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The pre-orogenic tectonic history of the Bracco gabbroic massif: review and news

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Abstract — We present some preliminary data on the oceanic tectono-magmatic history and deformation structures of the Bracco gabbroic Massif, recently collected through detailed structural fieldwork in the Bracco Pass - Mt. San Nicolao area (Eastern Liguria). The Bracco Massif (Vara Supergroup, Internal Ligurian Units) represents a fragment of Jurassic oceanic lithosphere. It is largely made of gabbros intruded in serpentinitic lherzolites and affected by very low-grade orogenic metamorphism (prehnite-pumpellyite facies); the gabbroic mass often shows a cumulitic texture and it is locally characterised by the presence of ductile shear zones, displaying a peculiar HT-LP oceanic metamorphic imprint. It is crosscut by basalt dykes and hornblende-oligoclase veins. We collected new data on the attitudes of the magmatic layering, shear zones, basalt dykes and hornblende-oligoclase veins, focusing on those areas where the Alpine to post-Alpine deformation is scarce, so that the pre-orogenic structural features were preserved and easier to interpret.

The data show that the younger oceanic structures (basalt dykes and hornblende-oligoclase veins) have a homogeneous trend in the whole studied area, whereas the magmatic layering and the ductile deformations (mylonites, flaser) have very different attitudes in the eastern and western sectors of the Bracco area. These sectors are separated by a NW-SE normal fault that runs immediately westwards from Mt. San Nicolao.

We also present a discussion on the tectonic significance of the ductile structures and an interpretation of the structural data in the geodynamic context of an ocean ridge near a transform fault intersection.

Riassunto — In questa nota sono presentati alcuni dati preliminari, raccolti durante una campagna di rilevamento strutturale effettuata sul Massiccio del Bracco. Il Massiccio del Bracco (Supergruppo del Vara, Liguridi Interne) rappresenta un lembo di crosta oceanica fossile. Esso è costituito in gran parte da gabbri, interessati da un metamorfismo orogenico di grado molto basso (facies prehnite-pumpellyite). I gabbri mostrano spesso tessiture cumulitiche e sono intrusi in serpentiniti lherzolitiche. Localmente, in corrispondenza di zone di taglio duttile, i gabbri sono foliati e ricristallizzati (metamorfismo oceanico di HT e LP). Sia le strutture magmatiche (*layering*) che quelle metamorfiche (miloniti, *flaser*) sono tagliate da filoni basaltici e da fratture e vene riempite da orneblenda e oligoclasio. Tutti questi eventi avvengono prima che il “basamento” oceanico gabbro-peridotitico sia denudato in un fondo oceanico. I nuovi dati strutturali raccolti riguardano il *layering* magmatico, le zone di taglio, i filoni basaltici e le fratture e vene

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ad orneblenda ed oligoclasio. Dall’analisi delle loro giaciture e dei rapporti geometrici tra i vari gruppi di elementi strutturali, si osserva che in queste rocce la tettonica orogenica ha prodotto soltanto una moderata deformazione; queste aree, nelle quali si suppone che l’assetto attuale sia alquanto simile a quello originario, si configurano quindi come zone-chiave per lo studio dettagliato della crosta oceanica della Tetide occidentale. I dati fin qui ottenuti, anche se ancora parziali, ci permettono di notare che le strutture più recenti tra quelle analizzate (filoni basaltici e fratture ad orneblenda-oligoclasio) hanno una giacitura abbastanza omogenea in tutta l’area studiata, mentre il *layering* magmatico e lo *shear* duttile (miloniti) possono avere nei vari settori giaciture anche molto diverse. In particolare l’intera area del Bracco può essere divisa in due zone (una orientale e una occidentale) dove le giaciture del *layering* e dello *shear* duttile mostrano in media diverse orientazioni. Le due aree sono divise da una faglia normale ad andamento NW-SE che passa poco a W di M. S. Nicolao. Si discute sul significato delle fasi duttili e sulle possibili interpretazioni dei dati strutturali nel contesto evolutivo di una zona di dorsale oceanica in prossimità di faglie trasformanti.

KEY WORDS: *Northern Apennines, Bracco gabbroic Massif, Jurassic ocean, magmatic layering, ductile shear zones, basalt dykes, hornblende-oligoclase veins.*

INTRODUCTION

The Bracco gabbroic Massif belongs to the Vara Supergroup (Abbate *et al.*, 1970, 1980; Bortolotti *et al.*, 2001; Marroni *et al.*, 1992), an ophiolitic sequence topped with turbidites, which is part of the Internal Ligurid Domain (Fig. 1), an oceanic sector of the Jurassic Western Tethys. This fragment of fossil oceanic lithosphere allows studying the complete evolution of an ophiolitic body, from the early igneous phase, through oceanic tectonisation, to its involvement in the Tertiary orogenic phases.

The stratigraphy, petrography and structure of the Bracco Massif has been initially studied by Cortesogno *et al.* (1981, 1987) and presented in the geological map schematically reproduced in Fig. 3. In this paper we present some new, preliminary field structural data on the oceanic deformations of the gabbroic mass, which allow us to constrain some pinpoints on its early igneous and tectonic history.

GEOLOGICAL SETTING

The ophiolites of the Northern Apennines belong to two distinct units: Internal Ligurids, which occupy the highest position in the Apennine structural pile, and the underlying External Ligurids (Fig. 1).

The Internal Ligurids crop out in the Ligurian Apennines, along the central Tuscan coast and in the Elba Island; they are made of a Jurassic-Palaeocene succession (Vara supergroup) which preserves an ophiolitic basement, represented by the Jurassic oceanic lithosphere, covered by a complete Late Jurassic-Cretaceous pelagic (cherts and limestones) succession. At the top, the succession ends with Late Cretaceous-Palaeocene siliciclastic and/or carbonatic turbidites.

The External Ligurids crop out in the Ligurian-Emilian Apennines, in the Tuscany hinterland and in the Tuscan-Marchean Apennines. They are characterised by Cretaceous-Eocene basinal successions and never preserve the pristine ophiolitic basement, which was probably tectonically detached at the level of the shaley formations known as “Basal Complexes” (i.e. Palombini Shales, Auctt.). Instead, in the External Ligurids, the ophiolites occur only as slide blocks (olistoliths), which often reach kilometric size, and clasts within breccias (olistostromes) in the Cretaceous-Eocene sedimentary successions.

The Bracco Massif (Fig. 1) is one of the best-exposed portions of gabbroic ophiolitic basement preserved in the Internal Ligurids (Abbate *et al.*, 1970). Cortesogno *et al.* (1981, 1987) subdivided the Vara Supergroup into two units: 1) Bracco Unit, consisting of the Jurassic/Early Cretaceous oceanic succession topped with the Cretaceous Palombini Shales Fm., and 2) the Gottero Unit, formed by the Late Cretaceous/Palaeocene sedimentary covers that lie on top of the Palombini Shales. In the Eastern part of Liguria the younger Gottero Unit was thrust over the older Bracco Unit. Thrusting occurred during the early Tertiary and cut through the Palombini Shales Fm.

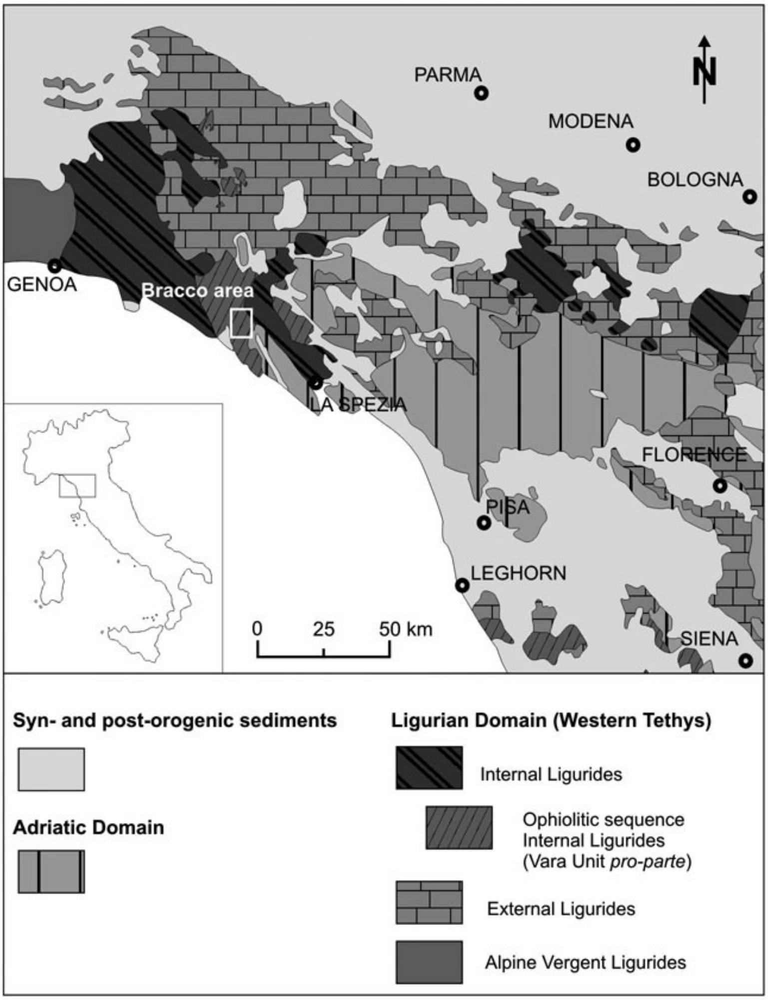

Fig. 1 – Geological sketch map of the Northern Apennines, with the location of the studied area (modified after Principi *et al.*, 2004).

