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ORIGINAL PAPER

The architecture of an incipient oceanic basin: a tentative reconstruction of the Jurassic Liguria-Piemonte basin along the Northern Apennines–Alpine Corsica transect

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Abstract In this paper, a scenario for the early evolution of the Jurassic oceanic Liguria-Piemonte basin is sketched. For this purpose, four selected examples of ophiolite sequences from the Northern Apennines and Corsica are described and analyzed. In the External Ligurian units (Northern Apennines), the ocean–continent transition of the Adria plate was characterized by a basement made up of subcontinental mantle and lower continental crust, covered by extensional allochthons of upper crust. Both, the basement rocks and the extensional allochthons are cut by basaltic dikes and covered by basalts and pelagic deposits. The conjugate ocean–continent transition of the Corsica margin, represented by the Balagne nappe (Corsica), was composed of mantle peridotites and gabbros covered by basaltic flows and minor breccias, that in addition include continent-derived clasts. By contrast, the innermost (i.e., closest to the ocean) preserved area observed in the Internal Ligurian (Northern Apennines) and Inzecca (Corsica) units consists of former morphological highs of mantle peridotites and gabbros, bordered by small basins where the basement is covered by a volcano-sedimentary complex, characterized by ophiolitic breccias and cherts interlayered with basaltic flows. The overall picture resulting from our reconstructions suggests an asymmetric architecture for the Liguria-Piemonte basin with a central area bounded by two different transition zones toward the continental margins. This architecture can be interpreted as the result of a rifting process whose development includes a final stage characterized by passive, asymmetric extension of the lithosphere along an east-dipping detachment fault system.

Keywords Ophiolites · Ocean–continent transition · Liguria-Piemonte basin · Corsica · Northern Apennines

Introduction

The Northern Apennines and Alpine Corsica are characterized by well preserved Jurassic ophiolite sequences and their original sedimentary cover. These sequences, regarded as representative of the Liguria-Piemonte oceanic basin, have been studied in detail since the early 1970s (e.g., Decandia and Elter 1972; Gianelli and Principi 1977; Abbate et al. 1980; Beccaluva et al. 1984; Cortesogno et al. 1987; Marroni and Meccheri 1993; Rampone et al. 1998; Bortolotti and Principi 2003; Piccardo et al. 2004; Principi et al. 2004). The ophiolites of Alpine Corsica and the Northern Apennines, as well as those of Calabria and the Alps, are characterized by incomplete sequences showing a stratigraphy, different from that regarded as a "typical" for an ophiolite sequence (e.g., Bernoulli et al. 2003 and references therein). This difference includes, e.g., evidence of exposure at the seafloor of mantle lherzolites before the emplacement of basaltic flows, the lack of a sheeted dike complex and the occurrence of ophiolitic breccias above and below the basaltic flows. In addition, strong differences between ophiolite sequences from Alpine Corsica and the Northern Apennines have been found. For instance, a close

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former association of the ophiolites with granulites and granitoids can be deduced from the assemblage of slide-blocks (Marroni et al. 1998) in the sequences that include the relics of the ocean–continent transition of the Adria continental margin. The observations from the slide-blocks allow an interpretation consistent with the examples mapped in Grisons, Switzerland (Froitzheim and Manatschal 1996; Hermann and Müntener 1996; Manatschal and Nievergelt 1997; Desmurs et al. 2001) or seismically imaged and drilled off Iberia (Manatschal and Bernoulli 1999; Hölker et al. 2002a, b). On the whole, the specific characteristics of the different sequences represent a valuable tool for a reconstruction of the architecture of the Liguria-Piemonte oceanic basin.

Our paper reviews these characteristics in four typical ophiolite sequences along a transect from the Northern Apennines to Alpine Corsica with the aim to provide a picture of the architecture of the Liguria-Piemonte basin and its transition to continental margins.

Geological setting

The Northern Apennines as well as Alpine Corsica (Fig. 1) are characterized today by the assemblage of oceanic and continental units belonging to the Alpine collisional belt (e.g., Elter 1975; Treves 1984; Malavielle et al. 1998; Marroni and Treves 1998). These units were derived from a branch of the western Tethys, i.e., the Liguria-Piemonte basin and its paired Adria and Corsica continental margins (e.g., Bortolotti et al. 1990 and references therein). The Liguria-Piemonte basin developed between Europe/Corsica and the Adria continental margins after different phases of Triassic to Middle Jurassic rifting and Middle to Late Jurassic spreading. According to different geodynamic reconstructions (e.g., Bortolotti et al. 1990 and references therein), the Liguria-Piemonte basin was narrow, and did not exceed 600 km. Starting from the Late Cretaceous, oblique convergence between Europe/Corsica and Adria resulted in the development of a subduction zone, probably within the oceanic Liguria-Piemonte basin (e.g., Boccaletti et al. 1971; Mattauer and Proust 1976; Abbate et al. 1980; Treves 1984; Doglioni 1991; Malavieille et al. 1998; Marroni and Treves 1998; Molli and Tribuzio 2004 and many others). During intraoceanic convergence, the ophiolite sequences of Alpine Corsica were deformed and metamorphosed through underthrusting and subsequent transfer to the accretionary wedge connected with the subduction zone (e.g., Warburton 1986 and references therein). Weakly metamorphosed but strongly deformed oceanic sequences occur in both the Northern Apennines and Corsica, mainly resulting from shallow level accretion (e.g., Marroni and Pandolfi 1996; Marroni and Pandolfi 2003). In the Early Tertiary, intraoceanic subduction was followed by continental collision leading to a thick orogenic wedge. During this stage, the oceanic units were thrust onto the continental margin units, eastwards in the Northern Apennines and westward in Corsica. The resulting structure is a wide, double-verging orogenic wedge, whereby the oceanic units represent the uppermost structural nappes of the belt in both the Northern Apennines and Corsica (e.g., Elter 1975; Nardi et al. 1978; Treves 1984; Malavieille et al. 1998). The margins of this orogenic wedge are preserved in Corsica and the Northern Apennines, whereas the central area today is below sea level due to the evolution of extensional basins in the Ligurian-Tyrrhenian sea.

In the Northern Apennines (Fig. 2), the ophiolites occur in two different groups of thrust nappes, the Internal and External Ligurian units, respectively (e.g., Elter 1975). Both groups of nappes were strongly deformed under very low-grade metamorphic conditions, as suggested by the metamorphic mineral assemblages observed in the metapelites (Leoni et al. 1996 and references therein).

In the Internal Ligurian units, an ophiolite sequence of Jurassic age (Lombardo et al. 2002 and references therein) represents the base of a sedimentary cover, which includes pelagic, trench and lower slope deposits ranging in age from Late Jurassic to Paleocene (Marroni et al. 1992 and references therein). By contrast, the ophiolites in the External Ligurian units occur only as huge slide-blocks in the Late Cretaceous sedimentary melanges, that represent the stratigraphic base of the Late Cretaceous carbonate turbidites, known as Helminthoid Flysch (Marroni et al. 2001 and references therein). Both Ligurian units were deformed during intraoceanic subduction and the following continental collision. Subsequently, the deformed sequences were thrust onto the Sub-Ligurian and Tuscan units during Oligo-Miocene post-collisional convergence. The Sub-Ligurian and Umbrian-Tuscan units were part of the Adria continental margin, and were detached from an unknown substratum, probably represented by thinned continental crust. The successions of the Sub-Ligurian units include only Tertiary deposits and do not record their Mesozoic history; however, the successions of the Tuscan and Umbrian units are representative of the evolution of the Adria passive continental margin, testifying to rifting and cooling subsidence of the margins during the opening of the Liguria-Piemonte basin (e.g., Bernoulli et al. 1979).

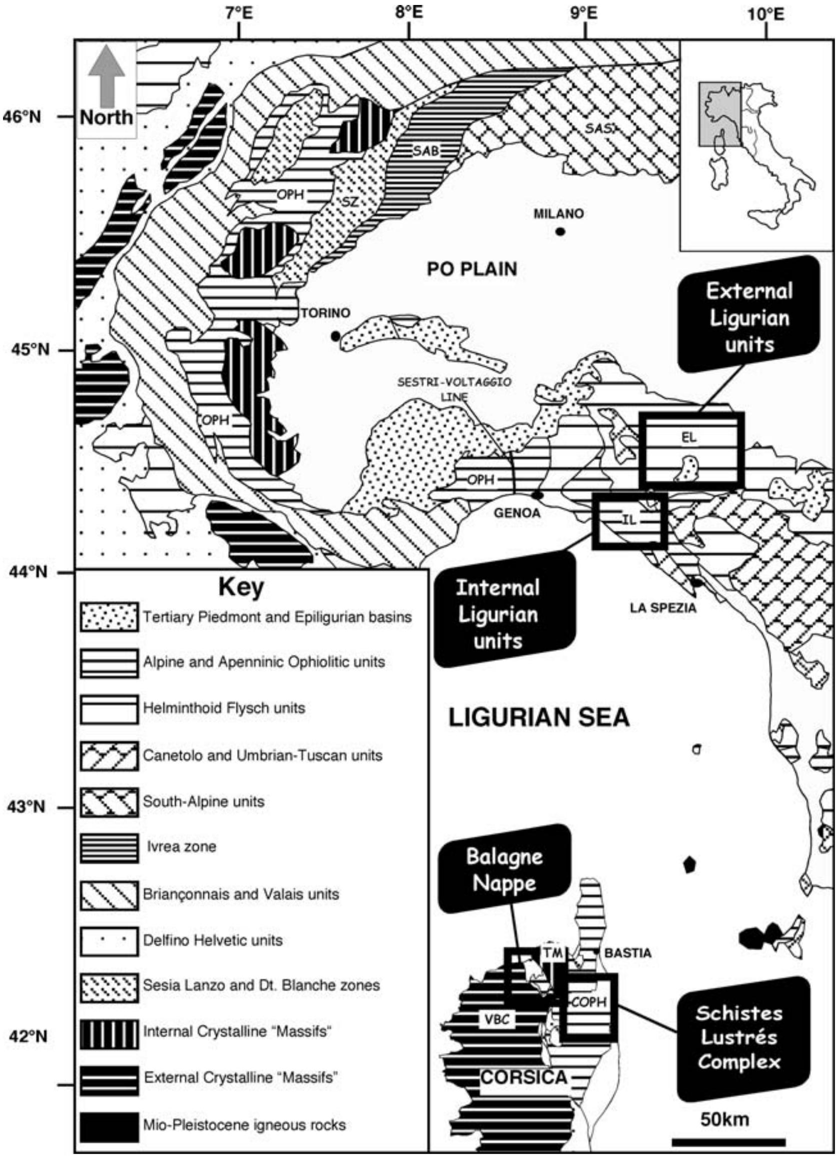

Fig. 1 Tectonic sketch map of the Western Alps, Northern Apennines and Corsica. The location of the study areas are indicated. *COPH* Schistés Lustrées of Corsica, *EL* External Ligurian units, *IL* Internal Ligurian units, *OPH* Sestri Voltaggio, Voltri Group, Piemontese units, *SAB* South Alpine basement, including Ivrea and Canavese zones, *SAS* south Alpine sedimentary cover, *SZ* Sesia zone, *TM* Tenda Massif, *VBC* Variscan basement of Corsica

