Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 75 (1982)

Heft: 3

Artikel: The structure of the northern lobe of the Maggia Nappe, Ticino, Switzerland

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DOI: https://doi.org/10.5169/seals-165240

Eclogae Helv. geol.	Vol. 75/3	Pages 495-516	10 figures in the text and 3 plates	Basle, November 1982

The structure of the northern lobe of the Maggia Nappe, Ticino, Switzerland

By CAROL SIMPSON[1])

ABSTRACT

Deformation in zones of ductile shear has played a dominant role in the formation of the structure of the Maggia Nappe in the Lower Pennine zone of the Central Swiss Alps. Four main phases of deformation have been identified.

Relatively undeformed, late-Hercynian granitoids were deformed into lineated gneiss, and foliated and compositionally banded gneiss within Alpine shear zones during nappe emplacement. One major phase of tight folding and a later, locally developed crenulation fold phase followed, during which all fold hinges were initiated, and have since remained, subparallel to the earlier stretching lineation. A thermal metamorphic event (the Lepontine metamorphism) reached a maximum of lower amphibolite facies conditions before the onset of a regional backfolding phase of deformation. The formation of the Maggia "steep-zone" was probably synchronous with the backfolding phase.

ZUSAMMENFASSUNG

Die Detailkartierung im Kern der Maggia-Decke, einer unterpenninischen Kristallindecke in den lepontinischen Alpen, erlaubte die Kinematik der Verformung als heterogene einfache Scherung (simple shear) zu beschreiben. Praktisch undeformierte, spätherzynische granitoide Intrusiva im Kern der Decke führen Xenolithen und aplitische Gänge, welche als Indikatoren zur Abschätzung von Verformungs- und Verschiebungsbeträgen im Kern und in den frontalen Deckenteilen dienen. Innerhalb von alpinen duktilen Scherzonen wurden diese Intrusiva zu geschieferten und gebänderten Gneisen deformiert. Diese Vergneisung ist die älteste beobachtete Deformation im Untersuchungsgebiet und wird mit der Platznahme der Decken in Zusammenhang gebracht. Scherzonen mit gleichem Verschiebungssinn umschliessen rhomboederförmige, relativ schwach deformierte Blöcke.

Danach folgen eine weitere wichtige Faltungsphase, welche enge Falten produzierte, sowie eine spätere (nur lokal ausgebildete) Krenulationsphase. Alle Faltenumbiegungen sind subparallel zu den alten Streckungslineationen angelegt worden und in dieser Orientierung geblieben. Ein thermisches Ereignis führte in den Maggia-Gneisen zum Höhepunkt der Metamorphose (in der unteren Amphibolit-Fazies), bevor die regionale Rückfaltungsphase einsetzte. Synchron zu dieser letzten Rückfaltungsphase dürfte die Ausbildung der «Maggia-Querzone» sein.

RIASSUNTO

La deformazione in zone di taglio duttile ha svolto un ruolo dominante nel determinare la struttura della falda della Maggia (Penninico inferiore, Alpi della Svizzera centrale). Quatro fasi principali di deformazione sono state riconosciute.

In una prima fase, durante la messa in posto della falda, nelle zone di taglio di età alpina, granitoidi tardo-ercinici con debole deformazione pre-alpina, sono stati deformati in gneiss caratterizzati da una marcata lineazione e in gneiss a bande fortemente scistosi. È seguita poi la fase principale caratterizzata

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da pieghe strette e, successivamente, una fase caratterizzata da crenulazione sviluppata solo localmente, durante la quale le cerniere delle pieghe si sono iniziate con orientazione subparallela alla preesistente lineazione di stiramento. Tale orientazione persiste tuttora. Il culmine del metamorfismo (metamorfismo lepontino, facies anfibolitica di basso grado) fu raggiunto prima del sorgere della fase di retropiegamento. La formazione della zona raddrizzata nella falda della Maggia è stata probabilmente sincrona con la fase di retropiegamento.

CONTENTS

Introduction

An area in the northern part of the Maggia Nappe, a lower Pennine crystalline basement nappe of the Lepontine Alps in southern Switzerland, was chosen for detailed study of the relationships among shear zones, large scale shape changes in the rock mass and nappe emplacement. Excellent glaciated outcrop surfaces allowed mapping on various scales from 1:10 to 1:10,000 in order to establish the regional geometry and variations in finite strain. Granitoid rocks of probable late-Hercynian age (Köppel et al. 1981) have been deformed predominantly by ductile shearing during the Alpine orogeny (Ayrton & Ramsay 1974, Huber et al. 1980). These rocks contain strain markers in the form of basic xenoliths and aplite dykes and show a wide spectrum of deformation intensity, from essentially undeformed to highly strained within ductile shear zones.

A comprehensive review of the geometrical properties of shear zones has been presented by Ramsay (1980). Shear zones are examples of inhomogeneous deformation (Ramsay & Graham 1970). They form when it becomes energetically more favorable to concentrate the deformation in relatively narrow zones within virtually undeformed host rock. In ductile shear zones, the differential displacement of the walls is entirely accomplished by ductile flow, i.e. the shear strain, γ, is always finite and variations in γ are continuous across the zone. Any marker layers present in the undeformed rock (e.g. dykes and veins) are deflected through the shear zone but remain unbroken (Ramsay & Graham 1970, Ramsay 1980).

This paper describes the relationships between shear zones and the structure of the northern lobe of the Maggia Nappe. Mapping on a scale of 1:10,000 was carried out utilizing photographic enlargements of existing 1:25,000 Swiss Federal topographic maps. Areas of relatively low deformation were mapped on scales of 1:10 to 1:50 by using a one meter square grid marked off into 10 cm units. Microstructural, grain aggregate shape, and mesoscopic shape changes across the shear zone boundaries are presented elsewhere (SIMPSON, in press).

General geological setting

The Lepontine Alps of southern Switzerland comprise north-closing fold anticlines, characterized by cores of pre-Triassic basement metamorphic complexes with envelopes of calcareous Mesozoic cover rocks (Fig. 1). The two groups of rocks show polyphase penetrative deformation and metamorphism of Alpine age (HEIM 1922, HIGGINS 1964, RAMSAY & GRAHAM 1970, AYRTON & RAMSAY 1974, MILNES 1974).

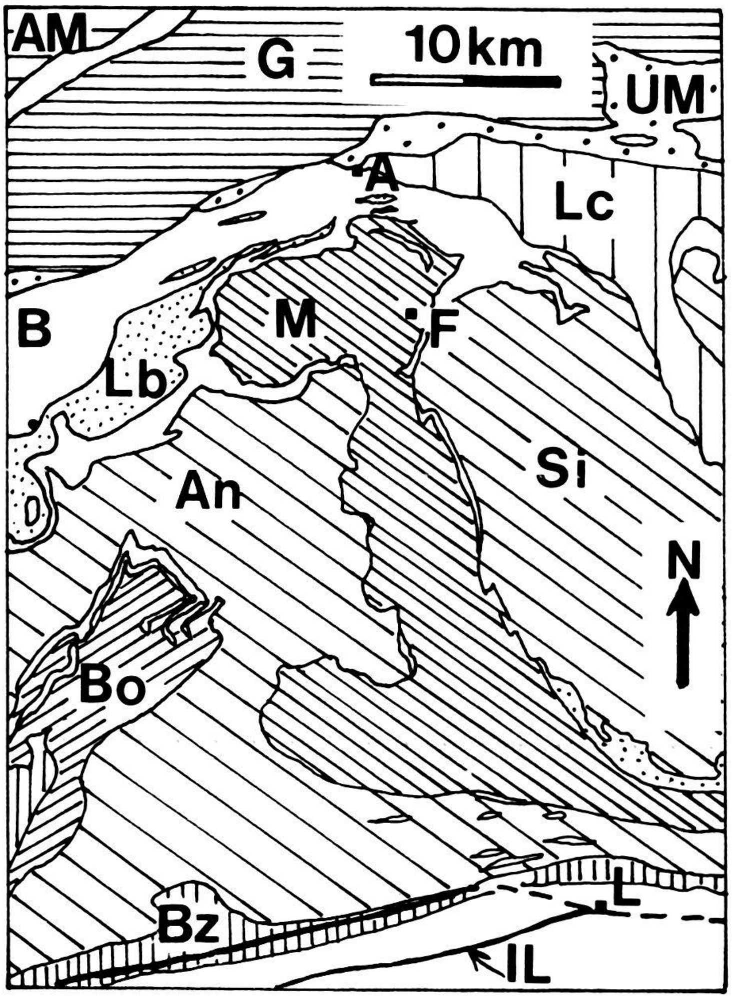

Fig. 1. The Lower Pennine nappes and external massifs in the Aar-Ticino Culmination of the Central Swiss Alps (after: Tektonische Karte der Schweiz).

A = Airolo, F = Fusio, L = Locarno. AM = Aar massif, UM = Ultrahelvetic Malm, B = Bündnerschiefer. Subpenninic complex comprises: G = Gotthard massif, Lc = Lucomagno Nappe, and Si = Simano-Campo-Tencio Nappe. Penninic basement complex comprises: M = Maggia Nappe, Lb = Lebendun Nappe, An = Antigorio Nappe, and Bo = Bosco Nappe. Bz = Bellinzona zone and IL = Insubric Line.

The Penninic zone lies structurally south of the external massifs and the Helvetic cover nappes, which contain Mesozoic and Tertiary shelf sediments from the northern continental margin, and north of the Austroalpine zone, which contains Mesozoic and Tertiary sediments and basement from the southern continental margin (TRÜMPY 1960).

The Maggia Nappe is one of the Lower Pennine nappes which are exposed in the broad region of uplift of the Aar–Ticino Culmination (Fig. 1). Within this Culmination zone, Barrovian metamorphic mineral assemblages of lower amphibolite facies occur in the metasedimentary cover rocks of the Maggia Nappe (BEARTH 1958, WENK 1962, EVANS & TROMMSDORFF 1970). The grade of metamorphism increases to the south, reaches a maximum of upper amphibolite facies near the Insubric line, and falls off to the east and west of the Culmination (NIGGLI 1960, NIGGLI & NIGGLI 1965).

Previous work in the study area

The Aar–Ticino Culmination zone has been the subject of a number of detailed structural and metamorphic investigations. PREISWERK (1918) produced the first 1:50,000 geological map of the frontal part of the Maggia Nappe; the tight synforms of Mesozoic rocks between north-closing lobes of crystalline basement were used to separate the crystalline nappe cores. Following this work, a number of tectonic interpretations were put forward by various authors over the next 18 years and these are summarized in NIGGLI et al. (1936). On more recently published geological and structural maps of the Maggia Nappe, mineral lineations and fold hinges were shown to be parallel to each other and to cross nappe boundaries without change in orientation, although no indication of the relative ages of the linear features was given (GÜNTHERT 1954, WENK 1955, 1962).

