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ANATOMY OF THE
LIGURIAN TETHYS
A geodynamic model based on field/laboratory studies and numerical/analogue modeling
AIM OF THE WORK

present a geodynamic model of passive rifting in the Ligurian Tethys domain of the Europe-Adria system, based on:

1) Field, structural and petrologic knowledge on tectonic/magmatic processes recorded in Alpine-Apennine ophiolitic peridotites;

2) Experimental results of numerical and analogue modelling of lithosphere extension and passive rifting;

3) Relevant positive feed-backs between our data from the natural laboratory and results from available experimental works.

The geodynamic model evidence coupling and interaction between deformation and melt infiltration in the extending mantle lithosphere
The Jurassic Ligurian Tethys

The Ligurian Tethys domain was a classic example of “passive rifting”, where far-field tectonic forces were the driving forces of whole lithosphere extension. Asthenosphere upwelled passively without melting since lithosphere was thinned to about half of its thickness, as a consequence of whole lithosphere extension (e.g., Foucher et al., 1982; Corti et al., 2007; Ranalli et al., 2007).

The Western Alps – Northern Apennine ophiolites are remnants of the oceanic lithosphere of the Ligurian Tethys and were recognized similar to the modern central Atlantic basement. Ligurian Tethys was compared to modern slow-spreading oceans, i.e., Atlantic (Lemoine et al., 1987; Lagabrielle and Cannat, 1990; Lagabrielle and Lemoine, 1997; Cannat, 1996; Cannat et al., 1997). The slow-ultraslow nature of spreading in the Ligurian Tethys has been inferred by stratigraphic, structural and petrologic studies on ophiolites (e.g., Tribuzio et al., 2000; Piccardo, 2008) and by kinematic analyses (Vissers et al., 2013).
This work deals with the main ophiolitic peridotite massifs of Western Alps, Northern Apennines and Northern Corsica (i.e., Lanzo Massif, Voltri Massif, External and Internal Ligurides, Monte Maggiore – Corsica), which are fragments of the mantle lithosphere of the Jurassic Ligurian Tethys oceanic basin and its Europe and Adria extended and rifted margins.

This work is based on present-day field, structural, petrologic and geochemical knowledge on mantle peridotites, and inference on their geodynamic relevance, as recently summarized/discussed by:


THE DESTABILIZING EFFECTS OF MELT INFILTRATION IN MANTLE LITHOSPHERE

It has been long evidenced, as recently summarized by Foley (2008), Roy et al. (2012), O’Reilly & Griffin (2013), that:

1) the deep lithosphere is weakened and altered by impregnation of magma, producing local density anomalies which have a destabilizing effect;

2) the sub-continental lithospheric mantle plays an important role in destabilizing continents and tectonic plates through thermal and chemical modifications caused by infiltration of melts;

3) The melt-infiltration process represents the primary mechanism for thermal weakening and rejuvenation of the continental plate.

Piccardo (2003), Ranalli et al. (2007), Corti et al. (2007) suggested that melt infiltration is a determinant factor for the transition from rifting to spreading in the slow-ultraslow Ligurian Tethys.
The role of melt porous flow infiltration and melt thermal advection within the mantle lithosphere, during the rifting stages, has not been taken into proper consideration by some opinion-maker geologists and geo-modelers when modeling onset/evolution of slow-ultraslow spreading oceans and OCT settings.

Lavier & Manatschal (2006, Nature) presented a model (new mechanism) for lithospheric thinning, based on attenuation of middle crust and serpentinization of mantle lithosphere, and considered these processes as key mechanisms for continental break-up of a strong lithosphere in absence of melt (i.e., of magmatic activity to weaken the lithosphere).

Cannat et al. (2009) reviewed the tectonic/magmatic/hydrothermal evolution of slow spreading ridges and focused on the rift to drift transition at magma-poor ocean–continent transitions (OCTs). They emphasized the importance of the thermal characteristics of the system in the installation of ridge-type thermal regime and focused mantle upwelling, They considered magmatism as intrusive (basaltic/gabbroic diking) but not melt infiltration and melt thermal advection.

