Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 90 (1997)

Heft: 2

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DOI: https://doi.org/10.5169/seals-168163

0012-9402/97/020337-08 $1.50 + 0.20/0
Birkhäuser Verlag, Basel, 1997

Eclogae geol. Helv. 90 (1997) 337–344

An example of the Alpine structural evolution of the Penninic zone in the Ligurian Alps: Tectonics of the Barbassiria area

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Key words: Basement deformation, sheath folds, back-thrusts, interference patterns
Parole chiave: Deformazioni nel basamento, pieghe a guaina, retroscorrimenti, figure di interferenza

ABSTRACT

The paper presents a map of four superposed tectonic units in the Barbassiria area. The two lowermost units are ascribed to the Briançonnais domain, the highest to the Piedmont domain and the third to an original location at the limit between the two domains.

The deepest unit (Mallare Unit) is made up of a metamorphic, originally rhyolitic, pre-Namurian basement, which is covered by an Upper Carboniferous, volcanic and sedimentary unit. Although with differing facies and age, a pre-Namurian basement and an Upper Carboniferous cover also constitute the subsequent unit (Pamparato-Murialdo Unit), whose sequence is completed at the top by a very "reduced" sedimentary cover of Upper Cretaceous calcareous schists. The third unit (Calizzano-Savona Unit) consists exclusively of various pre-Namurian metamorphites. Finally, the uppermost unit (Monte Sotta Unit) is represented by a Triassic-Liassic sedimentary series.

We undertook a detailed structural study of the two lower units, inside which we found three main superimposed folding phases (D1, D2, D3), which developed, with decreasing intensity, in progressively higher structural levels.

In the Mallare Unit, the widely exposed outcrop of the contact between the basement and Carboniferous cover enabled us to state that the D1 phase produced some kilometre-scale, gently inclined, "sheath"-like folds; the basement was involved in this SW-directed deformation. Both map and stratigraphic or mesostructural evidence suggests that the superposition of the units was achieved along a set of low-angle thrust planes, only after the first folding phase.

An interesting feature, possibly open to extrapolation to other sectors of the Alpine chain, is represented by the subsequent development of a new thrust system ("Late-D1" event); its NNW-vergence and relatively high degree of shortening are similar to those known at a regional scale for the D2 "back-folding and thrusting event". But detailed structural analysis has shown that in the Barbassiria area this system corresponds to an older phenomenon, that occurred during the main, foreland-directed deformation episode.

The D2 phase has produced open to moderately tight folds, which are characterised by an overall NW-directed, not very prominent, vergence; their mean direction is N50°.

The last phase has subvertical axial planes, which mainly trend toward the NW or NNW. It has produced large, spectacular, asymmetrical "dome-and-basin" interference patterns.

The above data fit in with the known regional framework and suggest a model both for the deformation geometry of the pre-Mesozoic cover and basement and for the relative chronology of internal folding of each unit and nappe superposition.

RIASSUNTO

Nella zona di Barbassiria sono state cartografate quattro unità tettoniche sovrapposte; di esse, le due più profonde sono attribuite al dominio brianzonese, quella più elevata al dominio piemontese, mentre la terza viene collocata al limite tra i due domini. L'unità più profonda (U. di Mallare) è costituita da un basamento metamorfico pre-Namuriano e da un tegumento vulcanico e sedimentario del Carbonifero superiore. Benchè con facies ed età differenti, un basamento metamorfico pre-Namuriano ed un tegumento carbonifero superiore compongono anche la seconda unità (U. di Pamparato-Murialdo), la cui successione è completata verso l'alto da una copertura sedimentaria particolarmente ridotta, essendo unicamente rappresentata da scisti calcarei verosimilmente di età cretacea superiore. La terza unità (U. di Calizzano-Savona) è unicamente formata da metamorfiti pre-namuriane. L'unità geometricamente più alta, infine (U. di Monte Sotta), è formata da una successione sedimentaria triassico-liassica.

Sulle due unità inferiori è anche stata condotta una dettagliata analisi strutturale, che ha messo in luce l'esistenza di tre principali fasi di piegamento sovrapposte (D1, D2, D3), realizzate con intensità decrescente in livelli strutturali progressivamente meno profondi.

Nell'unità di Mallare, l'esteso affiorare della superficie di contatto tra basamento e tegumento ha consentito di verificare che durante la fase D1 si sono prodotte alcune pieghe chilometriche rovesciate, del tipo "a guaina", con vergenza verso SW, che hanno coinvolto anche il basamento metamorfico. La sovrapposizione delle unità si è realizzata solo dopo il piegamento, lungo un sistema di thrust poco inclinati, che le ha trasferite verso l'esterno della catena.

Un aspetto interessante, forse suscettibile di estrapolazione ad altri settori della catena alpina, è rappresentato dal successivo sviluppo di un nuovo sistema di thrust (fase "tardo-D1"). La sua vergenza verso NNW e la non trascurabile entità del raccorciamento lo rendono simile alle strutture che, a scala regionale, sono indicate come "retropiegamenti e retroscorrimenti" associati all'evento D2. Ma l'analisi strutturale dettagliata nella zona di Barbassiria ha mostrato che si tratta invece di un sistema più vecchio, formato durante la prima, complessa fase di trasporto tettonico verso l'esterno della catena.

Alla successiva fase D2 sono imputabili pieghe da aperte a non molto serrate, a direzione media N50° e vergenza poco marcata, diretta in prevalenza verso il quadrante nord-occidentale.

L'ultima fase, con direzione dominante NW-NNW e piani assiali sub-verticali, ha prodotto grandi strutture di interferenza a "duomi e bacini" asimmetrici.

I dati ottenuti precisano il già noto contesto regionale, fornendo un modello sia per la geometria delle deformazioni nel tegumento e nel basamento, sia per la cronologia relativa tra piegamento e attivazione dei sovrascorrimenti.

