

# Evolution of the lithospheric mantle in an extensional setting: Insights from ophiolitic peridotites

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## ABSTRACT

We present a model of mantle lithosphere evolution in an extensional setting based on the structure and petrology of the Alpine-Apennine ophiolitic peridotites from the Jurassic Ligurian Tethys Ocean. Continental extension and rifting in the Ligurian domain were induced by far-field tectonic forces and were characterized by the interplay of tectonic and magmatic processes. Extension and thinning of the lithosphere induced adiabatic upwelling and decompression melting of the asthenosphere. Mid-ocean-ridge basalt (MORB) melts percolated by porous flow through the extending lithospheric mantle and were trapped therein by interstitial crystallization. Therefore, melt emplacement at the seafloor during continental rifting and breakup was prevented, and the resulting rifted margins of the basin were nonvolcanic. The asthenosphere-lithosphere interaction induced significant rheological modifications of the percolated mantle. Weakening and softening of the mantle lithosphere significantly lowered the total lithospheric strength. Accordingly, thermo-mechanical erosion of the mantle lithosphere promoted lithosphere stretching and thinning and enhanced the transition from distributed continental deformation to localized oceanic spreading.

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## INTRODUCTION

The ophiolites of the Alpine-Apennine belt (Fig. 1) preserve lithospheric remnants of the Jurassic Ligurian-Piemontese or Ligurian Tethys oceanic basin. Current evidence indicates that the Ligurian Tethys was characterized by nonvolcanic passive margins and seafloor exposure of the subcontinental mantle, similar to the actual paired Newfoundland-Iberia margins of the North Atlantic (e.g., Whitmarsh et al., 2001). The development of the Ligurian Tethys is believed to represent a case of passive (and hence cold) stretching of the pertinent Europe-Adria lithosphere induced by the action of far-field tectonic forces (see discussion in Piccardo and Vissers, 2007). Continental extension in the Europe-Adria system started, most probably, during Triassic times (around 220–225 Ma), and the onset of major rifting occurred in Liassic times (around 190 Ma), as shown by Capitano and Goes (2006), whereas only a minor amount of extension was contributed by earlier slow continental extension and rifting (e.g., Dercourt et al., 1986; Frotzheim and Manatschal, 1996).

Nevertheless, in reconstructing the development of the Ligurian Tethys basin, two major issues need to be adequately addressed, namely, the geological reasons for the nonvolcanic nature of the rifted margins and the transition from continental extension to seafloor spreading. The structural, petrologic, geochemical, and geochronologic features recorded by the mantle peridotites of the Alpine-Apennine ophiolites furnish appropriate information to discuss these points from a mantle lithosphere perspective and allow us to reconstruct a composite scenario of the tectonic and magmatic processes that occurred in the extending mantle lithosphere during the rifting stages of the Ligurian Tethys.

## LIGURIAN LITHOSPHERIC MANTLE

Studies of the Alpine-Apennine ophiolitic peridotites from the Ligurian Tethys (Fig. 1) have provided a wealth of structural, petrologic, and geochemical data that are relevant to the thermo-mechanical history of the lithospheric upper mantle during rift evolution of the continental lithosphere. It is well established that Alpine-Apennine peridotites record both: (1) significant effects of subsolidus evolution and nonadiabatic exhumation from subcontinental spinel-facies mantle depths to the seafloor (e.g., Hoogerduijn Strating et al., 1993; Montanini et al., 2006; Piccardo and Vissers, 2007); and (2) significant effects of interaction with percolating asthenospheric melts (e.g., Müntener and Piccardo, 2003; Piccardo et al., 2004, 2007a; Piccardo and Vissers, 2007). Exhumed subcontinental peridotites and melt-modified peridotites characterize, respectively, the ophiolite sequences deriving from ocean-continent transition zones and more internal oceanic settings of the basin (Fig. 2). Thus, mantle peridotites show strong compositional heterogeneity and strict relationships between paleogeographic settings and petrologic features, demonstrating that the various peridotite bodies record different processes related to distinct steps of lithosphere evolution (Piccardo, 2008, and references therein).