From 1960 onwards, several workers have concentrated on trying to establish the relationships among the different phases of deformation and metamorphism in the Lower Pennine nappes (HIGGINS 1964, CHADWICK 1968, HALL 1972, THAKUR 1973). Summaries of these works and the regional structural relationships in the Pennine zone are given by THAKUR (1973), AYRTON & RAMSAY (1974) and MILNES (1974).

The earliest Alpine thermal events have been dated at 125 ± 20 MY in the Monta Rosa Nappe by HUNZIKER (1969, 1970). These dates have been correlated with the main nappe-forming event by THAKUR (1973) who suggested that the first deformation phase in the Lower Pennine zone involved the formation of fold and thrust nappes, a hypothesis supported by the findings of HIGGINS (1964) and HALL (1972). AYRTON & RAMSAY (1974) considered that over much of the Lower Pennine region, the major structures have been produced during three main phases of deformation. These authors suggested that gravitationally controlled mechanisms operated in many cases of nappe formation during the first deformation phase. Three main phases of deformation were also recognized by HALL (1972) in the Antigorio Nappe, although HIGGINS (1964) recognized four deformation phases in the nearby Lebendun Nappe. In both areas, the peak of the Alpine metamorphism postdated the production and isoclinal refolding of the main fold nappes, and preceeded the last phase of deformation during which large backfolds were formed and a considerable amount of crustal shortening and thickening of the nappe pile occurred (HIGGINS 1964, HALL 1972, AYRTON & RAMSAY 1974).

Metamorphic isograd surfaces have been shown to cut across the nappe boundaries (BEARTH 1958, WENK 1962, EVANS & TROMMSDORFF 1970). A thermal maximum at 35-38 MY in the Monte Rosa Region was suggested by JÄGER (1973) on the basis of a $500 \pm 50\,°C$ blocking temperature for Rb/Sr in muscovites. A distribution of U/Pb ages in monazite and xenotime samples from the Lepontine region was taken to indicate mineral formation ages (i.e. the peak of the metamorphic event) between 20 MY and 30 MY (± 0.5 MY) (KÖPPEL & GRÜNENFELDER 1975). The lowest ages (20-21 MY) were given by the deepest units (the Leventina gneiss), with ages increasing to 22-23 MY in the higher units to the west and to 30 MY in the east. Samples from near the village of Fusio, in the area mapped as part of the present study, gave a mineral formation age of 22.4 ± 0.5 MY (KÖPPEL & GRÜNENFELDER 1975).

WERNER (1980) reconciled the apparent inconsistency of the radiometric ages by illustrating how a thermal maximum at 38 MY in the Monte Rosa region and at 23 MY in the Maggia region could be caused by different rates of uplift in the different regions. He pointed out that there most probably was not a thermal equilibrium over the entire Lower Pennine zone.

Although the main porphyroblast growth occurred during the Alpine thermal peak, before the backfolding phase of deformation, in some localities recrystallization persisted after this deformation phase (HIGGINS 1964, HALL 1972, AYRTON & RAMSAY 1974, HUBER et al. 1980).

In the following sections of this paper, the lithological units, metamorphic and structural history, and the relationship of ductile shear zones to the structure of the Maggia Nappe are discussed.

The lithological units of the Maggia Nappe

Three main lithological units are distinguished in the Maggia Nappe:
- metasedimentary rocks of probable pre-Hercynian age (KÖPPEL et al. 1981),
- intrusive granitic rocks of probable late-Hercynian age (KÖPPEL et al. 1981),
- Mesozoic marbles and calcareous schists (Bündnerschiefer).

Their distribution is shown in the sketch map, Figure 2.

1. Metasediments of probable pre-Hercynian age

Bands of noncalcareous paragneiss and schist occur throughout the crystalline core of the Maggia Nappe but are most prominently developed at the northern and southern boundaries of the area mapped, and in the region of Pizzo Sciresa in the center of the structure (Fig. 2). The metasediments comprise a very wide variety of rock types of which the most important are garnet-biotite schists, garnet-kyanite-staurolite-biotite schists, biotite-garnet-tourmaline schists and gneisses, banded amphibolite and biotite rich gneisses and biotite-muscovite schists. GÜNTHERT (1954) and GÜNTHERT et al. (1976) have made detailed petrographical and chemical

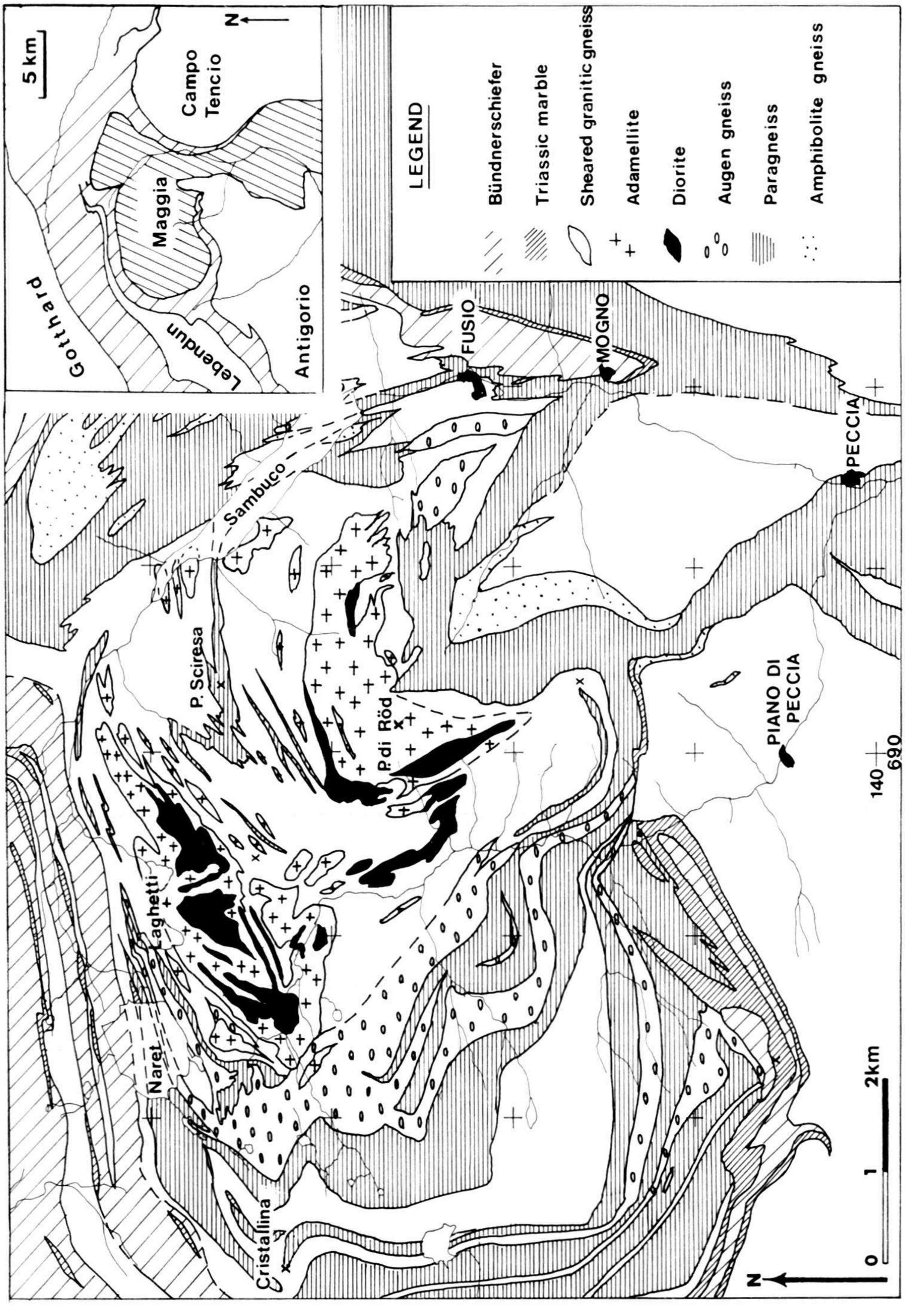

Fig. 2. Lithological sketch map of the northern lobe of the Maggia Nappe, Ticino. Inset: tectonic setting of the Maggia Nappe, wide spaced ruling is Bündnerschiefer, narrow spaced ruling is the Maggia Nappe.

analyses of each rock type, the sedimentary origin of the rocks being confirmed by the high aluminum content and undoubted detrital character of rounded zircon grains. The detrital zircons gave U/Pb primary crystallization ages of about 2000 MY and lead loss ages of about 35 MY (Köppel et al. 1981). Idiomorphic zircons in these rocks gave Caledonian as well as Hercynian U/Pb ages and were interpreted as indicating two periods of sedimentation, one pre-Caledonian and one between the Caledonian and Hercynian metamorphic events (Köppel et al. 1981).

The pre-intrusive metasediments display the most intense deformation of any of the rock types in the area. It was not generally possible to distinguish between the effects of the Alpine deformation and any earlier, remnant Hercynian fabric in these rocks, although in one locality near Lago Naret early folds in the paragneiss are cut by a basic lamprophyre dyke of probable late-Hercynian age. Foliation in the more massive rocks is defined by the alignment of biotite and muscovite flakes and by platy aggregates of quartz and feldspar grains. The micas help to define a mineral elongation lineation that is everywhere parallel to the hinges of intrafolial folds.

2. *Orthogneisses*

The predominant lithological units in the area mapped comprise granitic, dioritic and granodioritic rocks which in the core of the nappe still show their original intrusive relationships (Ramsay & Graham 1970, Ramsay & Allison 1979); at least two generations of aplites, mafic and felsic quartz-mica microdiorites and lamprophyres, and "composite"mafic/felsic quartz microdiorites which cut both the massive igneous rocks and the earlier paragneisses (Ramsay & Allison 1979); augen gneisses with K-feldspar augen of about 1 cm diameter; augen gneisses with average augen size of about 5 cm; and compositionally banded muscovite- and biotite-rich gneisses which are derived from the magmatic rocks. Günthert et al. (1976) have given the petrographic and chemical characteristics of the individual rock types.

Planar elements are weakly developed in the most part of the massive granitoids but become intense in the vicinity of ductile shear zones (Simpson, in press). The compositionally banded muscovite- and biotite-rich gneisses and the small-augen gneisses occur within these zones of high deformation. Micaceous minerals and platy aggregates of quartz and feldspar grains define a foliation in rocks with a fairly homogenous mineralogy, while in the more heterogeneous rock types, alternating bands of aplitic, lamprophyric, granitic/granodioritic and sometimes biotite-rich microdioritic rocks define a compositional banding which is usually parallel to the micaceous foliation planes. Isoclinal folding of the compositional banding is rarely seen. The development of these foliated and compositionally banded gneisses by the deformation of essentially isotropic igneous rock within zones of ductile shear is treated more fully elsewhere (Simpson, in press).

