Mapping of poliphase folding at upper structural levels: An example from the Val Borbera (Northern Apennines)

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ABSTRACT

The mapping of axial surfaces is fundamental toward the representation of folding deformations and understanding the complex tectonic settings of sedimentary units deformed at the upper structural levels of orogenic belts. Field mapping (1:10,000 scale) and structural analysis at the mesoscale have been performed on a north-western sector of the Northern Apennines (Borbera Valley), where the Antola Unit (Late Cretaceous-Paleocene) is unconformably overlain by the basal part of the Tertiary Piedmont Basin succession (Val Borbera Conglomerate, Early Oligocene). The resulting tectonic setting is characterised by two superimposed folding phases. The older of these, referable to the Meso-Alpine phase, only affected only the Antola Unit, while the younger phase also deformed the Val Borbera Conglomerate and is therefore post-Early Oligocene in age.

AIMS

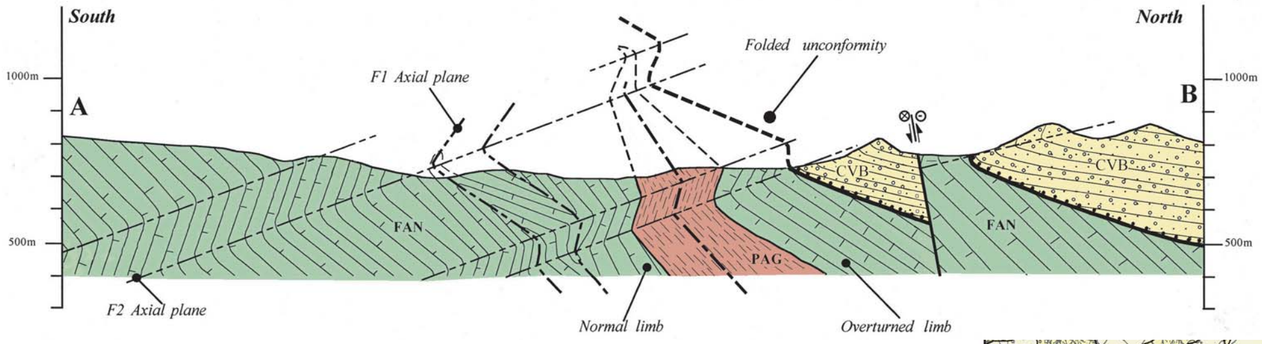
Geological-structural mapping methods are techniques commonly used to represent the complex tectonic setting of orogenic belt areas characterised by the superimposition of different folding phases.
Nevertheless, the application of these techniques has not been adopted as a standard procedure in the geological mapping of the tectonic units deformed at upper structural levels, i.e. without development of metamorphism and related structures.
The aim of this contribution is therefore to demonstrate - using a selected example of unmetamorphosed tectonic unit (the Antola Unit, in the Northern Apennines) - that the association of field mapping with structural analysis can produce a geological-structural map in which the complex deformation setting is fully detectable.
In particular, the tectonic setting derived by two folding phases is revealed in the geological-structural map by the interference between the traces of the different fold axial surfaces, mapped by outcrop-scale analysis of both sedimentary and deformation features.

KEY WORDS

Geological mapping, structural analysis, fold axial surface traces, polyphase folding, Antola Unit, Epimesoalpine Succession, Northern Apennines

RIASSUNTO

L'andamento cartografico delle tracce delle superfici assiali rappresenta, nell'ambito della deformazione plicativa, uno strumento indispensabile per la comprensione dell'assetto tettonico di settori di catena deformati a livelli strutturali superficiali. L'esempio qui presentato riguarda l'applicazione di questo concetto in un settore nord-occidentale dell'Appennino settentrionale (Val Borbera) dove affiora l'Unità Antola (Cretaceo sup.-Paleocene) ricoperta in discordanza stratigrafica dalla parte basale della successione del Bacino Terziario Piemontese (Conglomerati della Val Borbera; Oligocene inf.).
Il rilevamento geologico di dettaglio (scala 1:10.000) e l'analisi mesostrutturale hanno documentato un complesso assetto tettonico caratterizzato da due fasi plicative sovrapposte, la più antica delle quali, attribuibile alla Fase Mesoalpina, deforma esclusivamente l'Unità Antola e sviluppa strutture sigillate dalla discordanza alla base dei Conglomerati della Val Borbera, mentre la fase più recente deforma anche i Conglomerati della Val Borbera stessi ed è quindi necessariamente di età post-Oligocene inferiore.



