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The Maggia cross-fold: An enigmatic structure of the Lower Penninic nappes of the Lepontine Alps

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Key words: Alpine tectonics, nappe tectonics, superposed folding

ABSTRACT

The geometry and kinematics of the map scale Maggia cross-fold structure has been studied by several generations of geologists over seventy years and different models have been proposed for its formation. New observations indicate that the Maggia structure is a SW-verging cross-fold created after earlier NW-directed overthrusting of the Maggia nappe onto the deeper Simano and Antigorio recumbent fold nappes. The nappe emplacement and later cross-folding occurred under amphibolite facies conditions by detachment of the upper European crust during its SE-directed underthrusting below the Adriatic plate.

ZUSAMMENFASSUNG

Die Geometrie und Kinematik der Maggiaquerfalte der Zentralalpen wurde seit 70 Jahren von mehreren Geologengenerationen untersucht und verschiedene kinematische Modelle, welche die Abfolge der Faltungsphasen erklären, wurden vorgeschlagen. Neue Beobachtungen zeigen, dass die Maggiastruktur eine SW vergente Falte bildet, welche nach der früheren NW gerichteten Überschiebung der Maggiadecke auf die tieferen Simano- und Antigoriofaltendecken enstand. Die Platznahme der Decken und deren spätere Querfaltung erfolgte unter Amphibolitfaziesbedingungen durch Abscherung der oberen europäischen Kruste, während deren SE gerichteten Unterschiebung unter die adriatische Platte.

Introduction

The Lepontine Alps are one of the first regions in the world where recumbent gneiss fold nappes, characteristic of the ductile structures of deep tectonic levels of an orogenic belt, were observed (Fig. 1). Gerlach (1869) first described the flat lying and NW-verging Antigorio recumbent fold nappe with a minimum amplitude of about 9 km and a thickness of 2 km. Schardt (1903), based on his observations in the new Simplon railway tunnel, described the recumbent gneiss fold structures of the lower Penninic nappes. Schardt's discovery was an integral part of Argand's (1916) now classic description of the Pennine Alps. Since the beginning of this century, the geology of the Toce, Maggia, Verzasca and Ticino Valleys has been studied by geologists primarily from the University of Basel (so-called "Basler Schule"), (Schmidt & Preiswerk 1908, Preiswerk 1919, 1921, Preiswerk et al. 1934, Grütter 1929, Wenk 1955, Burckhardt & Günthert 1957, Keller 1968, Spicher 1972, Keller et al. 1980). The Maggia cross-fold was described by Preiswerk (1919, 1921) as a NNW–SSE-striking synformal structure, perpendicular to the ENE-WSW-oriented main fold and nappe-front structures of the Central Alps. This cross-fold is situated between the two nappe-dome structures of the Toce and Ticino valleys (Aar - Toce and Ticino culminations on Fig. 1). Modern structural investigations of the Maggia and Verzasca Valleys began with the work of Wenk (1955). Wenk demonstrated that the whole nappe stack underwent deformation by ductile flow under high temperature conditions, producing a penetrative linear rock fabric. Predominantly mainly parallel stretching lineations and fold axes may be followed over great distances throughout the whole recumbent fold nappe stack. Since the 1960's, geologists of the Imperial College of London and later from the ETH-Zürich (under the direction of John Ramsay and Geoff Milnes) started a systematic structural analysis of the same region. The most important investigations concerning the Maggia structure are the Ph.-D. theses by Huber (1981), Simpson (1982) and Grujic (Grujic & Mancktelow 1996). Huber et al. (1980) introduced the concept of successive folding phases. Grujic & Mancktelow (1996) gave an extensive summary of this and their own work. They concluded that the Maggia cross-fold is not a synform as proposed by Preiswerk (1919, 1921), Kündig in Niggli et al. (1936), Spicher (1972), Merle & Le Gal (1988), Merle et al. (1989), Klapper (1990), Steck (1990), Steck & Hunziker (1994), but an isoclinal

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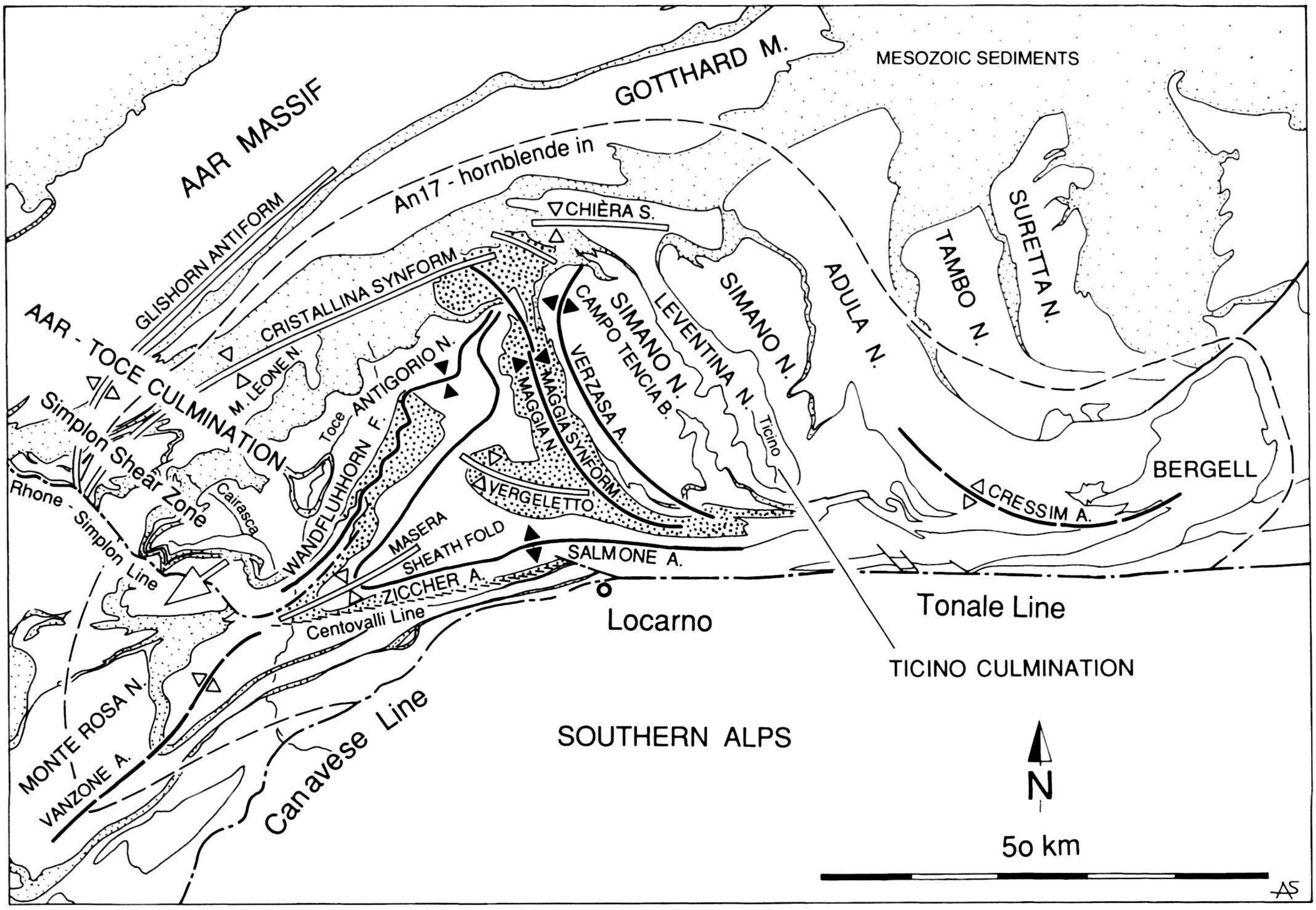

