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# THE PRE-OROGENIC VOLCANO-SEDIMENTARY COVERS OF THE WESTERN TETHYS OCEANIC BASIN: A REVIEW

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## ABSTRACT

The records of the Jurassic Western Tethys Ocean are the ophiolitic rocks now scattered in the Tertiary orogenic belts of the Alps, Apennines and Betic Cordillera.

These ophiolites, involved in a convergent margin environment, are affected I) by HP/LT metamorphism derived from a subduction process or II) by very low grade overprint, corresponding to the tectonic prism at the margin of the overriding plate. On the whole, they share common characteristics:

a- The MORB geochemical signature.
b- The ophiolitic successions often "reduced" and thin.
c- The volcano-sedimentary covers often directly overlying the serpentinised peridotites.
d- The widespread occurrence of cherts as Jurassic pelagic sediment.

In the thickest "complete" ophiolitic successions, basalt flows, generally thin, are preceded and followed by ophiolitic breccias. Only the basal portion of the breccias on top of the serpentinites (Levanto Breccias) has a tectonic origin, all other levels have a sedimentary origin. These breccia-basalt assemblages are overlain by thick sequences of Mt. Alpe Cherts and Calpionella Limestones, followed by Palombini Shales. In the reduced (or incomplete) successions, thin breccias and cherts were directly deposited, above the Levanto Breccias (ophicalcites pro parte), and followed by Palombini Shales.

This stratigraphic pattern seems to be widespread in the whole Western Tethys ocean.

In some sequences, transitional mid-ocean ridge (T-MOR) basalts are present and the ophiolitic rocks are associated with Variscan continental slices and debris, as in the Err-Platta succession (Central Alps) and in some exotic blocks in the flysch of the External Ligurides (Northern Apennines). In the Balagne (Corsica) T-MOR basalts are associated with quartzarenites. These occurrences show that an unroofed mantle and sections of oceanic crust evolved very near to a continental margin.

The different radiolarian ages of the cherts deposited before, within, or on top of the MOR basalts allow to infer a minimum time interval for the Western Tethys oceanisation. This interval can be considered between 16 and 21 Ma (from Late Bajocian to Kimmeridgian/Tithonian). If we assume 1cm/yr spreading rate during this time, the basin would have reached about 150-200 km width. The same ages suggest that the ocean opening was diachronous along the Western Tethys basin.

Mainly on the basis of the Northern Apennines and Corsica data, it is possible to reconstruct the following evolutive geodynamic, paleogeographic and sedimentary evolution of the Western Tethys ocean basin:

1- Bajocian/Bathonian stage: opening of the Ligurian Northern Apennines oceanic segment and, perhaps, also of the Ligurian, Western and Central Alps ones.
2- Bathonian/Callovian stage: opening of all the segments of the Western Tethys ocean basin. The volcano-sedimentary covers formed during these two stages are constituted by breccias, basalts and siliceous pelagites (cherts).
3- Tithonian/Berriasian: end of the ocean spreading (Tithonian) and beginning of the quiescent stage in the whole basin, marked by the lack of any tectonic activity and by the sedimentation of the Calpionella Limestones and, locally, of mixed siliceous-calcareous deposits (Nisportino-Murlo Fm.).
4- Hauterivian/Santhonian: this is the longest quiescent stage of the basin, dominated by the sedimentation of the Palombini Shales and Limestones. Some siliciclastic deposits are shed from both passive continental margin sides. During the Early Cretaceous, there is also evidence of a rare intraplate magmatism in Southern Tuscany.

The Western Tethys ophiolitic successions are similar to those of present day, slow spreading oceans, in particular to those of the Atlantic Ocean (Mutter and Karson, 1992; Tucholke and Linn, 1994). The Galician North Atlantic margin provides a model for the process of mantle denudation. For the oceanic evolution, the model of Tucholke and Linn (1994) is particularly taken in consideration. According to this model, tectonic extension was one major process in the Western Tethys oceanic development.

## INTRODUCTION

The Western Tethys was a small Jurassic ocean that separated the Europe-Iberia plates to the NW from the Africa-Adria plates to the SE (Abbate et al., 1970; 1980; 1986). The records of this ocean are the ophiolitic rocks now scattered in the Tertiary orogenic chains from the Eastern Alps, through the Central-Western Alps, Ligurian Alps, Northern Apennines, North-eastern Corsica, to the Tyrrhenian basin, Calabria and Betic Cordillera (Fig. 1).

In the Alps, Betic Cordillera and most of the Corsica and Calabria, the ophiolites mostly show a medium- to high pressure-low temperature (HP-LT) metamorphic signature and can attain pervasive alpine deformation In some portions of the Alps, Corsica and Calabria and all over the Northern Apennines, the ophiolites show very low grade

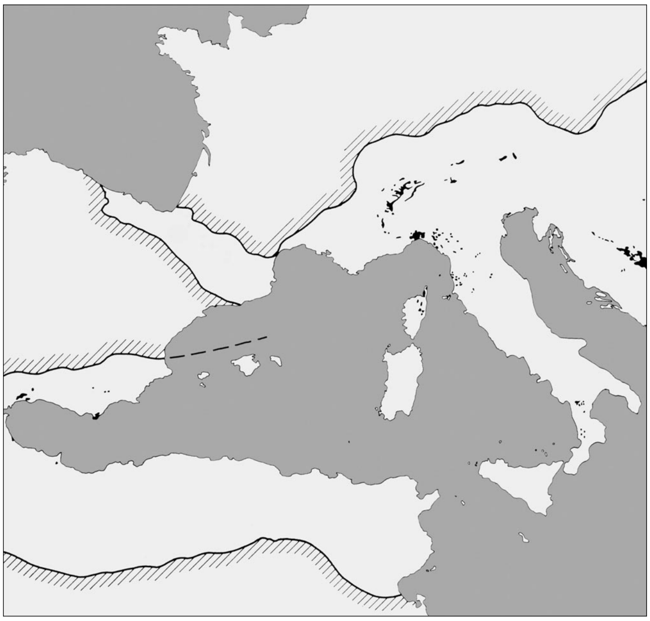

Fig. 1 - Distribution of Jurassic Western Tethys ophiolites. Segmented lines: orogenic fronts.

metamorphic conditions and weak orogenic deformations. The ophiolitic units occupy the more internal and higher position in the orogenic wedges.

The following characteristics are common to all these ophiolites,

a- The Middle-Late Jurassic age.

b- The mid-ocean ridge basalt (MORB) signature of the igneous products.

c- The abundance of “reduced” ophiolitic successions (e.g. Gianelli and Principi, 1974; Galbiati et al., 1976; Barrett and Spooner, 1977; Gianelli and Principi, 1977; Abbate et al., 1980; Lagabrielle et al., 1984; Cortesogno et al., 1987; Padoa, 1999; Bortolotti et al. 2001b). In particular, the exposed basement of the sedimentary covers is mostly represented by mantle-derived serpentinites, with only subordinate intrusives; a true sheeted dike complex is lacking and basalt flows are missing in several sequences.

d- The frequent exposure of serpentinised mantle peridotites on the ocean bottom (base of sedimentary-volcanic covers).

e- The widespread presence of cherts as first pelagic sediment above the magmatic section.

The origin of the Tethyan ophiolites has been interpreted through different mechanisms including:

1- Lithospheric scale detachment faulting leading to mantle exhumation (Peyve,1969; Decandia and Elter, 1972; Elter, 1972; Lemoine et al., 1987; Hoogerduijn et al., 1990; Piccardo, 2003). In recent years Froitzheim and Manatschal (1996) and Manatschal and Nievergelt (1997) observed and described on the field, in the Grisons, this type of detachment.

2- Uplift of mantle diapirs along transform faults (Galbiati et al., 1976; Gianelli, 1977; Gianelli and Principi, 1977, Abbate et al., 1980; 1986).

3- Rifting at a slow-spreading mid-ocean ridge, leading to the exposure of mantle and lower crust rocks (Barrett and Spooner, 1977; Lagabrielle and Cannat, 1990; Bortolotti et al., 1990; 2001b; Lagabrielle, 1994; Lagabrielle and Lemoine, 1997; Desmurs et al, 2002).

The knowledge of the present day oceans, thanks to the Deep Sea Drilling Program, Ocean Drilling Program and other oceanic investigation programs, allows to compare the environments of formation of present-day oceanic crust with that of the ophiolitic rocks (e.g., Manatchal and Bernoulli, 1993).

The link among all the sedimentary covers of the Western Tethys Mesozoic ophiolites is the ubiquitous presence, at their top, of radiolaritic levels, similarly to almost all the Phanerozoic ophiolites, as recognised by Steinman (1927).

The high-resolution radiolarian biostratigraphy provides the different ages of the basaltic events and allows to compare them with the radiometric ages of basalts, plagiogranites and gabbros and, finally, to reconstruct the timing of the magmatic evolution.

However, many questions are still unanswered, regarding the paleogeodynamic, paleogeographic, and sedimentological processes involved in the generation of the Western Tethys ophiolites.

A first group of questions concerns the origin of the “incomplete” crustal sequences. It is debatable whether this crust was generated within transform zones (see the paragraph on the ‘ophicalcites’), on an ocean-continent transition such as Iberia, or represents an ocean floor produced at a slow-spreading ridge.

A second group of questions are the following:

- The paleogeographic meaning of the ophiolitic breccias, in particular the role of tectonics, hydrothermalism and seawater-rock interaction in the genesis of the ophicalcites and ophicalcite-like breccias;
- The processes originating the radiolaritic cherts, and their sedimentation by direct deposition, or by reworking as turbidite-like contourites;
- The factors (magmatism, change of CCD level, upwelling of nutrients etc.) of the change from carbonatic to siliceous deposition in the pelagic environment, and viceversa;
- The connections between hydrothermalism, manganese metallogenesis and chert deposition;
- The paucity or absence of basalts, and their extrusion that in most cases follows the sedimentation of ophiolitic breccias and of the first pelagites (radiolarian cherts);
- The timing and duration of the oceanic spreading;
- The meaning of facies changes of the pelagic sediments, their environment and the mode of deposition, as well as their thickness variability (consequence of erosion or diastems ?);
- The contemporaneity of the radiolarian cherts in both oceanic basin and continental platforms;
- The change of composition of the pelagites from both oceanic and continental margin environment at the Late Jurassic - Early Cretaceous boundary in the peri-Adriatic realm.

This work summarises the present-day state-of-art concerning some of the questions above with the aim of providing answers to them.

This revue will deal mainly with the cover successions of the well known Northern Apennines and Corsica. Successively, we will add some notes regarding other Tethyan ophiolites (Central, Western and Ligurian Alps; Calabria; Betic Cordillera). Finally, we will try to define the evolution of the covers of all the Western Tethys, by reading the volcano-sedimentary logs.

In the Northern Apennines (Fig. 2) the ophiolites are present in the Liguride Units, thrust onto the continental

Adria Domain (Tuscan and Umbrian successions). The Ligurides consist of Jurassic-Paleogene successions, topped by turbiditic formations that show a rough eastwards younging (Late Cretaceous up to Middle Eocene). It is generally inferred that they all had an oceanic basement (except perhaps for the more external ones, and the Canetolo Complex, generally attributed to a "Sub-Ligurian" Domain) and a similar pelagic sedimentary succession until the early Late Cretaceous.

The Liguride Units successions have been described as "Eugeosynclinal Sequences" by Abbate and Sagri (1970). They were divided into two groups: "Internal" and "External" Ligurides, by Elter (1972; 1973; Abbate et al., 1980).

Being, in the Northern Apennines, the tectonic transport towards the east, the "Internal" Ligurides deposited in the northwestern side of the Western Tethys domain and occupy the higher tectonic position in the nappe pile; the "External" Ligurides deposited in the south-eastern side, and underly the "Internal" ones.

The ophiolitic Vara Unit represents the main unit of the "Internal Ligurides" (see Abbate et al., 1980; 1986; 1992; Principi and Treves 1984; Principi, 1994), and preserves an ophiolitic (oceanic) basement. On the contrary, in the "External Ligurides the ophiolites are present only as olistoliths or clasts of breccias (olistostomes) in the Cretaceous (e.g. Casanova, Caio and Monteverdi M.mo Units) and Eocene (Morello-Santa Fiora Units) clastic formations (Abbate et al., 1980; Bortolotti et al., 2001b).

Moreover, Beccaluva et al. (1980; 1984; 1989) found that the the Internal and External Ligurides ophiolites (at least those of the Liguria-Emilia Apennines) differ in composition: in the last ones the peridotites are more fertile, and the basalts more primitive.

## The Internal Ligurides

The Internal Ligurides (Fig. 2) crop out in the Ligurian Apennines, in the coastal central Tuscany and in the Elba Island.

The Internal Ligurides consist of Jurassic-Paleogene suc-

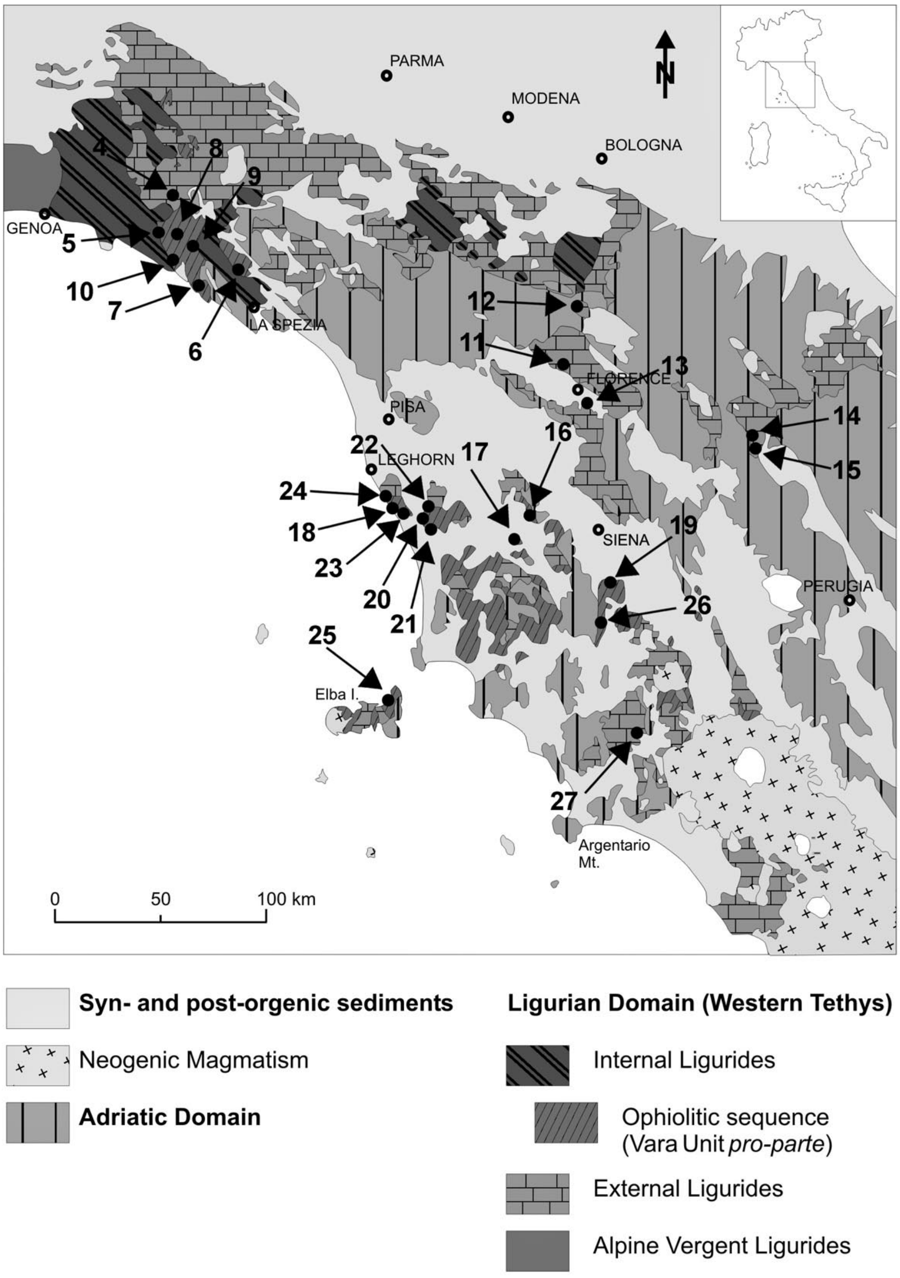

Fig. 2 - Northern Apennines geological sketch map, with location of the dated radiolarian cherts in Liguria (see Fig. 6) and Tuscany (see Fig. 7) (after Bortolotti et al. 2001, modified).
Liguria: 4- Costa Scandella; 5- Val Graveglia; 6- Rocchetta di Vara; 7- Mt. Rossola; 8- Mt. Zenone and Passo Broccheie; 9- Pavereto; 10- Case Gabbriello.
Tuscany: 11- Figline di Prato; 12- Sasso di Castro; 13- Impruneta; 14- Conventino; 15- Rio; 16- Gambassi; 17- Mandriolo (Larderello); 18- Romito; 19- Murlo; 20- Terriccio and Aiola; 21- Debbiare; 22- Mt. Vitalba; 23- Quercianella; 24- Castel Sonnino; 25- Volterraio; 26- Capannelle; 27- Sovana-Elmo.

cessions, and only the Vara Unit, preserves an ophiolitic (oceanic) basement and a complete Upper Jurassic-Cretaceous pelagic cover; the other Liguride successions (both Internal and External) are reduced and begin with Upper Cretaceous pelagites (Palombini Shales, or other shaly formations). All the Internal Ligurides successions end with Upper Cretaceous-Paleocene siliciclastic (e.g., Gottero Sandstones) or calcareous (e.g. Mt. Antola Helminthoid Flysch) or mixed (Elba Flysch) turbidites. Ophiolitic olistoliths and olistostromes are absent in the more internal Upper Cretaceous successions.

After the closure of the ocean basin, during the first orogenic phases (Paleocene-Early Eocene) the Internal Ligurides thrust eastwards onto the External Ligurides and, later on (Miocene), as a whole, onto the Adria continental margin (Tuscan and Umbrian successions).

## The Vara Unit succession

The Vara succession (Vara Valley Supergroup Auct.) is one of the best exposed and studied Jurassic oceanic crusts. It widely crops out in the western side of the Northern Apennines arcuate chain, alongside and inside the Tyrrhenian-Ligurian seas.

The best outcrops are sited in the Bargonasco-Val Graveglia (Fig. 2, n. 5 and 8), Bracco-Levanto (Fig. 2, n. 7, 9, 10) and Rocchetta di Vara (Fig. 2, n. 6) areas, in Liguria; in the Quercianella-Castel Sonnino (Fig. 2, n. 18, 23, 24), Mt Vitalba-Riparbella (Fig. 2, n. 20, 21, 22) and Murlo-Pari (Fig. 2, n. 19, 26) zones, in Tuscany; in the Elba Island (Fig. 2, n. 25).

The Vara ophiolites suite can be divided into two portions:
1)- a mafic-ultramafic ‘basement’
2)- a volcano-sedimentary unconformable ‘cover’.

## The “basement”

The Vara Unit basement mainly consists of serpentinised mantle peridotites, ranging from more or less depleted lherzolites to harzburgites, with minor intrusions of isotropic or layered cumulate gabbros and dunitic-troctolitic cumulate lenses (Figs. 3, 4, 23, 24).

The ultramafic basement was affected by upper mantle re-equilibration (from spinel- to plagioclase facies), associated with foliation and folding (tectonitic textures: see Beccaluva et al., 1984). The ultramafites are mostly lherzolites. Most of these peridotites are impregnated by MORB type melts coming from a deeper mantle lithosphere and originating both intrusive (rodingitic dikes, gabbro bodies) and extrusive (basaltic flows) rocks (see also Piccardo et al., 2004, with bibl.). Minor extraction of melts, probably due to melting events (Triassic?) preceding the mantle denudation, could be recorded by harzburgite bands, pyroxenite layers and dikes, and likely by dunite lenses. Everywhere, the contact between gabbros and peridotites underwent rodingitization.

The gabbro intrusion was followed, during the latest upwelling of the peridotite mass, by ductile deformations associated with high-grade (granulite to high temperature amphibolite facies) metamorphism and later on, by a brittle deformation phase, developed as a system of parallel fractures associated with seawater circulation and amphibolite to greenschist facies overprint (Cortesogno and Olivieri, 1974; Gianelli and Principi, 1974; 1977; Cortesogno, 1980; Cortesogno and Lucchetti, 1982; Cortesogno et al., 1975; 1977; 1987; 1994). The brittle phase is associated at depth to the intrusions of basalt dike parallel swarms (Cortesogno and Gaggero, 1992). In Southern Tuscany a small sheeted dike complex, some hundred metres in size crops out near Riparbella (Leghorn) (Bortolotti et al., 1976; Piombino, 1991).

In the Val Graveglia area the gabbros are dated at 164±14 Ma (Sm/Nd; Rampone and Hofmann, 1998). In the same area, U/Pb dating on zircon separates from plagiogranites in the Lower Breccias (Mt. Capra Breccia), yielded an age of 153±1 Ma (Borsi et al., 1996).

The low temperature metamorphism develops with a generalised serpentinisation on peridotites, associated with active tectonics, recorded by the ribbon textures and by breccia levels within the ultramafic rocks. Frequently, gabbros and serpentinites have been tectonically juxtaposed by brittle faults of Jurassic age (Abbate et al., 1980). The top of the basement is often characterised by tectonic breccias and is unconformably overlain by sedimentary breccias, radiolarian cherts and, locally, by basalts.

The tectonic breccias on top of serpentinites contains several generations of fractures filled with calcite, serpentinitic clasts, and micritic sediment. Repeated episodes of infilling and growth of sparry calcite provide evidence of fluid-rock interaction during faulting close to the ocean floor. This level, known as ‘Ophicalcites’ p.p. (Levanto Breccia, Cortesogno et al., 1978; 1987, with bibl. therein), is considered a tectonic-hydrothermal breccia, partly reworked at its top into a sedimentary breccia (Bonassola Breccia; Cortesogno et al., 1978). It marks the exposed surface of the serpentinised ultramafics, which just reached the ocean floor (Cortesogno et al., 1978; 1980; 1987, Treves and Harper, 1994).

## The volcano-sedimentary “cover”

The Bonassola Breccia was divided into several members, according to the composition (serpentinitic, gabbroic, polymict) and stratigraphic position (Lower and Upper Breccias, the former underlying and the latter overlying, often interfingered with, the basalts).

In Eastern Liguria (Bargonasco-Val Graveglia, Fig. 2 n. 5, 8 and Figs. 3 and 23; Bracco-Levanto, Fig. 2 n. 7, 9, 10 and Figs. 3 and 24; Rocchetta di Vara, Fig. 2 n. 6 and Fig. 3) the best and the first studied outcrops of the Bonassola Breccia occur (Passerini, 1965; Abbate, 1969; Galbiati, 1970; Decandia and Elter, 1972; Principi, 1973; Gianelli and Principi, 1974; Galbiati et al., 1976; Folk and McBride, 1978; Cortesogno et al, 1978; 1981; 1987; Abbate et al., 1980; Barrett, 1982a; Treves and Harper, 1994; Bortolotti and Principi, 2003; Bortolotti et al., 2005 in press).