GEOLOGICAL LAND STRUCTURAL MAP OF VAL BORBERA (NORTHERN APENNINES)

QUATERNARY CONTINENTAL DEPOSITS

a1 — Active landslides

a2 — Dormant landslides

a3 — Talus deposits

b1 — Alluvial deposits

b2 - b3 — Alluvial terraces

EPIMESOALPINE SUCCESSION

a / b — **Val Borbera Conglomerate (CVB)**
Thick and very thick beds of massive to crudely bedded conglomerates and minor coarse grained arenites showing clast supported texture. The clast composition is mainly characterized (up to 100%) by calcareous pebbles derived from the Antola Unit succession and minor clasts derived from a very low grade metamorphic ophiolitic succession.
(Early Oligocene)

ANTOLA UNIT

a / b — **Pagliaro Formation (PAG)**
Thin to medium beds of siliciclastic and minor calcareous turbidites mainly characterized by incomplete Tb-e, Tc-e Bouma sequence alternating with hemipelagic shales. Minor calcareous megaturbidites, up to 10 m thick, are also present.
(Late Maastrichtian-Late Paleocene)

a / b — **Mt. Antola Flysch (FAN)**
Medium to thick beds of calcareous turbidites interbedded with minor hemipelagic shales and calcareous megaturbidites. The calcareous turbidites show well developed Ta-e and incomplete Tb-e, Tc-e Bouma sequences.
(Late Campanian-Maastrichtian)