Fig 1. Tectonic map of the Lepontine Alps, limited by the Gotthard massif to the north and the Canavese and Tonale lines (Insubric or Periadriatic line) to the south. The ~40 - 35 Ma old Penninic recumbent fold nappes were overprinted some 35 Ma ago by the Wandfluhhorn, Ziccher-Salmone, Maggia and Verzasca cross-folds. The ductile Simplon shear zone was active between ~35 - 30 Ma, followed by the creation of the more discrete Rhone-Simplon line since 18 Ma with a second peak of normal fault extension some 10 Ma ago (Steck & Hunziker 1994). The Vanzone and Cressim antiforms have been created some 30 Ma ago in relation with the uplift and back-thrusting of the Lepontine Alps during the Insubric phase of Argand (1916). The Glishorn antiform, the (Berisal-) Cristallina and Chièra synforms are related to the late phase of backfolding creating the northern steep belt starting some 10 Ma ago. The age and age-relations of the Tertiary deformational structures are discussed in Steck & Hunziker (1994).

"steep zone" without a syncline structure (fig. 15 in Grujic & Mancktelow 1996), separating the lower Antigorio nappe from a higher Campo Tencia – Simano nappe. This difference in the interpretation raises an important question regarding the tectonic position of the Maggia nappe and is fundamental for the interpretation of the Lower Penninic nappe structures: does the Maggia nappe separate a lower Antigorio nappe from a higher Simano unit, or, is the Maggia nappe seated on top of both the Antigorio and Simano nappes, folded together with these two nappes into a synformal structure? In this paper an updated Maggia cross-fold model is presented, using published structural data and new field observations, favoring the synformal model.

The contacts between the Antigorio, Maggia and Simano nappes

The contacts between the different tectonic units on a detailed structural map (Fig. 2) mainly correspond to those indicated on the tectonic map by Spicher (1972), compiled for the Maggia region in direct collaboration with E. Wenk and his scientific staff. They are also based on the 1:25,000 scale geological maps "Basodino" by Burckhardt & Günthert (1957), "Val Bedretto" by Hafner et al. (1975), "Pizzo Campo Tencia" by Keller et al. (1980) and the 1:50,000 scale geological map "Tessineralpen" by Preiswerk et al. (1934). In many places the nappe boundaries follow slices of quartzites and marbles of

Tab. 1

Steck (this paper):

Main deformational phases	Nappe emplacement		Cross-folds	Northern backfolds	Vertical compression
	early deformation or overthrusting	main nappe emplacement			
Main structures	first schistosity Maggia nappe and early folds Mesozoic cover nappes S1, F1	Maggia nappe Antigorio - Simano nappes Leventina nappe Gotthard fold S2-S3, F2-F3	Verzasca antiform *Maggia synform* Salmone fold Wandfluhhorn fold S4, F4	Campo Tencia basin Chiera synform Cristallina synform San Carlo antiform F5	crenulation folds with horizontal axial surface S7, F7 (Steck, 1984)
Metamorphic grade	prograde	amphibolite facies prograde and peak conditions	amphibolite facies	greenschist facies retrograde	greenschist facies retrograde
Time	Late Eocene	Late Eocene - Early Oligocene	Oligocene	Neogene	Neogene

Grujic & Mancktelow (1996):

Main deformational phases	D1 Thrusting and isoclinal folding	D2 Main post-nappe folding	D3 Cross-folds	D4 Northern Backfolds	D5 Collaps folds
Main structures	Teggiolo zone	Antigorio antiform (-nappe) Lebendun synform Campolungo synform	Peccia-Basodino synform Campo Tencia synform *Maggia Steep Zone*	Basodino-Cristallina synform Chiera synform	?Wandfluhhorn fold?
Metamorphic grade	prograde	amphibolite facies	amphibolite facies	greenschist facies	lower greenschist facies
Time	Late Eocene-Oligocene	Oligocene (pre-Bergell)	Late Oligocene	Neogene	Neogene

supposed Mesozoic age. The so-called "Pertusio-Zug" or Pertusio zone of Mesozoic sediments (Keller et al. 1980) forms, over a long distance, the limit between the Maggia and Simano nappes. To the east of Peccia, the junction of the Pertusio zone with the Mogno – Campolungo antiform of Mesozoic sediments is covered by Quaternary deposits. For this reason the relationship between these two structures remains uncertain. The boundary between the Maggia and Antigorio nappes is only based on a few discontinuous slices of marble of the Someo zone. The Antigorio nappe itself is mainly recognizable by the occurrence of the distinctive Antigorio granodiorite gneiss. The homogeneous granodioritic and tonalitic Alpigia gneiss (Fig. 3) is separated from the Maggia gneiss by a sheet of Mesozoic marbles and is attributed to the Antigorio unit.