## Exhumed Subcontinental Peridotites

Exhumed subcontinental peridotites from ocean-continent transition settings are clinopyroxene-rich fertile lherzolites consistent with spinel-facies assemblages. They are usually veined by spinel(-garnet)-pyroxenite bands (Fig. 3A). Structural-paragenetic features and geothermometric data (Montanini et al., 2006; Piccardo et al., 2007b; Piccardo, 2008) indicate that these mantle protoliths were uplifted from garnet-facies conditions (pressure [ $P$ ] > 2.5 GPa), they were equilibrated at pressures compatible with spinel-facies conditions (2.5 GPa >  $P$  > 1.0 GPa), and they were formed at temperatures in the range 900–1100 °C, at an average continental

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geotherm. They were strongly deformed in up to kilometer-scale shear zones (Fig. 3B) that show syntectonic mineral assemblages varying from spinel- to plagioclase- to amphibole-(chlorite)-peridotite facies, followed by shallow serpentinization (Vissers et al., 1991). This indicates progressive recrystallization under decreasing pressure-temperature (*P-T*) conditions during exhumation. Accordingly, an extensional shear zone network accommodated stretching and thinning of the subcontinental lithospheric mantle and its exhumation toward the seafloor.

**Melt-Modified Peridotites**

Melt-modified peridotites from the more internal oceanic settings show extreme compositional heterogeneities, varying from pyroxene-depleted spinel harzburgites to plagioclase-enriched peridotites to pyroxene-free spinel dunites. Their structural and compositional features indicate significant effects of melt-rock interaction processes (Piccardo, 2003, 2008; Müntener and Piccardo, 2003; Piccardo et al., 2007a). Geochemical evidence indicates that interacting melts had mid-ocean-ridge basalt (MORB) affinity and were formed by fractional melting of a depleted mantle source under spinel-facies conditions. Early reactive infiltration of MORB melts in the extending lithospheric mantle caused pyroxene dissolution and olivine precipitation and transformed the peridotite protoliths into strongly pyroxene-depleted, reactive spinel harzburgites (Figs. 3C–3D). Subsequent MORB melt interstitial crystallization enriched the spinel peridotites in plagioclase and microgabbroic aggregates and transformed the preexisting peridotites into impregnated plagioclase peridotites (Figs. 3E–3F). Afterward, newly formed extensional shear zones were exploited for the focused and reactive migration of MORB melts and were transformed into channels of replacive spinel harzburgites and dunites (Figs. 3G–3H).

Depending on the silica-saturation of the percolating MORB melts and the depth and mode of melt-peridotite interaction, different types of melt-modified peridotites were formed. At the inception of percolation, most probably under spinel-facies conditions and temperatures higher than the pertinent liquidus conditions, silica-undersaturated melts migrating at high melt-rock ratios and open-system conditions caused significant dissolution of mantle pyroxenes and olivine precipitation. The percolated mantle peridotites were progressively transformed into pyroxene-depleted, olivine-enriched harzburgites (Kelemen et al., 1995). Further melt infiltration occurred, most probably, under plagioclase-facies conditions and slightly decreased temperatures (from slightly above to slightly below melt liquidus conditions). The percolating melts underwent interstitial crystallization of early cumulus phases, adding plagioclase and microgabbroic aggregates to the percolated mantle peridotites, which were thus refertilized and transformed into impregnated plagioclase peridotites enriched in basaltic components.

Information on the geochemical affinity of the percolating melts has been obtained from the trace-element composition of clinopyroxenes from the melt-modified peridotites, assuming their complete trace-element equilibration with the percolating melts. The calculated compositions are quite consistent with single melt increments of variable degrees (5%–7%) after fractional melting of a depleted mantle asthenospheric mantle source under spinel-facies conditions (Piccardo et al., 2007a; Piccardo and Vissers, 2007).

Geothermometric data indicate that the spinel-facies lithospheric mantle protoliths record temperatures in the range 900–1100 °C, which are related to their residence in the subcontinental lithosphere. The melt-modified peridotites record peak temperatures of ~1250–1300 °C, which indicate significant heating by asthenospheric upwelling and melt percolation, and asthenospheric thermal conditions in the percolated lithosphere (Piccardo,