SYMBOLS

10 — Normal beds

10 — Overturned beds

10 — Undeterminated beds

Vertical beds

Horizontal beds

25 — F2 Axes

Stratigraphic boundaries

Unconformities

Faults

F1 syncline axial surface traces

F1 anticline axial surface traces

F2 synform axial surface traces

F2 antiform axial surface traces

Alluvial fans

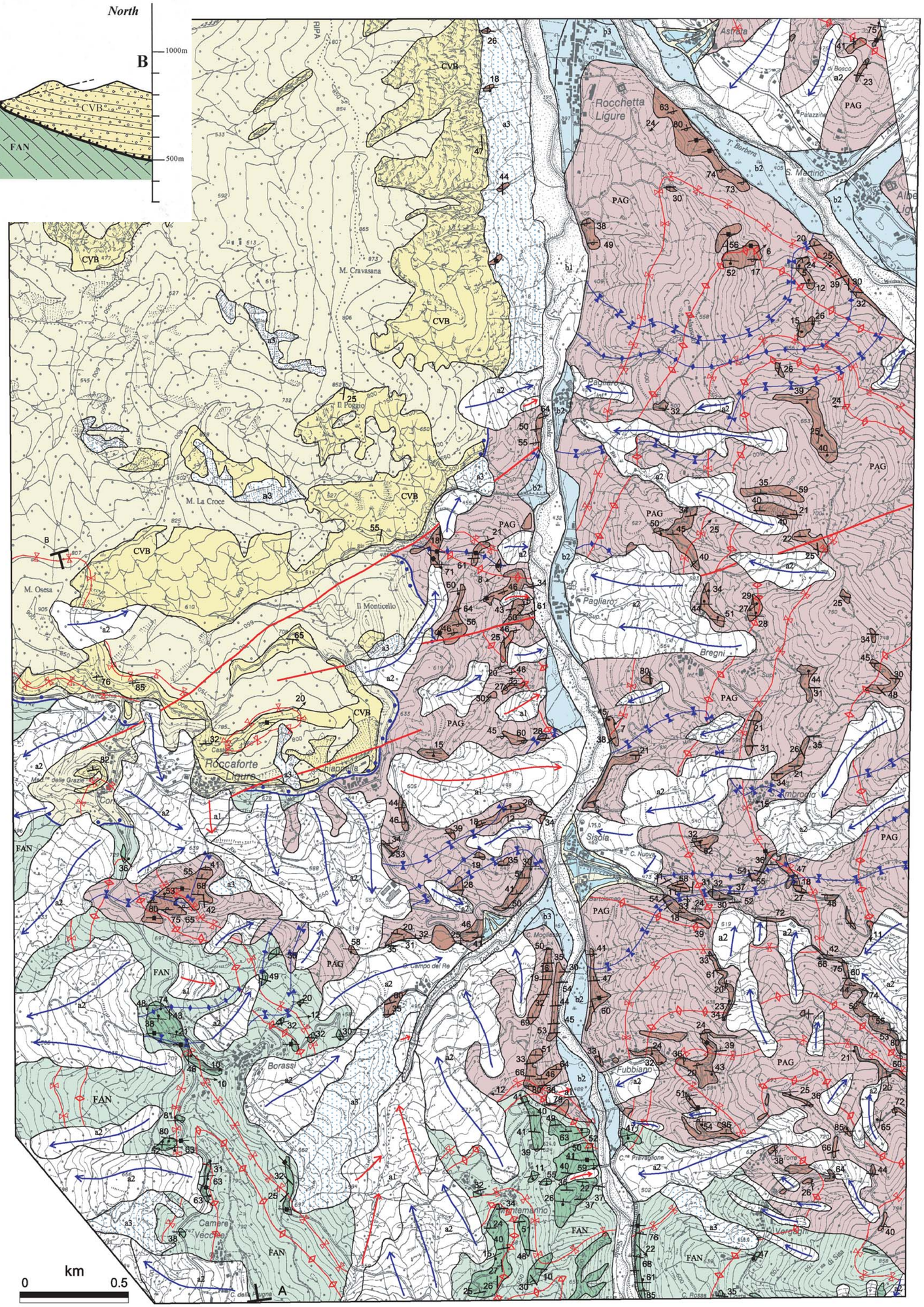


Fig. 1 - *Geological-structural map of the Borbera (between Cantalupo Ligure and Rocchetta Ligure) and Sisola Valleys, and related geological cross-section (CVB: Val Borbera Conglomerate; PAG: Pagliaro Formation; FAN: Mt. Antola Flysch). The location of the map area is reported in Fig. 2.*