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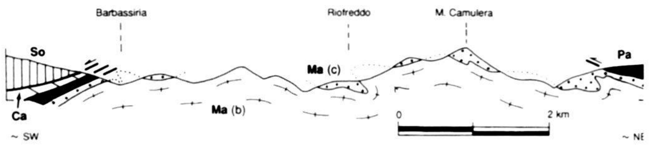

Fig. 1. Briançonnais and Piedmont nappe pile in the Barbassiria area. **So:** Monte Sotta Unit; **Ca:** Calizzano-Savona Unit; **Pa:** Pamparato-Murialdo Unit; **Ma:** Mallare Unit (b = pre-Namurian basement; c = Upper Carboniferous cover). The line of this section runs nearly parallel to the line of cross-section no. 2 of Plate 1. Both lines pass through M. Camulera. The direction of the present section is obtained by a 10° clockwise rotation, around this point, of the line of cross-section no. 2.

Introduction

Studies on the Ligurian Alps (Vanossi et al. 1986 and refs. therein, Vanossi 1991) have shown that, on the whole, their structure was produced during three main events: S/SW-directed tectonic transport and overthrusting, N/NW-verging backfolding, and late gentle folding phases, of which one in particular (with its axial direction nearly orthogonal to that of the older folds) is ubiquitous.

In recent years, research on the Penninic thrust belt of the Ligurian Alps, and specifically on the Briançonnais and Piedmont units, has focused on some still unsolved questions of general interest.

One of these questions concerns the geometric characteristics of deformation in pre-Mesozoic sequences. As a matter of fact, the geometry of the different ductile phases is often easily seen at a meso-scale in any lithologic unit; but at the kilometre-scale, it is easily reconstructed only in the Meso-Cenozoic covers, where stratigraphic guide-levels are mappable. Unfortunately, sedimentary covers in the Ligurian Alps are, on the whole, rather rare and, moreover, they are often probably – or at least possibly – detached. The lack of data on large-scale deformations in the widely outcropping pre-Mesozoic units has left some important questions open, not only as to geometry but also as to kinematics, which in turn casts obvious doubts on the palinspastic restorations.

Therefore, after a preliminary study (Cortesogno et al. 1995), we selected for detailed geological and structural mapping (at a scale of 1:10,000 and 1:5000) the Barbassiria area, where the pre-Namurian metamorphic basement, together with its Upper Carboniferous volcanic and sedimentary cover, is exceptionally well displayed; this feature offered a unique opportunity to map this basement-cover contact and thus to reconstruct the true geometry of the unit's deformation, for comparison with that observed in the sedimentary post-Palaeozoic cover.

A second aim of the present work concerned kinematics; we obtained interesting data on the mechanisms and directions of tectonic transport. Moreover, comparative structural analysis of the four superposed units exposed in the Barbassiria area yielded valuable information about the timing of nappe superposition in relation to that of their internal deformation phases.

General setting and stratigraphy

An overall view of the four units from the Briançonnais and Piedmont domains that are superposed in the mapped area is given in Figure 1. The principal stratigraphic data, which derive mainly from previous studies (Oxilia 1978, Cabella et al. 1991, Cortesogno et al. 1995), are briefly summarised in Plate 1 and in the following paragraphs.

Monte Sotta Unit (So)

In the Ligurian Alps, the Monte Sotta Unit is represented (Vanossi 1991) by a number of large klippen which are made up of a carbonate Mesozoic sequence and which are mainly located at the inner border of the chain; they rest on various Briançonnais nappes, and are locally covered by Piedmont-Ligurian metamorphic ophiolitic units. On account both of the geometric position and of the characteristics of the stratigraphic series, the unit has been ascribed to the Piedmont domain.

The unit, which crops out at the western margin of the map in Plate 1, is represented by a sequence (see stratigraphic column in Pl. 1) that begins with (Permian-) Lower Triassic quartzites and ends with Liassic limestones.

Calizzano-Savona Unit (Ca)

This basement nappe is formed by two very large klippen (Calizzano and Savona "Massifs") and by some minor slabs, with the entire nappe resting on various Briançonnais units.

The nappe's complex lithologic assemblages were the subject of a recent study (Cortesogno et al. 1993), which proposed a sequence of pre-Alpine tectono-metamorphic events. These events are documented by an older group of metamorphites (paragneisses, mica-schists, amphibolites and orthogneisses) which display a polyphase evolution, and by younger orthogneisses ("Orthogneisses II") which are affected by only one metamorphic pre-Alpine phase.

In the mapped area, the unit is only represented by the older metamorphites, which form a single, small, hitherto unknown klippe and the northernmost closure of the Calizzano "Massif".

Pamparato-Murialdo Unit (Pa)

Situated along the inner border of the Ligurian Alps, this unit forms a very wide, practically continuous outcrop from Savona to the Mondovì district. It supports various other units (Calizzano-Savona, Monte Sotta, Montenotte) from the Piedmont and/or Piedmont-Ligurian domains and, in turn, it rests on Briançonnais units (Mallare and Ormea respectively in the eastern and western sectors). Its geometric position and the characteristics of its Mesozoic cover have suggested an innermost Briançonnais original location.

On Plate 1, this unit appears to border the lowermost one (Mallare Unit) on its western, eastern and northern sides. As shown in the stratigraphic column, **Pa** begins with poorly exposed, pre-Namurian orthogneisses (*"Nucetto Orthogneisses", Pa1'*), which are locally followed by some metres of fine to coarse-grained paragneisses (*Pa1''*), representing an originally unconformable continental cover.

The greater part of the sequence is made up of two Upper Carboniferous (Stephanian?) heteropic formations: i) fine-grained continental metasediments (*"Murialdo Fm.", Pa2'*); ii) meta-andesites interbedded with mainly fine-grained pyroclastic deposits, which frequently grade into the above-described metasediments (*Eze Fm., Pa2''*).

In the southwestern corner of the map, the Upper Carboniferous sequence is directly covered by finely detrital, calcareous schists, which – on the bases of lithofacies and of geometrical position – possibly represent the Upper Cretaceous/Eocene stratigraphic top of the **Pa** series.

Intense Alpine deformations make it impossible to prove that the lack of all the terms from Upper Carboniferous to Upper Cretaceous has a non-tectonic origin; however, this seems a reasonable interpretation, in the light of the innermost Briançonnais palaeogeographic location which has been proposed for this unit. The Mesozoic sequence in the internal Ligurian Briançonnais domain is ubiquitously a "reduced" one, with a gap covering the interval between Early Triassic and Late Jurassic, or Late Cretaceous; in the Barbassiria area the gap is possibly longer.