The Mesozoic Lebendun conglomerates are not distinguished from the Mesozoic calcschists in Fig. 2. In this paper, the Lebendun conglomerates are considered as Mesozoic (Rodgers & Bearth 1960, Spring et al. 1992) and not as Permian sediments (Joos 1967, Huber & Alefi 1982, Grujic & Mancktelow 1996). The Lebendun conglomerates represent a part of a Mesozoic cover unit whose basement is locally present as the Valgrande gneiss in the Simplon region.

Deformational structures and phases

The structures of the Maggia nappe are represented on Fig. 2. The main gneiss structures indicated on this map are second, third and fourth phase schistosities (or crenulation cleavages) and folds, which formed under amphibolite facies metamorphic conditions. Younger schistosities have transposed older structures. The spatial orientation of these structures has been compiled from geological maps and publications (Preiswerk 1921, Grütter 1929, Preiswerk et al. 1934, Niggli et al. 1936, Wenk 1955, Burckhardt & Günthert 1957, Keller 1968, Spicher 1972, Hall 1972, Hafner at al. 1975, Keller et al. 1980, Huber et al. 1980, Huber 1981, Simpson 1982, Etter 1986, Merle & Le Gal 1988, Grujic & Mancktelow 1996) and completed by new observations and measurements. In many places the traces of axial surfaces and interpretations of fold structures are based on personal observations and some structures and their interpretation are different from previous structural maps. The structural evolution is presented in Table 1. The first, second and third phase schistosities and fold axes are related to the NW-verging and directed nappe structures. They have been formed during a progressive rotational deformation. The fourth phase folds and related fourth crenulation cleavage belong to the SW-verging Maggia and Verzasca cross-fold (Steck, 1984, 1987, 1990, Steck & Hunziker, 1994). The late San Carlo antiform, the Cristallina, Corno and Chièra F5-synforms and the Campo Tencia basin are related to the formation of the northern steep belt (Milnes 1974a, 1976, Etter 1986).

In Table 1 the data from this study are compared with the structural model proposed by Grujic & Mancktelow (1996). The observations of Steck (1984, 1990), Steck & Hunziker (1994) and new field work are consistent with the main types of deformational structures and the relationship between deformation and Barrovian metamorphism as proposed by Grujic & Mancktelow (1996). The fold-geometry of the different deformational phases is well documented with splendid out-

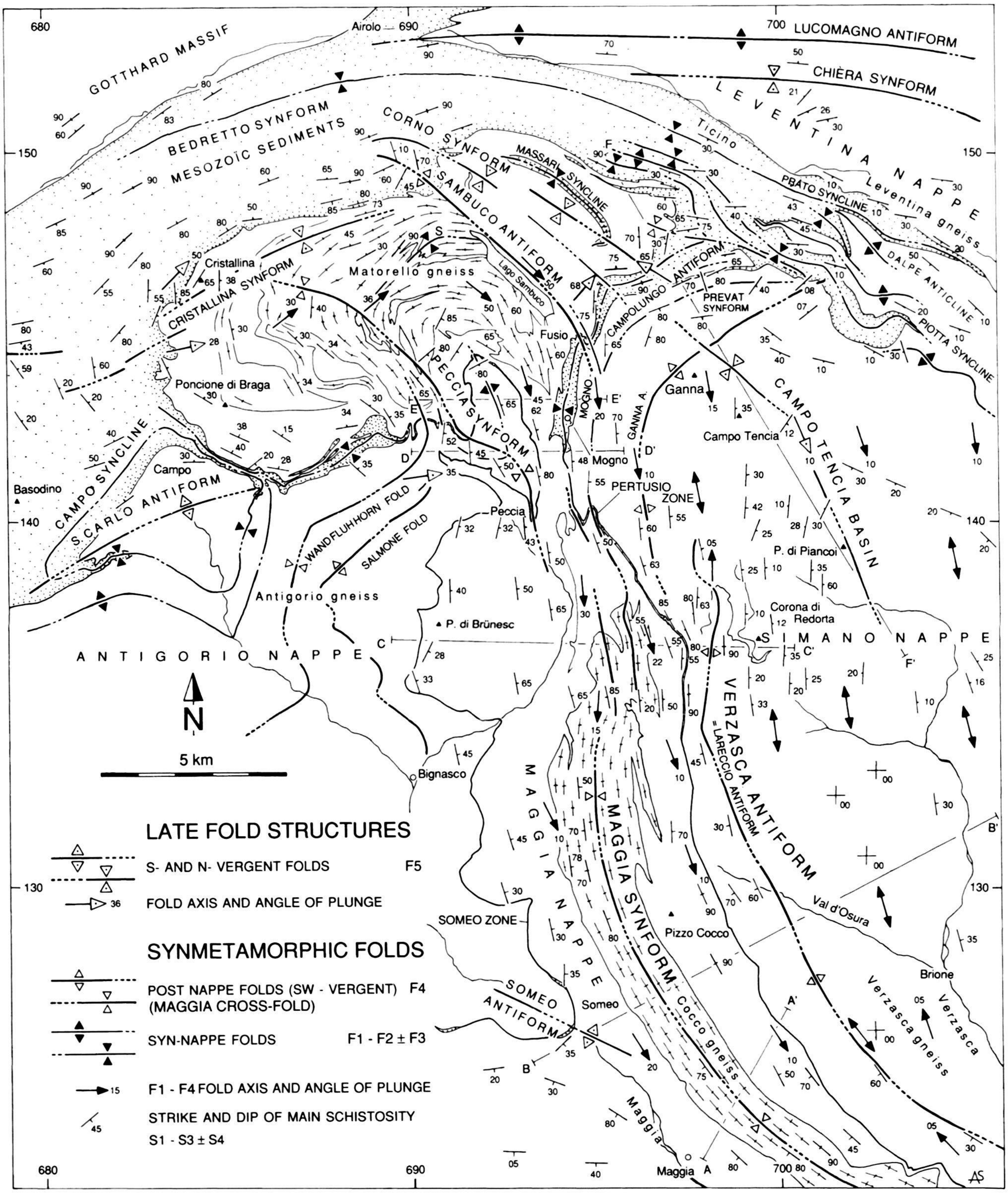

Fig. 2. Structural map of the Maggia–Verzasca cross-fold. This map is constructed using geological maps and publications of Preiswerk (1921), Grütter (1929), Preiswerk et al. (1934), Niggli et al. (1936), Wenk (1955), Burckhardt & Günthert (1957), Keller (1968), Spicher (1972), Hall (1972), Hafner at al. (1975), Keller et al. (1980), Huber et al. (1980), Huber (1981), Simpson (1982), Etter (1986), Merle & Le Gal (1988), Grujic & Mancktelow (1996) and completed by new observations and measurements. Profile traces AA' and BB' correspond to Fig. 4, profile traces CC', DD' and EE' to Fig. 3 and profile trace FF' correspons to Fig. 9 respectively.