Also the ophiolites of Alpine Corsica (Fig. 3) occur in two different complexes (e.g., Gruppo di Lavoro sulle Ofioliti Mediterranee 1977). The majority of the ophiolites occurs in a complex stack of tectonic units of Alpine age, known as the Schistes Lustrés complex. These units, derived from both oceanic and continental domains, were strongly deformed under high-pressure/low-temperature (HP/LT) metamorphic conditions during Late Cretaceous to Early Eocene subduction and continental collision (Malavieille et al. 1998 and references therein). Ophiolite units also deformed under very low-grade metamorphic units occur, mainly in the Balagne Nappe. They form the Nappes Supérieures, representing the top of the nappe pile of Alpine Corsica (e.g., Nardi et al. 1978; Marroni and Pandolfi 2003). Both, Nappes supérieures and Schistes Lustrés complex, are thrust onto the tectonic units derived from the Corsica continental margin (Caporalino-S.Angelo nappe, Corte units, Palasca unit and Tenda massif) consisting of slices of Mesozoic to Middle Eocene sedimentary cover associated with remnants of crystalline basement. All the units of Alpine Corsica are thrust over Variscan Corsica, consisting of Late Carboniferous to Early Permian granitoids intruded into Precambrian and Palaeozoic country-rocks at or after the end of the Variscan orogeny.

Models for the opening of the Liguria-Piemonte oceanic basin

The architecture of the Liguria-Piemonte basin is directly inherited from rifting. However, this process is still a matter of debate and different models have been

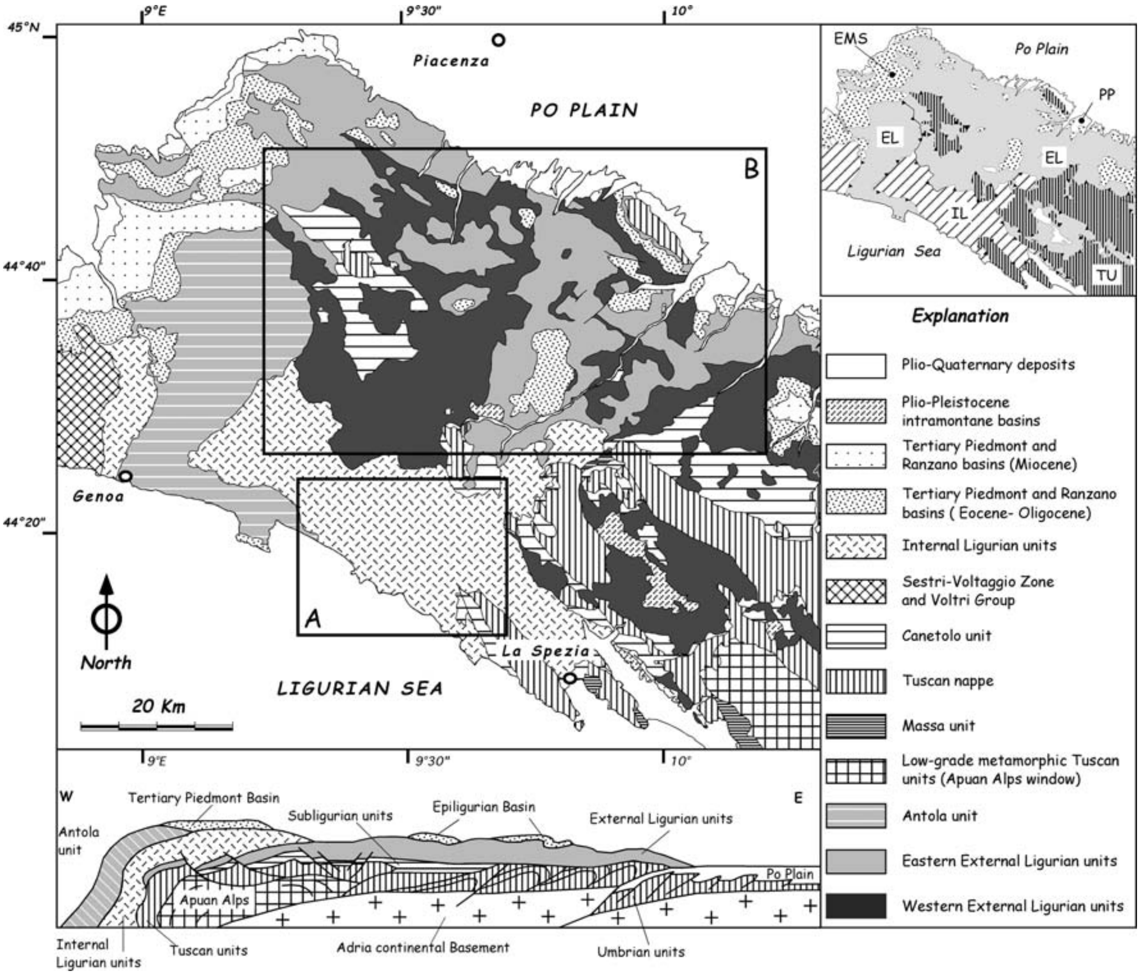

Fig. 2 Tectonic sketch map of the Northern Apennines with interpretative cross-section. *Inset*: *EL* External Ligurian units; *EMS* Epimesoalpine successions; *IL* Internal Ligurian units; *PP* Plio-Pleistocene deposits; *TU* Tuscan and Umbrian units. The *boxed areas* indicate the study areas: *A*: Internal Ligurian units, *B*: External Ligurian units

proposed for the opening of the Liguria-Piemonte oceanic basin.

In a first model, proposed by Decandia and Elter (1969), the opening of the Liguria-Piemonte ocean occurred by passive rifting, leading to the delamination of the continental crust by two opposite, landward-dipping detachment faults located at the crust-mantle boundary. As result of this process, a large area of subcontinental mantle was progressively unroofed and exposed on the seafloor during rifting. The resulting oceanic area was bounded by a pair of symmetrical continental margins, characterized by high-angle, seaward-dipping, normal faults. This model was also adopted by Piccardo (1976) and Beccaluva et al. (1984) and applied to the western Alps by Lombardo and Pognante (1982).

Later, Lemoine et al. (1987) proposed a different model, where the opening of the Liguria-Piemonte basin was achieved by passive, asymmetrical extension of the lithosphere by simple shear (cf. Wernicke 1981). In this model, the continental crust was delaminated by a low-angle detachment fault cutting across the whole continental crust into the lithospheric mantle. The low-angle detachment fault divided the continental lithosphere into a lower and an upper plate, characterized by an asymmetry in structural evolution. After the break-up, the lower plate margin consisted of a wide area, where subcontinental mantle was exposed at the seafloor. Later, it turned out that this exhumed mantle was covered with remnants of the upper plate displaced along the detachment faults, the extensional allochthons of Froitzheim and Manatschal (1996), Hermann and Müntener (1996), and Manatschal and Nievergelt (1997). By contrast, the opposite plate margin consisted of upper continental crust affected by a major flexure with small, continentward-dipping fault systems. In this model, the detachment fault was west-dipping, with the lower plate represented by the Adria

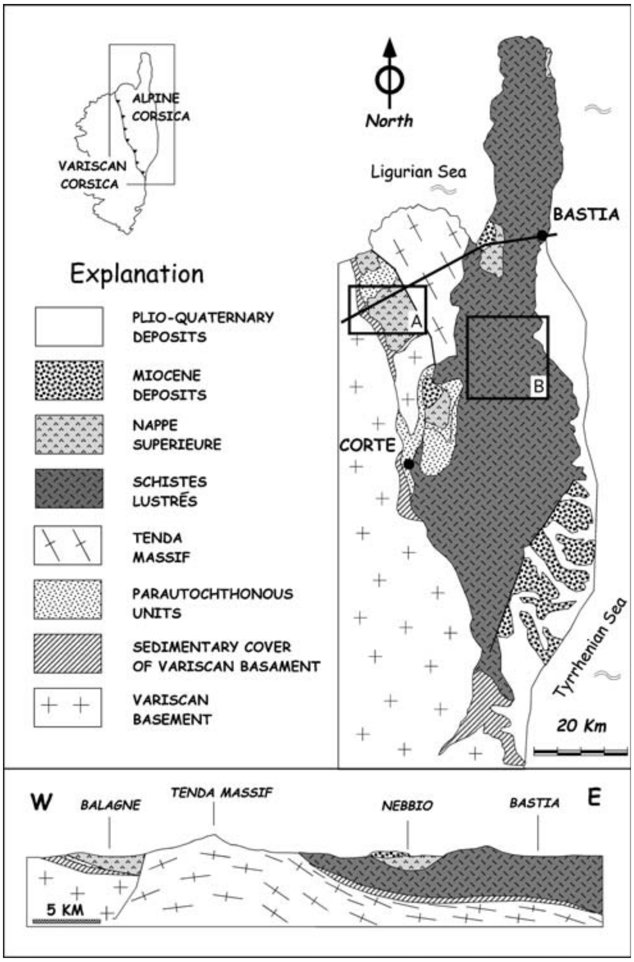

Fig. 3 Tectonic sketch map of Alpine Corsica with interpretative cross-section. The location of the cross-section is indicated by the heavy line. The *boxed areas* indicate the study areas; *A*: Balagne nappe, *B*: Schistes Lustrés complex (Inzecca area)

continental margin. A simple-shear model with a west-dipping detachment fault was adopted by Hoogerduijn Strating et al. (1993) and Hermann and Müntener (1996). Subsequently, Froitzheim and Manatschal (1996), Marroni et al. (1998), Whitmarsh et al. (2001) and Lavier and Manatschal (2006) proposed a rifting model, including two distinct phases. The first phase, mainly developed in Late Triassic to Early Jurassic times, was characterized by high-angle normal faults (e.g., Froitzheim and Eberli 1990), whose geometry suggests a rifting process dominated by lithospheric necking by pure-shear extension. The subsequent phase (Middle to Late Jurassic in age) produced large-scale exhumation in the seafloor of subcontinental mantle and associated lower crust through asymmetric extension by west-dipping, low-angle detachment faults. During this second stage, exhumation of subcontinental mantle was coupled with the displacement of upper crustal extensional allochthons along the detachment faults. According to Whitmarsh et al. (2001) and Lavier and Manatschal (2006), the change from a symmetric to an asymmetric mode is the result of a change in distribution of weak layers in the lithosphere, induced by the changing thermal structure and gravitional responses associated with a rising astenosphere.

