the south in Val di Prato (see also Wenk 1955). The second phase lineation has a progressively more southeasterly plunge toward the middle of the structure; east of the Maggia valley the second deformation lineation again has an easterly plunge. These geometric features suggest a dextral shear component along the Maggia Steep Zone at its northern end.

In summary, the Maggia Steep Zone in the study area is a complex structure. It is a high strain zone, about three kilometres wide, which represents the steep limb of the $D_3$ Campo Tencia synform. Two second phase folds are situated in this limb and one of these – the synform – has usually been taken as directly related to the Maggia Steep Zone. In its northernmost part, the Maggia Steep Zone has probably been reactivated as a dextral shear zone during the back-folding phase because of its inappropriate orientation for developing into a backfold (Chièra synform). This geometry is consistent with the common mesoscale observation of ductile shear zones developed on the limbs of $F_3$ folds.

*6.3 Basòdino fold (backfold)*

The Basòdino fold is a finite strain structure resulting from the combined effects of $D_3$ and $D_4$. Small-scale structures seen in the $D_3$ Campo Tencia and Peccia folds are very similar to the small-scale structures of the Basòdino fold. Minor folds have a characteristic chevron style, and show the same relative timing relationships to mineral growth. Nevertheless, on several outcrops around L. Nero it has been observed that the Basòdino folds refold the Peccia folds. It is proposed that the Basòdino fold developed by hinge migration from the northern continuation of the Peccia fold. It was probably a continuous process in which the initial fold was reactivated (Ramsay 1967, p. 548) producing further crenulation cleavage very similar to the $S_3$. The mechanism of hinge migration has already been described in the context of superposed folding by Tobisch (1967) and Odonne & Vialon (1987). In the Basòdino fold it has been found that the strain ellipsoid on the southern limb is of a flattening type, while on the northern limb it is of a constrictional type with the axis of maximal extension parallel to the fold axis (Huber-Aleffi 1982). On the other hand, in the northern limb of the Peccia fold the strain ellipsoid has a flattening geometry (Simpson 1981). The resulting strain geometry in the areas through which the hinge migrated depends on the initial strain geometry and on the superimposed one. If the initial and the superimposed strain ellipsoids are both of the flattening type, the resulting geometry is expected to be of the constrictional type. Accordingly, the regional strain pattern and slightly transected relation between the Basòdino fold and its related cleavage would argue in favour of hinge migration as a mechanism of the Basòdino fold development. Similarly, the cleavage of the Peccia fold is not refolded by the Basòdino fold but has a transected relation to it. Furthermore, in any area through which the hinge migrated, there should be a zone with a strongly developed cleavage in front of the trailing edge (in the zone between the initial location of the fold hinge and its final position). There is currently insufficient data to prove or disprove this. However, there is a strong difference in the intensity of the third phase cleavage development throughout the area. In the Basòdino – L. Nero region this cleavage is moderately developed, whereas in the region around L. Cavagnöö – Cristallina – Passo del Sasso Nero, the crenulation cleavage ($S_3$+$S_4$) is very strongly developed.

*6.4 Wandfluhhorn fold*

The Wandfluhhorn fold (Fig. 2, Pl. 5) is one of the most important post-nappe structures in the Lower Penninic zone. It is a large north-closing recumbent fold with the Bosco Group and Monte Leone nappe in the core and granite gneisses of the Antigorio nappe on the outside. The main Wandfluhhorn fold, first recognised by Schmidt & Preiswerk (1908), has been described in some detail by Grütter (1929), Hunziker (1966), Wieland (1966), Hall (1972), Milnes (1974a) and Klaper (1988). At its "type locality" the fold is very tight and plunges gently east-southeast. The Wandfluhhorn fold developed a strong axial planar crenulation cleavage in the hinge area, especially within the Antigorio gneiss. A broad foliated zone parallel to the axial plane of the Wandfluhhorn fold appears to continue to the west-southwest into the possibly coeval Simplon Fault Zone (Mancktelow 1990). Deformation related to the Wandfluhhorn fold outlasted the main period of porphyroblast growth (Hall 1972). Only locally have plagioclase porphyroblasts grown across the deformed main schistosity and biotite grown aligned in the crenulation cleavage (Klaper 1988). Minor folds of crenulation or chevron type have similar structural and metamorphic features to the late $D_4$ and $D_5$ folds described earlier in this work; the axial planes orientation (dipping southeast at low angles) is most similar to the youngest deformation phase $D_5$ (Fig. 3).

Northeast of the Wandfluhhorn the location of the axial trace of the Wandfluhhorn fold becomes problematic. Hall (1972, pp. 60–62, after Ramsay *pers. comm.*) suggested that it runs into the upper Valle di Peccia and through the Maggia nappe to the head of Lago del Sambuco. The bend of all structural elements into a north-south trend (Plates 2–4) in the area between Alpe di Röd and Pizzo Sciresa may indeed be related to a continuation of the Wandfluhhorn fold into the northern Maggia region, but confirmation must await a larger scale, more regional study.