GEOLOGICAL OUTLINE OF THE BRACCO UNIT

The Bracco Unit crops out a few kilometres inland from the Ligurian coastline between the Petronio River, to the north, and Monterosso, to the south. Within this area the Bracco Unit shows both “complete” and “reduced” sequences (both condensed in the column of Fig. 2) which, according to Cortesogno *et al.* (1987), formed adjacent to each other in the Jurassic oceanic realm.

The Bracco Unit comprises two subunits, the Velva and Mt. San Nicolao Subunits, located respectively at the top and at the bottom of the tectonic pile (Figs. 3 and 4). The Velva Subunit includes a basement of serpentinised lherzolites with ophicalcites at the top, and gabbros overlain by a thick sequence of ultramafic breccias, massive basalts, polygenic ophiolitic breccias, pillow lavas and pelagic sediments (Mt. Rossola element, in Cortesogno *et al.*, 1987; see left side of the column of Fig. 2, and the palinspastic restoration of Fig. 5). Locally, the Velva Subunit lacks the basalts and has cherts and Palombini Shales with reduced thickness lying directly above the serpentinised ultramafic basement, which is often topped with ophicalcites (Mezzema element in Decandia & Elter, 1970, 1972; Cortesogno *et al.*, 1987, column of Fig. 2).

The Mt. San Nicolao Subunit (right side of Fig. 2) mainly includes the gabbroic body of the Bracco Massif, and minor serpentinitic lherzolites, interpreted as host rocks. The cover succession is mostly absent; where present, it comprises breccias, ftanites and Palombini Shales (Canegreca element, Cortesogno *et al.*, 1981, 1987 and Principi *et al.*, 1992). In the lower portion of this subunit, in tectonic contact (Pavereto element), a cover similar to that of the overlying Mezzema element is present above the serpentinised lherzolitic basement (Cortesogno *et al.*, 1987).

The Tertiary Apenninic orogenic phase produced only weak deformation of the ophiolitic basement sequence, generally represented by brittle structures, mainly thrust faults, whereas the sedimentary cover, in particular the pelitic sediments, developed intense folding associated with penetrative foliation. Both thrusts and folds indicate a dominant tectonic transport towards the East.

In the Late Tertiary-Quaternary, the area was affected by extensional tectonics which produced NW-SE trending normal faults (the main one is the La Spezia Fault, at the eastern edge of the Bracco Massif, Fig. 3), and that created a horst and graben structure in the area. The Bracco Massif represents a horst cut by minor normal faults that produced a rugged morphology.

PETROGRAPHIC OUTLINE OF THE BRACCO OPHIOLITES

The serpentinitic lherzolites, which host the gabbro, sometimes display a coarse foliation, marked by the alignment of orthopyroxene crystals and, more rarely, by lherzolitic, harzburgitic, pyroxenitic or dunitic compositional layers. Dunitic lenses frequently occur and are often characterised by the presence of Cr-pyroxene (Cortesogno *et al.*, 1987). The petrographical and textural features of the serpentinites clearly point to an origin in mantle lherzolites and harzburgites (Cortesogno *et al.*, 1987). Serpentinisation affected mostly olivine and orthopyroxene, whereas clinopyroxene and spinel

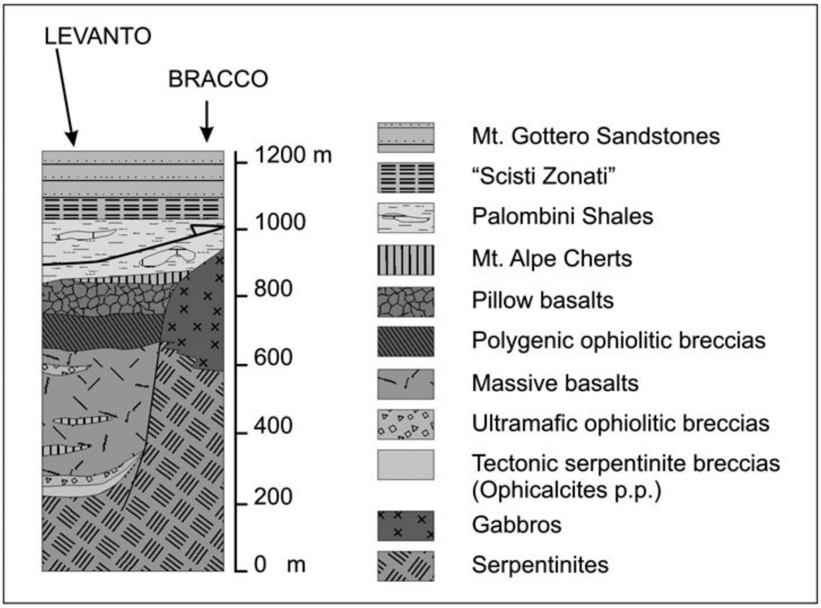

Fig. 2 – Stratigraphic section of the ophiolitic sequence of the Vara Supergroup (Internal Ligurids, Bracco-Levanto area)

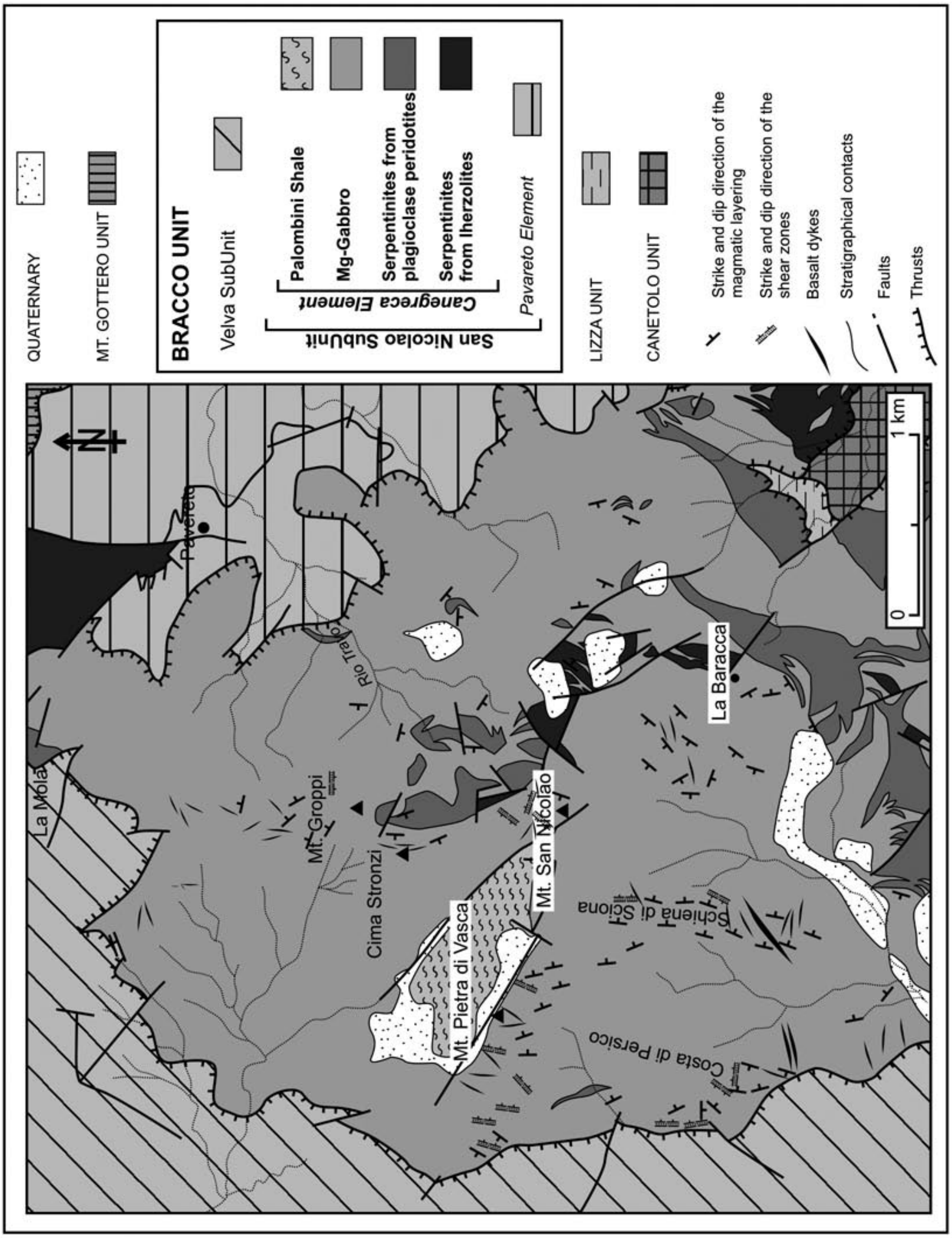

Fig. 3 – Geological sketch map of the Bracco Massif area (modified after Cortesogno et al., 1981).

occasionally occur as mineral relics. Plagioclase, where present, has been replaced by aggregates of chlorite.

The Bracco gabbroic Massif has a roughly circular shape over 5 km wide and with a minimum thickness of 500 m (Cortesogno *et al.*, 1987). It is made of leucocratic, rarely mesocratic, olivine and/or clinopyroxene-bearing gabbros. Inside the gabbroic mass there are some serpentinised plagioclase peridotites (dunites or wehrlites), which represent mafic differentiation products of the original melt (Cortesogno *et al.*, 1987). They occur as lens-shaped, melanocratic levels with a variable thickness, made of olivine (95-65%), plagioclase (5-30%), clinopyroxene (0-10%) and chromite (Bezzi and Piccardo, 1970; Beccaluva *et al.*, 1976, 1979; Bortolotti and Gianelli, 1976; Cortesogno *et al.*, 1977; Cortesogno *et al.*, 1987; Serri, 1980). The petrographical and textural features clearly point to a cumulitic origin for these products (Cortesogno *et al.*, 1987). A layered texture is only locally recognizable; where present, it is marked by levels of chromite. The olivinic and troctolitic rocks are often characterised by both compositional and crystal size variations. Isotropic coarse sized (euphotid) gabbros are also present, and intercalations of ultramafic cumulates become locally abundant.

