Metamorphosed ophiolitic units in the Ligurian Alps

Gisella REBAY*, Sergio TALLONE**, Daniele D'ANTONIO***, Marco SCAMBELLURI****, Andrea BISTACCHI *****, Bruno MESSIGA* & Guido GOSSO ******

* Dipartimento di Scienze della Terra, Università di Pavia, Pavia, Italia
** Istituto di Geoscienze e Georisorse, Consiglio Nazionale delle Ricerche (CNR), Torino, Italia
*** Dipartimento di Scienze della Terra, Università di Torino, Torino, Italia
**** Dipartimento per lo Studio del Territorio e delle sue Risorse, Università di Genova, Genova, Italia
***** Dipartimento di Geologia, Paleontologia e Geofisica, Università di Padova, Padova, Italia
****** Dipartimento di Scienze della Terra "A. Desio", Università di Milano, Milano, Italia.

ABSTRACT

This contribution provides a synthetic picture of the methodology and approach used to map metamorphic ophiolitic units. Metamorphic rocks have the peculiarity of preserving information regarding the transformations they underwent when involved in large-scale tectonic processes. Metamorphic evolution is inferred from a sequence of mineral assemblages at equilibrium, that are indicators of PT conditions. This sequence is determined through the study of superpositions of successive structures and parageneses in undeformed (coronites) and deformed (tectonites and mylonites) rocks of different chemical composition (meta-ultramafite, metabasite and metasediment). In this example, we show how different portions of an ophiolitic unit preserve a different structural and metamorphic "memory". Combining all these data allows the determination of a complex polymetamorphic evolution for the ophiolites of the Voltri group.

AIMS

This contribution focuses on the following elements which must be considered when mapping metamorphic ophiolitic units:
- mineral assemblages typical of different metamorphic facies in various lithologies (differences in chemistry of the protolith);
- superposition of structures with different equilibrium assemblages in deformed rocks;
- compositional zonations and reaction textures in undeformed, coronitic, rocks.

The interrelations between structures (that give a temporal framework) and mineral assemblages allow the reconstruction of metamorphic evolution and the distinction of different tectonometamorphic units in complex, polimetamorphic terrains.

KEYWORDS

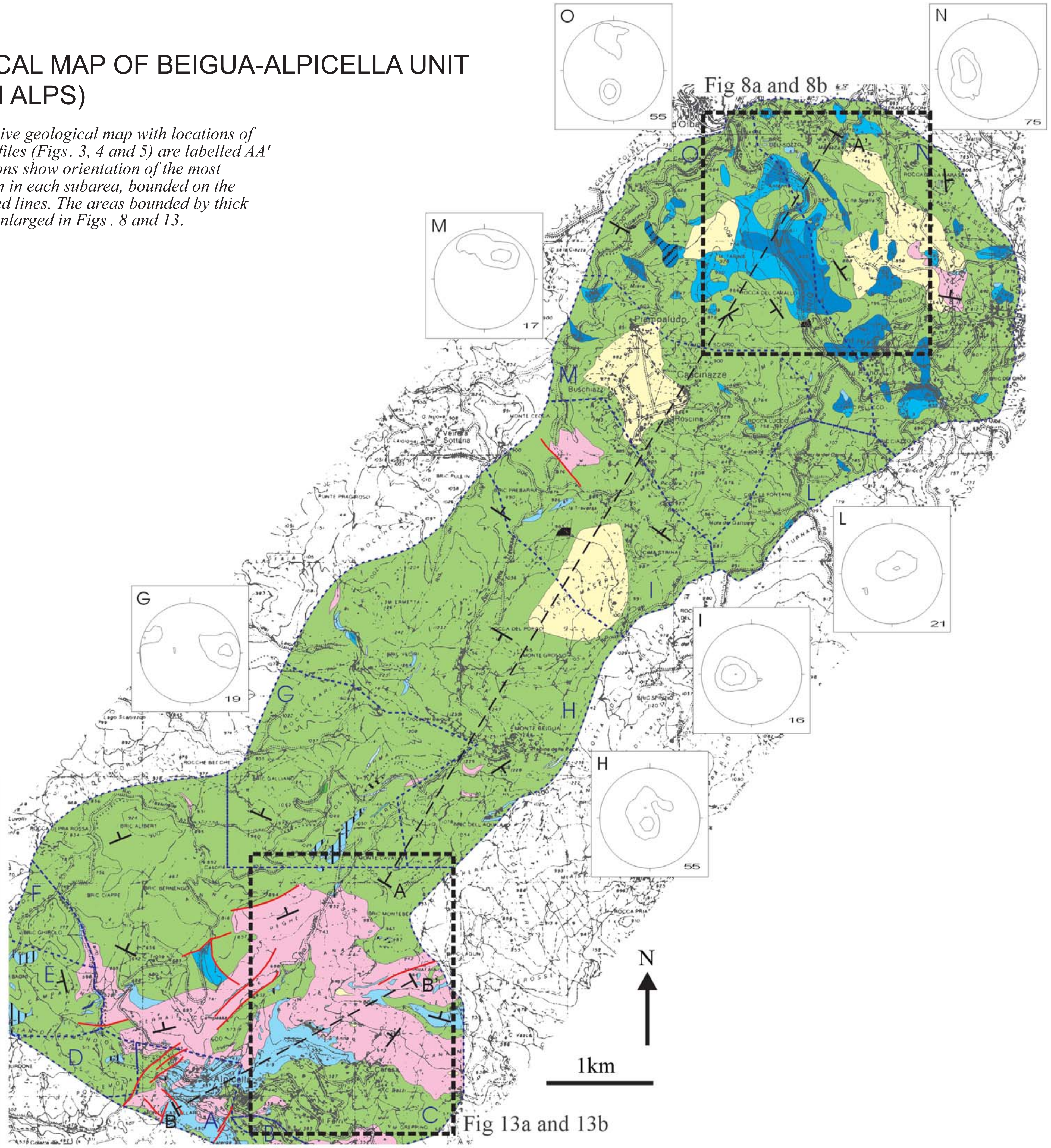
Metamorphic ophiolite, mapping, metamorphic transformation pervasiveness, Voltri group.

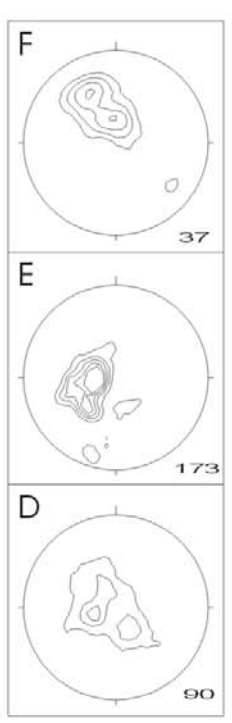
RIASSUNTO

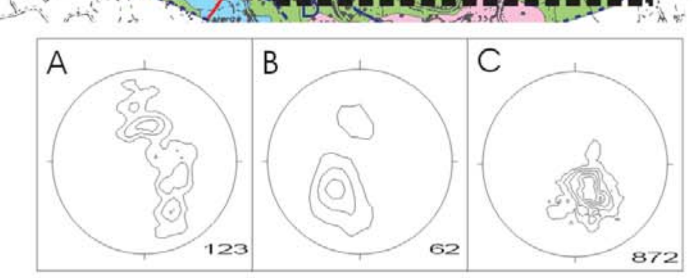
Scopo di questo lavoro è di fornire un quadro sintetico delle metodologie e dell'approccio utilizzati nella cartografia di rocce metamorfiche di unità ofiolitiche. Le rocce metamorfiche hanno la caratteristica di conservare informazioni sulle trasformazioni che hanno subito per il loro coinvolgimento nei fenomeni tettonici a grande scala. L'evoluzione metamorfica è dedotta attraverso la determinazione di una sequenze di associazioni di minerali all'equilibrio che indicano le condizioni di Pressione e Temperatura a cui si sono formate. Questa sequenza P determinata grazie allo studio delle sovrapposizioni di strutture tettoniche e paragenesi mineralogiche osservate nelle rocce indeformate e deformate (coroniti, tettoniti e miloniti) che hanno differenti composizioni chimiche (meta-ultramafiti, metabasiti e metasedimenti). In questo esempio viene mostrato come porzioni differenti di una stessa unità ofiolitica presentino una memoria strutturale e metamorfica variabile. Solo l'insieme delle informazioni preservate in porzioni differenti permette di ricostruire interamente la complessa storia polimetamorfica delle ofioliti Del Gruppo di Voltri.

