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Evolution of the ultra-slow spreading Jurassic Ligurian Tethys: view from the mantle

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Abstract — The Jurassic Ligurian Tethys was floored by tectonically exhumed mantle peridotites, discontinuously covered by MORB lava flows. It was characterised by along-axis alternance of: 1) a-volcanic segments, showing direct exposure of mantle peridotites below the oceanic sediments, and 2) volcanic segments, showing a volcanic cover on top of mantle peridotites.

Ophiolitic peridotites from the Ligurian Tethys show strong petrological and geochemical heterogeneity, varying from rather fertile lherzolites, to strongly depleted harzburgites and dunites, to refertilised plagioclase peridotites. Peridotites from Ocean Continent Transition (OCT) settings are mostly fertile lherzolites, which derive from the sub-continental lithospheric mantle of the Europe-Adria system. They were isolated from the convective mantle and accreted to the sub-continental thermal lithosphere starting from Proterozoic times, prior and independently to rifting and drifting in the Ligurian Tethys realm. Peridotites from More Internal Oceanic (MIO) settings are mostly represented by pristine sub-continental lherzolites, which have been transformed into reactive spinel peridotites, impregnated plagioclase peridotites and replacive spinel harzburgites and dunites by melt-peridotite interaction processes.

Stratigraphic-structural features (i.e. mantle at the sea-floor and alternance of a-volcanic and volcanic segments) and petrologic features of both magmas (i.e. presence of mildly enriched and alkaline melts) and peridotites (i.e. extreme compositional heterogeneity induced by melt percolation and melt-peridotite reaction processes) indicate the close similarity of the Jurassic Ligurian Tethys with modern ultra-slow spreading ridges (Gakkel and South-West Indian Ridges).

Petrological and geochronological data on the Ligurian Tethys ophiolitic peridotites and gabbros allow the following scenario to be documented:

1) Lithosphere extension started during Triassic and caused exhumation of sub-continental lithospheric mantle (as old as Proterozoic), by means of km-scale shear zones;

2) Lithosphere extension and thinning induced almost adiabatic upwelling and partial melting on decompression of the underlying asthenosphere, which started most probably during Early Jurassic times;

3) MORB melts from the asthenosphere percolated and reacted with the sub-continental lithospheric mantle, forming melt-modified, depleted/enriched transitional peridotites;

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4) Prior to sea-floor exposure, lithospheric and transitional peridotites were intruded by aggregated MORB magmas, from 180 Ma in OCT peridotites to 164-160 Ma in MIO peridotites;

5) Oceanic refractory peridotites, coeval and cogenetic with Jurassic MORB melts, were accreted to the thermal lithosphere.

Across-axis variation (from OCT to MIO settings) of mantle peridotites describe the different evolution stages of the basin, i.e.: 1) *Exhumed Sub-continental Mantle* characterises the OCT zones and represents the *rifting stages* dominated by subsolidus extension and thinning of the Europe-Adria lithosphere; 2) *Percolated Subcontinental Mantle* mostly characterised the more external MIO settings and represents the *drifting stage* after inception of asthenosphere partial melting on decompression along the axial zone of the future oceanic basin; 3) *Percolated Oceanic Mantle*, which is cogenetic with the Jurassic MORB melts, is sporadically present at More Internal MIO settings and represents the *oceanic stage*, after complete failure of the continental crust, when Jurassic refractory residua are emplaced at the sea-floor of the basin.

RIASSUNTO — Il bacino della Tetide Ligure Giurassica era pavimentato da peridotiti di mantello esumate per processi tettonici, e ricoperto in modo discontinuo da colate basaltiche di tipo MORB. Era caratterizzato dall'alternanza lungo l'asse di: 1) segmenti non-vulcanici, che mostravano la diretta esposizione delle peridotiti di mantello al di sotto dei sedimenti oceanici, e 2) segmenti vulcanici, che mostravano una copertura vulcanica al di sopra delle peridotiti di mantello.

Le peridotiti ofiolitiche delle Tetide Ligure mostrano una forte eterogeneita' petrologica e geochimica, e variano da lherzoliti relativamente fertili a harzburgiti e duniti fortemente impoverite, a peridotiti a plagioclasio rifertilizzate. Le peridotiti dagli ambienti di Transizione Oceano-Continente (OCT) sono principalmente lherzoliti fertili che derivano dal mantello litosferico sottocontinentale del sistema Europa-Adria. Esse sono state isolate dal mantello convettivo e accrete alla litosfera conduttiva sottocontinentale a partire da tempi Proterozoici, in tempi precedenti ed indipendenti dal rifting e drifting nel dominio della Tetide Ligure. Le peridotiti degli ambienti Oceanici Più Interni (MIO) sono principalmente rappresentate da precedenti lherzoliti sotto-continentali che sono state trasformate in peridotiti reattive a spinello, peridotiti impregnate a plagioclasio e harzburgiti e duniti a spinello di sostituzione da processi di interazione fuso-peridotite.

Le caratteristiche stratigrafiche e strutturali (cioe' la presenza e abbondanza di peridotiti di mantello sul fondo del bacino e l'alternanza di segmenti non-vulcanici e vulcanici) e le caratteristiche petrologiche sia dei magmi (cioe' la presenza di fusi moderatamente arricchiti fino a francamente alcalini) che delle peridotiti (cioe' l'estrema eterogeneita' composizionale indotta da processi di percolazione di fusi e di interazione fuso-peridotite) indicano la stretta somiglianza del bacino Giurassico delle Tetide Ligure con i moderni *ultra-slow spreading ridges* (Gakkel e South-West Indian Ridges).