## 7. Age of deformation

There has as yet been little attempt at direct dating of deformation phases in the northern Maggia region but the available mineral age data can be interpreted in terms of a cooling curve (e.g. Hurford 1986), which in turn provides some constraint on the timing of deformational events (Fig. 17). Correlation of deformation phases in the Maggia and Lebendun nappes with those established in other better-constrained regions of the Central Alps may also be possible, but the uncertainties obviously increase with distance and the correlations presented here must be considered tentative. The first Alpine deformation in the Maggia region is related to the main nappe emplacement, with a top-to-the-NW or -NNW movement direction, and is probably of regional extent throughout the Penninic zone. We correlate this event with the Ferrera phase of Milnes & Schmutz (1978) and Schreurs (1990, 1993) in the Schams and Suretta nappes, and with $D_1$ of Baudin et al. (1993) and Marquer et al. (1994) in the underlying Tambo nappe to the east of the current area (see Table). This deformation phase affects the Arblatsch Flysch containing Palaeocene to Lower Eocene fossils (Ziegler 1956, Eiermann 1988). In the uppermost Penninic nappe in eastern Switzerland (the Suretta nappe), K-Ar ages of white mica and Rb-Sr and K-Ar ages of phengites cluster around ~35-45 Ma (Steinitz & Jäger 1981; Schreurs 1990, 1993). These ages are considered to represent formation ages (Steinitz & Jäger 1981) and to date the syntectonic crystallisation of mica in the oldest alpine penetrative foliation $S_1$ (Schreurs 1990, 1993). Whether the oldest alpine deformation in Maggia area is strictly synchronous with that of the Suretta is open to debate, since there is a recorded E-W and N-S trend in all recorded ages (e.g. Hunziker et al. 1992), with mineral ages becoming younger towards the NW. $D_1$ in the Maggia region is, however, probably also of late Eocene/early Oligocene age.

$D_2$ structures may also be regionally pervasive, generally producing the main regional schistosity. In the Bergell region (over 80 km to the east of the current study area!), the main regional schistosity ($S_2$) and other $D_2$ structures are cut by the Bergell intrusions (Nievergelt et al. 1991), with published ages of $31.9 \pm 0.09$ Ma for the tonalite and 30.1 Ma for the granodiorite (von Blanckenburg 1990, Villa & von Blanckenburg 1991).

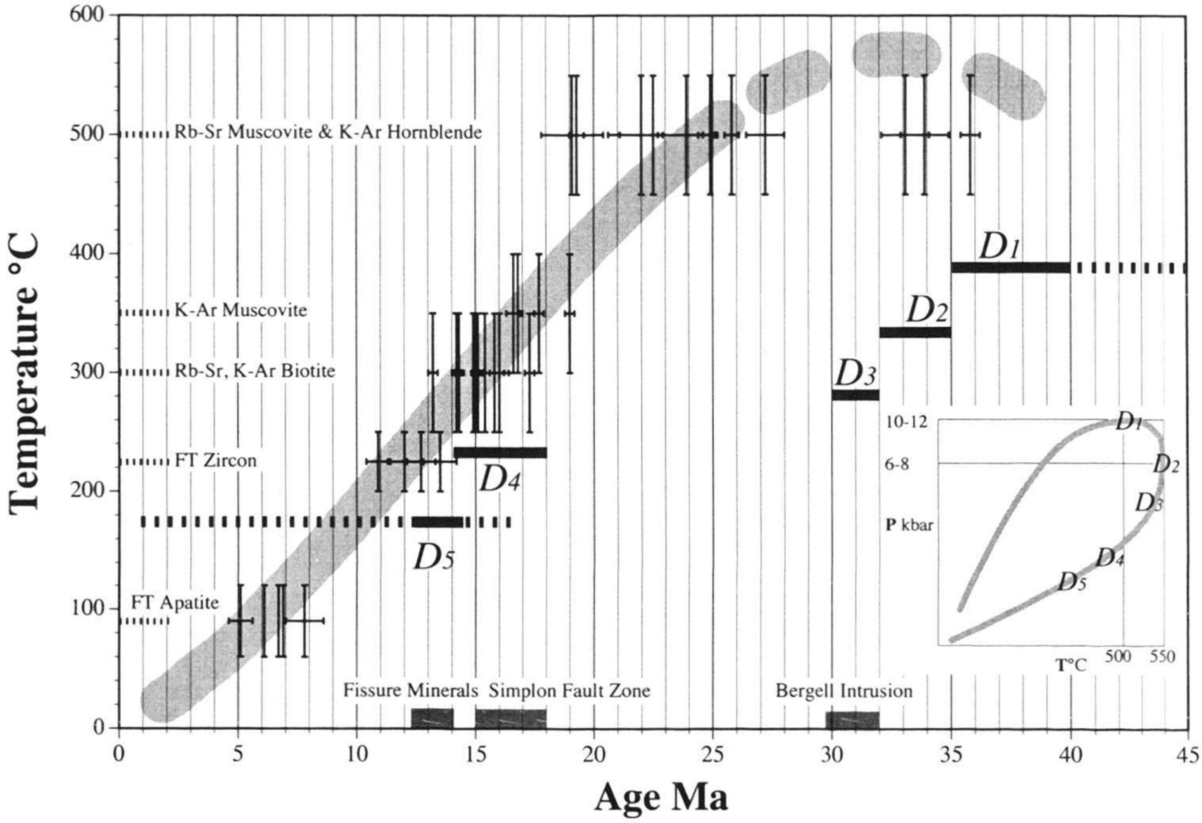



Fig. 17. Tentative time scale for the northern Maggia area based on regional correlation. Data for the construction of the cooling curve derived from Steiner (1984), Deutsch & Steiger (1985) and Hurford (1986). The isotopic systems and approximate blocking temperatures are from Hunziker et al. (1992). Additional data for reference events are from Purdy & Jäger (1976), Mancktelow (1985), and von Blanckenburg (1990).

