Data collecting and mapping for kinematic reconstruction: A case history from the Ligurian Alps

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ABSTRACT

Four superposed tectonic units crop out in the area considered. Detailed mapping and data on stratigraphy, tectonics and metamorphism were used to reconstruct the complex Alpine structural geometry and possible strain path. Using all available structural data (attitude of foliations, hinge lines, stretching lineation; finite strain measurements), a retro-deformation process was applied in order to reconstruct the most probable configuration and evolution of the top of the pre-Namurian basement during Late Carboniferous times. Local data and related processing have been inserted into a wider regional framework, characterised by the stacking of a great number of nappes. Starting from the most probable Late Jurassic palaeogeographical setting for this sector of the Alpine chain, the authors have produced a general model of the kinematic evolution of the Briançonnais units, in which a satisfactory fit is found for the characteristics of the nappes considered here.

AIMS AND METHODOLOGY

The research was developed in the following main steps.
1. - Structure geometry, at different scales. Deformation phases and relevant thermo-baric conditions.
Methodology - Detailed mapping, including data on foliations, lineations and other tectonic meso-structures (attitude, characters related to different lithologies, associated metamorphic parageneses) (Figs. 1 and 3). Fence diagram construction; 3D geometry of hinge lines reconstruction; block diagram construction (Fig. 4).
2. - Strain path identification.
Methodology - Finite strain measurements (Fig. 3). Strain factorisation (Fig.5).
3. - Check of structure geometries against the model assumed for their generation.
Methodology - 3D computer simulation (Fig. 6).
4. Construction of the kinematic model.
Methodology - Insertion in a wider regional frame: tectonic map (Fig. 9) and general section (Fig. 10). Selection of the most probable paleogeographical general setting (Fig. 9). Model for the progressive evolution of the chain sector considered, checked against relevant constraints at each step (Figs. 11 and 12).
5. - Although not directly related to the main line of the research, data on Alpine tectonics were used to restore Late-Variscan palaeogeography.
Methodology - Retrodeformation of Alpine structures involving basement and Permian-Carboniferous tegument in order to reconstruct the geometry and attitude of the bottom surface of the tegument (Fig. 7). Use of the restored surface to construct block diagrams showing a possible Permian-Carboniferous evolution, fitting in facies, thickness and lateral variations of the involved lithological units (Fig. 8).

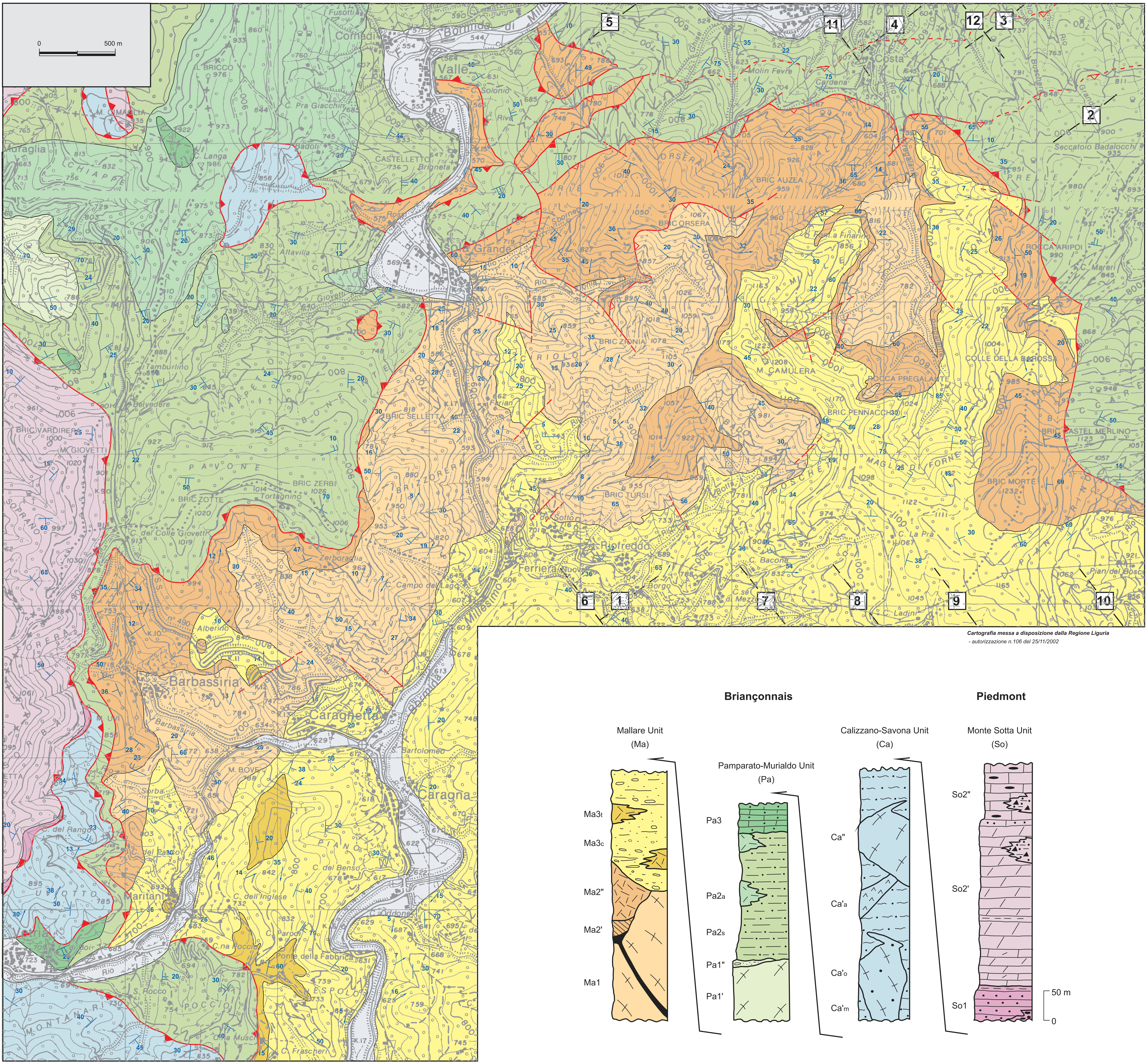
KEY WORDS

Ligurian Alps, Briançonnais, finite strain measurements, retro-deformation process, pre-Namurian basement evolution, Alpine strain path, Alpine kinematic model.

RIASSUNTO

Il rilevamento di un settore nel quale affiorano quattro unità tettoniche sovrapposte, e i dati di stratigrafia, tettonica e metamorfismo, hanno consentito di ricostruire le geometrie ed il possibile percorso della deformazione. Utilizzando tutti i dati strutturali raccolti (giaciture delle foliazioni, delle linee di cerniera, delle lineazioni di estensione; misure di strain totale), le strutture alpine sono state retrodeformate, ricostruendo la possibile articolazione tardo-ercinica dell'area. I dati locali e le relative elaborazioni sono stati inseriti in un più ampio contesto regionale che mostra la sovrapposizione di numerose unità. Partendo dalla ricostruzione della più probabile paleogeografia tardo-giurassica, è stato proposto un modello generale di evoluzione cinematica del dominio brianzonese nel quale i caratteri delle unità qui cartografate trovano un soddisfacente riscontro.

GEOLOGICAL MAP OF THE BARBASSIRIA AREA (LIGURIAN ALPS)



Legend

Continental deposits, mainly alluvial (Quaternary).

M. Sotta Unit (So)

So2
- Dark-grey siliceous limestones, with cherty nodules and minor breccia layers (Liassic) (**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) (**So2'**).

So1
- *Ponte di Nava Quartzites*. White and greenish micaceous quartzites; minor conglomeratic lenses; greenish pelites at the top (Scythian).

Calizzano-Savona Unit (Ca)

Ca
- "Orthogneisses II", showing sub-decimetric K-feldspars, muscovite, biotite, oligoclase and quartz assemblages (Early Carboniferous?) (**Ca"**).
- Amphibolites with hornblende, garnet, plagioclase, diopside and clinozoisite assemblages (Ordovician?-Cambrian) (**Ca'$_a$**).
- "Orthogneisses I", coarse to medium-grained, with K-feldspar, plagioclase, polycrystalline quartz, biotite, muscovite assemblages; they commonly show interbedded leucoaplitic layers, dykes and volcanites (Ordovician?-Cambrian) (**Ca'$_o$**).
- Micaschists and paragneisses characterized by the stability of kyanite and sillimanite, with staurolite, almandine, biotite and plagioclase assemblages (Ordovician?-Cambrian) (**Ca'$_m$**).

Pamparato-Murialdo Unit (Pa)

Pa3
- *"Calcschistes planctoniques"*. Greenish calcareous, finely detrital schists, with quartz, phengite and chlorite (Middle Eocene?-Late Cretaceous).