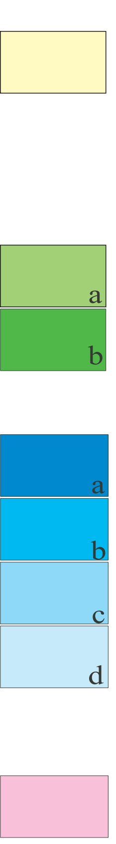
GEOLOGICAL MAP OF BEIGUA-ALPICELLA UNIT (LIGURIAN ALPS)

Fig.1 - *Interpretative geological map with locations of other figures. Profiles (Figs. 3, 4 and 5) are labelled AA' and BB'. Projections show orientation of the most pervasive foliation in each subarea, bounded on the map by thin dashed lines. The areas bounded by thick dashed lines are enlarged in Figs. 8 and 13.*









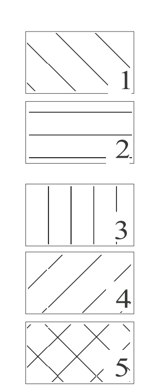
Quaternary cover

Beigua-Alpicella Unit

Serpentinised ultramafics (a), usually extremely foliated, containing metric to decametric less deformed lenses preserving mantle tectonitic textures with clinopyroxene relics or cumulitic textures with olivine relics. Eclogite-facies serpentinites with metamorphic brownish olivine (b), either as radial aggregates overprinting massive serpentinites or as an older foliation, or defining a high pressure foliation crosscutting an earlier serpentine pre-eclogitic foliation, or, together with titan-clinohumite, in veins that cut serpentine foliation.

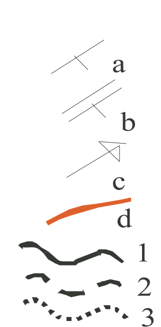
Metabasites deriving both from gabbroic rocks (relics of textures and of clinopyroxene) and from basalts. Eclogite-facies metabasites, with garnet and omphacite (a), usually with centimetric to decimetric bands defined by blue amphibole; b) amphibolite- or greenschist-facies amphibole metabasites with garnet relics; c) greenschist-facies chlorite/albite rocks (prasinites); d) rodingites, sometimes deriving from gabbroic dykes within the serpentinites.

Metasediments: calcschists, marbles and quartzites interbedded with mafic levels deriving from metabasites and ultramafites. They are multifoliated and pervasively reequilibrated under green schist facies conditions (white mica, chlorite, albite, quartz and carbonates in carbonatic portions, tremolite, epidote and albite in the mafic portions, white mica, chlorite, plagioclase, quartz + biotite in pelitic layers). Relics of garnet, white mica with high celadonite content or chloritoid are found in the less deformed domains.



Pre- eclogitic relict textures and protoliths (patterns):
Ultramafics: (1) cumulitic textures (+ olivine)
(2) tectonitic textures (+ clinopyroxene)

Metabasites: (3) paragenetic and textural relics indicating Mg-gabbros
(4) paragenetic and textural relics indicating Fg-gabbros
(5) detritic protolith



Symbols
Fabrics:
(a) foliation plane;
(b) banding;
(c) fold axes;
(d) traces of faults.
In the interpretative maps: limits according to quantity of interpretation:
1 - certain, 2 - deduced, 3 - uncertain.

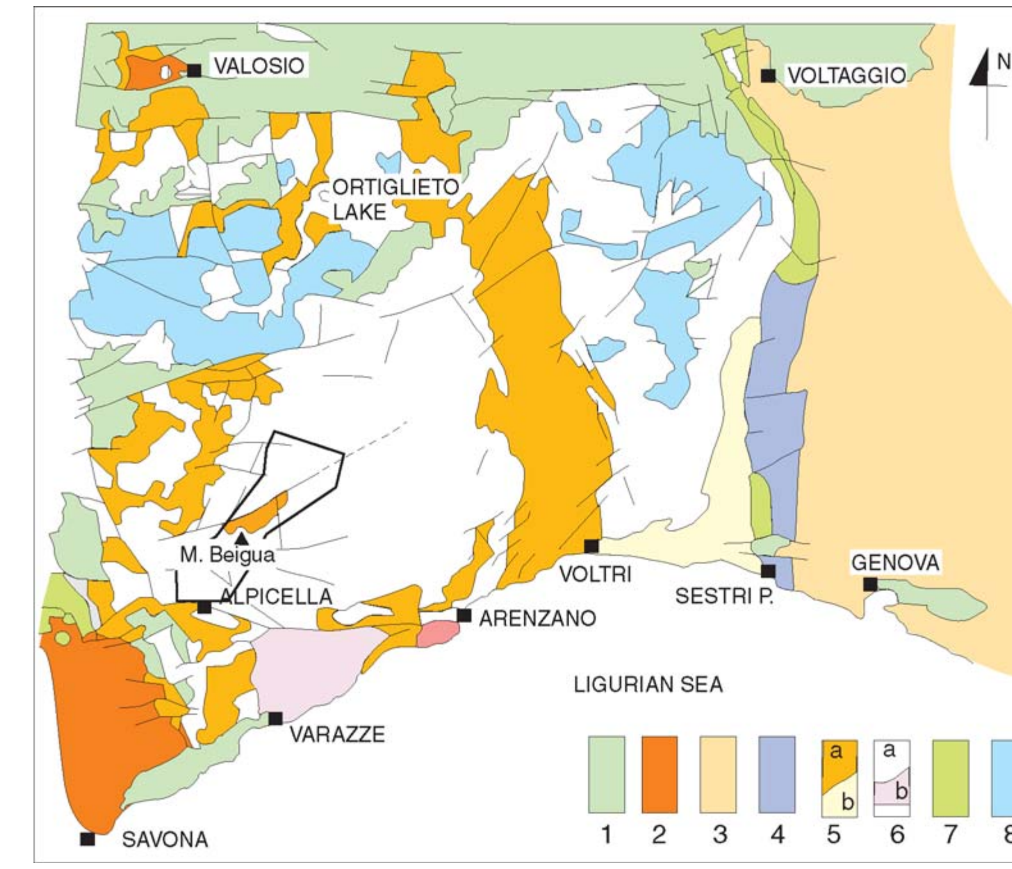


Fig. 2 - *Tectonic map of the Voltri Massif (modified after Messiga et al., 1989). 1 = Tertiary Piemontese Basin sediments (molasses); 2 = Pre-Ercynic Savona and Valosio basement; 3 = Ligurian Northern Apennine flysch; 4 = blueschist metaophiolites of the Sestri-Voltaggio zone; Voltri Group: 5a = greenschist metavolcanics (prasinites) and calcschists with relics of eclogitic assemblages; 5b = calcschists with blueschist mafic rocks; 6a = serpentinites with eclogitic metagabbros; 6b = serpentinised lherzolites with greenschist metagabbros; 7 = Blueschists metamorphic ophiolites of the Monte Notte nappe and underlying upper-Triassic, lower-Jurassic limestones and dolostones; 8 = Lherzolites (partially serpentinised) of the Erro-Tobbio Unit. The studied area (Figs 1, 8 and 13) is encircled by a thick black line.*