3. *Mesozoic cover rocks*

Calcite and dolomite marbles occur as almost continuous mappable units within the boundary zone between the crystalline nappe core and the calcareous schists and gneisses of the Bündnerschiefer cover rocks. The original sedimentary sequence has been shown elsewhere to be basement overlain by marble, in turn overlain by Bündnerschiefer (PREISWERK 1918, ARGAND 1934). At the northern boundary of the Maggia Nappe, by Lago Naret, marbles occur in isolated lenses and pods within the muscovite-rich foliated gneisses and the pre-intrusive paragneisses of the basement. Along the main nappe boundary which runs through Lago Naret, the distinctive garnet-kyanite-calcite bearing schists of the Bündnerschiefer have foliation planes subparallel to those in the orthogneisses of the basement. Thin, discontinuous bands of Bündnerschiefer are also found for a distance of 100 m to 150 m south of this boundary.

A mineral elongation lineation of micas and quartz rods in the Bündnerschiefer of the northern nappe boundary is always subparallel to the dominant mineral lineation in the adjacent basement gneisses.

To the northeast of the village of Fusio, a discordant contact between basement and Bündnerschiefer is preserved, despite considerable overprinting by a subvertical, north-south oriented foliation. No unambiguous evidence was found which would support either an original sedimentary or a tectonic origin for this discordance.

Structural history of the Maggia Nappe

1. Pre-Alpine history

Zircon U/Pb ages for detrital and idiomorphic grains in the paragneisses of the Maggia basement indicate two periods of sedimentation before the Hercynian metamorphic event (KÖPPEL et al. 1981). The granitoid suite was then emplaced into the metasediments in late-Hercynian times (KÖPPEL et al. 1981). The first magmatic rock to be intruded was diorite, followed by a suite of granitic, granodioritic and adamellitic rocks (RAMSAY & ALLISON 1979). Diorite xenoliths up to two meters in diameter occur in quantities at the contact with the granitic rocks. The massive igneous rocks were cut by at least two generations of aplite dykes, followed by a suite of "composite" mafic/felsic dykes. The youngest intrusive rocks in this region are a swarm of mafic lamprophyre dykes. No evidence for any large scale, pre-Alpine deformation was found in the magmatic rocks (RAMSAY & GRAHAM 1970, RAMSAY & ALLISON 1979).

Following these late-Hercynian intrusive events came a period of tectonic quiescence in the region, followed by uplift, erosion and the deposition of Triassic dolomites and limestones and Mesozoic calcareous and silty shales, now present as the Bündnerschiefer. Tectonic burial of the sedimentary pile followed at the onset of the Alpine orogeny. Later metamorphism has obscured the effects of this early burial but the rocks of the Maggia region were probably buried to a depth of about 10 km, sufficient to allow both the basement and cover rocks to deform in a ductile manner.

2. Alpine deformation

The Alpine deformation in the northern part of the Maggia Nappe can be divided into four geometrically separate phases. To assist in the structural analysis of the region a number of domains have been selected, within each of which the structures have more or less the same geometric styles and the same spatial orientations. HUBER et al. (1980) have recognized three main Alpine deformation phases in the region; the evidence from the area of the Maggia Nappe mapped indicates four phases and these are now described.

a) Deformation phase A_1

The earliest Alpine deformation structure observed is a strong mineral elongation lineation, AL_1 which is almost all-pervasive throughout the igneous rocks in the area mapped. This lineation is parallel to the long axes of deformed xenoliths and is defined by ellipsoidal aggregates of biotite and quartz. Locally, this linear fabric shows a variation in orientation where the pre-Alpine dykes are deflected into shear zones. At the shear zone boundaries a new, dominantly planar, weakly linear fabric (AS_1) is developed (Fig. 3). The lineation is modified so that it coincides with the maximum finite elongation direction, X_f (RAMSAY & GRAHAM 1970). Consequently, the mineral lineation outside a shear zone may have an orientation within a few degrees of, or at a high angle to, that inside the shear zone.

Although the linear fabric represents the total finite strain in a region which has undergone four phases of deformation, it is most strongly developed in areas of low deformation; areas which have a weak planar anisotropy and are crossed by discrete narrow shear zones (RAMSAY & ALLISON 1979). This strong development of a

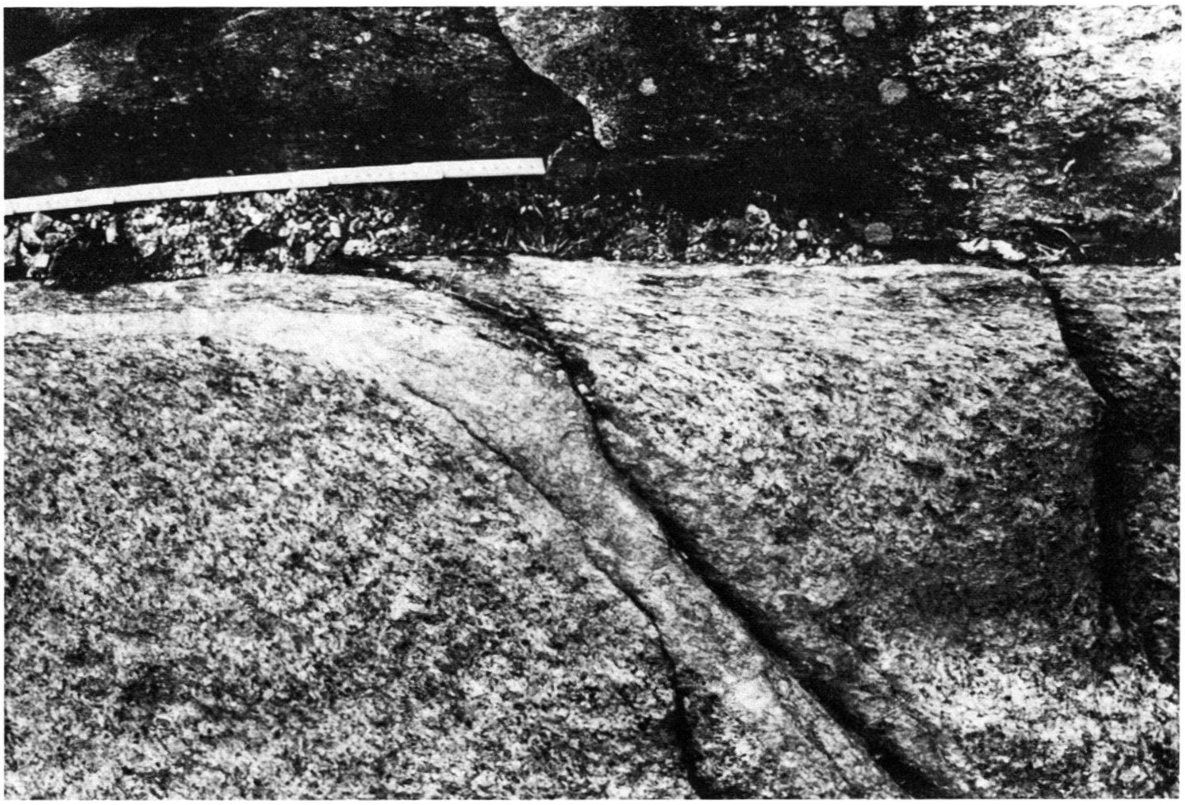

Fig. 3. A pre-Alpine aplite dyke deflected into an Alpine shear zone. Note the development of a new planar fabric within the shear zone.

stretching lineation in low deformation areas and the weakening and modification in orientation of this lineation in shear zones, suggests that the linear fabric was developed during the earliest Alpine deformation phase, although its orientation was probably modified during the later deformation events.

Regionally the finite stretching lineation in the basement is parallel to that in the Mesozoic cover rocks (Pl. 1). There is also a trend towards parellelism between the orientation of the mineral elongation lineation in the unsheared and sheared gneisses, which again suggests that the formation of all these structures was closely related in time. Ramsay & Allison (1979) show that the directions of maximum elongation are approximately subperpendicular to the poles to schistosity planes in the shear zones and also conclude that the linear fabric is probably related to the shear zone formation.

Figure 4 shows a sketch map of part of the Maggia Nappe with the trends and displacement senses of the major shear zones. These zones are all steeply dipping or vertical. Close to the northern and southern nappe boundaries, the predominant shear sense is sinistral, whereas in the central part of the structure and in the region of Passo di Sasso Nero, both sinistral and dextral sets occur with a tendency for shear zones of one displacement sense to be grouped together. For example, in the region north of Pizzo di Röd the rock is practically undeformed, but the few narrow shear zones which do occur all have a dextral sense of displacement. Only rarely are conjugate sets of right- and left-lateral shear zones observed together. However, a

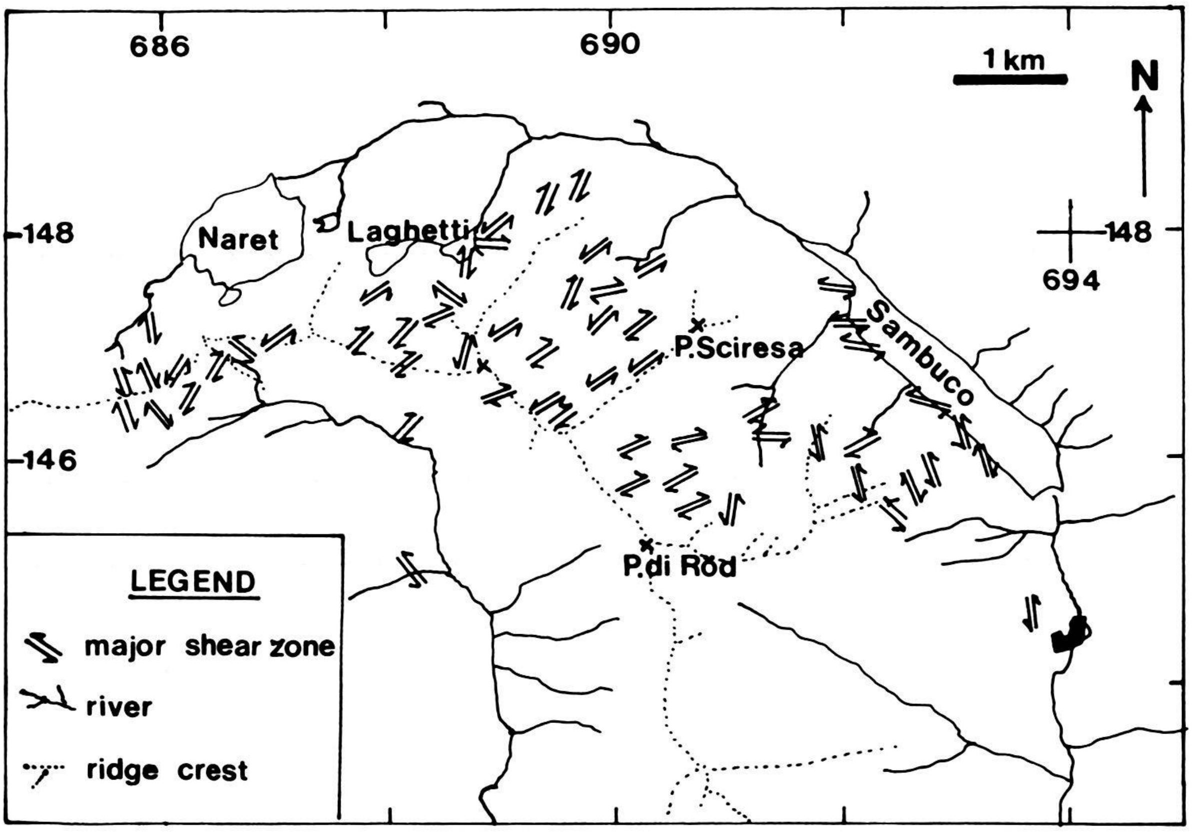

Fig. 4. Trends and displacement senses of the major shear zones in the Maggia Nappe. All the shear zones are steeply dipping or vertical.

group of shear zones of one displacement sense forms a conjugate set with a group of the opposite sense of displacement.