Pa2$_a$
- *Eze Formation*. Meta-andesites and andesitic metabasalts, with plagioclase and hornblende, sometimes pyroxene, and with plagioclase, ortho and clinopyroxene, and probable olivine assemblages, respectively (Stephanian?-Westphalian?).

Pa2$_s$
- *Murialdo Formation*. Blackish phyllites, quartz-albitic-phengitic and chloritoid schists, commonly characterized by quartz veins (Stephanian?-Westphalian?).

Pa1
- *Lisio Formation*. Minor lenses of paragneisses covering **Pa1'** (Namurian?) (**Pa1"**).
- *Nucetto Orthogneisses*. Orthogneisses bearing K-feldspar megacrysts, quartz, oligoclase, muscovite, biotite (Pre-Namurian) (**Pa1'**).

Mallare Unit (Ma)

Ma3$_t$
- *Bric Crose Tuffs*. Intercalations of pyroclastic agglomerates with rhyolitic to rhyodacitic xenoliths, showing K-feldspar, quartz and plagioclase contents; mainly found in the lower part of **Ma3$_c$**.

Ma3$_c$
- *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 (Stephanian-Late Westphalian).

Ma2
- *Case Lisetto Metarhyolites*. Rhyolitic-rhyodacitic ignimbrites with K-feldspar, quartz, plagioclase and biotite assemblages, in quartz-albitic-phengitic mesostase (Early Westphalian?) (**Ma2"**).
- "Lowermost Metavolcanites". Rare dacitic, with K-feldspar, minor quartz and biotite in quartz-phengitic mesostase, to trachyandesitic layers and dykes, showing albite, epidote, green biotite and minor clinopyroxene assemblages (Early Westphalian?-Late Namurian?) (**Ma2'**).

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 (Early Carboniferous?).

30 — L1 stretching lineation

28 — S_1 foliation

22 — S_2 foliation

10 — A_2 axis

Lithologic contact

D_1 foreland vergent thrust

Late D_1 thrust

Fault

2 — Line of section in Fig. 4

Fig. 1 - *Geological map of the Barbassiria area (Ligurian Alps) showing four superposed tectonic units. The legend and the stratigraphic columns provide information on the lithological characters and thickness of all the mapped formations. Columns are ranged in the assumed relative original location of the related units (three coming from the Briançonnais domain, one from Piedmont), starting from the relatively more external (Mallare Unit), which is also the lowest in the present nappe pile.*

GEOLOGICAL SETTING

The sketch-map (Fig. 2) shows the main groups of tectonic units that crop out in the Ligurian Alps, west of the Northern Apennines and the Sestri-Voltaggio "link-zone". On the whole, they form a pile of nappes that were displaced from their original domains and transported outwards during the principal (Eocene) Alpine orogenic event.

On the basis of widely accepted palaeogeographic reconstructions (LEMOINE *et alii*, 1986; VANOSSI 1986; STAMPFLI, 1993; DAL PIAZ, 1999), it may be assumed that nappes were initially located along three adjacent domains: Briançonnais, on the European continent, Piedmont -representing the margin of this continent- and Piedmont-Ligurian, corresponding to the oceanic basin. The "oceanic" Voltri Group rests on the Piedmont

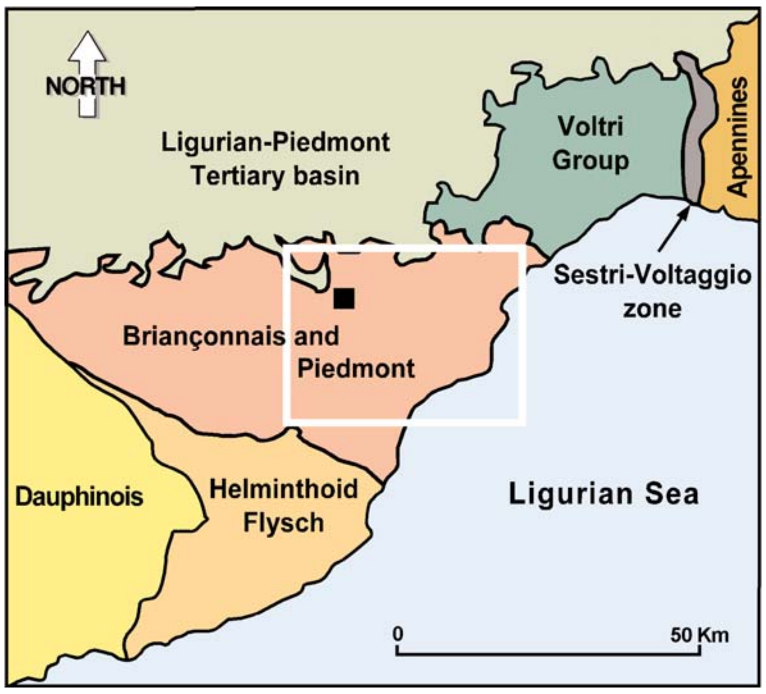


Fig. 2 - *Sketch-map, showing the present outcrops of the main groups of tectonic units in the Ligurian Alps (Briançonnais and Piedmont units could not be separated owing to the scale of the map). The original location of units, as well as the correspondence between their names on the map and the relevant palaeogeographic domain, are discussed in the text. Each nappe is characterised by a peculiar stratigraphic sequence. No detailed description of all the sequences (more than 20) is included, as it is beyond the scope of this work. Some examples are shown in the maps of Figs. 1 and 9. For more information see* VANOSSI *(1991),* DALLAGIOVANNA et alii, *(1995) and* SENO et alii *(2003).*
The little black square locates the area shown in Fig. 1. The wider white rectangle indicates the region mapped in Fig. 9.