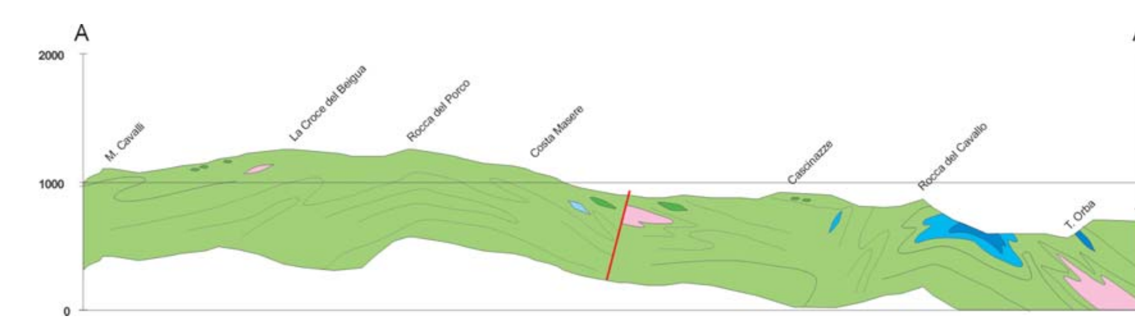


Fig. 3 - *Geological cross-section through the northern portion of the area (AA' in Fig. 1).*

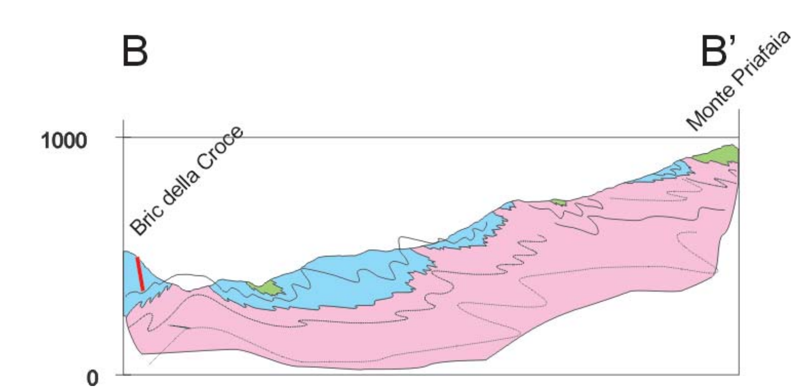


Fig. 4 - *Geological cross-section through the southern portion of the area (BB' in Fig. 1).*

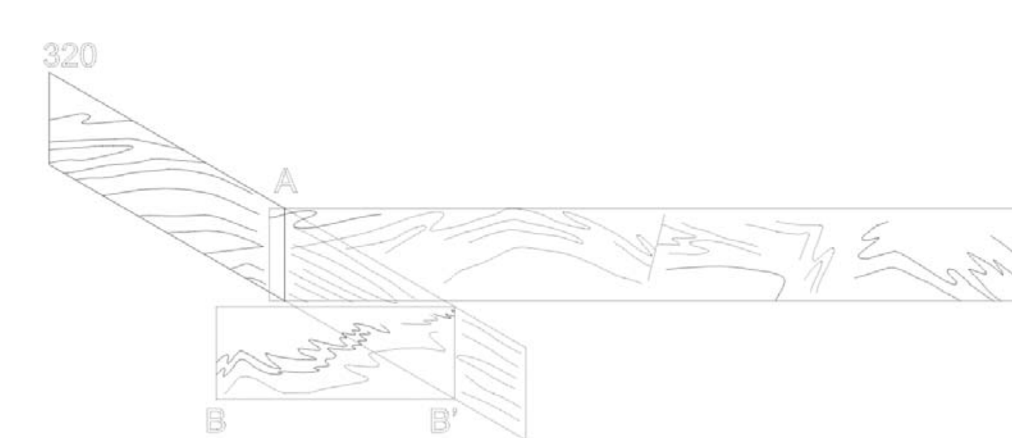


Fig. 5 - *Sketch showing the main orientations of the most pervasive foliation along the two geological sections and a plane with direction 140°.*

GEOLOGICAL SETTING

The Voltri Massif (Ligurian Alps) belongs to the internal Penninic Units of the Western Alps. It is separated from the Apennine chain to the E by the Sestri Voltaggio zone (a melange of ophiolites with blueschist metamorphic imprint and Triassic sediments) and bordered by the Tertiary sediments of the Piemontese basin to the N, while it overrides the Ercynian continental basement of Savona to the W (Fig. 2). The Voltri Massif is composed of various tectonic slices (serpentinised mantle, mesozoic ophiolites, oceanic and continental sediments), originated at different litospheric levels, and is overlain by the Erro-Tobbio thrust sheet (mantle peridotites) and the Montenotte Unit (blueschist and lower grade metamorphic ophiolites; Chiesa *et alii*, 1975; Messiga & Piccardo, 1974; Piccardo, 1977; Hoogerduijn Strating, 1993: Scambelluri & Rampone, 1999; Rampone *et alii*, 2001). The primary relations between Voltri rocks are mostly obliterated by Alpine tectonics. These rocks record a polyphasic, Alpine metamorphic evolution that took place during the exhumation of a Jurassic oceanic crust that had been previously subducted to depths of more than 40 km. The main structures are represented by a regional greenschist-facies foliation and mineral assemblages. Nonetheless, small rock volumes preserve mineral and structural relics of older oceanic and eclogite-facies stages.