Similar to the study area, porphyroblast growth related to the greenschist to amphibolite facies regional metamorphism is syn- to post-$D_2$ and is older than the Bergell contact metamorphism (Trommsdorff & Nievergelt 1983). A Rb-Sr age of 35.8 Ma for white mica from the Sambuco-Narèt area within the current study region was interpreted as the peak of Lepontine metamorphism (Steiner 1984). Other (smaller) grains yielded an age of 25.8 Ma (Steiner 1984). The older age is consistent with Rb-Sr phengite ages that are interpreted as formation ages marking the peak of prograde "Lepontine" (Wenk 1956, 1962) metamorphism (Jäger 1973). K-Ar dating of hornblendes suggests that conditions sufficient to produce high-grade assemblages were sustained until about 23 Ma ago (Deutsch & Steiger 1985). These observations are consistent with the conclusions of Marquer et al. (1994) from the Tambo nappe that the regional $D_2$ phase is around 35-30 Ma in age, although from the observations relevant to $D_3$ considered below, we would further restrict the range to ~ 35-32 Ma.

Field relationships of the Bergell intrusion also provide important constraints on the age of the $D_3$ "crossfolding" phase, which we would correlate on the basis of overprinting relationships, regional orientation and style with the "Cresem" fold phase (Kopp 1923) in the region west of Bergell (Table). The Bergell tonalite shows deformation over a range of conditions from magmatic to submagmatic to (more limited) solid state (Rosenberg et al. 1995). Folds in the sheared tonalite and the development of a schistosity parallel to the fold axial planes are related to the Cresem antiform, a major third phase fold in the area, which suggests that $D_3$ occurred during solidification of the Bergell tonalite, i.e. at around 32 Ma, but may have outlasted it during the waning stages of deformation.

Late fissure veins containing quartz, muscovite and adularia, which are found throughout the Maggia area, clearly postdate ductile deformation. From the region around Lago Cavagnöö, the veins yield K-Ar ages of 13.7 ± 0.4 and 13.0 ± 0.5 Ma for muscovite and 13.6 ± 0.2 Ma for adularia (Purdy & Stadler 1973). These ages are similar to or younger than Rb-Sr and K-Ar ages on biotite (~ 13.0–17.5 Ma) (Fig. 17) and the muscovite ages are therefore interpreted as crystallisation ages dating vein development (Purdy & Stadler 1973). Together with the onset of rapid cooling between 19.5 and 16 Ma (Hurford 1986), this limits the possible time of $D_4$ backfolding (Fig. 17). Similarly, the proposed age of important displacement on the Simplon Fault Zone is between 18 and 15 Ma (Mancktelow 1990, Grasemann & Mancktelow 1993). These data suggest that backfolding in the Basòdino-Cristallina-Campolungo area may be synchronous with that of the Simplon Pass (the Berisal-Glishorn folds) which are, in turn, broadly coeval with the Simplon Fault Zone (Mancktelow 1990, 1992).

A not dissimilar geometry to $D_5$, with the steep limb of the Berisal backfold overprinted by coaxial folds with more shallowly-dipping axial planes concordant with the detachment fault of the Simplon Fault Zone, can be observed in the Simplon Pass region (Mancktelow 1992, fig. 8; Mancktelow & Pavlis 1994, fig. 5). If the Wandfluhhorn fold can be related to the Simplon Fault Zone (e.g. Mancktelow 1990), it follows that backfolding in the study area and the curvature of earlier structures into the north-south steep zone (probably related to the Wandfluhhorn fold) are also coeval, or at least, part of a continuous deformation process. This relationship between backfolds and normal faulting indicates that NNW-SSE shortening was contemporaneous with extension in a WSW-ENE direction in the Early to Middle Miocene (Mancktelow 1992). These related structures, namely the Berisal-Glishorn backfolds and Simplon Fault Zone in the west (Mancktelow 1990) connected through the Wandfluhhorn fold to the Cristallina-Chièra backfolds and the reactivated Maggia Steep Zone in the current study area, are the expression of a dextral transpressive regime across the Alpine chain at this time (e.g. Zingg & Schmid 1983, Steck 1984, Schmid et al. 1987).

The $F_5$ folds are often associated with quartz veins in which the quartz is cut by well-oriented fluid inclusion planes outlining healed microcracks and reflecting a NE-SW extension, i.e. a late stretch parallel to the Alpine chain. Associated with this deformation are steep joints and faults that strike NNW-SSE with a downthrow to the northeast. The extension on these brittle $D_5$ structures may represent the symmetrical equivalent to extension on the Simplon Fault Zone developed on the other side of the Simplon subdome, as also suggested for the Tambo nappe further east by Baudin et al. (1993). $D_5$ may therefore be related to the Neogene exhumation history of the Central Alps, during which tectonic thinning was associated with lateral extension parallel to the Alps, as manifested by the Simplon and Brenner Fault Zones (Mancktelow 1985, 1990, 1992; Selverstone 1988, Behrmann 1988).