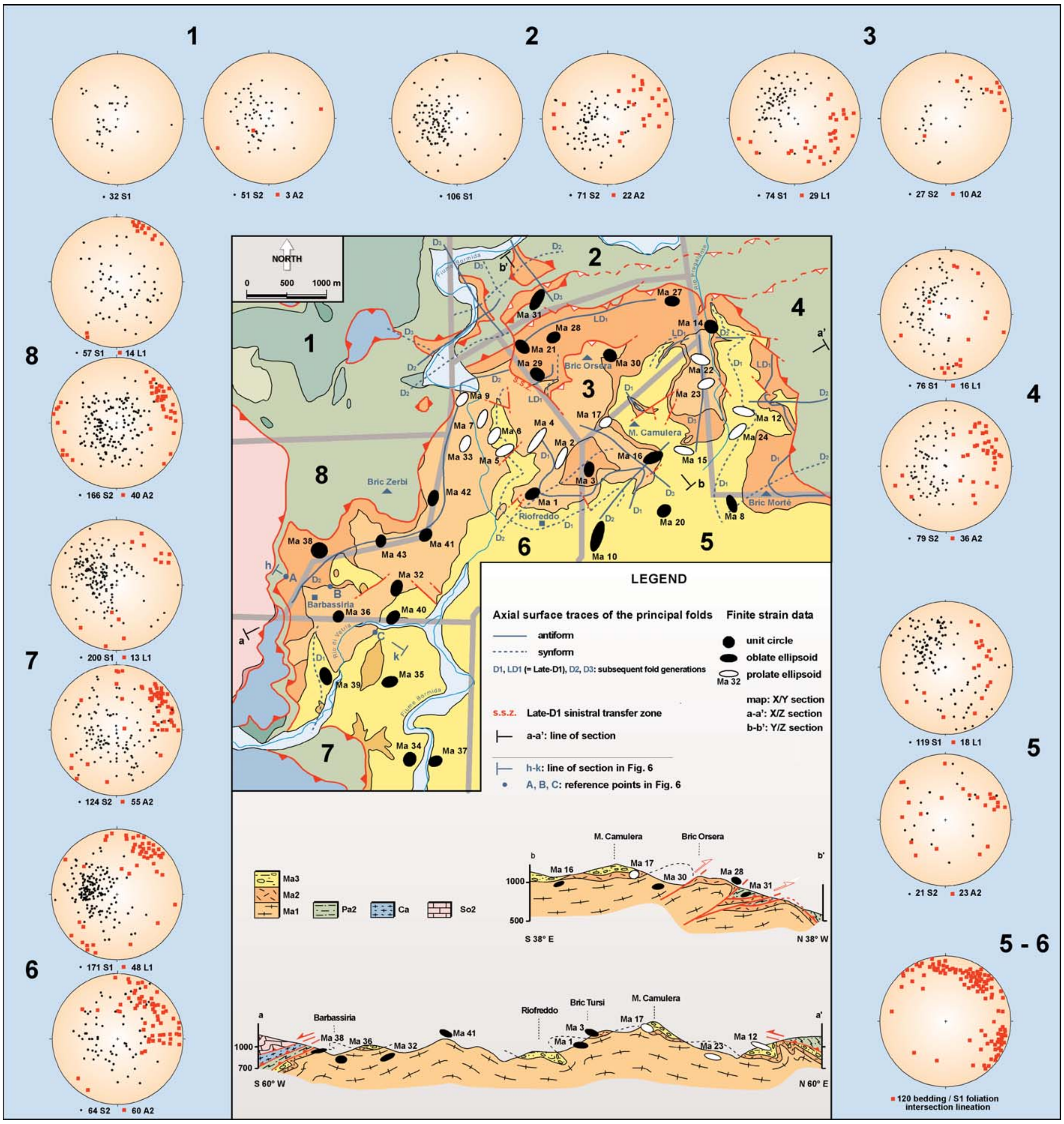
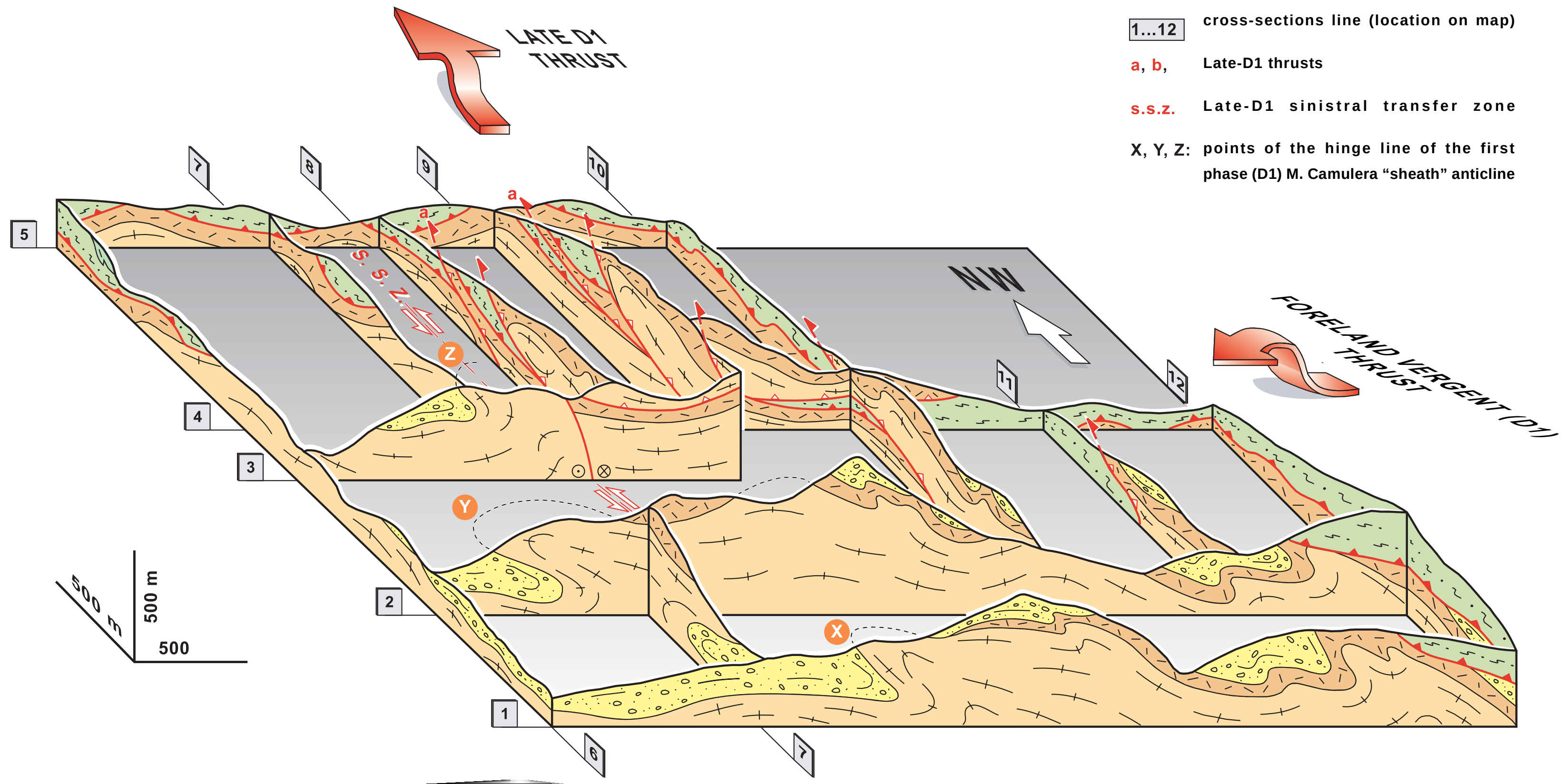


Fig. 3 - *Axial surface traces of the principal folds and finite strain data. The methodologies used for bulk strain determination are described in* SENO et alii *(1998, and references therein).*