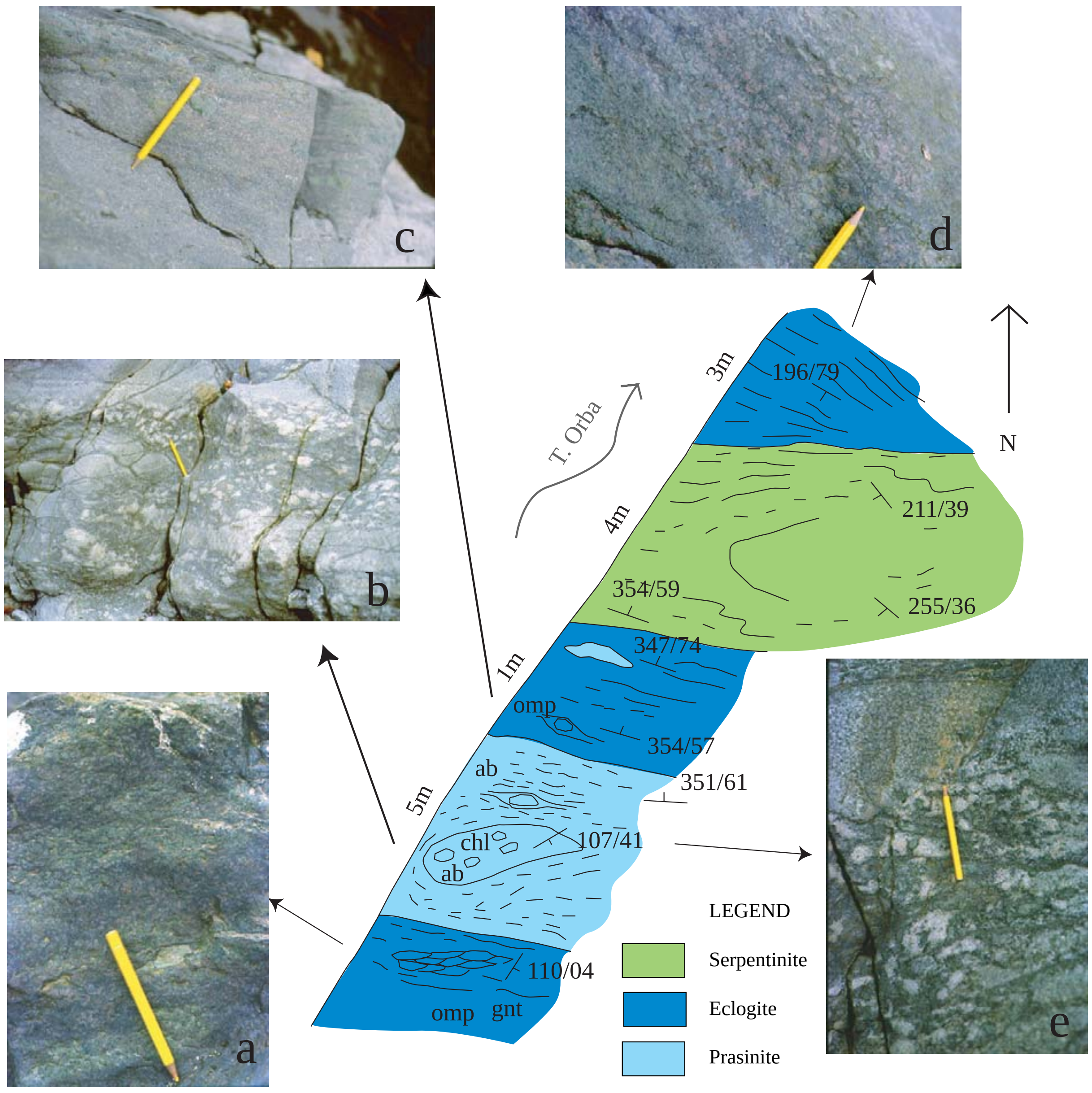


Fig. 6 - *Schematic drawing (not at scale) of an outcrop in which metabasites show highly variable textures and metamorphic transformations, with the preservation of early textures (prasinites with intrusive texture, photographs* **b**) *and* **d**) *and of evidence of various stages of the metamorphic evolution (eclogites* **a**, **c** *and* **d**), *amphibolites* (**a**) *and prasinites* (**b** *and* **e**); *relicts of igneous cpx). Serpentinites are extremely deformed, pencil is 10 cm.*

PROBLEMS AND METHODOLOGY

Metamorphic rocks preserve a series of different structural, paragenetic and textural records that allow the reconstruction of the tectonic path they have followed during oceanic evolution and orogenic cycles. This path can be reconstructed by recognising the time sequence of parageneses, which is specific for each chemical composition and indicative of different PT equilibration conditions. Parageneses are metastably preserved at various scales in different rocks portions. Paragenetic sequences are reconstructed on the basis of the uperposition and intersection of fabrics and of superposed reaction textures.

During mapping work, it is therefore important to consider the following: 1) rock fabrics, such as planar and/or linear structures of tectonites and relic textures in undeformed rocks; and 2) the paragenesis (and type of metamorphic transformation) associated to each fabric. Deformation and metamorphic processes are unevenly distributed at the outcrop scale due to the temporal and spatial heterogeneity of the deformation mechanisms and the efficiency of metamorphic transformations. The representation of critical fabric requires scale exaggerations (Figs. 6 and 14) in order to convey a sufficient amount of information in the map.

In this example, we have chosen a part of the Voltri Group with polymetamorphic ophiolitic lithologies that have undergone a common P T evolution. In order to unify them in a map representation of polimetamorphic rocks and their evolution, we have attempted to provide a picture of the volumes of rocks displaying different types and quantities of metamorphic re-equilibration, showing that most of the metamorphic history of a tectonic unit can be reconstructed from small volumes that have escaped pervasive re-equilibration, usually during late evolutionary stages.

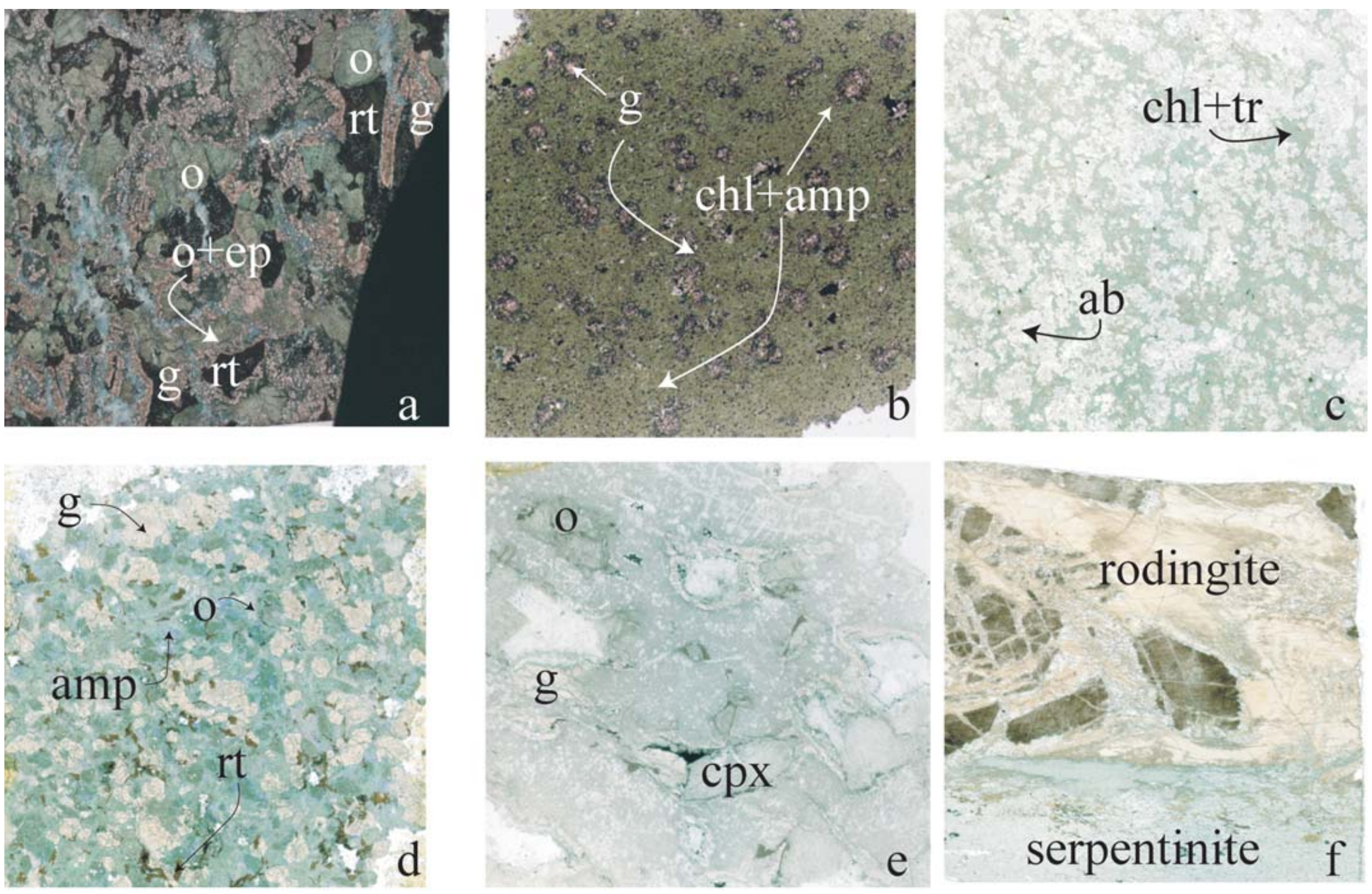


Fig. 7 - *Photomicrographs (textures observable with hand lens) of metabasic rocks. From top to bottom, left to right:* **a**) *Coronite of Fe-gabbro (note opaques, now rutile) completely eclogitised. Garnet corona develop between ancient plagioclase (now epidote + omphacite) and clinopyroxene (now omphacite);* **b**) *amphibolite metabasite with garnet relics;*
c) *prasinite (white = albite, green = chlorite + amphibole + epidote);*
d) *eclogite not preserving igneous texture;*
e) *Mg-gabbro, with high pressure relics (garnet) and greenschist partial retrogression;*
f) *rodingite (top) and serpentinite (bottom). All photos are approximately 2 cm wide).* **o** *= omphacite,* **g** *= garnet,* **rt** *= rutile,* **ep** *= epidote,* **chl** *= chlorite,* amp *= amphibole,* **cpx** *= clinopyroxene,* **tr** *= tremolite,* **ab** *= albite.*