Large shear zones with the same displacement sense show an anastomosing pattern to surround remnant pods or lenses of relatively undeformed rock (SIMPSON 1981). The shear zones become progressively wider and subparallel to each other as the remnant pods become smaller and fewer in number. Wherever possible the sense of displacement at the margins of the pods was estimated using the curvature of the new foliation or the deflection of pre-Alpine dykes and xenoliths across the shear zone boundary (RAMSAY & GRAHAM 1970). Other methods employed to estimate displacement sense include the use of asymmetric augen structures, asymmetric pressure shadows and displaced broken grains.

A small area of tightly infolded pre-Triassic paragneiss occurs within the foliated orthogneiss in the region of Pizzo Sciresa (Fig. 2). The infolding of the paragneiss may have been synchronous with the pre-Triassic intrusions, or it could have occurred during the earliest Alpine deformation event. The total deformation in these rocks has obliterated any evidence for original intrusive relationships.

b) Deformation phase A_2

The paragneisses which outcrop on Pizzo Sciresa are refolded into a large, upright, tight synform, AF_2, and are flanked by the AS_1-foliated orthogneiss. Thus the entire central region of the Maggia structure is formed from the sheared granitic gneiss with its infolded pre-Triassic paragneiss and occasional remnant unsheared pods. Large bodies of diorite occur on the limbs of the synform and have been used as marker horizons to elucidate the structure, particularly in the western closure.

The AF_2 fold axis plunges at 37° towards 038° (Pl. 2 and 3, domain V, stereonet D). Mineral lineations are all subparallel to this fold axis and are generally indistinguishable both in orientation and character from those produced by the earlier A_1 deformation event (Pl. 3, domain V, stereonet E). Except in the hinge regions of meter-scale folds, the AS_2 foliation related to the AF_2 synform is parallel to, and indistinguishable from, the earlier AS_1 foliation. The hinges of small scale AF_2 folds are parallel to the axis of the main synform and their sense of vergence is generally consistent with that of folds on the limbs of a major structure. However, near the core of the AF_2 synform, the predominant sense of the shear zones is observed to change across the synformal axial trace (Fig. 5a). The orientation of the preshearing lineation within the remnant pods also changes across the axial trace of the synform. This change of displacement sense across the AF_2 axis could not be brought about by a simple folding of the earlier shear zones (Fig. 5b and c) and suggests that a large part of the shearing in this region took place during the AF_2 folding event. Tightly folded and resheared shear zones up to 2 m in width occur occasionally in the less deformed areas (RAMSAY & ALLISON 1979, SIMPSON 1981). Nowhere have later shear zones been observed to deflect the foliation already developed within shear zones of more than 5 m width.

c) Deformation phase A_3

The western closure of the synform is complicated by the local superimposition of tight AF_3 folds, having axial surfaces that strike NNW and dip at moderate angles to the east (Pl. 3, domain I, and Fig. 6). The approximately east-west trend of the subvertical AF_2 foliation and compositional banding planes can be traced westwards into Valle di Peccia, where the schistosity becomes symmetrically crenulated about the AF_3 axial surfaces. Foliation planes in the Valle di Peccia region (Pl. 3, domain I, stereonet Q) are strongly folded about an axis plunging at 39° towards 038° which has the same general trend as the mineral elongation lineations and the AF_3 crenulation fold hinges (Pl. 1, 2 and 3, domain I, stereonets R and S). This superposition of AF_3 folds onto the AF_2 synform is also illustrated on

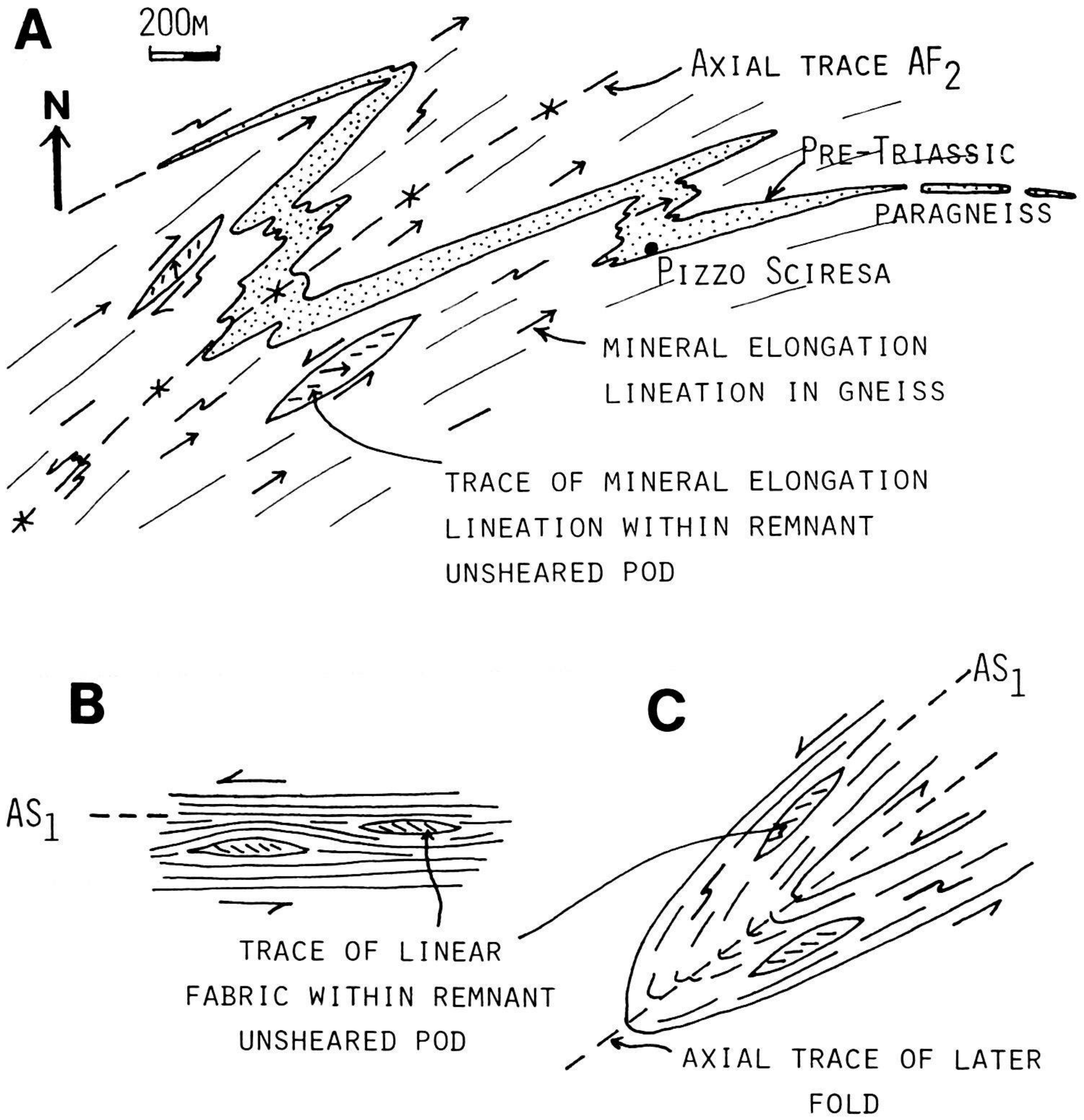

Fig. 5. A: Sketch of the axial region of the AF_2 synform north of Pizzo Sciresa to show the change in displacement sense of shear zones surrounding remnant, relatively undeformed pods across the axial trace of the synform. B and C: Sketches to illustrate the effect of simply folding AS_1 foliated rock containing the remnant unsheared pods: B = before folding and C = after folding. Note that the sense of displacement across the shear zones does not change across the axial trace of the later fold.

the simplified block diagram in Figure 7. The intensity of development of the AF_3 folds diminishes eastwards and northwards in the region of Sasso del Corbo; only rarely do they occur east or north of the lakes along the northern nappe boundary.

d) Deformation phase A_4

Along the northern boundary of the nappe, AS_2 foliation planes in the basement gneisses and Bündnerschiefer are folded about an axis AF_4, plunging at 38° towards 042° (Pl. 3, domain VI, stereonet A). Axial surfaces of the AF_4 folds dip moderately steeply northwest. These AF_4 folds are equivalent to those of the regional "backfolding" phase of HUBER et al. (1980). Westwards from Passo di Sasso Nero the intersection of these AF_4 folds with the AF_3 folds results in spectacular interference fold patterns in the banded gneisses. Indeed, the mountain Cristallina, immediately west of the area in question, is famous for these interference fold patterns in the banded amphibolites of the paragneiss series (RAMSAY 1962, 1967).