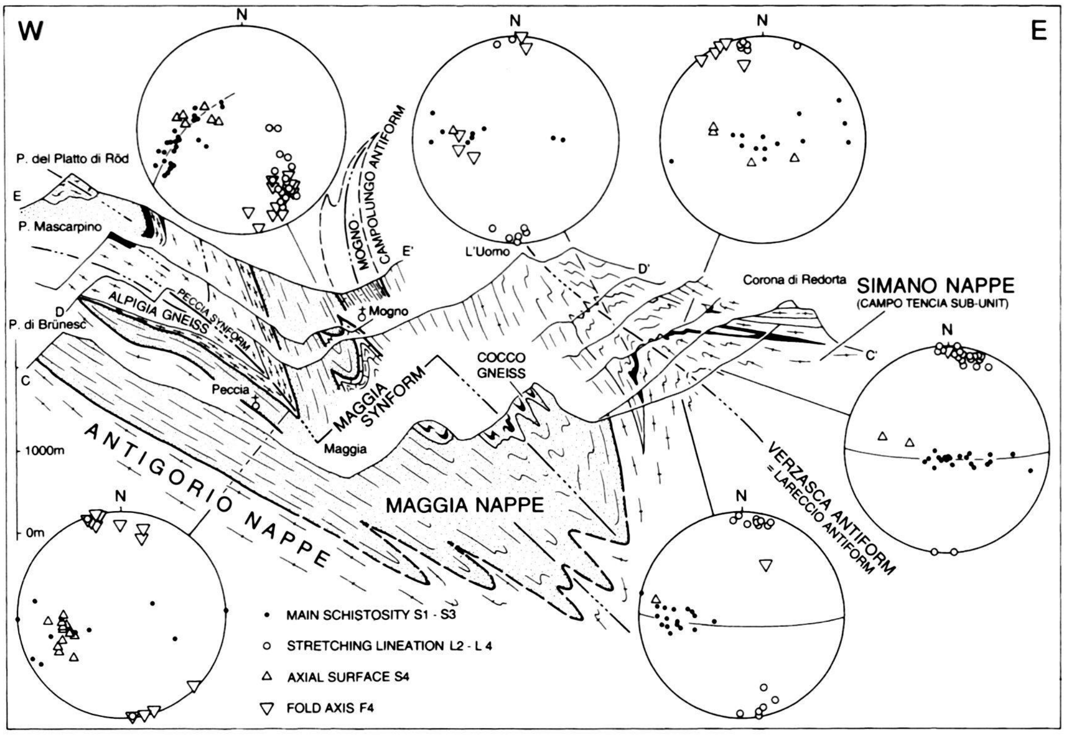

Fig. 3. E-oriented geological sections through the W-verging Maggia-Verzasca cross-fold. (Peccia–Corona di Redorta transect, profile traces CC', DD' and EE' on Fig. 2).

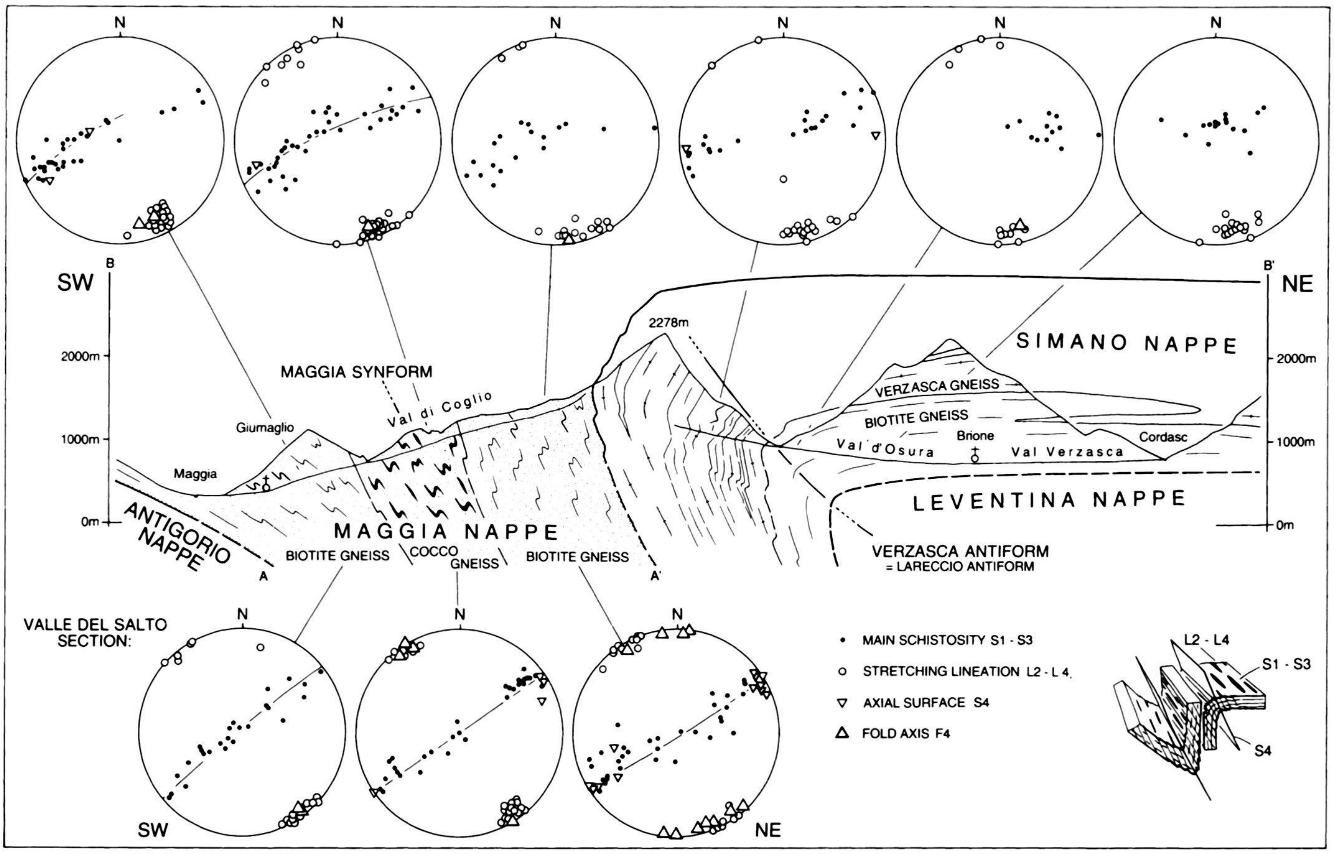

Fig. 4. NE-oriented geological section through the SW-verging Maggia-Verzasca cross-fold (Val di Coglio–Val d'Osura and Valle del Salto transects, profile traces AA' and BB' on Fig. 2).