In Tuscany (Castel Sonnino-Quercianella, Fig. 2 n. 18, 23, 24; Mt. Vitalba-Riparbella, Fig. 2 n. 20, 21, 22; Murlo, Fig. 2 n. 19; Monti Rognosi-Pieve Santo Stefano, Fig. 2 n. 14 and 15) the ophiolitic breccias are correlated with the breccias found in Liguria, on the basis of both the clast lithology and the stratigraphic position, with respect to the basalt flows (Gianelli and Principi, 1974; 1977; Brunacci and Manganelli, 1983; Bonechi, 1980; Bortolotti et al., 1992; 1994; 2001b). In the Elba Island (Fig. 2, n. 25 and Fig. 4) the ophiolitic breccias are lacking.

### *Lower Ophiolitic Breccias*

(Bonassola Breccia p.p. of Cortesogno et al., 1978; 1987).

The Lower Ophiolitic Breccias (Figs. 3, 23, 24) constitute the basal terms of the ophiolitic sedimentary cover. They mainly consist of serpentinitic clasts (Framura -sedimentary ophicalcites- or Case Boeno Breccia; Folk and

McBride, 1978; Cortesogno et al., 1978; 1987; Abbate et al., 1980; Bianco 1996; Bortolotti and Principi, 2003) or, locally, with Fe-gabbroic, dioritic and subordinate Mg-gabbroic and serpentinitic clasts (Mt. Capra Breccia; Gianelli and Principi, 1974), or mainly Mg-gabbroic clasts (Bargonasco-Val Graveglia, Bracco-Levanto areas). Inside them and, often, at their base, thin levels of cherty pelagites are interbedded. Generally, the composition of both clasts and matrix (mainly arenaceous) reflects the lithology of the underlying basement (except for the Mt. Capra Breccia). Breccias overlying the ultramafic basement commonly have sparry calcite cement, more rarely the clasts (mostly spinel and chloritised orthopyroxene serpentinites) lie in a micritic, hematite-rich matrix (Cortesogno et al., 1980; 1981; 1987). The clast size is variable, from centimetric to metric and, rarely, decametric. The thickness of the breccias (as the Mt. Capra and Case Boeno Breccias in the Val Graveglia-Bargonasco area) varies from zero to about 200 metres. The mechanism of deposition is mainly referable to debris-flows (Gianelli and Principi, 1974; Cortesogno et al., 1978; 1987; Abbate et al., 1980) deposited in small basins.

The age of the Lower Breccias is generally inferred from that of overlying cherts, or provided by radiolarian from interlayered cherty levels. At Broccheie Pass (Bargonasco-Val Graveglia) a radiolarian assemblage found in a metric cherty level in the Mt. Capra Breccia (Chiari et al., 2000) gave an age from late Bajocian-early Bathonian to late Bathonian-early Callovian (UAZ. 5-7). At Mt. Rossola (Levanto) a sample of radiolarian cherts at the top of the Framura Breccia, immediately below the massive basalts, gave a latest Bajocian-early Bathonian (UAZ. 5) age (Abbate et al., 1986; Chiari et al., 2000).

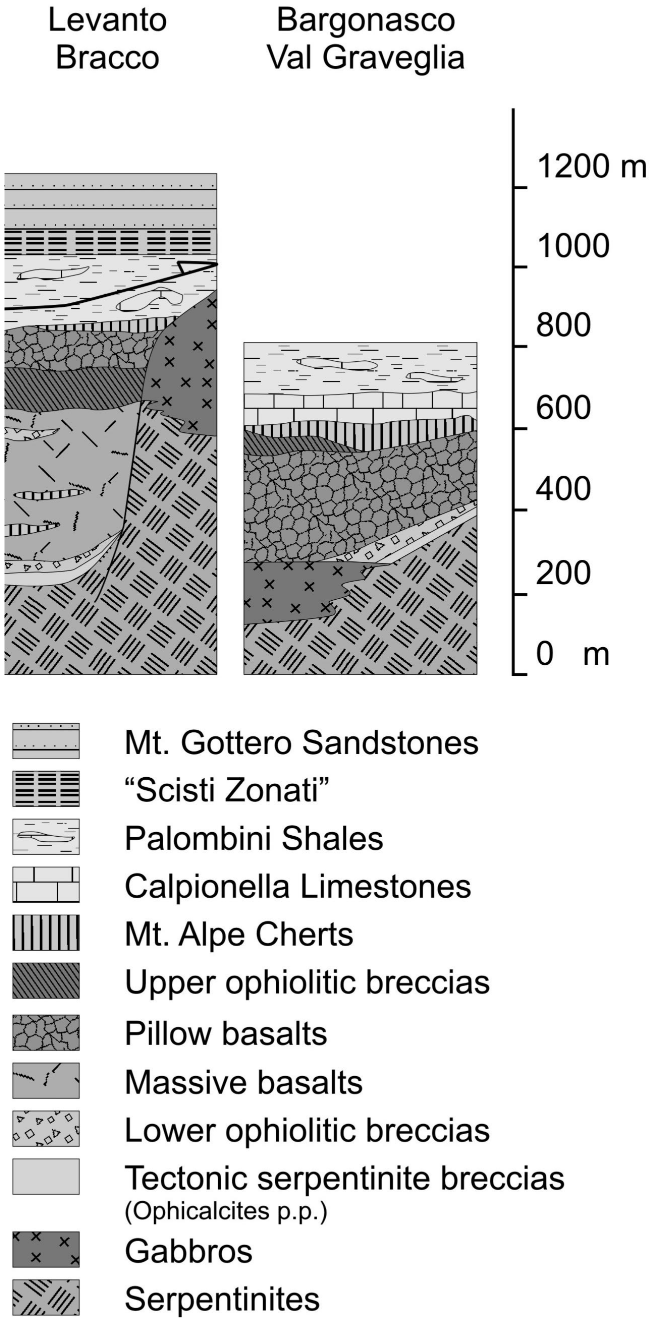

Fig. 3 - Columnar section of the ophiolite successions of the Internal Ligurides (Bargonasco-Val Graveglia and Bracco-Levanto areas).

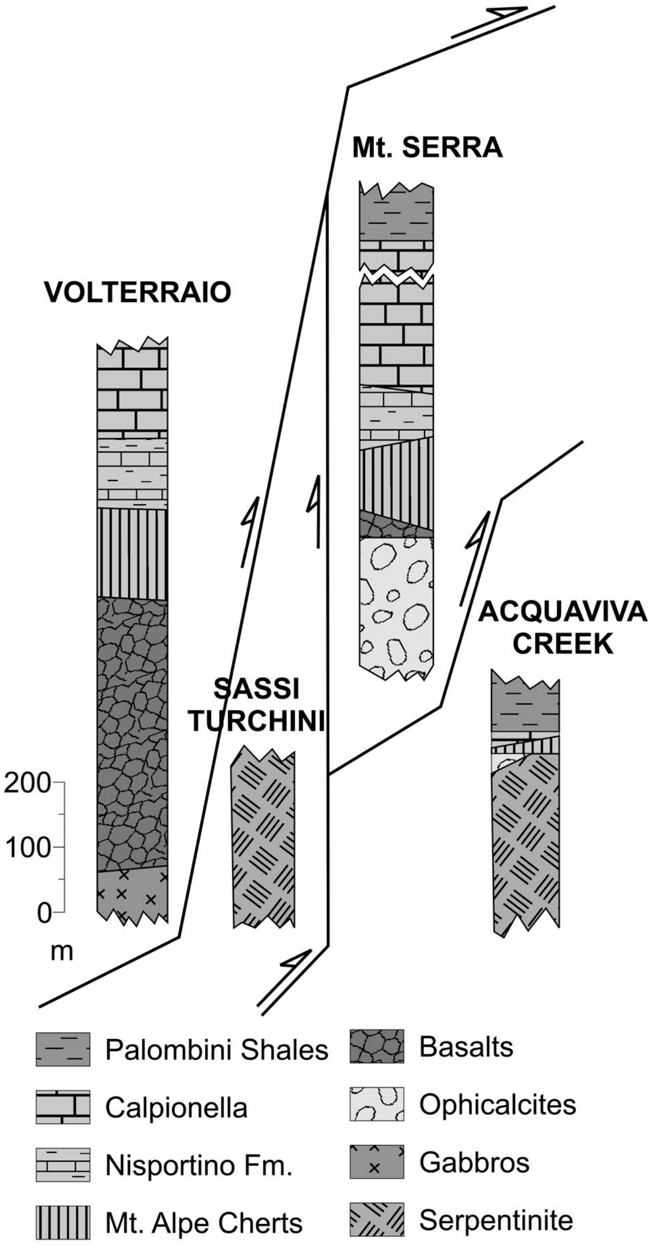

Fig. 4 - Columnar sections of the four main sheets of the Ophiolitic Unit of the eastern Elba Island.

### *Basalt Flows*

The Lower Breccias, are overlain by MOR-type basalt flows (Beccaluva et al., 1980; 1989; Venturelli et al., 1981; Figs. 3, 23, 24), mainly pillow lavas and locally-massive lava~~s~~ (Levanto) in the so-called "complete sequences". Feeder dikes are rarely found in the lower breccias and are locally frequent within lava flows. The massive flows and dikes induced a thermal rise at the contact with the breccias (Cortesogno et al., 1987; 1994).

In the "reduced sequences" the basalts are generally lacking and the ophiolitic breccias are mainly serpentinic (more or less ophicalcitised: Framura type). The breccias and the ophicalcitised mantle carapace are directly covered by thin chert deposits.

The basalt thickness is very variable and ranges from few metres in the reduced sequences, up to more than 400 m in the complete sequences (Mt. Rossola), where the average thickness is about 200 metres.

The age of the cherts (Figs. 2, 5, 6, 7) allows indirectly to date also the associated basalts. However, rarely the intercalated chert levels have significative biostratigraphic records. At Terriccio (Southern Tuscany, Fig. 2, n. 20) a sample found in a thin cherty intercalation very close to the base of the basalts provided a middle Callovian-early Oxfordian to middle-late Oxfordian age (UAZ. 8-9) (Nozzoli, 1986; Chiari et al., 2000). In the same area (Aiola) the radiolarian assemblage of the cherts at the top of the same basalt body provided a late Oxfordian-early Kimmeridgian age (UAZ. 10; Nozzoli, 1986; Chiari et al., 2000). Hence, in Southern Tuscany the basalt flows occurred during the Oxfordian.

In Liguria, on the contrary, the basalt flows seem to be older, in fact the chert level below the basalts (Broccheie Pass, see before) is late Bajocian-early Bathonian to late Bathonian-early Callovian (UAZ. 5-7) and at Mt Zenone (Fig. 2, n. 8) a radiolarian assemblage from a chert level at the top of the same basalt level, gave a late Bathonian-early Callovian age (UAZ. 7) (Bortolotti et al., 1991b; Chiari et al., 2000). We can argue that in this zone the basalt flows occurred during a time interval comprised between the late Bajocian and the early Callovian. Accordingly, the Ligurian oceanic crust results to be older than that of Southern Tuscany (i.e., a younging occurs from E to W in the restored Tethys Ocean; see Figs. 25-28) (see Abbate et al., 1986; 1992; Chiari et al., 2000).

### *Upper Ophiolitic Breccias*

(Bonassola Breccia p.p. of Cortesogno et al., 1978)

The basalts are often covered by ophiolitic breccias (Principi, 1973; Gianelli and Principi, 1974; Abbate et al., 1980; Barrett, 1982a; Bortolotti and Principi., 2003; Brunacci et al., 1982). They are both monogenic and polygenic, with clasts of flaser gabbros (Mt. Zenone Breccia), serpentinites (Mt. Bianco Breccia), or polymictic (Movea and Mt. Rossola Breccias). These breccias form lens-shaped bodies, from zero up to 100 m thick. Their age is comprised between the basalts and the overlying cherts ages (Figs. 3, 23, 24).

### *Mt. Alpe Cherts*

Above the Upper Ophiolitic Breccias, the sequence continues with a thick level of radiolarian cherts (Mt. Alpe Cherts; Figs. 3, 4, 23, 24), ranging from few up to 200 m. At the base they often alternate with thin strata of ophiolitic sandstones and breccias (Abbate, 1969; Principi, 1973; Cortesogno and Galli, 1974; Gianelli and Principi, 1974; Folk and McBride, 1978; Barrett, 1982b; Cortesogno et al., 1987; Aiello, 1994; 1997).

Very thin levels (decimetric or metric) of cherts were normally deposited also before the extrusion of the basalt flows, within the Lower Breccias.

In the Bargonasco-Val Graveglia (Fig. 2 n. 5, 8) and Rocchetta di Vara (Fig. 2 n. 6) outcrops, the variations in mineralogical and geochemical composition, petrography, textural features and sedimentary structures (lamination, bioturbation and slumping) allow to recognise in the Mt. Alpe Cherts different depositional lithofacies (Cortesogno and Galli, 1974; Gianelli and Principi, 1974; Folk and McBride, 1978; Cortesogno et al., 1979; Aiello, 1994; 1997; Cabella et al., 1995; Marescotti and Cabella, 1996; Cortesogno and Gaggero, 2003).

From the base upwards the following lithofacies can be distinguished:

a- Reddish or greenish detrital cherts rich in pelitic component, with subordinate laminated radiolarites, intercalated with ophiolitic sandstones and/or ophiolitic breccias and slumps (facies C and A of Aiello, 1994).

b- Laminated red cherts with radiolaritic beds (hematite up to 10% in volume), often bioturbated, with interbedded millimetric argillitic films, interpreted as counturites (facies B); at the bottom of the red cherts or at the transition between a) and b) lithofacies, thin (1-5 cm) manganesiferous (braunite) layers, more rarely hematite or apatite layers, are interlayered, up to a total thickness of several metres. They lack in the reduced sequences.

c- Turbiditic greenish siliceous pelites (illite + chlorite) alternated with red cherts and radiolarites and light grey radiolarites; parallel lamination and graded bedding are commonly developed within radiolarites ("ribbon chert" of Garrison, 1974; facies D of Aiello 1994; "vari-

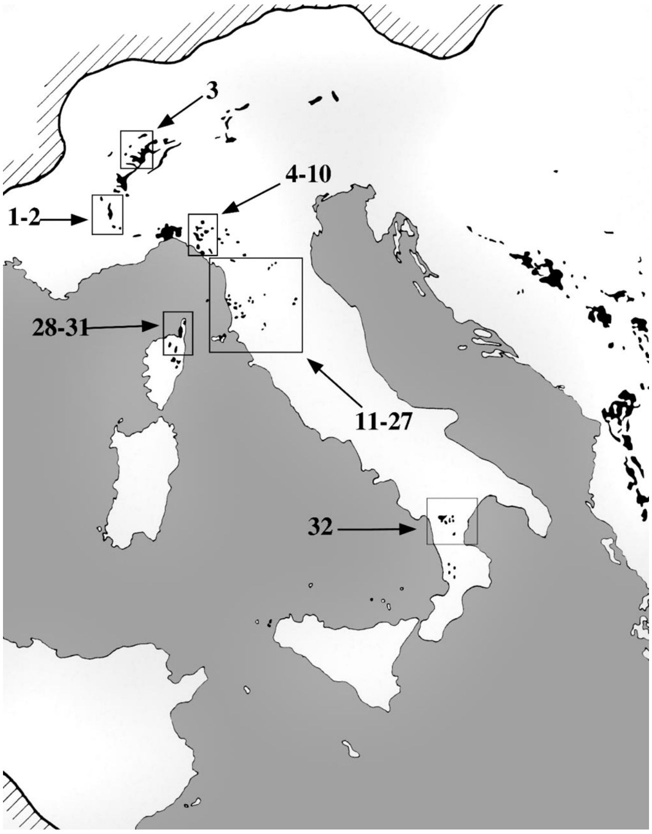

Fig. 5 - Sample sites of the dated radiolarian cherts in the studied areas. 1-3, Western Alps; Northern Apennines: 4-10, Liguria; 11-27, Tuscany; 28-31, Corsica; 32, Calabria. Ophiolite outcrops in black.

coloured cherts” of Cabella et al., 1995; Marescotti and Cabella, 1996).

d- Pseudostratified reddish pelitic to silty siliceous beds ($Al_2O_3$, 7.81-15.87; Marescotti and Cabella, 1996) devoid of radiolarians and with millimetric green laminae (facies E).

Facies A and C are regarded as transitional to the ophiolitic breccias. The facies A is present in the thicker successions (e.g. Ponte di Lagoscuro, Monte Zenone, Rocchetta di Vara). Slumps are often present, producing hard siliceous radiolaritic nodules embedded in shaly cherts (Cortesogno and Galli, 1974; Cabella et al., 1995). At the Rocca del Sasso (between the Bargonasco and the Graveglia Valley) a thick slump includes ophiolitic clasts and silicified woods (araucarioid type) in a silty matrix (Abbate et al., 1980; Bortolotti and Principi, 2003). In the same area, araucarioid (comparable to *Araucariopytis* Jeffrey) debris are often found near the base of the cherts (Cortesogno and Galli, 1974). In Val Graveglia, the thick chert sequence overlies conspicuous pillow lavas above thick ophiolitc breccia; at M. Rocchetta, thick cherts directly deposited on coarse gabbro and subordinate serpentinite breccias. Conversely, in the sequences of Mt. Alpe and Monte Zenone, the cherts overlying thick breccias are thinner and begin with the facies B.

Radiolarian-rich levels in the different lithofacies show radiolarian size gradation and size grading, considered as products of countourites (facies B) or turbidites (facies D). Facies E of the Bargonasco-Val Graveglia successions is considered the transition to the Calpionella Limestones. Aiello (1994) correlates these facies with the Scisti ad Aptici of the Tuscan Sequences and with the Nisportino Fm. of Elba Island Vara Succession (see below).

The age of the formation, is comprised between Bathonian and Tithonian (Figs. 2, 5, 6, 7). In particular, the radiolarian biostratigraphy in Liguria (Figs. 2, 6) gives the oldest age as latest Bajocian- early Bathonian (UAZ. 5 - Rossola section, Abbate et al., 1986; Chiari et al. 2000). Due to the scarce radiolarian preservation, in the upper part of the Mt. Alpe Cherts it is not possible to assign a precise age utilising the radiolarian biostratigraphy. Cobianchi and Villa (1992), using the nannoplancton biostratigraphy, indicate a late Tithonian age for the base of the overlying Calpionella Limestones.

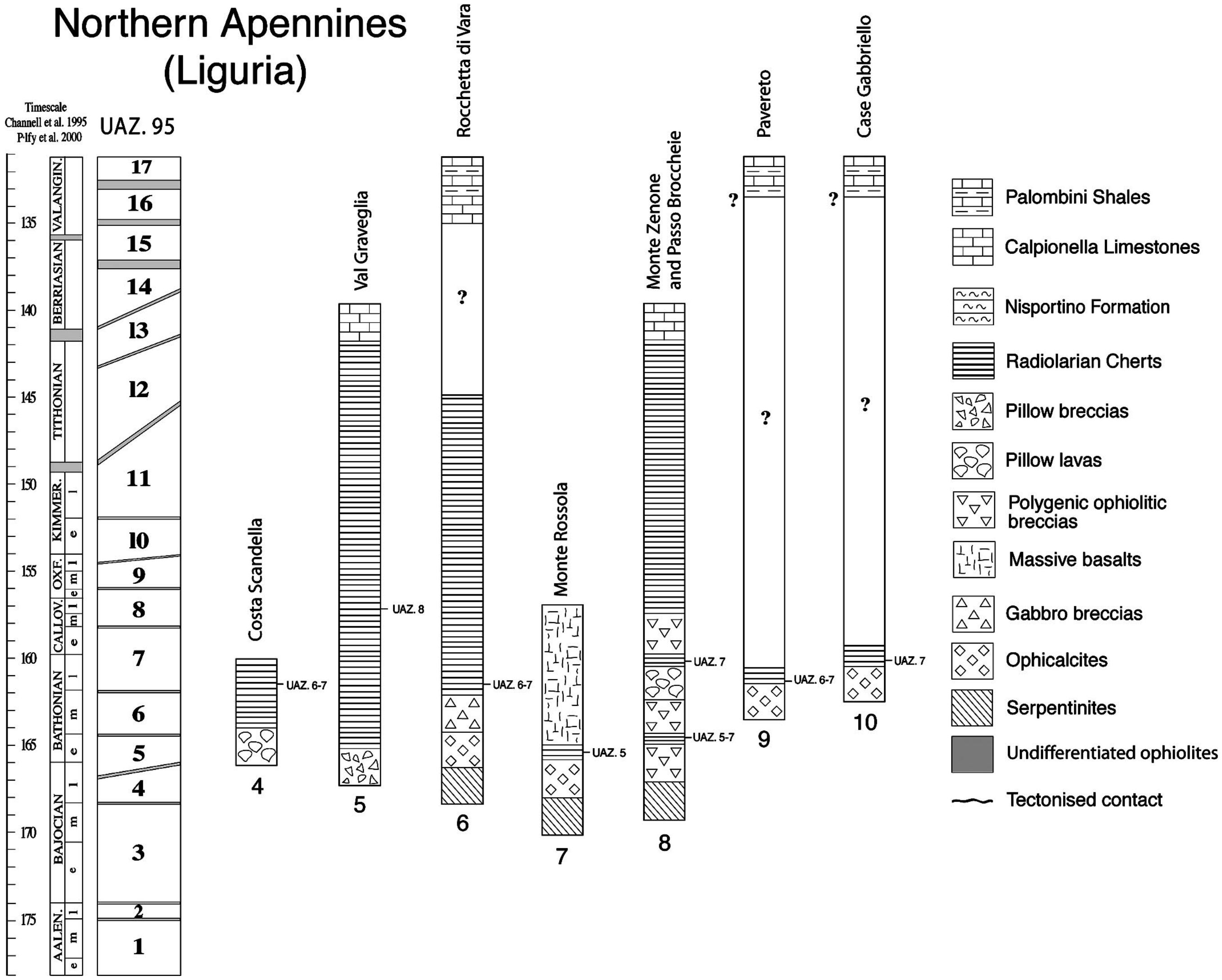

Fig. 6 - Radiolarian age determinations in the Northern Apennines (with schematic stratigraphic sections): Liguria (UAZones, after Baumgartner et al., 1995; time scale after Channel et al., 1995 and Pálfy et al., 2000). The location of the studied sections is reported in Figs. 2 and 5.

4- Costa Scandella, Conti et al. (1988); Chiari et al. (2000); 5- Val Graveglia, Conti and Marcucci (1991); Chiari et. al. (2000); 6- Rocchetta di Vara, Baumgartner (1984); Chiari et al. (2000); 7- Monte Rossola, Abbate et al. (1986); Chiari et. al. (2000); 8- Monte Zenone and Passo Broccheie, Rosi (1995); Chiari et al. (2000); 9- Pavereto, Rosi (1995); 10- Case Gabbriello, Rosi (1995); Chiari (com. pers., 2004).

In Tuscany (Figs. 2, 7) at Sasso di Castro (Fig. 2 n. 12), Terriccio (Fig. 2 n. 20) and Sovana Elmo (Fig. 2 n. 27), the base of the formation is comprised between the middle Callovian-early Oxfordian and the middle-late Oxfordian (UAZ. 8-9, Chiari 1994b; Nozzoli, 1986; Marcucci and Marri, 1990; Chiari et al., 2000). A Tithonian age has been found at the top of the Mt. Alpe Cherts at Figline di Prato (Fig. 2 n. 11), (Chiari, 1994a), and a Tithonian-early Berriasian one in the Elba Island (Bortolotti et al., 1994).