Although the AF_4 and earlier AF_2 fold axes have almost identical orientations, their axial surfaces are differently oriented (Fig. 7). The AF_2 axial surfaces trend predominantly NE-SW and are vertical; the AF_4 axial surfaces dip on average 60-80° to NNW. The AS_2 foliation is seen to be deformed by the AF_3 folds in Valle di

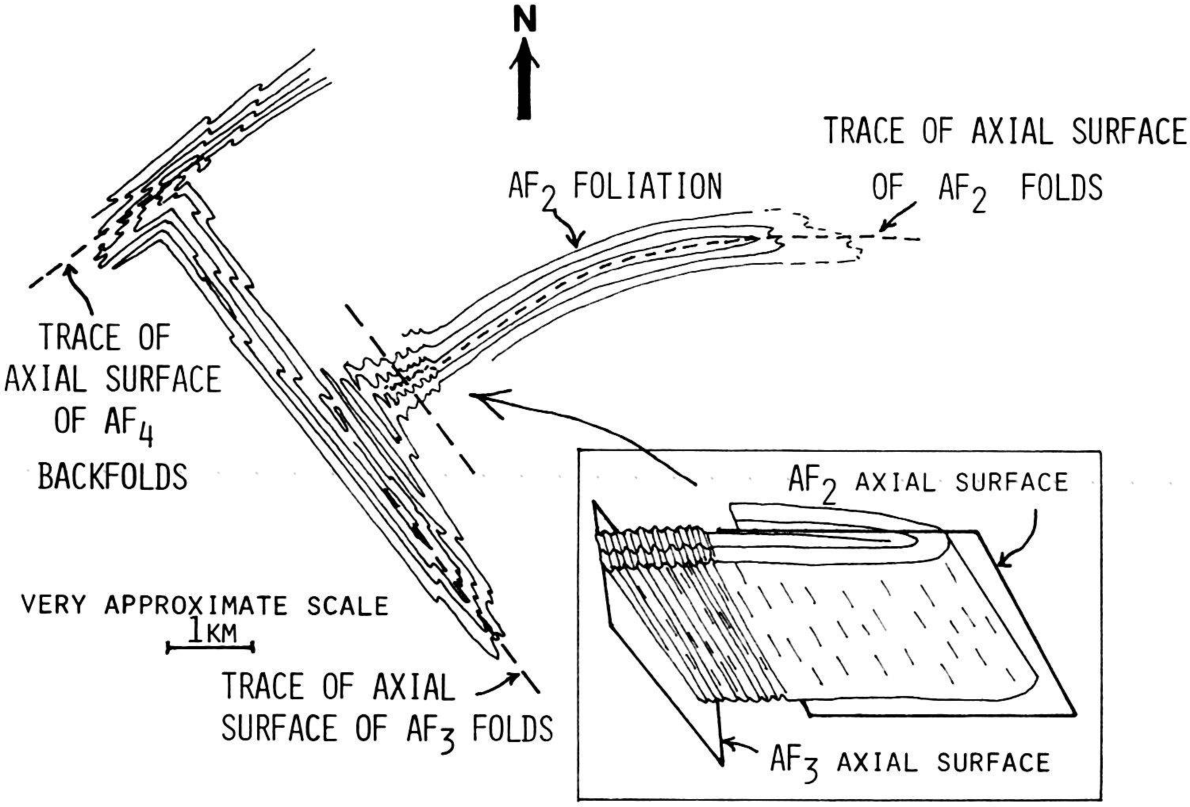

Fig. 6. Sketch to illustrate the superposition of AF_4 onto AF_3, and AF_3 onto AF_2 structures in the northern part of the Maggia Nappe (see text for details). Inset detail of the superposition of AF_3 crenulations onto AF_2 foliation planes - the mineral elongation lineation, AF_2 fold hinge, and AF_3 fold hinges are parallel but the AF_3 axial surfaces are subperpendicular to the AF_2 axial surface.

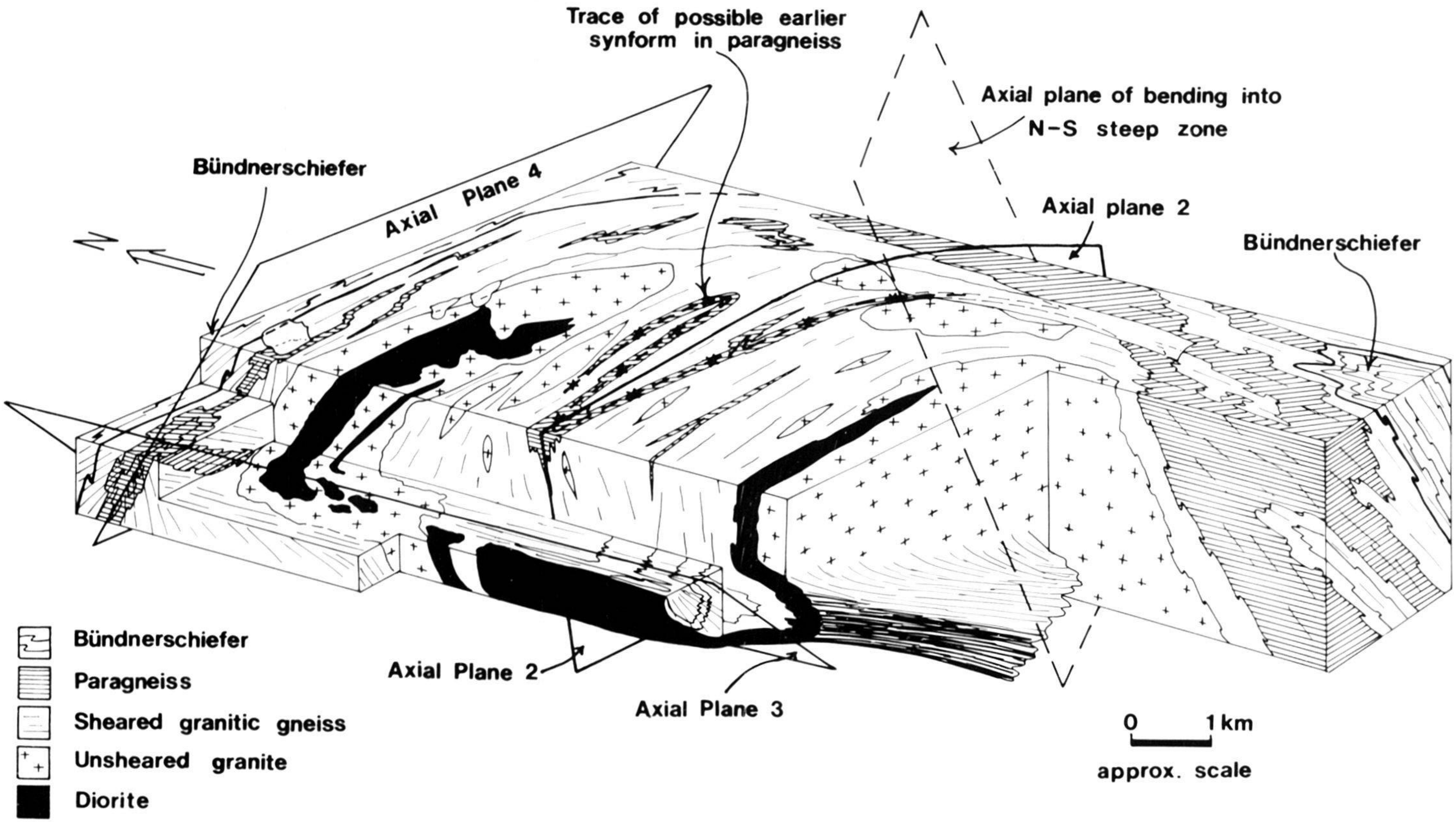

Fig. 7. Simplified block diagram to illustrate the structure of the frontal lobe of the Maggia Nappe. Drawn only approximately to scale. Compare with Figure 2.

Peccia and these AF_3 folds are themselves deformed by the AF_4 folds in the northern boundary region of the Maggia Nappe (see Fig. 6 and 7).

A mineral elongation lineation, AL_4, is developed within the axial surfaces of the AF_4 folds, parallel to AF_4 fold hinges. In the weakly foliated gneisses previously stretched xenoliths are folded by AF_4 folds (Fig. 8). The AL_4 lineation is usually observed as the alignment of minute muscovite and biotite flakes scattered throughout the rock, or the realignment of tiny biotite flakes within aggregates that still retain an earlier AL_1 or AL_2 extension direction.

e) The Maggia "steep zone"

On the eastern boundary of the area mapped, a steeply dipping, NNW trending zone is found at the northern end of Lago Sambuco and extends 40 km southwards to the Insubric Line (see Fig. 7). This "steep zone" has been named the Maggia "Quer" Zone by PREISWERK (1918).

Poles to foliation planes in the eastern boundary of the area (domains IV, III and II on Pl. 3) all show evidence of folding about axes which have a progressively more southeasterly plunge as the structure is traced to the south (Pl. 3, stereonets G, N and K). In each of these areas the mineral elongation lineations tend to remain parallel to fold hinges. In other words, all of the foliation planes, fold hinges and stretching lineations are rotated into the "steep zone" about a northeast trending, southeast dipping axial surface (see Plates). In the hinge regions of meter scale folds the axial

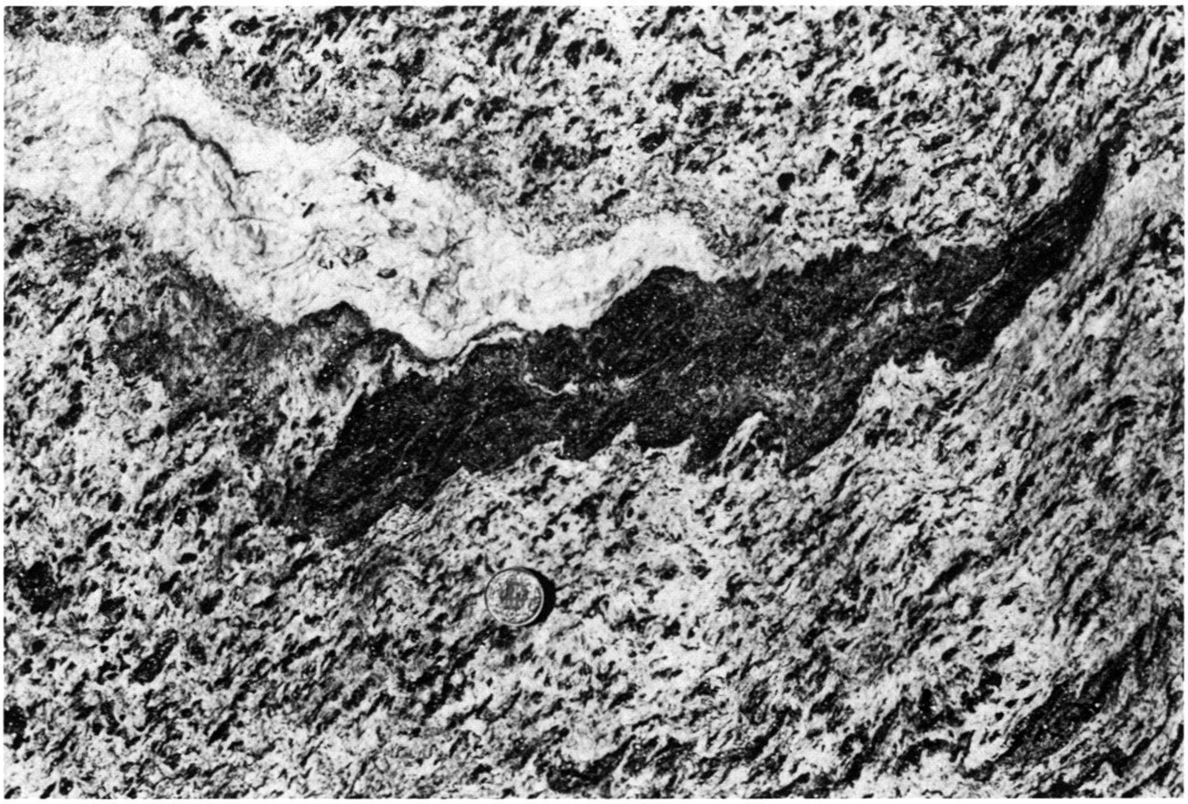

Fig. 8. AF_4 crenulation folds affecting a previously stretched basic xenolith (dark) and aplite dyke (light) in a weakly foliated orthogneiss from Laghetti.

surfaces of the crenulation cleavage form a new foliation discordant to the compositional banding (Fig. 9).