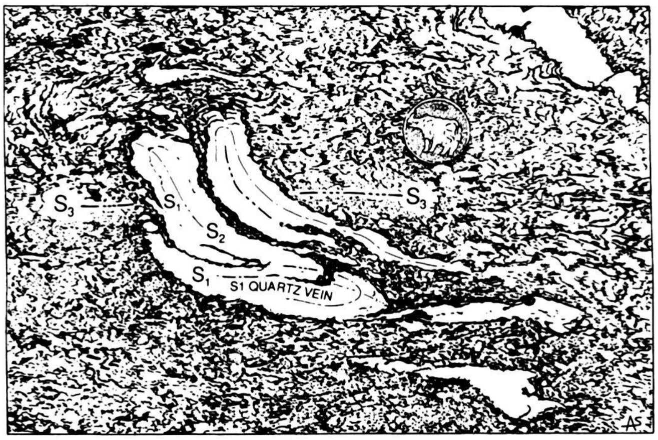

Fig. 5. The axial surface schistosity in the metapelites of the Prevat synform is a third schistosity. This main schistosity S3 is overprinting second phase isoclinal folds and schistosity S2 and first phase quartz veins parallel to S1. After Voll in Nabholz & Voll (1968), the formation of quartz veins in deformed Liassic metapelites of the Gotthard massif is related to a first phase of deformation and early dehydration reactions in the metamorphosed pelitic sediments.

crop photographs in publications by Huber et al. (1980), Simpson (1982) and Grujic & Mancktelow (1996). However, there are some important fundamental differences in the interpretation of the deformational structures in relation to the kinematics of nappe emplacement and folding. The formation of first phase folds and schistosity is not necessarily identical with the formation of a nappe structure as postulated by Milnes (1974a, b) and Grujic and Mancktelow (1996). In the Aar- and Gotthard massifs and in the Antigorio gneiss a first schistosity is concomitant with the overthrusting of higher sedimentary cover- and crystalline fold-nappes. The development of the Aar- and Gotthard massif basement folds and the recumbent Antigorio fold-nappe (Gerlach 1869, Milnes 1974a, Steck 1984) is younger; it started with the formation of a second axial surface schistosity S2 and F2-folds of the crystalline basement rocks. The second axial surface schistosity S2, of the deeper Antigorio recumbent fold is folding a first S1-schistosity and a second main S2-schistosity of the higher Lebendun nappe. Thus, in the Lebendun nappe the second schistosity of the Antigorio nappe becomes a third schistosity S3 of this nappe (figs. 4, 7 & 9 in Steck 1984, Steck 1987). A similar situation is observed in the frontal part of the Simano nappe in the Campolungo region, where the main schistosity is a third schistosity S3 (Fig. 5). The nappe emplacement occurred during a process of progressive rotational deformation in time and space generating successive phases of thrusting and folding by detachment of the upper European crust during its underthrusting below the Adriatic plate (Milnes 1974a, b, Huber 1981, Steck 1984, 1987, 1990, Voll in Nabholz & Voll, 1963: "Continued rotational deformation results in symmetry-constant repeated refolding and recleaving", definition of progressive deformation, see also: Flinn 1962, Ramsay, 1967). The ductile deformation and thrusting of the lower Penninic nappes occurred below a stack of higher Penninic and Austroalpine nappes during regional metamorphism at medium pressure and temperature (kyanite-sillimanite type) (Mesoalpine metamorphism, Steck & Hunziker 1994). The fact that the metamorphic isograds cut the nappe boundaries discordantly does not necessarily mean that a first phase of brittle nappe thrusting and stacking is followed by regional metamorphism and ductile post-nappe folding as proposed by Chatterjee (1961). The discordance of the isograds with the nappe boundaries may be interpreted in such that the metamorphic peak temperature outlasted nappe thrusting. The deformation started earlier in more internal parts of the subducted European crust and simply migrated progressively through more external parts (e.g. Hall 1972, Milnes 1976, Steck 1984, 1987, 1990, Grujic & Mancktelow 1996). In the Penninic nappes, the deformation started earlier in internal and higher tectonic units and for the same reason the latter often have more developed deformational structures. In the Aar–Ossola transect up to three schistosities and crenulation cleavages can be distinguished, related to nappe emplacement in a NW direction (Steck 1987, figs. 4 & 5, Escher et al. 1993). In addition, ductile calcschists intercalated between more competent gneiss layers sometimes show more deformational structures than the latter. That means that two to three generations of schistosities S1–S3 and folds F1–F3 have been created during Grujic & Mancktelow's (1996) deformational phases D1 and D2. It is also important to note that in the amphibolite facies grade gneisses and schists the distinction of 2 or 3 phases of schistosities and folds is often very difficult (Fig. 5).

Relations between metamorphic crystallization and deformation

The relationships between metamorphic crystallization and deformation suggest that nappe emplacement was simultaneous with prograde regional metamorphism. In the Maggia region this Tertiary metamorphism reached amphibolite facies conditions with kyanite-staurolite in metapelites, plagioclase – hornblende in metabasites and diopside – calcite mineral assemblages in metamorphic siliceous marbles some 38 Ma ago (Niggli & Niggli 1965; Wenk & Keller 1969; Hunziker 1969; Trommsdorff 1972; Klapper 1982; Steck & Hunziker 1994; Grujic & Mancktelow 1996). The crustal thickening related to underthrusting and nappe stacking may be responsible for the Barrovian type metamorphism (Niggli & Niggli 1965), and high temperature conditions were maintained until about 22 Ma, followed by rapid cooling (Hurford 1986, Steck & Hunziker 1994). A thermo-barometric study by Engi et al. (1995) suggests that a first regional metamorphism of Barrovian type with a temperature peak at 38 Ma (Hunziker 1969) is in the central and eastern part of the Lepontine region influenced by the later extrusion of deep seated hot tectonic units (Adula-Cimalunga nappe and Bergell magmatic body, of the latter some 32–28 Ma ago (von Blanckenburg 1992, Berger et al.