After the cherts deposition, the pelagites change radically in composition, from siliceous to carbonatic (Calpionella Limestones). This change chronologically corresponds to the Jurassic/Cretaceous boundary and is widespread in both the oceanic realm (Mt. Alpe Cherts to Calpionella Limestones) and the Tuscan-Umbrian continental margin successions (Tuscan Cherts to Maiolica). Nevertheless, this compositional change is not as abrupt elsewhere in the oceanic realm, as in Liguria. Transitional shaly-marly-silty formations interpose between Mt. Alpe Cherts and Calpionella Limestones in some “complete sequences” of Elba Island (Nisportino Fm., Bortolotti et. al., 1994; 2001a) and of Tuscany (Murlo Fm., Signorini, 1963; Bonechi, 1980; Brunacci et al., 1982). Thin levels (up to few metres) of transitional facies are present in other Tuscan outcrops (Gambassi, Ciscato, 1992, Bianco, 1996; Monti Rognosi, Conti and Marcucci, 1986, Sarri, 1990, Chiari et al., 2000). In the Bracco-Levanto area the Mt. Alpe Cherts are stratigraphically topped by the Palombini Shales, with a probable hiatus.

*Nisportino and Murlo Formations*

The **Nisportino Formation** of the Elba Island (Figs 2 n. 25, and Fig. 4) shows three main lithofacies (Bortolotti et al., 1994; 2001a):

i- At the base 2-3 m of siliceous, sometimes cherty, limestones are followed by reddish siliceous-marly siltstones, shales and rare siliceous cherty limestones. This facies ends with grey limestones. The age is Tithonian-Berriasian, the thickness is about 20-25 m.

ii- The central section (Rivercina Member) is made up of medium to dark grey non stratified marly limestones. The thickness ranges from 10 to 30 m. The age is early Berriasian.

iii-The upper section begins with 5-13 m of reddish siltstones and shales with rare siliceous limestones. 9-25 m of non stratified marly-silty shales, with two calcareous beds follow. Upwards, the micritic limestone beds (pinkish at the top of the section) prevail on siliceous and marly siltstones. At the top a marly-silty shales level crops out. The thickness ranges from 50 to 70 m.

The total thickness of the formation ranges from 90 to 130 m.

The Nisportino Fm. is not limited to the Elba Island: it is present, often with a very reduced thickness, in some outcrops of Southern Tuscany (e.g. Mt. Vitalba, Leghorn; Gambassi, Florence; Ciscato, 1992).The formation is heteropic with the lower portion of the Calpionella Limestones.

In the Vara Supergroup of Southern Tuscany (at Murlo, Fig. 2 n. 19; etc.) also the **Murlo Formation** (Signorini, 1963; Brunacci and Manganelli, 1980), very similar to the Nisportino Fm. crops out. It consists of cherty limestones at the base, followed by marlstones with scattered levels of siliceous/marly siltstones and, upwards, of marly limestones

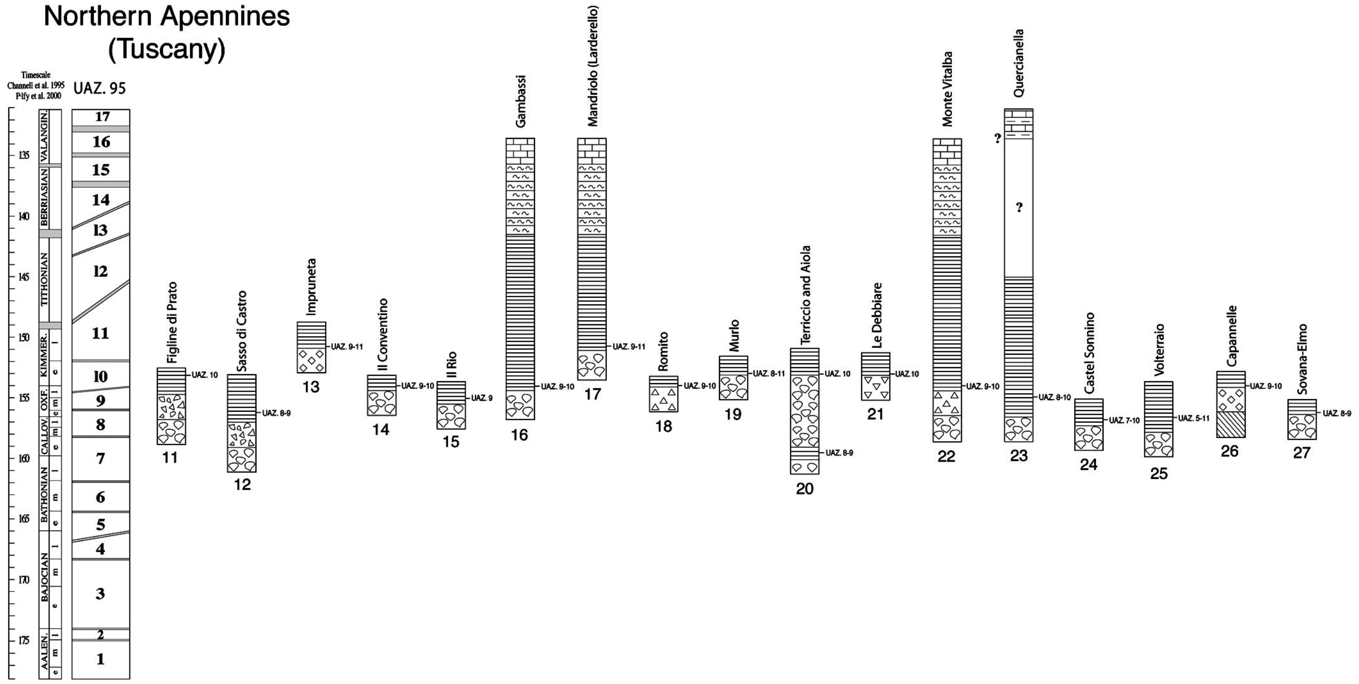

Fig. 7 - Radiolarian age determinations in the Northern Apennines (with schematic stratigraphic sections): Tuscany (UAZones from Baumgartner et al., 1995; time scale after Channel et al., 1995 and Pálfy et al., 2000), The location of the studied sections is reported in Figs. 2 and 5.

11- Figline di Prato, Chiari (1994a); Chiari et al. (2000); 12- Sasso di Castro, Chiari (1994b); Chiari et al. (2000); 13- Impruneta, Chiari and Marcucci (1995); 14- Il Conventino, Conti and Marcucci (1986); Chiari et al. (2000); 15- Il Rio, Conti and Marcucci (1992); Chiari et al. (2000); 16- Gambassi, Ciscato (1992); Chiari et al. (1995); 17- Mandriolo (Larderello), Bianco (1996); 18- Romito, Marcucci and Marri (1990); Chiari et al. (2000); 19- Murlo, Conti and Marcucci (1986); Chiari et al. (2000); 20- Terriccio and Aiola, Nozzoli (1986); Chiari et al. (2000); 21- Le Debbiare, Chiari et al. (1997); Chiari et al. (2000); 22- Monte Vitalba, Picchi (1985); Chiari et al. (2000); 23- Quercianella, Nozzoli (1986); Chiari et al. (2000); 24- Castel Sonnino, Chiari et al. (1997); Chiari et al. (2000); 25- Monte Volterraio, Baumgartner (1984); Chiari et al. (2000); 26- Capannelle, Marcucci and Marri (1990); Chiari et al. (2000); 27- Sovana-Elmo, Marcucci and Marri (1990); Chiari et al. (2000).

(Balzani Limestones, considered a local haeteropy of the Calpionella Limestones). This formation has the same stratigraphic position as the Nisportino Fm., between Mt. Alpe Cherts and Palombini Shales, and the same Berriasian age (Fig. 7) (Bonechi 1980; Brunacci et al.,1982; Conti and Marcucci, 1986; Bortolotti et al., 1994; Chiari et al., 2000). The thickness ranges from a few to more than one hundred metres. The formation is heteropic with the Calpionella Limestones.

These southern Vara Unit successions differ from the typical ones of the eastern Liguria (Bargonasco-Val Graveglia, Bracco-Levanto, Rocchetta di Vara areas), where the Calpionella Limestones overlie almost directly the Mt. Alpe Cherts. Nevertheless, also here few metres of transition (cherty limestones and red shales and siltstones) are present.

### *Calpionella Limestones*

The Calpionella Limestones are almost ubiquitous in the complete sequences of the Bargonasco-Val Graveglia zone (Figs. 2, 3, 23). In the Bracco-Levanto and Rocchetta di Vara zones (Figs. 2, 3) the Palombini Shales directly lie on top of the ophiolites or cherts, both in complete (Levanto, Rocchetta di Vara) and reduced (Bracco Massif) sequences. In Tuscany and Elba Island (Figs. 2, 4), the Calpionella Limestones are always present on top of the Mt. Alpe Cherts or of the Nisportino Fm., except in an incomplete succession of the Elba Island (Acquavia Subunit) and in the Murlo area,

The Calpionella Limestones consist of a succession of micritic calcareous beds (often amalgamated, specially at the base), or separated by very thin shaly intercalations. A metre thick marly level occur near the base throughout the Val Graveglia Zone. Rare decimetric up to metric shales levels are present, mostly in the middle-upper portion. The internal sedimentary structures testify a turbiditic origin (Andri and Fanucci, 1975; Cobianchi et al., 1994).

The age of the formation is Tithonian-early Valanginian according to Decandia and Elter (1972), Berrasian-early Valanginian according to Andri and Fanucci (1973). According to the recent studies (Cobianchi and Villa, 1992), the age ranges from late Tithonian-early Berrasian to early Valanginian-late Hauterivian. The presence of late Tithonian is documented by the Calpionellid Zone A and corresponds to the transitional facies E of the Mt Alpe Cherts by Aiello (1997).

Where the Calpionella Limestones lie on the Nisportino Fm., their base is not older than the early Valanginian (Bortolotti et al., 1994). The thickness of the Calpionella Limestones ranges from zero, to about 150 m in the complete successions.

### *Palombini Shales*

The very long lived (Hauterivian to Santonian: 83-132 Ma) Palombini Shales formation was widespread throughout the Liguride Domain (Figs. 3, 4, 23, 24) (Zanzucchi, 1963; Abbate et al., 1970; Decandia and Elter, 1972; Abbate et al., 1980; 1984; Weissert and Bernoulli, 1985; Cortesogno et al., 1987; Marroni and Perilli, 1990; Marroni and Meccheri, 1993; Cobianchi et al., 1994).

The formation consists of an alternance of shales and subordinate micritic limestone beds. The limestones, often silicified along the bed surfaces (typical anvil-shaped erosion), are more abundant near the base and become very rare and thin towards the top. At the base, the limestones of the Calpionella Limestones, rapidly reduce to 50/50 limestone/shale ratio; upwards the shales become prevalent. Calcareous shales, marlstones, siltstones and sandstones can alternate in different percentages with the main lithologies. In the Ligurian successions siltstones and sandstones are common near the top, close to the “Scisti Zonati”.

In Liguria, in the Bracco-Levanto zone and in the reduced successions of Tuscany, the Palombini Shales directly lie on the Mt. Alpe Cherts or on the ophiolitic basement.

In Liguria, the shales are composed of 70-80% clay minerals (illite, and subordinate kaolinite, chlorite and chlorite/vermiculite, Pacciotti, 2000). Similar compositions were found in other Apenninic areas.

In the Southern Tuscany, some quartzarenitic levels with carbonatic cement are often intercalated in the Lower Cretaceous portion of the Palombini Shales (Lazzarotto, 1967; Uberti, 1999).

The age of the Palombini Shales has been attributed to the Tithonian-Neocomian boundary on the base of a tintinnid association studied by Ghelardoni et al. (1965). Cobianchi and Villa (1992) and Cobianchi et al. (1994) attributed the base of this formation to the Hauterivian-Barremian and, in the reduced sections, to the middle-late Barremian, on the base of nannoplancton biostratigraphy. The younger age, in the Vara succession of Statale (Val Graveglia) is early-late Aptian (Zone NC7). Perilli and Nannini (1997) found an early/late Valanginian age for the base of this formation in the Rocchetta di Vara outcrops. At the top of the formation in the Lavagna-Gottero succession Marroni and Perilli (1990) found a nannofossil association of late Santonian age.

Considering that the late Campanian is present in the basal portion of the overlying Scisti Zonati, we can infer that the Palombini Shales should also reach the Campanian. Hence, the age of this formation could be comprised between the late Hauterivian and the late Santonian or even the Campanian.

In the Case Luxardo succession, near Levanto, and in the reduced successions (Cobianchi et al., 1994) an important chronological hiatus (from Tithonian to Barremian) is present. Also on the Bracco Massif (Mola Pass, between Velva and Carro), the Palombini Shales seem to be interbedded with, and directly sedimented on the gabbroic breccias. Here they include, near the base, small olistoliths of ophicalcites. It is likely that, in spite of the lack of chronological data, where the Palombini Shales were directly deposited on cherts, basalts or ophiolitic breccias, a sedimentary-chronological hiatus occurs. The possible significance of these hiatuses is discussed below.

It is difficult to calculate the thickness of the Palombini Shales because they are always strongly deformed. Moreover, often the ophiolitic succession of the Vara Unit is bounded by tectonic surfaces within the Palombini Shales. Their visible thickness is in the order of some hundred metres.

Upwards, in Liguria, the Palombini Shales grade into the Scisti Zonati of the Lavagna Valley Group (Bortolotti et al 2005, in press, and bibl. therein).

### *Scisti Zonati*

They consist of siltstones, shales, marlstones and fine-grained silicoclastic sandstones alternating in variable proportions. The marlstone turbiditic beds have sometimes a calcarenitic base. The thickness is not less than 250 m. They grade to the Mt. Gottero Sandstones through an increase of the sandstone beds.

The nannofossils give a late Campanian age (Marroni and Perilli, 1990; Bortolotti et al., 2005, in press).

*Mt. Gottero Sandstones*

The Mt. Gottero Sandstones consist of arenaceous-pelitic turbidites, including prevalent quartz-feldspatic sandstones, argillites and siltstones. The beds are some decimetres to more than one metre thick, and often amalgamated. The thickness of the sandstone beds decreases at the top. Near the base, polychrome argillite levels (Mt.Vallai Shales; Marini, 1992) are present. The thickness of this formation is not less than 600-800 m.

Its age is comprised between late Campanian and Paleocene on the base of foraminifers and nannoplancton associations (Passerini and Pirini, 1964; Monechi and Treves, 1984; Marroni and Perilli, 1990).

According to Bortolotti and Principi (2003) and Bortolotti et al. (2005, in press), in the Bargonasco-Val Graveglia area the Mt. Gottero Sandstones grade upwards to the Giaiette Shales, without any evidence of the paraconformity described by Pertusati (1968), to the north.

*Giaiette and Tavarone Fm.*

The **Giaiette Shales** consist of stratified brown shales with rare fine quartz-rich sandstones. Yellowish marlstones (Salino Marls, Marini, 1992) locally crop out in the uppermost portion. The shales have the same composition as the Palombini Shales (Pacciotti, 2000). Upwards, the formation includes olistoliths of Palombini Shales and polygenic breccias. The age is Paleocene, on the base of foraminifers and nannofossil associations (Passerini and Pirini, 1964; Monechi and Treves, 1984)

The **Tavarone Formation** (Decandia and Elter, 1972; Marroni and Meccheri, 1993; Bortolotti et al., 2005, in press) is very similar to the Giaiette Shales in lithology and age, and for the presence of olistoliths and olistostromes. The olistoliths are more abundant, come from the underlying formations, and consist of ophiolites (serpentinites, gabbros, Mt. Capra Breccia, basalts), Palombini Shales, and Mt. Gottero Sandstones. There are also olistoliths of a Helminthoid Flysch in which nannofossil associations give a Cenomanian age (Zones CC9 - CC10, Bortolotti et al 2005, in press).

Some foraminifers found in calcareous beds suggest a probable Paleocene age.

It is noteworthy that ophiolitic olistoliths are found in the Internal Liguride Vara Unit succession, for the first time, in this Paleocenic formation. On the contrary, in the External Liguride Units they are present from the Late Cretaceous (see later).

## The External Ligurides

The External Liguride Units crop out in the Ligurian-Emilian Apennines, in the Tuscany hinterland and in the Tuscan-Marchean Apennines (Abbate et al., 1970; 1980; Bortolotti et al., 2001b; Marroni et al.,1998; 2001). They consist of thick units where the ophiolites occur as huge slide-blocks and clasts in the Cretaceous-Eocene successions. In particular:

a- in the more internal units, they are enclosed in the Santonian-lower Campanian sedimentary mélanges (e.g., Casanova Complex) and in the overlying Campanian-Maastrichtian Helminthoid Flysch (e.g., Mt. Caio Fm., at Montaione, Gardin et al., 1994, and ref. therein) (Abbate et al., 1980; Principi and Treves, 1984; Marroni et al., 2001 and ref. therein)

b- in the more external units, they are found in the Paleocene-Lower Eocene sedimentary mélanges included in the Sillano Fm., and in the overlying Middle Eocene Helminthoid Flysch (Mt. Morello Fm., Bortolotti, 1962). Also in the Western Liguria olistoliths of basaltic rocks (likely comparable with the External Ligurides ones) occur, in the Cretaceous and Eocene basal complexes of the Moglio - Testico, Borghetto di Arroscio and Colla Domenica - Leverone units. (Cortesogno et al., 1988).

Two most remarkable characteristics differentiate the ophiolitic blocks found in the External Ligurides of the Emilian-Ligurian Apennines from the ophiolites of the Internal Ligurides: the geochemistry of the basalts (T-MORB versus N-MORB) and the scant association with continental crust rocks.

The Palombini Shales constitute the base of most Liguride thrust sheets, and represent the stratigraphic link between all Upper Cretaceous-Lower Tertiary Internal and External Liguride successions, and the Middle-Upper Jurassic-Lower Cretaceous ophiolitic succession. During the early orogenic phases (Paleocene-Eocene), due to the rheology of highly pelitic deposits, the Palombini Shales played the role of decollement level between the ophiolites and the overlying pelagic-turbiditic succession.

*Ligurian-Emilian Apennines*

The External Ligurides of the Ligurian - Emilian Apennines are organised in two groups of tectonic units.

The first group includes the Casanova, Cassio, and Caio Units (Late Cretaceous to Early Paleocene) and encloses ophiolite debris and slide masses.

The second group comprises the Dosso, Sporno, and Luretta Units (Late Cretaceous-Middle Eocene), and do not contain any ophiolite debris. The second group units underthrust those of the first group from east to west during the Ligurian orogenic phase.

In particular, the successions of the first group consist of Santonian-Campanian mono- and polymict, coarse-grained sandstones, and mudstones (e.g., Casanova Complex) and Campanian-Lower Paleocene Helminthoid carbonatic turbidites (e.g., Caio Unit). The older, and paleogeographically more internal formations, enclose sedimentary mélange levels and isolated, huge, slide blocks ("olistoliths") of mantle ultramafics, basalts, minor gabbro and pelagic sediments. Gabbro-derived slide-blocks and quartz-feldspar granulites, granitoids, rare micaschists and gneisses also occur, generally closely associated with the mantle peridotites (Marroni et al. 1998, and bibl. therein). In the large slide-blocks, the primary relationships between different lithologies, in particular between granitoids, basalts and radiolarian cherts, are sometimes preserved (e.g., Pagani et al., 1972; Conti et al., 1988).

Southwards, the Helminthoid Flysch become prevalent but some olistoliths and olistostromes still sporadically occur (e.g. Casanova-Caio in Zignago, Treves, 1983; Treves and Andreani, 1984).

*The oceanic basement rocks*

The mantle rocks are represented by slabs of spinel peridotite with common pyroxenite bands considered of subcontinental origin (Beccaluva et al., 1984; Ottonello et al., 1984; Rampone et al., 1996; Piccardo 2003 and references therein), associated with slices of lower and upper continental crust. The peridotites were intruded by rare gabbro bodies and basalt dikes (Marroni et al., 1998).

Major and trace elements of whole-rocks and primary clinopyroxenes evidence a fertile chemical signature (Ottonello et al., 1984; Rampone et al., 1996; Piccardo et al., 2002).

Sm/Nd isochrons on plagioclase-clinopyroxene pairs (External Ligurides peridotite) gave ages of 164±20 Ma, interpreted as the time of the plagioclase facies re-equilibration (Rampone et al., 1995).

*The upper and lower continental crust rocks*

Pre-Jurassic continental mafic rocks (derived from tholeiitic gabbro protoliths), felsic granulites, granitoids with minor gneisses and micaschists, are closely associated with the mantle ultramafites either as slide-blocks or as clasts in breccias. Primary relations between granulitic and mantle lithologies are not observed, but are suggested by their strict association in the breccias (Marroni and Tribuzio, 1996; Montanini, 1997; Marroni et al., 1998),

Slide-blocks of Hercynian (about 300 Ma, Eberhardt et al., 1962), granitoids (two-mica leucogranites, biotite-bearing granodiorites and rare biotite-bearing tonalites to diorites) are frequently associated with mafic and felsic granulites (Montanini and Tribuzio, 2001), and also with serpentinites and basalts. The granitoids show brittle deformations (200° to 300°C, at a depth of 5-10 km; Molli, 1996; Marroni et al., 1998), and locally preserve primary stratigraphic contacts with radiolarian cherts and basalts (e.g. Pagani et al., 1972). These features allow recognising that the deformations predate the basalt effusion, and that they were exposed, probably on the Tethyan floor. The age of the radiolarian cherts constrains the deformations to be older than the Middle-Late Jurassic.

These continental rocks - peridotite associations are interpreted as remnants of a “Galician like” transition from continental and oceanic domains realised at the beginning of the Western Tethys opening (Marroni et al., 1998).

*The oceanic cover rocks*

The ultramafic rocks, as well as the granitoids were intruded by basaltic dikes with MOR affinity (see also Molli, 1996), and are directly covered by massive and pillowed MOR basalts. Lava flows and dikes are slightly less LREE-depleted than those of the Internal Ligurides and show intermediate geochemical features between normal- and transitional MOR-basalts (Venturelli et al., 1981; Ottonello et al., 1984; Vannucci et al., 1993; Marroni et al., 1998; Rampone et al., 1998). The igneous parageneses are often extensively affected by greenschist- to subgreenschist oceanic metamorphism, at least partly related to interaction with seawater-derived fluids (Rampone et al., 1998).

The basalts are stratigraphically overlain by Middle Jurassic radiolarian cherts in some blocks and, in general, also associated with blocks of Cretaceous pelagic sediments similar to the Calpionella Limestones and Palombini Shales. Radiolarian assemblages indicating a middle Bathonian to late Bathonian-early Callovian age (UAZ. 6-7) were found in a chert sample 6.50 m above pillow-lavas from Costa Scandella (Casanova Complex, Emilian Apennines; Fig. 2, n. 4) (Conti et al., 1988; Chiari et al., 2000).

The stratigraphic relationships between the Mt. Alpe Cherts and the cataclastic continental granitoids described by Molli (1996) suggest that the cherts were deposited also on some slices of continental crust rocks.

The association of ultramafites, granulites, granitoids, Jurassic basalts and sedimentary rocks, in the Cretaceous sedimentary mélanges and flysch of the External Ligurides, like in the Platta-Err Zone (e.g. Froitzheim and Eberli, 1990; Froitzheim and Manatschal, 1996; Manatschal and Nievergelt, 1997; Desmurs et al., 2001) and in the present-day Galician margin (Boillot et al., 1987; 1988; Whitmarsh et al., 2001) may testify an ocean-continent transition zone. This zone was close to the Adria continental margin, which originated from passive lithosphere stretching.