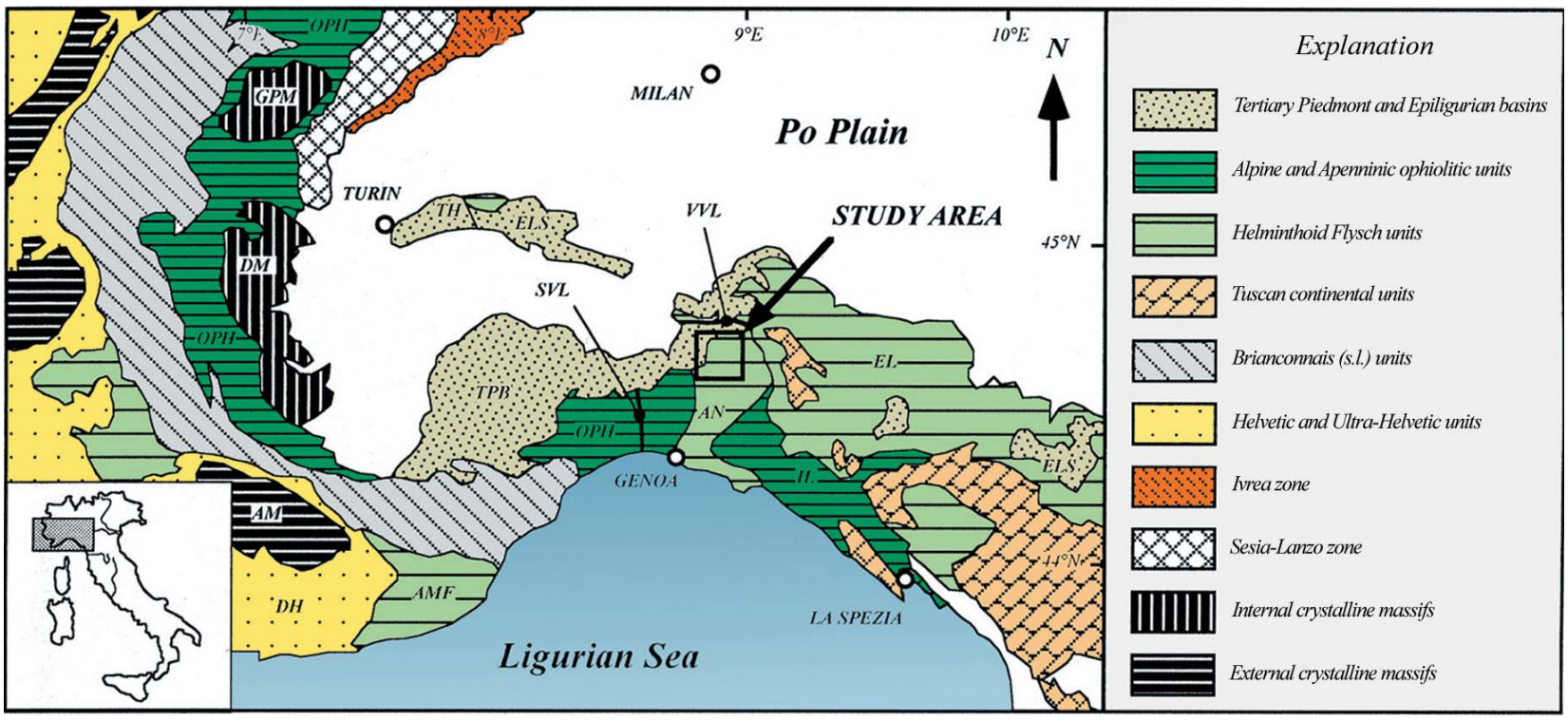


Fig. 2 - *Tectonic sketch-map of the Northern Apennines and Ligurian Alps; the study area is indicated. TPB: Tertiary Piedmont Basin; TH: Torino Hill; ELS: Epiligurian Succession; OPH: Western Alps ophiolitic units; IL: Internal Liguride units; AMF: Maritime Alps Flysch; AN: Antola unit; EL: External Liguride units; GPM: Gran Paradiso massif; DM: Dora Maira massif; AM: Argentera-Mercantour massif; SVL: Sestri-Voltaggio Line; VVL: Villalvernia-Varzi Line.*

The Northern Apennines are characterised by wide areas where the oucropping sedimentary successions were affected by polyphase folding developed at upper structural levels under very low-grade or unmetamorphic P/T conditions.

In Fig. 4, a full understanding of the tectonic setting becomes very difficult by the absence of the main structural elements, such as foliations and mineralogical lineations. This difficulty generally leads to an undervaluation of the structural complexities in these areas.

Nevertheless the structural analysis at the mesoscale, performed during the geological survey, provides data (bedding attitude and facing, fold axes and related axial planes) that allow to trace the fold axial surfaces at the map-scale.

Mapping of axial surfaces represents the fundamental tool for representing folding deformations in the areas characterised by superimposed folding phases. Moreover, the association of the fold axes (measured and/or calculated) to the related axial surfaces allows to highlight the structural rotations.

The applicability of these concepts has been positively tested in the Borbera Valley (north-western sector of the Northern Apennines) where the outcropping units (Antola Unit unconformably overlain by the Val Borbera Conglomerate) have been previously mapped as a monocline plunging toward the Po Plain .

The Borbera Valley is located in the complex geological area where the connection between Ligurian Alps and Northern Apennines occurs (cf. Ligurian Knot of Laubscher *et alii*, 1992). The Alpine Units (Voltri Group and Brianconnais) and Apennine Units (Ligurids), already deformed during the Eo- and Meso-Alpine tectonic phases, are unconformably covered by a thick sedimentary succession deposited from Late Eocene to Late Miocene in an episutural basin, known as Tertiary Piedmont Basin (thereafter referred as TPB). The TPB belongs to a wider episutural basin (epi-Mesoalpine Basin; Mutti *et alii*, 1995) including also the epi-Ligurian Basin whose deposits crop out in the Emilia sector of the Northern Apennines (Fig. 2).

The study area is characterised by the occurrence of the basal unconformity surface between the TPB succession and the underlying Antola Unit which represents the structurally uppermost Ligurian Unit. In this area, the Antola Unit is formed by the Mt. Antola Flysch and the Pagliaro Formation. The Mt. Antola Flysch is a typical upper Campanian-Maastrichtian Helminthoid Flysch made up of thick, fine-grained calcareous turbidites, interbedded with thin, silty turbidites. The Pagliaro Formation (Late Maastrichtian-Early Paleocene) mainly consists of arenaceous-pelitic and subordinately calcareous turbidites alternating with hemipelagic shales. The basal part of the TPB succession in this area is represented by the Val Borbera Conglomerate, consisting of an up to 2500 m thick succession of continental to marine conglomerates of Early Oligocene age (Gelati & Gnaccolini, 1978; Gnaccolini, 1988; Mutti *et alii*, 1995) (Fig. 3).

The Val Borbera Conglomerate grades upward to a predominantly arenaceous-pelitic succession of frankly marine and progressively deeper deposits as a consequence of a regional transgression (Lorenz, 1969).

Detailed field mapping and analysis of the outcrop-scale structures have been carried out in the Borbera Valley, between Cantalupo Ligure and Rocchetta Ligure, and along the Sisola Valley. Particularly the field mapping and structural analyses methods performed in this study consist of:

· mapping of the outcrop areas and therefore the contacts between exposed and unexposed rocks;

· determination of the outcrop-scale fold features (axes and axial surfaces) and analysis of the primary sedimentation structures for determining the bedding polarity;

· mapping of the fold axial surface traces with the consequent display of the map-scale interference patterns.