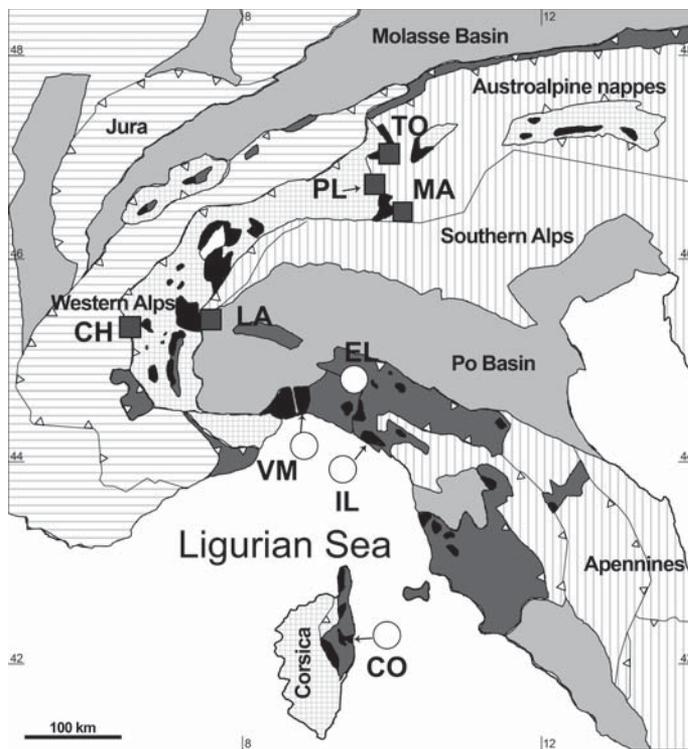


Figure 1. Ophiolite distribution in the central-western Ligurian Alps and Northern Apennines (and Corsica). Central Alps: TO—Totalp, MA—Malenco, PL—Platta; western Alps: LA—Lanzo, CH—Chenaillet; Liguria: VM—Voltri Massif, EL—External Ligurides, IL—Internal Ligurides; Corsica—CO (Monte Maggiore).

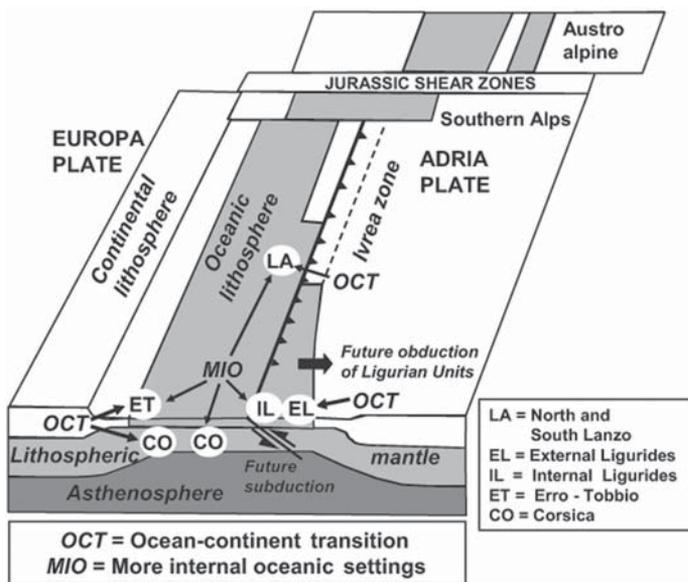
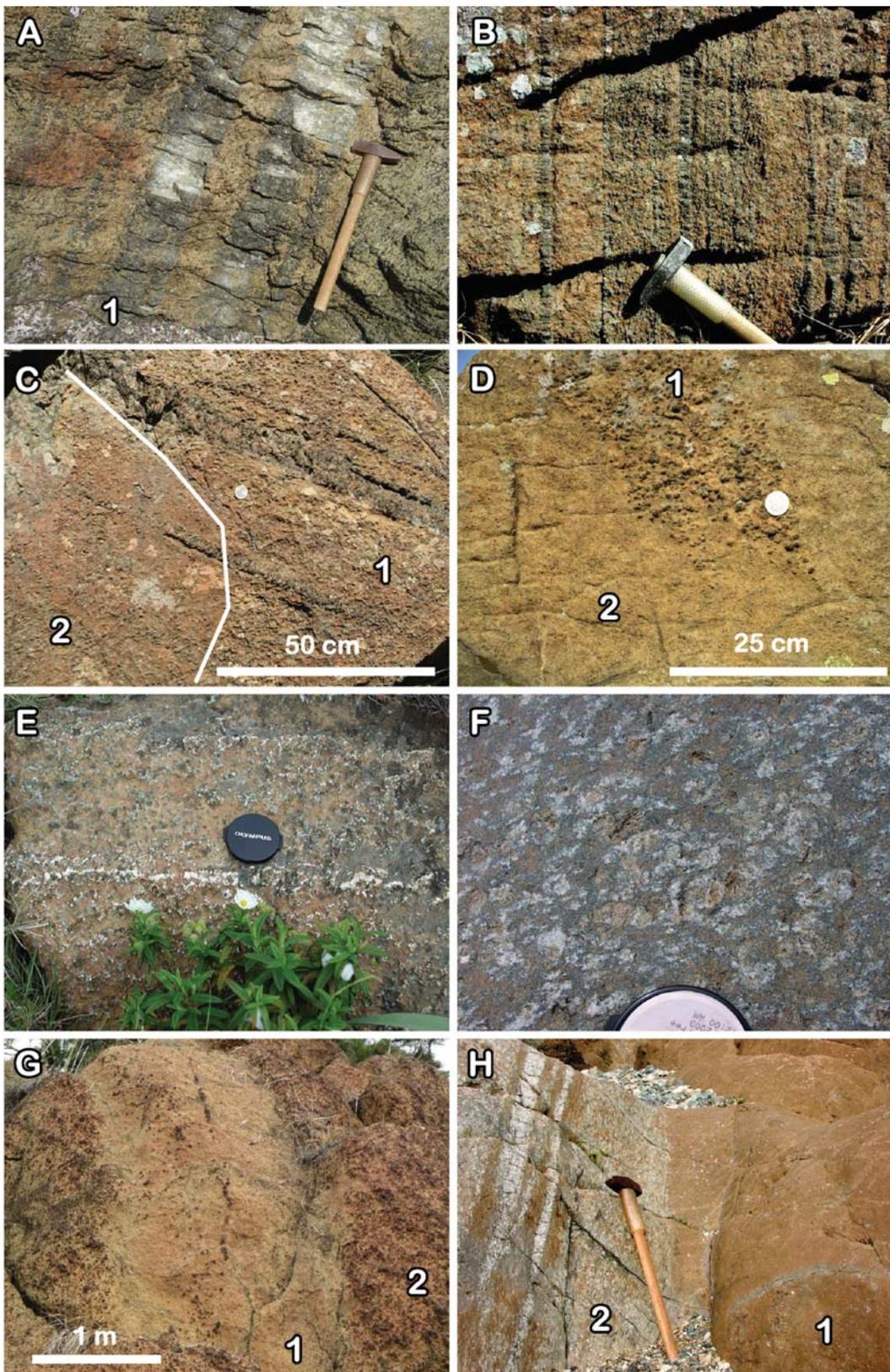