A third model was proposed by Dal Piaz (1993), Trommsdorff et al. (1993), and Rampone and Piccardo (2000). In this model, the opening of the Liguria-Piemonte basin was achieved by continuous simple-shear extension accommodated by an east-dipping detachment fault. As a result of this process, the lower continental crust and the subcontinental mantle would be exposed along the Corsica margin.

Elements for the reconstruction of the Liguria-Piemonte basin

For the reconstruction of the architecture of the Liguria-Piemonte basin, four examples of ophiolite sequences were selected along the Northern Apennines–Alpine Corsica transect. They are (Fig. 1) (1) the External Ligurian units, (2) the Internal Ligurian units in the Bracco-Val Graveglia area, (3) the Schistes Lustrés complex in the Inzecca area and (4) the Balagne nappe. These units represent (1) the ocean–continent transition of the Adria plate, (2) and (3) the innermost preserved zones of the oceanic basin and (4) the area close to the Corsica continental margin.

External Ligurian units

According to Marroni et al. (2001 and references therein), the External Ligurian units can be divided into western and eastern successions based on their differing stratigraphic sequences.

In the western External Ligurian units, the ophiolites occur only as slide-blocks in the Santonian–Early Campanian sedimentary melanges. These sedimentary melanges, generally referred to as ‘‘basal complexes’’, consist of variable amounts of mono- and polymictic pebbly sandstones and mudstones with intercalations of coarse-grained litharenites. In addition, huge slide-blocks (olistoliths) are present and, locally, largely prevailing (Fig. 4). Different sedimentary melanges (known as Casanova, Mt. Ragola and Pietra Parcellara complexes, Fig. 2) were distinguished by their tectonic position, but all can be regarded as derived from the same paleotectonic domain. The sedimentary deposits of the basal complexes generally grade upward into Late Campanian-Maastrichtian Helminthoid Flysch, represented by thick, monotonous sequences of calcareous turbidites (Fig. 4). By contrast, the eastern units of the External Ligurian units contain a thick, well-preserved succession that lacks mafic and ultramafic rocks. These eastern successions include Cretaceous pelagic, and younger siliciclastic deposits (Palombini Shale, Ostia Sandstone and Salti del Diavolo Conglomerate) overlain by the Late Campanian–Maastrichtian Helminthoid Flysch (Marroni et al. 1992 and references therein). According to Marroni et al. (2001), the substratum of this succession is represented by carbonate platform to pelagic, mainly carbonate deposits consisting of dolomitic limestones (Middle Trias) capped by sedimentary breccias with Diplopora-bearing dolomitic clasts (Late Trias), cherty limestones (Liassic), marls (Dogger-Malm), bedded cherts (Malm), Aptychus-bearing calcareous red marls (Malm) and Calpionella-bearing pelagic limestones (Early Cretaceous). On the whole, this sequence is interpreted as the cover of the thinned continental crust representing the westernmost edge of the Adria continental margin (Elter et al. 1966; Marroni et al. 2001).

The source area of the External Ligurian sedimentary melanges was paleogeographically located in the domain representing the transition from the Liguria-Piemonte basin to the Adria continental margin (Marroni et al. 2001 and references therein). This domain experienced compressive/transpressive movements in the Late Cretaceous (Marroni and Treves 1998, and references therein). The sudden appearance of extensive sedimentary melanges indicates tectonically controlled sedimentation along the western margin of the Adria plate in the Late Campanian (Marroni et al. 2002). These melanges were affected by several phases of folding and thrusting in Tertiary times during their progressive eastward thrusting over the margin of the Adria plate; however, the metamorphic overprint did not exceed subgreenschist-facies conditions (Meli et al. 1996; Balestrieri et al. 1997).

The most common slide-blocks are mantle peridotites, consisting of fertile spinel lherzolites, characterized by a coarse-grained granular texture (Piccardo et al. 2004 and references therein). The Sr and Nd isotopic compositions of clinopyroxenes are typical of subcontinental mantle. Major and trace element abundances of whole-rock samples and primary clinopyroxenes display evidence for a relatively fertile chemical composition (Ottonello et al. 1984; Rampone et al. 1995; Piccardo et al. 2002). The peridotites, generally showing pyroxenite bands, are characterized by the intrusion of MORB dikes and rare gabbroic bodies. Temperature estimates of the spinel-facies assemblage (1,000–1,050°C) are compatible with continental geothermal gradients (Beccaluva et al. 1984; Rampone et al. 1995; Piccardo et al. 2004). Both, the peridotites and the pyroxenites, display partial recrystallization to plagioclase-bearing assemblages at lower temperatures (*T* = 900–950°C), locally accompanied by ductile deformation that led to tectonite and mylonite fabrics. Geothermometry suggests that decompression to plagioclase-facies conditions was accompanied by slight cooling. The MORB dikes appear to postdate the re-equilibration under plagioclase-facies conditions. Sm/Nd isochrons on plagioclase-clinopyroxene pairs from two samples of the peridotites gave ages of 164 ± 20 Ma that were interpreted as the time of

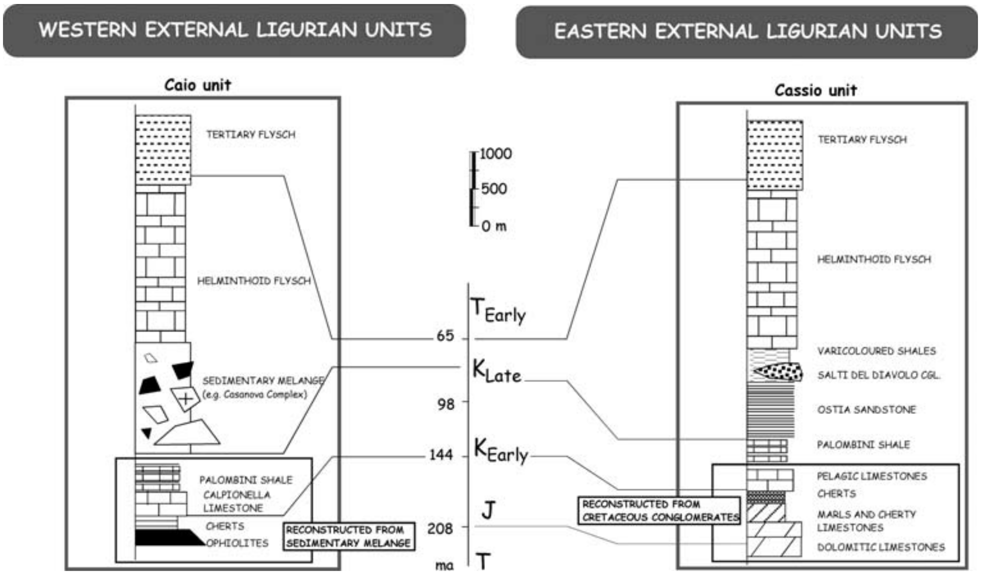

Fig. 4 Reconstruction of the Western and Eastern successions of the External Ligurian units (redrawn from Marroni et al. 2001)

metamorphic re-equilibration under plagioclase-facies conditions (Rampone et al. 1995).

Rare gabbroic slide-blocks are represented by troctolite to olivine-bearing gabbro, showing an MOR geochemistry (Marroni et al. 1998; Tribuzio et al. 2000). Sm/Nd isochrons on plagioclase-clinopyroxene-whole rock from one sample of gabbro yielded an age of 179 ± 9 Ma interpreted to date igneous crystallization (Tribuzio et al. 2004). The gabbros are locally characterized by the occurrence of ductile shear zones with mylonitic fabrics developed under amphibolite-facies metamorphic conditions. The gabbroic slide-blocks are locally intruded by discordant bodies of Fe-Ti-oxide-bearing microgabbro or by basaltic dikes.

The basalts occur as huge slide-blocks of massive and pillow-lavas and as dikes intruded into ultramafics and gabbros. Geochemically, massive, pillow-lavas and dikes range between Normal- and Transitional MOR-basalts (Venturelli et al. 1981; Vannucci et al. 1993; Marroni et al. 1998). In the largest slide-blocks, stratigraphic relationships between basalts and their pelagic sedimentary cover are preserved. This cover includes Middle to Late Jurassic cherts (Late Callovian/Early Oxfordian, Chiari et al. 2000), Early Cretaceous Calpionella Limestone and Early to Late Cretaceous Palombini Shale (Decandia and Elter 1972; Marroni et al. 1992).