Subordinate levels and veins of plagioclasites (plagioclase rich layers, anorthosites, Cortesogno *et al.*, 1987), and more rarely pyroxenites occur inside

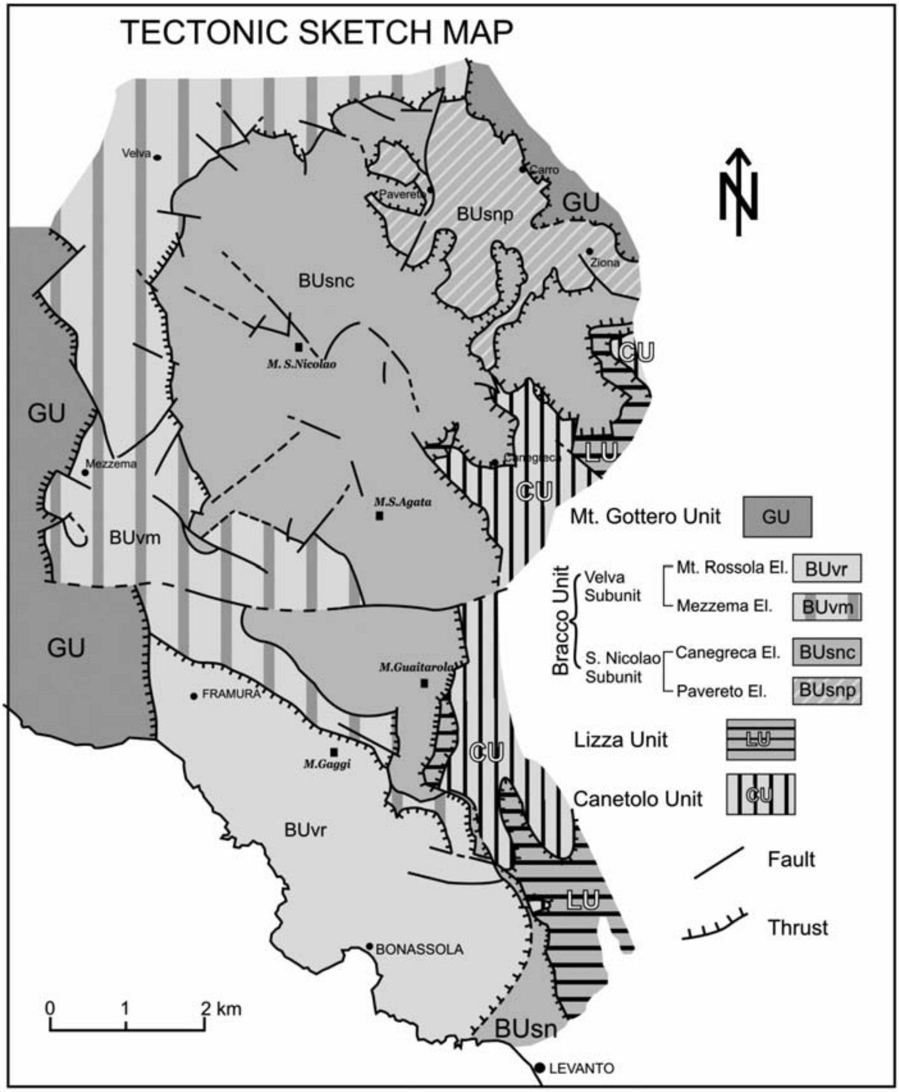

Fig. 4 – Tectonic sketch map of the Bracco Unit between Levanto and Pavereto, Eastern Liguria.

the gabbroic body; the plagioclasites are coarse-grained, with plagioclase (An$_{70}$; Serri, 1980) generally saussuritised, and interstitial femic minerals (olivine and, more rarely, clinopyroxenes; Cortesogno *et al.*, 1987). The plagioclasite levels are often parallel to the magmatic layering inside the gabbro.

The pyroxenites are also coarse-grained and consist of clinopyroxene and scarce plagioclase. Cortesogno *et al.* (1987) recognised their presence at the contact between gabbroic lenses and lherzolitic serpentinites and less frequently in the stratified gabbro masses.

As regards the oceanic deformations of the gabbroic massif, subject of this paper, previous works described the occurrence of ductile shear zones and portions of foliated (flaser Auctt.) gabbro that can reach a mylonitic and ultramylonitic texture, with thickness ranging from few centimetres to few metres (Gianelli and Principi, 1974; Cortesogno *et al.*, 1975; Hoogerduijn-Strating, 1988; Molli, 1992, 1994, 1996; Principi *et al.*, 1992). These shear zones are associated with a mineral paragenesis of red/brown hornblende + (diopsidic) clinopyroxene + plagioclase (An $_{40-20}$), which corresponds to an amphibolitic to greenschist metamorphic facies, developed in oceanic conditions (Gianelli and Principi, 1974; Cortesogno *et al.*, 1975; Cortesogno & Lucchetti, 1982, 1984; Molli, 1992).

The primary relationships between the gabbro and the peridotitic host-rock are difficult to understand, also because of frequent tectonisation and later reactivation of the contacts. Nevertheless, in some areas (e.g. at Canegreca), it is possible to observe some primary igneous contacts, sometimes marked by pyroxenitic bands, probably related to a rock-fluid reaction (Cortesogno *et al.*, 1987) and by alternations of gabbro and serpentinite. Dykes of gabbro (often rodingitised) locally cut the lherzolitic peridotite (Lambruscato area).

The youngest oceanic structures observable, consist of basalt dykes up to several metres in thickness that intrude the gabbroic body and of fractures and veins with a metamorphic/metasomatic paragenesis of hornblende and oligoclase that frequently cut the gabbro. The fractures and veins are observed to either cut the basaltic dykes or vice versa, suggesting that they

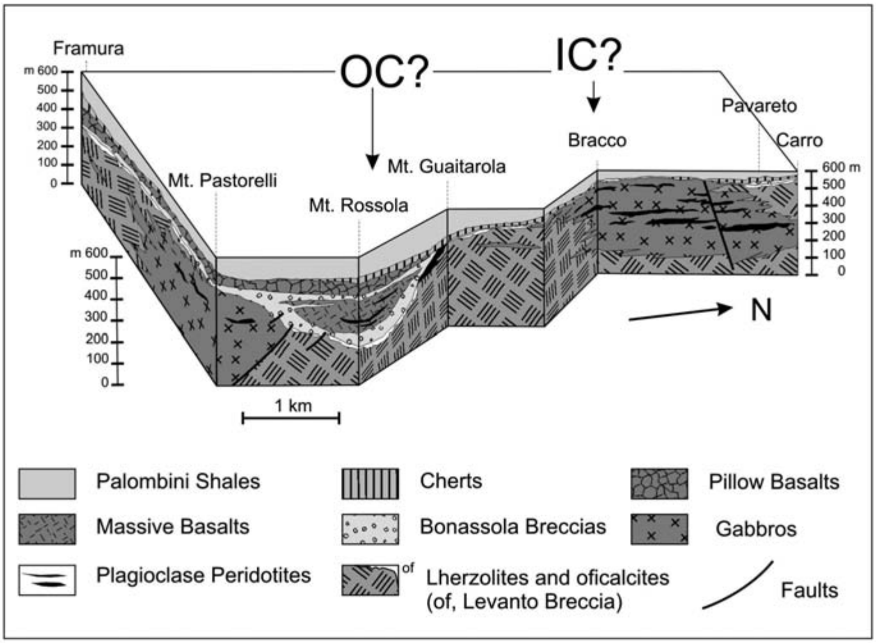

Fig. 5 – Palinspastic reconstruction of the ocean crust of the Bracco-Levanto ophiolites (Eastern Liguria, after Cortesogno *et al*., 1987).
IC=Inner Corner and OC=Outer Corner, as from Tucholke and Lin (1994).

are almost contemporaneous. The basalt dykes are some centimetres to some metres thick and up to some hundred metres long and their frequency and orientation vary in the different zones. They clearly cut the magmatic layering and also the mylonitic texture. The basalt dykes show a quite homogeneous petrography, a generally porphyric structure with plagioclase and rarely olivine phenocrysts, in an ophitic, medium- to fine-grained matrix. The dykes show chilled margins at the contact with the host gabbro.

The veins are filled with brown or green hornblende and/or actinolite (Cortesogno *et al.*, 1987, 1994) in the central part, and with oligoclase along the borders; they occur in swarms and are organised in sets.

Cortesogno *et al.* (1978) put in a chronologic sequence these igneous and metamorphic events and interpreted the paleogeographic position of the Bracco Massif within the general magmatic, metamorphic, tectonic and sedimentary evolution of the Western Tethys Jurassic Ocean (Fig. 6).

The described oceanic succession was subsequently involved in the Tertiary Alpine-Apenninic orogenesis and underwent further metamorphism in prehnite-pumpellyite facies. In the gabbro, for example, the orogenic metamorphism is attested by substitution of plagioclase by pseudomorphic albite with prehnite, pumpellyite and chlorite inclusions and by the development in olivine of concentric coronitic reaction rims of chlorite (Cortesogno *et al.*, 1987; Principi *et al.*, 1992).

FIELD OBSERVATIONS AND STRUCTURAL DATA

The structural data collected in the field concern the primary (igneous) and deformation structures recognizable in the gabbros and serpentinised peridotites. Orientation measurements have been taken systematically in an area almost coincident to the St. Nicolao sub-unit (see the sketch map in Fig. 7). In the following description of the data we will often refer to a western side and an eastern side of the Bracco Massif, areas that are physically divided by a NW-SE trending high angle normal fault (Fig. 3), running immediately westwards of Mt. San Nicolao. The western side includes the areas of Costa di Persico, Mt. Pietra di Vasca, and Schiena di Sciona; the eastern side comprises the areas of Mt. San Nicolao, Cima Stronzi, Mt. Groppi, and Rio Travo. The latter areas are often grouped as Mt. San Nicolao area.