The first result consists of a geological-structural map where each outcrop has been delimited. The structural analysis pointed out a tectonic setting characterised by the occurrence of two folding phases (D1 and D2), with the younger one that affects both the Val Borbera Conglomerate and the Mt. Antola Flysch and Pagliaro Formation. The D1 and D2 folding phases developed under diagenesis/anchizone boundary conditions (Bonazzi & Costa, 1991), typical for the deformation at upper structural levels.

The representation of these structures on the geological map has been done using the trend of the axial surfaces belonging both to F1 and F2 folds, associated with strike and dip of the related fold axes.

A subsequent processing includes two simplified tectonic sketches where the overturned limbs of F1 and F2 folds have been respectively pointed out (Fig. 4). In this way the

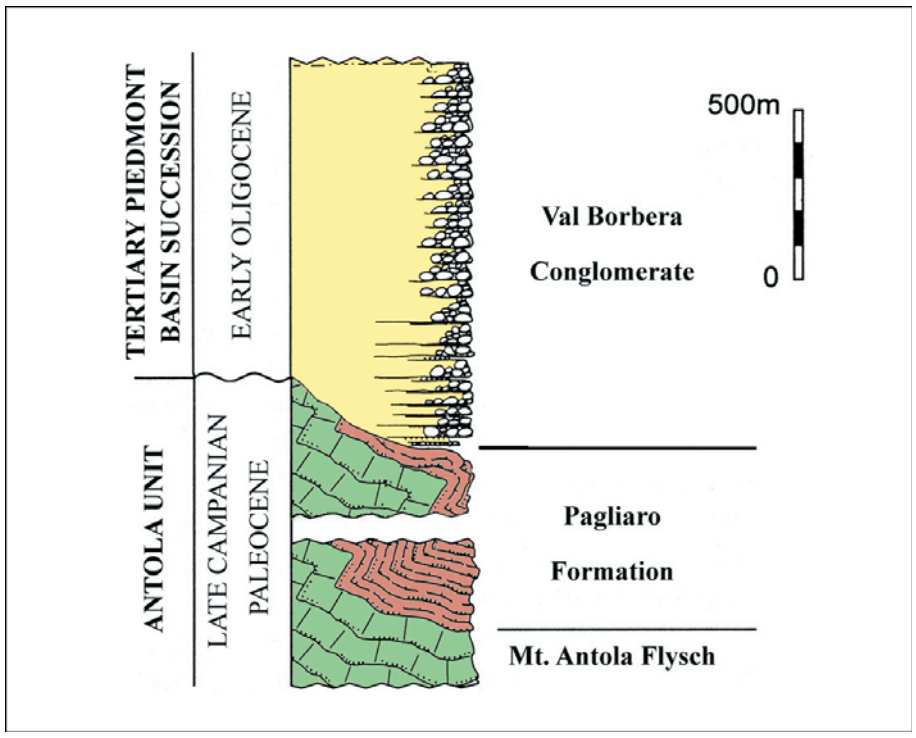


Fig. 3 - *Schematic stratigraphic log of the study succession.*