Le conoscenze petrologiche e geocronologiche su peridotiti e gabbri ofiolitici derivanti dalla Tetide Ligure permettono di documentare il seguente scenario:

1) l'estensione litosferica inizio' durante il Triassico e causo' l'esumazione del mantello litosferico sottocontinentale (di eta' variabile a partire dal Proterozoico) mediante zone di *shear* di spessore chilometrico;

2) l'estensione e l'assottigliamento della litosfera indusse la risalita pressocche' adiabatica e la fusione parziale in decompressione della sottostante astenosfera, fusione che inizio' molto probabilmente durante tempi Giurassici precoci;

3) fusi di tipo MORB risalenti dall'astenosfera percolarono e reagirono con il mantello litosferico sotto-continentale, formando peridotiti transizionali, modificate dall'interazione con i fusi, sia arricchite che impoverite;

4) prima della esposizione sul fondo dell'oceano, peridotiti litosferiche e transizionali furono intruse da fusi MORB aggregati, da 180 Ma nelle peridotiti degli ambienti OCT a 164-160 Ma nelle peridotiti degli ambienti MIO;

5) peridotiti refrattarie oceaniche, coeve e cogenetiche dei fusi Giurassici MORB, furono accrete alla litosfera conduttiva.

Le variazioni delle rocce peridotitiche attraverso il bacino (da ambienti OCT a MIO) descrivono i differenti stadi evolutivi del bacino, cioe': 1) *Mantello Sotto-continentale Esumato* caratterizza gli ambienti OCT e rappresenta gli *stadi di rifting continentale*, dominati dall'estensione ed assottigliamento in condizioni di subsolidus della litosfera del sistema Europa-Adria; 2) *Mantello Percolato Sotto-continentale* che principalmente caratterizza gli ambienti MIO e rappresenta gli *stadi di drifting* dopo l'inizio della fusione dell'astenosfera in decompressione lungo la zona assiale del futuro bacino oceanico; 3) *Mantello Oceanico Percolato*, che e' cogenetico con i fusi Giurassici di tipo MORB, e' sporadicamente presente negli ambienti MIO piu' interni e rappresenta lo *stadio oceanico*, dopo la completa elisione della crosta continentale, quando i residui refrattari delle fusioni Giurassiche vengono messi in posto sul fondo del bacino oceanico.

KEY WORDS: *mantle petrology, Jurassic Ligurian Tethys, geodynamic evolution, ultra-slow spreading ocean.*

INTRODUCTION

The present knowledge on Western Alpine (WA) – Northern Apennine (NA) ophiolites indicates that: 1) Serpentinised mantle peridotites underlie both basaltic lava flows and oceanic sediments, thus supporting the interpretation that the Ligurian Tethys basin was floored by a peridotite basement (Decandia and Elter, 1969; Bezzi and Piccardo, 1971; Piccardo, 1976,1983; Lemoine *et al.*, 1987; Cortesogno *et al.*, 1987; Cortesogno *et al.*, 1994; Abbate *et al.*, 1994); 2) Ophiolitic peridotites were former subcontinental lithospheric mantle exhumed to the sea-floor during rifting and drifting stages (Müntener and Piccardo, 2003; Piccardo, 2003; Müntener *et al.*, 2004; Piccardo *et al.*, 2004, 2007; Piccardo and Vissers, 2007, and references therein).

Peridotites deriving from more "external", pericontinental Ocean Continent Transition (OCT) zones (parts of the Erro-Tobbio, External Ligurides and Platta peridotite massifs), maintain their pristine lithospheric characteristics, whereas peridotites deriving from More Internal Oceanic (MIO) settings of the basin (parts of Erro-Tobbio and Platta, Southern Lanzo, Internal Ligurides and Corsica peridotite massifs) show structural-compositional features suggesting interaction with and modification by MORB-type melts (Piccardo *et al.*, 2004, 2007, and references therein).

Structural, petrological and geochemical knowledge on mantle peridotites deriving from different settings of the Late Jurassic Ligurian Tethys basin evidence their strong compositional heterogeneity (e.g. Piccardo, 1976; Beccaluva and Piccardo, 1978; Ernst and Piccardo, 1979; Beccaluva *et al.*, 1984; Piccardo, 2003, 2007; Piccardo and Vissers, 2007; Piccardo *et al.*, 1990, 2004, 2007, Rampone *et al.*, 1995, 1996, 1997, 1998, 2004, 2005) and reveals the structural-paragenetic characteristics of their exhumation from the sub-continental lithospheric mantle to the sea-floor of the basin, which was driven by km-scale extensional shear zones (e.g. Drury *et al.*, 1990; Vissers *et al.*, 1991; Hoogerduijn Strating *et al.*, 1993; Molli, 1996; Piccardo and Vissers, 2007).

The distribution and abundance of melt-modified spinel and plagioclase peridotites within the WA-NA ophiolitic peridotites indicate that substantial volumes of lithospheric mantle underwent these melt-related processes along the axial zone of the future Jurassic Ligurian Tethys basin (Piccardo *et al.*, 2004, 2007). The formation of melt-modified mantle peridotites is to be related to the inception of decompression melting in the underlying upwelling asthenosphere and to melt percolation in the overlying extending lithospheric mantle (Piccardo, 2007, and quoted references).

In the last ten years it has been shown that along slow spreading ridges vulcanites are limited (Cannat, 1993, 1996; Dick *et al.*, 1984; Michael *et al.*, 2003) and that the direct exposure at the sea-floor of crust-free mantle lithosphere is more common than previously recognised (Bonatti *et al.*, 2001; Cannat, 1996; Cannat *et al.*, 1997; Michael *et al.*, 2003). On the basis of recent investigations of the South-West Indian and Arctic Ridges, the new class of ultra-slow spreading ridges has been identified (e.g. Dick *et al.*, 2003). They are characterised by intermittent volcanism and continuous emplacement of mantle to the seafloor over large regions, whereas the spreading rate is approximately lower than 20 mm yr $^{-1}$. Other major distinctive characteristics of ultra-slow spreading ridges are: (1) the relative abundance of mildly enriched or even alkaline basalts (e.g. Gakkel Ridge and the associated Lena Trough) (e.g. Mühe *et al.* 1997; Michael *et al.*, 2003; Dick *et al.*, 2003; Nauret *et al.*, 2005) and the strong variability in composition of the exposed abyssal peridotites (e.g. Hellebrand *et al.*, 2006; von der Handt *et al.*, 2006).