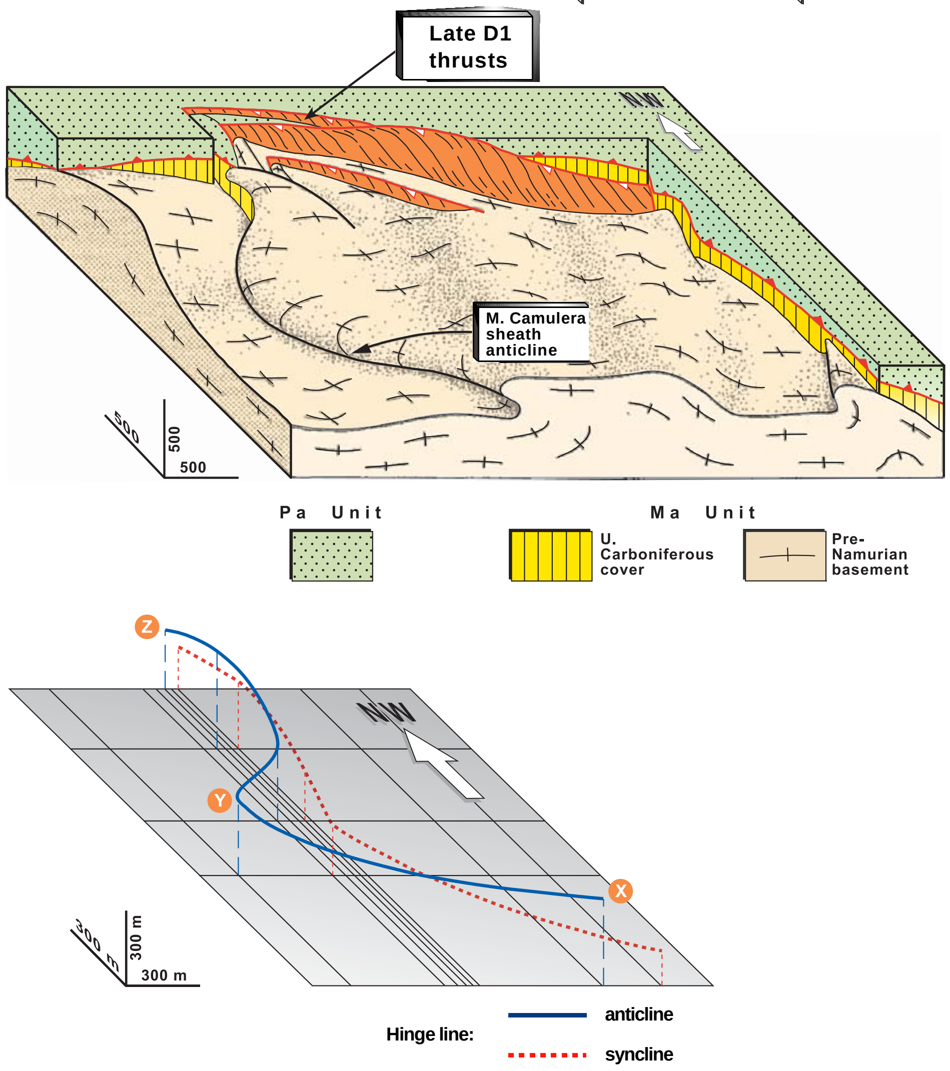


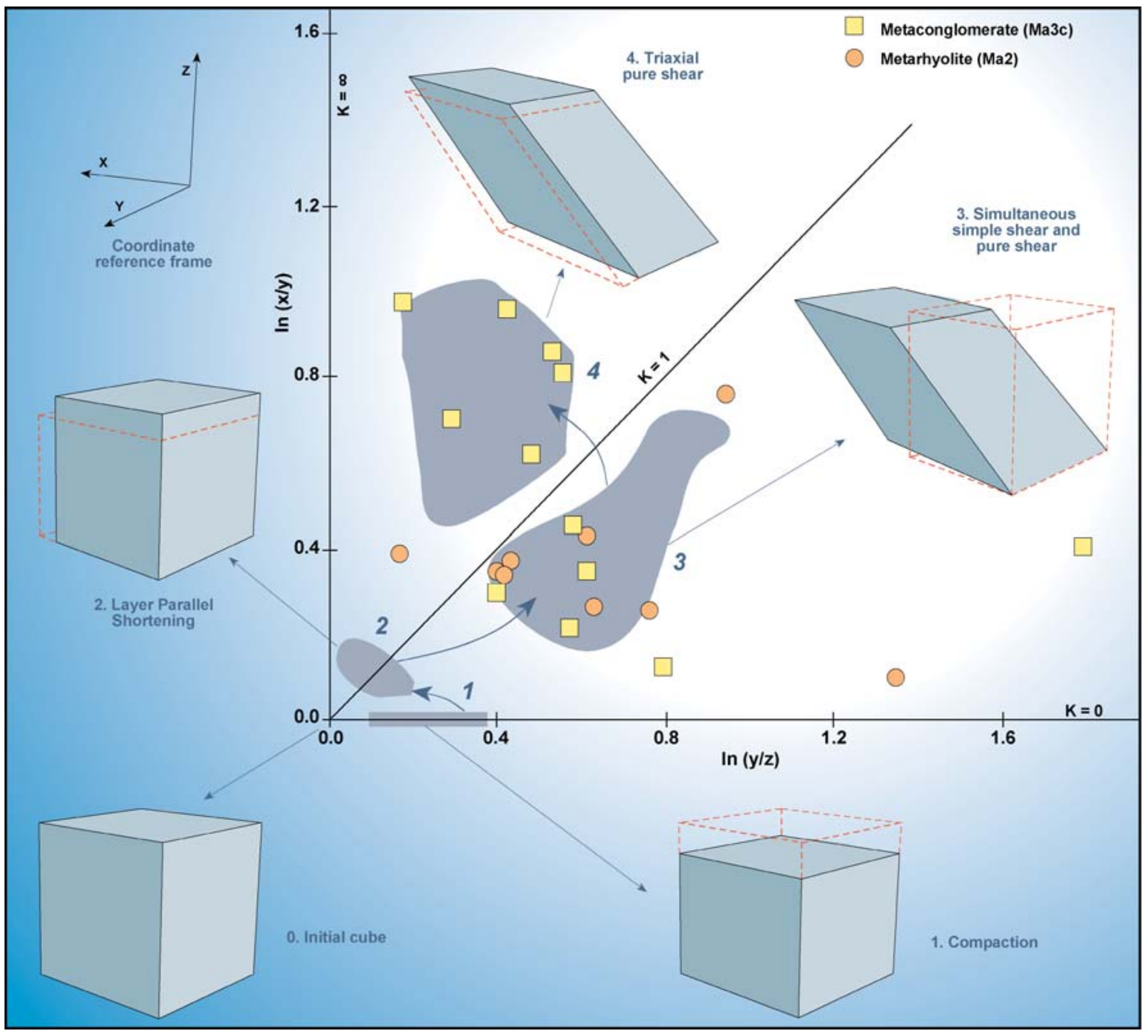
Fig. 4 - *3D reconstruction of the structures. The complex geometry of the structure was reconstructed using a fence-diagram* (above). *The three-dimensional development of the hinge lines of the two D1 kilometre-scale folds that crop out on the south-western side of Mt. Camulera is also shown* (below*; see cross-sections* 1, 2, 3 *in the fence-diagram for location of points* X, Y *and* Z *on the anticline hinge). The sheath-like geometry (more pronounced in the anticline than in the underlying syncline) is apparent. It should also be noted that both lines are affected by vertical variations connected with the* D3 *deformational event. The bedding/schistosity* (S_0/S_1) *intersection lineation* (L_{01}) *that was measured in the Ollano metasediments shows that the hinge lines are clearly curved in the sub-horizontal axial surface of the folds. The* 3D *shape of one* D1 *km-scale SW-verging "sheath"-like fold involving the basement, as deformed by subsequent late-*D1, D2 *and* D3 *events, has also been reconstructed.*

nappes, that in turn are thrust on to the Briançonnais sector. This ensemble, which goes to form the Penninic realm, has been transferred onto the outermost Dauphinois domain. The top of the pile is represented by the Helminthoid Flysch nappes belonging to the oceanic domain, which -having bypassed the Penninic realm- rest on the Briançonnais-Dauphinois contact.
When considered in detail, the present structure of the Ligurian Alps chain is particularly complex and not easy to unravel (VANOSSI, 1991 and refs. therein). More than 20 tectonic units have been mapped and analysed over an area of about 2,500 km^2. These either comprise basement and cover-still stratigraphically joined locally- detached covers only or basement only. Their complex pattern is mainly the result of three subsequent deformation phases. On the whole, the order of nappe superposition acquired at the end of the first (D1) event has not been greatly modified. Hence this event is by far the most important, as it led to the stacking of the nappe pile, producing four main families of duplexes (from the bottom: outer Briançonnais, inner Briançonnais, Piedmont and Piedmont-Ligurian), all outward SSW-directed. In some places, this first phase ended with a Late-D1 event, which generated back-thrusts, not to be confused with those produced by the following phase (D2), when the nappes underwent a general NNW-verging backfolding deformation, with intensity decreasing towards the outer sectors. At a later stage, the chain was involved in a deformation (D3) phase (trending nearly at right angles to the older folds) that produced asymmetrical dome-and-basin interference patterns. This event -probably linked to the opening of the Ligurian sphenochasm (VANOSSI *et alii*, 1994)- also rotated the former structures to variable degrees. Hence, for the sake of clarity we have referred the original direction of tectonic transport to the present geographical framework.
In the north, the late- to post-orogenic unconformable deposits of the Piedmont Tertiary Basin indicate that contacts between nappes must have been acquired before Early Oligocene times. The study in question refers to the analysis of a number of Briançonnais and Piedmont units.

WHY THE AREA WAS SELECTED

In the Ligurian Alps, the geometry of the different ductile phases is often easily seen at a meso-scale in any lithological unit, but at the kilometre scale, it can be reconstructed only in the Meso-Cenozoic covers, where stratigraphic guide-levels are mappable. Unfortunately, sedimentary covers are, on the whole, rather rare and usually 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 their geometry but also regarding their kinematics, which in turn casts obvious doubts on palinspastic restorations.
Therefore, following a preliminary study (CORTESOGNO *et alii*, 1995), the Barbassiria area was selected for detailed geological and structural mapping (at a scale of 1:10,000 and 1:5,000), as here the pre-Namurian metamorphic basement, together with its Upper Carboniferous volcanic and sedimentary cover, is exceptionally 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.

Fig. 5 - *Possible strain paths accompanying the pre-*D2 *complex deformation history. The reconstruction was obtained by multiplying the following series of matrices.* 1) *Diagenesis: regional data (*Vanossi *1986; 1991) suggest that the total thickness of the stratigraphic sequence originally lying on the Upper Carboniferous volcanics and sediments was probably around 1.5-2 km. With such a load, the initial porosity of rhyolitic volcanics is highly reduced (*Fisher *&* Schmincke*, 1984) and the loss of volume can be estimated at about 15-20%. These same values are indicated (*Loup*, 1992) for compaction of heterometric sediments similar to ours. The volume reduction is obviously accomplished mainly by shortening along the vertical axis; the possibility of a concomitant axial symmetrical extension on the horizontal plane depends on many factors, but mainly on lateral confinement. On this basis, we have assumed that diagenesis produced the same loss of volume in the volcanics and sediments. Moreover, as both the rhyolites (which form a discontinuous layer) and the sediments (fluvial-lacustrine) represent laterally confined bodies, we have expressed the total volume loss as a vertical shortening. As will be seen, the range of values for this first strain increment that best combines with subsequent increments to give the finite strain values extends between 10% and 25% of shortening, and is then in agreement with the above figures taken from literature.* 2) *Coaxial plane strain related to an early-*D1 *open folding, preceding the development of sheath folds. A 15% of shortening along* x *(layer-parallel shortening,* LPS*) was assumed. This value fits both in the following steps and in the computer simulation developed in order to check the results.* 3) *Development of "sheath-like" folds: obtained by the contemporaneous superposition of layer-parallel simple shear and pure shear achieved in a crustal-scale shear zone. Values were selected in order to fit the bulk strain data.* 4) *Late-*D1 *strain, that followed the stack of the upper nappes on the* Ma *(Mallare) unit and produced a shortening normal to the stretching lineation direction, confined in the northern part of the unit. The superposition of a triaxial pure shear, with 15 to 25% shortening parallel to* y*, fits all the constrictional ellipsoids that were measured in the late-*D1 *deformation belt.*