Figure 2. Generalized paleogeographic reconstruction of the Ligurian Tethys in the Late Jurassic, with location of the main ophiolite sequences at the ocean-continent transition (OCT) and more internal oceanic (MIO) settings and the future subduction zone (redrawn and modified after Piccardo, 2008). Note that two major sections across the Adria margin, i.e., Lanzo and the Ligurides, are characterized by exhumed subcontinental peridotites close to the continental margin (i.e., ocean-continent transition zones: North Lanzo and External Ligurides) and melt-modified peridotites at more internal oceanic settings (i.e., South Lanzo and Internal Ligurides).



**Figure 3.** Alpine-Apennine ophiolitic peridotites: some field evidence from Mount Maggiore, Corsica (A, E), Erro-Tobbio, Voltri Massif (B, C, F, and H), and South Lanzo, western Alps (D, G). (A) Pyroxenite (1)-bearing fertile subcontinental lithospheric peridotite. (B) Pyroxenite-rich tectonite-mylonite in shear zone. (C) Tectonite-mylonite of the shear zone (1) partially replaced by pyroxene-depleted reactive spinel harzburgite (2). Note the progressive dissolution of the pyroxenite bands in the reactive rock. (D) Compositional-structural variability of the reactive spinel peridotites: (1) coarse granular harzburgite; (2) fine-grained orthopyroxene (opx)-bearing dunite. (E) Strongly impregnated plagioclase peridotite. Note the thin gabbroic veins. (F) Strongly plagioclase-enriched impregnated peridotite. (G) Meter-wide replacive dunite channel (1) running through spinel harzburgite (2). (H) Decameter-wide replacive dunite channel (1) running within tectonites-mylonites (2) of a kilometer-scale shear zone.

2003; Piccardo and Vissers, 2007). Abundance of “hot” melt-impregnated peridotites along the axial zone of the extending system indicates that: (1) substantial volumes of asthenospheric melts were entrapped in the mantle lithosphere, and (2) significant portions of the extending lithosphere underwent thermo-chemical erosion.