The aim of the paper is:

1) to review present knowledge on petrology and geochemistry of the ophiolitic peridotites from the Jurassic Ligurian Tethys;

2) to evidence the relationships between mantle petrology and geodynamic setting in the ancient Ligurian Tethys;

3) to describe the evolution of the basin from the mantle viewpoint;

4) to compare the structural and petrological features of the ancient Ligurian Tethys with modern oceanic basins.

PERIDOTITE PETROLOGY

Peridotite petrology and geodynamic setting

The mantle peridotites occur as: 1) huge olistoliths, in close association with MORB pillowed lava flows and continental crust material, within the structural units deriving from the Ocean Continent Transition (OCT) zones of the Adria margin [e.g. External Ligurides (EL)]; 2) the basement of MORB lava flows and oceanic sediments in the ophiolite sequences from More Internal Oceanic (MIO) settings [e.g. Internal Ligurides (IL)] (Abbate *et al.*, 1994; Marroni *et al.*, 2002, and quoted references).

The majority of NA Internal Liguride Units and of WA Pennidic Units, presumably deriving from the More Internal MIO settings of the basin, consist of serpentinised mantle peridotites, associated with MORB vulcanites (or meta-vulcanites) and oceanic sediments (or meta-sediments).

These sequences preserve the oceanic stratigraphy which indicates the presence of both: 1) *a-volcanic sequences*, which are characterised by direct mantle exposure at the sea-floor, without interposed basalts, below the sedimentary cover; 2) *volcanic sequences*, which are characterised by hundred metres-thick basaltic cover interposed between oceanic sediments and serpentinised mantle peridotites (Abbate *et al.*, 1994, and references therein). Thus, MIO settings were characterised by mantle exposure at the sea floor and by alternance of both a-volcanic and volcanic segments.

As recently focused by Piccardo (2007), structural and petrologic-geochemical characteristics of mantle peridotites from different structural units, which derive from different geodynamic settings of the ancient Ligurian Tethys, significantly change in relation with the inferred geodynamic setting of provenance. Accordingly, a close correlation exists between peridotite petrology and geodynamic setting, going from more external OCT zones to more internal MIO settings of the ancient basin.

Lithospheric sub-continental peridotites at OCT settings

Mantle peridotites from OCT settings [Platta, North Lanzo (NLA), sectors of External Ligurides (EL) and Erro-Tobbio (ET)] are mostly fertile lherzolites showing Ti-pargasite-bearing spinel-facies assemblage, and widespread garnet/spinel pyroxenite bands. Petrologic, geochemical and isotopic studies (e.g. Rampone *et al.*, 1995; Bodinier *et al.*, 1991; Piccardo *et al.*, 2004, 2007; Piccardo and Vissers, 2007, and references therein) indicate that: i) they maintain records of decompressional evolution from the asthenosphere and of annealing recrystallisation during accretion to the lithosphere under spinel-facies conditions, and ii) they were isolated from the convective mantle and accreted to the thermal lithosphere starting from Proterozoic times.

Thus, it has been inferred (Piccardo, 2007, and references therein) that OCT peridotites derive from the sub-continental lithospheric mantle of the Europe-Adria system. They were isolated from the convective mantle and accreted to the sub-continental thermal lithosphere prior and independently to rifting and drifting in the Ligurian Tethys realm.

In pre-Triassic times mantle protoliths of future OCT peridotites were located at different levels in the sub-continental mantle lithosphere and at different positions relative to future continental margins and axial zone of the oceanic basin. The OCT peridotites underwent strong localised deformation along km-scale extensional shear zones, coupled with syn-tectonic metamorphic parageneses varying from spinel- to plagioclase- to amphibole (chlorite)-peridotite facies assemblages, followed by oceanic serpentinite mylonites. This subsolidus tectonic-metamorphic path indicates that subcontinental lithospheric mantle was progressively exhumed from the subcontinental lithosphere to the sea floor of the basin. In good agreement with geological data (e.g. Molli, 1996, and references therein), extension and thinning in mantle lithosphere was already active in Triassic times as evidenced by the minimum age of 220 Ma deduced for the subsolidus spinel- to plagioclase-facies transition recorded by some EL peridotites (Montanini *et al.*, 2004, 2006).

Accordingly, it has been evidenced (Piccardo, 2007, and references therein) that sub-continental peridotites from OCT settings underwent decompressional evolution, from Triassic times, during extension of the continental lithosphere of the Europe-Adria system.

Melt modified peridotites at MIO settings

The peridotites from MIO settings are mostly represented by pristine sub-continental spinel lherzolites which have been transformed to different types of granular rocks, both spinel and plagioclase peridotites; they show structural and compositional features indicative of melt-peridotite interaction processes (Piccardo *et al.*, 2004, 2007, and references therein). These “melt-modified” peridotites, hereafter referred to as *reactive*, *impregnated* and *replacive peridotites* show mutual relationships in the field which indicate that: 1) pristine sub-continental spinel peridotites are transformed to reactive spinel peridotites; 2) sub-continental and reactive spinel peridotites are transformed to impregnated plagioclase peridotites; 3) impregnated plagioclase peridotites are cut and replaced by channels of replacive spinel peridotites.

Recent studies (Piccardo, 2003; Piccardo *et al.*, 2004, 2007, and references therein) evidence that:

1) The reactive spinel peridotites (mostly pyroxene-depleted spinel harzburgites) formed by interaction of pristine sub-continental lithospheric peridotites with silica-undersaturated MORB-type melt increments.

2) The impregnated plagioclase peridotites (plagioclase-enriched lherzolites) were formed by interstitial crystallisation and refertilisation of pristine spinel peridotites by silica-saturated melt increments with MORB affinity, which attained silica-saturation during reactive percolation in the lithospheric mantle column prior to reaching the impregnation level.

3) The replacive spinel peridotites (pyroxene-depleted spinel harzburgite and pyroxene-free spinel dunites) formed by focused migration of MORB melts within channels.

Focused melt percolation within spinel dunite channels and intrusions in fractures (forming gabbroic dykes) allowed shallow level delivery of aggregate MORBs.