The orientation of the structural elements and the resulting sequence of deformation events were reconstructed analyzing some selected outcrops, where the superposition of the several generations of structures was clear (Figs. 8, 9).

The analysed structures are divided into four groups (see Cortesogno *et al.*, 1987): 1) magmatic layering, 2) mylonitic bands, 3) basalt dykes and 4) hornblende-oligoclase veins (Fig. 7, 9).

Magmatic layering - The magmatic layering is found both in mafic and ultramafic igneous bodies and it is related to fractional crystallisation (Figs. 8, 10). In the Bracco gabbroic mass this layering is characterised by compositional and/or textural (grain size) anisotropies but it is often discontinuous and difficult to recognize. The compositional (modal) variations, in the outcrop, correspond to chromatic differences, which may be gradual or abrupt, as in the case of plagioclasite levels (Fig. 11) or troctolitic intercalations.

A magmatic foliation, underlined by isorientation of crystals, may be at times visible within the principal magmatic layering. The two foliations often look concordant, but in some cases they may form a small angle. Sometimes, especially in the plagioclasite levels, some plagioclase crystals appear rotated and folded. This kind of texture suggests sliding phenomena inside the magma chamber, during an advanced stage of crystallisation (Cortesogno *et al.*, 1987) (Fig. 11).

The magmatic layering shows quite homogeneous orientation in most of the studied areas (Costa di Persico-Mt. Pietra di Vasca-Schiena di Sciona), with a mean dip towards the East, and dip angles between 30° and 65°. In the area between Mt. St. Nicolao and Mt. Groppi the layering has almost constant dip, but towards the opposite quadrant (W and W-WSW) with angles of about 50°-60°. In the area south of Baracca, the magmatic layering dips towards W, sometimes towards NW (Figs. 7, 9).

The layering orientations vary gradually in most of the studied areas, rarely they change very abruptly.

Shear zones (mylonites, flaser Auctt.) - Intense ductile shear deformations locally characterize the

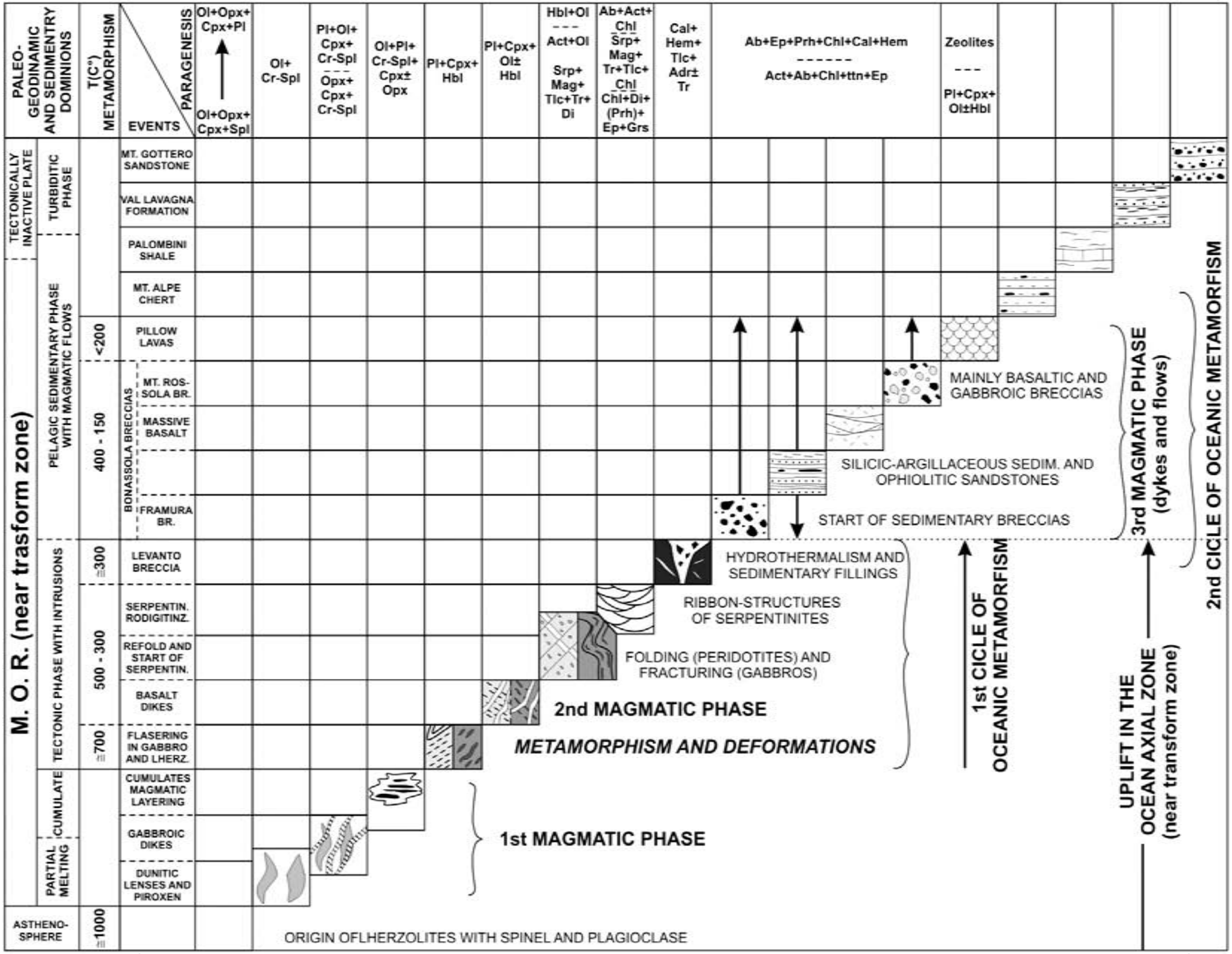

Fig. 6 – Sequence of the oceanic magmatic, metamorphic, tectonic and sedimentary events reconstructed in the Eastern Ligurian ophiolitic sequence (modified after Cortesogno *et al.*, 1987).

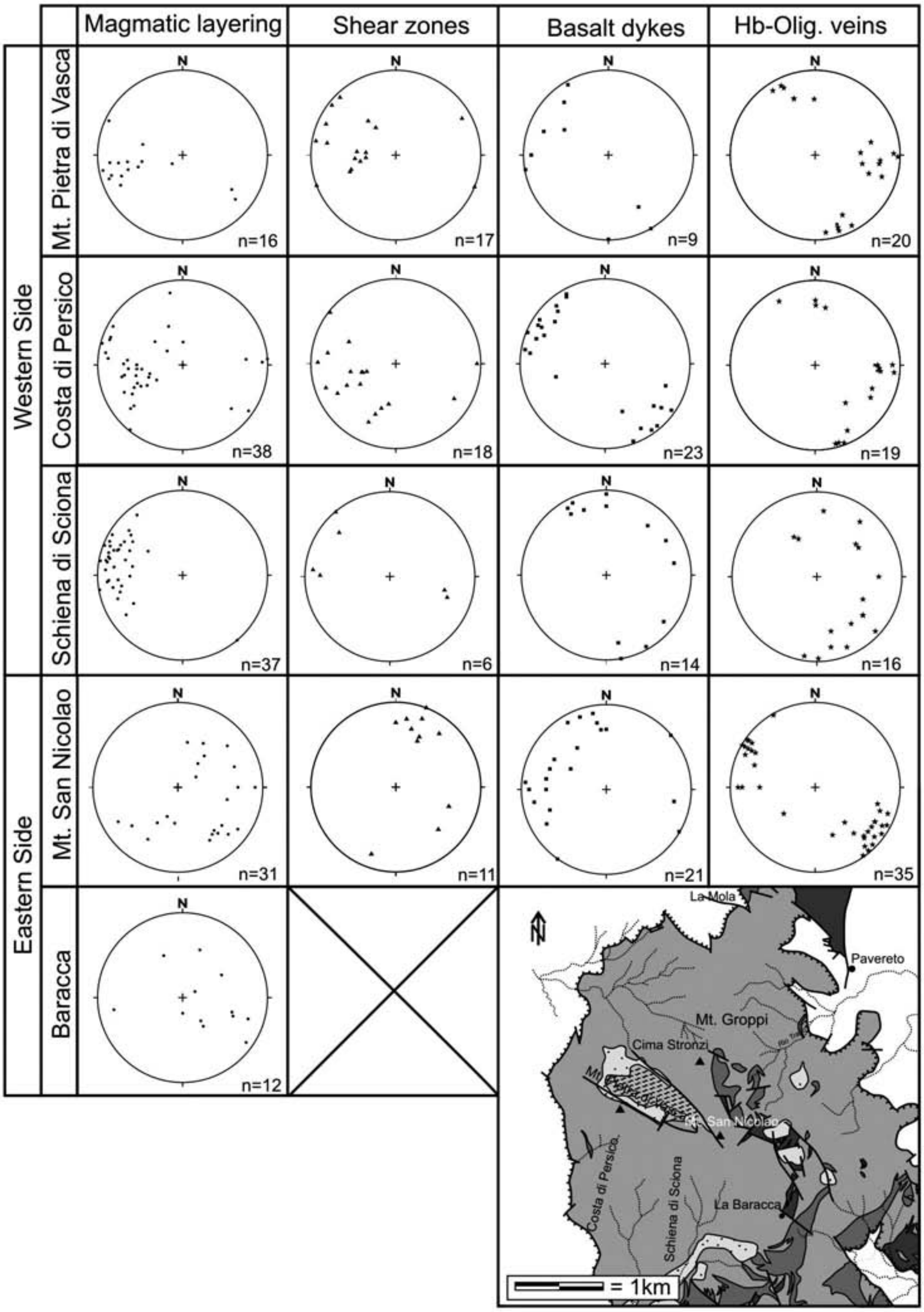

Fig. 7 – Stereonets summarizing the attitude of the four groups of structural elements in the studied Bracco area (Schmidt nets, lower hemisphere). The data are referred to the Canegreca Element (San Nicolao Sub-unit) only; symbols as in Fig. 3.

gabbro; the shear bands have a thickness ranging from centimetres to some metres (Figs. 8, 12). They are associated with pre-orogenic (oceanic) HT/LP metamorphism (Molli, 1994; 1996). These shear zones (Cortesogno and Olivieri, 1974, Gianelli and Principi, 1974, Cortesogno *et al.*, 1975, 1987) are characterised by a very penetrative mylonitic foliation that ranges from coarse grained (flaser, gneiss) to ultramylonitic (Passchier and Trouw, 1996), with scattered intrafoliar folds. The finer grained mylonitic texture consists of a submillimetre to millimetre thick alternation of pyroxene-rich and plagioclase-rich layers. In the gabbros with coarse-grained mylonitic texture, lens-shaped aggregates or single crystals of olivine, plagioclase and pyroxene mark the foliation. Augens of rotated and re-crystallised pyroxene porphyroclasts may be abundant, often showing shear sense indicators, represented by δ- and σ-structures and s-c bands (Fig. 12).