### TIME CONSTRAINTS ON MANTLE PROCESSES

Available isotope data for peridotites and gabbros from the Alpine-Apennine ophiolites allow us to put time constraints on the mantle processes in the Ligurian Tethys domain. Reliable geochronologic information is mostly provided by Sm-Nd clinopyroxene–plagioclase–whole rock isochron ages and Sm-Nd model ages calculated using as reference the depleted mantle (DM) and the chondritic uniform reservoir (CHUR). These latter, although largely indicative and questionable, may help to depict a comprehensive scenario if discussed in the frame of the more reliable isochron ages.

Some peridotites from the External Ligurides (EL) and North Lanzo (NL) ocean-continent transition settings preserve Proterozoic DM and CHUR model ages (in the range 0.8–2.5 Ga) (data from Bodinier et al., 1991; Rampone et al., 1995). Regardless of the absolute values, these ages reflect their long-term isolation from the convective mantle and accretion to the thermal lithosphere. The Triassic onset of Mesozoic extension is constrained in extensional shear zones by Lu-Hf isochrones (minimum age of  $220 \pm 13$  Ma) on External Ligurides pyroxenites (Montanini et al., 2006) and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages (225 Ma) on amphiboles from Malenco peridotites (Müntener and Hermann, 2001).

In contrast with the suggestion that mantle exhumation is a late-stage process in the story of continental extension (e.g., Lavier and Manatschal, 2006), available age data indicate that exhumation of the lithospheric mantle occurred quite early (i.e., Triassic times), and these data point to Liassic times (190 Ma) for the onset of major rifting (Capitanio and Goes, 2006). Important geodynamic implications for the evolution of the extensional system include the early necking of the subcontinental lithospheric mantle (see, for instance, the model of Brun and Beslier, 1996) and the adiabatic upwelling and decompressional melting of the asthenosphere.

The first appearance of melts in the lithosphere is an important event in reconstructing the evolution of the asthenosphere–lithosphere system, since it documents the inception of decompression-induced partial melting of the asthenosphere. Available isotope data point to an Early Jurassic age, as documented by Sm-Nd clinopyroxene–plagioclase–whole-rock isochron ages of some gabbroic intrusions in peridotites from the paired Europe and Adria ocean-continent transition margins of the basin (Erro-Tobbio— $180 \pm 14$  Ma, Borghini et al., 2007; External Ligurides— $179 \pm 9$  Ma, Tribuzio et al., 2004). DM model ages of clinopyroxene from some Erro-Tobbio reactive and impregnated peridotites (data from Rampone et al., 2005) yield consistent ages of 170–175 Ma. Lithosphere stretching and decompression-induced melting of the asthenosphere are, accordingly, closely related. In summary, Triassic extension and Liassic major rifting (Capitanio and Goes, 2006) caused significant thinning of the lithosphere and adiabatic upwelling of the asthenosphere, which underwent decompression-induced partial melting starting from 180 Ma.

The timing of large impregnation/intrusion events is also well constrained. Jurassic ages (164 Ma) are furnished by Sm-Nd clinopyroxene–plagioclase(–whole-rock) isochron ages in External Ligurides impregnated plagioclase peridotites (data from Rampone et al., 1995) and Internal Ligurides gabbroic intrusions (data from Rampone et al., 1998). Middle–Late Jurassic Sm-Nd clinopyroxene–plagioclase(–whole-rock) isochron ages are recorded by one impregnated peridotite ( $155 \pm 6$  Ma) and one gabbroic dike ( $162 \pm 10$  Ma) from Mount Maggiore, Corsica (data from Rampone et al., 2008), whereas clinopyroxene DM model ages from Mount Mag-

giore reactive and impregnated peridotites furnish consistent Late Jurassic age estimates (150 Ma).

In summary, peridotites that were exhumed and exposed on the seafloor closer to Europe and Adria ocean-continent transition margins record the earlier episodes of MORB percolation and intrusion documented by the slightly older, Early Jurassic ages (ca. 180–170 Ma). In contrast, peridotites exposed on the seafloor at more internal oceanic settings record slightly younger melt percolation and intrusion events (Middle–Late Jurassic, i.e., ca. 162–150 Ma).

In this scenario, the meaning of the Permian ages provided by clinopyroxene–plagioclase(–whole-rock) isochrons for some Erro-Tobbio plagioclase-bearing peridotite mylonites (Rampone et al., 2005) is a matter of concern. These ages are regarded as the best estimate for the onset of exhumation. Nevertheless, we believe that these Permian ages are poorly constrained, given the lack of evidence for complete equilibrium between clinopyroxene and plagioclase in these mylonites and the variability of the in situ trace-element composition of plagioclase grains (laser ablation–inductively coupled plasma–mass spectrometry data) relative to the bulk analysis of mineral separates (thermal ionization mass spectrometry data in Rampone et al., 2005). In contrast, the analyzed clinopyroxenes exhibit a constant composition that unequivocally yields Early Jurassic DM model ages. On this basis, the Permian ages are not further considered in this paper.