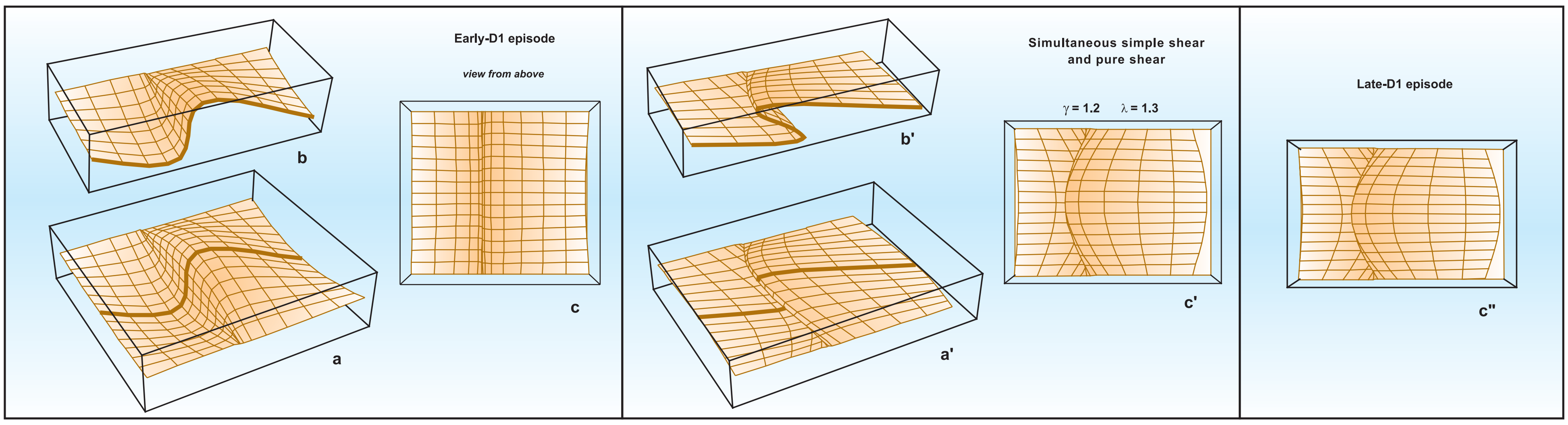


Fig. 6 - *Computer simulated sheath-like folds comparable to those observed on the field (see Fig. 4). The construction used a sinusoidal folded single layer representing the possible geometry of the basement-cover interface at the end of the early-*D1 *buckling. The layer deforms as a passive marker and represents the contact between two homogeneous and isotropic bodies*. (a)-(c) *The first episode ("early-*D1*") produces open, asymmetrical, non-cylindrical folds*. (a')-(c') *The further simultaneous application of relatively low values of pure and simple shear generates sheath-like folds with a pronounced inverted limb.* (c'') *Subsequent shortening normal to the former extension direction ("late-*D1*" episode) slightly increases the hinge-line curvature of the folds. The simulation approaches the present shape of the folds fairly well; in fact, the hinge-line curvature that is obtained is greater than 90°, but this value is more closely approached when the "late-*D1*" event is also taken into account.*

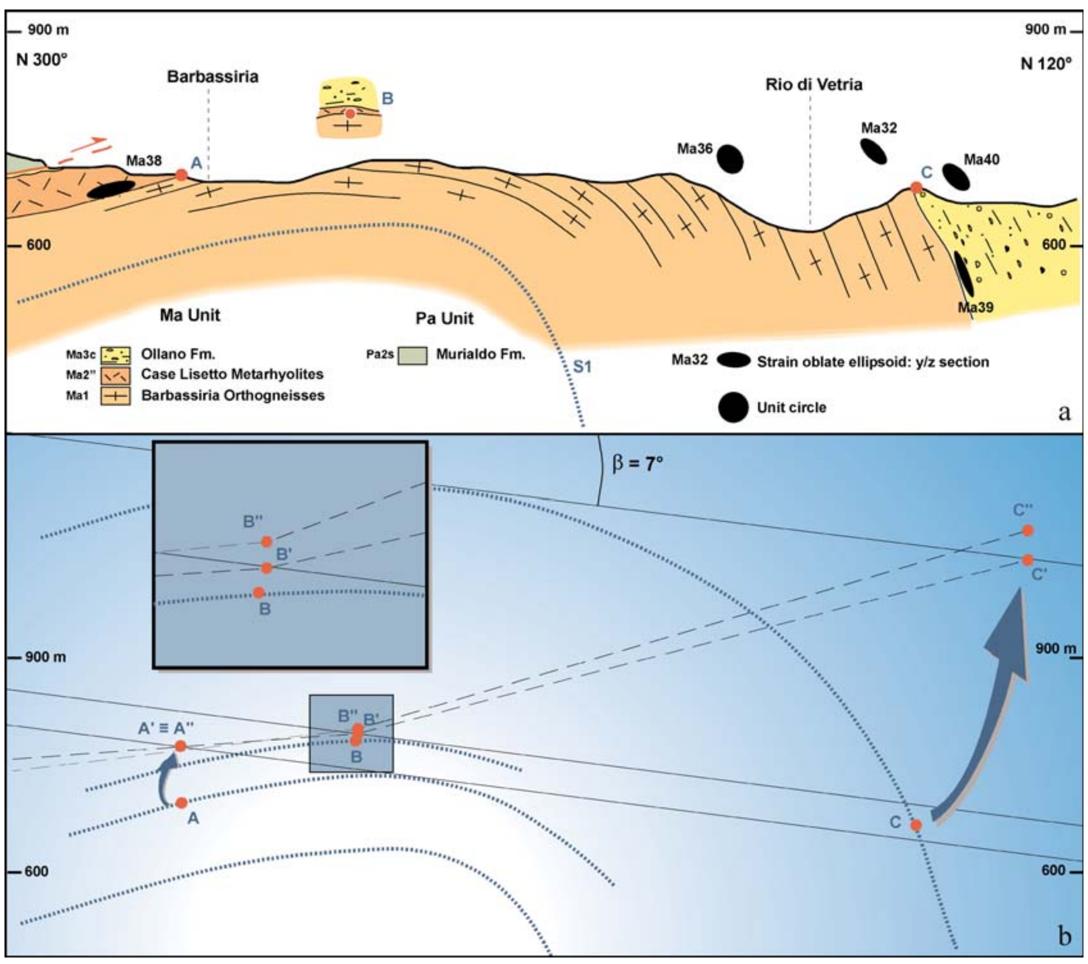


Fig. 7 - *Cross-section, trending N120°, through reference-points* A *and* C*, located on Fig. 3. Orthogonal projection was used to locate point* B *on the section. See text for comments.*

THE LOCAL SETTING

The detailed mapping of the different geological formations (Dallagiovanna *et alii*, 1997) has shown the presence of four superposed tectonic units. A comparison of their stratigraphy with that already known at a regional scale for the various palaeogeographic domains, has led to ascribe the two lowermost units to the Briançonnais domain, the third to the boundary-zone between the Briançonnais and Piedmont, and the highest to the Piedmont domain.

The structural analysis was focused on the **Pa** (Pamparato-Murialdo) and **Ma** (Mallare) Briançonnais units, which cover the largest part of the area; most of the data collected are presented in the map.

Because of their fundamental importance in helping to understand the structures presented in the map, the axial traces of folds generated by subsequent events (D1, Late-D1, D2, D3) and finite strain data collected on the **Ma** (Mallare) unit (Seno *et alii*, 1998) should also have been included in the map itself. However, for the sake of clarity, these are shown separately in Fig. 3, together with the stereographic plots of foliation and lineation attitudes.

The metamorphic parageneses affecting the earliest Alpine schistosity in the **Ma** (Mallare) and **Pa** (Pamparato-Murialdo) units indicate high pressure conditions (P ~ 0.8 GPa, T ~ 350°C ± 25° C). These data, coupled with the outcrop width in the direction of tectonic transport, suggest that **Ma** (Mallare) and **Pa** (Pamparato-Murialdo**)** were deformed and piled-up (D1 phase) within a hinterland-dipping duplex, whose roof comprised the **Ca** (Calizzano-Savona) and **So** (M. Sotta) units, among others.

As already mentioned in the presentation of the regional framework, an interesting feature is that concerning the development of a later 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". However, a detailed structural analysis has shown that in the Barbassiria area this system corresponds to an older phenomenon, which occurred during the main, foreland-directed deformation episode and was accompanied by the development of a sinistral transfer zone ("**s.s.z.**"). At a later stage, the units underwent the regional backfolding event (D2 phase) and, finally -as shown in Fig. 4, and as can also be inferred from the map-, they were involved in the D3 phase that produced asymmetrical dome-and-basin interference patterns.