| | $D_1$ | $D_2$ | $D_3$ | $D_4$ | $D_5$ |
|---|---|---|---|---|---|
| **Main Structures** | *Thrusting and isoclinal folding*<br>Teggiolo zone | *Main post-nappe folding*<br>Antigorio antiform (-nappe), Lebendun synform Campolungo synform | *Cross-folds*<br>Peccia-Basòdino synform, Campo Tencia synform, Maggia Steep Zone | *Northern Backfolds*<br>Basòdino-Cristallina synform, Chièra synform | *Collapse folds*<br>?Wandfluhhornfold? |
| **Main Features** | | Main regional schistosity | Crenulation cleavage | Weak crenulation cleavage | no axial plane cleavage |
| **Tectonic Setting** | Thrusting and crustal thickening | Gravitational collapse | Unclear origin | Dextral transpression and exhumation | Tectonic exhumation |
| **Mineral Growth** | | muscovite, biotite, epidote, zoisite, clinozoisite, garnet, staurolite, kyanite and quartz in schists and hornblende in amphibolites. In some places tourmaline, rutile and ilmenite | helicitic-poikiloblastic plagioclase, garnet, kyanite, zoisite and clinozoisite in schists and gneisses; tremolite and scapolite in marbles | biotite, muscovite and quartz | quartz, muscovite, adularia, epidote filled vein systems; |
| **Time** | Late Eocene - Oligocene | Oligocene (pre-Bergell) | Late Oligocene (pre- to (?)syn-Bergell) | Neogene Onset (?)20 Ma | Neogene |
| Chatterjee (1961) | **$B_0$** | **$B_1$** | **$B_2$** | | |
| Higgins (1964) | **$F_1$** | **$F_2$** | **$F_3$** | **$F_4$** | **F5, F6, F7** |
| Milnes (1964) | | **main alpine** | | **late alpine** | |
| Chadwick (1965) | **nappe transport** | **B** | | **V** | |
| Cobbold (1969) | **$B_0$** | **B** | **T** | **V** | |
| Sibbald (1971) | **$D_1$** | **$D_2$** | **$D_3$** | **$D_4$** | |
| Thakur (1971) | **$F_1$** | **$F_2$** | | **$F_3$** | |
| Hall (1972) | **$F_1$** | **$F_1$** | **$F_2$, ($F_3$)** | **$F_3$** | **$F_3$** |
| Milnes (1974, 1978) | **early overthrusting** | **main nappe emplacement** | **regional isoclinal folding** | **late stage deformation** | **late stage deformation** |
| Huber et al. (1980) | **$D_1$** | **$D_2$** | **$D_3$** | **$D_3$** | |
| Probst (1980) | **$B_1$, $B_2$** | **$B_3$** | **$B_4$** | **$B_5$** | |
| Simpson (1981) | **$A_1$** | **$A_2$** | **$A_3$** | **$A_4$** | |
| Huber (1981) | **$F_0$** | **$F_1$** | **$F_2$** | **$F_3$** | **$F_2$ (?)** |
| Huber-Aleffi (1982) | **$D_0$, $D_1$** | **$D_2$** | **? $D_3$** | **$D_3$** | |
| Klaper (1985) | **$A_1$** | **$A_2$** | **? $A_3$** | **$A_3$** | |
| Berchtold (1990) | **$D_1$** | **$D_2$** | **$D_3$** | **$D_4$** | |
| Rüffer (1990) | **$D_1$** | **$D_2$** | **$D_3$** | **$D_4$** | |
| Hohl (1990) | **$D_1$** | **$D_2$** | **$D_3$** | **$D_4$** | |
| Stoll (1990) | **$D_1$** | **$D_2$** | **$D_3$** | **$D_4$** | |
| Baudin et. al. (1993) | **$D_1$** | **$D_2$** | **? $D_3$** | **$D_4$** | |
| Schreurs (1993) | **$D_1$** | **$D_2$** | **? $D_3$** | | |

## 8. Conclusions

As is typical of the whole Lower Penninic zone, the Basòdino-Cristallina-Campolungo area has had a very complex deformation history and its current geometry represents the finite strain effect of superposed structures on all scales, from microscopic to regional. Field work in the studied region has established the existence of five Alpine folding phases:

$D_1$ the first Alpine deformation phase led to a complex imbricate nappe structure as the result of recumbent folding and overthrusting (Higgins 1964), and to heterogeneous shear zone formation in Hercynian intrusive rocks (Simpson 1981);
$D_2$ the second deformation phase isoclinally refolded the interleaved Penninic basement-cover nappe sequence on a regional scale and caused the formation of the regionally dominant schistosity (Milnes 1974a);
$D_3$ the third deformation phase resulted in NW-SE to N-S trending major folds (with an axial planar crenulation cleavage) to produce cross folds and the Maggia "Querzone" (e.g. Preiswerk 1918, Niggli et al. 1936, Wenk 1953);
$D_4$ the fourth, late Alpine deformation phase produced a broad, regional, south-vergent, synformal backfold with a steep to overturned northern limb, which is known as the "northern steep zone" (Milnes 1974b);
$D_5$ the fifth, late Alpine deformation phase produced flat lying, kink-like folds locally within the steep zone.