Age data on melt percolation in MIO peridotites are available for some Monte Maggiore (Corsica) plagioclase peridotites (Rampone and Piccardo, 2003), which gave Sm-Nd cpx-plg isochron ages of 155±6 Ma, closely similar to the estimated intrusion ages (162 Ma) of the associated MORB gabbroic dykes (Rampone *et al.*, 2005). Moreover, some plagioclase peridotites from the Mt. Nero body of the External Liguride units yielded Sm-Nd cpx-plg isochron ages of 163±20 and 165±20 Ma, interpreted as the age of subsolidus spinel- to plagioclase-facies transition during exhumation (Rampone *et al.*, 1995). These rocks have been recognised as impregnated plagioclase peridotites (Müntener and Piccardo, 2003; Piccardo *et al.*, 2004, 2006; Poggi *et al.*, 2006), formed by melt-peridotite interaction. It has been envisaged by Montanini *et al.* (2006) and Piccardo (2007), that these ages refer to a stage of MORB melt – peridotite interaction and MORB impregnation in the External Liguride mantle. These ages are closely similar to intrusion ages of MORB melts at MIO settings [i.e. IL gabbros 165±14 Ma, Rampone *et al.*, (1998), and MM gabbros 162±10 Ma, Rampone *et al.* (2005)].

It can be speculated that: i) MORB melt percolation and impregnation in MIO peridotites occurred during Jurassic times; ii) MORB melt percolation and subsequent MORB melt intrusion were closely related. They can be referred to the same asthenosphere melting stage during the formation of the Jurassic Ligurian Tethys (Piccardo and Vissers, 2007).

Oceanic refractory residua at MIO peridotites

Sm/Nd isotope data on depleted spinel peridotites from Monte Maggiore (Corsica) furnished Sm-Nd cpx model ages of 164±14 Ma, which have been interpreted (Rampone *et al.*, 2005) as model age of depletion after Jurassic partial melting. According with this interpretation, MM depleted peridotites can be interpreted as refractory residua after Jurassic oceanic partial melting.

In this hypothesis, these depleted peridotites represent oceanic peridotites, i.e. refractory residua after asthenosphere partial melting during the Jurassic oceanic evolution. It can be suggested that oceanic Jurassic mantle residua were sporadically emplaced at the sea floor of more mature oceanic segments.

MANTLE PROCESSES AND GEODYNAMIC EVOLUTION

Our studies indicate that the geodynamic evolution (i.e. lithospheric extension) of the Europe-Adria continental lithosphere induced tectono-metamorphic and melt-related processes in the extending mantle lithosphere (Piccardo, 2007) and outline the close relationships between tectonic and magmatic processes.

The following scenario can be evidenced:

1) Lithosphere extension, presumably started during Triassic (already active at 220 Ma as recorded in EL mantle, Montanini *et al.*, 2006), caused subsolidus exhumation of the sub-continental lithospheric mantle, by means of km-scale shear zones, which led to the sea-floor exposure of the sub-continental mantle during Jurassic times (e.g. Drury *et al.*, 1990; Vissers *et al.*, 1991; Hoogerduijn Strating *et al.*, 1993; Molli, 1996);

2) Lithosphere extension and thinning induced almost adiabatic upwelling of the underlying asthenosphere and its partial melting on decompression (Piccardo *et al.*, 2007; Piccardo and Vissers, 2007), which started most probably not later than Late Triassic – Early Jurassic times [179-180 Ma of the oldest MORB gabbros in OCT (Tribuzio *et al.*, 2004; Rampone *et al.*, 2005)] (Fig. 1);

3) Asthenospheric MORB-type melts migrated upwards by diffuse porous flow and percolated the extending sub-continental mantle lithosphere (Piccardo *et al.*, 2004, 2007; Piccardo and Vissers, 2007);

4) Asthenospheric melts reacted with the mantle lithosphere and, significantly, with the deformed rocks of the extensional shear zones, thus indicating that inception of asthenosphere partial melting and MORB percolation occurred during lithosphere extension and thinning (Piccardo and Vissers, 2007);

5) Oceanic refractory peridotites, coeval and cogenetic with the Jurassic MORB melts, were accreted to the thick thermal lithosphere, starting from the rifting stages of the Europe-Adria system, and were percolated by newly formed MORB melts from the underlying melting asthenosphere before exposure at the sea-floor of the basin.

THE TECTONIC EVOLUTION OF MAGMA-POOR RIFTED MARGINS

A recent study (Lavier and Manatschal, 2006) has proposed a conceptual, lithosphere-scale model based on inferred sequential modes of lithosphere extension from pure shear to simple-shear to sea-floor spreading, mainly based on geophysical/geological observations from the present-day West Iberia - Newfoundland conjugate margins and the ancient Europe-Adria conjugate margins in the Alps. Three stages of development are inferred: (1) the stretching mode A, which is characterised by distributed listric normal faulting cutting through the brittle upper crust and soling out at mid-crustal levels; (2) the thinning mode B, which is characterised by the occurrence of crustal-scale shear zones thinning the crust to less than 10 km, without the presence of distributed normal faulting in the upper crust; (3) the exhumation mode C, which is characterised by downward concave faults that generate fault offsets more than 10 km, without producing major observable topography, because the subcontinental mantle is exhumed at the sea floor. Exhumed mantle in the ocean continent transition is serpentinised at temperature under 600 °C and at depths less than 10 km. Lavier and Manatschal (2006) sustain that (1) attenuation of the middle crust in the initial stage of rifting and (2) serpentinisation of the mantle lithosphere during the last exhumation phase, are capable to weaken the lithosphere and explain the evolution of rifting. They suggest that mid-crustal weakening and serpentinisation allow for thinning and exhumation of an originally strong mantle. These two processes are believed by Lavier and Manatschal (2006) to represent key mechanisms allowing continental break-up in a strong lithosphere *in the absence of magmatic activity to weaken the lithosphere.*

In this model, little attention has been dedicated to the behaviour of the upper mantle, both subcontinental lithospheric and asthenospheric during the various stages of lithosphere attenuation. This model does not take into proper consideration available data from WA-NA ophiolitic peridotites, which indicate that: (1) significant tectono-metamorphic processes in the mantle lithosphere accommodated extension and thinning of mantle lithosphere during pre-oceanic extension (e.g. Drury *et al.*, 1990; Vissers *et al.*, 1991; Hoogerduijn Strating *et al.*, 1993); (2) fundamental magmatic processes like asthenosphere partial melting and melt percolation in the lithospheric mantle provoked the percolation-induced asthenospherisation of the mantle lithosphere (Piccardo, 2003; Müntener and Piccardo, 2003; Piccardo *et al.*, 2004), Accordingly, their effects on the geodynamic evolution of the extensional system have been completely disregarded by the conceptual model of Lavier and Manatschal (2006).