The exact age relationship between the late NNW trending "steep zone" and the AF_4 backfolding structures seen in the northern boundary region remains unclear, as the two sets of structures are never seen together. No evidence has been found to indicate that one set of structure is superimposed on the other, which suggests that the two sets may have approximately the same age.

f) Late-Alpine deformation and joint systems

Throughout the Maggia Nappe and in the paragneisses in particular, late stage internal boudinage and pinch-and-swell structures are observed, similar to those reported from other Lower Pennine basement nappes (Milnes 1964, Hall 1972). Crenulation fold hinges of the AF_4 and "steep zone" structures are deflected into the boudin necks, where quartz, biotite and epidote filled veins occur. The majority of the boudins are symmetrical in form, suggesting compression perpendicular to the layering (Cobbold et al. 1971), and their long axes generally trend towards the northwest.

A master joint system, striking NNW is observed over the entire Maggia Nappe. The fractures are commonly filled with quartz, epidote, adularia or chlorite. Quartz crystals both in vein fillings and within grain aggregates are transected by parallel

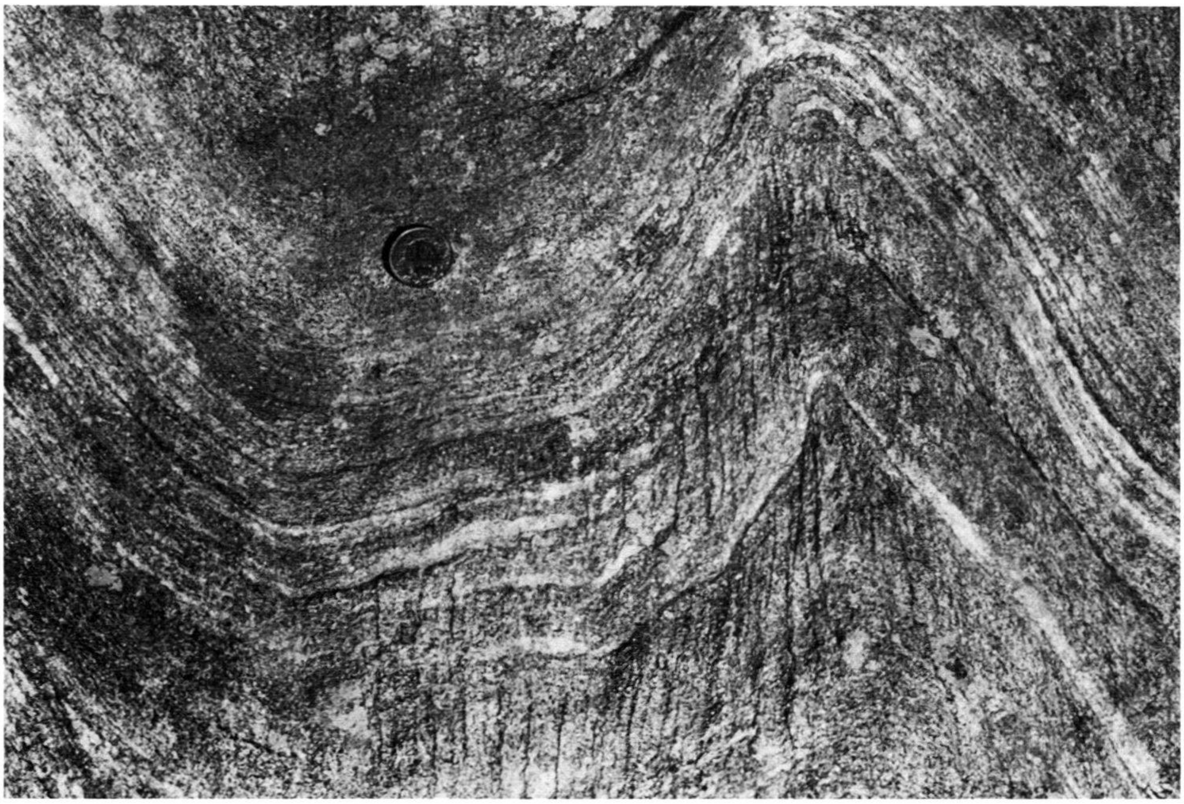

Fig. 9. Subvertical crenulation folds associated with the late "steep" zone ("Quer" zone) of the Maggia Nappe, superimposed onto an earlier isoclinal AF_2 fold in banded pre-Hercynian paragneiss west of the village of Fusio.

spaced fracture planes with a predominantly ENE trend. These fractures are the last deformation structures observed in the Maggia Nappe.

3. Alpine metamorphism

The entire region has been subjected to an Alpine regional metamorphism which reached amphibolite grade and caused the recrystallization of all minerals involved in deformation phases A_1 to A_4 (HIGGINS 1964, HALL 1972, AYRTON & RAMSAY 1974, HUBER et al. 1980). Garnet and staurolite crystals are distributed within AS_2 foliation planes of the paragneiss, suggesting that these minerals grew during the peak of the metamorphism, before the onset of the AF_4 backfolding phase. The paragenesis gar-staur-bi-qtz-plag-ep in the paragneisses indicates that the metamorphic peak reached middle amphibolite facies (WINKLER 1976).

In mafic gneisses, biotite and chlorite are replaced by epidote and hornblende, indicating prograde metamorphic conditions. Large orthite grains in the felsic orthogneiss are always surrounded by epidote rims. These composite orthite-epidote grains cut across biotite crystals that lie along AS_4 crenulation surfaces, suggesting that at least the alteration of orthite to epidote was post A_4 in age (SIMPSON 1981).

An almost complete absence of deformed mineral grains in any of the rock types in the area investigated (with the exception of some minerals within one or two very small, very late ductile shear zones) indicates that the recrystallization generally outlasted the deformation over this region of the Maggia Nappe. Maximum temperature estimates of 550 °C and pressure estimates of about 4 kb have been reported from the adjacent Mesozoic cover rocks on the northern boundary of the nappe (KLAPER 1980). Postmetamorphic deformation has been recorded from these Mesozoic rocks (AYRTON & RAMSAY 1974) and in nearby regions, e.g. HALL (1972) in the Antigorio Nappe, and HIGGINS (1964) in the Basodino region (see also HUBER et al. 1980). However, the evidence suggests that no significant postmetamorphic deformation occurred in the central core of the Maggia Nappe.

Displacement estimates for the Maggia Nappe

A very rough estimate of the values of total displacement across the shear zones in the Maggia Nappe can be obtained by the simple method of multiplying the average shear strain γ by the total width of the shear zones, assuming plane strain simple shear deformation (RAMSAY & GRAHAM 1970). Since the majority of the shear zones are subvertical in orientation, the total width of the shear zones is approximated by the total distance across the outcrops of sheared rock, taken perpendicular to the strike of the foliation. When measured across the Maggia Nappe from Pizzo di Röd northwestwards to the northern boundary with the Mesozoic cover rocks, a distance of 4.5 km, the cumulative width of shear zones with a sinistral displacement sense is approximately 1.56 km and that of shear zones with a dextral displacement sense is approximately 0.36 km. Using an average shear strain of $\gamma = 9$ (SIMPSON 1981), obtained by using deformed xenoliths, quartz grain aggregates and the angular relationships between the foliation within a shear zone and the shear zone boundary (RAMSAY & GRAHAM 1970, RAMSAY & ALLISON 1979), displacements of the order of 14 km in a sinistral sense and 3 km in a dextral sense are found for this part of the Maggia Nappe.

These displacement estimates do not take into account the deformation in the unsheared gneisses, nor has it been possible to separate out the various components of strain history. Consequently, the shear strain values and displacement estimates computed for the Maggia Nappe are only very rough approximations.

Discussion

The structural history of the Maggia Nappe described above accords reasonably well with that of the neighbouring Lower Pennine basement nappes. However, whereas both HALL (1972) in the Antigorio Nappe and HIGGINS (1964) in the Lebendun Nappe, equate their first phases of isoclinal folding with nappe emplacement, the first recognizable events in the Maggia Nappe are the formation of a strong penetrative linear fabric, AL_1, locally accompanied by a planar fabric, AS_1, within ductile shear zones, and these events are most probably directly related to nappe emplacement. The main displacements occurred along zones of high shearing strain, many tens of meters wide, near the boundary between the basement and its Mesozoic cover rocks, and between the orthogneisses and pre-Hercynian paragneisses within the basement rocks. Both the dip of the shear zones and the plunge of the stretching lineation were probably at a low angle to the south (Fig. 10). Between the large deformation zones, the rock of the basement accommodated the strain and changed its bulk shape by continuing to stretch parallel to the movement direction, at the same time forming new, smaller, and sometimes conjugate sets of shear zones, both parallel to and at a low angle to the main deformation zones.

A major phase of tight folding formed the main AF_2 synform of the Maggia Nappe core, and was accompanied by continued deformation in ductile shear zones. Linear and planar fabric elements related to the first and second phases of deformation in the part of the Maggia Nappe studied are difficult to separate because they are generally coaxial, although locally AS_1 foliations are seen to be folded into tight AF_2 folds (HUBER et al. 1980, SIMPSON 1981). In fact, the separation into A_1 and A_2 phases in this region is in some respects rather artificial, as the process is envisaged as a continuous sequence of deformation. The distinction between the two phases A_1 and A_2 has been made on the grounds that the production of foliated gneiss within shear zones must have predated the folding of the same foliated rock into the main synformal structure. Elsewhere in the Maggia Nappe, AF_1 and AF_2 folds have