Mallare Unit (Ma)

At a regional scale (Vanossi et al. 1986, Vanossi 1991, Cortesogno et al. 1993), this unit occupies a very wide area of the central-eastern part of the Ligurian Alps, where it forms a number of tectonically superposed slabs (Cabella et al. 1991). On the bases of stratigraphy, present geometric position and tectono-metamorphic history, it was suggested that the unit might originally have been located in the internal-intermediate Briançonnais domain.

In the Ligurian Alps, the Barbassiria region (where **Ma** covers the greatest part of the mapped area, cropping out from below the other units) is the only one that shows the pre-Namurian basement of the series. According to a recent study by Cortesogno et al. (1995), **Ma** stratigraphy in the mapped area can be summarised as follows.

The basement is represented by orthogneisses (*"Barbassiria Orthogneisses", Ma1*); their volcanic origin differentiates them from the plutonic rocks presently represented in **Ca** and **Pa** by Orthogneisses II.

The first rock unit that was emplaced after the Variscan events is mainly represented by rhyolitic to rhyodacitic ignimbrites (*"Case Lisetto Metarhyolites", Ma2''*), which – as can be deduced from present outcrops – probably filled some depressions without covering the whole area. Their effusion was preceded by local trachyandesitic to dacitic lava flows (*Ma2'*), accompanied by dykes that cut through the basement, and probably by some subvolcanic masses of granophyres.

Both on the volcanics and directly on the basement – with original stratigraphic contacts locally preserved – there lie fluvial-lacustrine detrital sediments (*Ollano Fm., Ma3*) of Late Westphalian – Stephanian age (Bloch 1966, Vanossi 1970). The persistence throughout this time-span of rhyolitic-rhyodacitic volcanic activity is documented by some intercalations of ignimbritic layers and pyroclastic agglomerates (*"Bric Crose Tuffs"*).

Alpine structure

Most of the collected data are presented in the two plates. Besides the stratigraphic columns and the main relevant information, Plate 1 contains the geologic map and the cross-sections. In order to highlight the geometrically complex interference pattern which has been produced by three main episodes (D1, D2, D3) of ductile deformation, the geologic map has been printed on a topographic background. For the sake of clarity, the attitudes of tectonic surfaces and lines are represented separately on simplified maps in Plate 2; this also shows stereograms for all the measurements from these structures. Structural analysis has been concentrated on the **Pa** and, above all, **Ma** units, which cover the largest part of the map.

D1 structures

1) Mallare unit

The first deformation phase of this unit is recorded by three complete, gently inclined, kilometre-scale tight folds, involving both basement and cover (Fig. 1). Their 3-D development can be followed on Plate 1 (map and cross-sections 1, 2, 3). The polarity of the sequence, the relationships between long and short limbs of the major folds, as well as the asymmetry of minor folds on such limbs, indicate a SW vergence. The folds are accompanied by a very well developed axial plane schistosity (S1), on which former foliations – Ollano sediments *(Ma3)* stratification, Barbassiria gneisses *(Ma1)* pre-Alpine schistosity – are more or less completely transposed.

The best exposed of these folds is represented by a syncline ("Rio Freddo syncline") and the overstanding anticline ("Bric Tursi anticline"), first described by Boni et al. (1971), and subsequently by Menardi Noguera (1982). It crops out on the southwestern side of M. Camulera (Pl. 1, cross-sections 1, 2, 3). The bedding/schistosity (S1) intersection lineation (L01) that was measured in the Ollano metasediments (see plot in Plate 2) shows that the hinge lines of both the syncline and the anticline are clearly curved in the sub-horizontal axial surface of the fold. This bent has also been reconstructed in Figure 2.

In the S1 planes lies a very well developed stretching lineation (L1), shown by K-feldspars in the gneisses and the meta-

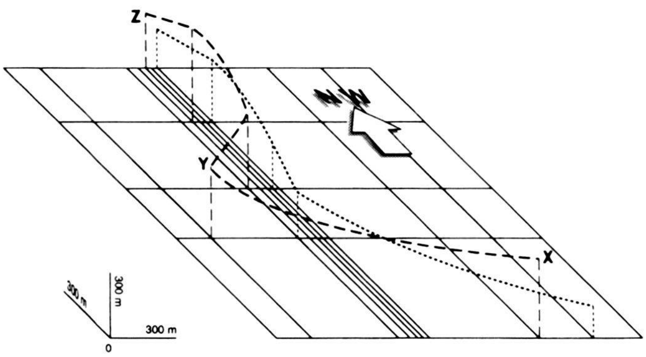

Fig. 2. Three-dimensional development of the hinge lines of the two D1 kilometre-scale folds (dashes: anticline; dots: syncline) that crop out on the south-western side of M. Camulera. See cross-sections 1, 2, 3 in Plate 1 for location of points X, Y and Z on the anticline hinge. The sheath-like geometry (more pronounced in the overlying anticline) is apparent. Also note that both lines are affected by vertical variations, which are connected with the D3 deformational event.

rhyolites, and by quartz pebbles in the metasediments. Its mean direction is to the SW, in good agreement with the fold vergence. All over the mapped area – leaving aside a local exception connected with a "Late-D1" event (see below) – L1 is not deflected (Pl. 2); the angle it makes with the fold hinge lines varies between 90° and 20° and the mean value may be set at about 40° (compare plots in Pl. 2). Hence, it must be concluded that the above-mentioned curvature of the hinge lines (both of the anticline and of the underlying syncline) of the kilometric fold was set up during folding. Because the hinge line variation is more than 90° (plot in Pl. 2 and Fig. 2), the fold displays a sheath-like geometry (Ramsay & Huber 1986; Skjernaa 1989), such as would be produced by a deformation whose dominant mechanism is represented by simple shear.

Other structures confirm both the overall simple shear deformation and the tectonic transport direction. The *s-c* systems affecting the thin metasedimentary levels in the basement, the very frequent thin mylonitic shear bands in the gneisses, and the microscopic aspects of the S1 schistosity, which often appears as being composed of two, nearly parallel sets of planes that have been interpreted as microscopic *s-c* systems (Cortesogno et al. 1995), all show a "top to the SW" shear sense. The same indication is given by σ- and δ-structures (Ramsay & Huber 1986) around rotated porphyroclasts, which were found in gneisses as well as in metarhyolites.