In the sedimentary melanges, slide-blocks of continental crustal rocks are common. They include blocks of granitoids, up to 100 m across, showing a wide variety of rock-types, ranging from two-mica leucogranites to biotite-bearing granodiorites and rare biotite-bearing tonalites and diorites. In addition, fragments of gneisses and micaschists have been found associated with granitic clasts in sedimentary breccias. The geochemical data (Marroni et al. 1998) indicate that the granitoids were related to an orogenic setting. A late to post-Variscan age of crystallization may be inferred for a sample of a two-mica leucogranite, based on its K/Ar and Rb/Sr muscovite ages (310–280 Ma, Ferrara and Tonarini 1985). The granitoids are cut by basaltic dikes and/or covered by basaltic flows, showing the same geochemical features as the basalts from other slide-blocks (Marroni et al. 1998). In addition, these granitoids show cataclastic to ultracataclastic deformation between 200 and 300°C, i.e., at a depth of 5–10 km (assuming a reasonable geothermal gradient), as suggested by the absence of dynamic quartz recrystallization and by the mineral assemblage of the recrystallized matrix (quartz + epidote + albite + chlorite) (Molli 1996; Marroni et al. 1998). K/Ar and Rb/Sr age determinations on biotites from other undeformed granitoid samples yielded ages of 229 ± 8 Ma and 222 ± 7 Ma, respectively (Ferrara and Tonarini 1985). The K/Ar and Rb/Sr sytems in biotite yield a closure temperature of about 300°C that suggests brittle deformation after the Middle Triassic. These data and the observed relationships with the basalts and the overlying cherts (Molli 1996) constrain the timing of the brittle deformation in the granitoids to a Middle Triassic–Middle Jurassic time interval.

Also slide-blocks of mafic granulites, up to 100 m across that preserve primary relationships with felsic granulites, are found. Relics of igneous textures, and mineral and whole-rock compositional variations indicate that the protoliths of the mafic granulites were gabbroic rocks, crystallized at intermediate levels from tholeiite-derived liquids (Marroni and Tribuzio 1996; Montanini 1997; Marroni et al. 1998). A Sm/Nd mineral-whole-rock isochron of 291 ± 9 Ma, obtained for an undeformed gabbro-derived granulite (Meli et al. 1996) has been interpreted as the time of emplacement of the gabbroic precursor. The mafic granulites underwent post-magmatic subsolidus re-equilibration under granulite-facies conditions ($P = 0.7$–0.8 GPa, $T = 800$–900°C; Marroni and Tribuzio 1996; Montanini 1997). Granulite-facies ductile deformation is testified by protomylonitic to mylonitic and ultramylonitic rocks. The petrographic and mineral compositional variations suggest that the granulite-facies evolution of these rocks was characterized by temperature and pressure decrease (e.g., Montanini 1997). Retrogression to lower temperature conditions was commonly accompanied by deformation, progressively changing from plastic to brittle. Such a deformation path is testified by the retrogression of granulite-facies rocks to mylonitic amphibolites showing later cataclastic deformation, mainly developed under greenschist-facies P/T conditions (Montanini 1997; Marroni et al. 1998). A ^{40}Ar/^{39}Ar age of 228 ± 2 Ma obtained on a Ti-pargasite from an undeformed granulite was interpreted as the age of cooling below a temperature of about 500°C (Meli et al. 1996). This suggests that brittle deformation is younger than Middle Triassic, i.e., the granulite- to amphibolite-facies ductile shear zones were most likely active in Permian to Middle Triassic times.

The felsic granulites are generally represented by blocks, up to 100 m across, of medium-grained granoblastic rocks with a quartzo-feldspathic composition (Montanini and Tribuzio 2001). Rare quartz-poor to quartz-free granulites, locally preserving primary contacts with quartzo-feldspathic granulites, are also present. They have been interpreted as anatectic and migmatic rocks originating through multi-stage melting of lower-crustal basement rocks (Montanini and

Tribuzio 2001). The quartzo-feldspatic granulites underwent a complex polyphase deformational history that started with an early deformation event developing under high-temperature, granulitic-facies conditions (Marroni et al. 1998). Lower temperature deformation can then be observed within mylonites, developing into grain-boundary-migration recrystallization, indicating lower amphibolite- to upper greenschist-facies conditions. A late stage of brittle deformation, with recrystallized quartz and albite, was most likely associated with very low-grade metamorphism. Fission tracks in zircons (249 ± 52 Ma) indicate that the quartzo-feldspathic granulites reached sub-greenschist-facies conditions during their pre-orogenic evolution (Balestrieri et al. 1997).

Internal Ligurian units in the Bracco-Val Graveglia area

The Internal Ligurians units occur in an uppermost structural position along the western side of the Northern Apennines. These units include a Middle to Late Jurassic ophiolite sequence covered by Jurassic to Paleocene pelagic to turbiditic deposits (e.g., Elter 1975). The sedimentary cover of the ophiolites displays evidence of a pre-Oligocene, polyphase structural evolution under metamorphic conditions ranging from very low-grade to blueschist facies. This structural evolution is assumed to reflect a deformation history that includes underthrusting, underplating and exhumation within the accretionary wedge associated with Alpine subduction (e.g., Marroni et al. 2004). The Bracco–Val Graveglia area displays the best-preserved ophiolite sequence and, consequently, also the best-studied in the Northern Apennines (see the detailed maps of Decandia and Elter 1972; Cortesogno et al. 1987; Marroni and Meccheri 1993; Bortolotti and Principi 2003). The detached ophiolite sequence, today preserved in the Internal Ligurian units, is only up to 1 km thick. It represents a relatively thin oceanic basement nappe that includes serpentinized mantle peridotites and gabbros, covered by a volcano-sedimentary complex consisting of basaltic flows, interfingering with ophiolitic breccias and sediments (Figs. 5, 6). No well-developed sheeted dike complex is present.

The peridotites consist of moderately depleted cpx-poor spinel lherzolites, which underwent static recrystallization under spinel-facies conditions (T ranging from 1,100 to1,250°C; Rampone et al. 1996). The mantle peridotites, characterized by pyroxenite layers and minor dunitic lenses, are intruded by a shallow-level gabbroic complex and cut by rare clinopyroxenite and widespread gabbro dikes (Beccaluva et al. 1984; Rampone et al. 1998; Piccardo et al. 2004). The gabbroic complex consists of large, up to several kilometer-wide bodies, volumetrically dominated by isotropic olivine-bearing gabbros showing small lenticular bodies of layered melatroctolites and troctolites (Tribuzio et al. 2000 and references therein). Chromitite layers or pockets also occur in the largest layered gabbros bodies. The gabbros, as well as the serpentinites are cut by Fe-Ti-oxide gabbro, diorite and plagiogranite dikes and small stocks (Serri 1980). A Sm/Nd age of 164 ± 14 Ma on whole rock and clinopyroxene from gabbros, interpreted as the age of igneous crystallization, has been obtained by Rampone et al. (1998). In addition zircons separated from plagiogranites yielded an U/Pb age of 153 ± 0.7 Ma (Borsi et al. 1996). Both mantle peridotites and gabbros are cut in turn by basaltic dikes showing a N-MORB geochemical affinity (Cortesogno and Gaggero 1992). The top of the peridotites is formed by ophicalcites (Levanto Breccia), regarded as a tectono-hydrothermal breccia partly reworked at its top into a sedimentary breccia (Framura Breccia). The ophicalcites represent the surface of the serpentinized mantle peridotites, exposed at the sea floor before the emplacement of basaltic flows and/or sedimentary breccias (Treves and Harper 1994 and references therein).

For the gabbros (Fig. 6), a polyphase, ductile to brittle tectono-metamorphic history can be reconstructed for the time after their emplacement (Molli 1994 and references therein). This history includes a first phase of ductile, localized deformation that produced flaser (gneissic) textures and folding in the gabbros and the host lherzolites. The second phase, represented by hornblende + plagioclase-filled fractures, is followed by a third phase, during which brittle normal faults with the formation of cataclasites developed. Deformation was accompanied by retrograde metamorphism reflecting conditions from upper amphibolite (T ranging from 730°–660° to <500° and $P < 0.3$ GPa) to lower amphibolite and upper greenschist ($T < 300°$ and $P < 0.1$–0.2 GPa) facies. Frequently, the contact between gabbro and serpentinite is a fault active in the oceanic environment during the last phase.

Where the ophiolite sequence is well developed, the basement is overlain by a volcano-sedimentary complex, up to 400 m thick, that generally includes the Lower and Upper Ophiolitic Breccias separated by basaltic flows (Decandia and Elter 1972). The Lower Ophiolitic Breccias are characterized by fragments mainly of serpentinites (Framura Breccia and Casa Boeno Breccia) or of Fe-gabbros and diorites (Mt. Capra Breccia), interfingering with rare layers of

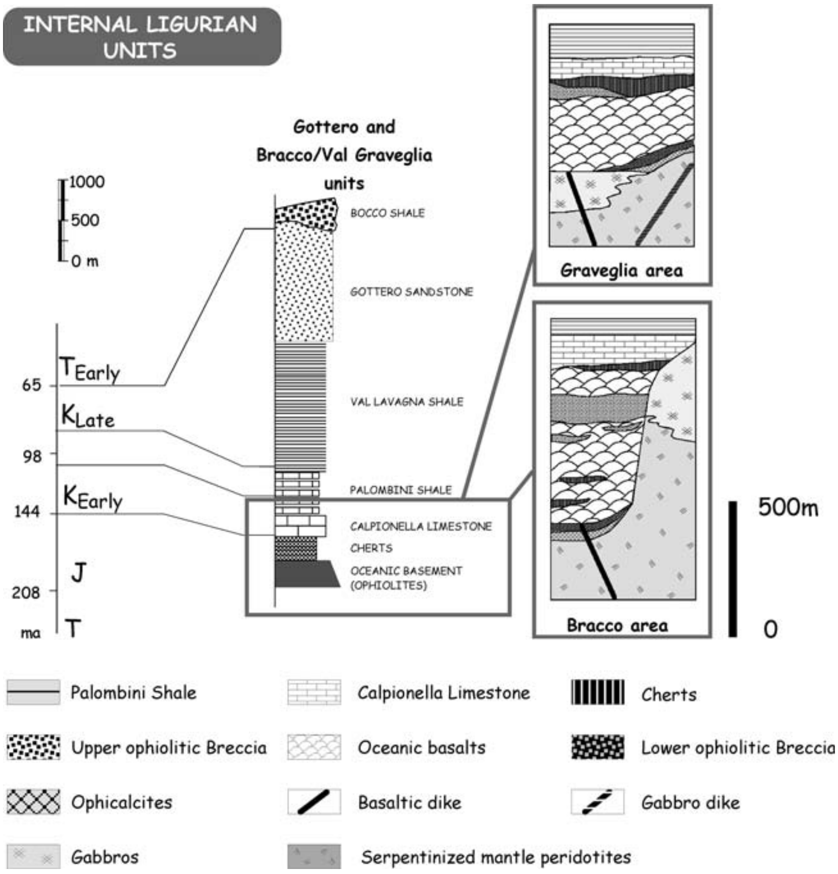

Fig. 5 Reconstruction of the succession of the Internal Ligurian units (redrawn from Marroni and Pandolfi 1996; Principi et al. 2004). The Lower Ophiolitic Breccias comprise Framura Breccia, Casa Boeno Breccia and Mt. Capra Breccia; the Upper Ophiolitic Breccias comprise Mt. Zenone Breccia, Mt. Bianco Breccia, Movea Breccia and Mt. Rossola Breccia. Details of the ophiolite sequences are shown in the *boxed areas*