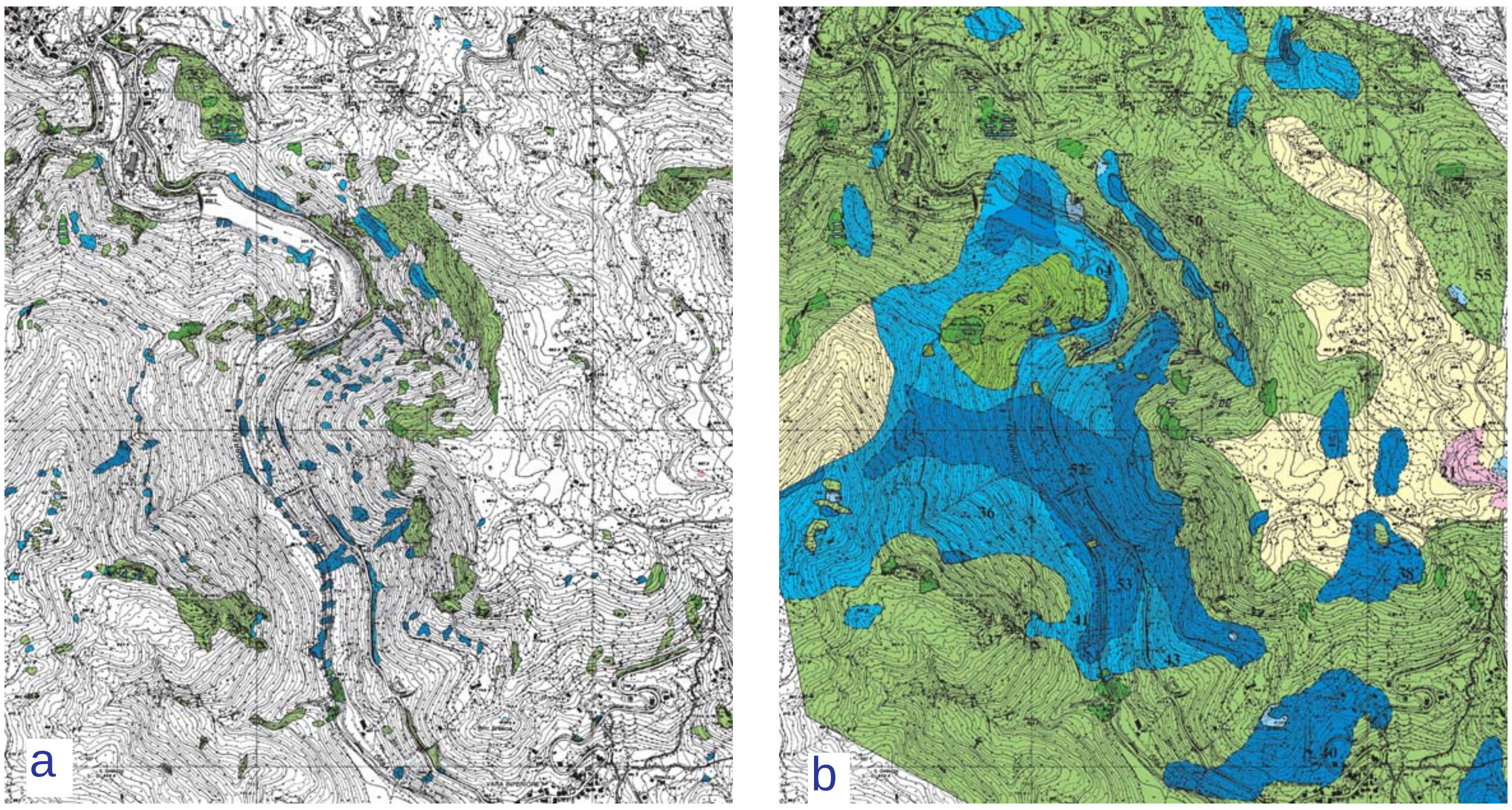


Fig. 8 - *Example of outcrop* (**a**) *and interpretative* (**b**) *maps of the northern portion, where large metabasic bodies prevail. North is to the top of figures; a square covers one square kilometer.*

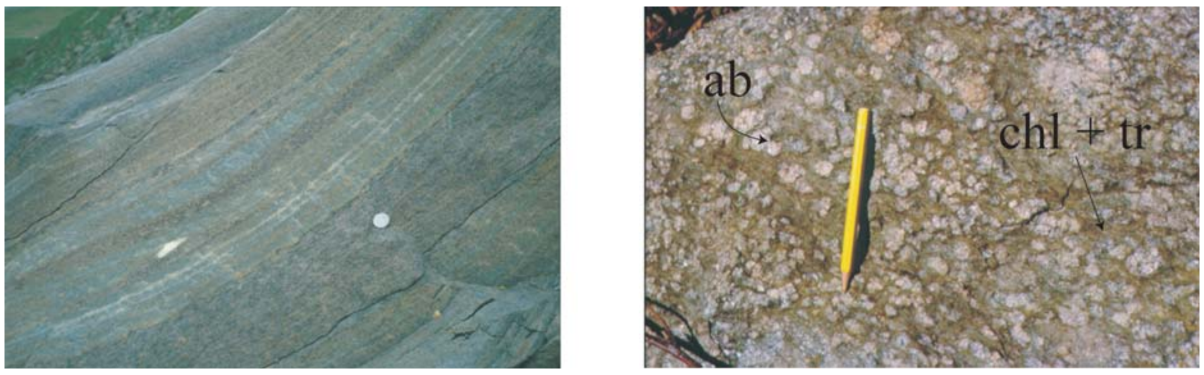


Fig. 9 - *Field appearance of banded eclogites (the original igneous texture is completely obliterated) and of prasinites. Pencil approximately 7 cm long.*

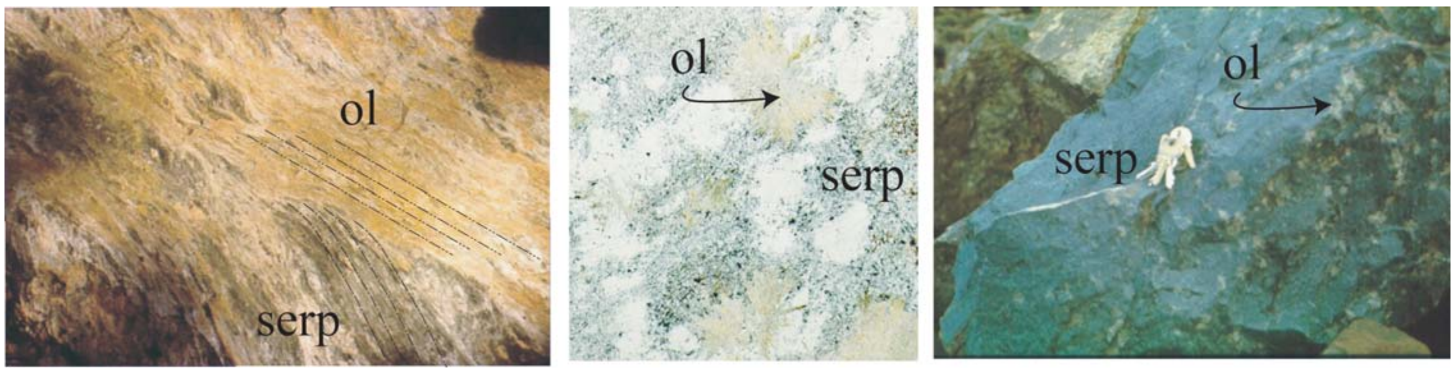


Fig. 10 - *Ultramafites. From left to right: olivine bearing foliation (top) crosscuts serpentine bearing foliation, which is overgrown by olivine (left). Photo of a thin section showing brown radial aggregates of olivine overgrowing serpentine. Outcrop view of radial metamorphic olivine.* **Serp** *=* *serpentine,* **ol** *= metamorphic olivine.*