The largest structure of the first deformation phase is the "Teggiolo zone" synform situated between the Lebendun and Maggia nappes on one side, and the Antigorio nappe on the other. The Teggiolo zone is folded around the hinge of the Antigorio antiform, the major structure of the second deformation phase. The Antigorio antiformal hinge is in detail a complex structure with several almost *M*-shaped second order folds. Due to later overprinting the outcrop pattern of these folds is very complex. As a result, these second phase folds were mapped in the past as structures of different generations: this study interprets them as component parts of a single large structure. The principal second order folds in the hinge of the Antigorio antiform *s.l.* are, from bottom to top: the Antigorio antiform *s.s.*, the Lebendun synform (Milnes 1974a) and the equivalent Sciresa synform in the Maggia nappe (Simpson 1981), the Massari synform (which has an almost identical structural position to the previous two) and the Röd antiform. The major synformal structure above the antigorio antiform *s.l.* is the Campolungo synform. The next antiformal structure above the Campolungo synform is the Simano nappe (a $D_2$ antiform), with the Lareccio antiform as a second order fold on its lower limb. The Caralina synform, in the Lebendun nappe, and the rest of the second deformation phase folds discussed above are third order structures. The original orientation of the axial planes to second phase folds was probably flat, with fold hinges plunging at low angles towards the northeast to east-northeast in the eastern part of the area.

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Table. Correlation table of deformation events and metamorphism in the Lower Penninic nappes.

The principal structure of the third deformation phase in the eastern part of the study area is the Campo Tencia synform. This synform has several un-named second order folds. The major structures of the third deformation phase in the western part of the study area are the Peccia and Basòdino synforms which probably represent a single structure. The main deformation in the Maggia Steep Zone probably also occurred during the third deformation phase.

The fourth deformation phase resulted in the so-called northern steep zone. The major fold related to this structure, in the western part of the area, is the Cristallina synform. As a result of the moderate initial angle between third and fourth phase fold hinges, the fourth deformation phase resulted in hinge migration of the pre-existing Basòdino fold. The Basòdino fold therefore has a finite geometry produced by the combined effects of $D_3$ and $D_4$. The major fourth phase synform in the eastern part of the area is the Chièra synform. There, the fold hinges of the third and fourth phase were initially at a high angle resulting in a regional Type 1 interference pattern. The deformation in the Maggia Steep Zone continued during this deformation phase. The initiation of the Wandfluhhorn fold, whose axial trace can be followed into the central part of the study area, is also probably related to the fourth deformation phase. The most recent deformation phase $D_5$, which may be a continuation of $D_4$, indicates an overall vertical shortening (by recumbent kink-like folding of the steep limbs of $D_4$ folds) apparently coeval with NE-SW extension (indicated by faulting and vein formation). This strain geometry corresponds to a late "orogenic collapse" and orogen-parallel extension during continued convergence.

## Acknowledgements

This work represents a summary of combined experience accumulated over many years in the Central Alps and discussions, field mapping courses and excursions with many colleagues and students have greatly contributed to our understanding of a very complex region. In particular, thanks are due to Peter Berchtold, Lukas Bleiker, Antonio Greco, Alain Hohl, Eva Klaper, Geoff Milnes, Laura Montresor, John Ramsay, Michael Rüffer, Carol Simpson, Stefan Schmid, Guido Schreurs, Thomas Stoll, Volkmar Trommsdorff, Peter Visser and Markus Weidmann. The manuscript benefited from thoughtful reviews by Eva Klaper and Stefan Schmid. A. Uhr helped in drafting. Financial support from ETH Research Credits No. 0-20-154-86 and 0-12-405-91 is gratefully acknowledged.

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Manuscript received September 14, 1994
Revision accepted September 21, 1995

## Plate Captions

Plate 1. Outcrop map of banded gneisses in Val del Coro (685.20/146.06). Three fold generations seen in this outcrop can be attributed to the first three deformation phases observed elsewhere in the area. Even later cleavage is related to the backfolding phase $D_4$.