Only recently (e.g., Mohn et al., 2010, Muentener et al., 2010, and Whitmarsh and Manatschal, 2012) the geodynamic relevance of melt infiltration/storage in lithosphere has been considered, when recognizing that “mechanical or thermally induced weaknesses in the lithosphere … guided the asthenosphere ascent which …. led to the typical focused magmatism and tectonism of a mid-ocean ridge”.
LIGURIAN TETHYS STUDY CASE

NATURAL EVIDENCE OF PASSIVE RIFTING IN OPHIOLITIC PERIDOTITES

1. Passive a-magmatic extension Melt-free shear zones
opx+sp clusters in granular spinel lherzolite

The structurally oldest rock type has cpx-rich lherzolite composition and relict banded structures inherited by a precursor garnet-facies peridotite. Generally it shows complete spinel-facies equilibrium recrystallization and granular textures. It preserves clusters of opx+spinel, indicating provenance from garnet-facies depths (P >2.5GPa).
MELT-FREE SPINEL-FACIES SHEAR ZONES

The structurally oldest shear zones do not show any compositional and microtextural features which indicate melt-peridotite interaction.

The syntectonic cpx-opx-ol-sp matrix is equilibrated at T around 1000°C.

These features indicate lack of HT equilibration with a percolating HT asthenospheric melt (at T = 1250°C).
EXPERIMENTAL CONSTRAINTS

Numerical simulations of passive lithosphere extension, applying thermo-dynamic - style models (e.g., Regenauer-Lieb et al., 2001; Kaus & Podladchikov, 2006; Braeck & Podladchikov, 2007; Regenauer-Lieb et al., 2009), evidenced that the lithosphere rheology is controlled by weakening processes during extension.

These models have produced the spontaneous development of a number of structures that match well-documented features of extensional systems. Localisation processes make the lithosphere weaker than previously estimated.

Muhlhaus et al. (2012) evidenced that melts are not required at the initial rifting stages of continental breakup, particularly for the formation of slow-ultraslow spreading oceans by slow-ultraslow continental extension.

They evidenced the tendency to form *porosity localization bands* and *strain localization bands* in the extending lithosphere.

Localization of deformation processes result in physical anisotropy in the extending mantle lithosphere and should promote formation of melt-free shear zones, as observed in the Erro-Tobbio peridotites.
Muhlhaus et al. (2012) noted that the porosity of localization bands is only about 30% higher than outside the bands for $n = 1$ (where $n$ is the strain-dependence exponent).

Their experimental results indicate that high growth rates (and hence strong localization) are only expected for materials with strong strain dependence (high values of the strain-dependence exponent $n$).

$n = 1$ (fig. a): almost vertical porosity and shear bands.

$n = 6$ (fig. b): high-angle oblique conjugate porosity and shear bands.

The strain concentration within the shear bands obtained for $n > 3$ (i.e. oblique conjugate shear bands) is much more significant and consistent with results familiar from simulations based on plasticity models (Lemiale et al., 2008).
THE A-MAGMATIC PASSIVE RIFTING STAGE

A

Crust

50

spinel

100
garnet

150 Km

Lithospheric mantle

Asthenosphere

B

Extension melt-free shear zones

50

spinel

100
garnet

Passively upwelling asthenosphere

A-magmatic stage
NATURAL EVIDENCE OF PASSIVE RIFTING IN OPHIOLITIC PERIDOTITIDES

2. Passive magmatic extension
Melt diffuse and focused porous flow infiltration
Melt porous flow reactive infiltration formed pyroxene-depleted spinel-facies reactive harzburgites. They show micro-textural (pyroxene dissolving / olivine precipitating) and compositional features indicating melt-peridotite interaction.

Reactive spinel harzburgites both:
1) Replaced lherzolite shear zones
2) Formed concordant bands inside the shear zones
MELT-PRESENT, SPINEL-FACIES SHEAR ZONES

The exsolved orthopyroxene porphyroclasts in these shear zones show replacements of new undeformed and unstrained olivine.

These micro-textures indicate that the spinel-facies protolith was percolated by a silica-undersaturated liquid (orthopyroxene-dissolving / olivine-precipitating), prior to the formation of these spinel-facies shear zones.

Field and structural evidence indicate that this group of shear zones crosscut the shear zones that were formed earlier, in the absence of melt.
Numerical modelings (Muhlhaus et al., 2012; Mohajeri et al., 2013) evidenced the tendency to form porosity localization bands and strain localization bands in the mantle lithosphere. The porosity localization bands were characterized by significantly higher porosity for fluid media and enhanced melt localization and melt infiltration through the extending mantle lithosphere after onset of asthenosphere melting.