Tab. 2. Liste of amphibolite facies mineral assemblages which have crystallized during and after the F4 Maggia and Verzasca cross-folds (Fig. 6).

Sample No	Rock type	Mineral assemblage	Locality (location on topographical map)
AS9515	Alpigia gneiss	quartz-plagioclase(An 20-43) -biotite-hornblende	Sasso del Tiro (693.1/141.12)
AS9516	Alpigia gneiss	quartz-plagioclase(An 35-55) -hornblende-biotite	Sasso del Tiro (693.1/141.12)
AS9517	Cocco gneiss	quartz-oligoclase(An 24-27) -biotite	Valle di Coglio (696.9/126.85)
AS9518	Biotite gneiss	quartz-oligoclase(An 23-27, IZ) -biotite	Arnased, Val d'Osura (700.1/129.8)
AS9519	Biotite gneiss	quartz-oligoclase(An 17-23) -biotite-muscovite	Motto dei Mersc, Fusio (694.25/145.0)
AS9520	Biotite gneiss	quartz-oligoclase(An 20) -biotite-muscovite-garnet	Motto dei Mersc, Fusio (694.35/144.95)
AS9521	Granite gneiss	quartz-K-feldspar-oligoclase(An 24-33) -biotite-musc.	Valle di Pertüs (698.6/135.95)
AS9523	Granite gneiss	quartz-K-feldspar-oligoclase(An 22) -biotite-musc.-garnet	Valle di Pertüs (697.9/135.1)
AS9525	Mica schist	quartz-oligoclase(An23-26) -biotite-muscovite-garnet-staurolite-kyanite	Larecc (Lareccio fold) (697.85/138.25)
AS9527	Mica schist	quartz-oligoclase-biotite-muscovite-garnet-staurolite-kyanite	Larecc (Lareccio fold) (698.85/138.45)
AS9529	Amphibolite	quartz-plagioclase(An22-35, IZ) -hornblende-biotite-epidote-garnet	Larecc (Lareccio fold) (698.2/138.4)
AS9530	Biotite gneiss	quartz-plagioclase(An27-39) -biotite-epidote	Valle di Salto (698.65/124.35)

1996, Oberli et al. 1996, Schmid et al. 1996). The Maggia cross-fold (synform) has formed under amphibolite facies conditions. The amphibolite facies mineral assemblages which crystallized before and during the formation of the Maggia cross-folds are presented in Table 2 and Fig. 6. The Maggia cross-fold structures have been formed under amphibolite facies conditions with crystallization of staurolite and kyanite in mica schists and oligoclase-andesine in amphibolites and biotite gneisses, and not under greenschist facies conditions as proposed by Merle & Le Gal (1988) and Merle et al. (1989). Late subhorizontal greenschist facies shear zones, with top-to-the W shear sense are younger than the cross-folds and probably related to the top-to-the SW movements on the younger Rhone-Simplon Line farther to the W (Steck 1984, 1987, 1990, Hubbard & Mancktelow 1992, Mancktelow 1992, Steck & Hunziker 1994).

The Maggia cross-fold and the structural relations between the Maggia, Antigorio and Simano nappes

Fig. 2 is a structural map of the Maggia cross-fold integrating published structural data and new observations. The occurrence of the granodioritic Matorello and Cocco gneisses in a synformal position in the core and on top of biotite paragneisses of the Maggia unit is an important argument for the synformal position of this nappe on top of the deeper Antigorio and Simano units, as suggested on the tectonic map of Switzerland by Spicher (1972) and Figs. 2, 3, 4 & 7. The geometry of the Maggia–Verzasca cross-folds is illustrated in two geological sections on Figs. 3 and 4 and the block-sketch on Fig. 7. The Verzasca antiform and the Maggia synform belong to the same W-verging, S-shaped F4-fold, created under amphibolite facies conditions (Table 2). The geometry of the outcrop scale F4-folds, with an amphibolite facies axial surface crenulation cleavage, is the same in the Maggia synform and in the Verzasca antiform. An intense stretching lineation is oriented parallel to the cross-fold axis. The difference in fold style of the latter F4 folds is explained by the difference of the rheological behaviour of more competent granite gneisses compared to the more ductile mica schists. The main stretching lineation L4 results from the total synmetamorphic rock deformation (finite strain) related to the older nappe emplacement in a NW direction, followed by a last stretching parallel to the cross-fold axis. Interference patterns of different generations of stretching lineations may sometimes be recognized in fold hinges. The geometric relation between the Simano and Maggia nappes to the N of Peccia (Fig. 2, 3, 4 & 7) is difficult to understand. Grujic & Mancktelow (1996, fig. 11) suggest, from top to base, the following nappe stack:

Campo Tencia nappe
Campolungo synform of Mesozoic sediments
Maggia nappe
Someo– Campo syncline of Mesozoic sediments
Antigorio nappe.