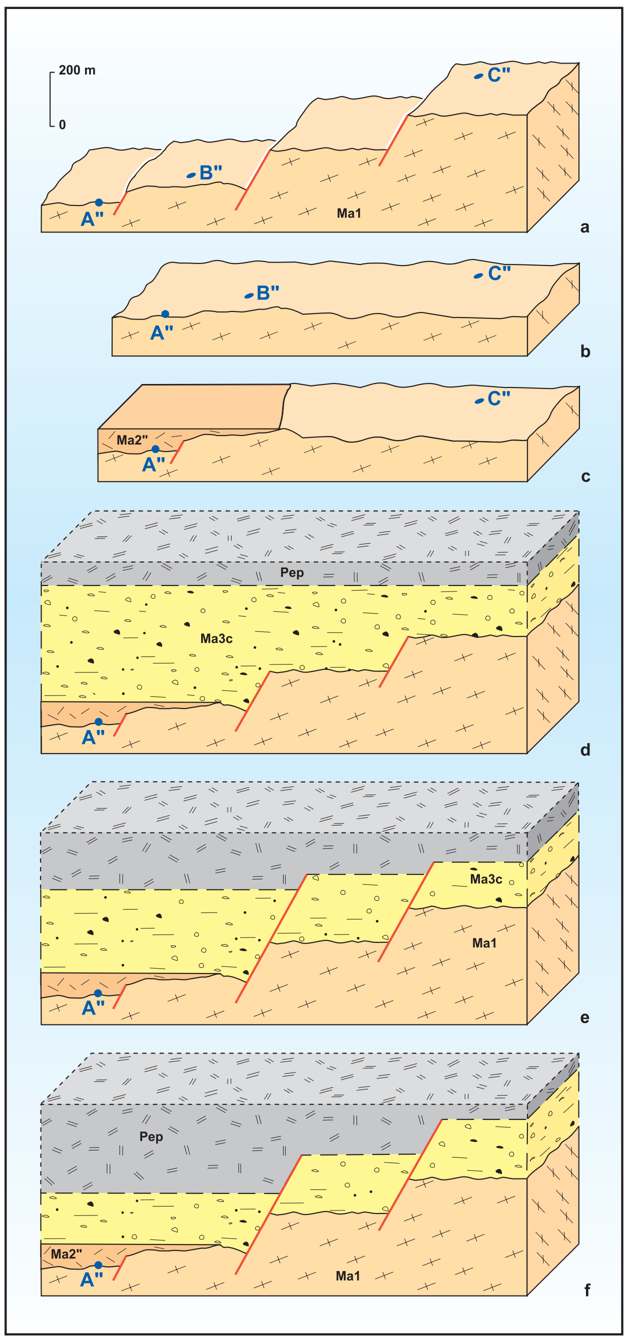


Fig. 8 - *Palaeogeographic schemes, parallel to the section in Fig. 7.* (a): *Possible setting of the top of the basement* (Ma1) *at the beginning of Mesozoic times and location of* A'', B'', C'' *reference-points; the surface is crossed by a set of normal faults.* (b): *the erosional surface at the beginning of the Late Carboniferous.* (c): *a "first phase" fault accompanies the emplacement of Case Lisetto rhyolites* (Ma2''). (d, e, f): *Three different arrangements, concerning the period of activity of the "second phase" faults (only during Late Carboniferous, during Late Carboniferous and Early Permian, only during Early Permian times). In any case, the continental sediments (Ollano Formation,* Ma3c*) are deposited on the rhyolites and/or the basement and are in turn covered by Early Permian ignimbrites* (Pep)*, which will undergo detachment during the* D1 *Alpine deformation event (see Fig. 12). Note that, of the above settings, which are all theoretically possible, some arguments lead to a preference for those including Early Permian times:* i) *all over the future Alpine system, volcanism and faulting are generally associated;* ii) *faults may explain why thickness of volcanics in originally adjacent sectors displays remarkable, sudden variations;* iii) *thrust ramps that bound present tectonic units appear to have been guided by pre-existing faults.*

THE STRAIN PATH

Strain analysis is generally considered to be a fundamental tool in helping to understand the present tectonic setting, and, consequently, the geological map. However, in this case, the main aim of the strain investigation was not just to gain a better understanding of the deformation history of a limited sector of the Ligurian Alps. Rather, the authors wished to ascertain whether and how bulk strain measurements can be exploited to a wider extent than is generally the case.

Finite strain measurements were performed only in places where the **Ma** (Mallare) sequence appeared not to be affected by D2 and D3 events, so that they relate only to the bulk strain at the end of the complex D1 phase. In order to analyse the deformation path linked to this first Alpine event, data from the basement were disregarded and only the Carboniferous cover (both sediments and rhyolites) was considered. On the basis of regional constraints, it was assumed that deformation continued through the following major events: diagenesis, "early-D1" open folding, sheath-like fold development and the "late-D1 thrust" episode. A system of coordinates was defined in the deformed state with the **z** axis vertical, **y** normal to the regional trend of the stretching lineation L1, and **x** parallel to it. On the basis of the strain factorization method (SANDERSON, 1976; FLINN, 1978; RAMSAY & HUBER, 1987), the investigation proceeded by multiplying a series of matrices, each representing a strain increment (Fig. 5). The strain partitioning calculated agrees with our total strain data, but leaves the question open as to whether sheath folds really do develop when using a combination of relatively low values of pure and simple shear. In order to test this important point, a computer simulation model was developed (Fig. 6).

METHODOLOGY FOR THE PALINSPASTIC RESTORATION OF A LATE VARISCAN STRUCTURE

A cross-section of the present structure is shown in Fig. 7a (SENO *et alii*, 1997). The stratigraphic unconformity between basement and cover lies parallel to the S_1 Alpine foliation and is involved in a D2 antiform; three reference points -A, B and C- were located on the unconformity surface, in a sector corresponding to the normal limb of a D1 anticline.

The D2 structures where retrodeformed (Fig. 7b) on the following bases: (**i**) throughout the area investigated, the stretching lineation L_1 – which lies on S_1 schistosity – runs parallel to the S_1 dip; its initial (i.e. pre-D2) mean plunge was about 20°-25° towards N30°-N60°: therefore, a dip of 25° toward N45° was assumed for the initial attitude of S_1; and (**ii**) as the D2 event produced concentric folds, a rigid-body, retro-rota-