2) Other units

Pa unit – The lack of guide-levels and of a sufficient number of minor structures has prevented the discovery of possible large D1 folds in the **Pa** sequence. Regarding the meso- and microstructures, the main characteristics are as follows.

In the basement *(Nucetto Orthogneisses, Pa1)* the pre-Alpine metamorphic foliation is more or less completely transposed onto the S1 schistosity. In the basaltic-andesitic lavas *(Eze Fm., Pa2'')*, S1 contains pyroxene megacrysts rimmed by asymmetric pressure shadows, and is accompanied by shear bands. In the phyllites *(Murialdo Fm., Pa2')*, as well as in the *Calcschistes planctoniques (Pa3)*, S1 has produced sub-millimetric metamorphic differentiated layering, in which micas alternate with quartz + albite (respectively calcite + quartz) layers. In the black Murialdo phyllites *(Pa2')*, very frequent centimetre-scale quartz veins lie parallel to the main foliation, thus offering a precious aid to the reconstruction of the geometry of post-D1 deformations. In the meta-andesites of the Eze Fm. *(Pa2'')*, metre-scale, sub-isoclinal, SW-verging folds sometimes occur, as well as different kinds of meso- and microstructures from which a SW-directed sense of movement can be deduced.

Ca and **So** units – These units are too little represented in Plate 1 for large structures to be identified, and therefore no systematic mesostructural analysis was carried out. We can only report that in **Ca** the oldest Alpine schistosity (S1), while rarely observable in the amphibolites, is well displayed in the gneisses and mica-schists, where it is marked by the coexistence of pre-Alpine muscovites (and biotites) with Alpine phengites. Mesoscopic, N330°-trending folds, which deform the older foliations, are sometimes present. Rare δ-structures indicate a "top to the SW" movement.

As for the **So** unit, in the Lower Triassic quartzites *(So1)*, and in both Triassic *(So2')* and Jurassic *(So2'')* limestones, the S1 foliation, which is defined by phengitic micas, forms a set of sub-centimetre spaced planes that are frequently slightly inclined to the stratification. In contrast, in the massive dolomitic bodies, the S1 foliation is usually confined to the pelitic intervals. S2 cleavage is barely apparent.

"Late-D1" structures

A remarkable NNW-verging thrust and fold system, involving **Ma** and **Pa** units, develops in the northern part of the area (Pl. 2: sectors 2, 3 and, partially, 4). The map and sections 8, 9, 10 and 11 (Pl. 1) show that this system is confined on its western side by a NW-directed strike-slip fault (**s.s.z.** on sections and Pl. 2); in the field the shear appears either ductile or brittle, depending on the involved lithologies, and a sinistral sense of movement is deduced from both local kinematic indicators and displacement of lithologic contacts.

On the sections and on Plate 2, the three main thrusts of the system have been labelled (from the bottom to top) **a**, **b** and **c.** The two lower ones (**a** and **b**) also involve the limit between the **Pa** and **Ma** units. At the top of the main thrust-plane (plane **b**), the **Ma** rock sequence is antiformally folded. In a SE direction, away from the lowest, northernmost thrust, ductile deformation becomes prominent, and the shortening is accomplished without any further reverse faulting.

Because it affects the S1 foliation and since it rotates the stretching lineation L1 (Pl. 2: compare plots referring to the involved sectors with plots from the other areas), the system clearly post-dates the above-described D1 structures. At first sight, it seems ascribable to the second phase of deformation (D2), all the more so because its axial trend does not differ excessively from that of the D2 folds.

Nevertheless, the thrust-related foliation that is locally developed ("Late-S1") is cut by the S2 cleavage. Moreover, the structures here under question display a much greater degree of shortening than that connected with the D2 event. This is not only apparent at the map scale, but is also demonstrated by the dispersion of poles to S1 schistosity, as is apparent in the stereograms of Plate 2: in area 3 poles are all concentrated in the NW sector of diagram, thus indicating NNE-trending folds with an overturned limb; in contrast, in the other areas (e.g. areas 7, 8), pole distributions depict folds that display a similar axial trend, but show an open geometry, one that is comparable with that of the folds that have been attributed to the D2 event (see below).

It may also be added that these "Late-D1" structures are confined to a limited area, while the D2 phase affects the whole mapped zone. Finally, L1 lineation is rotated only in this sector; in the other mapped areas the original L1 trend is not deflected by the D2 phase.

D2 structures

Ma unit – The second event generated folds whose axes (A2) have a mean direction toward ~ N50° (see map and stereograms in Pl. 2).

At a kilometre-scale, folds involve both the basement and the cover, and generally appear to be open, with steeply inclined axial planes, so that clearly overturned limbs are frequently missing, and vergence may be toward either the SE or NW.

The largest structure of this phase is represented by an antiformal fold, which shows the basement at its core and runs between Riofreddo and Barbassiria (Pl. 1). The fold is non-cylindrical: the inclination of its southeastern limb progressively increases from the Riofreddo region (fold geometry at this place is shown – although somewhat distorted – in cross-section no. 6 of Pl. 1) to the Barbassiria area, where this same limb is very steeply inclined.

The axial plane traces of other subkilometre-scale folds of this type are shown in Plate 2.

Minor folds belonging to this event occur in all the formations of the Mallare sequence, but they are more apparent (and probably much more frequent) mainly in the metasediments of the Ollano Fm. *(Ma3),* where they seem to be distributed in discrete, 10–100 m domains. Their geometry varies in relationship to the grain size of the rock, but, on the whole, they are tight, of a flattened concentric type, and they are accompanied by a very well developed crenulation cleavage (S2); in the phyllitic lithotypes, the former foliations are nearly always completely transposed on this new set of planes. Possibly as a result of décollement phenomena, most of these folds in the Carboniferous metasediments are clearly NW-verging.

Pa and **Ca** units – The above-mentioned D2 antiform, which trends from Riofreddo to Barbassiria region, also involves **Pa** and **Ca** units; this is shown by the closure of the limits between the different units in the southwestern corner of the map (Pl. 1). This feature also indicates that the antiform has an axial plunge to the SW, which is probably a result of the D3 event. In the northwestern sector (Colle dei Giovetti area), there is a D2 antiformal fold, with an inverted limb. Involving the **Pa** and **Ma** units, the fold deserves a mention because its vergence is clearly toward the NW.