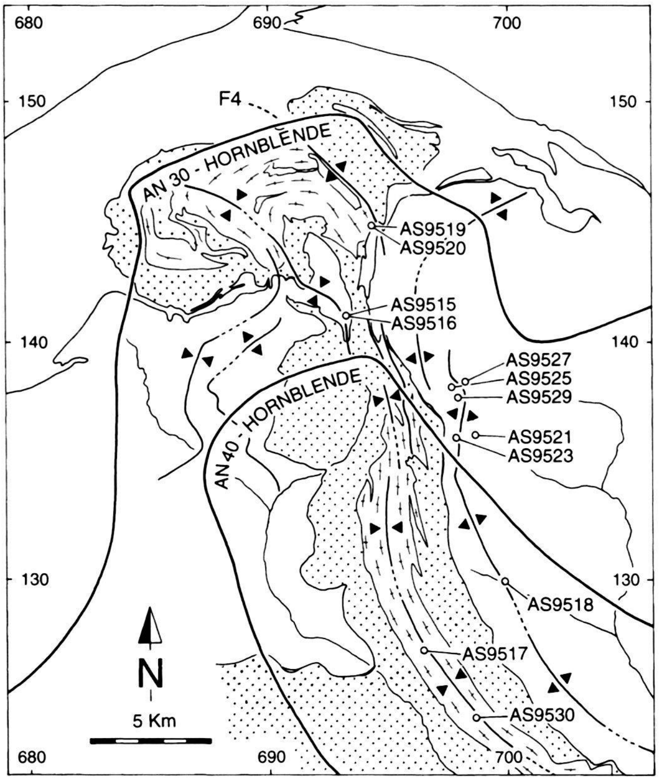

Fig. 6. Metamorphic map of the studied region showing the An 30- Hornblende in and An 40-Hornblende in lines or «isogrades» after Wenk & Keller (1969). The whole region lies in the amphibolite facies zone of the Central Alps, with oligoclase amphibolites to the N and andesine amphibolites to the S. The geometric relation btween the An 30 and An 40-Hornblende in isogrades, which form a symetric envelope of the Maggia cross-fold, is interpreted by Wenk and Keller (1969) as related to elevated heat flow parallel to the steep structures of the Maggia cross-fold. Following this interpretation, the Maggia cross-fold has been formed before or during amphibolite facies conditions. This conclusion is also confirmed by the mineral assemblages in F4 fold hinges (Nrs. AS9515–AS9530 and Table 2).

This model would imply that the Simano nappe is overthrusted during an early phase of nappe emplacement onto the Maggia nappe as postulated by Grujic and Mancktelow (1996). It would also implie a closure of the F1 fold to the N and a top-to-the S overthrust direction. This interpretation is incompatible with the fact that the root zone of the Penninic nappes is situated to the S and that the early overthrusting is directed to the NW. This model is also incompatible with the fold interference patterns of the geological map (Fig. 2). Based on new structural observations the following model is proposed here (Figs. 2 and 8).

On the structural map (Fig. 2), the Mogno-Campolungo fold of Mesozoic sediments is not identical with the Piotta syncline as proposed by Grujic & Mancktelow (1996, fig. 11). The Mogno-Campolungo fold is a syncline of Mesozoic sediments in a antiformal position separating an originally lower Simano nappe (Campo Tencia sub-unit) from a structurally higher Maggia nappe. This ~30° S-dipping antiform may be observed to the S of Mario Botta's chapel of Mogno (built in 1996) (Figs. 2 & 3). In the Valle Leventina, the Piotta syncline of Mesozic sediments separates the higher Simano nappe from a lower Dalpe anticline of the same nappe. Thus, the nappe stack before the formation of the Maggia cross-fold was from top to the base the following:

- Maggia nappe
- Someo syncline and Mogno-Campolungo-Pertusio synclines of Mesozoic sediments
- Antigorio-Simano nappe (or Antigorio and Simano nappes)
- Piotta syncline of Mesozoic sediments
- Dalpe anticline of the Simano nappe
- Prato syncline of Mesozoic sediments
- Leventina (– Lucomagno) nappe.

This interpretation means that the Ganna antiform, a northern branch of the Verzasca F4-fold (Fig. 2 and 8), is responsible for the rotation of the frontal Campo Tencia fold (Simano nappe front) from an original antiformal to its present synformal position. The P. del Prevat synform (Bianconi 1971, plate 3) is a second order F3-anticline of the Simano nappe front (Campo Tencia sub-unit) rotated together with the nappe front into a synformal position. The main axial surface schistosity of the Prevat fold is a third schistosity and not a second schistosity as proposed by Grujic & Mancktelow (1996). The first schistosity is recognizable by small quartz veins, and is later folded by a second and a third schistosity, the axial surface schistosity S3 of the Prevat synform (Figs. 5 and 8). Preiswerk (1919, fig. 1) proposed that a N-verging anticline in the Mesozoic sediments of the Campolungo region in front of the Campo Tencia (= Simano) nappe has been rotated into a S-dipping synformal structure ("überkippte Tauchfalte am Campolungopass"). In his Fig. 1 he draws also the Prevat synform, but without explanations.

Correlation between the Antigorio and Simano nappes

Following the proposition of Spicher (1972) on the tectonic map of Switzerland, the Antigorio nappe is laterally correlated with the Simano nappe (Figs. 3 & 4). This correlation is only based on the symmetric position of the two nappes on the two fold limbs of the Maggia synform. The two nappes are composed of different types of ortho- and para-gneisses and belong to one single or two different nappes. It is possible that the limit between the Antigorio gneiss and the Simano nappe represents a mechanically active limit that has guided the formation of the younger Maggia cross-fold at this place. Preiswerk (1921), in his cross-fold model, correlates the Antigorio gneiss with the Tessinergneiss (=Leventinagneiss). This means that the hinge of the Maggia syncline is squeezed between a lower Leventina and a higher Simano nappe. The geo-

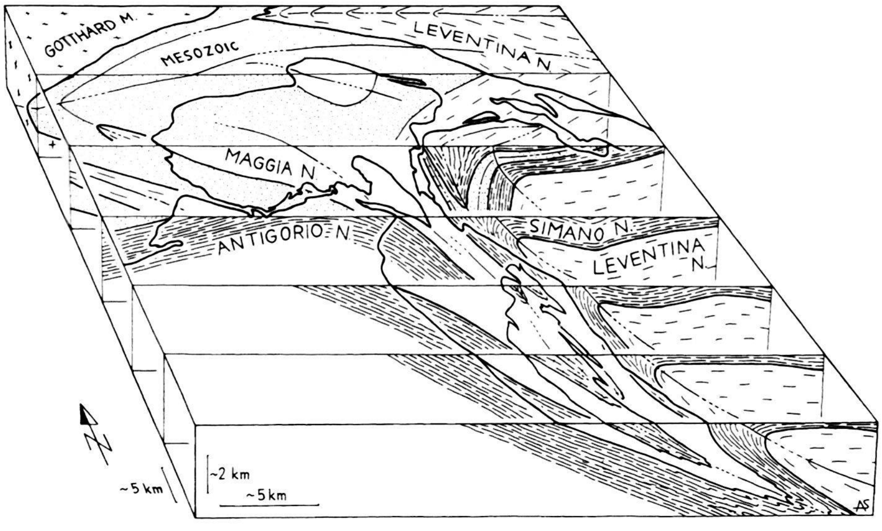

Fig. 7. Block-sketch of the Maggia-Verzasca cross-fold structure ("Maggialöffel" or "Maggia spoon"). The horizontal section represents a vertical projection of the nappe limits on geological map of Fig. 2. The sketch is not to scale.

metric construction of the geological profile in Fig. 4, based on new structural observations and measurements in the Val di Coglio–Val d'Osura section (Fig. 2), is inconsistent with this geometry.