### CONTINENTAL EXTENSION IN THE LIGURIAN TETHYS DOMAIN

From laboratory experiments, Brun and Beslier (1996) derived a model to explain passive-margin formation leading to mantle exhumation under progressive stretching of the lithosphere. Strain softening in local zones leads to a necking of the whole lithosphere, while the relative displacement between the crust and the lithospheric mantle is accommodated by reversal of the shear sense on each side of the lithosphere neck axis. Extreme crustal thinning and breakup in the central part of the lithosphere neck result in the exhumation and seafloor exposure of the subcontinental lithospheric mantle. The mantle rocks that are exhumed at the two passive margins are those that have been sheared along mantle shear zones (Brun and Beslier, 1996). The model proposed by Brun and Beslier (1996, their Figure 6, p. 168) is highly appropriate to describe the tectonic evolution from rifting to spreading of the Ligurian Tethys, which led to the formation of the passive margins and to the seafloor exposure of the subcontinental lithospheric mantle (see Fig. 4).

Available field, structural, petrologic, and geochronologic data from the Alpine-Apennine ophiolitic peridotites allow us to envisage the geodynamic scenario for the tectonic and magmatic evolution of the lithospheric mantle during extension and rifting, from exhumation to seafloor exposure at the continent-ocean transition. We infer that: (1) extension of the mantle lithosphere was accommodated by a network of shear zones; (2) the asthenosphere underwent adiabatic upwelling and decompression melting during lithospheric extension and thinning; and (3) asthenospheric melts infiltrated through, and were trapped in, the mantle lithosphere. Asthenosphere melting and lithosphere melt infiltration were accompanied by early gabbroic intrusions into the lithospheric mantle sectors that were later exhumed and exposed at the paired Europe (Erro-Tobbio) and Adria (External Ligurides) ocean-continent transition zones during oceanic opening. The almost identical intrusion ages of these gabbroic intrusions (179–180 Ma) strongly suggest a symmetric pure shear evolution for extension and rifting (Fig. 4).

Lithosphere extension was, most probably, an ultraslow process, as inferred, for example, by Pérez-Gussinyé et al. (2006) for rifting where “mantle exhumation begins before melting.” Extension was already active