Conjugated shear and porosity bands are determinant structures for both passive extension and melt infiltration
Lithospheric extension and thinning enhanced the passive adiabatic upwelling of the asthenosphere, which underwent decompression partial melting when lithosphere have been thinned by a factor $\beta \approx 2$ (i.e., to about half of its original thickness; Foucher et al., 1982; Corti et al., 2007; Ranalli et al., 2007). Melt increments from the asthenosphere infiltrated by diffuse and focused porous flow into the mantle lithosphere, exploiting the porosity location bands. The presence of melts in the extending lithosphere enhanced the positive feed-back between deformation of, and melt migration through the mantle lithosphere.
MELT DYNAMICS DURING RIFTING

It has been suggested (Piccardo, 2014, and references therein) that the migration of isolated and unmixed single melt increments through the mantle lithosphere during magmatic rifting in the Europe-Adria domain was enhanced by the peculiar coexistence of: 1) extremely slow extension of the whole lithosphere system, resulting in very slow asthenosphere passive upwelling; 2) the relatively cold mantle structure, with a thick thermal lithosphere which progressively modified its rheological characteristics during extension (i.e., grain-size reduction, increased porosity, formation of shear and porosity band, formation of shear zones); and 3) the reduced melt production in the asthenosphere at the onset of the melting process during rifting.

The migration of mantle melts by diffuse (or channelled) porous flow is estimated to range from a few meters to tens of meters per year (i.e., Ahern and Turcotte, 1979; Kelemen et al., 1997; Ranalli et al., 2007, and references therein).
Kelemen and co-workers (e.g., 1992, 1995) evidenced that liquids rising adiabatically from the asthenosphere attain silica-(orthopyroxene)-saturation, because of the reactive pyroxene dissolution/olivine precipitation.

The Ligurian peridotites show huge masses of reactive spinel harzburgites (i.e., pyroxene-poor sp harzburgites formed by melt/peridotite reactive interaction).

The percolating melt fractions became saturated in silica (silica-saturated derivative liquids), as evidenced by the composition of melts migrating and crystallizing at shallower, plagioclase-facies lithospheric levels (see below).
THE NATURAL EVIDENCE OF
SHALLOW MELT STORAGE

Melt stagnation ad crystallization
in the shallow mantle lithosphere

Melt impregnation and
gabbro-norites formation
The silica-saturated derivative liquids upwelled to shallow, plagioclase-peridotite facies conditions and reacted with the host peridotite (plagioclase + orthopyroxene replacement on olivine and clinopyroxene),

On migration to shallow lithospheric levels, heat loss by conduction prevailed on thermal advection and ascending melts underwent interstitial crystallization, impregnation, refertilization, stagnation and storage in the shallow lithosphere.

Plagioclase-impregnated peridotites and gabbro-norite bodies were formed.
GABBRO-NORITES

Note the abundance of euhedral green orthopyroxenes (and clinopyroxenes) and interstitial plagioclase
GEO-THERMOMETRIC ESTIMATES

Estimated equilibration temperatures (applying the method Seitz et al., 1999, that is based on cpx-opx distribution of some relevant trace elements, mobile at high T conditions) indicate that:

1) reactive spinel harzburgites, formed under spinel-facies conditions, were equilibrated with the percolating melts at T higher than 1200°C, calculated at P = 1.5 Gpa;

2) Plagioclase-enriched peridotites, formed under plagioclase-facies conditions, were equilibrated with the percolating melts at T around 1200°C, calculated at P = 0.5 Gpa.

Melt thermal advection increased thermal conditions (from T 1000°C to T more than 1200°C) in the wedge-shaped axial zone above the melting asthenosphere.
Numerical modeling (Ranalli et al., 2007) evidenced that melt thermal advection of hot liquids infiltrating from asthenosphere result in significant rheological softening and weakening of the mantle lithosphere, with a decrease in total strength from 10 to 1 TN m$^{-1}$ as orders of magnitude within the axial zone of extension above the melting asthenosphere.