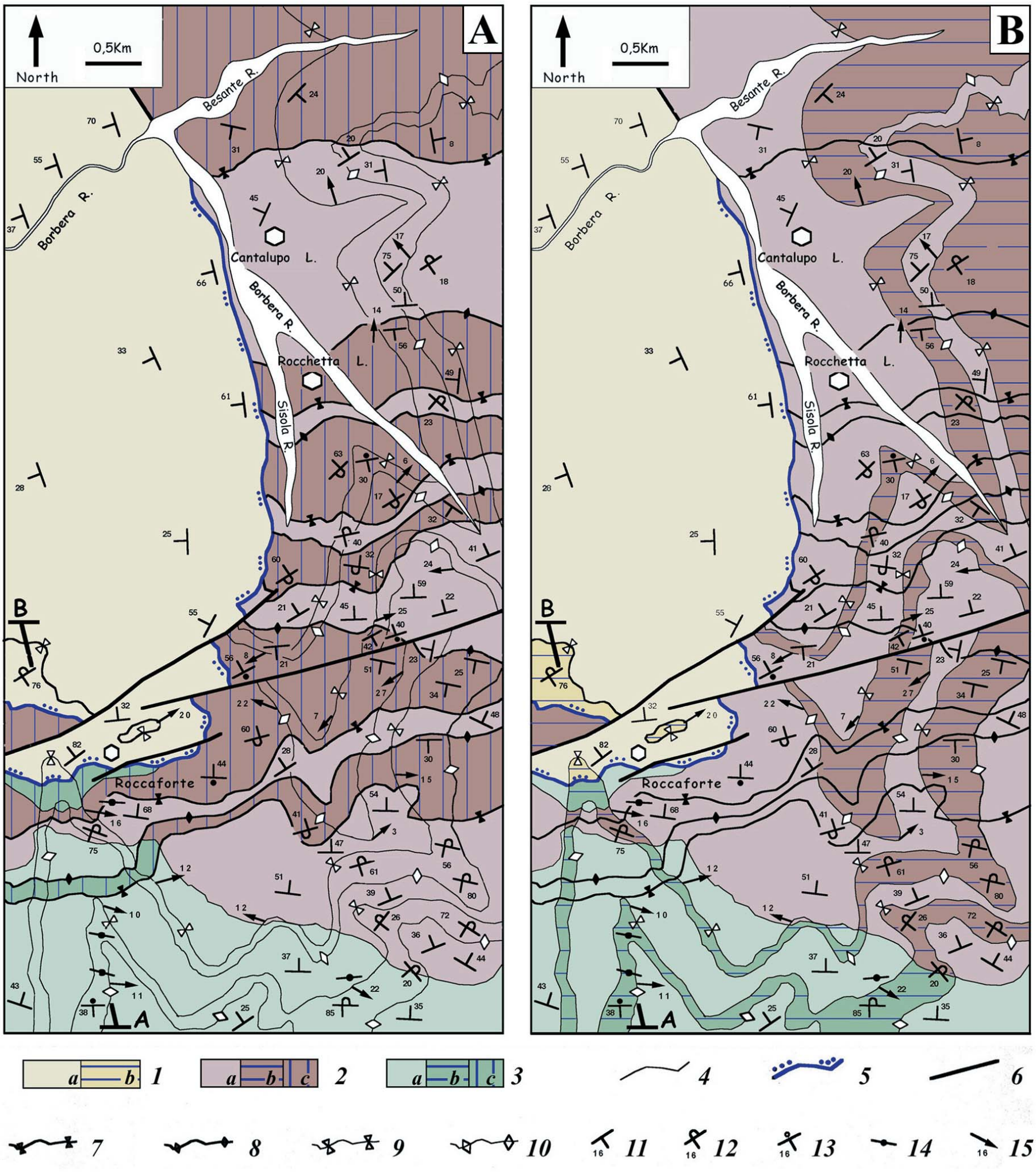


Fig. 4 - *Detailed structural sketch-map of the study area. In figure 4A the D1 phase normal and overturned limbs are evidenced, while in figure 4B the D2 phase normal and overturned limbs are evidenced.*

D1 folding phase is well documented by the occurrence of kilometric overturned fold limbs, unconformably covered by the Val Borbera Conglomerate. In particular, the studied area is characterized by several couples of anticlines and synclines that affected the Mt. Antola Flysch-Pagliaro Formation succession; these structures are sealed by the basal unconformity of the Val Borbera Conglomerate that cuts across the traces of F1 axial surfaces.

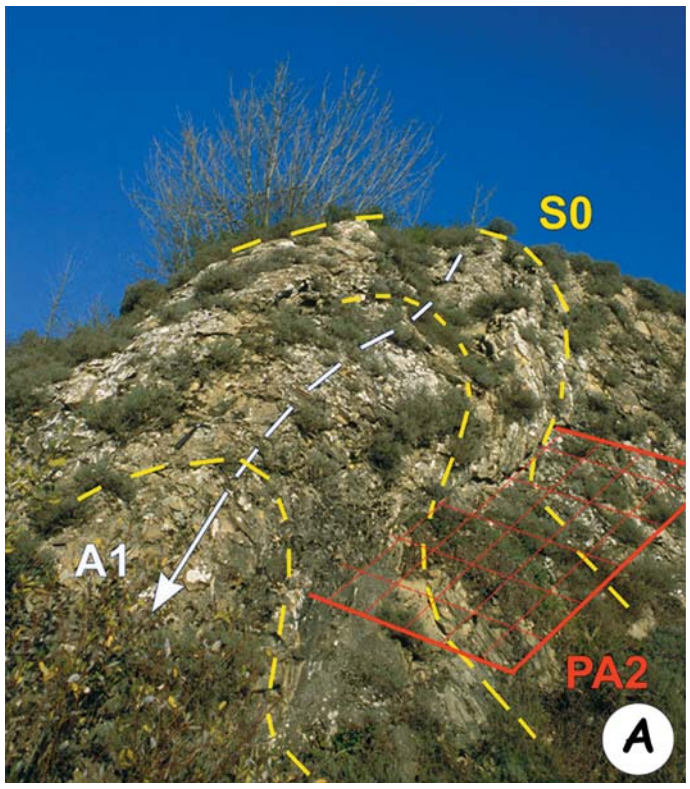
The polyphase folding which affected the Antola Unit is also evidenced by the occurrence of beds showing normal polarity in some overturned F2 limbs as a consequence of the overturning of beds belonging to overturned limbs of F1 folds (Fig. 4).