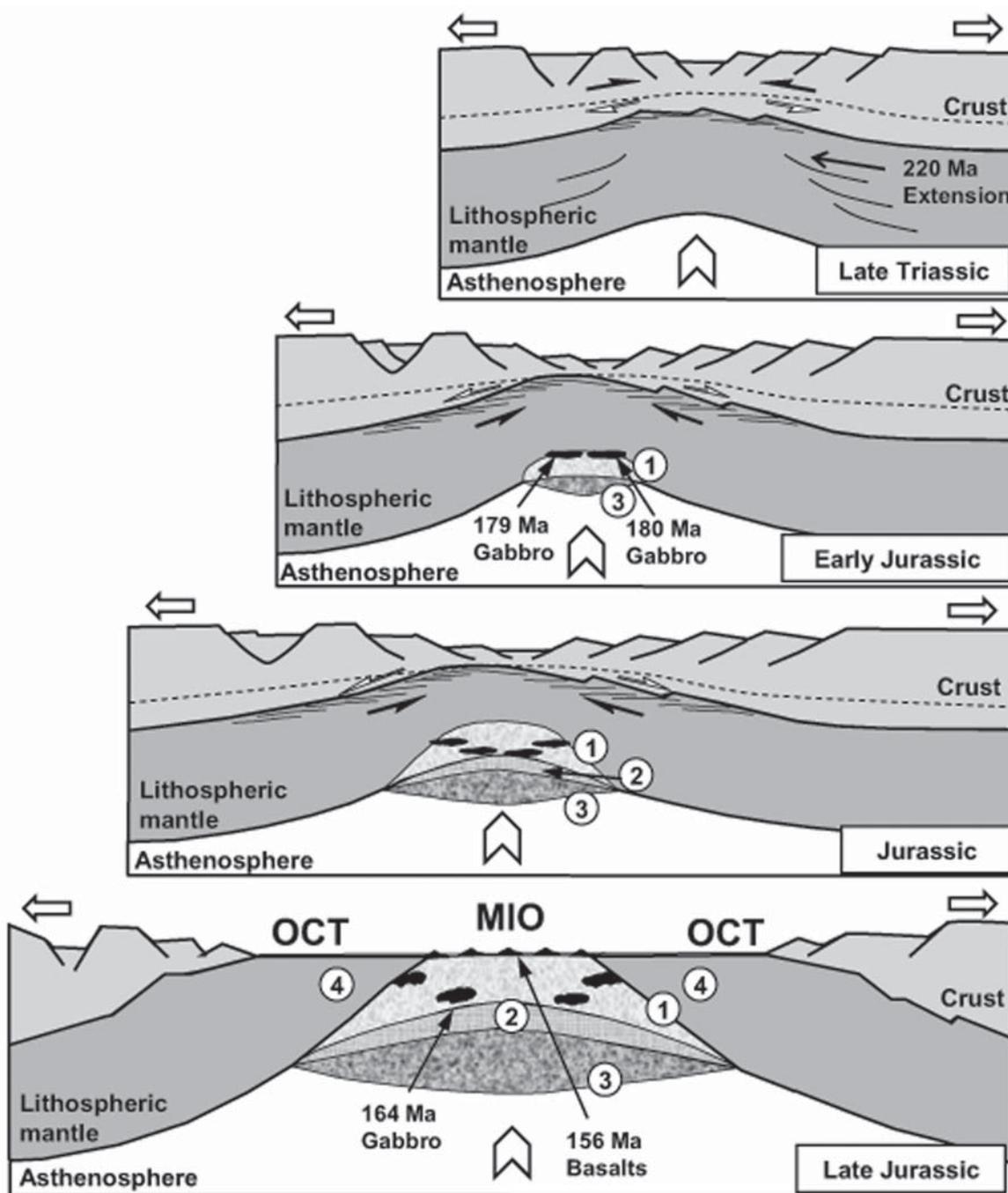


Figure 4. The geodynamic evolution of the Ligurian Tethys (from top to bottom). Late Triassic times—Extension of the continental lithosphere, tectonic exhumation of lithospheric mantle, and adiabatic upwelling of the asthenosphere. Lithosphere extension was already active during the Triassic (220 Ma) and was accommodated by kilometer-scale extensional shear zones. Early Jurassic times—The adiabatically upwelling asthenosphere underwent decompressional partial melting (3). The asthenospheric melts infiltrated by porous flow mechanisms through the extending lithospheric mantle (1) and formed sporadic gabbroic intrusions (black bodies). Jurassic times—Ongoing extension caused further lithosphere exhumation and significant asthenosphere upwelling. Refractory residua after Jurassic partial melting were accreted to the base of the lithosphere (2). Late Jurassic times—The continental crust underwent complete failure, the nonvolcanic passive margins were formed, and the subcontinental lithospheric mantle was exhumed and exposed at the seafloor. The lithospheric mantle peridotites, deriving from shallower mantle levels, were exposed at ocean-continent transition (OCT) zones, close to the continental margins (4), whereas melt-modified lithospheric peridotites were exposed at more internal oceanic (MIO) settings of the basin.

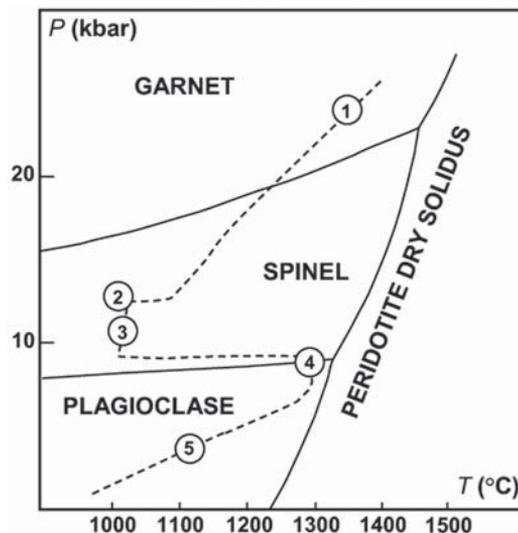
during Late Triassic times (220–225 Ma), and a major event in the evolution of the lithosphere-asthenosphere system was the inception of decompression melting of the asthenosphere. This process was attained not later than 180 Ma, i.e., after at least 40 m.y. of cold and rigid lithosphere extension. MORB melts were formed by fractional melting of a depleted mantle source at rather shallow depths (i.e., under spinel-facies conditions, at  $1.0 < P < 2.5$  GPa) (Piccardo et al., 2007a; Piccardo and Vissers, 2007). This suggests that decompression melting of the asthenospheric mantle occurred only after significant adiabatic upwelling was induced by thinning of the lithosphere. Migrating melts were completely trapped by impregnation and intrusion in the mantle lithosphere and never reached the seafloor of the Ligurian Tethys, as suggested by the lack of basaltic lava flows of this age within the Ligurian terranes.