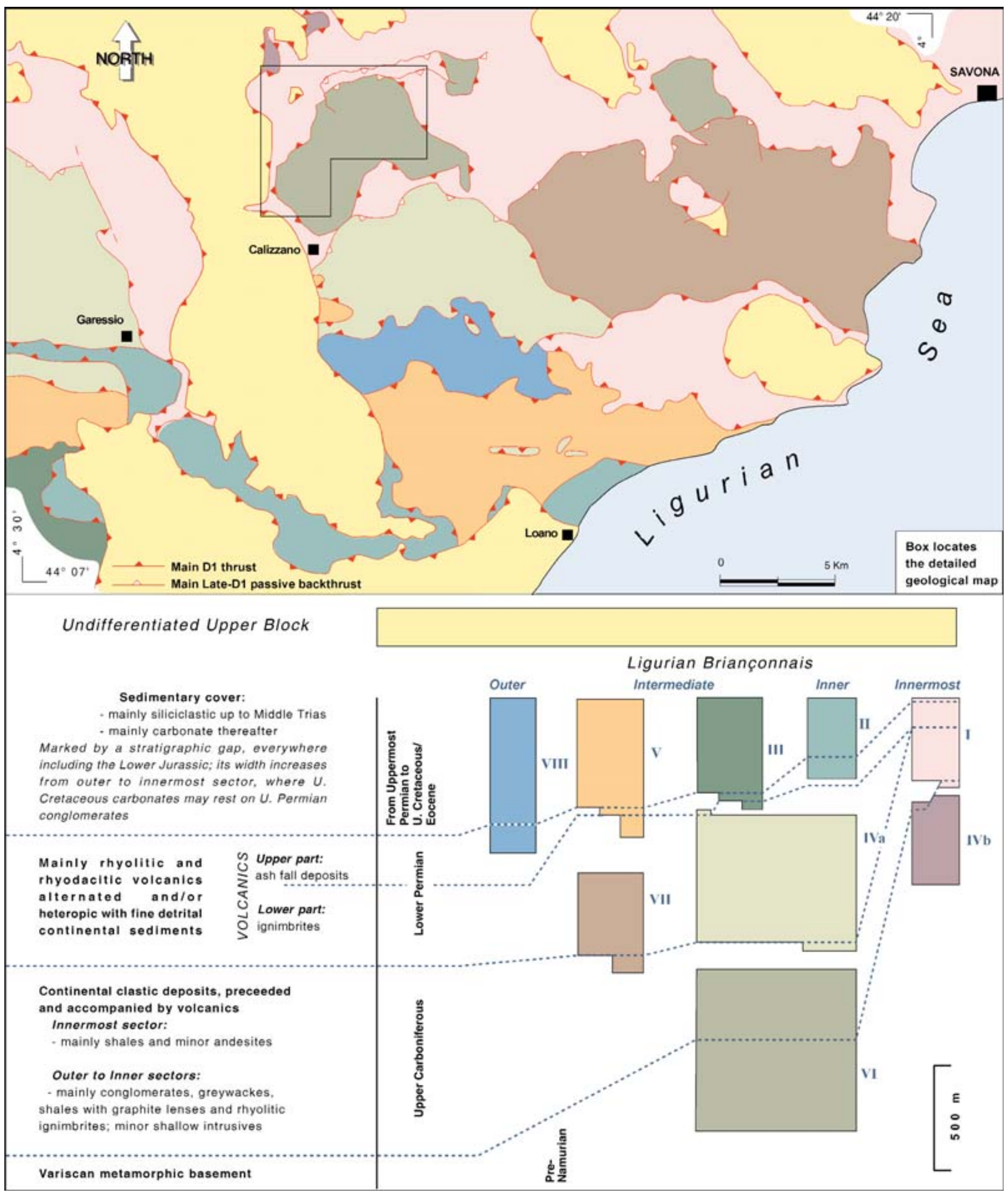


Fig. 9 - *Tectonic map of the central sector of the Ligurian Alps (see Fig. 2 for location). The stratigraphic sequence , extremely simplified, of the examined Briançonnais units* (I to VIII)*, as well as their assumed original locations, are presented in the lower part of the figure. The* Upper Block *is formed by units comprising sedimentary covers and/or basement, from the Piedmont and Piedmont-Ligurian domains. For the sake of clarity, the tectonic elements* (Ia, Ia', Ib) *of* Unit I *and* VIa, VIb *of* Unit VI*, drawn in Figs. 10 and 12, have not been distinguished on the map.*

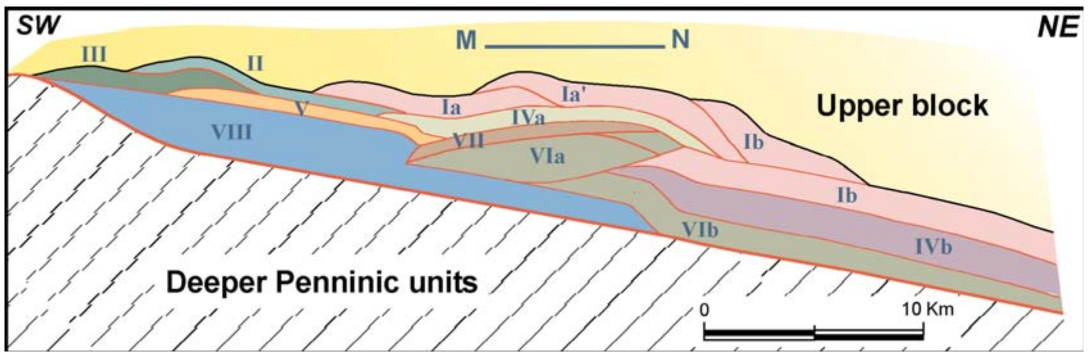


Fig. 10 - *Outline of the probable configuration of the Briançonnais nappe pile in the central sector of the Ligurian Alps at the end of the* D1 *phase. The restored cross-section, roughly parallel to the present direction of tectonic transport, runs within the central-western part of the region. The overall geometry is far from cylindrical; therefore, in order to show as much information as possible, it has been necessary to project on this single drawing settings from adjacent parallel planes. Segment* MN *approximately locates the area shown in the detailed geological map.*

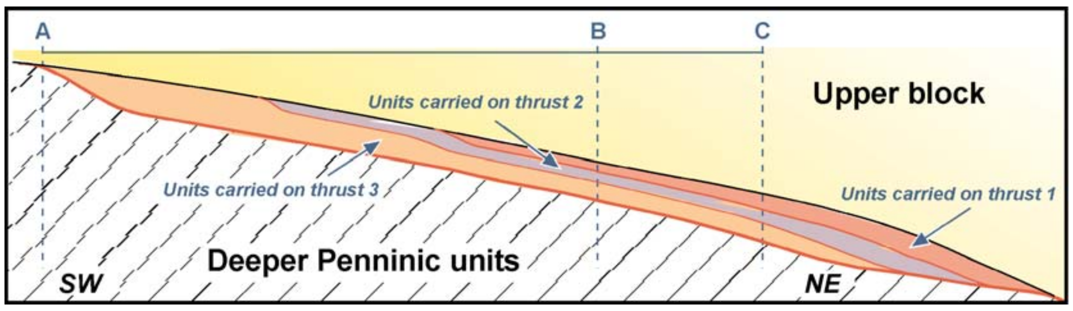


Fig. 11 - *Very simplified sketch. Sector* A-C *is the same as that represented in the cross-sections in Fig. 12, while sector* A-B *corresponds to the region mapped in Fig. 9. Taking into account the outward activation of the three main thrusts considered in this work, the drawing shows how they progressively enter the sections in Fig. 12. The sketch is also intended to depict the possible boundaries of the duplex.*

tion was applied.

The process led to the earlier location (A', B' and C') of points A, B and C; Fig. 7b shows that, at the end of the D1 phase, the distance between points A' and C' was about 1200 m and their difference in altitude about 260 m.

The subsequent removal of the D1 episode started by the factorisation of the bulk strain, which was measured in samples not affected by post-D1 fabrics; two increments (diagenetic and D1, tectonic) were calculated. Remembering that basement and cover were folded together and that A', B' and C' lie on top of the basement, the D1 strain increment calculated for the cover was subtracted in order to find the initial (i.e. Late Carboniferous) positions (A'', B'', C'') of the three reference-points.

Assuming that A'' coincides with A', B'' and C'' no longer lie on the plane of Fig. 7b, on which they have been projected. In this plane, the distance between A'' and C'' is about 1230 m and their difference in altitude becomes about 300 m. The restored geometry of the Late Variscan unconformity enables to draw the following conclusions: as the unconformity surface is parallel to the layering of the Late Carboniferous sediments, its pre-Alpine attitude was sub-horizontal and the difference in altitude calculated above would have been produced by a system of Late Palaeozoic normal faults, generating a Graben structure deepening towards the NW (Fig. 8).

THE KINEMATIC MODEL

In order to work out a possible kinematic model, data from the area presented above were assembled with data from adjacent sectors, and a tectonic map was prepared (Fig. 9). This shows the present location of the stacked Briançonnais units and their geometric relationships. Owing to the exceedingly high number of nappes present, it was decided to analyse the evolution of the Briançonnais units and that of the pile confining them at the roof separately. Therefore, all the latter have been amalgamated under a single label on the map ("Upper Block") and no stratigraphic subdivision has been evidenced within each Briançonnais nappe. The unit labelled as **Ma** (Mallare) in the preceding sections is n° **VI**, while n. **I** refers to **Pa** (Pamparato-Murialdo).

MAIN CONSTRAINTS ON THE MODEL

These are imposed by: (**i**) the palaeogeographic arrangement to be assumed on the basis of the stratigraphic sequences of the different units; and (**ii**) the data from structural analysis and metamorphic parageneses.

(**i**) The palaeogeographic framework was established by comparing the sequences of the nappes, in order to obtain, for each period, a picture consistent with depositional (including volcanic) environments, their lateral changes and vertical evolution. This has led to the introduction of a number of Mesozoic (or earlier: see, e.g., Fig. 8), normal faults separating adjacent sectors. The restoration was then checked against the general kinematic model for the Western Alps, which -as clearly indicated by the age of the top of the series involved in the orogen- assumes that deformation and tectonic transport started from