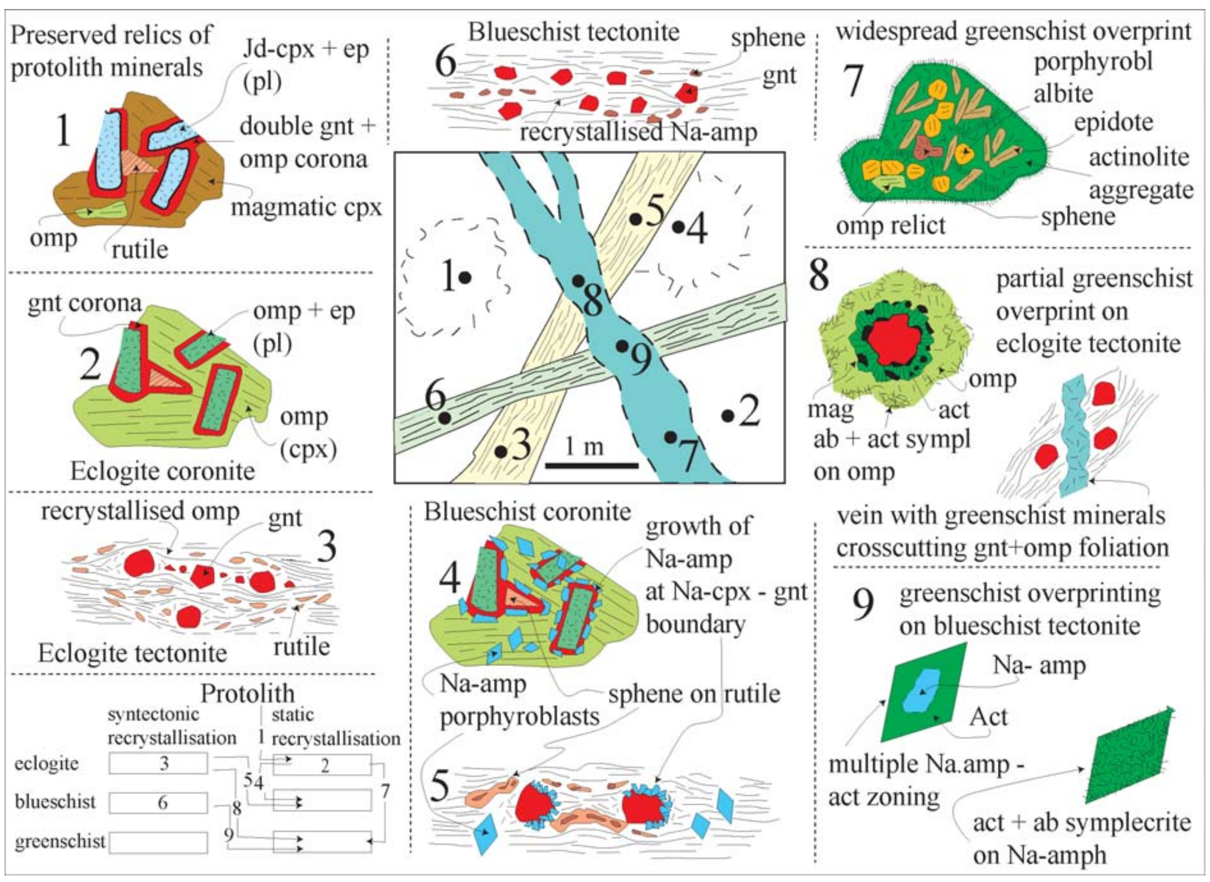
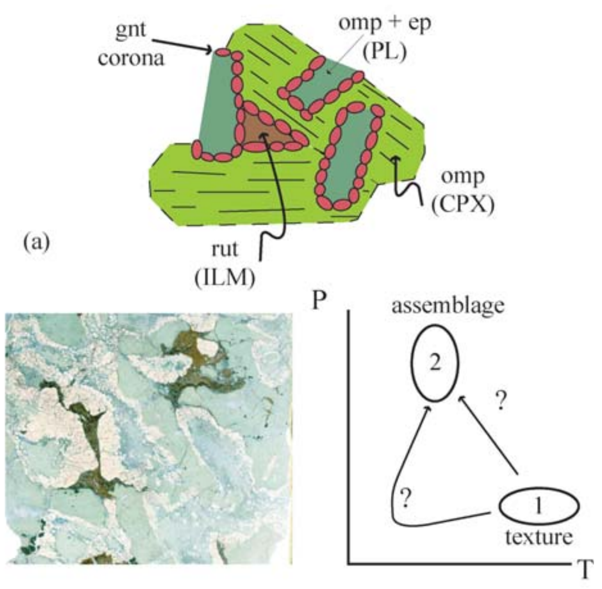


Fig. 11 - *Sketch of an hypothetical outcrop displaying mutual relationships between coronites and tectonites in a poliphased metamorphic unit. Numbers 1 to 9 represent different textures observed in the various subareas of the outcrop.*

THE NORTHERN PORTION

In the northern part of the map (Fig. 1), serpentinites and metabasics prevail. Serpentinite fabrics are mineralogically monotonous, except for rare outcrops where metamorphic olivine is found (Fig. 10). Weakly deformed metabasic boudins and veins preserve numerous relics of pre greenschist-facies metamorphic evolution (Figs. 6, 7, 8a, 8b and 9). This portion is characterised by a good paragenetic "memory" (i.e. abundance of relic and superposed parageneses) and a scarce structural "memory" (i.e. scarcity of superposed foliations and large-scale univocal deformation patterns). Different kinds of metamorphic re-equilibration are distinguished in metabasic rocks (Figs. 6, 7 and 9). A continuous range of assemblages is observed, from "fresh" eclogite (Figs. 7a, 7d and 9a) to partially amphibolitised eclogite, to amphibolite, to greenschist facies rock with garnet relics, to prasinite (Figs. 7c and 9b).



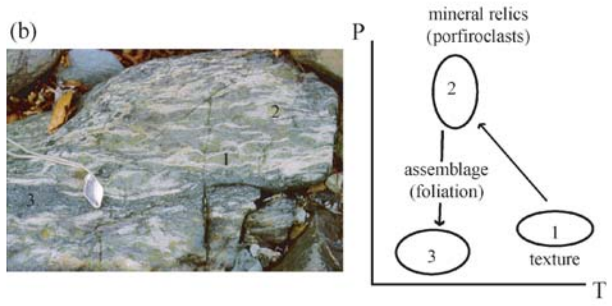


Fig. 12 - *Superpositions of mineral assemblages and fabrics are observed in undeformed, or coronitic, rocks* (a) *and in foliated rocks, or tectonites,* (b), *respectively. The metamorphic evolution is reconstructed thanks to key outcrops (see Figs. 6, 11 and 14) where the relationships among all these features can be observed, enabling the reconstruction of the* P-T *path (Fig. 16).*