Moreover, upwelling asthenosphere and melt percolation/impregnation induced significant rheological modification in the extending “cold” (temperatures in the range 900–1100 °C) mantle lithosphere, causing significant heating to asthenospheric conditions (temperatures up to 1300 °C) (Piccardo, 2003). The thermo-mechanical erosion of the lithosphere most probably induced the rapid decrease in the total strength of the lithosphere (TLS) along the melt-percolated zone. In fact, numerical and analogue modeling indicates that a decrease of one order of magnitude in local creep strength is expected, which translates into a decrease of approximately the same amount in the tectonic force required to deform lithosphere at significant strain rates (Ranalli et al., 2007; Corti et al., 2007). Accordingly, the significant rheological modification of the mantle lithosphere along the axial zone of the extending system should have caused a significantly faster extension and would have played an important role in the geodynamic evolution of the system, enhancing the transition from ultraslow diffuse continental extension to localized oceanic spreading.

In summary, taking into account available pressure and temperature conditions and time constraints recorded by the Ligurian mantle rocks, their evolution can be described progressively from Proterozoic isolation from the convective mantle to accretion to the subcontinental thermal lithosphere (decreasing pressure and temperature conditions), leading to annealing equilibration under spinel-facies conditions at ~1000 °C (Fig. 5). Inception of Triassic extension caused thinning of the lithospheric mantle, adiabatic upwelling, and Early Jurassic decompression-induced melting of the asthenosphere. Asthenospheric upwelling and melt percolation induced strong heating in the extending lithospheric mantle under spinel- to plagioclase-facies conditions and temperatures up to 1300 °C (asthenospherization). Further extension and mantle upwelling caused progressive heat loss on decompression, causing the percolated lithospheric mantle to be progressively exhumed and finally exposed at the seafloor (Fig. 5).

## CONCLUSIONS

Current knowledge of the structure and petrology of the Alpine-Apenine ophiolitic peridotites from the Jurassic Ligurian Tethys basin indicates that both tectonic and magmatic processes dominated the evolution of the lithosphere-asthenosphere system during the rifting stages of the basin. Tectonic and magmatic processes were interdependent and mutually enhanced each other. Their complex interplay can be summarized as follows: (1) extension and thinning of the lithosphere induced adiabatic upwelling and decompression melting of the asthenosphere; (2) migration of asthenospheric melts by porous flow through the extending mantle lithosphere, and their entrapment therein by interstitial crystallization, induced important rheological modifications in the lithosphere and caused significant reduction of the total lithospheric strength; and (3) the thermo-mechanical erosion of the mantle lithosphere enhanced lithosphere extension toward continental breakup and oceanic opening (Fig. 4).



**Figure 5.** Schematic pressure-temperature-time ( $P$ - $T$ - $t$ ) path for the Ligurian mantle. The numbers refer to: (1) Proterozoic (?) isolation from the convective mantle and accretion to the lithospheric mantle; (2) Proterozoic annealing recrystallization in the mantle lithosphere under spinel-facies conditions and average temperatures of 1000 °C; (3) Triassic subsolidus decompressional evolution following inception of continental extension; (4) Early–Middle Jurassic melt percolation and asthenosphere upwelling, causing significant heating (up to 1300 °C) (asthenospherization) of the extending lithospheric mantle; and (5) Late Jurassic exhumation to shallow lithospheric levels under significantly decreasing temperature due to conductive heat loss and final exposure at the seafloor of the Ligurian Tethys after complete failure of the continental crust.

Accordingly, the entrapment of asthenospheric melts in the shallow mantle lithosphere during the rifting stages of the system played a crucial role in the geodynamic evolution of the extensional system. In fact: (1) it prevented significant melt extrusion during continental breakup, which resulted in the nonvolcanic nature of the passive rifted margins, and (2) it induced the thermal erosion of the lithosphere, which enhanced the transition from ultraslow diffuse lithosphere extension to focused oceanic spreading.

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