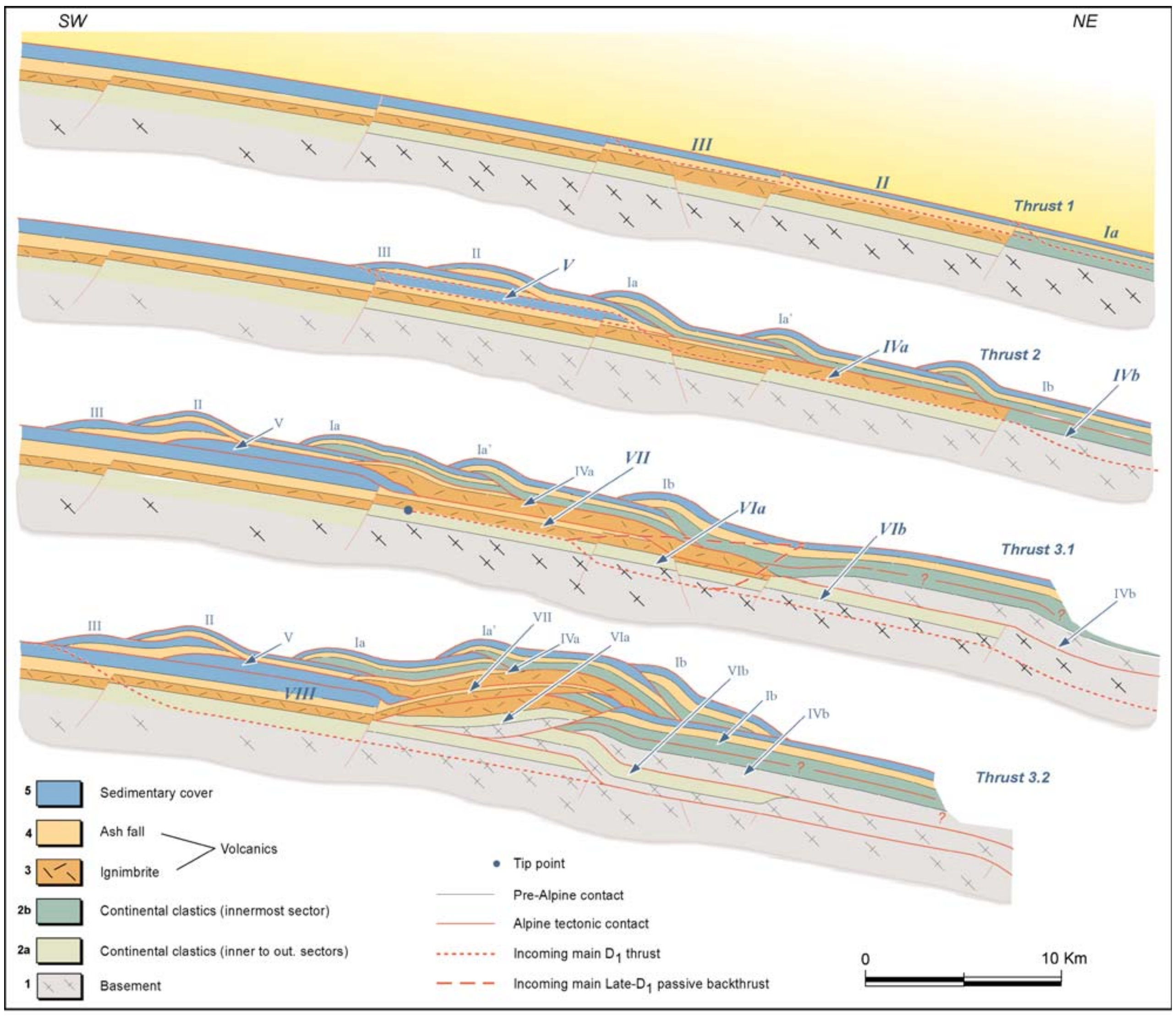


Fig. 12 - *Kinematic model for the emplacement of the Briançonnais nappes within a mega-shear zone. Cross-sections are located in the central-western sector of the region and their outer (SW) margin coincides with that of the map (Fig. 9). Each section shows both the geometry corresponding to the related step and the incoming structures, i.e. thrusts (red dash lines) and the corresponding Units (italic roman numerals). The top of each section is represented by the limit (roof thrust) with the Upper Block. Further information on the stratigraphic succession is given in Fig. 9.*

The text gives an example of how the subsequent sections should be interpreted, starting from the highest (and oldest) one. As a further example, in the second section Units Ia, II *and* III *have reached their provisional emplacement: at the same time, Units* Ia' *and* Ib *(representing sectors of Unit* I*, originally located in an inner position to* Ia*) have entered the section. As to the incoming events, which will generate Units* IVa, IVb *and* V, *this second section evidences the portion of the more external Th. 2 that will enter the third section and will act in two subsequent principal steps. The first step develops along a ramp-flat surface. The innermost flat is located within the basement; its connection with the outer décollement surface at the base of the Permian ignimbrites is afforded by a ramp at the inner margin of these volcanics. Outwards, another ramp - guided by the margin of a Palaeozoic Graben - propagates upwards to the shallowest flat provided by the outer part of the older Th. 1. The second step uses a décollement surface located within the ductile Permian ash-fall deposits at the top of the ignimbrites. Just as in the second section, and following the same mechanism, in the third section the intermediate stages are bypassed, to show the final emplacement of units at the end of the two steps of Th. 2.*

the inner sectors and progressively affected the outer domains. On the whole, these two different methodologies for the reconstruction of initial conditions have given comparable results, but, where differences were observed, the "stratigraphic" restoration was generally preferred.

(**ii**) The structural and metamorphic analysis indicates that:

- events D2 and D3, superimposed on D1, although influencing the overall present geometry, did not produce any significant further tectonic transport. Therefore, for the sake of simplicity, the model only takes into account the D1 tectonic event, disregarding the post-nappe evolution;
- the D1 event, producing the stacking of the Briançonnais nappes, was accomplished within a hinterland-dipping duplex, bounded by a sole thrust located within the basement, at an unknown depth, and by the "Upper Block" (indicated by the same colour as in the map at Fig. 9) at its roof (Fig. 10).

LOCATION, GEOMETRY AND SEQUENCE OF THE MAIN THRUSTS

Within the duplex, the geometry, relative location and timing of thrusts were selected in order to comply with the stratigraphic sequence and the geometry of each unit, as well as with its present location (that was not severely affected, as stated above, by the D2 and D3 events) within the pile. This seems to be achievable only through the progressive activation of a forward-breaking thrust sequence of three main surfaces (named *Th. 1, 2, 3).* Each surface, joining the two main (sole and roof) thrusts, is characterised by an overall stepped, ramp-flat geometry.

It should be noted that, within the general regional framework, the sector considered is relatively "external". Thus, as shown in Fig. 11, while *Th. 1* can be shown only by the outer part of its upper flat, the length of the progressively younger and more external *Th. 2* and *Th. 3* increases and deeper flats and ramps appear entering the sections in Fig. 12. In order to separate units with different stratigraphic sequences, the ramps must have been positioned near their sudden changes. It follows that in most cases the above-mentioned Mesozoic or earlier Graben boundaries will have affected the ramp location.

As in Fig. 10, the "Upper Block" is once more highlighted in Figs. 11 and 12 in the same colour used in Fig. 9. For reasons of scale, in all these drawings the top of the "Upper Block" has not been indicated. In particular, in Fig. 12 the block is partially highlighted only in the upper section; nevertheless, it should obviously be considered to also be present in all the lower sections.

KINEMATIC EVOLUTION

The main steps of duplex activation up to the end of the D1 event are shown in Fig. 12.

In order to better display the assumed mechanism, sections have been prolonged in the NE direction outside the map. As the finite strain is far from plane (SENO, 1992; SENO *et alii*, 1998), the cross-sections cannot be strictly balanced.

However, in order to simplify the picture as far as possible at the scale used, and without applying any special computer software, the drawing has been made with the assumption that the final area of each unit might roughly "balance" its initial value.

Each section presents the "initial" setting and incoming events. In order to show the stratigraphic sequence of each nappe and its connections with the décollement surfaces, internal folds (such as those illustrated in Figs. 3 and 4) have been omitted in the drawing.

In particular, in the first section (displaying the palaeogeographic pattern, with a rough estimate of the width of each sector, as well as lateral and vertical relationships not yet upset by thrusting) the stratigraphic boundaries have been traced as flat planes.

However, taking into account that folds within each unit are truncated by the overlying thrust and that there is no mutual involvement between folds of adjoining units, it seems necessary to argue that the main décollement surfaces began to function before duplex activation, allowing a disharmonic folding process.

At the same time, as the truncated portions are generally thin and because of the lack of wide and thick splays at the base of the different units, it might also be argued that these initial folds were gentle.

Their overall tight, recumbent geometry, accompanied by axial plane schistosity (developed -as stated above- under "high pressure" conditions), was necessarily acquired during thrust development, in a later, mainly simple shear regime (SENO *et alii*, 1998).

The authors hope that Fig. 12 is self-explanatory. Nevertheless, in order to facilitate its interpretation, the incoming events evidenced in the first section are commented on by way of example.

The drawing shows the location of the upper and more external part of the incoming *Th. 1*, which enters the section and develops in three subsequent steps (not separately drawn).

The first step *(Ia)* starts at the Innermost sector as a shallow flat - located within the Upper Carboniferous shales - which ends with a frontal ramp developed at the sharp limit between the Innermost and Inner sectors and joins the roof thrust. During the next step *(II)* the pre-existing flat propagates outwards along the upper boundary of Permian ignimbrites as far as a new ramp, which develops at the boundary between the Inner and Intermediate sectors.

The same mechanism (i.e. further outward prolongation of the former flat) acts during the third step *(III),* with a frontal ramp located inside the Intermediate sector and once more guided by the palaeogeographic setting.

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