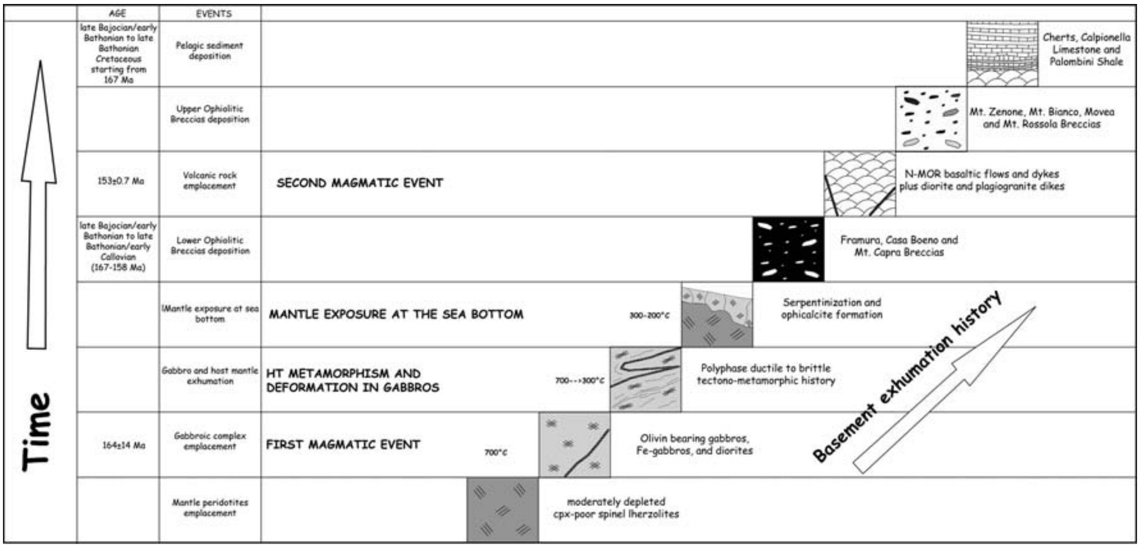

Fig. 6 Main tectono-metamorphic and sedimentary events recognized in the succession of the Internal Ligurian units. Age data from Borsi et al. (1996), Rampone et al. (1998), Chiari et al. (2000) and references therein

pelagic sediment. The intervening basalts, up to 200 m thick, are mainly pillow-lavas and pillow breccias; but locally, sills with a massive texture have been observed. The geochemical parameters indicate that also these basalts are of N-MOR type. The magmatic activity with its important advection of heat induced widespread hydrothermal metamorphism, reaching greenschist to lower amphibolite facies. The basalts are interlayered with or overlain by the Upper Ophiolitic Breccias characterized by fragments of flaser gabbro (Mt. Zenone Breccia) or serpentinite (Mt. Bianco Breccia); however, polymictic breccias (Movea and Mt. Rossola Breccias) characterized by fragments of basalt, gabbro and peridotite also occur. Fragments of continental crustal rocks are absent in the sedimentary breccias of the volcano-sedimentary complex. The age of the volcano-sedimentary complex ranges from late Bajocian/early Bathonian to late Bathonian/early Callovian (e.g., Chiari et al. 2000 and references therein). The Upper Ophiolitic Breccias are directly overlain by pelagic deposits (Decandia and Elter 1972; Perilli and Nannini 1997; Chiari et al. 2000) represented by cherts (Mt. Alpe Cherts, late Bajocian/early Bathonian to Tithonian), Calpionella Limestone (Early Cretaceous) or Palombini Shale (Early to Late Cretaceous), a pelagic sedimentary cover similar also to that of the External Ligurian units. Locally, the thickness of the volcano-sedimentary sequence is reduced to a few meters or to zero. In this case, the ophicalcites or the gabbros are directly overlain by the sedimentary cover (Fig. 5).

Schistes Lustrés complex in the Inzecca area

The ophiolitic units cropping out in the Inzecca area of Corsica belong to the Schistes Lustrés complex. The main features of these units include a reduced ophiolite sequence, characterized by a mantle basement covered by a volcano-sedimentary sequence without evidences of associated continental crustal rocks (Ohnenstetter et al. 1981). As proposed for the Internal Ligurian units, the ophiolite sequences of these units are regarded as representative of the innermost preserved area of the Liguria-Piemonte basin (e.g., Amaudric du Chaffaut et al. 1972). According to Padoa (1999), four major units can be recognized, each showing a different stratigraphy. All these units show polyphase deformation and HP-LT metamorphism evolving during accretion in the Alpine subduction zone. Despite the pervasive deformation and the accompanying metamorphism, the stratigraphy of the ophiolite sequence can be reconstructed, particularly in the Pointe de Corbara and Inzecca subunits, from the still preserved succession of the different lithologies.

In the Inzecca subunit (Fig. 7), this succession includes a basement consisting of metaserpentinites cut by metagabbro dikes and characterized by metaophicalcites at the top. The metaophicalcites are covered by ophiolitic metarenites alternating with red metapelites, showing an upward transition to a thick metabasalt sequence, originally pillow-lavas and pillow breccias with MOR affinity (Beccaluva et al. 1977), still interbedded with ophiolitic metarenites and red metapelite. The metabasalts are overlain by metacherts and the Erbajolo Formation, corresponding to the Palombini Shale of the Northern Apennines.

By contrast, the Pointe de Corbara unit displays a reduced sequence where metabasalts are absent (Fig. 7). The basement consists of metaserpentinites and minor metagabbros whose mutual contacts, magmatic and/or by faulting, were formed in the oceanic environment. The metagabbros are locally cut by oceanic mylonitic shear zones cut in turn by metabasaltic dikes. Both metaserpentinites and metagabbros, mainly Fe-gabbros, are directly covered by a few meters of ophiolitic metabreccias and metarenites. The poorly sorted breccias include clasts of gabbro,

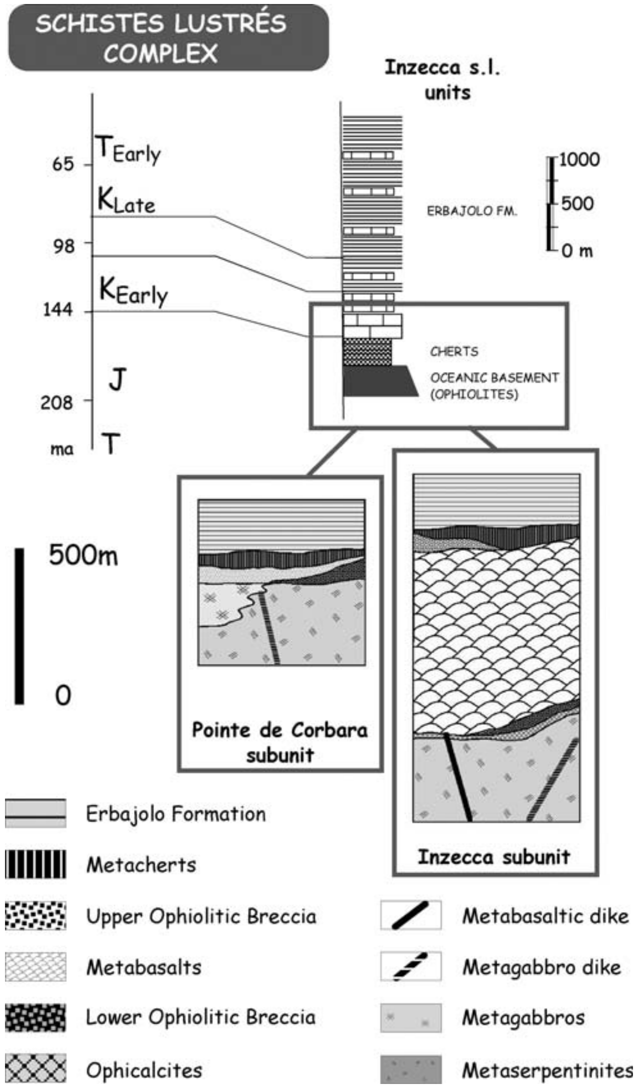

Fig. 7 Reconstruction of the succession of the Schistes Lustrés complex in Corsica. Details of the ophiolite sequence (redrawn from Principi et al. 2004) are shown in the *boxed areas below*

peridotite, plagiogranite, Fe-gabbro, basaltic dike fragments and ophicalcite. No fragments of continental crust rocks have been detected. U/Pb dating on zircons from plagiogranites indicated an age of 161 ± 3 Ma (Ohnenstetter et al. 1981). The metabreccias and metarenites are in turn, covered by metacherts followed by the Erbajolo Formation. Despite Alpine orogenic deformation and metamorphism, the ophiolites locally show very well preserved structures related to their pre-orogenic tectono-metamorphic history (Padoa 1999). The first stage of this history is represented by localized ductile deformation represented by shear zones developed under amphibolite-facies metamorphism, followed by a static recrystallization under greenschist-facies conditions. This retrograde history occurred before the deposition of the sedimentary breccias. The following emplacement of the basaltic flows produced a localized metamorphism under greenschist-metamorphic conditions that affected both the sedimentary breccias and the basement. On the whole, the pre-orogenic tectono-metamorphic history is similar to that of Internal Ligurian units.

Balagne nappe

The general stratigraphy of the Balagne nappe can be reconstructed from the successions of its different units and subunits. Again, a Jurassic ophiolite sequence is overlain by deep-sea deposits including pelagic sediments and turbidites (e.g., Nardi et al. 1978; Fig. 8). According to its stratigraphy (Durand-Delga et al. 1997), the ophiolite sequence comes from an area of the Liguria-Piemonte basin close to the Corsica continental margin. This interpretation fits very well with the reconstruction of the deformation history proposed by Marroni and Pandolfi (2003) that strongly supports an original location of the Balagne nappe close to the Corsica continental margin.