LEGEND

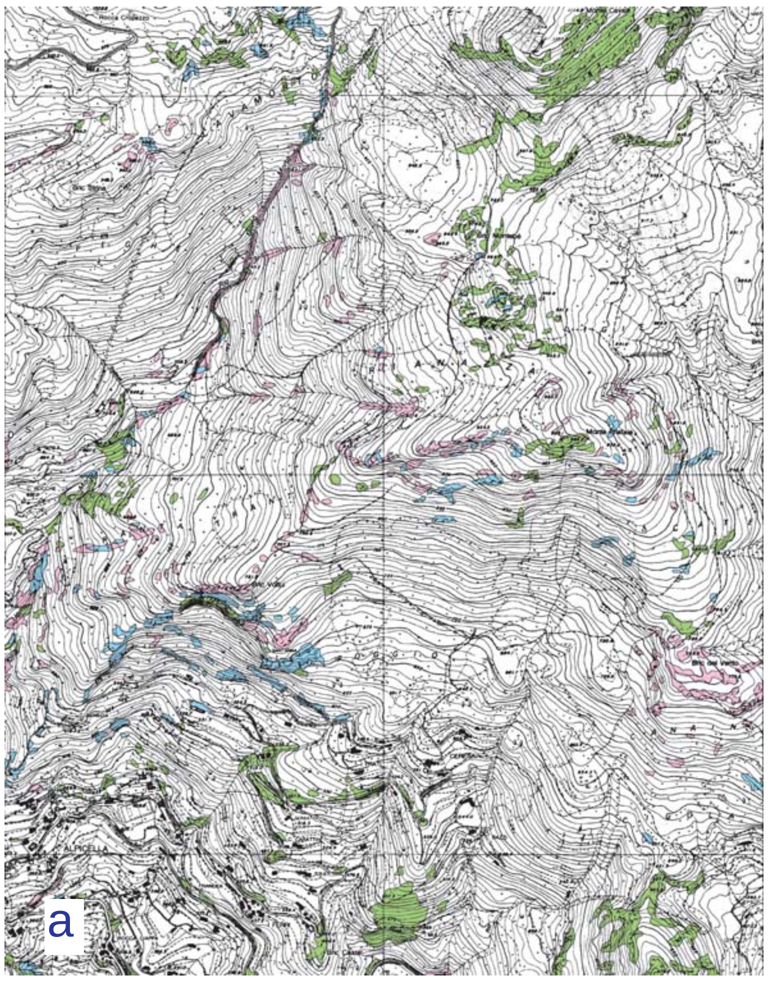
The legend was produced by grouping different kinds of data into logical categories. The first distinction was operated on the basis of the chemical composition of rocks, by distinguishing three main groups; ultrafemics, femic and pelitic-carbonatic rocks. Further information has been added to these groups to represent: (i) the type of metamorphic transformations (i.e. the prevailing metamorphic facies), by using different shades of the main colour; and (ii) the textures (ex. Cumulitic texture in a serpentinite) or protholits (e.g. Mg-gabbro) of the rocks, by using halftone screens and symbols. The most pervasive foliation of foliated rocks is represented (except in the cases in which superposed foliations are recognisable). This foliation is composite both as transpositive and in the metamorphic sense (e.g. a serpentine foliation in serpentinite can be pre- or post-eclogitic), so that the Sx in a different outcrop is not necessarily geometrically equivalent or contemporaneous. Data concerning foliation orientations are summarised in stereographic projections relative to sub-areas with relatively homogeneous deformation styles.

THE SOUTHERN PORTION

The southern part of the area, where metasediments prevail, is pervasively re-equilibrated under greenschist facies conditions (with few relics of the high pressure evolution), but is characterised by different superposed structures that allow a precise reconstruction of the late exhumation and thrust evolution (Figs. 13a, 13b, 14 and 15). This reconstruction is achieved by detailed mapping of key outcrops (Fig. 14).

COMMENTS ON METHODOLOGY

In order to unravel the complex metamorphic evolution undergone by a tectonic unit, it is necessary to distinguish domains having different degrees of deformation. Their mutual relationships are recognised on the field (an example is the summary of Fig. 14, centre). A close look at different key outcrops allows the recognition of different equilibrium assemblages and their temporal sequence, evidenced by superposition of foliations, coronitic structures and zoned minerals. Fig. 14 summarises the typical situations observed in metabasic rocks of the Voltri Group.



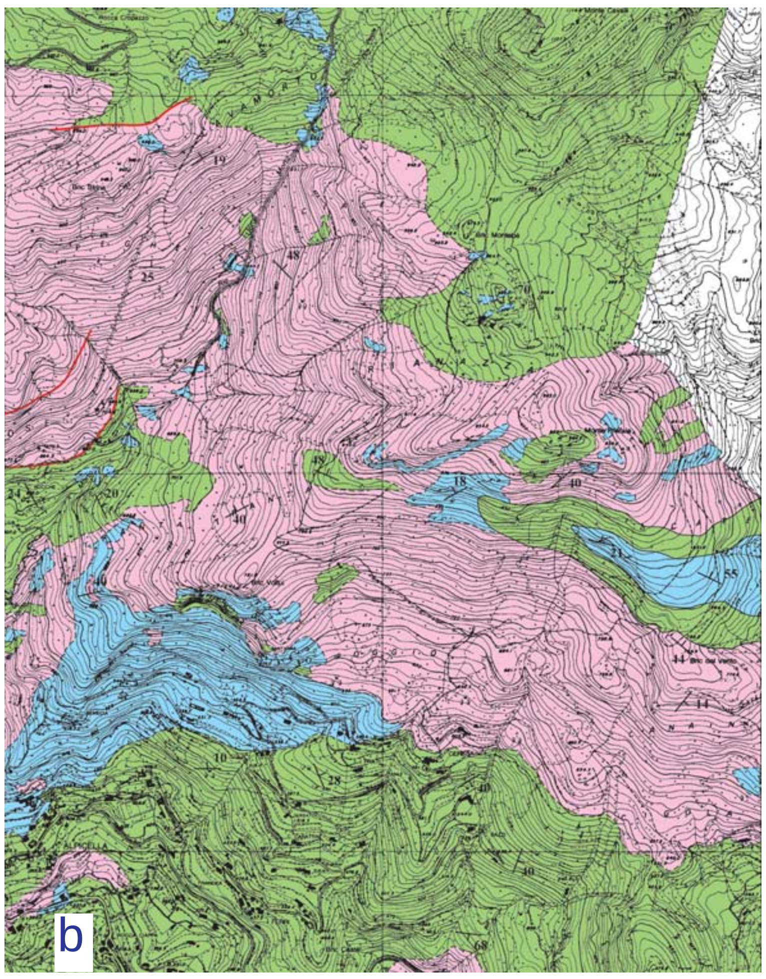


Fig. 13 - *Example of outcrop* (**a**) *and interpretative* (**b**) *maps of the southern area, where metasediments prevail volumetrically. North is to the top of figures; each square covers one square kilometre.*

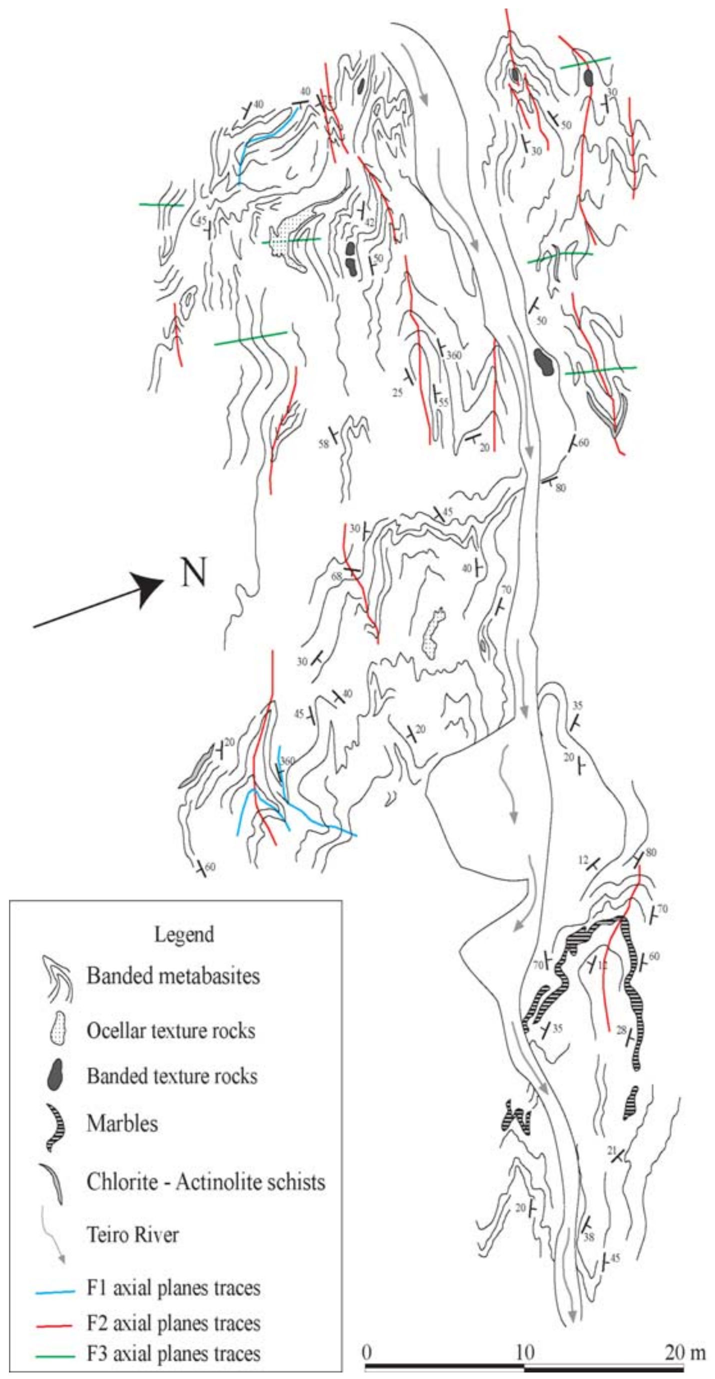


Fig. 14 – *Detailed map of a small outcrop along the River Teiro, located in the southern portion of the map in Fig. 13. Calcschists and metabasites (mainly prasinites) are highly deformed, indicating a succession of folding events. Metamorphic transformation is pervasive in greenschist – facies and no relics of previous metamorphic phases are found in the outcrop.*