Melt/peridotite interaction and melt thermal advection drastically modified the rheological characteristics of the lithosphere axial zone of the extensional system.
ANALOGUE MODELING

Corti et al. (2007) evidenced formation of an axial lithospheric mantle columnn (WLM) with weakened rheological characteristics.

Thermomechanical erosion: analogue model results

(a) After 1 Ma (4mm, 10 km ext)

Weakened lithospheric mantle axial zone

(After: Corti et al., 2007)
Passive rifting was, accordingly, characterized by an early a-magmatic stage and a subsequent magmatic stage.

The magmatic stage (i.e., positive deformation/melt infiltration feed-back) formed a weakened axial zone between the future margins, that had a determinant role in continental drift/split.
The softened/weakened axial zone may have represented a preferential zone for the active upwelling of the deeper/hotter asthenosphere.

Upwelling asthenosphere was characterized by increased partial melting, complete aggregation of the melt increments and deepening of the melting sources (i.e., onset under garnet-facies conditions), as possibly indicated by the garnet signature of the Ligurian MORBs (e.g., Montanini et al., 2008, 2012).

Aggregated MORBs migrated to shallow levels within dunite channels, and brittle fractures (dykes), without significant interaction with the host peridotite.
NATURAL EVIDENCE FOR MORBs UPWELLING

The shallow shear zones
The dunite replacive channels
Melt stagnation and interstitial crystallization prevented any further melt migration by diffuse porous flow. Bodies of plagioclase-enriched peridotites are cut by a new generation of shear zones, showing plagioclase (+ orthopyroxene) porphyroclasts. This group of shear zones represent channels for further melt migration.
FIELD EVIDENCE FOR FOCUSED MIGRATION OF MORBs

Plagioclase-enriched shear zones ① show widespread spinel dunite channels ②. As it is widely accepted, these dunite channels were formed by percolation of silica-undersaturated melts at high melt/rock ratio and open system conditions.

After complete pyroxenes dissolution, these channels were exploited for upward migration of MORBs without significant interaction with the host peridotites.

These aggregated MORBs formed olivine gabbro intrusions, in the shallow mantle lithosphere, and pillow lava flows and edifices, when extruded above the tectonically denudated and sea-floor exposed, lithospheric mantle peridotites.
Continental geotherms from Jaupart and Mareschal (2007), Dry peridotite solidus from Hirschmann (2000). Line s-p and g-s = spinel – plagioclase facies and garnet-spinel facies boundaries, respectively. Lithosphere-Asthenosphere boundary (LAB) at a maximum reference depth of GPa 4.0.

**PRE-RIFT EVOLUTION**

1. residence in the asthenosphere; (2) accretion to lithosphere; (3) exhumation from garnet to spinel-facies conditions (*P* and *T* highly speculative, timing unknown); (4) annealing recrystallization in the lithosphere at a mean continental geotherm, (*P* highly speculative, *T* about 1000°C, timing unknown).

**RIFTING EVOLUTION**

4) to (5) almost adiabatic exhumation during early rifting stages (*T* average around 1000°C) (onset of rifting probably Middle-Upper Permian);
5) to (6) Increasing *T* under decreasing *P* (exhumation, up to average *T* 1230°C), due to melt thermal advection during extension (Middle Jurassic);
6) HT plagioclase impregnation (*T* average value 1180°C) (probably during the Middle to Upper Jurassic);
7) to (8) late exhumation to the sea-floor and cooling by conductive heat loss.
TRANSITION FROM PASSIVE TO ACTIVE RIFTING

Huismans, Podladchikov and Cloetingh (2001) modeled and discussed the transition from passive to active rifting with a two-dimensional numerical code. Their models support a scenario in which passive stretching leads to an unstable lithospheric configuration and the asthenosphere thermal buoyancy drives active upwelling in the lithosphere.

Active divergent driving forces may compete with the far-field tectonic forces and even drive the system causing a change from passive to active rifting forces. The extensional system makes transition from passive rifting to active rifting.

A RIDGE-TYPE THERMAL REGIME IN THE LIGURIAN TETHYS

Accordingly, melt thermal advection and the softened/weakened axial zone (i.e., the “unstable lithospheric configuration” of Huismans et al., 2001) in the Ligurian Tethys may have enhanced the onset of active focused asthenospheric upwelling between the future Europe and Adria continental margins.