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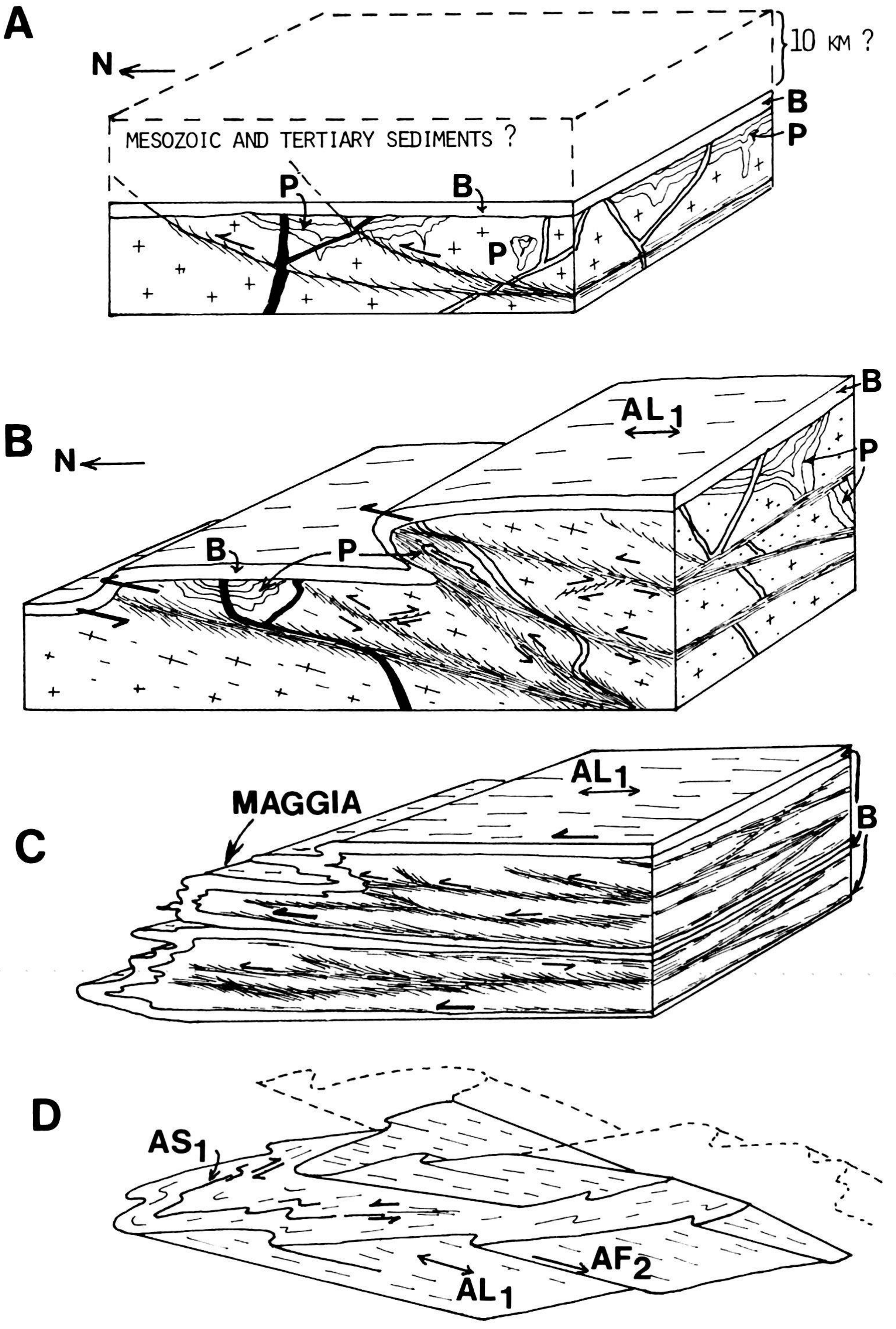
Fig. 10. The relationship of early ductile shear zones and linear fabric to nappe emplacement. *Not drawn to scale.*

A: At start of first Alpine phase of deformation; P = Pre-Hercynian paragneiss, B = Bündnerschiefer. B: During earliest stages of transport of the basement and cover sequences; formation of a strong linear fabric (AL_1) plunging down the dip of the shear zones. C: Strong development of AS_1 planar fabric in shear zones; tightly infolded Bündnerschiefer separates the crystalline nappe cores. D: Tight AF_2 folding of Maggia basement rocks with fold hinges parallel to earlier AL_1 lineation; continued development of shear zones.


A
N
10 KM ?
B
P
MESOZOIC AND TERTIARY SEDIMENTS ?
P
B
P
B
N
AL1
B
P
B
P
P
AL1
MAGGIA
C
B
D
AS1
AF2
AL1

differently oriented axial surfaces and are therefore easier to distinguish (HUBER et al. 1980).

Deformation events A_1 and A_2 described here for the northern lobe of the Maggia Nappe are probably equivalent to the first two fold phases of HIGGINS (1964), HALL (1972) and AYRTON & RAMSAY (1974). Published descriptions of the structures in the Gotthard and southern Aar "massifs" immediately to the north of the Maggia Nappe, also indicate that the main deformation phase produced a weakly planar, strongly linear fabric along with numerous shear zones (STECK 1968). This suggests that the mechanisms of deformation within the Gotthard "massif" and the Lower Pennine nappes were very similar and supports the findings of MILNES (1974, 1978) that the Gotthard is part of a "Subpenninic" structural unit underlying the Lower Pennine zone. The locally developed third deformation phase probably does not have great regional significance. HIGGINS (1964) also found evidence for a third deformation phase in the Basodino region, before the final backfolding event.

A thermal metamorphic event (the Lepontine metamorphism) reached a maximum of lower amphibolite facies grade in the Maggia gneisses before the onset of the backfolding phase of deformation. The entire Maggia structure was finally gently folded into a NNW trending "steep zone" extending southward to the Insubric line. The timing of the formation of the "steep zone" is uncertain but it was probably close to that of the backfolding event. The effects of the metamorphism outlasted those of the deformation and caused the recrystallization of almost all the minerals in the basement gneisses. Some movement took place along some very small ductile shear zones after the post tectonic recrystallization but did not result in a regionally significant amount of deformation.

A parallelism of linear fabrics and fold hinges similar to that described here for the Maggia structure has been recorded from a number of highly strained basement terrains and is usually ascribed to the rotation of fold hinges into parallelism with the stretching lineation (BRYANT & REED 1969, BORRADAILE 1972, ESCHER & WATTERSON 1974, BELL 1978, COBBOLD & QUINQUIS 1980, BERTHÉ & BRUN 1980). A model to explain this phenomenon by the escape of anatectic melts causing channel-flow, has been proposed by NICOLAS et al. (1977). However, in the Maggia Nappe, neither the rotation of fold hinges into the stretching direction, nor anatexis seem to have played a role in the deformation. Further, the absence of sheath-like folds or of deformed lineations suggests that the later fold hinges were actually initiated parallel to the earlier linear fabric. One possible explanation is that the presence of the linear fabric produced such a strong anisotropy in the rock that much less work was required to form folds with their hinge lines parallel to this lineation than would have been required to deform the lineation around new fold hinges (WATKINSON & COBBOLD 1981).

Conclusions

Emplacement of the Maggia Nappe into the Lower Pennine Nappe complex occurred under ductile conditions and produced a pronounced stretching lineation in the basement rocks, accompanied by a planar fabric in ductile shear zones. A major phase of tight folding formed the main synformal structure within the nappe core. A locally expressed third phase of deformation followed prior to the peak of the regional amphibolite grade metamorphism. The formation of the Maggia "steep zone" was probably closely associated in time with the final backfolding phase of deformation.

Acknowledgments

This work forms part of a Ph.D. dissertation submitted to the ETH Zürich. Financial support from the Zentenarfonds of the ETH is gratefully acknowledged. I would like to express my sincere thanks to J.G. Ramsay for his advice and helpful criticism throughout the course of the project. I am indebted to U. Briegel for assistance with the German abstract. Many useful and stimulating discussions with M. Casey, M. Greller, A. Günthert, M. Huber, J.C. Hunziker, A.G. Milnes and S.M. Schmid are gratefully acknowledged. I would also like to thank Betty Adams for invaluable secretarial assistance.

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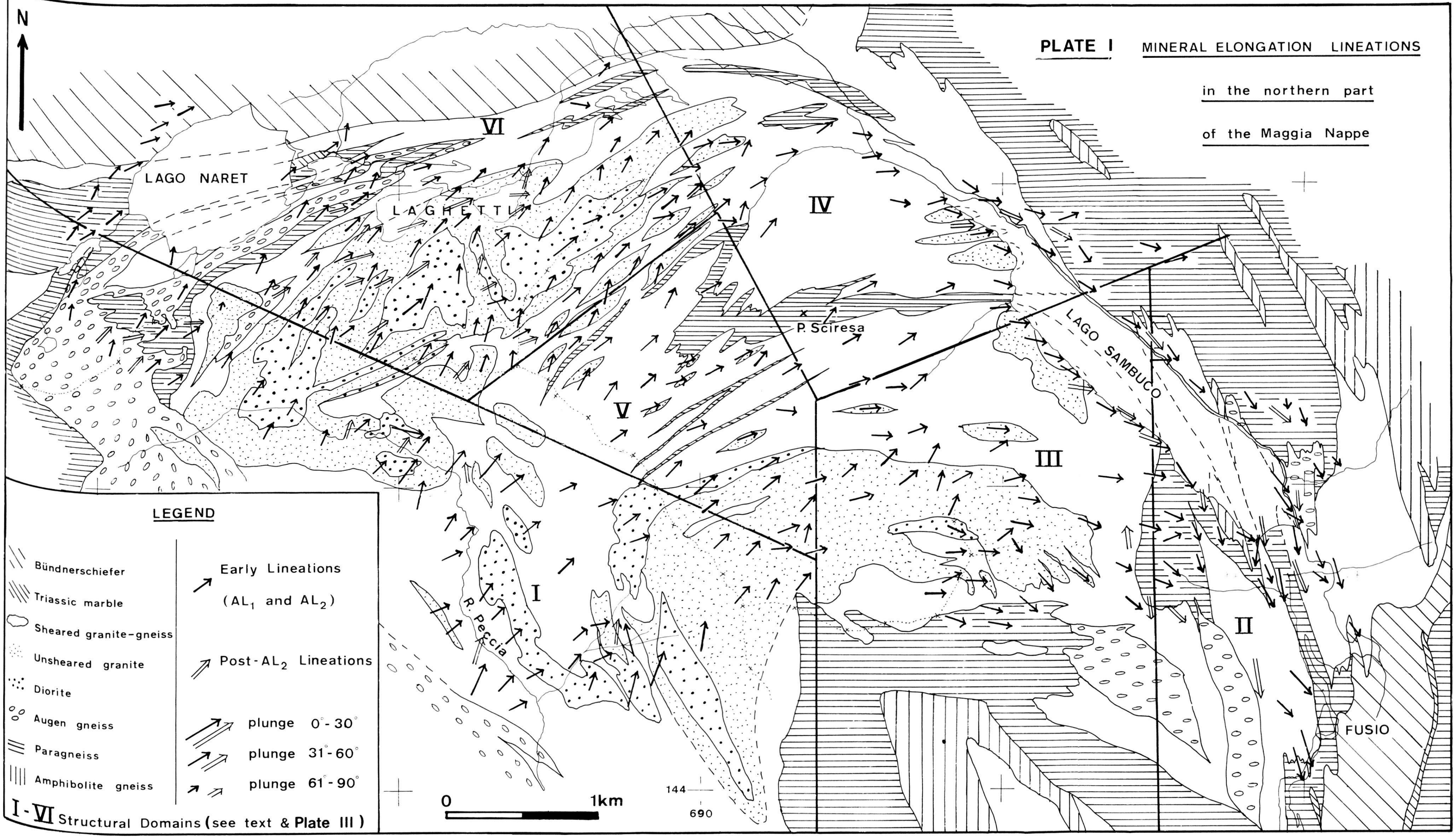