In the undeformed gabbro, the transition towards these ductile shear zones may be either gradual, with progressively more pervasive schistosity, or sharp. Increase of deformation usually corresponds to progressively decreasing size of the gabbro crystals and to development of a more penetrative foliation (Molli, 1992).

The collected data show that the frequency of these structures is variable and their attitude quite scattered in the studied area. Only between Mt. Pietra di Vasca and Schiena di Sciona the data are quite concordant: the dip directions are towards the East, with dip angles from 40° to 80° (Figs. 7, 9).

In the eastern side (Mt. San Nicolao-Cima Stronzi-Mt. Groppi areas) the data are more scarce and scattered, but the majority form a little cluster, which dips to the south.

Basalt dykes - In the studied area the basaltic dykes often intrude the gabbros (Figs. 8, 13), but they have never been up to now observed in the cumulitic peridotites or in the associated lherzolitic serpentinites. However, in other localities (e.g. Mt. Bocco in Bargonasco Val Graveglia area), basalt dykes are present in the peridotites too. The dykes generally have a semi-tabular shape and display a wide areal distribution. Sometimes, they occur in populous swarms and exceed in volume the host rock, or they are isolated, at distances of more than tens of metres. Their thickness varies from centimetres to 4-5 m, about 1-1,5 m on average. Their length varies from 1 m to some hundreds metres (Schiena di Sciona), but very often their dimensions are difficult to estimate, because of truncation and post-oceanic tectonics.

Where basalt dykes and shear zones occur together, the dykes clearly cut the shear zones: therefore they are younger (Fig. 8).

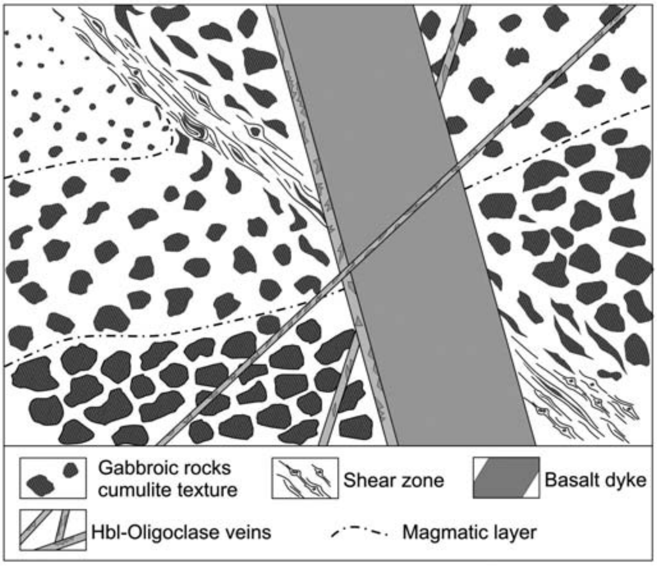

Fig. 8 – Scheme of the cross-cutting relationships among magmatic layering, shear zones (mylonites, flaser), basalt dykes and hornblende-oligoclase veins in the Bracco gabbroic massif.

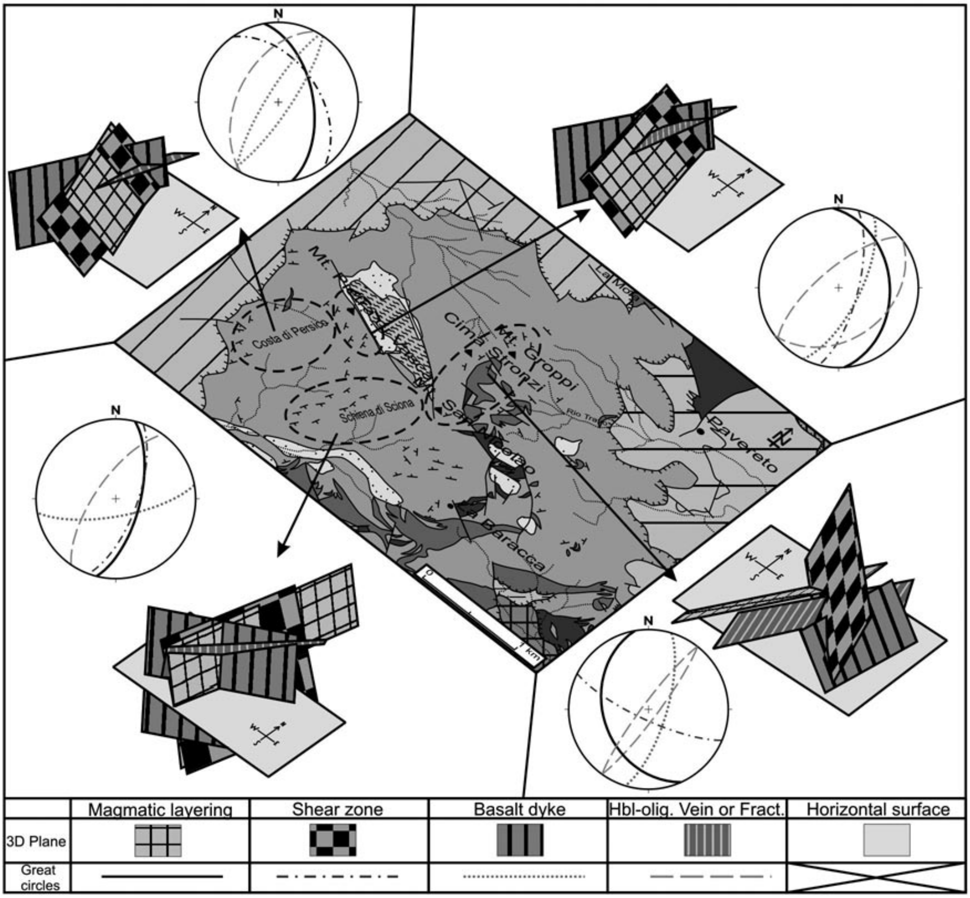

Fig. 9 – Three-d sketches representing for each studied area the combination of geometric relationships among magmatic layering, shear zones (mylonites), basaltic dykes and hornblende-oligoclase veins or fracture, with their respective orientation plots (Schmidt nets, lower hemisphere); the great lines represent the average value of orientation; when the data clustered into two evident groups, the attitude of the structure has been represented using two great lines; symbols for the map as in Fig. 3.

The dykes are mostly steeply dipping, frequently sub-vertical. The measured dykes (Figs. 7, 9) reveal variable strikes. In the western portion the average strike is about NE-SW in Mt. Pietra di Vasca and Costa di Persico, while at the Schiena di Sciona it varies from NNE-SSW to NW-SE. In the eastern zones of Mt. San Nicolao, Cima Stronzi, Mt Groppi and Rio Travo, the dykes trend mainly E-W, sometimes N-S and NNE-SSW.

In some localities (Mt. Pietra di Vasca and Schiena di Sciona) data are not abundant and statistically poorly significant, but it is generally possible to distinguish a principal NE-SW (NNE-SSW) trend and a minor E-W population. Intermediate orientations have been also observed.

Hornblende-oligoclase veins - The hornblende-oligoclase veins represent a metamorphic phase associated with the oldest recognizable brittle oceanic deformation (Cortesogno *et al.*, 1987) (Figs. 10, 11). These veins have a thickness ranging from 1 to 5-6 cm; rarely they can reach more than 1 dm. Their visible length varies from some centimetres to some metres. The thinner ones have a planar to anastomosing shape, sometimes dendritic. They may be isolated, but more frequently they occur in groups and they are often organised

Fig. 10 – Magmatic layering in gabbro (white dashed line) cut by a hornblende-oligoclase vein (white arrows) (Mt. Groppi).

in conjugate sets. They are locally associated with the basalt dykes, occurring either at the gabbro/basalt interface or inside the gabbroic mass, very close to the basalt. The superposition relationships

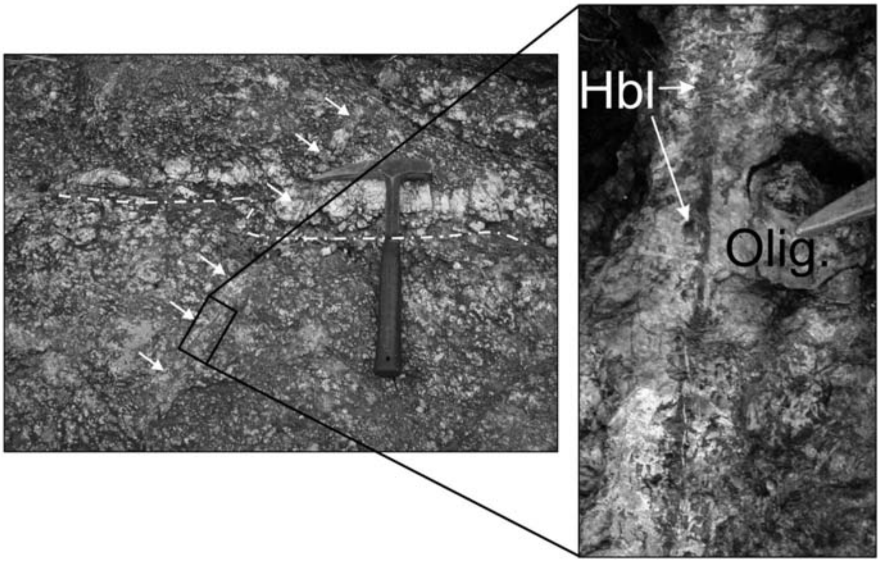

Fig. 11 – Magmatic fold in plagioclasite vein (white broken line) cutting the gabbro, crosscut by a hornblende-oligoclase vein (white arrows and magnification) (Cima Stronzi).

are not univocal: in fact, the veins may cut the basalt dykes and vice versa (Fig. 8). Therefore, the tectonic events causing intrusion of the dykes were likely contemporaneous to those forming the veins, both occurring in a brittle tectonic regime, probably linked to oceanic extension or to thermal contraction related to magma cooling.