Significance and age of the Maggia cross-fold in the deformation history of the Penninic nappes

The whole lower Penninic nappe stack of the Lepontine Alps (Fig. 1) is deformed by a succession of S to SW-verging recumbent folds like the S-verging Wandfluhhorn fold, an originally downwards closing fold later overturned in an antiformal position, the S-verging and origionally upwards-closing Ziccher – Salmone antiform (Ziccher antiform, Schärer et al. 1996) and the W to SW-verging and origionally downwards closing Maggia synform (= Maggia cross-fold) (Huber 1981, = early S-verging folding in Steck 1990 and Steck & Hunziker 1994). All these F4-folds have been formed under amphibolite facies conditions, and a well-developped stretching lineation is oriented parallel to the cross-fold axis. In this interpretation, the Maggia nappe and the Bosco-Isorno-Orselina units may be interpreted as nappe structures situated in a similar tectonic position or representing lateral equivalent units (Fig. 1). The stretching lineation L4 has been formed by transposition and further stretching of older SE oriented L1–L3 stretching lineations, the latter related to the nappe transport in a NW direction. Interference patterns of stretching lineations of different ages may some times be observed in hinges of isoclinal folds, where older lineations are refolded around the fold hinges and become parallel to the fold axes of the fold limbs because of the younger stretching. The isoclinal backfolding is younger than the ~40–35 Ma old nappe emplacement and older than the ~35–30 Ma old ductile Simplon shear zone and the 29–26 Ma old pegmatitic dikes of the Locarno–Domodossola steep belt (Romer et al. 1996, Schärer et al. 1996). In this southern steep belt (Milnes 1974b), the Ziccher – Salmone antiform is overprinted by the > 30 Ma old amphibolite facies dextral shear of the ductile Simplon shear zone (Steck 1990, Steck & Hunziker 1994), creating the Masera fold structure in the southern steep belt (Masera sheath fold on Fig. 1). I suggest that the Masera fold is a fold interference pattern, that has been strongly

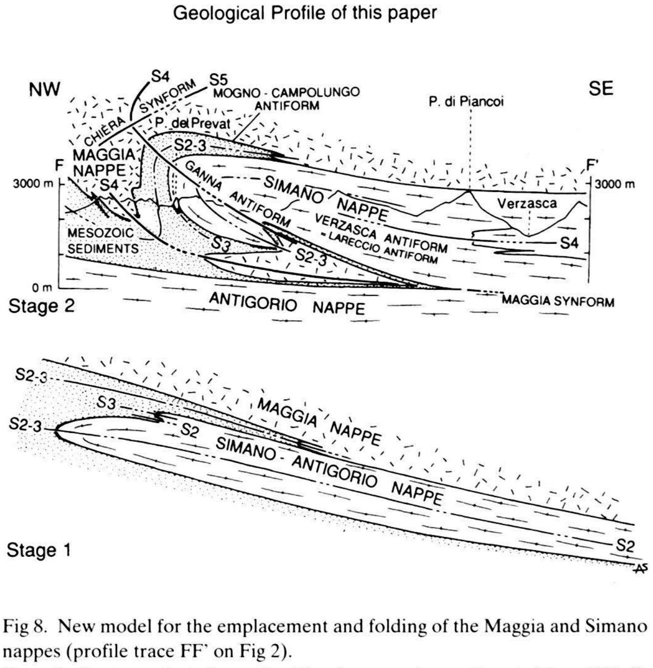

Fig 8. New model for the emplacement and folding of the Maggia and Simano nappes (profile trace FF' on Fig 2).

Stage 1: During a first phase, the Maggia nappe is overthrusted in a NW direction on the Simano and Antigorio recumbent fold nappes (Simano - Antigorio nappe). A second schistosity is the axial surface structure. Third schistosities are developed in the nappe front and the more ductile Mesozoic calcschists during a process of progressive rotational deformation. The axial surface schistosity of the Prevat fold is a third schistosity (Fig. 5).

Stage 2: In a fourth phase of deformation the entire nappe stack is refolded by the W-verging Ganna-Verzasca and Maggia F4-folds.

stretched in a western direction within the ductile dextral Simplon shear zone, creating a sheath fold structure (Cobbold & Quinquis 1980) (or sheath fold-like structure) of which the upper part is actually missing by erosion. The Vanzone and Cressim antiforms of the Insubric phase of Argand (1916) are younger than the cross-folds; they are folding the latter. They have been created during a strong uplift and a later S-directed back thrusting of the Lepontine Alps. The Vanzone backfold is younger than the early movements on the ductile Simplon shear zone. These backfolds are dated by the strong relative uplift of the Lepontine Alps along the Insubric Line some 30 Ma ago (Hurford 1986, Schmid et al. 1989, Steck & Hunziker 1994), during and after the 32–28 Ma old Bergell extrusion (von Blanckenburg 1992, Berger et al. 1996).

Conclusions

New observations in the Lepontine Alps confirm the interpretations of Preiswerk (1921) and Spicher (1972) that the Maggia cross-fold is a synformal structure on top of the Antigorio-Simano nappe. The Maggia cross-fold (synform) has been created together with the Wandfluhhorn fold (syncline in an antiformal position) and the Ziccher-Salmone antiform. These structures are folding the whole recumbent fold nappe stack of the Lepontine Alps after the main nappe emplacement in a NW direction. The SW-vergence of the cross-folds suggests an early ductile overthrusting of higher tectonic units in a SW direction. The SW-verging folding occurred under amphibolite facies conditions between the thermal peak of the Mesoalpine Barrovian type regional metamorphism some 38 Ma ago (Hunziker 1969) and before the early movements on the dextral Simplon shear zone earlier than 30 Ma and before the 32 - 28 Ma old magmatic activity along the Insubric line (von Blanckenburg 1992, Steck & Hunziker 1994, Berger et al. 1996, Schärer et al. 1996). Late top-to-the W directed overthrust shear movements under greenschist facies conditions may be related to the SW-directed normal shear on the Rhone-Simplon line of the Simplon region.

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