PLATE I MINERAL ELONGATION LINEATIONS
in the northern part
of the Maggia Nappe
N
LAGO NARET
LAGHETTI
P. Sciresa
LAGO SAMBUCO
R. Peccia
FUSIO
I
II
III
IV
V
VI
LEGEND
Bündnerschiefer
Triassic marble
Sheared granite-gneiss
Unsheared granite
Diorite
Augen gneiss
Paragneiss
Amphibolite gneiss
Early Lineations (AL_1 and AL_2)
Post-AL_2 Lineations
plunge 0°-30°
plunge 31°-60°
plunge 61°-90°
I-VI Structural Domains (see text & Plate III)
0
1km
144
690

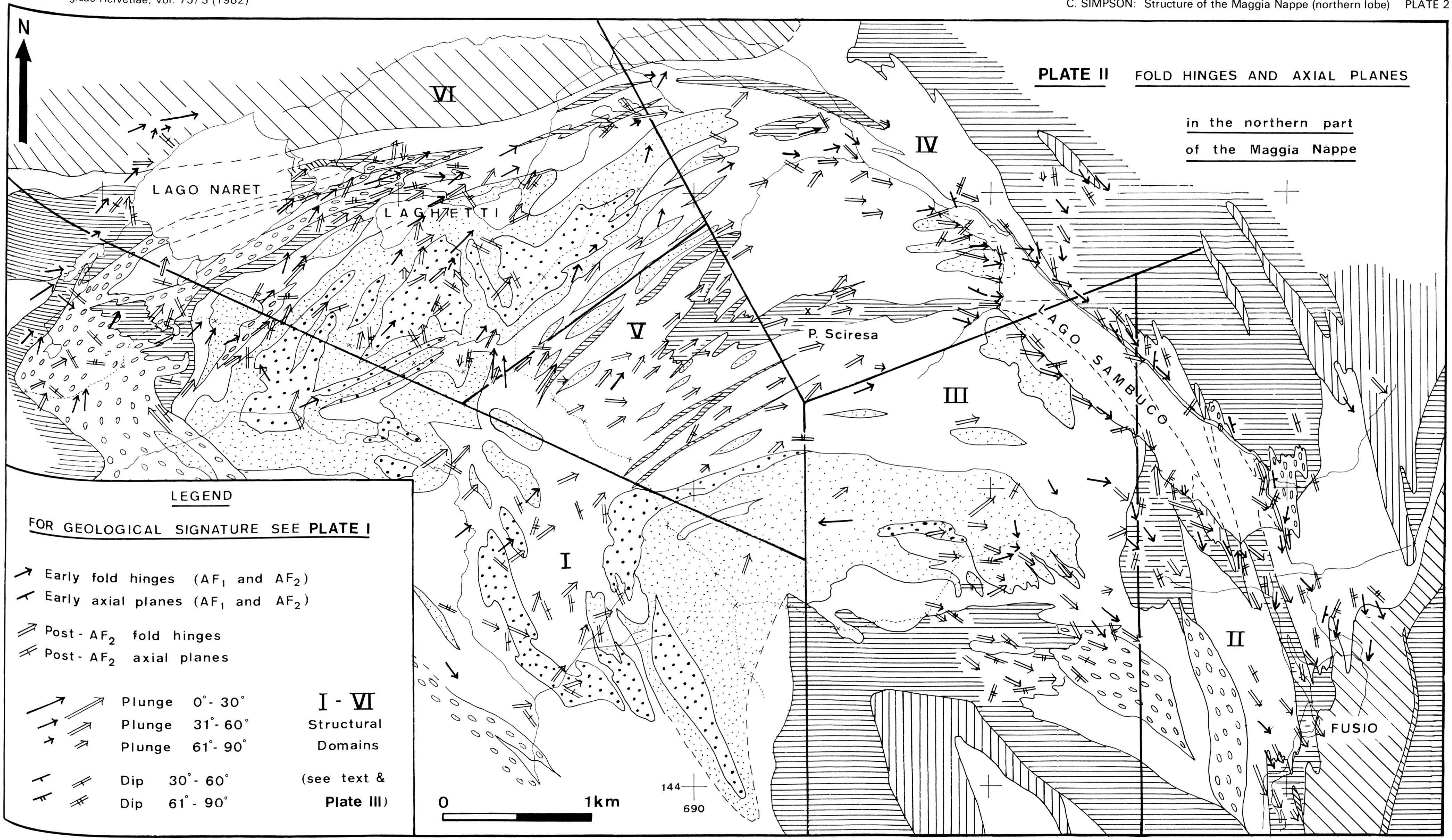
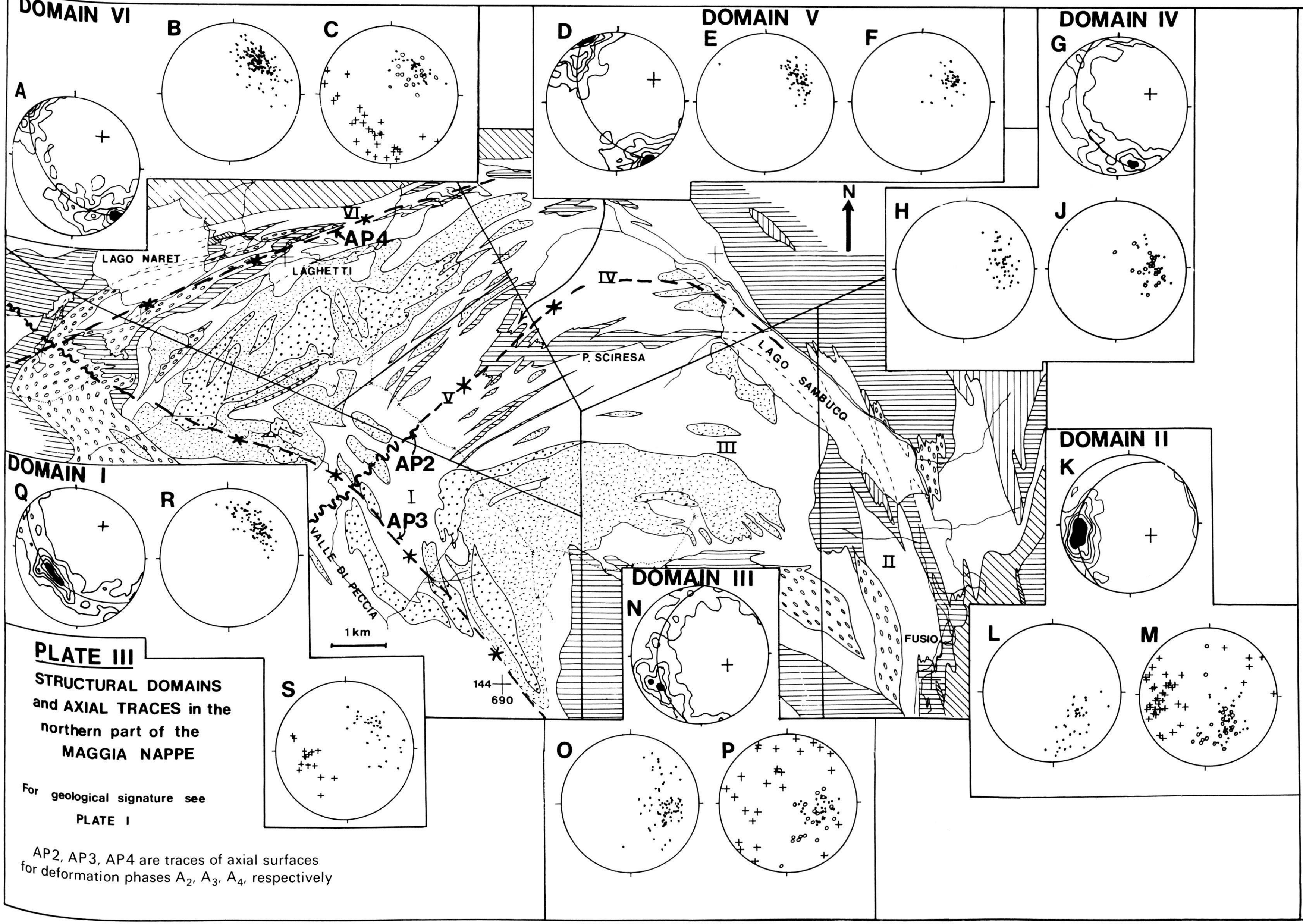


PLATE II FOLD HINGES AND AXIAL PLANES
in the northern part
of the Maggia Nappe
N
LAGO NARET
LAGHETTI
VI
V
IV
III
II
I
P. Sciresa
LAGO SAMBUCO
FUSIO
LEGEND
FOR GEOLOGICAL SIGNATURE SEE PLATE I
Early fold hinges (AF1 and AF2)
Early axial planes (AF1 and AF2)
Post-AF2 fold hinges
Post-AF2 axial planes
Plunge 0°-30°
Plunge 31°-60°
Plunge 61°-90°
Dip 30°-60°
Dip 61°-90°
I - VI
Structural
Domains
(see text &
Plate III)
0
1km
144
690



STEREONETS

A: 280 poles to foliation contoured at 1, 3, 5, 7, 9 points per 0.4% area.

B: 152 mineral elongation lineations AL_1 and AL_2 undifferentiated.

C: 28 poles to AF_4 axial planes (crosses), 15 AF_2 fold hinges (circles), 28 AF_4 fold hinges (dots).

D: 179 poles to foliation contoured at 1, 3, 5, 7, 9 points per 0.6% area.

E: 57 mineral elongation lineations AL_1 and AL_2 undifferentiated.

F: 34 AF_2 fold hinges.

G: 106 poles to foliation contoured at 1, 3, 5, 7 points per 0.9% area.

H: 47 mineral elongation lineations AL_1 and AL_2 undifferentiated.

J: 20 AF_2 fold hinges (circles), 32 AF_4 fold hinges (dots).

K: 157 poles to foliation contoured at 1, 3, 5, 7, 9 points per 0.6% area.

L: 36 mineral elongation lineations AL_1 and AL_2 undifferentiated.

M: 40 poles to AF_4 axial planes (crosses), 24 AF_2 fold hinges (circles), 39 AF_4 fold hinges (dots).

N: 191 poles to foliation contoured at 1, 3, 5, 7 points per 0.5% area.

O: 79 mineral elongation lineations AL_1 and AL_2 undifferentiated.

P: 26 poles to AF_4 axial planes (crosses), 18 AF_2 fold hinges (circles), 44 AF_4 fold hinges (dots).

Q: 263 poles to foliation contoured at 1, 3, 5, 7, 9 points per 0.4% area.

R: 85 mineral elongation lineations AL_1 and AL_2 undifferentiated.

S: 14 poles to AF_3 axial surfaces (crosses), 35 AF_3 fold hinges (dots).