*Tuscany and Tuscan Apennines*

The External Ligurides sequences of Tuscany are tectonically organised into two groups: an Upper Cretaceous-Paleocene group (Monteverdi M.mo Fm., Principi and Treves, 1984) and a Paleocene-Middle Eocene group (St. Fiora-Mt. Morello Fms.), which underthrust the former from east to west. Both groups contain ophiolitic debris in the Helminthoid flysch and in the basal complexes. In the first group slide-blocks are present only in the western outcrops.

The emplacement age of the ophiolitic gravity flows is Campanian-Maastrichtian in the Helminthoid Flysch of the Monteverdi Marittimo Unit (Marino, 1988; Marino and Monechi, 1994), and Early-Middle Eocene in the Morello Unit (Bortolotti, 1962; Fig. 8).

These ophiolitic debris were deposited as gravity flows and huge slide-blocks. In the whole area, continental rocks

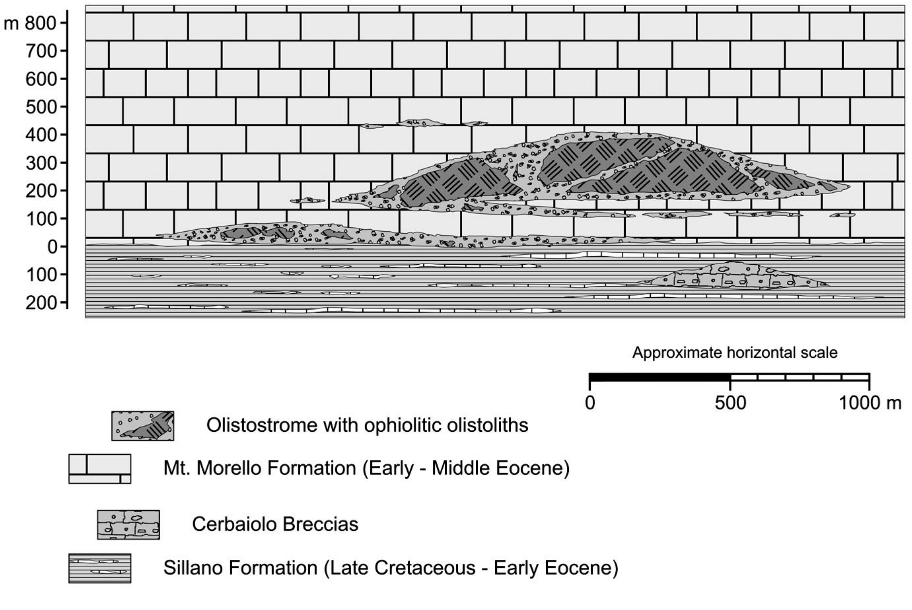

Fig. 8- Stratigraphic scheme of the Morello Unit succession in the Pieve Santo Stefano area, northeastern Tuscany (after Bortolotti, 1962).

are completely absent. Some blocks contain partially preserved ophiolite successions comprising fragments of the basement (serpentinites, often ophicalcitised: Monti Rognosi, Fig. 2, n. 14, 15; Impruneta, Fig. 2, n. 13, and rare gabbros) and of the covers: basalts, Mt. Alpe Cherts, Nisportino Fm., Calpionella Limestones, Palombini Shales. They are completely corresponding to the Vara succession covers described in previous chapters.

The cover successions are either complete (Figline di Prato, Fig. 2, n. 11; Sasso di Castro-Monte Beni, Fig. 2, n. 12; Gambassi, Fig. 2, n. 16) or lacking some formations (Impruneta, Fig. 2, n. 13; Monti Rognosi, Fig. 2, n. 14, 15), and generally very variable in thickness.

Ophiolitic breccias (ophicalcites or serpentinitic sedimentary breccias, at Pieve Santo Stefano; Fig. 8) and basalt blocks lie sometimes near the base of the Morello Unit succession, but often the basal contact is not well preserved.

Many successions include a chert level (Mt. Alpe Cherts) whose thickness varies from a few tens of metres (Monti Rognosi, Sasso di Castro, Figline di Prato) up to 50-60 metres (St. Martino-Gambassi).

The age of the base of the Mt. Alpe Cherts (Fig. 7) ranges from middle Callovian-early Oxfordian to middle-late Oxfordian (UAZ. 8-9) at Sasso di Castro (Chiari 1994b; Chiari et al., 2000), middle-late Oxfordian to late Oxfordian-early Kimmeridgian (UAZ. 9-10) at Conventino (Conti and Marcucci, 1986; Chiari et al., 2000) and Gambassi-San Martino (Ciscato, 1992; Chiari et al., 1995) to late Oxfordian-early Kimmeridgian (UAZ. 10) at Figline di Prato (Chiari 1994a; Chiari et al., 2000). The top of this formation provided a Tithonian age at Figline di Prato (Chiari 1994a**)**.

In some reduced succession (Monti Rognosi, Impruneta) the cherts directly lie on the basement (mainly serpentinites).

In the Gambassi area, on top of the cherts, the transitional Nisportino-Murlo formation is well exposed (40-50 m at St. Martino-Gambassi) and dated to the Berrasian-Valanginian (Ciscato, 1992).

Calpionella Limestones are usually widespread. Their age is generally attributed to the Berrasian - Valanginian. Also this formation has variable thickness. In many cases the succession is interrupted at this formation. In other ones it is truncated at the Palombini Shales level.

Stratigraphically associated to the Palombini Shales at the base of the External Ligurides Flysch (St. Fiora?), in some localities of the Southern Tuscany (Castiglioncello del Trinoro, Manciano, Murci, Bagnolo-Fiora Valley), alkaline olivine-basalts crop out (Passerini, 1964; De Benedetti, 1972; Gianelli and Passerini, 1974; Faraone et al, 1979; Marcucci and Passerini, 1980; 1982; Faraone and Stoppa, 1990; Brogi et al., 2001). Their radiometric age is referable to the base of the Late Cretaceous (K/Ar 110±5.5 Ma, Gianelli and Passerini, 1974). They are interpreted as due to a within-plate magmatism.

## THE CORSICA ISLAND

The so-called ‘Alpine Corsica’ includes several orogenic units overlying the Hercynian-Permian European basement (Fig. 9). These units mostly consist of Piedmont-Liguride successions (Schistes Lustrés-Balagne Units) and subordinately of continental margin successions (Corte Slices).

The ophiolitic successions are included in both the Upper (Inzecca) and Lower (Bastiese Castagniccia-Cape Corse) Schistes Lustrés Units. They have been affected by HP-LT metamorphism, but in some minor areas non- or very slightly metamorphosed successions crop out (Balagne-Nebbio, Pineto, Rio Magno areas).

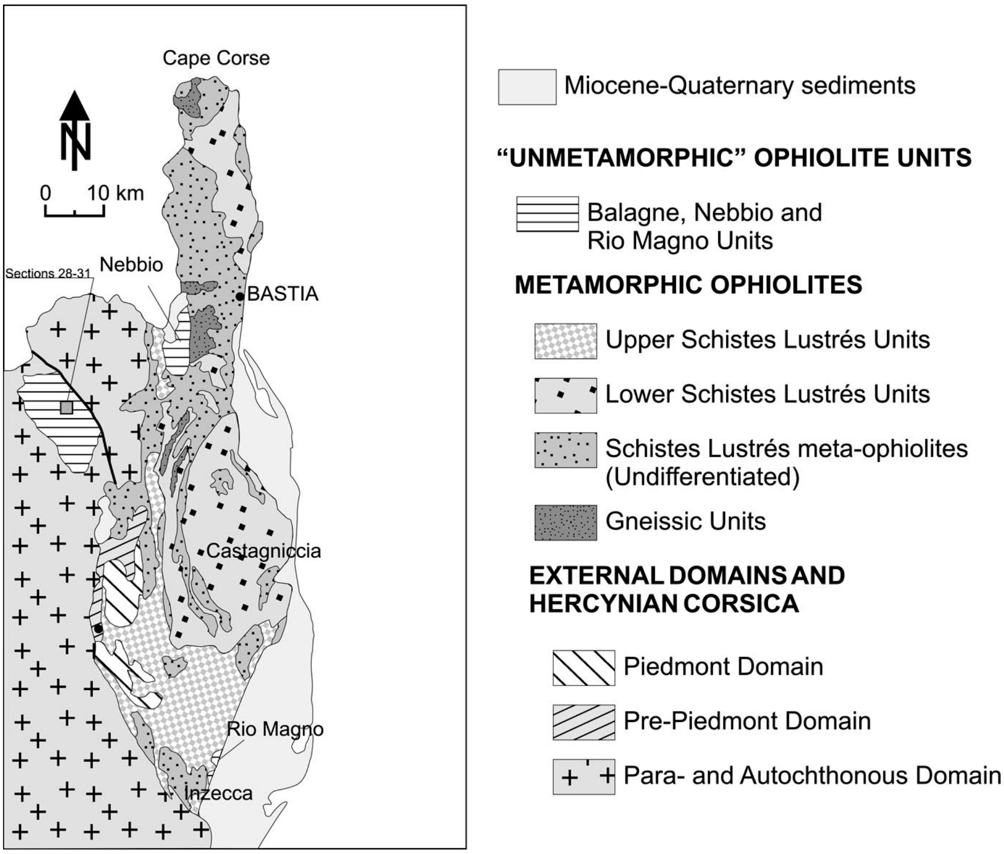

Fig. 9 - Alpine Corsica geological sketch.

### Bastiese - Castagniccia - Cape Corse

These successions pertain to the Lower Schistes Lustrés Unit (Durand Delga, 1984) and have been strongly deformed. They also suffered eclogitic or blueschist metamorphism retrograded to greenschist facies. Often, (e.g., Accendipipa eclogites, Golo Valley., Rossi et al., 2002) serpentinite-basalt-chert successions can still be recognised (Caron and Delcey, 1979; Durand Delga 1984; Lahondère and Lahondère, 1988; Rossi et al., 2002, with ref. therein). The basement is generally constituted by serpentinites and minor metagabbro. The covers consist of metabasalts which show a geochemical N-MOR signature (Saccani, 2003, and ref. therein), quartzites and, in places, marbles and metapelites (Schistes Lustrés). Thickness and ages are undefined.

### Balagne-Nebbio

A synthethic stratigraphic log of the Balagne-Nebbio "Liguride" succession can be reconstructed by adding the segments recognised in the different units and subunits (Nardi et al., 1978; Dallan and Puccinelli, 1995).

The stratigraphic log can be roughly subdivided into a Jurassic ophiolite sequence and its deep-sea sedimentary cover, including pelagic and deep-sea turbidite deposits.

The ophiolite sequence begins with a 500 m thick oceanic basement made up of serpentinised lherzolites, intruded by a gabbroic complex. This basement is covered by pillow basalts and pillows breccias (e.g., Gruppo di Lavoro sulle Ofioliti Mediterranee, 1977). Sills of massive basalt also occur. According to the Venturelli et al. (1979), Durand-Delga et al. (1997) and Saccani et al. (2000), the basalts have a T-MORB affinity, interpreted as indicative of basalts extruded during initial stages of oceanic spreading. In the Pineto and Rio Magno zone, instead, Liguride-type, non metamorphic basalts show N-MOR characteristics (Saccani et al., 2000; Saccani, 2003, and ref. therein).

Levels of terrigenous debris, made up of quartz and minor feldspar sandstones are found within the volcanic sequence (Durand-Delga et al., 1997; Rossi and Durand-Delga, 2001))

The ophiolites are overlain by radiolarian cherts.

Near Bocca di U Sorbello, along the railroad (Figs. 5 and 10, n. 28, 29), radiolarian assemblages gave a late Bathonian-early Callovian age (UAZ. 7; Conti et al., 1985; Chiari et al., 2000) and a latest Bajocian-early Bathonian to late Bathonian-early Callovian age (UAZ 5-7; De Wever et al., 1987b; De Wever and Danelian, 1995). At San Colombano

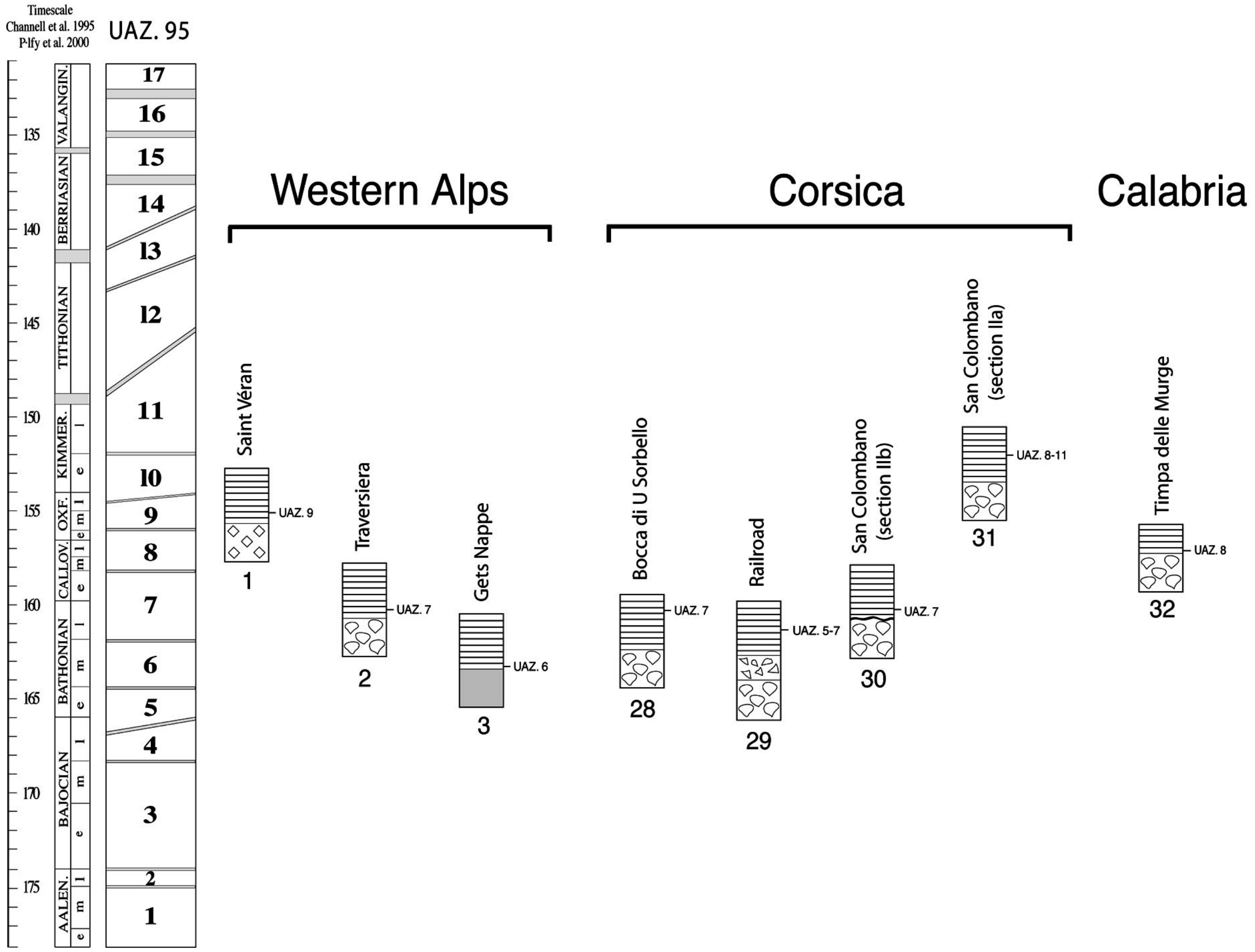

Fig. 10 - Radiolarian age determinations in the Western Alps, Corsica and Southern Apennines (with schematic stratigraphic sections). (UAZones from Baumgartner et al., 1995; time scale after Channel et al., 1995 and Pálfy et al., 2000). The location of the studied sections is reported in Fig. 5.
1- Saint Veran: De Wever and Caby (1981), De Wever and Baumgartner (1995); 2- Traversiera: De Wever et al. (1987a), De Wever and Baumgartner (1995); 3- Gets Nappe: Bill et al. (2001); 28- Bocca U Corbello: Conti et al. (1985), Chiari et al. (2000); 29- Railroad: De Wever et al. (1987b), De Wever and Danelian (1995); 30- San Colombano: De Wever and Danelian (1995); 31- San Colombano: De Wever and Danelian (1995); 32- Timpa delle Murge: Marcucci et al. (1987), Chiari et al. (2000). Symbols as in Fig. 6.

(Figs. 5 and 10, n. 30, 31) a late Bathonian-early Callovian age (UAZ. 7) was found in another outcrop (De Wever and Danelian, 1995).

Hence, the age of the underlying basalts is not younger than Bathonian-Callovian.

The cherts pass upwards to the Calpionella Limestones (?Tithonian-Berriasian) through a few metres of alternance. Like in the Northern Apennines, the Calpionella Limestones consist of turbiditic calcilutites and marls. Coarse-grained continental debris beds occur within the Calpionella Limestones in the San Colombano area. The formation grades upwards to the San Martino Fm. (Durand-Delga, 1977), consisting of up to 100 m of marlstones, shales and silicified calcilutites of early Berriasian-early Barremian age (Marroni et al., 2000). This formation can be correlated with the Palombini Shales of the Liguride Units of the Northern Apennines (Marroni et al., 2000). The age and some lithologies, however, are comparable to the “transitional” levels described in the Northern Apennines (Nisportino and Murlo Fms.).

The San Martino Fm. grades upwards to the Lydienne Flysch (early Barremian, Marroni et al., 2000; early Turonian, Marino et al., 1995), consisting of thin bedded, mixed turbidites. According to Nardi et al. (1978), the Lydienne Flysch, up to 300 m thick, is laterally and vertically heteropic with the Toccone Breccia and Novella Sandstones, as can be observed in the Toccone and Novella subunits. The 200 m thick Novella Sandstones (late Cenomanian-Turonian) are characterised by thick amalgamated beds of coarse-grained arenites and rudites. The Toccone Breccia, less than 200 m thick, is characterised by thick beds of ruditic debris of the same composition of the Novella Sandstones and Lydienne Flysch. According to Sagri et al. (1982), these formations represent a portion of a complex turbidite system fed during the Cretaceous by the Europe/Corsican continental margin.

The most impressive feature of the Balagne Nappe succession is the presence of terrigenous debris throughout the whole sequence, from the Jurassic basalts (Durand-Delga et al., 1997; Rossi and Durand-Delga, 2001) up to the Novella Sandstones (Sagri et al., 1982). The terrigenous debris have a mixed siliciclastic-carbonatic composition. The carbonatic debris consist mainly of Triassic to Jurassic extrabasinal rock fragments, whereas the siliciclastic ones are granitoids, low grade metamorphic rocks and acidic volcanic rocks. This mixed composition suggests a continental margin source, with its Mesozoic carbonate platforms. According to Durand-Delga et al. (1997) the source area can be identified in the western Corsica Hercynian basement and its Permian to Jurassic carbonate cover.

Nardi et al. (1978) consider the Balagne Nappe sequence topped by a coarse-grained siliciclastic deposit (Alturaia Arkose) of unknown origin. Recently, a palynological assemblage of early-middle Aptian age has been found in it by Marroni et al. (pers. comm.). According to these authors, the Alturaia Arkose can be regarded as a clastic deposit supplied by the Hercinyan rocks of Corsica. The early-middle Aptian age seems to indicate probable stratigraphic relationships between the Alturaia Arkose and the coeval Lydienne Flysch.

## Inzecca

The Inzecca Ophiolite Units crop out mainly in the median valley of the Fiumorbu and Tagnone Rivers, in the southern part of Alpine Corsica.

A new geological survey made by Padoa (1999) divides the metaophiolites and metasediments of this area into four main units: the Quinzena, the Pointe the Corbara, the Inzecca and the Punta Razzete Units. The successions, despite the metamorphic signature and deformations, preserve the primary stratigraphic and lithologic characteristics.

**The Quinzena Unit (QU)** only consists of brown-black quartzitic schists and black, recrystallised limestones of the Erbajolo Fm. (Amaudric du Chaffaut et al., 1972).

**The Pointe the Corbara Unit (PCU)** consists of reduced sequences (Fig. 11), where the basement, mainly serpentinitic and subordinately metagabbroic, is directly covered by ophicalcites, ophiolitic breccias and sandstones (few to several tens of metres thick) and few metres of cherts, followed by the Erbajolo Fm.

Peridotites and gabbros show both igneous and ocean floor tectonic contacts before the breccias deposition. The gabbros mainly consist of Fe-Ti-oxide gabbros locally affected by strong oceanic ductile deformations (flasering). The flaser fabric is cut by basalt dikes. The gabbroic basement (to the west, Pointe d’Ecilasca) is directly covered by ophiolitic sandstones and cherts; the serpentinitic basement (to the east, Pointe de Corbara) is ophicalcitised at the top; upwards, sedimentary ophicalcites and cherts alternate. The breccias locally become very thick, roughly sorted, and contain clasts and blocks of gabbro, peridotite, plagiogranite, Fe-Ti-oxide gabbros, dismembered basalt dikes and ophicalcites. The matrix is impregnated by haematite. These breccias form a lenticular level, from zero to about 200 m in thickness.

The overlying chert level is a few metres thick. The Erbajolo Fm. covers all.

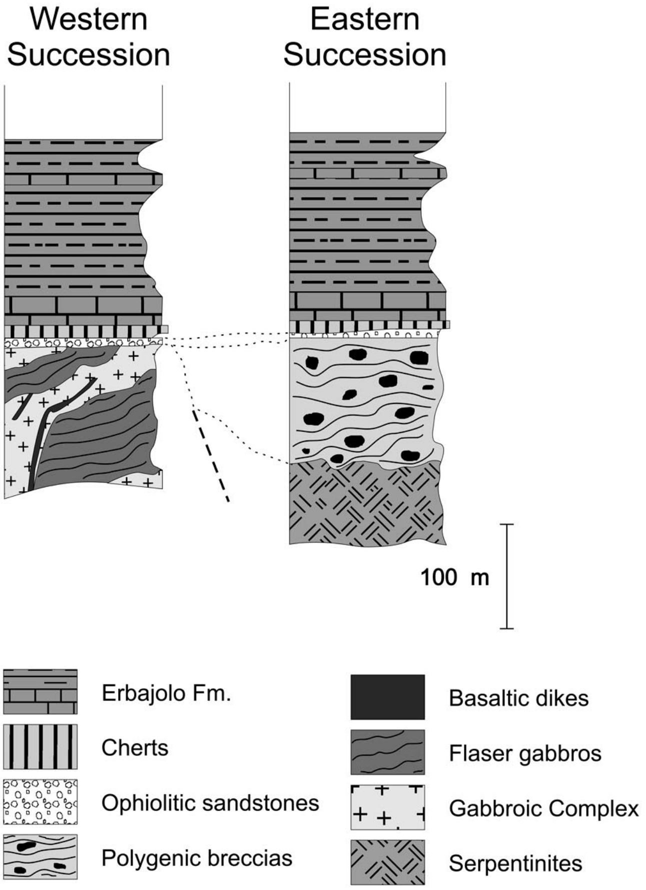

Fig. 11 - Columnar sections of the reduced successions of the Pointe de Corbara Unit (Inzecca zone, Corsica; after Padoa, 1999).