All through the different lithologies of the **Pa** and **Ca** units, S2 foliation is represented by a well developed crenulation cleavage, on which (in the very fine-grained rocks) the older foliations are often completely transposed; the S2 planes accompany mesoscopic, tight A2 folds, whose mean axial trend is SW-directed (see Pl. 2 for details about the various sectors).

D3 structures

The D3 event is very well displayed at the map scale: the western and northeastern margins of the **Ma** unit outline large basin-like structures that border the central "dome" and are made by the upper units (**Pa** in the N and the E; **Pa, Ca** and **So** in the W). Likewise, the contact between the basement and the cover in the **Ma** unit shows an asymmetrical dome-and-basin interference pattern, in general similar to type E of Ramsay (1967). The same dome-like geometry is apparent both in the cross-sections in Plate 1 and in many of the stereograms in Plate 2. In particular, the dispersion of the poles to S2 planes and A2 axes demonstrates that a later, D3 ductile event contributed to the above pattern.

The axis and axial plane attitude of this last regional folding event is, however, not immediately apparent everywhere. Mainly in the northern sector of the map (Pl. 2), there are some axial plane traces that show an overall NW- to NNW-trending direction, which also involve the contact between the **Pa** and **Ma** units (see also cross-section no. 5 in Pl. 1).

The mesofolds of this phase (mainly represented by open N120°- to N150°-trending kinks) are only rarely observable; likewise, a zonal, very widely spaced subvertical fracture cleavage that trends between N330° and N20° is very occasionally detectable; but, because of its overall varied distribution, it cannot be connected with certainty to a post-D2 fold system. Nor is it possible to avoid errors in attempts to infer the D3 trend from the stereograms in Plate 2. The above-described overall characteristics make it reasonable to choose a nearly vertical axial plane and a sub-horizontal axis. But, even if this very simple solution is adopted, the direction around which pre-existing structures should be rotated is not precisely determined, because it obviously depends on which former attitude is selected for each group of structures (S1, L1, S2, A2).

To sum up briefly, on the grounds of the tests which we performed, it seems possible to obtain much of the present geometry, if a ~NW axial trend is assumed for the D3 phase;

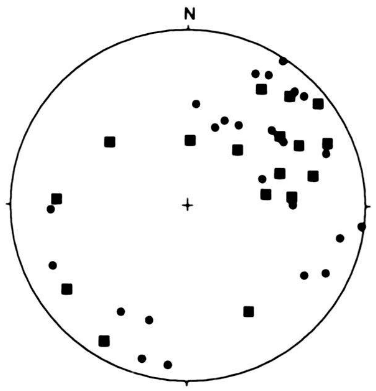

Fig. 3. Poles to 41 minor fault planes measured in some outcrops of the Mallare unit (*Ma1* and *Ma3* formations). Dots and squares distinguish planes on which the pitch of striations is respectively high and low.

often, however, it appears that an additional ~E-W axial trend might also be involved.

Alpine metamorphic conditions

As established by Cabella et al. (1991) and by Cortesogno et al. (1995), only the first two Alpine tectonic events are associated with significant metamorphic parageneses. S1 schistosity developed under high pressure conditions [P ≈ 0.8 (± 0.1) GPa, T ≈ 350°C (± 25°C) in the **Ma** and **Pa** units; P ≈ 0.5 (± 0.1) GPa, T ≈ 300°C in **Ca**; local data on **So** are lacking], while the S2 foliation is characterised by a decompressional evolution, possibly accompanied by a slight temperature increase.

Late fault and joint systems

As is apparent in Plates 1 and 2, a certain number of faults have been mapped. On the whole, they are steeply inclined, and can be grouped into two sets trending ~NW and ~NE. Striations on planes are always oblique, with pitch ranging from high (50° or more) to low (30° or less). As is commonly observed, these faults cut the S2 planes, and are frequently accompanied by gouges.

We undertook no systematic mesostructural analysis on these brittle structures. Most of the collected data (Fig. 3) come from Barbassiria Orthogneisses *(Ma1)* and from the Ollano Fm. *(Ma3)*. Mutual displacements on the two sets of planes (NW- and NE-trending) were only rarely observed. Likewise, kinematic indicators were generally insufficient for us to establish the sense of movement. Thus, on the basis of present knowledge, it is impossible to state whether faults can be grouped into two conjugate sets. Various attempts have been unsuccessfully made to ascertain whether after a convenient retro-rotation, the pitch of the slip directions approaches either 0° or 90°. The fact that the slip direction seems to be inclined, the inclination of the slip direction can be either high or low on planes with nearly the same attitude, and superimposed slip directions are very rare, might suggest, among other possibilities, either transtension or transpression for the stress field.

Finally, we report that – mainly in the **Ma** basement gneiss outcrops – some joint systems are very frequently exposed.

Concerning the relative age of the above brittle structures, the only certainty that can be advanced is that, on the whole, they post-date the D2 deformation, and might be contemporary with or younger than the D3 "doming" phase.

Tectonic events and their relative chronology

Of the questions that arise from the above data and that have been left aside until now, we shall briefly and selectively discuss those that, in our opinion, may help our understanding – not only at a local scale – of how and when Alpine events occurred.

As shown by the map and cross-sections 1, 2, 12 (Pl. 1), the sole thrust of the **Pa** unit cuts the D1 folds affecting the **Ma** unit; hence, **Pa** was emplaced on **Ma** only after the latter had been involved in the D1 folding phase. As **Pa** and **Ma** had been folded together since the "Late-D1" phase, it follows that the **Pa** unit too had already been folded by the D1 event at the time of its superimposition on **Ma**.

The high pressure-low temperature metamorphic conditions accompanying the D1 folding phase suggest that the deformation might have developed in a sort of "ensialic subduction zone". If so, it should be admitted that a slab (formed by at least two contiguous sectors of the Briançonnais domain) entered this zone (i.e. a large, hindward dipping belt) where it was folded without loss of the original adjacency relationship of its individual parts.