The active, focused asthenosphere upwelling drove the system to the installation of a ridge-type thermal regime.
Reactive spinel-facies harzburgites

Plagioclase impregnate peridotites

Spinel-facies fractional melting model

Equilibrium melts with clinopyroxenes from spinel and plagioclase melt-reacted peridotite closely resemble modeled single melt increments of about 7% fractional melting of a sp-facies DMM source.
Plagioclase peridotites and gabbro-norites show clinopyroxenes and plagioclase strongly depleted incompatible trace elements. Cpx: (Mg# in the range 88.9-91.7), very low Sr (0.33-2.75 ppm) and Zr (2.50-25.60 ppm). Plg: (high An 78.7-93.1) and very low Sr contents (2.40-38.94 ppm).

The parental melts were significantly different from ophiolitic/oceanic MORBs.
THE OCEANIC MORB MAGMATISM

Gabbroic (and basaltic) dykes related to the MORB magmatism were intruded at shallow levels, frequently after partial serpentinization of the host peridotite.

Compositional data suggest that these rocks derived from aggregated MORB melts, which formed variably differentiated Al-Mg and Fe-Ti liquids, as they are presently represented by Mg-gabbros and Fe-Ti-gabbros bodies and dykes.

Inferred primary liquids, in equilibrium with clinopyroxenes from the less differentiated olivine gabbros, are closely similar to MORB of Hofmann (1988).

Olivine gabbro suite: whole rock

Olivine gabbro suite: minerals
The hidden magmatism was produced by strongly depleted single melt increments from DM mantle source under spinel-facies conditions during passive rifting. The subsequent oceanic magmatism was produced by deeper upwelling asthenosphere during sea-floor spreading. It formed the aggregated MORB melts parental of oceanic gabbros and basalts.
TIME CONSTRAINTS

Timing is based on reliable geochronological informations: i) Sm/Nd, Lu/Hf and Ar/Ar isochron ages and Os isotopes and Sm/Nd model ages of spinel peridotites; ii) U-Pb SHRIMP, Ar/Ar and Sm/Nd ages of intrusive rocks, iii) biochronology of supra-ophiolitic radiolarites in the Alps and Apennines, from recent bibliography;

*Melt-free shear zones*

Melt-free shear zones within (ex-garnet-)pyroxenites from the External Ligurides (Montanini et al., 2006) yielded Lu-Hf isochrons which indicate a minimum age of 220+/-13 Ma for subsolidus transition to plagioclase-facies assemblages. Upper Triassic ages of spinel to plagioclase-facies transition represent intermediate steps of the a-magmatic passive rift evolution, which should have been started significantly earlier, during Triassic (or even during transition from Permian to Triassic).

*Melt percolation, impregnation and stagnation (hidden, non extrusive magmatism)*

Sm/Nd DM model ages of reactive spinel harzburgites yielded: i) 170-175 Ma in Erro-Tobbio (data from Rampone et al., 2005); ii) 165 Ma in Mt. Nero Massif (External Ligurides) (Piccardo et al., 2004, data from Rampone et al., 1995). Sm/Nd isochron ages of plagioclase-enriched lherzolites and gabbro-norite veins in Mt. Maggiore (Corsica) yielded Late Jurassic ages (155±6 Ma) (data from Rampone et al., 2008). These few data seem to indicate that melt percolation was lasting in the range 175 Ma - 155 Ma (*from Middle to Upper Jurassic*), being relatively older in the marginal subcontinental peridotites and younger in the distal oceanic peridotites.
**MORB Melt intrusion and extrusion (oceanic, intrusive and eruptive magmatism)**

Middle Jurassic ages (164 Ma) are provided by Sm-Nd isochrons from Internal Liguride gabbros and Mt. Maggiore (Rampone et al., 1993, 1998; Rampone et al., 2009). Kaczmarek et al. (2007) reported that the MORB magmatism in the Piemont–Ligurian ophiolites started in Middle Jurassic and lasted from about 170 to 155 Ma (Upper Jurassic). Li et al. (2013), based on the compilation of the reliable literature U–Pb age data, reported that the ophiolitic gabbros from Eastern, Central and, Western Alps, Liguria and Corsica crystallized nearly synchronously at 166-158 Ma. Accordingly, intrusion of aggregated MORBs, and their differentiates, within the shallow lithospheric mantle occurred during **Middle to Upper Jurassic**.