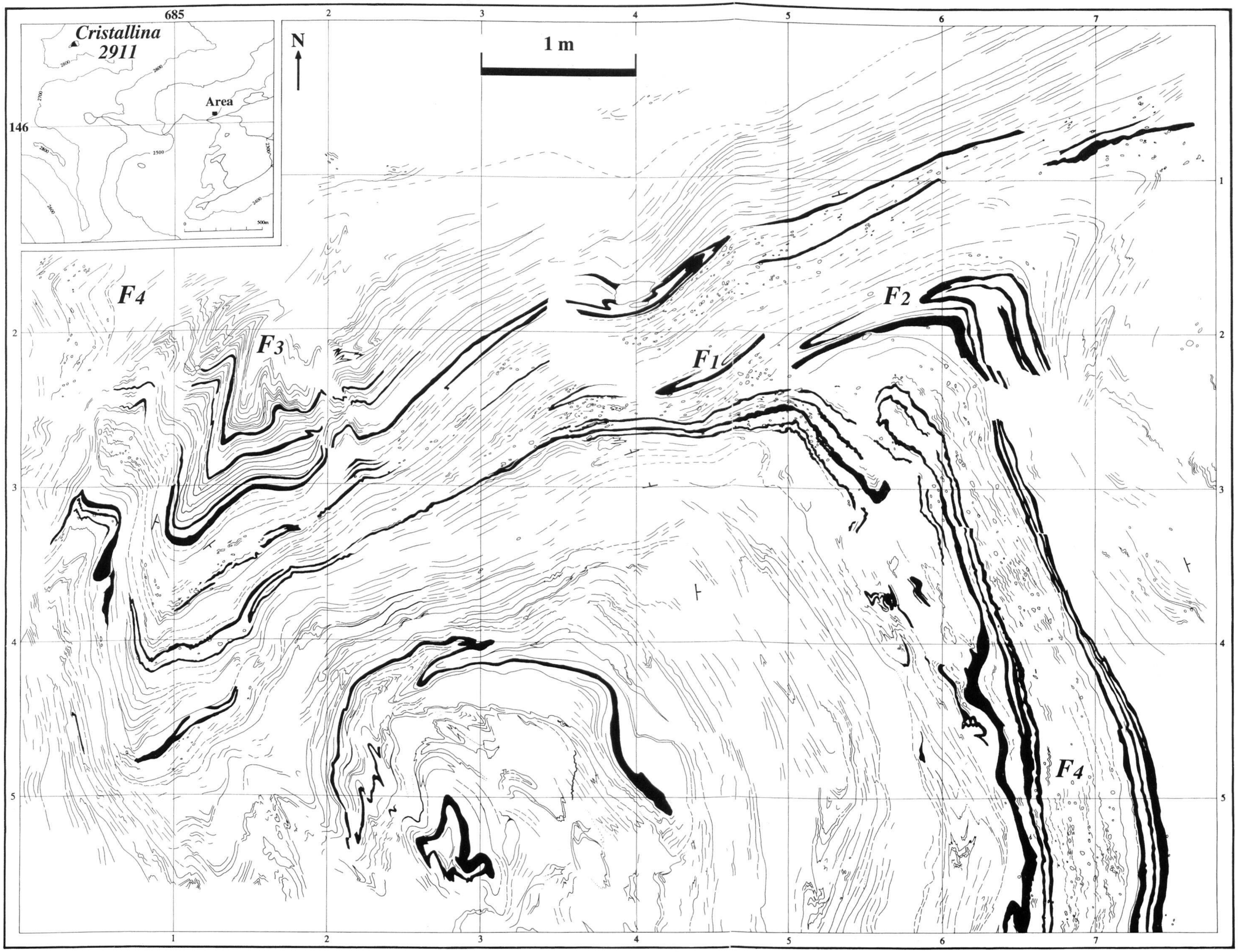
Plate 2. Trend map of the main regional schistosity. Individual measurements are compiled from Hasler (1949), Burckhardt & Günthert (1957), Higgins (1964), Keller (1968), Heitzmann (1969), Grubenmann (1970), Bianconi (1971), Sibbald (1971), Simpson (1981), Huber-Aleffi (1982), Oppizzi (1984), Aebischer (1985), Bleiker (1989), Zimmermann (1989), Berchtold (1990), Hohl (1990), Rüffer (1990), Stoll (1990), Platzman (unpublished) and own data. Coordinate system is from the Swiss national topographic map grid. Main tectonic units and nappe boundaries after: Hasler (1949), Burckhardt & Günthert (1957), Bianconi (1971), Hafner et al. (1975) and Keller et al. (1980). Positions of cross-sections are indicated. **1–3:** Fig. 8a–c respectively; **4:** Fig. 11; **5–9:** Fig. 13a–e respectively; **10:** Fig. 14.

Plate 3. Map of axial traces of main second phase folds, based on data from Higgins (1964), Keller (1968), Bianconi (1971), Simpson (1981), Huber-Aleffi (1982), Klaper (1985), Bleiker (1989), Berchtold (1990), Rüffer (1990), Stoll (1990), and own data. **A:** Antigorio antiform hinge zone (dotted line), **C:** Caralina synform; **Cl:** Campolungo synform; **G:** Ganna antiform (?); **L:** Lebendun synform hinge zone (dotted line); **La:** Lareccio antiform, **M:** Massari synform; **R:** Röd antiform; **S:** Sciresa synform, and its hinge zone (dotted line).