Where convenient lithologies and suitably exposed lithologic boundaries exist – as occurs in **Ma** – a stretching lineation (L1) was observed and it was possible to map the sheath-like geometry of at least one major fold; these types of structure, in association with *s-c* systems, σ and, above all, δ-structures, indicate a dominant simple shear component of D1 deformation, as predicted on the basis of the above model.

The individualisation of the present **Ma** and **Pa** units started only after this folding event, with the birth of thrust surfaces along which forward-directed transport and nappe piling occurred. The same conclusion may also be applied to **Ca** and **So**, as each nappe rests on various stratigraphic units of the underlying ones.

Something of the original attitude of the thrust surfaces can be deduced from the map. The pre-Namurian basement (i.e. the lower part of the stratigraphic sequence of **Pa**) is missing all along the contact between **Pa** and **Ma.** In other words, the floor thrust of **Pa** cuts the already folded sequence at levels that become higher in the direction of the tectonic transport. This indicates that the thrust had a hinterland dip.

This same conclusion also applies to **Ma**. As a matter of fact, the orthogneisses in the core of the antiformal D2 fold which runs from Riofreddo towards the SW (Pl. 1, map and section no. 6) are bordered by the Ollano Fm. *(Ma3)* on their southern side and by the Lisetto Metarhyolites *(Ma2)* on their northern limb; the metavolcanic rocks are, in turn, directly covered by the **Pa** unit. The *Ma2* metarhyolites are missing on the southern limb, probably as a consequence of Late Carboniferous events (Seno et al. 1997). But the lack of the Ollano Fm. (i.e. the youngest part of the sequence of **Ma** cropping out in the mapped area) all along the contact with **Pa** seems to be much better explained by Alpine tectonics. A possible solution consists in detaching the Ollano Fm. from its stratigraphic base before this latter is overridden by the **Pa** unit. Moreover, if one moves towards the southern quadrants (i.e. in the direction of tectonic transport), the Ollano Fm. appears in turn to lack its post-Carboniferous cover. To find outcrops of this cover, one must move further to the south, just beyond the southern limit of our map. Hence, one is led to draw a thrust surface that cuts through the already folded **Ma** sequence, with an attitude on the whole similar to that of the **Pa** floor thrust. As **Pa** proceeded forward and covered **Ma**, the upper part of this latter in turn moved in the same direction, and is presently to be found outside the Barbassiria area, in more external sectors of the chain. The map as well as the cross-sections (Pl. 1) clearly show that each of the three units (**Ma, Pa** and **So**) for which the stratigraphic polarity can be established, although involved in D1 folds with inverted short limbs, is made up of an overall normal (i.e. not overturned) slab: this finding agrees with the expected geometry of thrust-bounded, overriding nappes.

From the above, the D1 event was probably accomplished inside a hinterland dipping belt, where units were firstly folded and then piled up.

The following step is represented by the "Late-D1" thrust system. A special problem concerning this event lies in the vergence of the structures it produces. No reliable explanation can as yet be offered, but there is sufficient evidence to warrant a hypothesis.

It should firstly be remarked that, in spite of the considerable amount of observed shortening, the northern limit between **Pa** and **Ma** is only slightly displaced along the sinistral shear zone (*s.s.z.* in cross-sections of Pl. 1 and map of Pl. 2). This means that it plays the role of a transfer (or tear) zone. Although important, the system has a local distribution and, as one moves southward – i.e. away from the bottom thrust (plane **a** in cross-sections of Pl. 1 and in map of Pl. 2) – the shortening decreases. It may be postulated that the foreland-directed deformation produced the onset of a local buried, somewhat transversal, obstacle in front of **Ma** and **Pa**; this, in turn, caused their folding and thrusting.

It is probable that the D2 folding phase took place soon after the above event. That the time interval between these two deformations was short seems to be suggested by the P-T conditions during the S2 development; in effect, they indicate that the units were still buried at a not inconsiderable depth.

The absence of metamorphic paragenesis on those fracture cleavage planes that are possibly associated with the D3 "doming", and the clearly "cold" character of gouges that accompany the late brittle systems, combine to indicate that this last set of events was accomplished in the upper structural level. As already observed, the lack of a detailed, complete study of faults and joints prevents the determination of a reliable relative timing for these structures.

Conclusions and regional comparisons

Some of the results of the present study seem to deserve special attention, because of their possible application to other sectors of the Penninic Zone, at least in its Ligurian segment.

In the Mallare unit, which is ascribed to the intermediate-internal Ligurian Briançonnais domain, the pre-Namurian basement is still adherent to its stratigraphic Upper Carboniferous cover. It was possible to ascertain that the foreland SW-verging, kilometre-scale tight folds usually associated with the first Alpine ductile event here involve both basement and cover.

The unconformities that were outlined by the detailed mapping, together with data on the geometric and metamorphic character of folds, show that nappe piling-up followed the first phase of internal ductile deformation. Hence, the high pressure-low temperature conditions during the D1 folding event cannot have been produced by a nappe pile, but must have been produced inside an intracrustal shear zone. The lack of increasing thicknesses of the upper part of the original stratigraphic sequence of **Pa** and **Ma** when one moves toward the hinterland suggests that the thrust belt that developed during the following overriding phase was in turn foreland-verging.

On the whole, the evolution of the studied sector fits into the regional framework.

As for the D1 phase, this is true both in terms of geometric and of metamorphic characteristics and, in particular, of the forward (~ SW-ward) direction of tectonic transport of the Ligurian Briançonnais units (Vanossi 1991, Seno 1992, Dallagiovanna 1995): this latter finding indicates that no important rotations occurred among these units. The relationship between the above data and interpretations and the regional setting is further confirmed by the fact that, far to the south, the **Ma** unit rests over other units (Cabella et al. 1991) whose first Alpine metamorphic parageneses indicate a much lower pressure (P ~0.5 GPa) than that found for **Ma**. One possible suggestion is to consider these units as representing an originally more external part of the palaeogeographic Briançonnais domain, which remained at shallower levels inside the intracrustal shear belt and were overthrusted by inner slabs during the piling of the nappes.