**Ocean opening and MORB extrusion**

Bill et al. (2001) revised the biochronology of supra-ophiolitic radiolarites in the Alps and Apennines and provided information on the onset of oceanic spreading in the Alpine Tethys and of oceanic MORB extrusion, since basaltic lava flows are frequently interbedded with the radiolarites. They suggested that biochronologic and isotopic ages currently indicate that oceanic spreading of the Alpine Tethys began during the Middle Jurassic and continued until the Upper Jurassic. Accordingly, it can be extrapolated that onset of oceanization of the Ligurian Tethys basin and MORB eruption occurred during **Middle to Upper Jurassic**.
SUMMARY

Our field/laboratory data and the significant positive feed-back between natural evidence and numerical/analogue modelling of passive rifting, melt infiltration and melt thermal advection, allow to propose an integrated geodynamic model for rifting to spreading in the Ligurian Tethys realm, that is characterized by:

- early passive lithosphere extension - **a-magmatic rifting**;
- asthenosphere decompression partial melting - **magmatic rifting**;
- lithosphere **melt reactive percolation/storage**, thermal advection;
- formation of a **softened/weakened, axial zone** between the future continental margins, above the melting asthenosphere;
- **active asthenosphere upwelling** inside the wedge;
- **continental break-up** and passive margin formation;
- upwelling, intrusion and sea-floor **extrusion of MORB melts**.
Continental extension induced lithosphere thinning by melt-free extensional shear zones and asthenosphere passive upwelling.

This early stage of rifting was a-magmatic (a-magmatic passive rifting) until lithosphere was thinned to half of its thickness and the passively upwelling asthenosphere reached his melting conditions on decompression.

Isolated single melt increments, which were strongly trace elements depleted and silica-undersaturated, infiltrated the extending mantle lithosphere under spinel-facies conditions by diffuse and focused porous flow (magmatic passive rifting).

Migrating melts induced melt/peridotite interaction (pyroxene dissolving – olivine forming), percolating melts were transformed into derivative silica(-opx)-saturated liquids and percolated peridotites were modified to depleted, reactive spinel harzburgites.
The derivative, silica-saturated liquids percolated by porous flow to shallow lithospheric levels (i.e., plagioclase-peridotite facies conditions), where increasing heat loss by conduction induced their stagnation, storage and progressive crystallization, giving rise to plagioclase(+orthopyroxene)-enriched peridotites and opx-rich gabbro-norite pods (the hidden magmatism).

Melt percolation, from spinel-facies conditions, and melt storage, at plagioclase-facies conditions, represent important processes of melt thermal advection which formed a wedge-shaped, softened and weakened zone above the melting asthenosphere, along the axial zone of extension and future continental break-up.

Under the regime of passive extension, the drifting forces should have enhanced the mechanical erosion of the softened lithosphere of the axial zone.
Increased extension and the presence of the weakened/softened axial lithospheric zone should have allowed and facilitated the active focused upwelling of the deeper asthenosphere along the strongly modified wedge between the future continental margins. Passive rifting underwent a progressive transition to active rifting, since the horizontal stresses induced by the active asthenospheric upwelling enhanced the far-field tectonic forces and led the system to a from passive to active rifting. Further extension led to the break-up of the continental crust, the formation of the new extended Europe and Adria margins, and the tectonic denudation and sea-floor exposure of sub-continental lithospheric mantle, which preserved structural/compositional records of the hidden magmatism.
The deeper/hotter upwelling asthenosphere should have been characterized by increased partial melting and deepening of the melting sources (i.e., onset of melting under garnet-facies depths).

This partial melting process was the source of the aggregated MORB-type liquids (MORB oceanic magmatism), which migrated within dunite channels through the shallow melt-reacted mantle peridotites, without significant interaction with the host peridotite.

The aggregated MORB melts formed shallow olivine gabbro intrusions, and MOR pillow basalt flows, that discontinuously covered the variably serpentinized mantle peridotites and breccias. The MOR basaltic volcanism extruded after break-up of the continental crust, above the already denuded, and sea-floor exposed, lithospheric mantle peridotites.
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PERIDOTITE WORKSHOP
Lanzo, 2005

ALPINE OPHIOLITES and MODERN ANALOGUES WORKSHOP
Parma, 2009