Recent contributions (Corti *et al.*, 2007; Ranalli *et al.*, 2007) take into account field and petrologic evidence from WA-NA ophiolitic peridotites, evidencing widespread melt percolation during lithosphere extension which was accompanied by significant heating of the subcontinental mantle to asthenospheric conditions (i.e. the thermo-chemical erosion of the mantle lithosphere). They investigate the influence of weakening of mantle lithosphere by

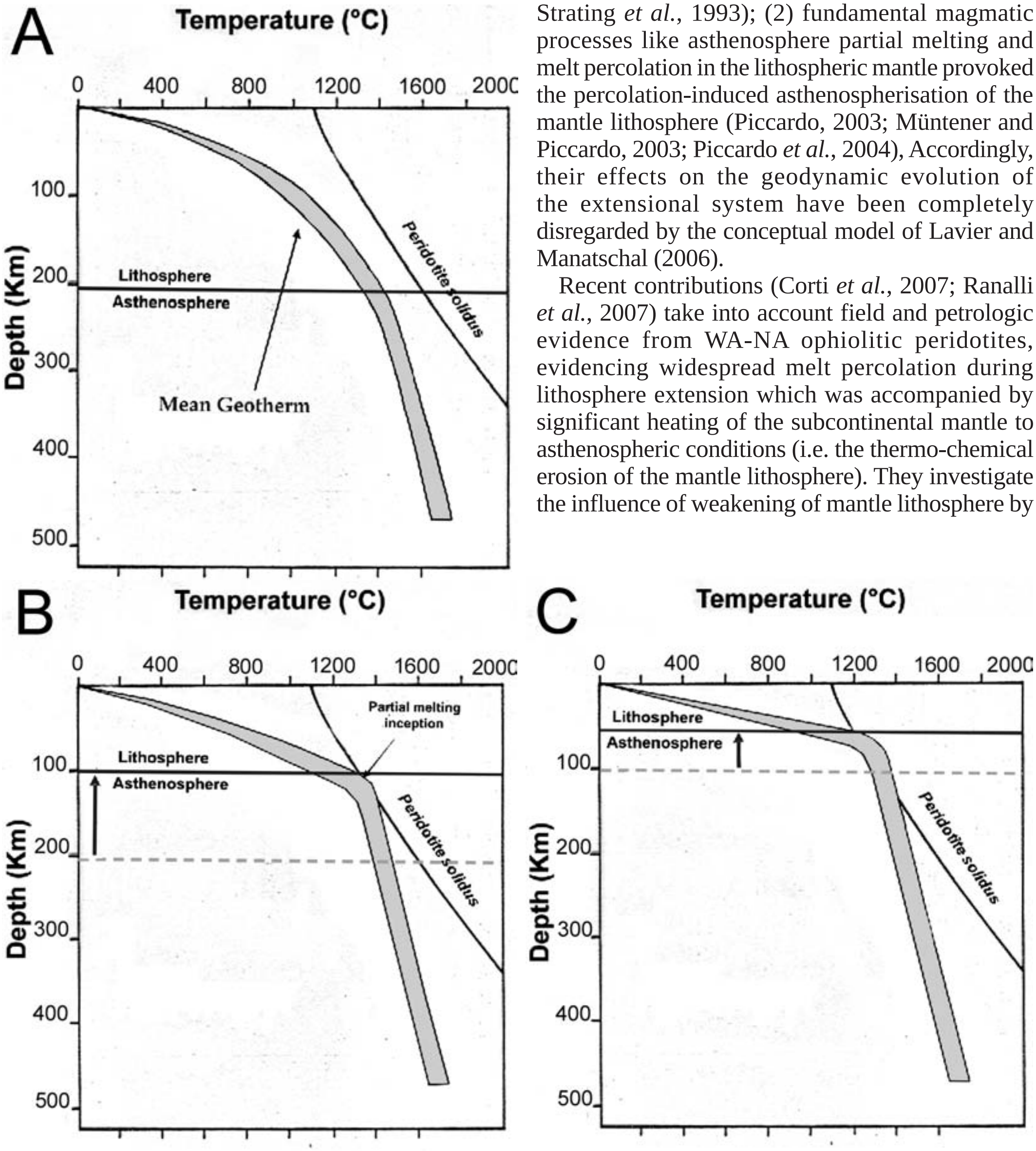


Fig. 1 – Schematic reproduction on a P-T diagram of the relationships between lithosphere thickness reduction by lithosphere passive extension and asthenosphere upwelling. It is assumed that asthenosphere decompressional uplift was almost adiabatic. Starting from an hypothetical pre-rift 200 km thick lithosphere, upwelling asthenosphere cross its solidus, and begins to underwent partial melting, after broadly 50% reduction of the original lithosphere thickness.
Accordingly, it can be evidenced that the two processes, lithosphere extension and asthenosphere partial melting, were interdependent.

melt percolation on continental break-up by means of thermal and rheological modelling coupled with analogue modelling. They suggest that the thermo-mechanical erosion (or asthenospherisation) of the mantle lithosphere may have been represented a controlling factor in the rapid continental break-up and the transition to localised oceanic spreading in the Ligurian Tethys.

The above inferences are in contrast with the assumptions by Lavier and Manatschal (2006) that magmatic activity was absent to weaken the lithosphere and, on the contrary, stress out that the thermo-mechanical erosion by lithosphere-asthenosphere interaction (i.e. combination of asthenosphere partial melting and lithosphere melt percolation) was important during thinning and exhumation of the mantle lithosphere and played a significant role in softening the strong mantle lithosphere (Piccardo, 2007).