As to comparisons with the D2 regional phase, the unexpected existence of the "Late-D1" system should be underlined. Its NNW-vergence and relatively high degree of shortening are similar to those known at a regional scale for the D2 "back-folding and thrusting event". Only detailed structural analysis has shown that in the Barbassiria area this system corresponds to an older, although local, phenomenon, that occurred during the main, foreland-directed deformation episode. We would like to suggest that this interpretation is possibly open to extrapolation to other sectors of the Alpine chain.

Finally, here as everywhere in the Ligurian Alps, the "dome-and basin" phase – even if not severe in itself – is apparent, and greatly influences the present geometry of structures. On the whole, its local trend, although somewhat uncertain, seems to agree with that of the regional event, which is known (Vanossi et al. 1994) as the "Apenninic-trending phase".

Acknowledgements

The authors wish to thank P. Philippot and R. Sacchi for reviewing the manuscript. The research was supported by M.U.R.S.T. and C.N.R. grants.

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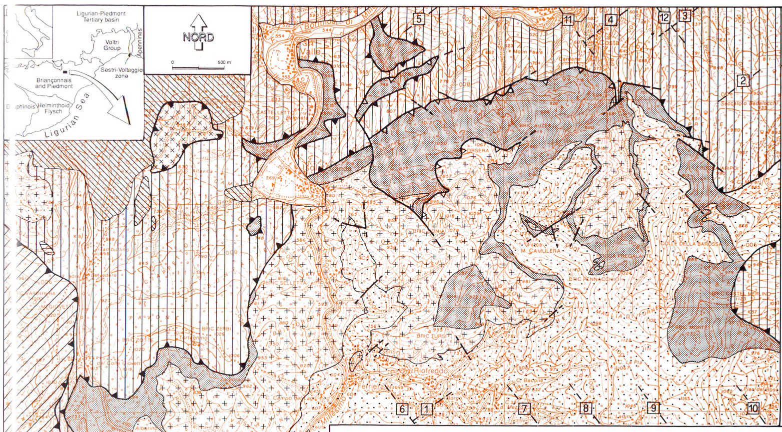
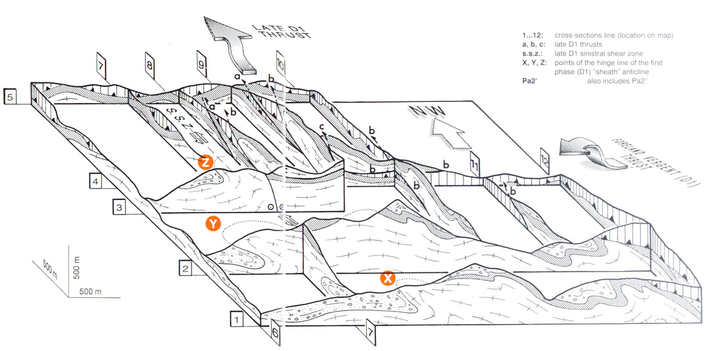
Manuscript received September 25, 1996
Revision accepted March 27, 1997



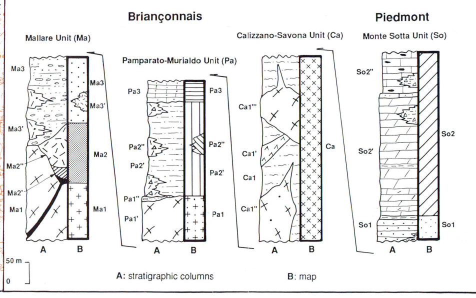
An example of the Alpine structural evolution of the Penninic Zone in the Ligurian Alps:

Tectonics of the Barbassiria area

by G. Dallagiovanna, S. Seno & M. Vanossi



1...12: cross-sections line (location on map)
a, b, c: late D1 thrusts
s.s.z.: late D1 sinistral shear zone
X, Y, Z: points of the hinge line of the first phase (D1) "sheath" anticline
Pa2' also includes Pa2''



Monte Sotta Unit (So)

So2" Dark-grey siliceous limestones, with minor breccia layers (Lias).
So2' Dark fossiliferous limestones and yellowish dolomitic limestones (Rhaetian) grey dolostones, interbedded with breccias (Norian); discontinuous pelitic layers (Carnian ?); grey, light-brown and blackish-coloured limestones and dolostones, with decimetric to metric well stratified layers (Ladinian- Anisian).
So1 *Ponte di Nava Quartzites*. White and greenish micaceous quartzites; minor conglomeratic lenses; greenish pelites at the top (Scythian).

Calizzano-Savona Unit (Ca)

Ca1''' "Orthogneisses II", showing K-feldspars, muscovite, biotite, oligoclase and quartz assemblages (Pre-Namurian).
Ca1" "Orthogneisses I", coarse to medium-grained, with K-feldspar, plagioclase, polycrystalline quartz, biotite, muscovite assemblages; they commonly show interbedded leucoaplitic layers, dykes and volcanites (Cambrian - Ordovician?).
Ca1' Amphibolites with hornblende, garnet, plagioclase, diopside and clinozoisite assemblages (Cambrian- Ordovician?).
Ca1 Paragneisses and micaschists, characterized by the stability of kyanite and sillimanite, with staurolite, almandine, biotite and plagioclase assemblages (Cambrian-Ordovician?).

Pamparato-Murialdo Unit (Pa)

Pa3 *"Calcschistes planctoniques"*. Greenish calcareous, finely detrital schists, with quartz, phengite and chlorite (Upper Cretaceous-? Middle Eocene ?).
Pa2" *Eze Formation*. Metaandesites and andesitic metabasalts, with plagioclase and hornblende, sometimes pyroxene, and with plagioclase, ortho and clinopyroxene, and probable olivine assemblages, respectively (Upper Carboniferous).
Pa2' *Murialdo Formation*. Blackish phyllites, quartz-albitic-phengitic and chloritoid schists, commonly characterized by quartz veins (Upper Carboniferous).
Pa1" *Lisio Formation*. Minor lenses of paragneisses covering Pa1' (Upper Carboniferous).
Pa1' *Nucetto Orthogneisses*. Orthogneisses bearing K-feldspar megacrysts, quartz, oligoclase, muscovite, biotite (Pre-Namurian).