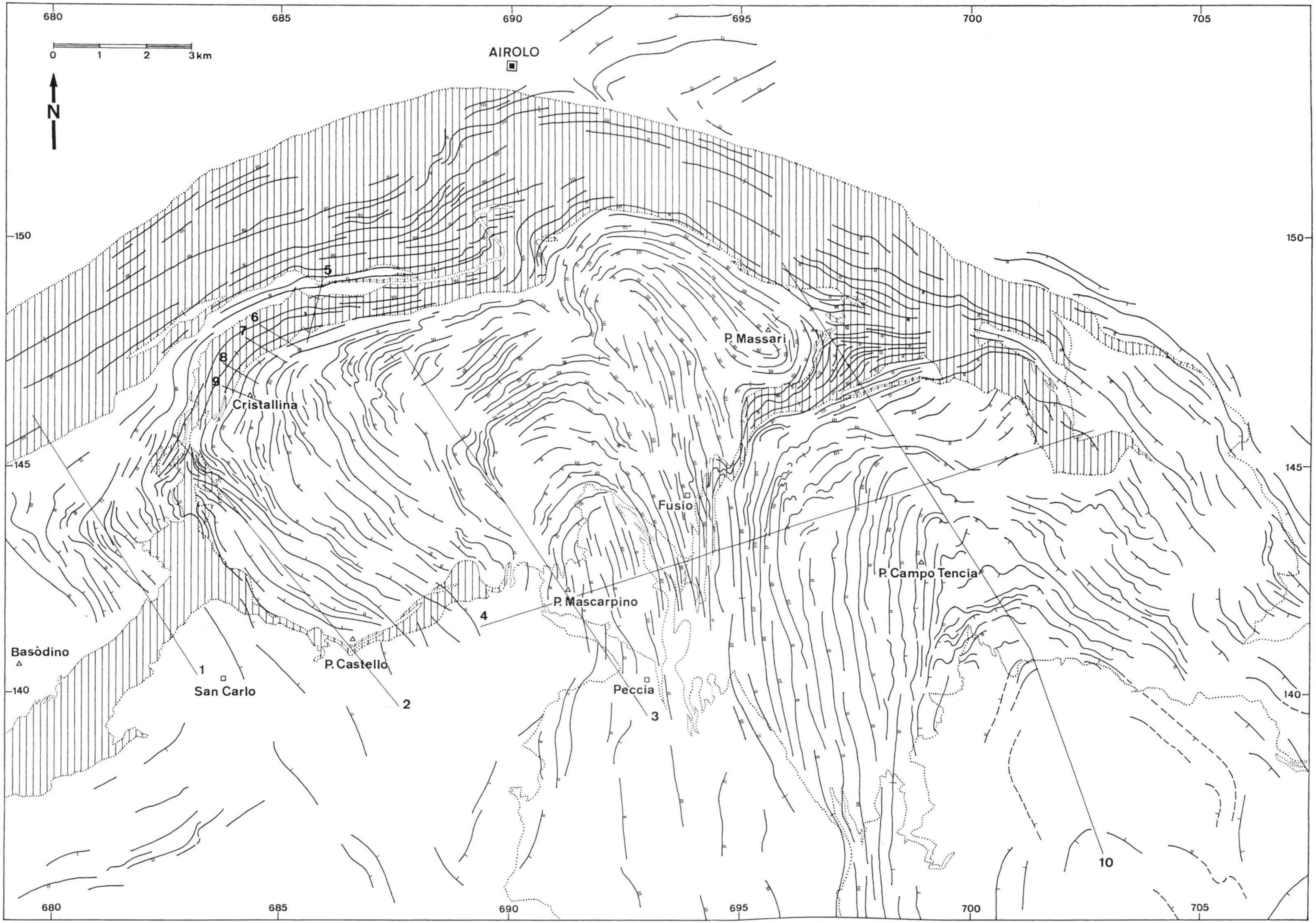
Plate 4. Axial traces of main third phase folds, based on maps from Higgins (1964), Keller (1968), Bianconi (1971), Simpson (1981), Huber-Aleffi (1982), Klaper (1985), Bleiker (1989), Berchtold (1990), Rüffer (1990), Stoll (1990) and own data. Third phase folds: **B:** Basòdino synform; **CT:** Campo Tencia synform; **P:** Peccia fold; **MSZ:** Maggia steep zone (horizontal line pattern).

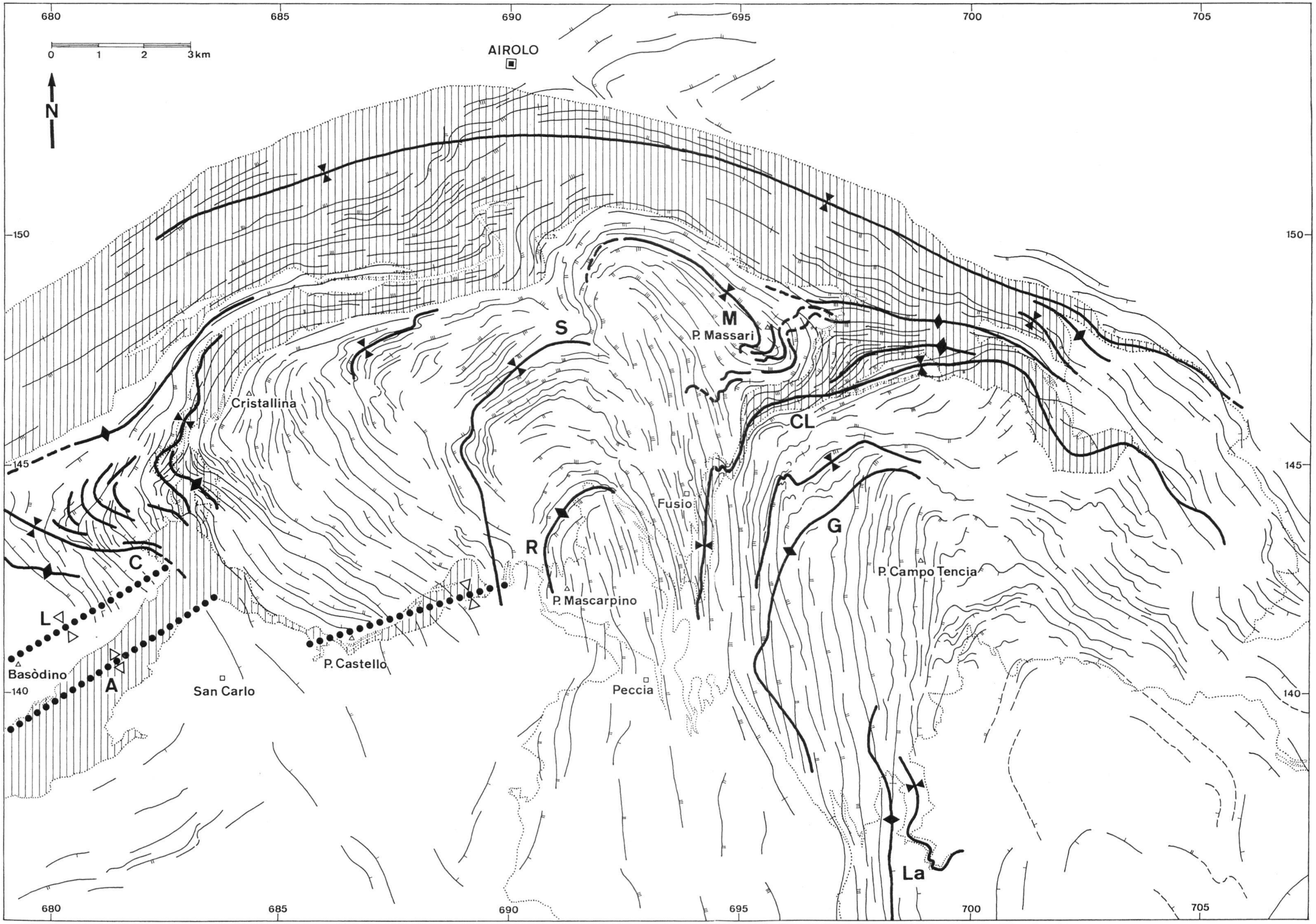
Plate 5. Axial traces of main fourth phase folds: **C:** Cristallina backfold; **Ch:** Chièra backfold; **W:** likely position of Wandfluhhorn fold axial trace (possible $D_4/D_5$ structure?).