The metamorphism reached blueschist facies conditions (crossite/glaucophane + lawsonite + aegirine; Padoa 1997; 1999).

**The Inzecca Unit (IU)** has the more complete successions (Fig. 12). The basement consists of schistose serpentinite cut by rodingitised gabbroic dikes. At the beginning of the Inzecca Gorge (U Pinzalone), the top of the serpentinite is ophicalcitised and a thin sedimentary level marks the contact with the overlying basalts. Southwards (Lugo di Nazza) the ophicalcitic level is overlain and partially replaced by ophiolitic sandstones interlayered with red pelites.

Upwards, the ophicalcites and the ophiolitic sandstones and pelites are overlain by N-MOR metabasalts (Beccaluva et al., 1977; Venturelli et al., 1981; Saccani, 2003) similar to the Upper Schistes Lustrés (Saccani, 2003) and the Internal Ligurides basalts. They consist of metamorphosed pillow and massive basalts, pillow-breccias, ophiolitic sandstones, and red pelites, which alternate irregularly. The hyaloclastitic matrix is totally chloritised. The massive metabasalts (dolerites) are generally aphanitic, and constitute metric up to decametric levels intercalated within the pillow flows. Ophiolitic metasandstones and metapelagites occur both at the base and at the top of these levels. The pillow breccias have a chloritised glassy matrix.

On top of the basalts, well-stratified cherts (from few metres to ten metres), crop out. They consist of an irregular alternance of meta-radiolarites and slaty metapelites. They are often totally recrystallised. The primary characteristics are still preserved in some outcrops (St. Polo Lake, Agheri).

In the chert succession three facies can be recognised:

a- at the base, a few metres of meta-radiolarites and/or cherty-shales, with subordinate meta-argillites;
b- a few metres of a regular alternance of meta-radiolarites and meta-argillites;
c- at the top, an alternance of meta-siltites and meta-argillites, with silicic limestones in the upper portion.

The formation is attributed to the Middle-Late Jurassic.

At the top of the cherts the Erbajolo Formation (the Schistes Lustrés sensu stricto) consists of an irregular alternance of black quartzitic schists and recrystallised, boudinated calcarenites.

Caron et al., (1979) attribute an Early Cretaceous age to the Erbajolo formation.

The metamorphic assemblage (Mg-riebeckite + chlorite) indicates very low grade HP-LT conditions. The main schistosity is parallel to the axial planes of east-vergent kilometric structures (Padoa, 1999).

**The Punta Razzete Unit (PRU)**, consists only of gabbros and subordinate Fe-Ti-oxide gabbros, cut by basaltic dikes, which may be frequent locally. They are affected by HP-LT metamorphism (glaucophane/Fe-glaucophane/crossite; Padoa, 1999).

This unit crops out in the southern area of the Inzecca zone, south of the Fiumorbu River.

The ophiolites locally show well-preserved structures and parageneses, both magmatic and related to the oceanic metamorphism. The Jurassic (see 161±3 Ma ages from plagiogranites, Ohnestetter et al., 1981) evolution of this oceanic crust is very similar to that of the Vara ophiolitic Unit of the Northern Apennines. A first magmatic event (gabbro lenses and dikes intruding the peridotites) was followed by ductile deformation (flasering), associated to HT-LP oceanic metamorphism (brown hornblende, pyroxene, Ca-rich plagioclase). A second magmatic event (basalt dikes) followed by low-grade metamorphism (including serpentinisation of the peridotites and rodingitisation of the gabbro dikes) preceded a final event of ophicalcitisation. This latter event occured when the denudated serpentinitic-gabbroic oceanic basement was exposed at the ocean bottom on which ophiolitic debris (breccias and ophiolitic sandstones) and pelagites (cherts) were deposited. A third magmatic event produced the basalt flows, and was followed by a new oceanic metamorphic cycle (albite + epidote + sericite + chlorite + actinolite + calcite) which also affected the ophiolitic debris and the basalts.

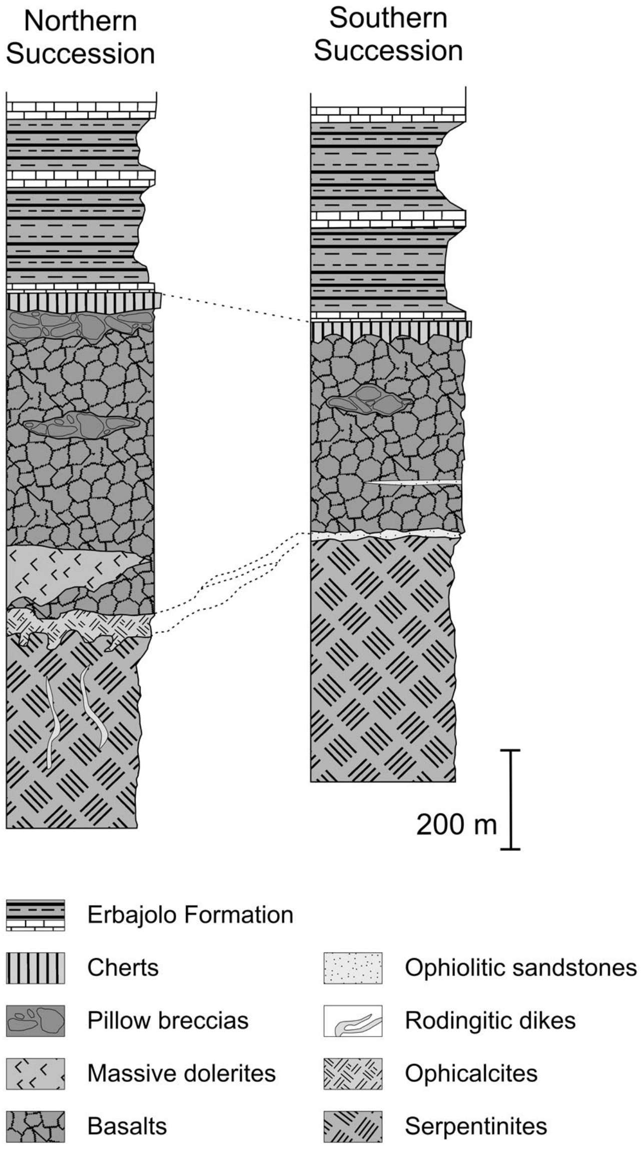

Fig. 12 - Columnar sections of the ophiolitic successions of the Inzecca Unit (Inzecca zone, Corsica; after Padoa, 1999).

Upper Jurassic cherts and Cretaceous shaly-siltitic-carbonatic pelagites covered this oceanic crust.

## SOME NOTES ON THE COVERS OF ALPINE, CALABRIAN AND BETIC CORDILLERA OPHIOLITES

### CENTRAL ALPS

In this area the ophiolitic units belong to the Platta, Arosa-Totalp, Malenco zones (Figs. 13, 14), and to Tasna

Nappe. The first group of ophiolitic units are sandwiched between the Middle Pennine (Briançonnais) units at the base, and the Err-Margna Australpine nappes, at the top (Bernoulli et al., 2001, with bibl. therein). The ophiolitic and the Austroalpine units suffered an Alpine metamorphism that increases southwards, from the deep burial diagenesis in the Arosa zone to the epidote-amphibolite facies in the Malenco area (Desmurs et al., 2001, with bibl. therein). The Platta, Arosa-Totalp, Malenco alignment is considered as pertaining to the South Penninic domain. At the contrary, the Tasna Nappe is generally considered part of the north Penninic Domain (Valais trough) (see Trumpy 1972; 1988; Schmid et al., 1990; Florineth and Froitzheim, 1994), but this paleogeographic attribution is poorly documented and, for us, still debatable. The possible belonging of the Tasna ophiolite succession to a "Valais Ocean" succession, and the scarce and poorly dated covers suggest us to not consider in this work these very interesting outcrops.

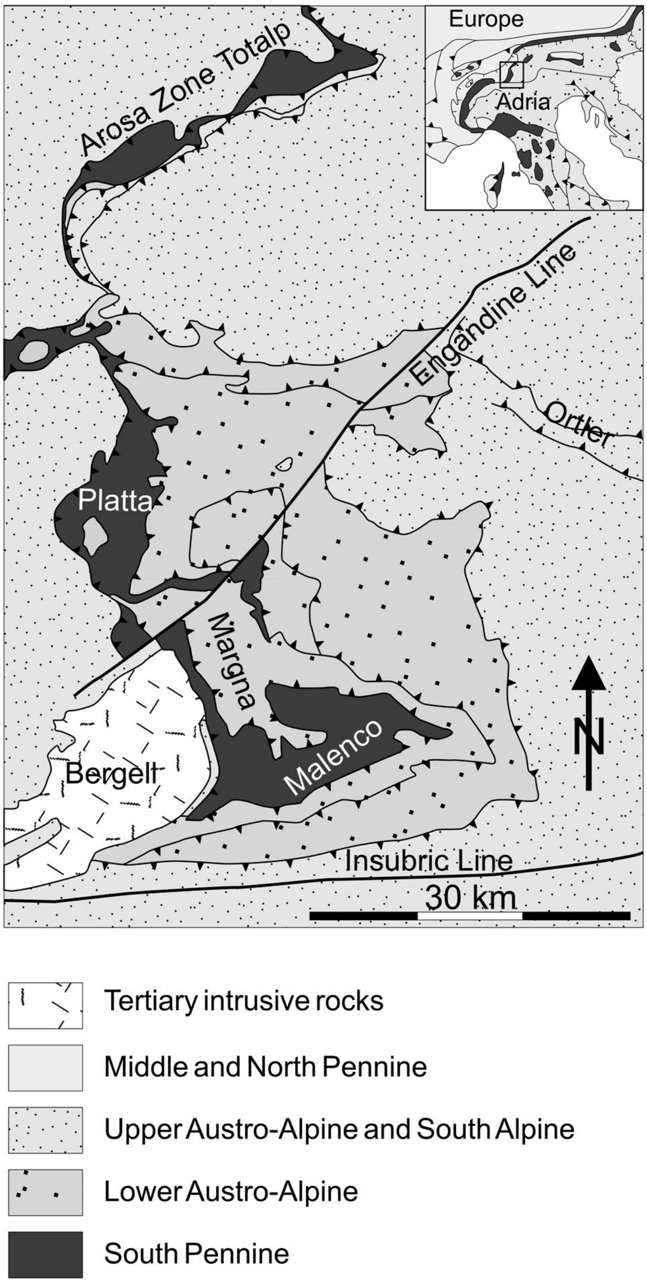

Fig. 13 - Structural Units of the Central Alps (redrawn after Bernoulli et al, 2001).

## The basement

The basement is transitional between continental and oceanic environment. In fact, in the western portion (Platta Unit) the basement is peridotitic, with slices (up to 100 m thick) of granitoids and gneisses considered as extensional allochthons in a "Galician like" continent-ocean transition; in the eastern portion (Err) the basement is continental (Desmurs et al., 2001, with bibl therein). A detachment fault mechanism for the mantle exhumation is also documented by a Jurassic pre-cover tectonic, metamorphic and metasomatic records (Manatschal and Muentener, 2003, with bibl. therein).

The Platta Nappe mantle rocks (mainly serpentinised lherzolites) constitute two thrust sheets: the Upper and Lower Serpentinite Units (Desmurs et al., 2001).

In the lower one the peridotites are moderately deformed. A retrograde pre-Alpine metamorphism, from high-(clinopyroxene-brown hornblende), to low-grade (tremolite-serpentine) to very low-grade (calcite-talc) grade (Desmurs et al., 2001) is still recognisable. In the serpentinised peridotite small gabbro bodies (161±1 Ma, U/Pb from zircons in gabbros and albitites, Shaltegger et al., 2002), intruded at shallow depth, and basalt dikes occur.

In the upper serpentinitic unit, the peridotites show a spinel foliation with parallel pyroxenite bands. Several mylonite (top-to-east) shear zones with high-degree neoblastesis (Al-diopside, orthopyroxene, olivine, spinel), in turn affected by a low-grade metamorphism (chlorite, serpentine, magnetite), cut the previous foliation (Desmurs et al., 2001).

A greenschist-facies imprint, linked to a top-to-west shear zone, affected the previous paragenesis. Basalt dikes cut finally all these structures.

The amount of basalts increases from the upper to the lower serpentinitic units.

## The covers

In the western portion (Platta) the basaltic-pelagitic cover rests on a peridotitic basement. In the eastern one (Err) it rests on a continental basement (Figs. 13, 14). The cover of the Upper Serpentinitic Unit is composed of polymictic breccias and a basalt flow (South of Bivio, Desmurs et al, 2002) followed by cherty and shaly-carbonatic pelagites (post-rift).

The slices (up to 100 m thick) of granitoids and gneiss overlying the serpentinites are covered by some metres of cataclasite and then by a thin level of shales (Desmurs et al., 2001).

In the Lower Serpentinitic Unit the cover begins with either ophicalcites or breccias, associated with a gabbroic body. They are overlain by basalts or (Arosa Zone, Fruh-Green et al., 1990) directly by cherts. The basalts are either massive or in pillows, and up to150 metres thick (Manatschal et al., 2003). Their chemistry ranges from T-MORB to N-MORB, related respectively to a depleted mantle source (asthenosphere) and to an enriched-mantle source (lithospheric subcontinental mantle) (Desmurs et al., 2002).

Desmurs et al. (2002) compared the T-MORB to those of the Gets Nappe (Western Alps, Bill et al., 2000), of the External Ligurides (Vannucci et al., 1993) and of the Balagne Nappe (Corsica, Venturelli et al., 1981), and the N-MORB to those of Mongenèvre (Western Alps, Venturelli et al., 1981), of the Internal Ligurides (Venturelli et al., 1981; Vannucci et al., 1993; Rampone et al., 1998), and of the

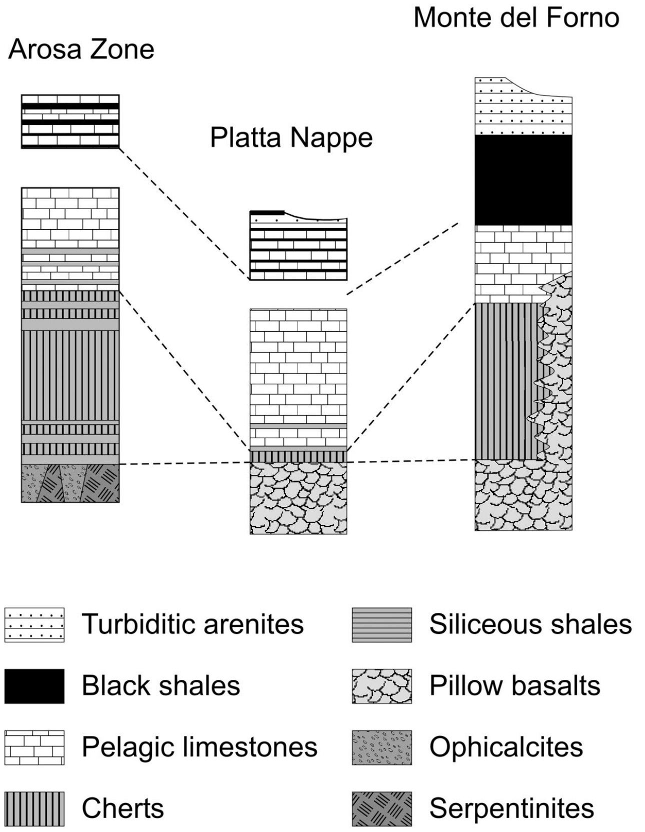

Fig. 14 - Ophiolitic successions of the Arosa and Platta Nappes and Malenco zone (Monte del Forno) (redrawn after Weissert and Bernoulli, 1985).

Inzecca Nappe (Venturelli et al., 1981). They conclude that the compositional variation represents the gradual transition from a near-sub-continental inception of oceanisation (like the Galicia Bank, Charpentier et al., 1998, with bibl. therein) to a more evolved slow spreading ridge (like the Central Atlantic, Karson and Lawrence, 1997).

The cherts, considered as post-rift pelagites, overlie both the basalts and the peridotitic and gabbroic basement. They range in thickness from 0 to more than 20 metres (Fruh-Green et al., 1990).

The cherts (?Middle - Late Jurassic) are overlain by micritic (Apticus) limestones (correlatable to the Calpionella Limestones of the Northern Apennines). An alternance of siliceous shales, calcarenites and dark micritic limestones (like the Palombini Shales), follows. The top of the succession consists of Aptian-Cenomanian (Dietrich, 1970) marls with interbedded turbiditic sandstones, lithologically similar to the Val Lavagna Fm. of the Northern Apennines (Weissert and Bernoulli, 1985). The Cherts, Apticus limestones, and shales have several intercalations of breccias with ophiolitic, felsic and pre-rifting sedimentary clasts that document the vicinity of the passive margin during a long depositional history (Manatschal and Nievergelt, 1997).

## WESTERN ALPS

The ophiolitic sequences of the Western Alps (Fig. 15) are metamorphic and belong to the oceanic Piedmont (Schistes Lustrés) Nappe system. This system consists of some transposed units among which two main groups can be distinguished (Dal Piaz, 1965; Elter, 1971; Dal Piaz and Ernst, 1978; Kienast, 1983; Lagabrielle, 1994, with bibl. therein):

a-A westernmost group (Combin, Queyras) pinched, in the Combin zone, between the overlying Australpine System and the underlying Adria and European continental margins (Dal Piaz, 1999). Southwards, this group is metamorphosed under the blueschists-greenschists facies.

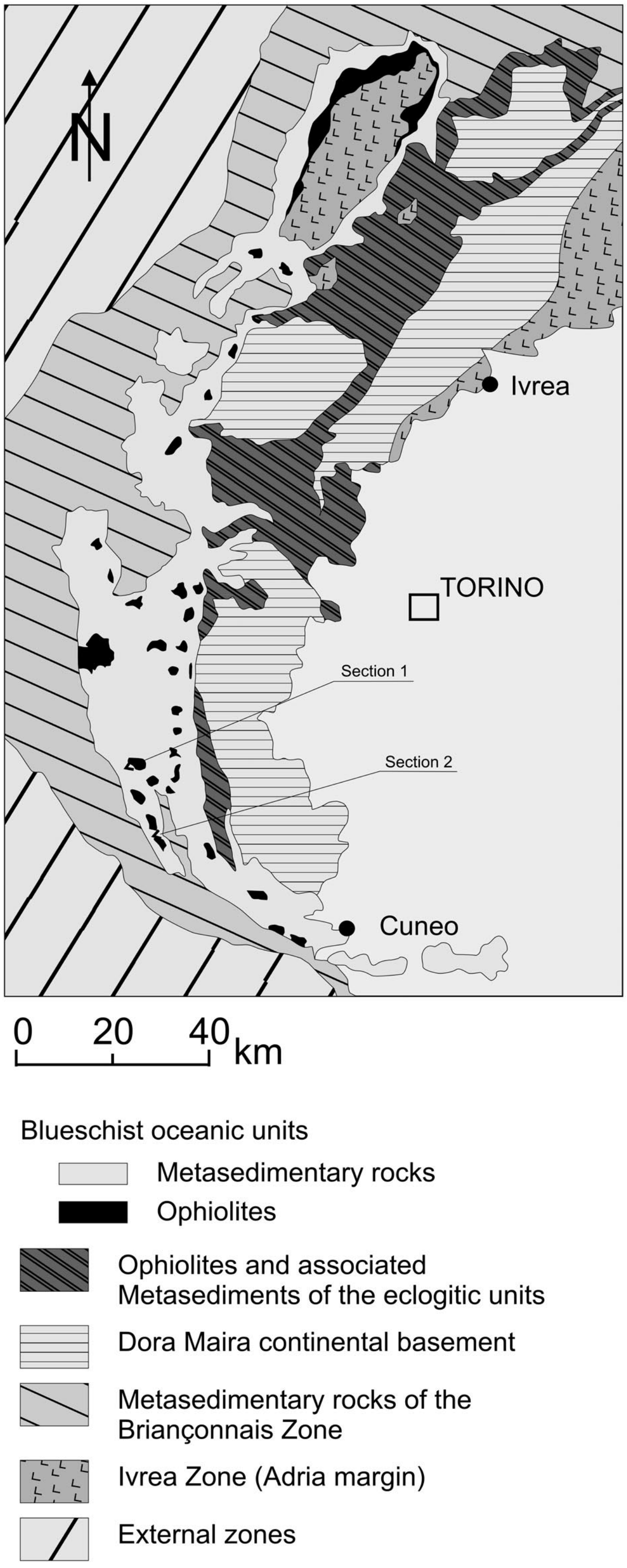

Fig. 15 - Western Alps geological sketch map with ophiolites distribution (redrawn after Lagabrielle, 1994). Section 1 (Saint Veran) and 2 (Traversiera), the location of dated radiolarite samples.

b- An easternmost group (Viso, Rocciavrè-Lanzo, Zermatt-Saas) pinched between the overlying Australpine System and the underlying Pennine units in a backthrust system. The metamorphic evolution ranges from eclogite-blueschist to greenschist facies.

Many authors documented the presence of metamorphic covers on top of the meta-ophiolites in the Western Alps (Dal Piaz et al., 1979; Lemoine, 1980; Lagabrielle et al., 1984; Polino, 1984; Lagabrielle and Polino, 1985; 1989; Martin and Tartarotti, 1989; Lagabrielle, 1994; Burroni et al., 2003).

Despite the metamorphic overprint, the stratigraphic succession and the sedimentary features are usually recognisable in all the covers (Dietrich, 1980; Lagabrielle et al., 1984; Lagabrielle, 1994). Ophiolitic breccias (also metaophicalcites), basalts (metabasites), cherts (quartzites), limestones (marbles), shales (schistes), and terrigeneous metasediments occur.

Ophiolitic olistoliths occur in the Late Cretaceous-Early Tertiary of the Penninic and Australpine flysch successions (Dietrich, 1980).

We will describe only the successions on top of the Mongenèvre-Chabrière, Queyras and Col de Gets ophiolites, which are the more representative of the dated ophiolitic covers.

## Montgenèvre-Chabrière

The "Chabrière series" (Fig. 16a), belonging to the Lago Nero Unit, is the best studied ophiolitic succession of the Western Alps (Lemoine et al., 1970; Bertrand et al., 1982; 1984; Burroni et al., 2003).

The ophiolite consists of meta-serpentinites (from a lherzolitic protolith) cut by rodingitised gabbroic dikes (Bertrand et al., 1982; 1984). At their top, a few metres of meta-ophicalcites occur. The meta-ophicalcites include two end-members: a meta-serpentinite cut by a net of carbonatic veins (type 1 ophicalcite of Barféty et al., 1995), and a meta-breccia where serpentinitic clasts are embedded in a calcareous matrix (type 2 ophicalcite of Barféty et al., 1995).

A polymict meta-breccia, consisting of clasts derived from both continental and oceanic source areas, crops out at the top of the meta-ophicalcites. The lithic fragments consist of granitoids sometimes biotite-bearing (Polino and Lemoine, 1984); subordinate basalts, were also found. At the top of the polymict meta-breccia, or of the meta-ophicalcite, a very thin level of meta-basalts, still showing pillow-lava and pillow-breccia textures is exposed.