The ophiolite sequence (Fig. 8) is characterized by a 400 m thick oceanic basement, represented by mantle peridotites cut by basaltic and gabbroic dikes. The mantle peridotites are also intruded at a shallow level by a gabbroic complex, mainly represented by fine- and coarse-grained olivine-gabbros. The mantle peridotites and the associated gabbros are covered by a few meters of sedimentary breccia that predates the emplacement of the basaltic flows. This breccia is characterized by fragments of olivine-gabbro, Fe-gabbro, plagiogranite and basalt. U-Pb (SHRIMP) dating of zircons indicated an age of 169 ± 3 Ma for the plagiogranites (Rossi et al. 2002). In addition, the arenitic matrix of the breccia includes detrital mineral grains of zircon, whose typology indicates an origin from calco-alkaline rocks, similar to those cropping out in the Variscan basement of Corsica. The oceanic basement is covered by an up to 500 to 600 m thick succession of basaltic flows, generally showing pillows and pillow breccias. Sills of massive basalts also occur. According to Gruppo di Lavoro sulle Ofioliti Mediterranee (1977) and Durand-Delga et al. (1997), the geochemistry of the basalts suggests an E-MORB affinity, typical of crust formed during the transition from rifting to spreading. Coarse-grained arenites and fine-grained breccias occur in up to 6 m thick packages intercalated between the pillow-lavas. These breccias include fragments of basalt, micaschists,

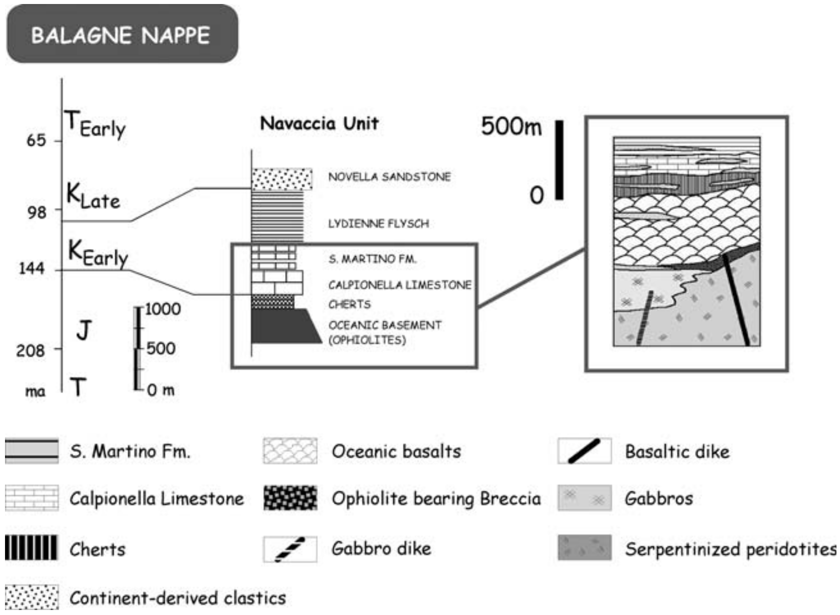

Fig. 8 Reconstruction of the succession of the Balagne nappe. A detail of the ophiolite sequence is shown in the *boxed area*

rhyolites and oolite-bearing limestone of Middle-Late Jurassic age (Rossi and Durand-Delga 2001). The basalts are overlain by Middle to Late Jurassic cherts (middle Callovian-Kimmeridgian, De Wever and Danelian 1995), grading upward into the Calpionella Limestone (Tithonian-Berriasian) and into the San Martino Formation (early Berriasian to late Hauterivian/early Barremian; Marroni et al. 2000). This formation can be correlated with the Palombini Shale of the Ligurian units of the Northern Apennines. The San Martino Formation grades upward into Lydienne Flysch (early Albian to early Turonian, Marino et al. 1995), Toccone Breccia and Novella (= Gare de Novella) Sandstone (late Cenomanian). The occurrence of coarse-grained, continent-derived debris occurring in the cherts, the Calpionella Limestone and the San Martino Formation, yield important information on the original position of the Balagne nappe: the breccias are characterized by a mixed siliciclastic-carbonate composition, whereby the carbonate clasts are mainly Triassic to Jurassic extrabasinal rock fragments, whereas the siliciclastic debris are derived from granitoids, low-grade metamorphic and felsic volcanic rocks. This mixed composition points to a continental margin source area, including a Mesozoic carbonate platform. According to Durand-Delga et al. (1997), this source area was situated in the west-Corsica Variscan basement and its Permian to Jurassic sedimentary cover. However, no fragments of lower continental crust or subcontinental mantle have been detected in the sediments within and above the ophiolite sequence.

The architecture of the Liguria-Piemonte oceanic basin: a tentative reconstruction

With the previously illustrated material, a reconstruction of the crustal structure of the Liguria-Piemonte basin, along the Northern Apennines–Corsica transect, can be attempted. The ocean–continent transition toward the Adria plate can be only reconstructed from the fragmentary data collected in the External Ligurian units. Additional useful information for this reconstruction can be found in the central Alps, where the record of the distal Adriatic margin of Adria is more complete in the south Pennine-Austroalpine boundary units in Grisons (Froitzheim and Manatschal 1996; Hermann and Müntener 1996; Manatschal and Nievergelt 1997; Manatschal and Bernoulli 1999; Desmurs et al. 2001) and in Val Malenco (Hermann and Müntener 1996; Hermann et al. 1997).

In Grisons, the distal margin of the Adria plate has been reconstructed in the Err nappe, where Variscan basement rocks intruded by Paleozoic granitoids on the one side and km-size, tilted blocks consisting of pre-Permian gneiss, Paleozoic granites and Triassic pre-rift sediments on the other side are separated by a system of low-angle detachment faults, accompanied by pre-Alpine cataclastic fault rocks (Froitzheim and Eberli 1990). The km-size blocks in the hanging wall have been interpreted as extensional allochthons displaced and rotated along the detachment faults. This portion of the margin can be combined with the record of the Platta nappe, whose succession can be regarded as a remnant of crust recording the transition from rifting to spreading. This nappe is characterized by a basement of serpentinized mantle peridotites, different types of tectono-sedimentary breccias including ophicalcites, in which, fragments of serpenitinite, gabbro, continent-derived crustal rocks and pre-rift sediments have been found. The mantle peridotites are intruded by shallow-level gabbros of Middle Jurassic age and overlain by basaltic flows and Middle to Late Jurassic cherts (Desmurs et al. 2001). Finally, in the Malenco unit, a former subcontinental mantle-crust transition is exposed that was exhumed in Jurassic times (Hermann and Müntener 1996; Hermann et al. 1997).

External Ligurian units

Taking into account the record of the Pennine and Austroalpine units, the compositional spectrum of the slide-blocks in the sedimentary melanges of the western successions of the External Ligurian units allows the reconstruction of the stratigraphy of their source area that is assumed to be representative of the ocean–continent transition of the Adria margin. Following Marroni et al. (1998), a structure (Fig. 9) characterized by a basement consisting of subcontinental mantle rocks, overlain by felsic and mafic granulites and intruded by minor shallow-level gabbroic bodies may be proposed for the basement of the ocean–continent transition of the External Ligurian units. In our reconstruction, this basement is covered by slices of upper continental crust interpreted as extensional allochthons. Both the basement of the ocean–continent transition and the allochthons of upper continental crust were cut by basaltic dikes and directly covered by massive and pillow-lava basalts, both showing T to N-MOR affinity. No simple mantle-residua and basaltic-melt genetic relationships exist between the peridotites and the overlying basalts (Rampone et al. 1995; Piccardo et al. 2004). The basalts were, in turn covered by Middle Jurassic to Late Cretaceous pelagic deposits, represented by cherts, Calpionella Limestone and Palombini Shale. Both mantle and continental crustal

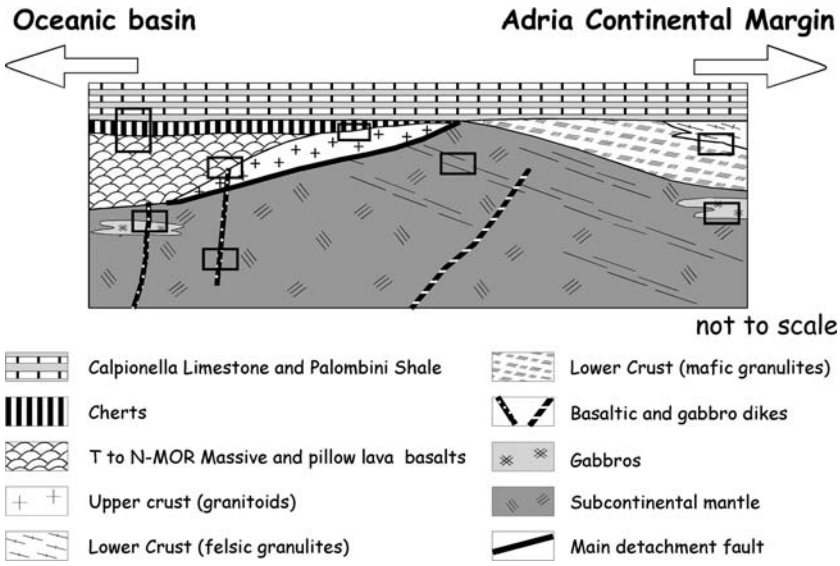

Fig. 9 Simplified model of the ocean–continent transition at the Adriatic margin based on data from the External Ligurian units (redrawn from Marroni et al. 1998). Observed field relationships are indicated by *boxed areas*

rocks, as well as the MOR-type gabbros, were affected by localized mylonitic and cataclastic shear zones, developing at different times and structural levels but connected to the exhumation of deeper crustal levels before the Late Jurassic.

A similar reconstruction has been proposed for the distal Adria margin in the Canavese zone (Elter et al. 1966; Ferrando et al. 2004), regarded as the original southern continuation of the Err and Platta nappes. In this segment of the distal margin, the basement consists of lower continental crustal rocks represented by migmatic gneisses associated with leucogranites and mafic granulites, similar to rocks of the Ivrea zone. In the reconstruction of Ferrando et al. (2004), this basement is overlain by extensional allochthons of upper continental crust. Serpentinite bodies also occur, but their relationships with the other lithologies are unclear. However, both basement and extensional allochthons are covered by sediments including syn-rift breccias grading into pelagic post-rift sediments similar to those of the Ligurian units (Middle to Late Jurassic cherts, Early Cretaceous Maiolica Limestone and Palombini Shale). The similarities between the ocean–continent transition of the External Ligurian units and the Canavese zone suggest lateral continuity in structure and composition along the Adria margin.