Eclogae geol. Helv. 89/1 (1996)
Plate 1



Eclogae geol. Helv. 89/1 (1996)
Plate 2

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Cristallina
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Basòdino
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P. Castello
Peccia
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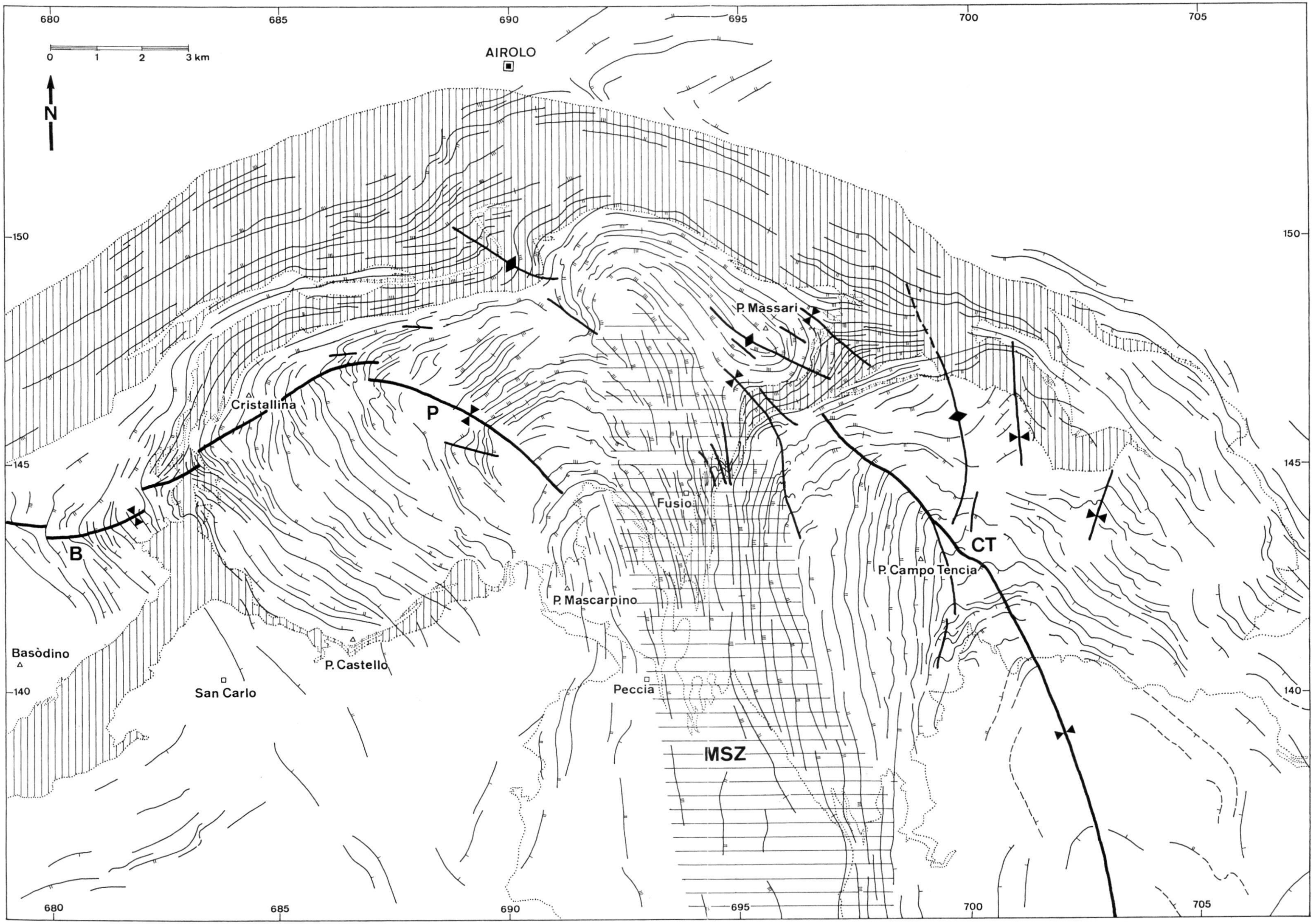
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P. Mascarpino
Basòdino
P. Castello
San Carlo
Peccia
MSZ

Eclogae geol. Helv. 89/1 (1996)
Plate 5