The metabasalt and/or the meta-ophicalcite are topped by the Radiolarite Fm. consisting of a few metres of meta-chert alternating with very thin layers of schists. The Radiolarite Fm. is assigned to the late Oxfordian - early Kimmeridgian by radiolarian assemblages (Schaaff et al., 1985 and bibl. therein). A well-exposed transition from the basalts to the Radiolarite Fm. can be observed at Mt. Cruzore (Polino, 1984): the reconstructed sequence includes pillow meta-basalt followed by a few metres of a meta-breccia, consisting of pillow-lava fragments, and the Radiolarite Fm., which bears thin intercalations of ophiolitic debris at the base.

The Radiolarite Fm. is topped by the Meta-limestone Fm., consisting of an alternance of thick cherty meta-limestone beds with thin schist layers. In the lower part of the Fm., meta-chert layers are quite common. In some areas, the meta-limestones directly overlie the ophiolitic basement, without the Radiolarite Fm.

The Meta-limestone Fm. shows a gradual transition to the Replatte Fm., which consists of an alternance of thick schist layers and thin meta-limestone beds.

This sedimentary succession has been correlated, since long time, with the Mt. Alpe Cherts (Bathonian-Tithonian),

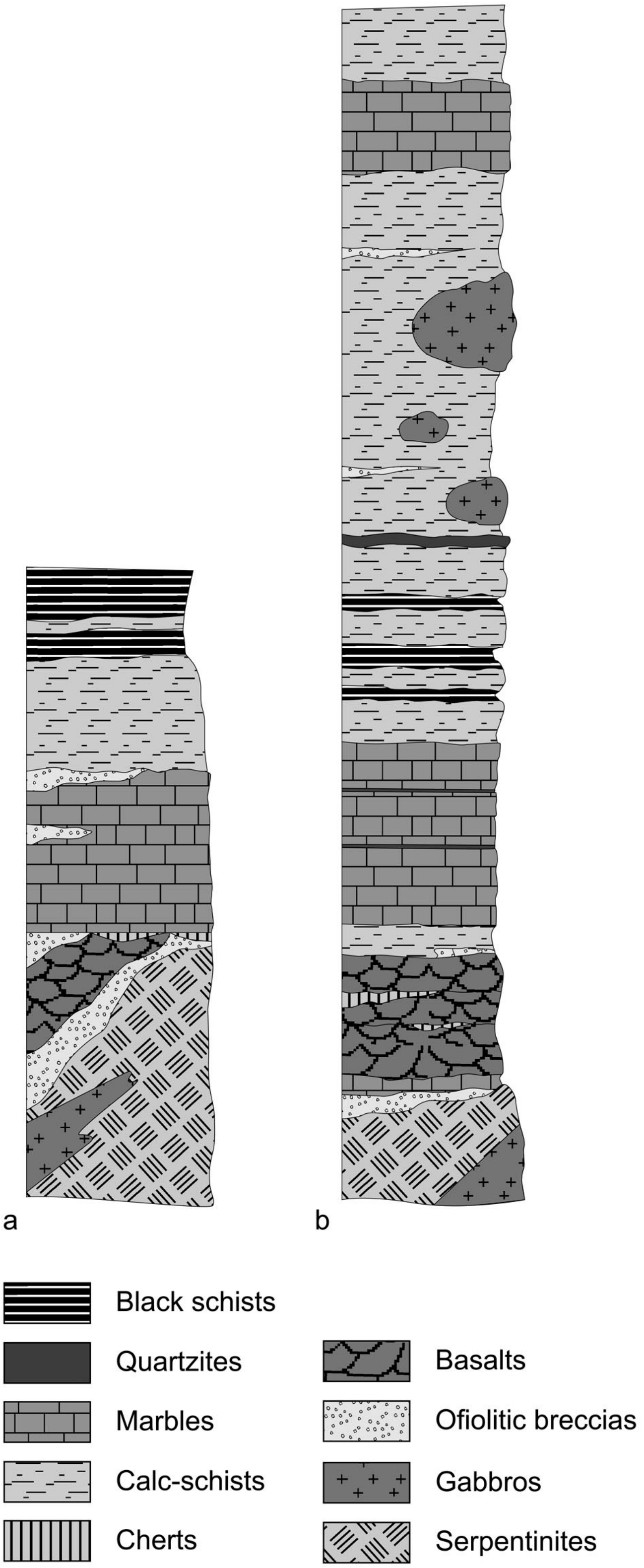

Fig. 16 - a: Columnar section of the ophiolite succession in the Chabrière sequence. Modified after Lemoine (1970, in Lagabrielle, 1994). b: Columnar section of the La Taillante sequence (after Lagabrielle, 1994).

Calpionella Limestones (Berriasian-Valanginian) and Palombini Shales (Valanginian-Santonian), the typical sedimentary cover of the Jurassic ophiolites of the Internal Liguride Units of the Northern Apennines (Polino, 1984; Lemoine and Tricart, 1986).

The Replatte Fm. is followed upsection by the Gondran Flysch, which is made up of an alternance of calcschists and meta-sandstones. The Gondran Flysch consists of thin-bedded turbidites with minor thick and coarse-grained terrigenous meta-sandstones (arkoses with quartz, feldspars and minor lithics). The rock fragments mainly derive from granitoids and carbonatic rocks (sometimes oolitic-grainstones coming from of a carbonate shelf); low-grade metamorphic and acidic volcanic rock fragments are also recognised. The presence of veins inside the fragment, pore-filling cement and angular shape indicate their non-coeval and extrabasinal origin probably from a Triassic-Jurassic carbonatic platform. Even if no fossil has been found, the Gondran Flysch is generally referred to a Late Cretaceous age (Polino and Lemoine, 1984; Barfety et al., 1995).

A sedimentary complex, hereafter referred to as Rocher Renard complex, occurs associated with these formations. This complex has been partially mapped in “Black Shale Fm.” (Barfety et al., 1995) and also described as “dissociated facies” of the Replatte Fm. by Lemoine and Tricart (1986). The glacial deposits prevent to determine its stratigraphic relationships with the formations of the Lago Nero Unit. The Rocher Renard complex is mainly constituted of homogeneous dark schists, which locally include several blocks derived from an ophiolitic sequence and a related sedimentary cover similar to that of the Lago Nero Unit. The ophiolitic blocks are mainly metabasalts, metaophicalcites and minor metaserpentinites, and metagabbros. The stratigraphic relationships between meta-ophicalcites and meta-basalts are still preserved in a decametric block, in the lower part of the outcrop. The blocks derived from the sedimentary cover are mainly meta-limestones, probably derived from the Replatte and the Meta-limestone Fms. A small block of meta-cherts has been also observed. Blocks derived from continental crust are missing at all. No data about the age are available.

### Queyras

In the Queyras area, the metamorphic ophiolites of the Piedmont Zone crop out extensively, and some of them show sedimentary covers (Lagabrielle, 1994, and bibl. therein). A common feature of these covers is the presence of ophiolitic sedimentary breccias of Jurassic age, lying on both ultramafics, meta-gabbros and meta-basalts. In particular, along the La Taillante Creek, a representative sequence crop out (Fig. 16b). The serpentinite and gabbro body is covered by ophiolitic breccias, topped by basalts. Radiolarian cherts constitute thin intercalations and the top of the basalts. Upwards, a marble formation include levels of ophiolitic debris. This formation grades to a thick sequence of black schists and calcschists including ophiolitic olistoliths and breccias. No significant microfaunas were found, but nearby, at Saint Veran (Fig.10, n. 1 and Fig. 15, Section 1), middle-late Oxfordian age (UAZ 9), and at Traversiera (Fig. 10, n. 2 and Fig. 15, Section 2) late Bathonian-early Callovian (UAZ 7) ages were found in the radiolarian cherts (De Wever and Baumgartner, 1995, and bibl. therein).

### Col de Gets

Northwards, in the Prealps, in the Gets Nappe, the northernmost ophiolite-bearing sequence of the Alpine orogen crop out. Here, in the wildflysch (= mélange) at the base of the nappe, fragments of ophiolites (serpentinites, gabbros, basalts) and of their cover (radiolarites, pelagic limestones and shales) are present. In a chert block associated with the ophiolitic rocks, a radiolarian assemblage yielded a middle Bathonian age (UAZ. 6, Bill et al., 2001) (Fig. 10, n. 3). A gabbro sample gave a radiometric age (U-Pb) of 166±1 Ma and an amphibolite ($^{39}Ar/^{40}Ar$) 165±2.2 Ma (Bill et al., 2001).

The ophiolite covers just described have been correlated with the very low-grade metamorphic and non metamorphic covers of the Northern Apennines: Ophiolitic breccias, Mt. Alpe Cherts, Calpionella Limestones and Palombini Shales (see before).

## LIGURIAN ALPS AND SESTRI-VOLTAGGIO ZONE

The Sestri-Voltaggio Zone is a narrow N-S trending complex polyphase positive tectonic flower structure, that includes platform and ophiolitic units, presently verging both westwards and eastwards. It separates the Internal Ligurides to the southeast, from the high-pressure metamorphic Alpine ophiolite units of Voltri Group (Ligurian Alps) to the northwest.

In the Sestri-Voltaggio Zone two main ophiolitic units occur: the Cravasco-Voltaggio Unit and the Mt. Figogna Unit.

In the Voltri Group, the volcano-sedimentary sequences, found in Palmaro-Caffarella and Beigua-Ponzema Units are generally detached from the basement, and rarely preserve the inner stratigraphy. However, in the Palmaro-Caffarella Unit and, locally, in the Beigua-Ponzema Unit (Chiesa et al., 1975), the basement - cover succession can be restored.

The Voltri Group is overthrust by an ophiolitic unit (Montenotte Unit) folded with a Middle Triassic - Liassic platform succession (St. Pietro ai Monti Unit). The lithology, stratigraphy and metamorphic evolution of the Montenotte ophiolites are at all comparable with those of the Cravasco - Voltaggio Unit.

### Figogna Unit

In the Figogna Unit (Fig. 17) the serpentinites (chrysotile serpentinite), with harzburgite and lherzolite relicts, are ophicalcitised at the top. In places, the cover begins with meta-breccias and/or meta-sediments. The meta-basalts (pillow lavas, pillow breccias and hyaloclastites) are discontinous (0 to > 100 metres thick). They are often cut by porphyritic basalt dikes. The metamorphic overprint is under pumpellyite-actinolite facies with localised lawsonite (Cortesogno and Haccard, 1984). The meta-cherts, laterally grading to siliceous pelites, are very thin (up to few metres) or absent, and are followed by discontinuous, well stratified, sometimes detrital (with quartz and mica fragments) meta-limestones, that can be assimilated to the Calpionella Limestones. This formation is covered by phyllitic shales with subordinate detrital meta-limestones, siltstones and fine sandstones, comparable to the Palombini Shales (Cortesogno and Haccard, 1984).

The succession continues with a level of shales with siltstone and fine sandstone intercalations (Mignanego Shales Auct.) that upwards evolves in a facies rich of calcareous-marlstones and detritic limestones (Montanesi Shales and Ronco Fm., Busalla Flysch Auct.). In the Busalla Flysch a reworked middle-upper Albian ammonoid fauna is found (Haccard and Thieuloy, 1973), suggesting a Cretaceous age. The Flysches strongly resemble those of the Val Lavagna Shales Fm. of the Northern Apennines (Cortesogno and Haccard, 1984).

### Cravasco-Voltaggio and Montenotte Units

The Cravasco-Voltaggio U. (Fig. 17) is the westernmost west-vergent unit of the Sestri Voltaggio Zone, affected by latest west-vergent folds, the Montenotte U. is the uppermost, unit of the Voltri Massif, affected by post-Oligocene back-thrusting to the E-N-E. The Alpine overprint is characterised by blueschist assemblages (Na-amphibole + albite + chlorite + pumpellyite ± Na-Ca clinopyroxene ± lawsonite ± epidote ).

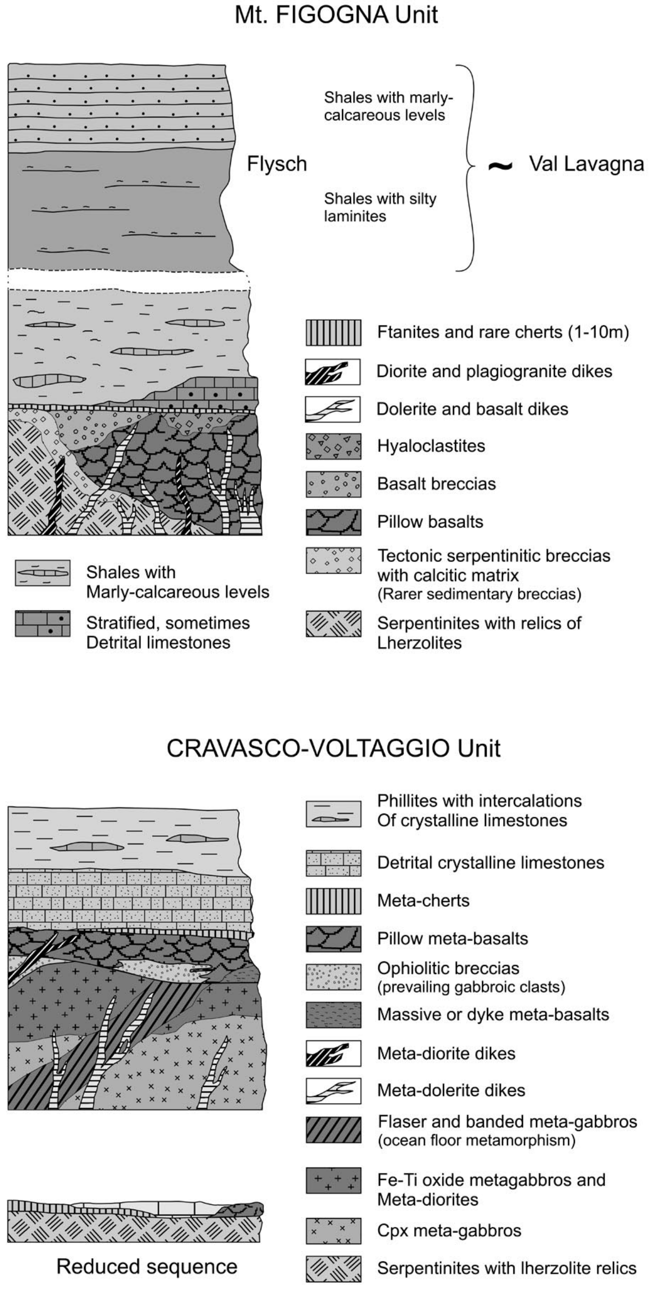

Fig. 17 - Synthetic columnar sections from the ophiolitic successions of the Figogna and Cravasco-Voltaggio Units (Sestri-Voltaggio Zone). Redrawn from Cortesogno and Haccard (1984).

In the complete successions, the basement is mainly composed of meta-gabbros, meta-Fe-Ti-oxide gabbros and minor meta-diorites (U/Pb on zircon: 156±1 Ma; Borsi et al., 1996). In the Cravasco - Voltaggio Unit, also a reduced succession is recognised, characterised by an ophicalcitised serpentinite (chrysotile and subordinate antigorite serpentinite) basement. The meta-gabbros preserve also the high-grade ocean floor metamorphic parageneses and deformations cut by diorite dikes. Meta-breccias, mainly consisting of gabbroic and basaltic reworked clasts are covered by massive and pillow basalts, and locally cut by MORB-type dolerite (Bortolotti et al., 1976), diorite and plagiogranite dikes (U/Pb on zircon: 153±1 Ma; Borsi et al., 1996). Siliceous meta-sediments (meta-cherts) follow with discontinous thickness (up to 10 m). Quartz-micaceous detrital crystalline limestones, zero to a few tens metres thick, overlie the cherts, and are compared with the Calpionella Limestones. The succession ends with phyllites and limestone beds (Palombini Shales).

### Voltri Group

In the Palmaro - Caffarella Unit, affected by blueschist facies metamorphism ((Na-amphibole + Na clinopyroxene / Na-Ca clinopyroxene ± Lawsonite ± Epidote ) and minor greenschist overprint, a relatively well preserved ophiolitic succession starts with serpentinites (antigorite serpentinite) intruded by gabbroic rocks (Cpx- and Fe-Ti oxide gabbros). The gabbros locally developed flaser textures under HT-LP ocean floor conditions, cut by diorite, plagiogranite (U/Pb on zircon: 150±1 Ma; Borsi et al., 1996) and dolerite dikes.

Discontinuous meta-breccias (with prevailing gabbro clasts) and meta-basalts cover the basement, in turn followed by quartzschists (meta-cherts), locally with Mn-rich levels and calcschists (Chiesa et al., 1976).

In the Beigua-Ponzema Unit, affected by eclogite-bearing blueschist facies (Omphacite+Garnet + Na-amphibole + Rutile ± Ti-magnetite ± (Clino)zoisite ± Talc) metamorphic peak, and by later evolution up to greenschist facies conditions, the relationships between basement and cover are only rarely recognisable. Two reduced successions are described overlying a gabbroic or gabbro/serpentineschist basement (Fig. 18); in this case, marbles with femic and ultrafemic clasts are widespread, likey derived from ophiolitc breccias in abundant carbonatic matrix, similar to those rarely found in the Internal Ligurides of Eastern Liguria).

## SOUTHERN ITALY (CALABRIA)

In Southern Italy, ophiolitic units crop out in the Liguride Complex of Calabria and of the Calabrian-Lucanian Apennines, which suffered different tectonic evolution in the “Apenninic Chain” and in the “Calabrian Arc”.

In the Apenninic Chain the ophiolites are present at the base of the Calabrian-Lucanian Flysch Unit and in the Frido Unit (Amodio Morelli,et al., 1976), which tectonically overlies both the preceding one and the platform Carbonatic Units.

In the Calabrian Arc the ophiolites belong to the Lower and the overlying Upper Ophiolitic Unit (Piluso, 1997, and bibl. therein)

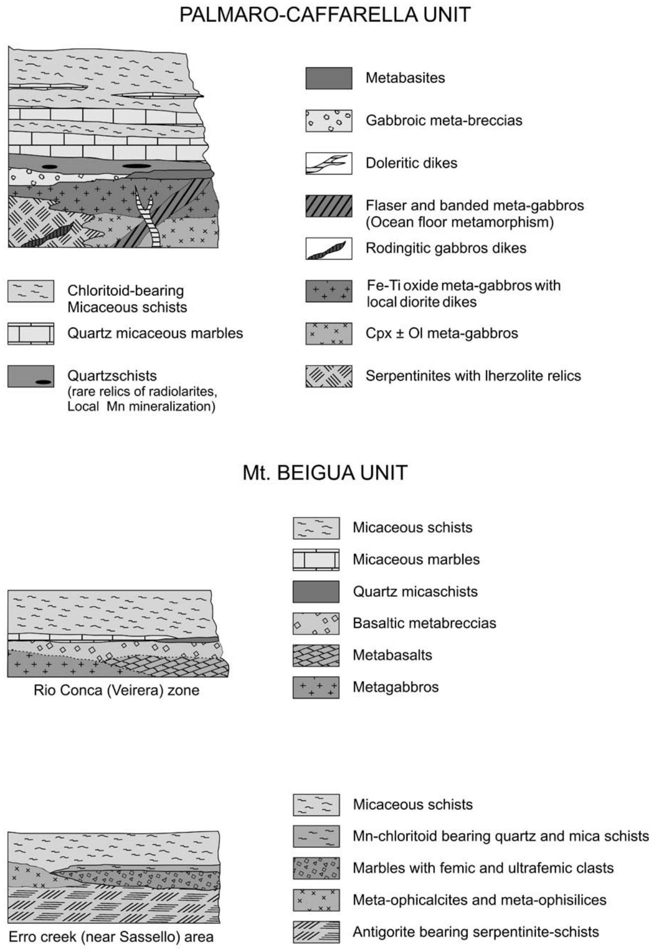

Fig. 18 - Schematic columnar sections of the ophiolitic successions of the Palmaro-Caffarella and Mt. Beigua Units (Voltri Group-Ligurian Alps).

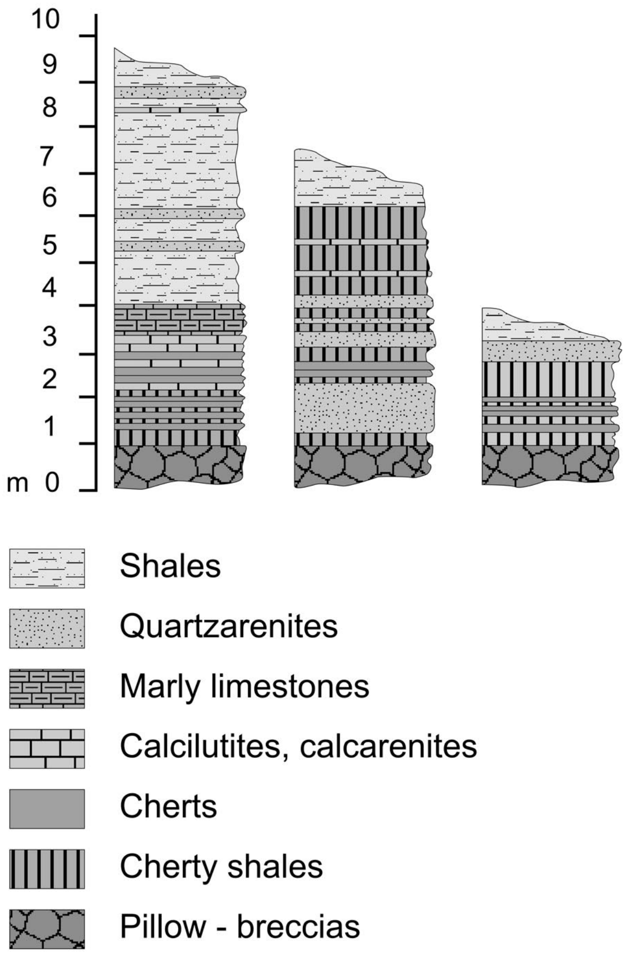

Fig. 19 - Columnar sections of the Timpa delle Murge ophiolitic succession (after Marcucci et al., 1987).

### Apenninic Chain

The **Calabro-Lucanian Flysch Unit**. This Unit consists of a non-metamorphic and strongly disrupted complex made of a pelitic-calcareous-arenaceous sequence, which encloses blocks and slivers of different lithologies: black shales, siliceous limestones, volcanoclastics and ophiolites (serpentinites, gabbros and basalts) wich preserve in places their sedimentary cover.

The most representative sedimentary cover, is exposed at Timpa delle Murge on top of a pillow breccia (Lanzafame et al., 1978; Marcucci et al., 1987). The Timpa delle Murge succession consists of a basal level of shales and cherts with radiolarian assemblages of middle Callovian-early Oxfordian age (UAZ 8; Marcucci et al, 1987; Chiari et al., 2000), covered by varicoloured shales with quartz-arenite interbeds (Figs. 10, 19).

The **Frido Unit.** It consists of a succession with polymetamorphic rocks, subdivided into two subunits. The lower one consists of meta-shales with arenite and siltite interbeds, and the upper one of calcschists. The Frido Unit includes blocks of different lithologies: granofels, amphibolites, serpentinites, meta-basalts and calcschists (Spadea, 1982). The most representative meta-sedimentary cover, exposed at Mt. Tumbarino (Lanzafame et al., 1979), lies on top of a pillow breccia. It consists of an irregular alternance of aragonite-bearing low-grade metamorphosed, siliceous limestones, calcareous rudites with clasts of quartz and phyllites, cherts and pelites. No fossils have been found.

### Calabrian Arc

The **Lower Ophiolitic Unit.** It consists of meta-basalts and meta-hyaloclastites, with a cover mainly consisting of calcschists.