Internal Ligurian Units and Schistes Lustrés complex

The stratigraphic successions and the geometrical relationships reconstructed for the Internal Ligurian units and the Schistes Lustrés complex allow reconstruction of the structure of the central parts of the Liguria-Piemonte ocean. The younger age of part of the basalts together with their geochemistry and the occurrence of still younger plagiogranites suggests that these sequences represent a more evolved stage in the oceanization process (e.g., Lombardo et al. 2002). Despite the different imprint of Alpine metamorphism, the general setting reconstructed for the two areas is quite similar (Fig. 10). The differences in metamorphism indicate only that the different oceanic fragments were added at different times to the Alpine accretionary wedge and subducted to different depth; however, their similar pre-Alpine architecture indicates that they are representative of the structure of the oceanic crust of the Liguria-Piemonte basin at the onset of spreading. This structure was characterized by a basement consisting of mantle peridotites intruded at shallow level by minor gabbroic bodies. There exists, however, like in the External Ligurian units, no genetic relationship between relatively fertile peridotites and the N-MOR basaltic melts (Tribuzio et al. 2004 and references therein).

The basement had a polyphase, ductile to brittle tectonic history under retrograde amphibolite- to greenschist-facies metamorphic conditions, reflecting the progressive exhumation of the mantle peridotites and the associated gabbros in the seafloor during the Middle Jurassic. The ophicalcites covering the exhumed peridotites everywhere probably mark the trace of the low-angle detachment(s) along which, the mantle was exhumed (Treves and Harper 1994; Bernoulli et al. 2003).

Exhumation of the mantle was achieved before the deposition of the ophiolitic sedimentary breccias and basaltic flows that in turn, are covered by pelagic sed-

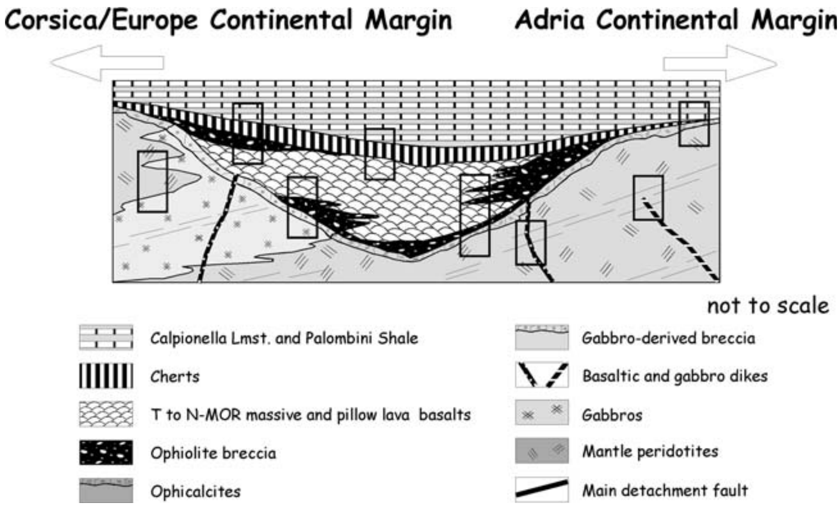

Fig. 10 Simplified model of the oceanic domain based on data from the Internal Ligurian units and the Schistes Lustrés complex of Corsica. Observed field relationships are indicated by *boxed areas*

iments. However, the oceanic crust was also characterized by tectonic highs of peridotites and gabbros, today represented by sequences where the volcano-sedimentary complex is lacking and the basement is directly covered by pelagic deposits.

Balagne nappe

A similar stratigraphy can been reconstructed for the ophiolite sequence of the Balagne nappe (Fig. 11). As in the Internal Ligurian units and the Schistes Lustrés complex, the basement consists of mantle peridotites, intruded by minor gabbroic bodies and covered by basaltic flows and ophiolitic breccias. However, the Balagne nappe shows a relevant difference, i.e., the occurrence of fine-grained clastics, derived from the Corsica continental margin and occurring below and intercalated with the basaltic flows. Very coarse-grained clastic deposits of the same origin are also recognized in the overlying cherts and Calpionella Limestone. Therefore, the ophiolite sequence of the Balagne nappe probably represents an area of the Liguria-Piemonte basin that was very close to the Corsica continental margin, the source area of the clastic deposits. Amaudric du Chaffaut et al. (1984) have depicted the transition from the oceanic basin to the Corsica continental margin as a sharp boundary with escarpments induced by high-angle normal faulting (Fig. 11). The occurrence of such, probably steep scarps, is consistent with the very corse-grained and immature debris associated with the basalts and their sedimentary cover. In addition, the stratigraphy of the tectonic units derived from the Corsica continental margin (Caporalino-S.Angelo nappe, Corte units, Palasca unit, and Tenda massif) indicates that this margin was characterized by a basement of upper continental crust covered by pre- and syn-rift sediments, mainly carbonate. The only exception is the Santa Lucia

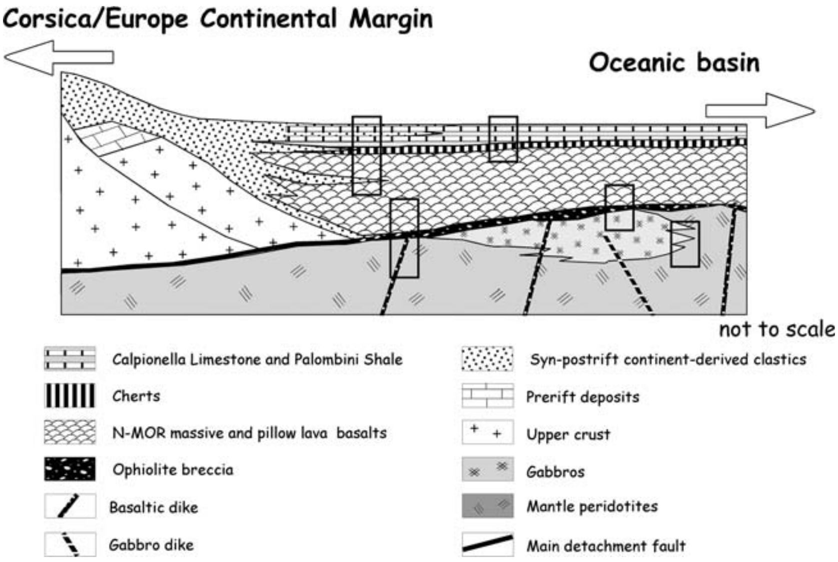

Fig. 11 Reconstruction of the ocean–continent transition at the Corsica/Europe margin based on data from the Balagne nappe. Observed field-relationships are indicated by *boxed areas*

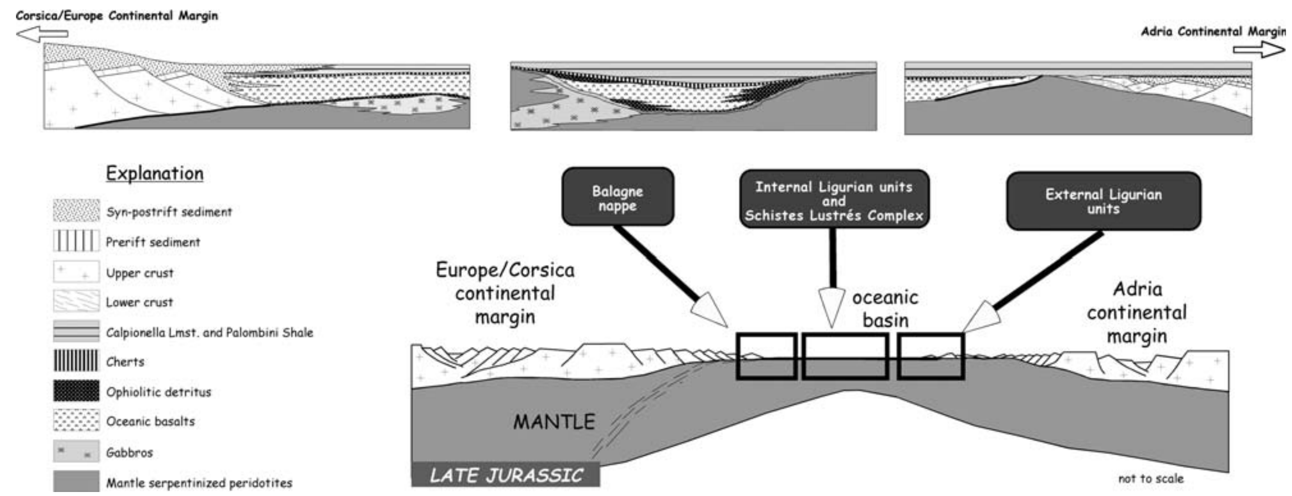

Fig. 12 Tentative reconstruction of the Jurassic Liguria-Piemonte basin along the Northern Apennines–Alpine Corsica transect

nappe, the basement of which includes a granulite complex of Permian age associated with granitoids both covered by Cretaceous sediments (e.g., Libourel 1988). However, the pre-orogenic history of this nappe is still a matter of debate: even an origin from the Adria continental margin has been proposed, for instance, by Dallan and Nardi (1984).

The overall architecture

From the evidence collected across the Northern Apennines and Corsica and from a comparison with the analogous situations in Pennine and Austroalpine units of the Alps, a picture of the Liguria-Piemonte basin results that includes a rugged morphology, where highs of peridotites and/or gabbros are bounded by small basins and where these rocks are covered by a volcano-sedimentary complex (Fig. 12). This oceanic crust is bounded by two markedly different transition zones toward the continental margins. Along the Corsica continental margin, the transitions to the oceanic crust are sharp with escarpments induced by high-angle normal faulting. Seaward from those, continent-derived clastics overlie the mantle peridotites and are intercalated between the basaltic flows and the pelagic sedimentary cover. The ocean–continent transition at the Adria margin is totally different: here, an area of exhumed subcontinental mantle and lower continental crustal rocks were covered by extensional allochthons of upper continental crust emplaced along low-angle detachments. Basaltic dikes cut across the allochthons and basaltic flows cover them locally.