The D1 folding phase structures are represented by tight to subisoclinal F1 folds with scattered axes trend, even if an E-W trend seems to be prevailing. The F1 folds show a parallel geometry, whereas thickening of the hinge zone or boudinage of the limbs have never been recognized. The axial plane foliation is a discontinuous surface that in the shaly and calcareous beds occurs as a disjunctive cleavage.

The outcrops showing the fold hinges are rare; the few examples recognized during the field mapping indicate a northward vergence for the F1 folds, such as the syncline represented in Fig.

1a/b- Val Borbera Conglomerate;
2a/b/c- Pagliaro Formation;
3a/b/c- Mt. Antola Flysch;
(a, b and c indicate respectively the normal limbs, the overturned F2 limbs and the overturned F1 limbs);
4- stratigraphic boundaries;
5- unconformities;
6- faults;
7- F1 syncline axial surfacetraces;
8- F1 anticline axial surface traces;
9- F2 synform axial surface traces;
10- F2 antiform axial surface traces;
11- normal beds;
12- overturned beds;
13- undeterminated beds;
14- vertical beds;
15- F2 fold axes;

A-B: location of the geological cross section of Fig. 1.



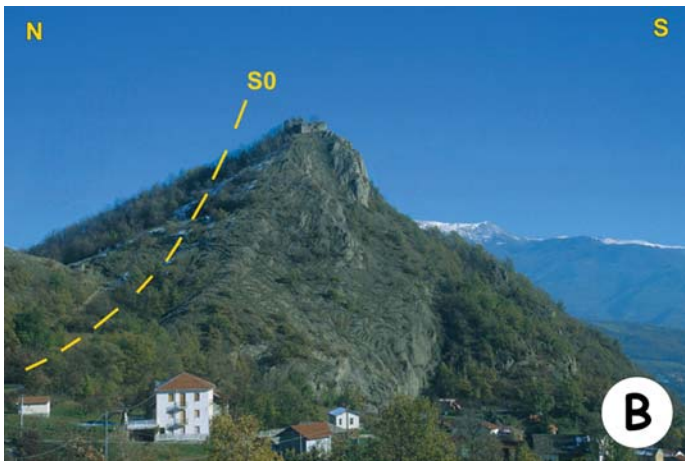


Fig. 5 - *Examples of D1 and D2 phase related structurs from the investigated area.*
A) refolded D1 phase syncline in the Mt. Antola Flysch nera Borassi; the D2 phase axial plane (PA2), the D1 phase axis (A1) and the bedding (S0) are indicated.
B) D2 phase fold in the Val Borbera Conglomerate near Roccaforte Ligure castle. C) D2 phase fold in the Mt. Antola Flysch.

5A, occurring in the Mt. Antola Flysch along the geological cross-section A-B (Fig. 1).
The analysis of the superimposed folds in the southern sector of the studied area shown by the geological cross-section indicates a type 3 interference pattern (RAMSAY, 1967).
The D2 folding phase structures are represented by open parallel folds that affect all the F1 folds and the related axial surfaces as well as the Val Borbera Conglomerate. The F2 folds are represented by open to tight overturned asymmetric folds, characterised by a parallel geometry. An example of F2 fold, deforming the Val Borbera Conglomerate, is represented by the map-scale syncline outcropping NW of Roccaforte Ligure (Fig. 5B, C).

The general trend of the F2 fold axes ranges from ESE-WNW in the southern areas to NNW-SSE in the northeastern ones, through a central zone where the axes are about NE-SW. The F2 fold vergence in the three sectors is respectively toward the NNE, the WNW and the NW. Therefore, assuming the ESE-WNW Apenninic trend as the original axial direction, the change of the F2 fold axes can be related to a gradual anticlockwise rotation (Fig. 6).
The general structural setting of the Borbera Valley is therefore characterised by a D2 folding phase which affected both the Val Borbera Conglomerate and the Antola Unit. The F2 folds are superimposed onto an early D1 folding phase which affected only the Antola Unit. The D1 phase pre-dates the deposition of the Val Borbera Conglomerate, and it is therefore pre-Early Oligocene in age. At the regional scale the D1 phase identified in the Antola Unit can be related to the collisional stage, i.e. the Ligurian or Meso-Alpine phase, of Middle Eocene age (ELTER, 1975).
On the contrary, the D2 phase, deforming the Val Borbera Conglomerate, is necessarily post-Early Oligocene in age. Taking into account the deformations and the unconformities occurring in the younger TPB succession, the D2 phase can be related to a tectonic stage developed between the Late Oligocene and the Early Miocene (MARRONI *et alii*, 2002).
In the 3D reconstruction of the study area (Fig. 7) the observed change in F2 axial trends is seemingly related to a subsequent folding phase showing a vertical axis. Really, the structural data up to now collected in the Borbera Valley do not allow to state if the F2 fold-axis rotation is successive or contemporary to the fold formation, i.e. if the axis dispersion was induced by strike-slip fault systems or represents a ductile axial torsion due to a gravitational nappe emplacement.