The **Upper Ophiolitic Unit.** It includes pillow meta-basalts, hyaloclastites and a sedimentary cover constituted by a basal level of siliceous slates, meta-radiolarites and cherty meta-limestones grading upwards to meta-limestones which sometimes show a relict detrital structure (Spadea et al., 1980). The meta-limestones yielded a Tithonian-Neocomian microfauna (Lanzafane and Zuffa, 1976).

## BETIC CORDILLERA

In the Betic Cordillera (Fig. 20), the ophiolites constitute an ocean-derived tectonic unit sited between two continent-derived tectonic units: the Caldera and the Sabinas, all pertaining to the Mulhacen nappes. The Mulhacen nappes, tectonically lay on the Veleta nappes, which are the lowermost tectonic units of the Internal Betic Zone. The Ophiolite Unit as the other Mulhacen units, suffered high-pressure eclogite facies metamorphism during the early Alpine tectono-metamorphic phases (Puga et al., 1993; 2002, and bibl. therein). Remnants of an ocean-floor metamorphism can be recognised in the ophiolite unit.

The ophiolite comprises basal serpentinised ultramafites, harzburgites and dunite lenses, cut by meta-rodingite dikes.

Thin levels of ophicarbonates occur at the top.

The ophiolitic magmatic sequence conprises a plutonic and a volcanic section. The first one consists of troctolites and gabbros, cut by basalt dikes. The second one consists of basalts, sometimes pillow lavas, cut by basalt dikes. All these rocks are transformed into eclogites and/or amphibolites.

The sedimentary cover, is made up of garnet calc-schists with marble intercalations, and quartzites probably derived from radiolarian cherts. Garnet micaschists are also present

It is noteworty that the base of the overlying Salinas Unit, contains conglomeratic marbles with pebbles of the upper portion of the underlying Ophiolite Unit.

Radiometric Ar/Ar datings gave a 213±2.5 Ma (Triassic-Jurassic boundary) for a meta-gabbro, and 158±4.5 Ma (Middle Jurassic) for an ocean floor metamorphism brown amphibole vein in a meta-basalt (Puga et al., 1991; 1995). Remnants of Albian-Turonian foraminifers are also found in the calcschists from the ophiolite sedimentary cover.

## DISCUSSION AND CONCLUSIONS

### The basement history

A remarkable common character of all the Western Tethys ophiolite successions is that the volcano-sedimentary covers were deposited above a denudated and more or less ophicalcitised mantle carapace, locally intruded by gabbroic bodies.

Based on igneous, metamorphic and sedimentary features recorded in the Western Tethys ophiolitic successions (chiefly in the Alps - Apennines system), the following generalised history can be inferred:

In a first stage, a fertile mantle lherzolite uplifted changing its metamorphic paragenesis from spinel to plagioclase facies and probably suffered a very limited partial melting (Trias?). Successively (Early-Middle Jurassic), during the resumation and the denudation ("Galicia like" stage?), was intruded by igneous vents from deeper sources that produced, in a first stage, only intrusive bodies and veins and, in a second stage, a more wide magmatic MOR production, intrusive in the lherzolites (Piccardo e Muentener, 2004, cum bibl.). The composition of fractionation products includes a whole sequence from melatroctolites and rare peridotites, troctolites, gabbros.

A metamorphic event developed in ocean floor conditions is widespread and characterised by ductile deformation (flasering) under high temperature to amphibolite facies (750°-600°C). Subsequent deformative events are characterised by the transition to brittle regime, developed under amphibolite (hornblende+oligoclase ± clinozoisite) up to greenschist facies conditions.

Basaltic dikes cut peridotites and gabbros after the ductile deformation event. In the Bracco area (Northern Apennines) the contemporaneous intrusion of basaltic dikes in hornblende + oligoclase fractures has been recorded.

Hydrothermal metamorphic conditions, characterised by significant seawater - rock interaction mainly developed associated with fractures, and ruled the ophicalcitisation processes in the serpentinised ultrafemic rocks exposed at the ocean floor.

Afterwards, the volcano-sedimentary history began on the uplifted mantle slice.

It is worthwhile to briefly summarise the proposed mechanisms of mantle denudation, ocean opening and ophicalcite genesis, that were subjects of strong debate (e.g., Passerini, 1965; Abbate et al., 1972; 1980; 1986; Elter, 1972; Bortolotti et al., 1976; Folk and Mc Bride, 1976; Cortesogno et al., 1978; 1987; Lemoine, 1980; Weissert and Bernoulli, 1985; Lemoine et al., 1987; Piccardo et al., 1994; Piccardo and Rampone, 2000). A first group of works (Gianelli and Principi, 1974; 1977; Galbiati et al., 1976; Gianelli, 1977; Cortesogno et al., 1978; 1987; Abbate et al., 1980; Lemoine, 1980; Weissert and Bernoulli, 1985) considered both the

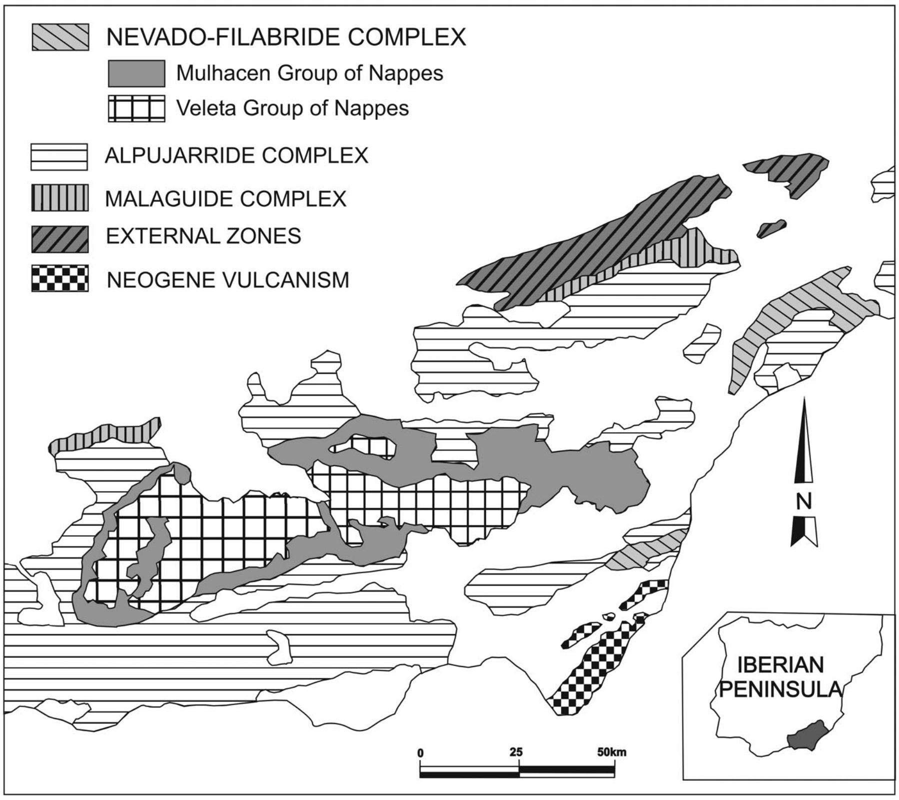

Fig. 20 - Geological sketch of the Nevado-Filabride Units (Betic Cordillera) (redrawn after Puga et al., 1993).

mantle diapirism and the ophicalcitisation as related to a transform zone, as described by Bonatti et al. (1971; 1974), Bonatti (1976) and Bonatti and Honnorez (1976).

More recent data (Lagabrielle and Lemoine, 1997; Cannat, 1993; Mutter and Karson, 1992; Tucholke and Lin, 1994; Mével et al., 1991; Auzende et al., 1994, odp leg 153, etc.) document that the mantle and the gabbroic intrusives are exposed to the ocean floor also along the ridge zones of slow spreading segments of the Atlantic and Indian Oceans. On the other hand in the Western Tethys ophiolites show that mantle unroofing represents the active mechanism during the entire oceanisation stage. We interpret the so called "peculiar" oceanic crust (Abbate et al., 1980) of Western Tethys as a "normal" slow spreading ridge crust like the two biggest intra-Pangean Mesozoic Atlantic and Indian oceans (Lagabrielle and Cannat, 1990; Treves and Harper, 1994; Lagabrielle and Lemoine, 1997; Piccardo and Muentener, 2004), as previously hypothesised by Bortolotti et al. (1976) and Barrett and Spooner (1977) but without excluding that part of the denudation can be produced in transform fault zones.

Being the sampled ophiolitic crust biased by the subsequent accretionary processes, we can argue about the representativity of the slices presently exposed in the Tethyan orogenic belts. Accordingly, a combination of transform and slow spreading ridge environments is still a viable hypothesis for the Tethyan ophiolites.

We can suppose that where the succession includes abundant basalt flows we may be close to an active mid-ocean ridge, and where there are very incomplete successions without basalts, the sampled crust derived from a transform or an amagmatic ridge environment. The actualistic slow spreading ridge models that we prefer, are those of Mutter and Karson (1992) and Tucholke and Lin (1994). The Fig. 21 shows the Tucholke and Lin (1994) interpretative model for the Central Atlantic spreading axis near the Atlantis Fracture zone. This model points out the structural and topographic characteristics of a low spreading ocean ridge segmented by major (first order) and minor (second order) transform discontinuities. According to these authors the generally well documented topographic highs (IC, inside corners) and depressions (OC, outside corners) of the axis ridge are related to the kind of coupling with axis and active (IC) or inactive (OC) side of the transform discontinuities.

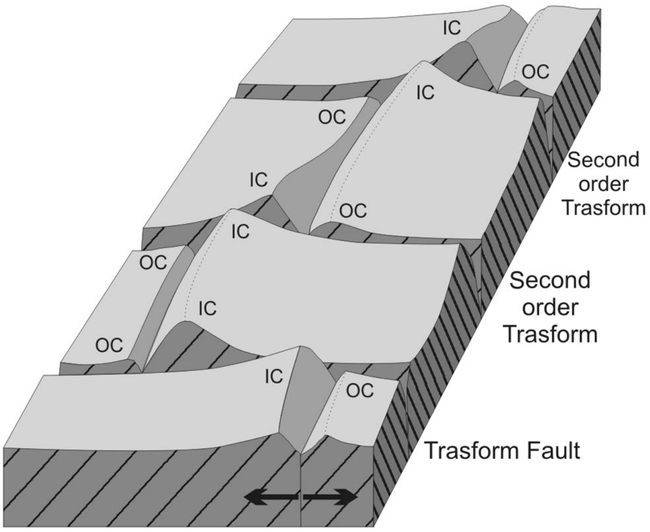

Fig. 21 - The along axis Inner Corners (IC) and Outer Corners (OC) and transform faults model for the mid-ocean ridge of the Atlantic Ocean (redrawn after Tucholke and Lin, 1994).

In the Inside Corners, intrusive mafics and ultramafics rocks and derivated breccias are widespread, and basalts are lacking. In the Outside Corners basalt flows prevail.

Good examples of crustal fragments possibly representing an IC-OC couple paleoenvironment are that of of the ophiolites of the Western Alps (Fig. 22) and those of the ophiolites of the Bargonasco-Val Graveglia (Fig. 23) and Bracco-Levanto (Fig. 24) areas. The palinspastic reconstruc-

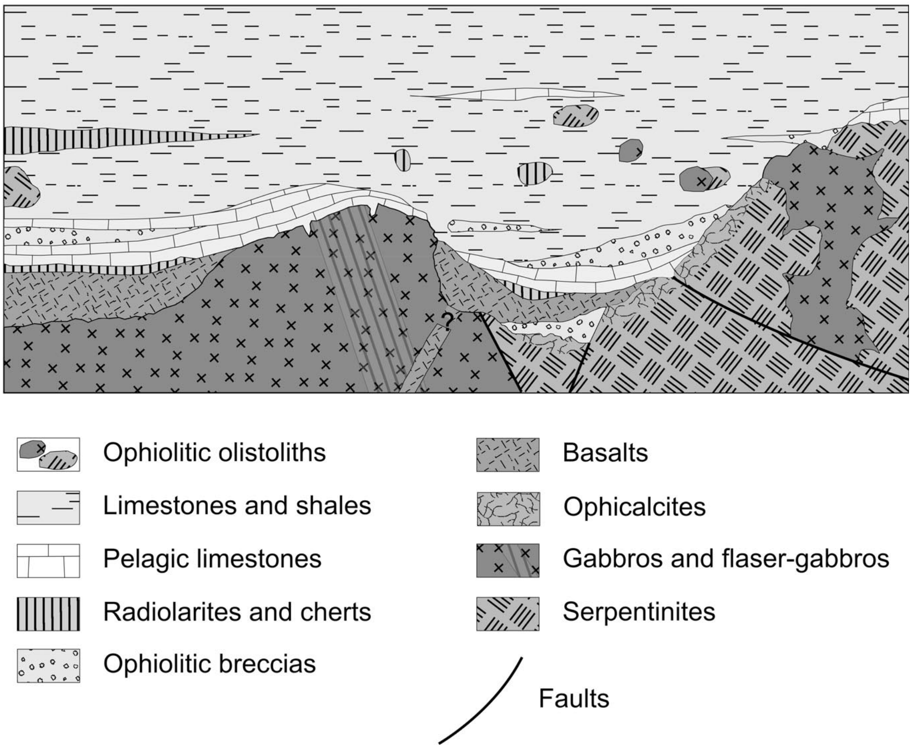

Fig. 22 - Schematic reconstruction of the Piedmontese Ocean floor in the Western Alps sector. (after Lagabrielle, 1994).

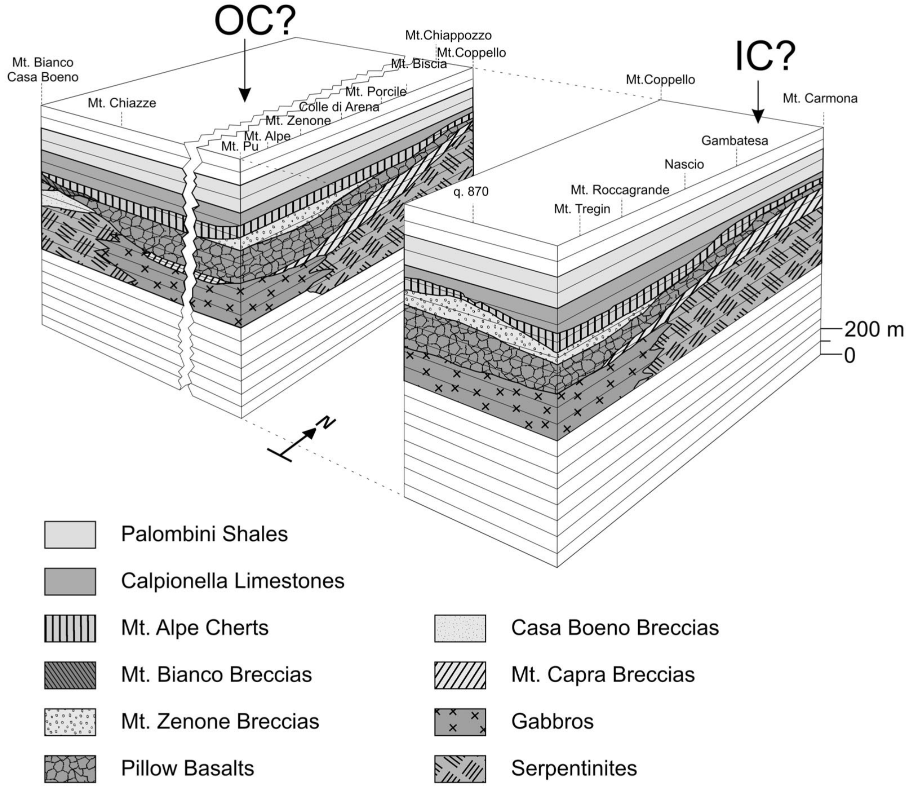

Fig. 23 - Palinspastic reconstruction of the oceanic crust of the Bargonasco-Val Graveglia ophiolites (Eastern Liguria) (after Abbate et al., 1992, and Bortolotti and Principi, 2003). IC and OC, Inner Corners and Outer Corners of Tucholke and Lin (1994), respectively.

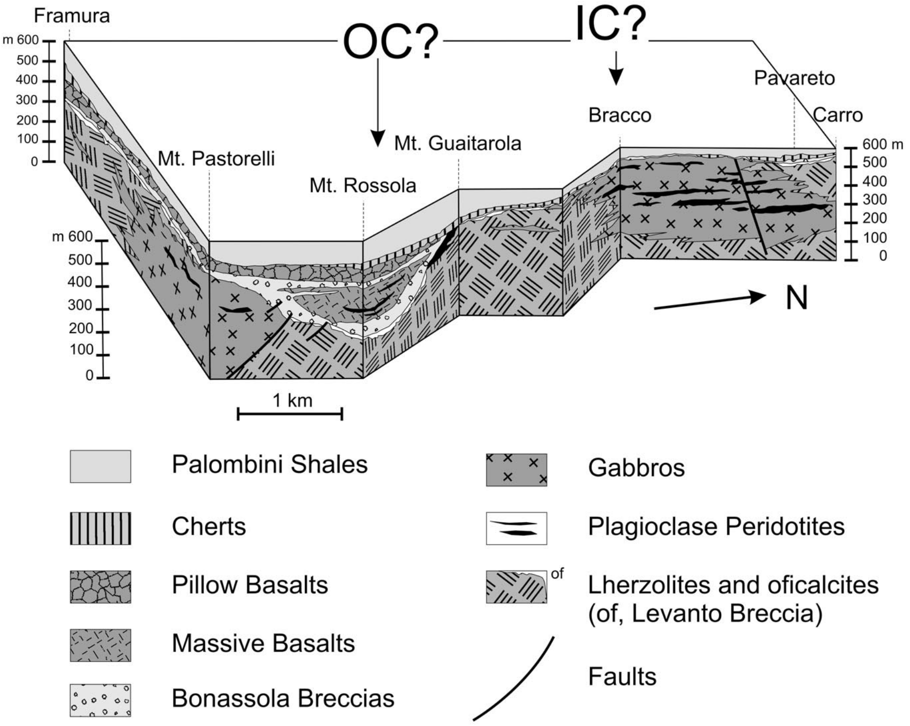

Fig. 24 - Palinspastic reconstruction of the oceanic crust of the Bracco-Levanto ophiolites (Eastern-Liguria) (after Cortesogno et al., 1987). IC and OC, Inner Corners and Outer Corners of Tucholke and Lin (1994), respectively.

tions of these areas, obtained with very detailed field and petrographic data, show the paleogeographic coupling of denudated ophiolitic basements, as paleohighs, and of complete successions, as topographic depressions .

The lack of important sheeted dyke levels, the sporadicity of gabbroic bodies and the small or even zero thickness of the basalt flows, lead to suppose that the ratio of tectonic versus magmatic extension in the Western Tethys ocean ridge was even higher than in the present Atlantic Ocean.

Hence, the construction of new ocean crust in the Western Tethys ridge could be mainly due to tectonic mantle uplifting mechanisms, and at minor extent to magmatic activity. The serpentinitic-gabbroic basement denudation could be realised through low angle detachments as hypothesised by many authors (see, Lemoine et al., 1987; Overduijng Strating et al., 1990; Treves and Harper, 1994; Froitzheim and Manatschal, 1996; Lagabrielle and Lemoine, 1997; Desmurs et al., 2001; 2002; Manatschal, 2004).

This mechanism, like in present-day ocean bottoms (Mutter and Karson, 1992; Tucholke and Lin, 1994), was likely active from the first continental rifting stages (Desmurs et al., 2001; 2002) like in the Galicia Bank, to the "mature" oceanic ridge stages (Treves and Harper, 1994; Bortolotti et al., 2001b).

Ophicalcites seem to form all along the extension history, from rifting to spreading.

In fact, we find ophicalcites in the Platta and Totalp successions at the transition between continental and oceanic crust, which seemingly formed during the first stages of the Western Tethys opening (Desmurs et al., 2002), and in the Northern Apennines and Corsica ophiolites during their "mature" ocean stages (Cortesogno et al., 1978; 1987; Treves and Harper, 1994).

## The volcano-sedimentary events and time correlations

Igneous and sedimentary processes at the sea floor-were reconstructed mainly from the best known Northern Apennines and Corsica ophiolitic successions.

Sedimentary ophiolitic breccias and sandstones (Lower Ophiolitic Breccias), with ultramafic and mafic clasts and matrix, and siliceous pelagites (shales and cherts) constitute the earliest deposits covering the ultramafic-mafic basement, also in the successions where basalt flows are present. This fact should confirm that the magmatic events in the Western Tethys Ocean ridge are always subordinate to the tectonic processes.

Upwards, basaltic flows occur at places, but lack in the reduced and very reduced successions. In the complete succession their thickness does not exceed a few hundred metres. The geochemical signature is N-MOR or T-MOR. The latter are generally restricted to the oceanic crust close to the paleocontinental margins (Balagne, Platta, External Ligurides).

The basalts are locally overlain by the Upper Ophiolitic Breccias (Bargonasco, Murlo) which have clast composition generally gabbroic or polymictic (with abundant basalts).

The deposition of breccias, ophiolitic sandstones and lava flows can be considered as occasional events that occurred along the first phase of siliceous pelagic sedimentation in the whole Western Tethys basin.

The basalts and the ophiolitic debris, in fact, are sporadically intercalated along the base of the cherts and of the thin phtanites and thin siliceous pelagite levels that overlie at places the mantle basement. The main chert level lies directly on top of the basalts and Upper Ophiolitic Breccias.

This poses some questions regarding the significance and extent of volcanism in the 'ocean', and in consequence also about the nature and extension mode of the basin.

The facies distribution of the Northern Apennines (Elba, Bargonasco) cherts allows to reconstruct the evolution of sedimentation above the preserved parts of the oceanic crust. Four sedimentation stages can be recognised in one of the most representative successions in Eastern Liguria (Ponte di Lagoscuro; Aiello, 1994; 1997; Aiello and Chiari, 1997):

1- A "transition to ophiolites stage" (facies A and C);
2- A "quiet deposition stage" (facies B);
3- A "turbiditic stage" (facies D, ribbon cherts);
4- A "transition to limestones stage" (facies E, partially corresponding to facies A of the Calpionella Limestones, according to Cobianchi et al., 1992).

In the reduced successions, the turbiditic facies (D, resedimented) and the transition to limestones stage (facies E) are lacking, facies B prevails, but mineralised layers are lacking, and the inception of chert sedimentation is generally younger (at least in the Liguria successions).

The consistent sequence of the different facies in the various outcrops of the Northern Apennines, indicates that these stages could be related to variations of the tectonic activity and the consequent paleomorphology changes in the whole oceanic basin and could mark the sedimentary evolution from the inner to the outer sides of a mid ocean ridge.

The considerable thickness and the presence in the Mt. Alpe Cherts, of turbiditic chert levels in the complete successions (OC?) and, on the contrary, the thinness or the absence of turbiditic cherts in the reduced (IC/transform zones?) successions (possible sources of the turbidites) suggest that a tectonic regime was active, at least during the first three stages, which could have occurred inside or very near to the tectonically active ridge axis.

The age of the beginning of chert deposition above the basalts, is very important for determining the age of oceanisation. As noted before, a clear diachrony has been detected along the Alps - Apennines Chain (Chiari et al., 2000). In particular, in the Apennines-Corsica segment, the oldest chert ages are: in Liguria latest Bajocian-early Bathonian; in Corsica late Bathonian-early Callovian; in Calabria middle Callovian-early Oxfordian; in Tuscany middle Callovian-early Oxfordian to middle-late Oxfordian.