Our reconstruction is consistent with the petrographic and geochemical data of the clastic sediments of the Balagne nappe and of the Internal and External Ligurian units (Bracciali et al. 2006). Only sediments older than Campanian, i.e., those preceding the large-scale deformation of the continental margins, are considered. The petrography of the pebbles from rudites and lithic fragments from arenites in the Lydiennes, Toccone and Val Lavagna Shale Fms. indicates that the clastic material of Balagne and the Internal Ligurian units is derived from low-grade metamorphic terrains and from carbonate platforms. By contrast, the clasts in the Ostia Sandstone and Salti del Diavolo Conglomerate of the External Ligurian units came from low-, medium- and high-grade metamorphic rocks and even mm-sized chromian spinel mineral grains, probably derived from mantle rocks are found. Sedimentary lithoclasts include carbonate platform and pelagic rock fragments. Geochemical data on pelites from Palombini Shale and Ostia Sandstone from the External Ligurian units suggest a more mafic/ultramafic character, compared to samples from the Lydiennes, Toccone, Palombini Shale and Val Lavagna Shale Fms. of Balagne and the Internal Ligurian units. Petrographic and chemical data thus suggest that the clastic material of the Balagne nappe and the Internal Ligurian units came from the upper continental crust of the Corsica continental margin and its carbonate sedimentary cover, whereas, by contrast, the clastic material of the External Ligurian units was supplied by the Adria continental margin, where in particular, deeper continental crust and mantle rocks were exposed.

Comparison with the Cretaceous Iberia–Newfoundland continental margins

Our reconstruction of the architecture of the Liguria-Piemonte basin can be compared with an example not involved in orogeny and with only moderate post-rift deformation: the Early Cretaceous Iberia–Newfoundland conjugate margins of the northern Atlantic ocean (Manatschal and Bernoulli 1998, 1999; Whitmarsh et al. 2001; Manatschal 2004).

ODP Legs 103, 149 and 173, investigated the Iberian margin and revealed its complex architecture. The proximal margin, including the Interior and Porto basins (Montenat et al. 1988; Pérez-Gussinyé et al. 2003), is characterized by a 20–30 km-thick continental crust with superimposed elongate symmetrical basins bounded by normal faults dipping toward the basin centers. An alignment of non-volcanic seamounts, Galicia bank, represents the boundary that separates the proximal from the distal margin. The distal margin and the ocean–continent transition, is characterized by tilted blocks, up to 7 km thick, overlying a prominent reflection in seismic profiles. This reflection, known as the S reflector (Boillot et al. 1987), can be followed oceanward, where it represents the top of a basement of serpentinized peridotites interpreted as subcontinental mantle. The tilted blocks, consisting of continental crustal rocks and pre-rift sediments and decreasing in size towards the ocean, are bounded by downward-flattening and concave-upward listric faults and covered by onlapping syn-rift sediments. Oceanward, a ridge of serpentinized peridotites (the ‘‘peridotite ridge’’ of Boillot et al. 1980) is interpreted to separate this transitional crust from a truly oceanic domain. Basalts and gabbros occur locally on the peridotite ridge, that along its eastern flank it is characterized by a tectono-sedimentary breccia with clasts of mafic, ultramafic and continent-derived rocks. In the Iberian margin, the ocean–continent transition, thus consists of a 40–130 km wide area (Zone of Exhumed Continental Mantle, called ZECM by Manatschal 2004), where the top of the serpentinized peridotites is thought to be an exhumed detachment fault and the tilted blocks of continental crust are interpreted as extensional allochthons emplaced during the final stage of rifting.

Less information is available on the Newfoundland margin, where only two wells have been drilled by ODP (Tucholke and Sibuet et al. 2004). However, the available seismic profiles show that the continental crust, affected by east-dipping normal faults, thins dramatically over a distance of about 75 km toward the oceanic basin (e.g., Funck et al. 2003). Indeed, the two conjugate margins of Iberia and Newfoundland display very contrasting architectures, particularly along the transition from continental to oceanic crust. This asymmetry is very similar to the one observed for the Liguria-Piemonte basin (Hölker et al. 2002a, b). The occurrence of a basement of subcontinental mantle rocks overlain by suspected extensional allochthons of continental upper crust can be compared to the situation of the Iberian margin and contrasts with the sharp transition from continental to oceanic crust observed along the Corsican and the Newfoundland margins. These pronounced analogies suggest that the rifting processes in both areas were similar.

Discussion of genetic models

The different models proposed for the rifting of the west-Mediterranean Tethys (symmetric, asymmetric with a west-dipping detachment fault system, and asymmetric with an east-dipping detachment fault system) can now be compared with the architecture reconstructed by us for the Liguria-Piemonte. The asymmetry of its margins has been emphasized earlier: in the External Ligurian units, the exhumation of subcontinental mantle and lower crust to the sea floor, the probable existence of extensional allochthonous, and a wide, ocean–continent transition, suggest that the role of lower plate was played by the Adria plate, as proposed, for instance, by Lemoine et al. (1987); Hoogerduijn Strating et al. (1993); Froitzheim and Manatschal (1996); Hermann and Müntener (1996); Manatschal and Nievergelt (1997); Hermann et al. (1997); Marroni et al. (1998); Manatschal and Bernoulli (1999); Desmurs et al. (2001); Manatschal (2004) and many others. This asymmetric configuration developed, however, only during the second stage of the rifting, as proposed by Whitmarsh et al. (2001) and Lavier and Manatschal (2006).

Another problem is the significance of the innermost preserved part of the Liguria-Piemonte basin. The Internal Ligurian units and the Schistes Lustrés complex of the Inzecca area preserve only a thin, incomplete sequence with a basement of serpentinized mantle peridotites and younger intrusive gabbros, covered by ophiolitic sedimentary breccias interfingering with basaltic flows. The geochemistry of the mantle peridotites is similar to that of residual abyssal peridotites; however, significant differences exist (Rampone et al. 1996; Piccardo et al. 2004). By contrast, the gabbros and basaltic rocks display a clear N-MORB Nd-isotopic signature (Rampone et al. 1996; Tribuzio et al. 2000; Tribuzio et al. 2004). Geochemically, the basalts and gabbros from Internal Ligurian ophiolites sequence are representative of a more evolved stage among the today-exposed remnants of the Liguria-Piemonte basin.

Gianelli and Principi (1977) suggested an origin of the ophiolites of the Northern Apennines and Corsica in an ocean dominated by transform faults. In their model, exhumation of the mantle peridotites occurred by diapirism in a transform fault valley together with serpentinization. In this context, the basaltic flows were emplaced when the transform valley was transported close to the segment of an active spreading ridge, whereas the sedimentary breccias were derived from the flanks of the valley. However, this model seems not to be consistent with the complete lack in all oceanic units, from the Alps to Calabria, of remnants of ''complete'' oceanic crust generated in a ridge. To explain this lack, selective sampling of the oceanic crust during subduction has been postulated by Abbate et al. (1980).

An alternative model, interpreting the oceanic crust of the innermost preserved areas as the product of slow spreading, has been proposed by Barrett and Spooner (1977) and, more recently, by Lagabrielle and Cannat (1990), Lagabrielle and Lemoine (1997) and Principi et al. (2004). In this type of oceanic basin, magmatic and amagmatic stages are alternating; in a first stage a complete section of oceanic crust is built up, whereas in the following stage, the newly formed crust is destroyed by extension. During extension, the oceanic crust is delaminated by low-angle normal faults and mantle peridotites and gabbros are exhumed to the sea floor (e.g., Tucholke and Lin 1994).

This latter model is consistent with the geochemical MOR affinity of the basalts of the ophiolites but does not fit with the characteristics of the mantle rocks of the Internal Ligurian units: Petrological evidence suggests that these rocks are subcontinental mantle rocks that underwent exhumation during Jurassic pre-oceanic extension (Rampone and Piccardo 2000, Piccardo et al. 2004 and references therein). As suggested by Whitmarsh et al. (2001) and Lavier and Manatschal (2006), an association of subcontinental mantle and MOR basalts may develop at the onset of seafloor spreading, under the influence of a rising astenosphere. During this phase, MORB magmatic rocks may intrude into and/or be extruded onto the previously exhumed subcontinental mantle, leading to the close association of subcontinental mantle and MOR basalts as observed in the Internal Ligurian units. If this interpretation is correct, no record of a spreading phase is known up to date. However, the subcontinental mantle rocks record a history of two different magmatic cycles, an early magmatic, non-volcanic stage followed by a late volcanic one (Piccardo et al. 2004). These characteristics are typical of the ophiolites derived from slow- and very slow-spreading ridges, as suggested by the data from the present-day Atlantic ocean (e.g., MARK area; Mével et al. 1991; Karson and Lawrence 1997; Cannat et al. 1997). Therefore, the ocean crust of the Liguria-Piemonte basin could possibly also be derived from a slow- to very-slow spreading ridge.

Conclusions

Our reconstruction of the architecture of the Liguria-Piemonte basin is based on the characteristics of a few selected examples of ophiolite sequences from the Northern Apennines and Corsica. The resulting picture shows a strong asymmetry between the two conjugate basin margins. Along the Corsica margin, the transition from continental to oceanic crust is sharp and characterized by a escarpments induced by high-angle normal faults, and the exhumed mantle peridotites are overlain, the basalts interbedded with continent-derived clastics. By contrast, the Adria continental margin shows a wide ocean–continent transition, occupied by subcontinental mantle rocks exhumed to the seafloor, intruded by gabbros and covered by extensional allochthons of upper continental crust. This basement is in turn, covered by basaltic flows and pelagic sediments. The innermost preserved area is characterized by a rugged morphology where highs of peridotite and/or gabbro are bordered by small basins where the basement is covered by a volcano-sedimentary complex. This architecture can be interpreted as the result of final rifting characterized by passive, asymmetrical extension of the lithosphere along one or more west-dipping detachment faults. Rifting was followed by the onset of oceanic spreading, probably leading to the development of a very slow- or slow-spreading mid-ocean ridge. However, the spreading stage remains still very hypothetical and further investigations are required to confirm it for the Apenninic and Corsican ophiolites.

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