Fig. 15 - *Metasediments are highly deformed, with superposition of several deformational events (see Fig. 13). They comprise calcsilicates, marbles, mica rich layers (where occasionally relics of high pressure chloritoid (center) can be found) and basic layers, in part deriving from erosion of gabbros and ultramafites on ocean floor.* Cld = *chloritoid.*

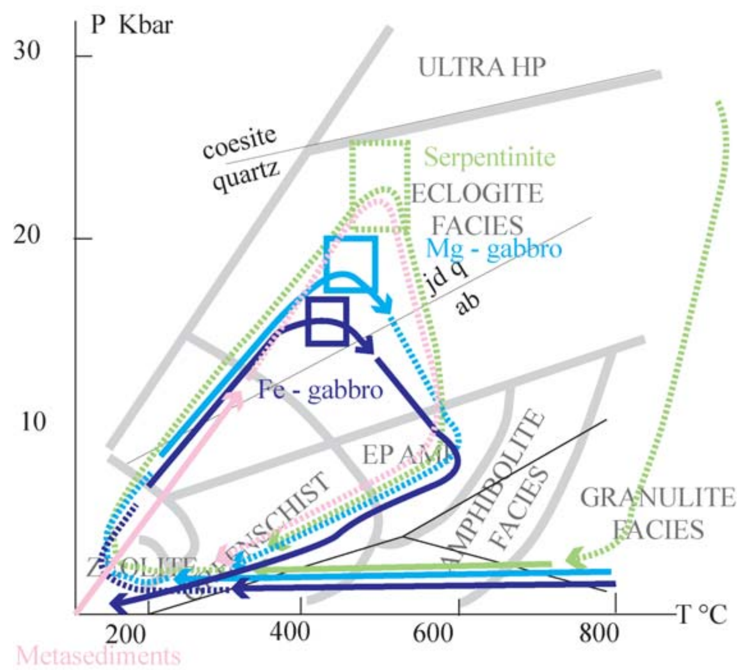


Fig. 16 - *Summary of* P-T *evolutions calculated for the different lithologies. Full lines show portions of the metamorphic history that have been recognised in good detail; dotted lines are presumed evolutions.*

PT PROJECTION

PT evolution data is summarised in Fig. 16 in a synoptic PT diagram. Two peculiarities of this diagram should be noted:

- different chemical compositions record the common metamorphic history with different detail, for instance Fe- rich metabasics record exhumation history in extreme detail. Metabasics allow the recognition of longer parts of the path than, for example, ultrafemics. This results from the fact that some chemical compositions develop distinctive assemblages over short PT ranges, while others develop assemblages that are stable over large spans of the PT space (i.e. stability of serpentine).
- different chemical compositions seem to record different peak metamorphic conditions. This apparent inconsistency is a consequence of the fact that we usually deal with minerals that are complex solid solutions and are thus stable over parts of the PT space according to their composition. For example, magnesium end members are usually more stable at higher pressures than their Fe-equivalents; as it is possible to calculate minimum P and T, an iron system will give us minimum P and T lower than Mg even though they have undergone the same PT conditions due to conditions of preservation of metamorphic assemblages (GUIRAUD *et alii*, 2000).

CONCLUSIONS

The eclogitic imprint is mainly preserved at cores of large metabasic boudins, while small boudins and the margins of large boudins are mainly retrogressed to greenschist facies. Only small volumes preserve information about pre-eclogitic evolution (textures and relics represented by means of patterns). Metabasics are best suited for the reconstruction of poliphased metamorphic evolution, and serpentinites allow determination of maximum peak conditions, while metasediments allow reconstruction of a complex post-eclogitic tectonic evolution during exhumation.
Summing up, it is advisable to represent rock volumes with a common prevalent metamorphic imprint by using different shades of the same colour indicating a specific chemical compositions, i.e. different lithologies.

REFERENCES

CHIESA S., CORTESOGNO L., FORCELLA F., GALLI M., MESSIGA B., PASQUARE G., PEDEMONTE G.M., PICCARDO G.B. & ROSSI P.M. (1975) - *Assetto strutturale ed interpretazione geodinamica del Gruppo di Voltri.* Boll. Soc. Geol. It., **94**: 558-581.

CIMMINO F., MESSIGA B. & PICCARDO G.B. (1981) - *Le caratteristiche paragenetiche dell'evento eo-alpino di alta pressione nei diversi sistemi (pelitici, femici, ultrafemici) delle ofioliti metamorfiche del Gruppo di Voltri (Liguria occidentale).* Rend. S. I. M. P., **37**: 419-446.

CORTESOGNO L., ERNST W.G., GALLI M., MESSIGA B., PEDEMONTE G.M. & PICCARDO G.B. (1977) - *Chemical petrology of eclogitic lenses in serpentinite, gruppo di Voltri, ligurian Alps.* J. Geol., **85**: 255-277.

D'ANTONIO D., GOSSO G., MESSIGA B., SCAMBELLURI M. & TALLONE S. (1984) - *Analisi strutturale e ricostruzione litostratigrafica al margine sud-occidentale del Massiccio di Voltri, Zona Piemontese-Ligure, Alpi liguri.* Mem. Soc. Geol. It., **28**: 447-460.

GUIRAUD M., POWELL R. & REBAY G. (2001) - *H_2O in metamorphism and unexpected behaviour in the preservation of metamorphic mineral assemblages.* J. Met. Geol., **19**: 445-545.

HOOGERDUIJN-STRATING E.H., RAMPONE E., PICCARDO G.B., DRURY M.G. & VISSERS R.L.M (1993) - *Subsolidus emplacement of mantle peridotites during incipient oceanic rifting and opening of the Mesozoic Tethys (Voltri Massif, NW Italy).* J. Petrol., **34**: 901-927.

MESSIGA B. (1991) - *Reconstruction of the evolution of eclogitic rocks based on microstructure analysis.* V Summer School Lectures, Siena, 131-147.

MESSIGA B. & PICCARDO G.B. (1974) - *Rilevamento geo-petrografico e strutturale del Gruppo di Voltri. Il settore nord-orientale: la zona fra M. Tacco e M. Orditano.* Mem. Soc. Geol. It., **13**: 301-315.

PICCARDO G.B., MESSIGA B. & MAZZUCOTELLI A. (1979) - *Chemical petrology and geodynamic evolution of the ophiolitic metavolcanites (prasinites) from the Voltri Massif Piemontese ophiolite nappe (Western Liguria, Italy).* Ofioliti, **4**: 373-402.

RAMPONE E., PICCARDO G.B. & ROMAIRONE A. (2001) - *Mantle petrology as key to the understanding of oceanic lithosphere formation; inferences from the Ligurian ophiolites.* GSA meeting, Abstracts with Programs, **33**(6): 172.

SCAMBELLURI M. & RAMPONE E. (1999) - *Mg-metasomatism of oceanic gabbros and its control on Ti-clinohumite formation during eclogitization.* Contrib. Mineral. Petrol., **135**: 1-17.