A similar diachronism is present also in the Western Alps, from middle Bathonian to middle-late Oxfordian, respectively, in the various sections. This can be interpreted as due either to random tectonic sampling of the oceanic crust during the orogenic stage, or to a real diachronism of the ocean opening. The latest Bajocian-early Bathonian (perhaps also Aalenian, see above) age of the more evolved Ligurian basalts and the late Bathonian-early Callovian age of the less evolved Corsica ophiolites would agree with the second hypothesis. However, the scarcity of data outside the Northern Apennines does not permit a definite interpretation.

Radiometric ages are very scarce; those obtained from gabbros, pyroxenites, diorites and trondhjemites (Borsi et al., 1996; Bill et al., 1997; Peters and Stettler, 1987, Rampone et al., 1998; Rubatto et al., 1998; Costa and Caby, 2001; Rossi et al., 2002; Schaltegger et al., 2002) are similar (about 169 to 156 Ma) all over the Western Alps, Northern Apennines and Corsica; those from the basalts and plagiogranites (Bortolotti et al., 1990; 1991; 1995; Borsi et al., 1996; Hohnenstetter et al., 1981) are slightly younger, and show a narrow range (about 161 to 150 Ma).

These data pose the intriguing problem of the correlation between radiometric and biostratigraphical data. In the Western Tethys, according to the GSA time scale (G.S.A., 1999, revised in march 2004) the radiometric ages of the magmatic secion and the biostratigraphy ages on radiolarian cherts roughly correspond.

The strict contemporaneity between the ages of gabbro cooling, basalts, plagiogranites and those of cherts deposition found in some areas appears highly unlikely. This leads to think that the current age data on the Tethyan ophiolites are hard to fit in the radiometric and biostratigraphic time scales.

Unfortunatly, because of the lack of data, we can not take in consideration what occurred during the first amagmatic stages, between the beginning of the new Jurassic continental rifting, which is evidenced by the Sinemurian downing of the carbonate platform along the ingoing western Adria margin, and the Bajocian, the oldest age of the basalt/cherts contact. A former widespread Upper Triassic rifting phase, is separated from the Jurassic one, as detected (e. g. in the

Northern Apennines) by the uninterrupted sedimentation from the Middle Triassic to Hettangian of shallow water continental formations ("Verrucano" - carbonate platform).

According to the cherts biostratigraphic ages (See Figs. 6, 7), ocean spreading in the Western Tethys was still active from the latest Bajocian (oldest ages of the Ligurian cherts) through the late Bathonian/early Callovian (Corsica-Toscana), up to the late Kimmeridgian (early Tithonian).

The oldest biostratigraphical ages are confirmed also by the radiometric data and by the ages of the Balagne and Platta oceanic crust that developed near the continental margin.

The youngest ages, on the other hand, could not be representative, if we admit a demise of even younger crust during subduction. However the total absence of younger ages in the whole ophiolitic areas testifies that the late Kimmeridgian (early Tithonian) could be the age of the end of oceanisation processes in Western Tethys. If this is true, the oceanisation interval covers, at most, about 20 my (170-150 Ma), and can be estimated from 16 to 21 my (Chiari et al., 2000). Regarding the width reached by the Jurassic oceanic basin, if we assume 1cm/yr spreading rate, during the 16-21 my oceanisation interval, the basin would have reached 150-200 km width, plus an unassessable width due to the first amagmatic spreading stage. This is more or less the dimension of the present-day Aden Gulf Basin.

Upwards in the succession, the cherts are overlain by at least three types of pelagic sediments: Calpionella Limestones, the marly-silty Nisportino-Murlo Fms; the Palombini Shales.

The Calpionella Limestones and Nisportino-Murlo Fms are generally present in the complete successions. The Palombini Shales lie directly on the cherts in the very reduced successions. Among the complete successions, only in the Mt. Rossola (eastern Liguria) the Palombini Shales directly cover the Mt. Alpe Cherts (see Fig. 24)

A connection between the Nisportino-Murlo Fms and the St. Martino Fm. (Balagne) is proposed by Marroni et al. (2000). If this is true the marly-silty material could have been supplied by the European passive margin. In the complete successions that represent the topographic depressions, the Calpionella Limestones cover both the cherts and these 'transitional' formations.

The Calpionella Limestones and Nisportino-Murlo-San Martino Fms. occur at the transition between Jurassic and Cretaceous. The fact that this siliceous versus carbonatic pelagites occur at this same time over a wide peri-Mediterranean area, both in the oceanic and continental domain (e.g. cherts-Maiolica or cherts-Biancone transitions), leads to think that its origin is related to large-scale events as, for instance, the global change of CCD level (Winterer and Bosellini, 1981), or the change of the nutrient upwellings (Baumgartner, 1987).

An intriguing significance can be attributed to the paraconformities between cherts and Palombini Shales as are described for the Eastern Liguria. If we consider the gabbroic Bracco Massif as a paleo-morphological high and the Levanto succession as a relative high (considering that the thick basin must have been later uplifted) formed close to a Jurassic ocean ridge, the Kimmeridgian-Valanginian lack of

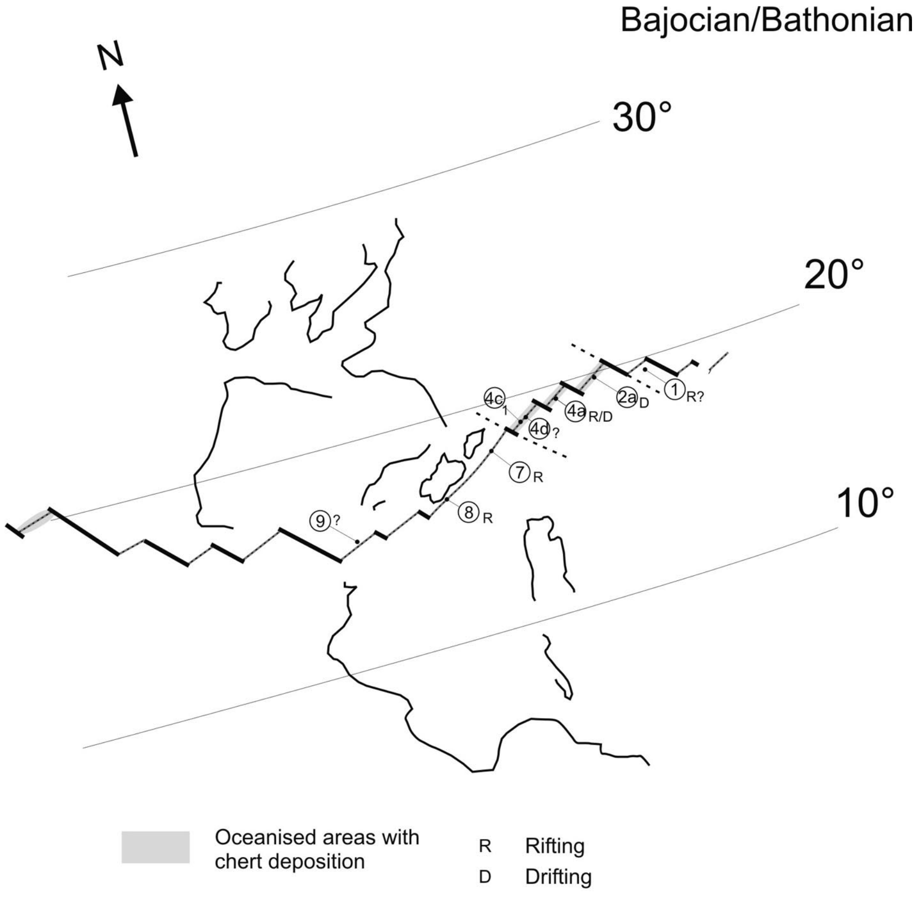

Fig. 25 - Paleogeographic sketch of Western Tethys in the Bajocian-Bathonian. Latitudinal references for this and the following sketches, from Dercourt et al. (1993). 1- Platta-Totalp; 2a- Western Alps (Col de Gets); 2b- Western Alps (Traversiera); 3- Ligurian Alps; 4a- External Ligurides (with continental slices); 4b- Other External Ligurides (Liguria); 4c- Internal Ligurides (Ligurian Vara Unit): $4c_1$- Rossola and Val Graveglia older covers, $4c_2$ – Rocchetta di Vara and Val Graveglia younger covers; 5- Internal and External Ligurides (Tuscan Vara Unit); 6a- Castagniccia (Corsica); 6b- Inzecca (Corsica); 7. Balagne (Corsica); 8a- Calabria (Calabrian Arc); 8b- Timpa delle Murge; 9- Betic Cordillera.

sedimentation could be the interval that marks the axis to off axis displacement of these oceanic crust portions and the end of thermal subsidence.

The long (about 40-50 Ma) and essentially monotonous period during which the Palombini Shales sedimented marks a quiescent stage in the tectonic and geodynamic evolution of the Western Tethys basin. This period was interrupted only by some intraplate magmatism (alkaline basalts of Castiglioncello del Trinoro), by sporadic quartz-arenites deposition, during the Early Cretaceous and by thin siliciclastic turbidites during the early Late Cretaceous, supplied from both the European (Novella, Alturaia etc.) and the Insubric (Ostia Scabiazza, Pietraforte) passive margins (Gardin et al., 1995).

## Paleogeographic restorations

In Figs. 25 to 28 we propose a schematic evolution of the Western Tethys from the Bajocian-Bathonian to the Hauterivian-Santonian times. Fig. 25 (Bajocian-Bathonian) is referred to the opening stage; Fig. 26 (Bathonian-Callovian) to the spreading stage; Figs. 27 (Tithonian-Berriasian) and 28 (Hauterivian-Santonian) to the geodynamic-tectonic quiescient stage (= stop of the drifting and lack of convergence).

Taking into consideration the different ages of the radiolarites, the ages and petrological characteristics of basalts (T or N-MORB), and the evidences of the vicinity or not of a continental margin (presence or lack of continental derived sediments and of extensional allochthons), we try to reset the remnants of the Tethyan oceanic crust in an evolutive scheme.

### *Opening stage*

In Fig 25 (Bajocian-Bathonian) the earliest opening stage is shown. We can observe that the beginning of the ocean spreading has been diachronous.

A rather mature oceanic crust is documented only in the Bargonasco-Val Graveglia and Bracco-Levanto ophiolites (4c$_1$). Also for the Col de Gets (2a) a precocious opening can be supposed. The ophiolites with continental extensional allochthons of External Ligurides (4a), probably formed during this period. An embryonic ocean can also be hypothesised for the Central Alps (1).

The Ligurian-Tuscan (4a, 4b and 5) segment and, perhaps, also the Alpine one (1, 2a, 2b and 3), should have begun to open before the Balagne (7) segment.

For the other localities a rifting stage was still persisting, but very near to the beginning of the ocean opening.

During the first opening stages, in all the Western Tethys ocean basin, ophiolitic breccias, cherts and sporadic basalt flows characterised the sedimentary covers of the embryonic ocean basin. Near the continental passive margins (Balagne, Calabria, External Ligurides, Platta) siliciclastic material intercalated within the basalts, breccias and pelagites occur.

### *Spreading stage*

As shown in Fig 26, all the ocean segments were active during Bathonian-Callovian times.

The re-setting of the outcrops to the northwest or to the southeast of the mid-ocean ridge often represents a problem. For instance, the Inzecca N-MOR basalts (161±3) and Balagne (T-MORB) represent a roughly contemporaneous (UAZ 7) oceanic crust: they were unlikely generated in the same ocean ridge segment. A possible solution (Fig. 26)

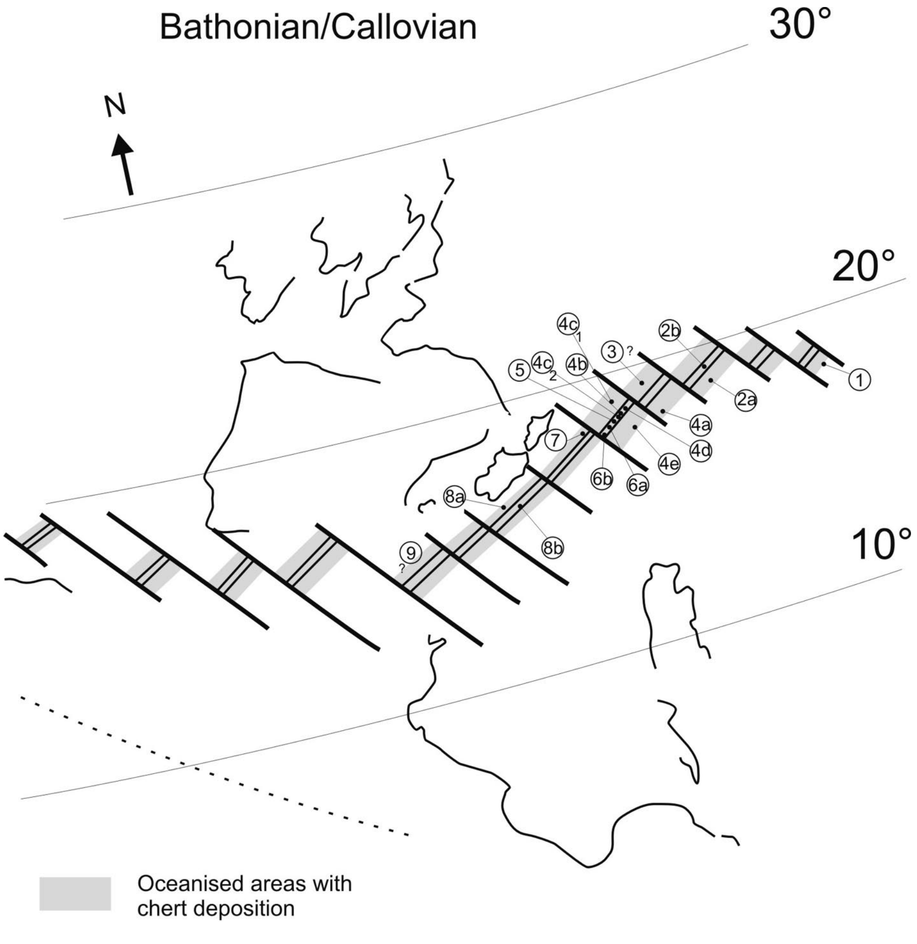

Fig. 26 - Paleogeographic sketch of Western Tethys in the Bathonian-Callovian. Symbols in Fig. 25.

could be that the Balagne segment was located SW of the Ligurian-Tuscan one, and opened at the Bathonian/Callovian boundary, while the more evolved Inzecca (6b) with the slightly younger and very similar Tuscan (5) oceanic crust could represent the younger crust of the southern side of the Ligurian-Tuscan segment.

Very uncertain is the resetting of the Ligurian Alps successions (3): they could be sited in a segment between the Western Alps (2) and the Liguria-Tuscany (4-5) ones, probably in the NW drifting side. At the southeastern corner of the segment, near the Adria continental margin, we can locate the External Liguride successions with continental allochthons (4a).

The External Liguride Units nowadays without the basal ophiolitic successions, probably occupied the Adria side of the Ligurian-Tuscan segment. The 4d could be the location of the oceanic crust of the Units with Cretaceous flysch (e.g. Caio Unit); 4e the location of the oceanic crust of the Units with Eocene flysch (e.g. Morello Unit).

The Calabrian ophiolites (8a and 8b) were probably located in the opposite sides of the ridge: the non-metamorphic Calabro-Lucanian Flysch Unit ophiolites (Timpa delle Murge succession, 8a) near the European margin; the Calabrian Arc metamorphic ophiolites (8b) in the southern side.

Site (9) is the possible location of the Betic Cordillera ophiolites.

The direction of migration of the different ophiolitic outcrops that we propose, can be observed in Figs 26 and 27.

*Quiescient stage*

The Tithonian-Berriasian boundary (Fig. 27) marks the end (Tithonian) of oceanisation in the Western Tethys ocean basin and the beginning (Berriasian) of its quiescent stage.

The beginning of the Cretaceous is characterised by the deposition, in the persistent topographic highs, of the Calpionella Limestones, continuously removed and redeposited in the nearby depressions. Marly-silty deposits (e.g., Nisportino and Murlo Fms.) locally substituted the Calpionella Limestones (Corsica-Tuscany).

The long lasting (more than 40 my) Palombini Shales deposition (Fig. 28) accompanied this long quiescent stage of the oceanic domain. In their typical shaly-calcareous facies, in the latest Early Cretaceous, quartzarenites are locally intercalated (Tuscany). These sandstones probably came from the European continental margin. In the earliest Late Cretaceous, siliciclastic turbidites (Liguria, Tuscany) of probable Insubric provenance occur.

During the Early Cretaceous in the Tuscan External Ligurides an intraplate magmatism is documented (Faraone et al., 1979; Faraone and Stoppa, 1990) .

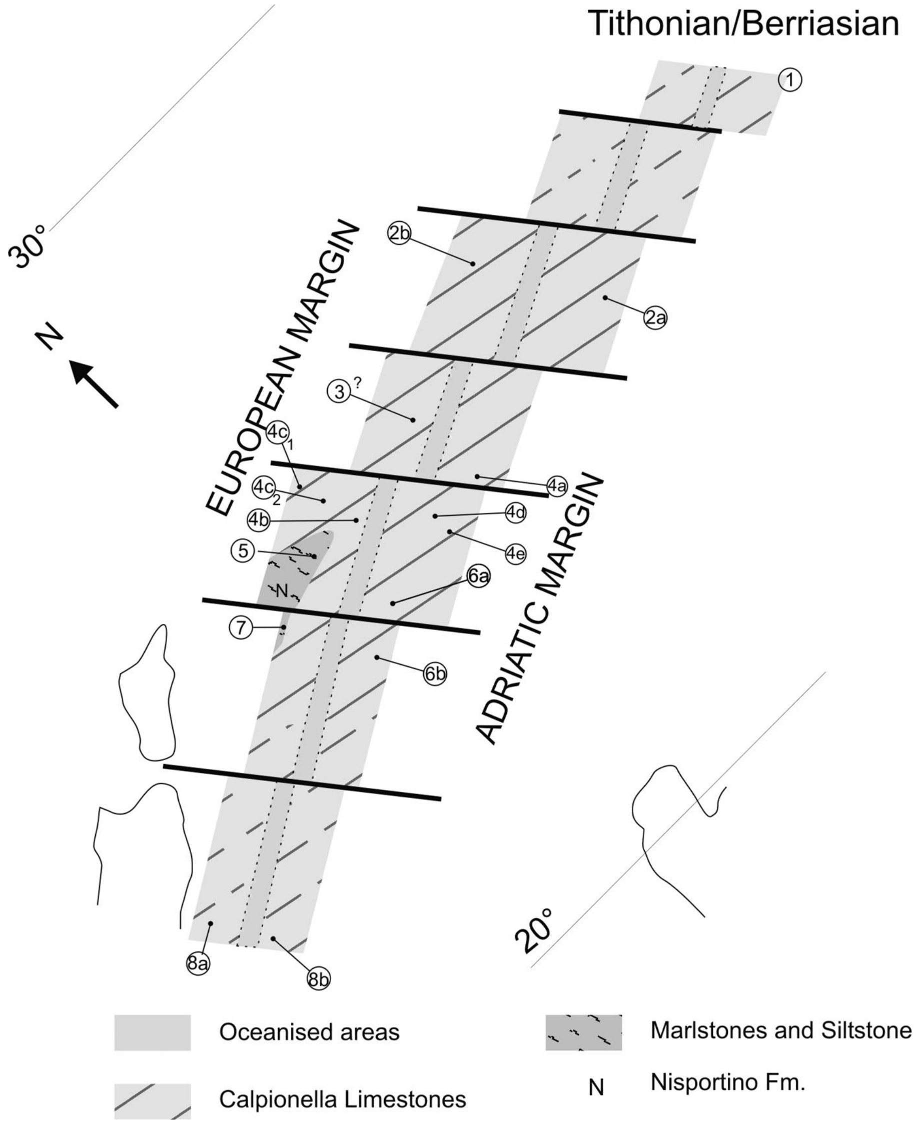

Fig. 27 - Paleogeographic sketch of Western Tethys in the Tithonian-Berriasian. Symbols in Fig. 25.

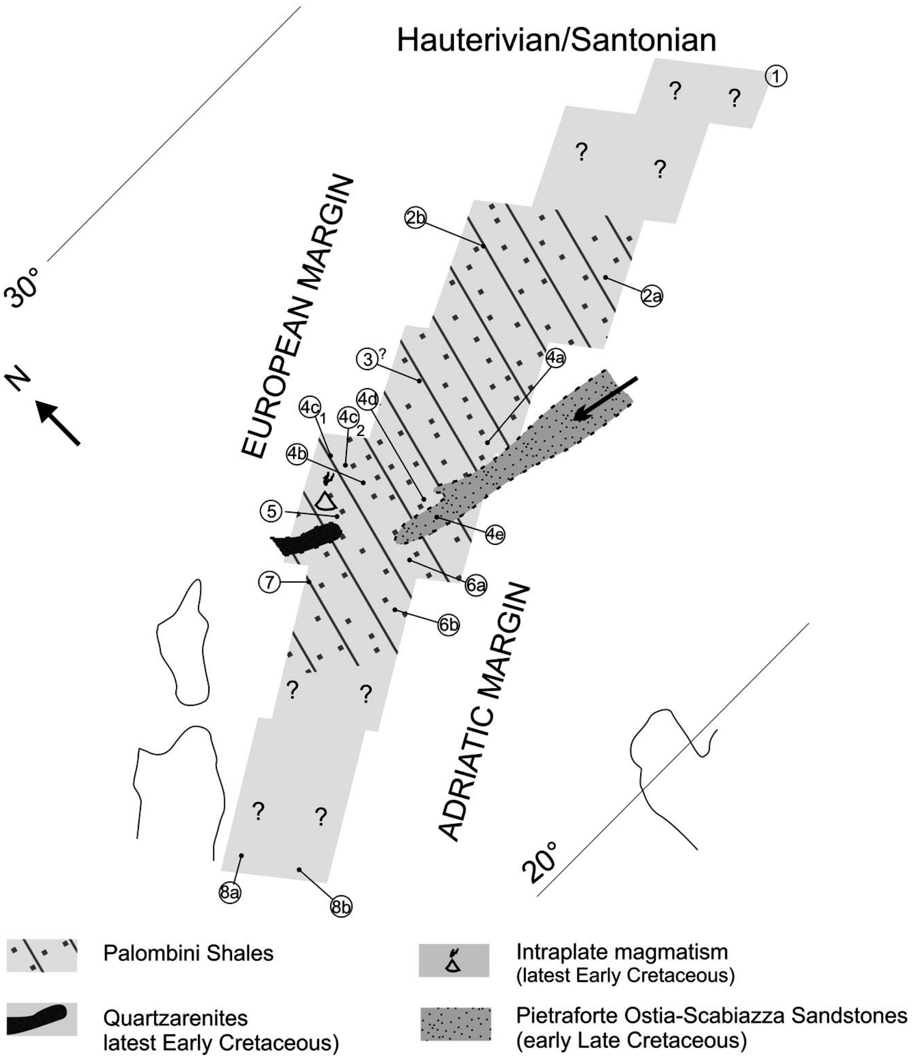

Fig. 28 - Paleogeographic sketch of Western Tethys in the Hauterivian-Santonian. Symbols in Fig. 25.

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