All over the studied area, the veins can be distinguished into two sets; both sets have NE-SW strike and they are always steeply dipping with dip-direction towards NW and SE. In the Schiena di Sciona area the data are more scattered (Figs. 7, 9).

DISCUSSION AND INTERPRETATION

The collected field data allow to better defining the geometry and distribution of the igneous and metamorphic structures present in the Bracco gabbroic Massif (Figs. 7, 9).

Although these data do not yet cover all the Bracco area, they are sufficient to give some geometrical constraints on the structure of the Jurassic mid oceanic ridge and to focus some discussion about the events that occurred during the Jurassic oceanisation stage of the Ligurian oceanic basin (part of Western Tethys).

As a whole, these structures appear quite dispersed; however, when they are analyzed in small areas they show a homogeneous and distinct distribution and a difference between the western and the eastern portion of the Bracco Massif. In particular, in the western side (Schiena di Sciona, Costa di Persico and Mt. Pietra di Vasca), the igneous and metamorphic deformation structures, dykes and veins, show quite homogeneous attitudes, as described in the previous chapter (Fig. 7). Moreover, also the superposition order between the structures and their geometrical relationships (angle of intersection) are quite constant, as shown in Fig. 9.

On the contrary, in the eastern side (Mt. St. Nicolao, Cima Stronzi, Mt. Groppi), the attitudes of the various structures (Fig. 7), as well as their angles of intersection (Fig. 9), are rather scattered if compared to the previous ones, except for the basalt dykes.

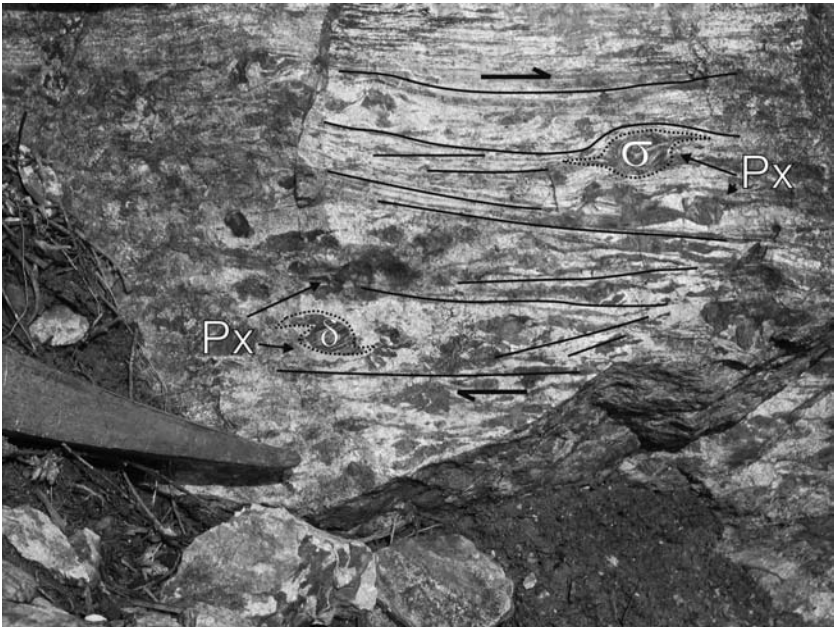

Fig. 12 – Shear zone in gabbro with pyroxene porphyroclasts as shear sense indicators (pyroxene σ- and δ-structure and s-c bands) (Costa Persico).

We here attempt to interpret these differences as originating in the oceanic lithosphere. The eastern and western sides of the Bracco Massif are divided by a high angle normal fault running along a NW-SE direction (Fig. 3) and dipping towards the southwest. This structure produces an offset of more than 250 m and a slight tilting of the footwall. No other important Alpine orogenic structures have been observed in the area. Restoration of the normal fault movement does not cancel the observed differences in the major trends of the basalt dykes and we can therefore exclude an implication of Alpine deformations in the present geometrical relationships among the studied oceanic structures.

Therefore, since the basalt dykes and hornblende-oligoclase veins are the youngest oceanic structures, we can constrain to the Jurassic oceanic phase the causes of the geometric differences of magmatic layering and shear structures between the two sides of the Bracco Massif.

Here below, we try to discuss and interpret point by point the analyzed constraints, with a reading key inspired to the evolution of an active mid oceanic ridge.

Magmatic layering - In all the studied localities (Fig. 9), the magmatic layering forms an angle of about 90° with the basalt dykes planes.

The NW dip of the layering characterizes all the eastern area of the Bracco Massif. The same consideration is valid also for the SE dip of the layering in the western area. In any case, in both areas the strikes are almost the same.

The syn-magmatic deformations, well visible in outcrop as foliations and small (from centimetre to decimetre) folds, could have been associated with bigger structures. However, evidence of bigger structures has never been found with the exception of tens to hundred metres open fold, complicated by faults, visible on the left side of Rio Travo, one kilometre N-E from Mt. San Nicolao.

The subdivision of the orientation data of the magmatic layering into two main different groups could be due to the presence of syn-magmatic folds or to the superposition of two different magmatic chambers that evolved at two different times after an amagmatic gap, as it likely happens during the evolution of a slow spreading ridge, like that of Western Tethys (Principi *et al.*, 2004 and references therein). Nevertheless, the observed geological constraints do not so far support this hypothesis either.

Fig. 13 – Basalt dyke (β) intruded in gabbro (Γ) (Mt. Groppi).

Shear zones (mylonites, flaser) - The distribution of dips and strikes of the shear zones differs in the eastern and western portions of the Bracco Massif (Fig. 9). In the eastern side, the strike is almost WNW-ESE and the dip is toward the south; in the western side the strike is almost N-S or NNE-SSW and the dip is mostly eastwards (Fig. 9).

The interference pattern between shear zones and magmatic layering is also very different in the two areas: in the western one, their major clusters are almost parallel, while in the eastern area there is a high angle between them. However, it is necessary to point out that the data in the eastern zone are statistically not very significant (10 measurements), and that at least two measurements are congruent with those of the western area (Fig. 7). Generally, if we consider the present horizontal plane, the dip of the shear zones varies everywhere from medium to high angle, with a prevalence of the latter.

In the Western Tethys ophiolites these structures are ubiquitously present and have been variously interpreted. The association of shear structures (flaser Auctt.) of the Northern Apennine ophiolites with an oceanic tectonic phase was first proposed in the mid 1970's (Gianelli and Principi, 1974; Cortesogno and Olivieri, 1974; Cortesogno *et al.*, 1975). Later on, some authors (Cortesogno *et al.*, 1982, 1987) proposed that the hot shears were related to oceanic spreading and/or to transform fault mantle/crust diapirism. In the 1980's and 1990's, the shear zones of the Bracco Massif were interpreted as formed along a subcontinental asymmetric lithosphere detachment and mantle/crust denudation surface, like in the Galitian North Atlantic oceanic basement (Hoogerduijn Strating, 1988; Piccardo *et al.*, 1994; Molli, 1996).

As regards this interpretation, we should give credit to an early model by Elter (1972), that envisaged symmetric detachments inside the continental lithosphere, caused by divergent shearing above an unroofing mantle, in correspondence of the incipient Ligurian ocean opening. The author however did not mention a relation with the shear structures. An analogous idea, according to which the ocean opening was preceded by denudation of an uprising mantle, was also favoured by Piccardo (1976). More recent works (Treves and Harper, 1994; Bortolotti *et al.*, 2001; Principi *et al.*, 2004), in the light of modern findings on the tectonics of slow-spreading ridges (e.g. Tucholke and Lin, 1994), returned to consider the shear zones as evidence of oceanic faulting and detachment surfaces produced in a ridge or ridge-transform setting.

All these hypotheses may be substantially divided into two main groups:

1) Shearing occurred during asymmetric detachment of the continental lithosphere, with passive exposure of the lithospheric mantle.

2) Detachment and shearing occurred during oceanic spreading and/or transform tectonics.

The MORB geochemical characteristics (Beccaluva *et al.*, 1979) of the Bracco Massif gabbroic rocks and their radiometric ages (164±14 Ma, Sm/Nd isochrone, Rampone *et al.*, 1998), as well as the radiolarian biostratigraphic age (Bajocian-Bathonian, around 169 Ma, see Principi *et al.*, 2004 and references therein) of the associated cherts, indicate that these ophiolitic suites must be assigned to an already oceanic context; this consideration excludes in our opinion the first hypothesis. Also the absolute lack of any continental lithosphere fragment linked to serpentinitic and gabbroic bodies, reinforces this opinion. This is typical not only of the Bracco area but of all the Internal Ligurids, while in the External Ligurian Units continental fragments are found in the Cretaceous ophiolitic olistholiths and olisthostromes (Marroni *et al.*, 1998).