Comparison with modern ocean ridges

As recently summarised by Piccardo *et al.* (2006, and references therein), the lithostratigraphic features of the Ligurian Tethys ophiolites were in the past related to transform faults (Gianelli and Principi, 1977; Lemoine, 1980; Weissert and Bernoulli 1985; Cortesogno *et al.*, 1987), on the basis of similarities to modern oceanic settings. However, structural studies at regional and local scale in recent years, both in the mantle (Vissers *et al.*, 1991; Hoogerduijn Strating *et al.*, 1993) and crustal sections (Molli, 1995; 1996), do not agree with a transform fault setting. For instance, geometry and regional distribution of high temperature foliations suggest a low to medium angle instead of steep orientation expected for a transform fault environment.

The lithostratigraphy of the Ligurian Tethys ophiolites was also ascribed in the late seventies to a magma-poor slow spreading centre (Barrett and Spooner, 1977). This hypothesis was re-proposed by Lagabrielle and Cannat (1990), and Lagabrielle and Lemoine (1997) for the Western Alps ophiolites, on the basis of the comparison with the crustal structure of the Mid-Atlantic Ridge, and it has been suggested that IL ophiolites show lithostratigraphic similarities to the MARK area and to the 15°N region of the Mid-Atlantic Ridge. On the other hand, the sub-continental nature of the EL ophiolitic mantle peridotites clearly contrasts with the oceanic lithosphere formed at mid-ocean ridges (Decandia and Elter, 1969, 1972; Piccardo, 1976).

On the basis of the atypical association of fertile sub-continental mantle and MORB-type magmatism in the External Ligurides, the Ligurian Tethys was considered as an embryonic oceanic basin similar to the Red Sea, or as an ocean-continent transition zone similar to the a-volcanic continental margin of Western Iberia (Piccardo, 1977; Beccaluva and Piccardo,1978; Piccardo *et al.*, 1990; Rampone and Piccardo, 2000). Rifting, thinning and break-up of the continental crust was modelled through low-angle detachment faulting of the lithosphere (Lemoine *et al.* 1987; Froitzheim and Eberli 1990; Piccardo *et al.* 1990; 1994; Froitzheim and Manatschal, 1996). Denudation of subcontinental mantle and rare intruded gabbroic plutons, in association with slicing of the continental crust as “extensional allocthons”, is clearly recorded by the External Liguride units (Molli, 1996). The gabbro-peridotite basement and some relics of stretched continental crust have been later injected basaltic dykes and lava flows derived by partial melting of the rising asthenosphere (Marroni *et al.*, 1998).

On the other hand, the similarity between the IL ophiolites and the Mid Atlantic Ridge lithosphere was evidenced on the basis of structural, magmatic and metamorphic similarities of the gabbroic bodies (Molli, 1995; Tribuzio *et al.*, 1995; 2000a). However, the development at a slow spreading ridge is not consistent with the extremely depleted Nd isotopic signature of some IL peridotites, which yielded Early Permian model ages, assuming a depleted mantle source (Rampone *et al.*, 1996). Accordingly, it has been suggested that melt-residue genetic relation does not exist for the IL crust-mantle association, and that IL peridotites differ from the mantle rocks of modern oceans (Rampone *et al.*, 1996; 1998). Tribuzio *et al.* (2004), on the basis of recent isotopic investigations of modern oceanic lithosphere, showing that mantle rocks are commonly isotopically depleted relative to associated gabbros and basalts (Salters and Dick, 2002), similarly to IL ophiolites, suggest that the progression of the rifting process in the Ligurian Tethys, associated with low budget magma generation, could have resulted in a slow spreading basin, whose remnants are represented by the IL ophiolites.

Where the ophiolite sequences from the Ligurian Tethys preserve the original oceanic stratigraphy, as most of the ophiolite sequences from MIO settings, field and structural evidences indicate that the oceanic settings of provenance were characterised by mantle exposure at the sea floor and by both a-volcanic and volcanic segments, with complete lacking of sheeted dyke complexes and crustal gabbroic Layer 3.

Recent investigations of the South-West Indian and Arctic ultra-slow spreading ridges have revealed that most of them are characterised by intermittent volcanism and continuous emplacement of mantle to the seafloor over large regions, whereas the spreading rate is approximately lower than 20 mm yr $^{-1}$ (e.g. Dick *et al.*, 2003).

Besides the presence of a-volcanic segments and mantle at the sea-floor, other major distinctive characteristics of ultra-slow spreading ridges are: (1) the relative abundance of mildly enriched or even alkaline basalts (e.g. Gakkel Ridge and the associated Lena Trough) (Muhe *et al.* 1997; Michael *et al.*, 2003; Dick *et al.*, 2003; Nauret *et al.*, 2005), enriched in LREE and other incompatible elements and showing alkaline and/or isotopically enriched signatures; (2) the strong variability in composition of the exposed abyssal peridotites, ranging from lherzolites, cpx-poor harzburgites and dunites, which have been interpreted as the result of large-scale reaction with percolation melts (Hellebrand *et al.*, 2006) and plagioclase peridotites which have been related to impregnation of transient depleted melts at low pressure (von der Handt *et al.*, 2006).

Although magmatic rocks from the Ligurian Tethys (gabbros and basalts) are mostly derived from N-MORB melts, available data from the Southern and Northern Lanzo and Mt. Nero massifs (as discussed by Piccardo, 2007, and references therein) suggest that in the Ligurian Tethys melts showing slightly enriched compositions and even alkaline affinity were present, and were related to the last stage of focused melt percolation. LILE-enriched Cpx compositions are widespread replacive harzburgite-dunite channels and associated gabbroic dykelets and dykes at Mt. Musine', Southern Lanzo massif (Piccardo *et al.*, 2007), whereas magmatic clinopyroxenes with clear alkaline affinity are widespread in replacive harzburgites cutting impregnated plagioclase peridotites of the Mt. Nero (External Ligurides) and Lanzo North massifs (Piccardo *et al.*, 2006, 2007b).