Mallare Unit (Ma)

Ma3 *Ollano Formation*. Metaconglomeratic-sandy-pelitic fluvial-lacustrine sequences, sometimes with graphitic lenses. Pebbles in conglomeratic layers are mainly quartzitic; sandstones and siltites are always micaceous. Intercalations of pyroclastic agglomerates with rhyolitic to rhyodacitic xenoliths, showing K-feldspar, quartz and plagioclase contents *("Bric Crose Tuffs",* **Ma3'**) are mainly found in the lower part of the formation (Upper Westphalian-Stephanian).
Ma2" *Case Lisetto Metarhyolites*. Rhyolitic-rhyodacitic ignimbrites with K-feldspar, quartz, plagioclase and biotite assemblages, in quartz-albitic-phengitic mesostase (Lower Westphalian?).
Ma2' "Lowermost Metavolcanites". Rare dacitic, with K-feldspar, minor quartz and biotite in quartz-phengitic mesostase, to trachyandesitic layers, showing albite, epidote, green biotite and minor clinopyroxene assemblages (Upper Namurian ? - Lower Westphalian?).
Ma1 *Barbassiria Orthogneisses*. Metaderivates from rhyolitic protoliths affected by a Variscan metamorphic phase, showing K-feldspar, quartz, muscovite and neoblastic alpine garnet assemblages; frequently interbedded with thin layers of quartz-micaceous metasediments (pre-Namurian).

White: Quaternary deposits, mainly alluvial.

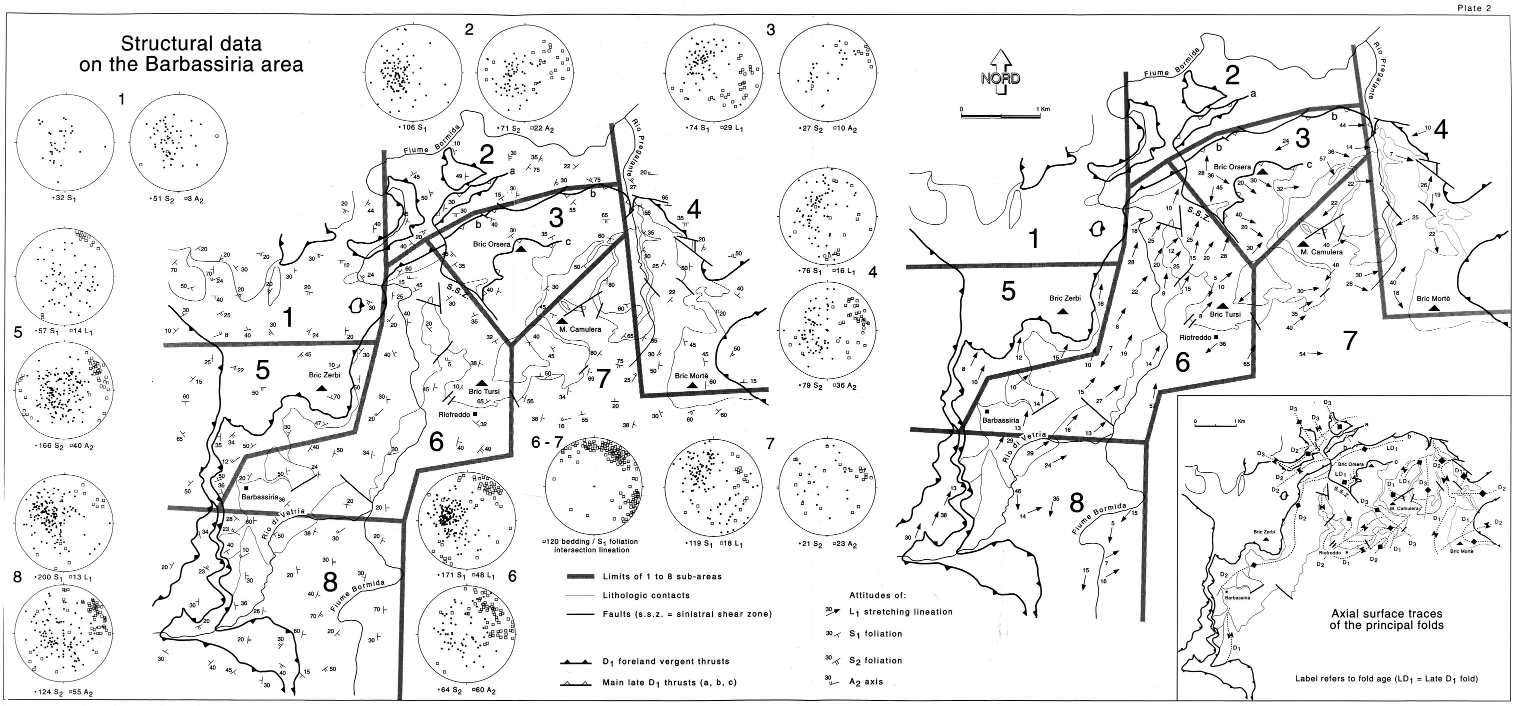
Lithologic contact:

D1 foreland vergent thrust:

Late D1 thrust:

Fault:

Line of section:


Structural data
on the Barbassiria area
•32 S1
•51 S2 ▫3 A2
•106 S1
•71 S2 ▫22 A2
•74 S1 ▫29 L1
•27 S2 ▫10 A2
•57 S1 ▫14 L1
•166 S2 ▫40 A2
•76 S1 ▫16 L1
•79 S2 ▫36 A2
•200 S1 ▫13 L1
•124 S2 ▫55 A2
•171 S1 ▫48 L1
•64 S2 ▫60 A2
▫120 bedding / S1 foliation
intersection lineation
•119 S1 ▫18 L1
•21 S2 ▫23 A2
Fiume Bormida
Rio Pregalene
Rio di Vetria
Bric Orsera
M. Camulera
Bric Zerbi
Bric Tursi
Riofreddo
Bric Mortè
Barbassiria
S.S.Z.
NORD
1 Km
Limits of 1 to 8 sub-areas
Lithologic contacts
Faults (s.s.z. = sinistral shear zone)
D1 foreland vergent thrusts
Main late D1 thrusts (a, b, c)
Attitudes of:
L1 stretching lineation
S1 foliation
S2 foliation
A2 axis
Axial surface traces
of the principal folds
Label refers to fold age (LD1 = Late D1 fold)