Moreover, similar shear structures are reported from modern oceans (Mevel *et al.* 1991; Auzende *et al.*, 1994; Gaggero and Cortesogno, 1997), and models involving detachments occurring along mid oceanic ridges have been proposed (e.g. Mutter and Karson, 1992).

Basalt dykes - The average NE-SW and NNE/SSW orientations of the basalt dykes are consistent with those of the hornblende oligoclase veins (Figs. 7 and 9). In the field, many times the basalt dykes seem to use the veins filled by hornblende oligoclase to develop. The cross-cutting relationships between dykes and fractures show always a very little angle and often the hornblende-oligoclase paragenesis tends to be parallel to the border of the dykes.

Summarising the previous description (see scheme of Fig. 6), all the studied structures developed during the chronological interval comprised between the two igneous events, which correspond to the cooling of the gabbroic magma chamber (Bracco Massif) and the intrusion of the basalt dykes. A third, younger igneous event (Fig. 6), is represented by the basaltic pillow lavas, which crop out in adjacent units. The third event closed a first oceanic metamorphic cycle and marked the beginning of a further metamorphic cycle (Cortesogno *et al.*, 1978, Fig. 6).

It is very difficult to quantify the chronological interval between the gabbro emplacement and the basalt dykes intrusion. In fact, unlike the gabbro that has been dated to 164 ±14 Ma (Rampone *et al.*, 1998), no age determination is available for the basalt dykes. The available ages are biostratigraphic ages of the overlying cherts: 169 Ma (Bajocian-Berrasian, among the oldest ones) for the base of the massive basalt in the Mt. Rossola element (Principi *et al.*, 2004 and ref. therein), and about 165-155 Ma (Callovian-Kimmeridgian, Chiari *et al.*, 2000) for the cherts deposited over the basalt flows of the Vara succession (Bortolotti and Principi, 2005) in Eastern Liguria.

On the other hand, Borsi *et al.*, (1996) dated at 153±1 Ma (U-Pb zircon age) a rodingitised plagiogranite intruded in the serpentinitic lherzolites of Rio Gavotino (Near Masso) belonging to the immediately northwards Val Graveglia-Bargonasco ophiolitic area, close to the Velva subunit. This younger age, if we dare to compare radiometric and biostratigraphic chronological data, seems to be linked to the third igneous event. Even with these scarce and inhomogeneous chronological data, we can try to assign the studied tectonic and igneous events to an early phase of the Western Tethys (Ligurian) ocean opening. On the basis of these chronological constraints and of the supposed small width of the Ligurian basin (Bortolotti *et al.*, 1990, 2001), it is possible to add the following consideration: if the life span of ridge magmatism was really comprised between 169 and 153 Ma, or, comparing only the radiometric data, between 164 and 153 Ma, the ridge of the western Tethys must have been a very slow spreading one, slower than that of the present Central Atlantic.

Hornblende-oligoclase fractures and veins - These veins are the oldest brittle structures observed in the gabbroic mass and the paragenesis of their infilling minerals represents a complex metamorphic process developed as a consequence of heated brine circulation (Cortesogno *et al.*, 1994). On the bases of the mineral chemistry data in literature (Cortesogno *et al.*, 1994), the veins can be assigned to a metamorphic phase subsequent to the formation of the HT shear zones, characterised by lower temperature conditions. Cortesogno *et al.* (1987) interpret these fracture/veins as the result of cooling of the ocean ridge environment, due both to a rising and/or to a lateral movement of the gabbro away from the ridge. In our opinion, being the veins penecontemporaneous and quite systematically sub-parallel to the basalt dykes, their formation might be referred preferentially to the regional stress regime rather than to the contraction of the rock resulting from cooling.

Cooling and fracturing of the magma was likely produced during a reduced igneous activity or an amagmatic pause, in presence or not of upward or lateral removal of the rock, as in Tucholke and Lin (1994). In any case the almost contemporaneous basalt dyke intrusion constrain the hornblende-oligoclase vein formation in a MOR environment, reducing the possibility of a hypothetical important lateral spreading.

CONCLUSIVE CONSIDERATIONS

We can attempt to put the above data in a paleotectonic frame. Considering the present mean orientation of the dykes of the Bracco Massif and subtracting all the subsequent tectonics, we can try to tentatively reconstruct the orientation of the Jurassic spreading (Nicolas *et al.*, 1988 and references therein).

The only traceable reference frame is the paleo-vertical direction indicated by the mean values of the vertical planes of the dykes. Because of the extensional tectonic regime, the paleo-vertical direction should also represent σ_1 (direction of maximum compressive stress). With the present cardinal references, the ridge axis should have had a roughly NNE-SSW direction and that would represent σ_2 (direction of intermediate compressive stress). Consequently, we can hypothesise a WNW-ESE direction of spreading, that we need to restore with the post-oceanic tectonic movements that affected the area. Basing our considerations on paleotectonic constraints (Principi *et al.*, 2004 and references therein), the only rotational restorations that we need to apply are two anticlockwise rotations about the Eulerian poles of the Ligure-Balearic and Northern Tyrrhenian basins openings respectively. The resulting configuration is very close to that of the Central Atlantic.

A comparison with the recent models of Mutter and Karson (1992) and Tucholke and Lin (1994), regarding the central Atlantic Ocean, reveals an interesting convergence between the Atlantic slow spreading ridge and the supposed

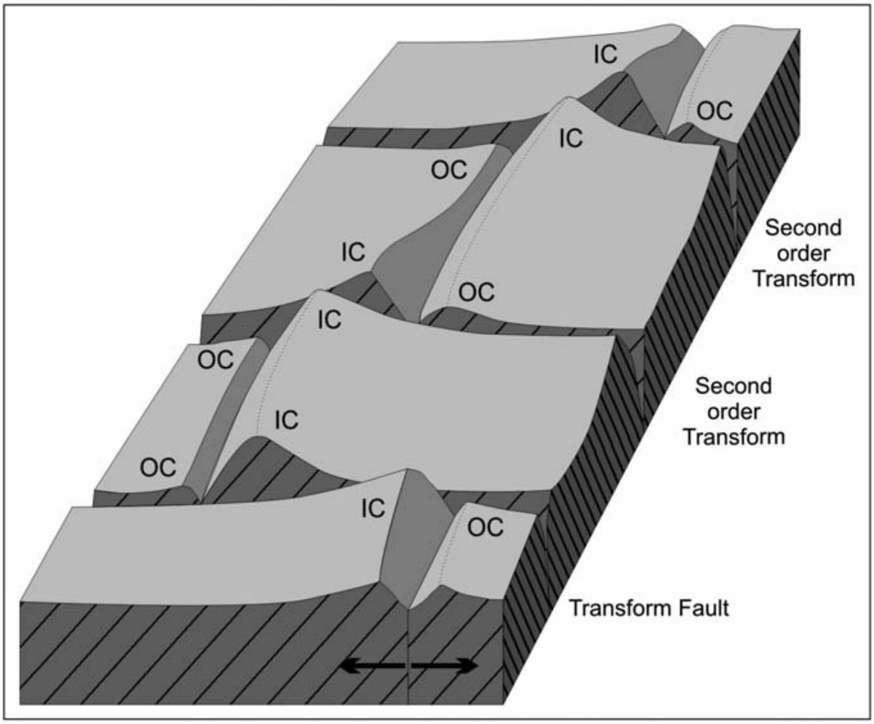

Fig. 14 – The along axis Inner Corners (IC) and Outer Corners (OC) and transform faults model for the mid-ocean ridge of the Atlantic Ocean (redrawn after Tucholke and Lin, 1994).

ocean ridge reconstructable from the Bracco Unit (Principi *et al.*, 2004).

Tucholke and Lin (Fig. 14) admit that the geophysical and topographic unhomogeneity along the ridge axis is linked to the presence of first and second order transform faults. In particular, crosscutting transform faults would give rise to topographic highs (IC, inside corners) and depressions (OC, outside corners) nearby the axis ridge. The formation of IC or OC depends on whether the ridge axis couples with the active or inactive side of the transform discontinuities respectively. In the inside corners, the rising oceanic basement rocks (serpentinites, gabbros) are denudated and move away from the ridge axis, rotating around both vertical and horizontal axes, while in the outside corners basalt flows and sediments fill up the topographic depressions.

This model can explain i) the non-homogeneous geometric orientation of the shear zones in the study area, and perhaps also the magmatic layering divergences, ii) why this configuration occurred so early and iii) why it occurred in an inclined and near axis position. Moreover, it could explain also the geometry of the basalt dykes and fractures. In the uprising Jurassic corner, where extensional tectonics (i.e. normal faulting) was prevailing, no basalt flow occurred, but only dykes intrusion.

Our still preliminary study allowed a first attempt of interpretation of these structures and the proposition of a new hypothesis, but other parts of Bracco area and other ophiolitic sites of the Northern Apennines need to be studied to get to more documented and reliable interpretations. The results presented encourage us to continue the study of such an interesting topic and localities where Lucio Cortesogno began very acute pioneering studies thirty years ago.

REFERENCES

Abbate E., Bortolotti V., Passerini P. and Sagri M. (1970) - *The Northern Apennines geosyncline and continental drift*. In: G. Sestini (Ed.), Development of the Northern Apennines geosyncline. Sedim. Geol., **4**, 637-642.

Abbate, E., Bortolotti, V. and Principi, G. (1980) - *Apennine ophiolites: A peculiar oceanic crust*. In Rocci, G. (Ed.), Tethyan ophiolites, 1, Western area: Ofioliti, Special Issue, **1**, 59–96.