Accordingly, stratigraphic-structural features (i.e. mantle at the sea-floor and alternance of a-volcanic and volcanic segments) and petrologic features of both magmas (i.e. presence of mildly enriched and alkaline melts) and peridotites (i.e. presence of extreme compositional heterogeneity induced by melt-peridotite interaction processes) are in favour of the interpretation of the Ligurian Tethys as a Jurassic analogue of present-day ultra-slow spreading ridges (Piccardo, 2007).

CONCLUSION

The Jurassic Ligurian Tethys was floored by tectonically exhumed mantle peridotites, discontinuously covered by MORB lava flows. Along-axis stratigraphic-structural variations indicate that the oceanic basin was characterised by alternance of: 1) *a-volcanic sectors*, showing direct exposure of mantle peridotites below the oceanic sediments; 2) *volcanic sectors*, showing a volcanic cover on top of mantle peridotites.

Stratigraphic-structural features (i.e. mantle at the sea-floor and alternance of a-volcanic and volcanic segments) and petrologic features of both magmas (i.e. presence of mildly enriched or even alkaline melts) and peridotites (i.e. extreme compositional heterogeneity induced by melt percolation and melt-peridotite reaction processes) are in favour of the interpretation of the Ligurian Tethys as a Jurassic analogue of present-day ultra-slow spreading ridges (i.e. Gakkel and South-West Indian Ridges).

Ophiolitic peridotites from the Ligurian Tethys show a strong petrologic-geochemical heterogeneity, which is related to their provenance and the mantle processes they underwent during the evolution of the basin. Mantle peridotites deriving from different palaeogeographic settings of the basin show different structural-petrologic features, recording different mantle processes.

Peridotites from Ocean Continent Transition (OCT) zones (sectors of Platta-Malenco, North Lanzo, sectors of External Ligurides and Erro-Tobbio) are mostly fertile lherzolites, which derive from the sub-continental lithospheric mantle of the Europe-Adria system. They were isolated from the convective mantle and accreted to the sub-continental thermal lithosphere starting from Proterozoic times, prior and independently to rifting and drifting in the Ligurian Tethys realm.

Peridotites from More Internal Oceanic (MIO) settings (sectors of Platta, South Lanzo, Internal Ligurides, sectors of External Ligurides and Erro-Tobbio, Corsica) are mostly represented by pristine sub-continental spinel lherzolites which have been transformed to different types of granular rocks, i.e. reactive spinel peridotites, impregnated plagioclase peridotites and replacive spinel harzburgites and dunites, by melt-peridotite interaction processes.

Reactive spinel peridotites (mostly pyroxene-depleted spinel harzburgites) formed by interaction of pristine sub-continental lithospheric peridotites with silica-undersaturated MORB-type melt increments. Impregnated plagioclase peridotites (plagioclase-enriched lherzolites) were formed by interstitial crystallisation and refertilisation of pristine spinel peridotites by silica-saturated melt increments with MORB affinity, which attained silica-saturation during reactive percolation in the lithospheric mantle column prior to reaching the impregnation level. Replacive spinel peridotites (pyroxene-depleted spinel harzburgite and pyroxene-free spinel dunites) formed by focused and reactive migration of MORB melts.

Across-axis variations of peridotite petrology in the Jurassic Ligurian Tethys record the different evolution stages of the basin, i.e.:

1) Exhumed sub-continental lithospheric peridotites of the OCT zones record the rifting stage of the basin, when subsolidus exhumation of the mantle lithosphere was mainly driven by extension-related km-scale shear zones under progressively decreasing P and T conditions;

2) Melt-modified peridotites of the MIO settings record the drifting stage preceding complete failure of the continental crust, when lithosphere extension and thinning induced asthenosphere almost adiabatic upwelling and decompressional partial melting and the asthenospheric melts percolated through and reacted with the thinned sub-continental mantle lithosphere;

3) Monte Maggiore (Corsica) residual peridotites, cogenetic with the Jurassic MORB melts could represent the oceanic stage, after complete failure of the percolated sub-continental mantle, characterised by sea floor emplacement of refractory residua of Jurassic asthenosphere partial melting.

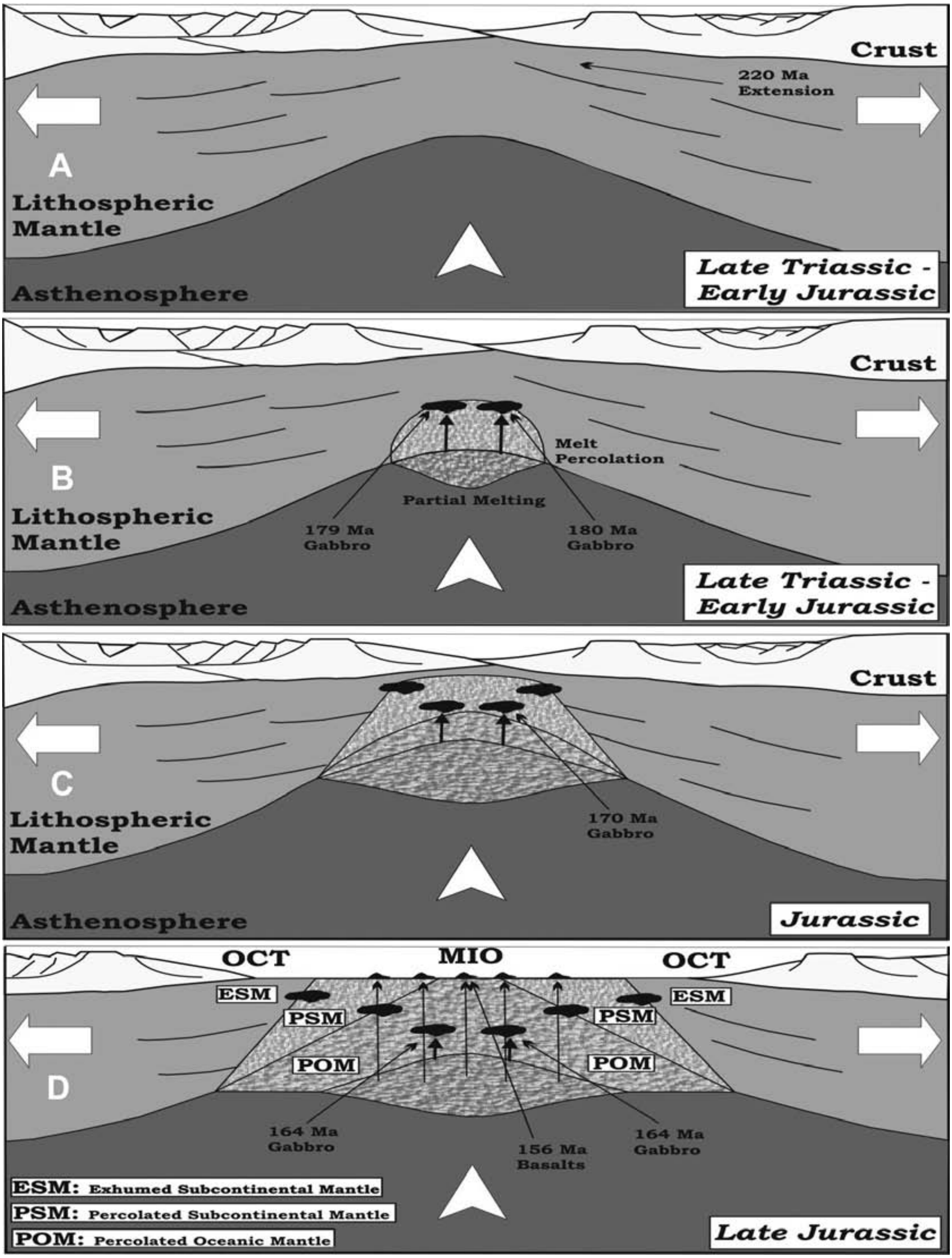
The mantle perspective allows presenting a conceptual model for the evolution of an oceanic basin, whose formation was dominated by the passive extension of the continental lithosphere.