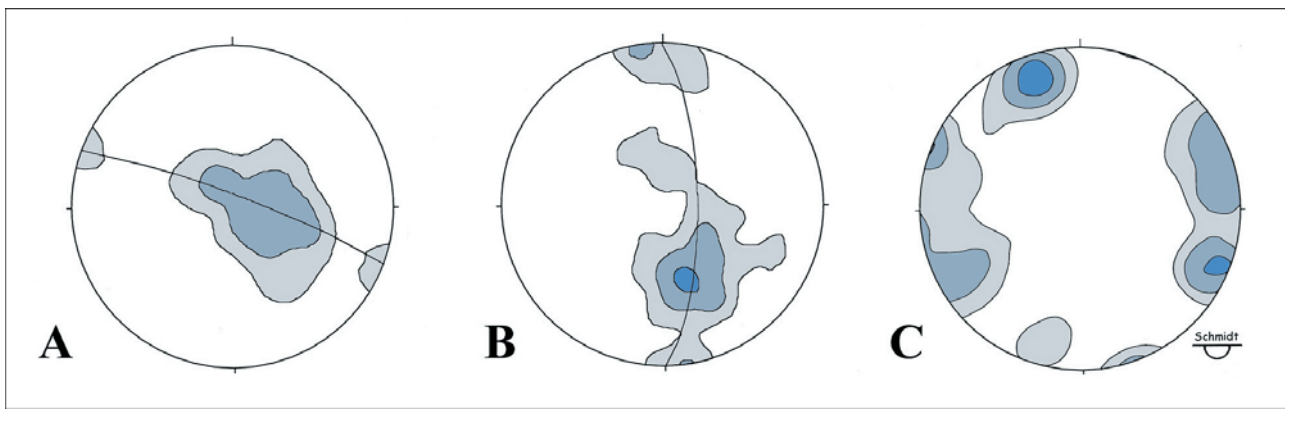


Fig. 6. *Equal-area, lower hemisphere stereographic representation of structural data.*
A) S0 - Mt. Antola Flysch and Pagliaro Formation in the northeastern sector of the study area, 34 data, contoured at 1.5 - 3.5 times uniform.
B) S0 - Mt. Antola Flysch and Pagliaro Formation in the southern sector of the study area, 168 data, contoured at 1.3 - 3.3 - 7.3 times uniform.
C) F2 fold axes distribution, 26 data, contoured at 1 - 2.5 - 4 times uniform.

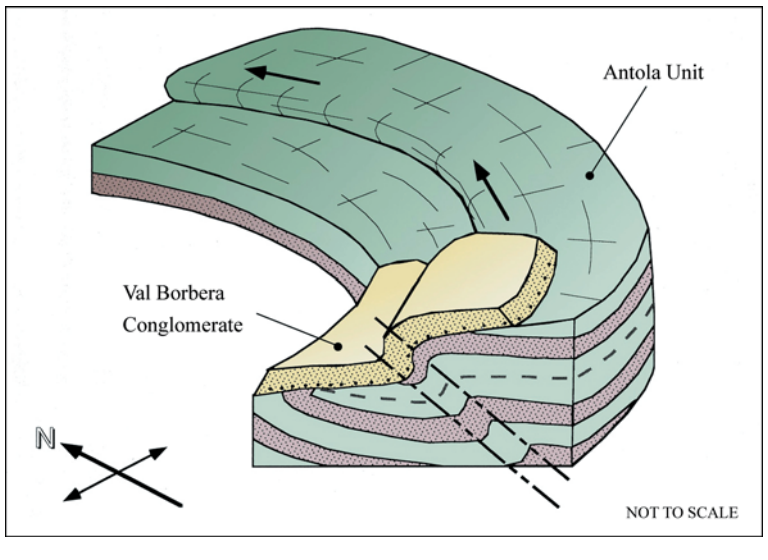


Fig. 7- *Block diagram representing the Borbera Valley structure.*

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