Auzende J.M., Cannat M., Gente J.P., Henriet T., Juteau J., Karson J.A., Lagabrielle Y., Mevel C. and Tivey M.A. (1994) - *Observations of sections of oceanic crust and mantle cropping out on the southern wall of Kane FZ (N. Atlantic)*. Terra Res., **6**, 143-148.

Beccaluva L., Macciotta G., Piccardo G. B. and Venturelli G. (1976) - *Le rocce gabbriche dell'Appennino settentrionale: II – Le caratteristiche chimiche*. Ofioliti, **1**, 107-126.

Beccaluva L., Piccado G. B. and Serri G. (1979) - *Petrology of the Northern Apennines ophiolites and comparison with other Tethyan ophiolites*. Ofioliti, **4**, 43-66.

Bezzi A. and Piccardo G. B. (1970) - *Studio petrografico sulle formazioni ofiolitiche della Liguria. Riflessioni sulla genesi dei complessi ofiolitici in ambiente appenninico alpino*. Rend. Soc. It. Mineral. Petrol., **36**, 1-42.

Borsi L., Scharer U., Gaggero L. and Crispini L. (1996) - *Age, origin and geodynamic significance of plagiogranites in lherzolites and gabbros of the Piedmont-Ligurian basin*. Earth. Planet. Sci. Lett., **140**, 227-242.

Bortolotti V. and Gianelli G. (1976) - *Le rocce gabbriche dell'Appennino settentrionale: I. Dati recenti su rapporti primari, posizione stratigrafica ed evoluzione tettonica*. Ofioliti **1**, 99-105.

Bortolotti V. and Principi G. (2005) – *Tethyan ophiolites and Pangea break-up*. The Island. Arcs, **14**, 442-470.

Bortolotti V., Principi G. and Treves B. (1990) - *Mesozoic evolution of Western Tethys and the Europe/Iberia plate junction*. Mem. Soc. Geol. It., 45, 393-407.

Bortolotti V, Principi G. and Treves B. (2001) - *Ophiolites, Ligurides and the tectonic evolution from spreading to convergence of a Mesozoic Western Tethys segment*. In: P.I. Martini and G.B. Vai (Eds.), Anatomy of an orogen: Apennines and adjacent Mediterranean basins. Kluwer Acad. Publ., Dordrecht. 151-164.

Chiari M., Marcucci M. and Principi G. (2000) - *The age of the radiolarian cherts associated with the ophiolites in the Apennines (Italy) and Corsica (France): a revision*. Ofioliti, **25**, 141-146.

Cortesogno L., Gaggero L., and Molli G. (1994) - *Ocean floor metamorphism in the Piedmont-Ligurian Jurassic basin: a review*. Mem. Soc. Geol. It, **48**, 151-163.

Cortesogno L., Galbiati B. and Principi G. (1987) - *Note alla "Carta geologica delle ofioliti del Bracco" e ricostruzione della paleogeografia giurassico-cretacia*. Ofioliti, **12**, 261-342.

Cortesogno L., Galbiati B., Principi G. and Venturelli G. (1978) - *Le brecce ofiolitiche della Liguria orientale: nuovi dati e discussione sui modelli paleogeografici*. Ofioliti, **3**, 99-160.

Cortesogno L., Galbiati B., Principi G. and Vercesi del Castellazzo G. (1981) - *Carta geologica delle ofioliti del Bracco*. S.E.L.C.A.

Cortesogno L., Gianelli G. and Messiga B. (1977) - *Le rocce gabbriche dell'Appennino settentrionale: III. Evoluzione metamorfica in ambiente oceanico ed orogenico, confronto con metagabbri e metamorfismo alpinotipo*. Ofioliti, **2**, 75-114.

Cortesogno L., Gianelli G. and Piccardo G. B. (1975) - *Preorogenic metamorphism and tectonic evolution of the ofioliti mafic rocks (Northern Apennines and Tuscany)*. Boll. Soc. Geol. It., **94**, 291-327.

Cortesogno L. and Lucchetti G. (1982) - *Il metamorfismo oceanico nei gabbri ofiolitici dell'Appennino Ligure: aspetti mineralogici e paragenetici*. Rend. Soc. It. Mineral. Petrol., **38**, 561-579.

Cortesogno L. and Lucchetti G. (1984) - *Ocean floor metamorphism of metagabbros and striped amphibolites (T. Murlo, Southern Tuscany, Italy)*. N. Jarhb. Miner. Abh., 276-300.

Cortesogno L. and Olivieri F. (1974) - *Fenomeni metamorfici di alta temperatura ed evoluzione polimetamorfica in ambiente «oceanico» e orogenico di diabasi, brecce e sedimenti associati, affioranti presso Framura (Liguria orientale)*. Rend. Soc. It. Mineral. Petrol., **30**, 931-959.

Decandia F. A. and Elter P. (1970) - *Carta geologica della zona del Bracco*. S.E.L.C.A.

Decandia F. A. and Elter P. (1972) - *La zona ofiolitifera del Bracco nel settore compreso tra Levanto e la Val Graveglia (Appennino Ligure)*. Mem. Soc. Geol. It., **11**, 503-530.

Elter P. (1972) - *La zona ofiolitifera del Bracco nel quadro dell'Appennino Settentrionale*.

Introduzione alla geologia delle Liguridi. 66° Congr. Soc. Geol. It., Guida alle escursioni, Pacini, Pisa, 5-35.

Gaggero L. and Cortesogno L. (1997) - *Metamorphic evolution of oceanic gabbros: recrystallization from subsolidus to hydrothermal conditions in the MARK area (ODP Leg 153)*. Lithos, **40**, 105-131.

Gianelli G. and Principi G. (1974) - *Studies on mafic and ultramafic rocks. 4. - Breccias of the ophiolitic suite in the Monte Bocco area (Ligurian Apennine)*. Boll. Soc. Geol. It., **93**, 277-308.

Hoogerduijn-Strating E. H. (1988) - *High temperature shear zones on the gabbroic Bracco massif (N. Apennines, Italy); possible implications for tectonic models of ocean floor generations*. Ofioliti, **13**, 111-126.

Marroni M., Molli, G., Montanini A. and Tribuzio R. (1998) - *The association of continental crust rocks with ophiolites (Northern Apennine, Italy): implications for the continent-ocean transition*. Tectonophysics, **292**, 43-66.

Marroni M., Monechi S., Perilli N., Principi G. and Treves B. (1992) - *Cretaceous flysch deposits of the Northern Apennines, Italy: age of inception of orogenesis-controlled sedimentation*. Cretaceous Res., **13**, 487-504.

Mével C., Cannat M., Gente P., Marion E., Auzende J.M. and Karson J.A. (1991) - *Emplacement of deep crustal and mantle rocks on the west median valley wall of the MARK area (MAR 23 N)*. Tectonophysics, **190**, 31-53.

Molli G. (1992) - *Evoluzione strutturale di shear zones nel complesso gabbrico del Bracco (Appennino settentrionale)*. Atti Ticinesi Sci. Terra, **35**, 19-24.

Molli G. (1994) - *Microstructural features of high temperature shear zones in gabbros of the Northern Apennine Ophiolites*. J. Struct. Geol., **16**, 1535-1541.

Molli G. (1996) - *Pre-orogenic tectonic framework of the northern Apennine ophiolites*. Eclogae Geol. Helv. **89**, 163-180.

Mutter J. and Karson J. (1992) - Structural *processes at slow spreading ridges*. Science, **257**, 627-634.

Nicolas A., Ceuleneer G., Boudier F. and Misseri M. (1988) – *Structural mapping in the Oman ophiolites: mantle diapirism along an oceanic ridge*. Tectonophysics, **151**, 27-56.

Passchier C.W. and Trouw R.A.J. (1996) – *Microtectonics*. Springer Verlag, Berlin, 289 pp.

Piccardo G. B. (1976) – *Le ofioliti dell'areale ligure: petrologia e ambiente geodinamico di formazione*. Ofioliti, **3**, 469-500.

Piccardo G. B., Rampone E., Vannucci R. and Cimmino F. (1994) – *Upper mantle evolution of ophiolitic peridotites from the Northern Apennine: Petrological constraints to the geodynamic processes*. Mem. Soc. Geol. It., **48**, 137-148.

Principi G., Bortolotti V., Chiari M., Cortesogno L., Gaggero L., Marcucci M., Cassani E. and Treves B. (2004) - *The pre-orogenic volcano-sedimentary covers of the Western Tethys ocean basin: a review*. Ofioliti, **29**, 177-211.

Principi G., Cortesogno L., Cellai D., Gaggero L., Garuti G., Gazzotti M., Passerini P. and Treves B. (1992) - *Guida all'escursione: B1 - Le ofioliti dell'Appennino settentrionale*. 76ª Riunione estiva S. G. I.: L'Appennino settentrionale. Firenze 21-23 settembre 1992, Guida alle Escursioni post-congresso, 1-76.

Rampone E., Hofmann A.W. and Raczek I. (1998) - *Isotopic contrasts within the Internal Liguride ophiolite (N. Italy): the lack of a genetic mantle-crust link*. Earth Planet. Sci. Lett., **163**, 175-189.

Serri G. (1980) - *Chemistry and petrology of the gabbroic complexes from the Northern Apennines ophiolites*. In: A. Panayiotou, (Ed.), Ophiolites, Proceed. Intern. Ophiolites Symposium, Cyprus 1979. 296-313.

Treves B.A. and Harper G. D. (1994) - *Exposure of serpentinites on the ocean floor: sequence of faulting and hydrofracturing in the Northern Apennine ophicalcites*. Ofioliti, **19**, 435-466.

Tucholke B.E. and Lin J. (1994) - A geological model for the structure of ridge segments in slow spreading ocean crust. J. Geophys. Res., **99**, 11937-11958.