Fig. 2 – Formation of the ultra-slow spreading ocean of the Ligurian Tethys: the mantle perspective. A) **The rifting (sub-continental) stage**, dominated by extension of continental lithosphere and tectonic exhumation of lithospheric mantle; lithosphere extension, presumably started during Triassic (already active at 220 Ma in EL, Montanini *et al.*, 2006), caused subsolidus exhumation of the sub-continental lithospheric mantle, by means of km-scale shear zones (e.g. Drury *et al.*, 1990; Vissers *et al.*, 1991; Hoogerduijn Strating *et al.*, 1993).

B) **The drifting (transition) stage**, characterised by melt-related processes, i.e. inception of partial melting of the asthenosphere and melt percolation through, and melt intrusion within the overlying lithospheric mantle. Lithosphere extension and thinning induced almost adiabatic upwelling of the underlying asthenosphere and its partial melting on decompression (Piccardo *et al.*, 2007a, Piccardo and Vissers 2007). Asthenospheric melts percolated through, and reacted with the mantle lithosphere and with the deformed rocks of the extensional shear zones, thus indicating that inception of asthenosphere partial melting and MORB percolation occurred during lithosphere extension and thinning (Piccardo and Vissers 2007). Available ages of MORB gabbroic intrusion [179-180 Ma of the oldest MORB gabbros in O.C.T. (Tribuzio *et al.*, 2004; Rampone *et al.*, 2005)] indicate that asthenosphere partial melting started most probably not later than Late Triassic – Early Jurassic times.

C) **The drifting (transition) stage**, characterised by: i) melt-related processes, i.e. partial melting of the asthenosphere and melt percolation through, and melt intrusion within the overlying lithospheric mantle; ii) formation of melt-modified peridotites, both depleted (harzburgite-dunite) and enriched (plagioclase peridotite); iii) accretion of “oceanic” refractory residua after asthenosphere partial melting, coeval and cogenetic with the Jurassic MORB melts, to the thick thermal lithosphere. It must be recalled that during the last stages of focused melt percolation within harzburgite-dunite channels, enriched and alkaline melts migrated from deeper levels and/or different mantle sources than previous MORB-type melts.

D) **The spreading (oceanic) stage**, characterised by the complete failure of the continental crust and the “modified” sub-continental lithospheric mantle; oceanic peridotites i.e. the refractory residua after oceanic partial melting, were later exposed at the sea-floor along the axial zone of the basin. Oceanic refractory peridotites were continuously accreted to the thermal lithosphere after MORB melt extraction, were percolated by newly formed MORB melts from the underlying melting asthenosphere (Percolated Oceanic Mantle POM) and were exposed at the sea-floor of the basin. MORB magmas sporadically reached the sea floor, extruded above mantle peridotites and formed volcanic segments along the axis of the basin.


Crust
220 Ma Extension
A
Lithospheric Mantle
Asthenosphere
Late Triassic - Early Jurassic
Crust
Melt Percolation
Partial Melting
B
Lithospheric Mantle
179 Ma Gabbro
180 Ma Gabbro
Asthenosphere
Late Triassic - Early Jurassic
Crust
C
Lithospheric Mantle
170 Ma Gabbro
Asthenosphere
Jurassic
OCT
MIO
OCT
ESM
PSM
POM
ESM
PSM
POM
D
164 Ma Gabbro
156 Ma Basalts
164 Ma Gabbro
ESM: Exhumed Subcontinental Mantle
PSM: Percolated Subcontinental Mantle
POM: Percolated Oceanic Mantle
Late Jurassic

THE LIGURIA MODE OF FORMATION OF AN ULTRA-SLOW SPREADING OCEAN

The evolution of the basin in characterised by (Fig. 2):

A) *the rifting (continental) stage*, dominated by extension of continental lithosphere and tectonic exhumation of lithospheric mantle;

B) *the drifting (transition) stage*, characterised by melt-related processes, i.e. inception of partial melting of the asthenosphere and melt percolation through the overlying lithospheric mantle;

C) *the spreading (oceanic) stage*, characterised by the complete failure of the continental crust and the sea-floor exposure of (1) sub-continental peridotites from the Europe-Adria mantle lithosphere, (2) melt-modified sub-continental peridotites, formed by melt-peridotite interaction after inception of asthenosphere partial melting and (3) oceanic peridotites i.e. the refractory residua after Jurassic oceanic partial melting and MORB melt extraction.

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