

**MELT PERCOLATION AND  
MELT/ROCK INTERACTION IN THE  
LITHOSPHERIC MANTLE**

**INSIGHTS FROM OPHIOLITIC PERIDOTITES**

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# INTRODUCTION

Mantle peridotites exposed in the orogenic belts record the tectonic and magmatic processes they underwent during their evolution in the convective asthenosphere, their accretion and composite history in the thermal lithosphere and the fingerprints of the geodynamic setting of shallow evolution and emplacement.

Aim of this talk is to discuss some of the most prominent features that were induced in the mantle peridotites by the porous flow diffuse percolation of melts, the melt-rock interaction and the peridotite refertilization by reaction/interstitial crystallization of the migrating melts.

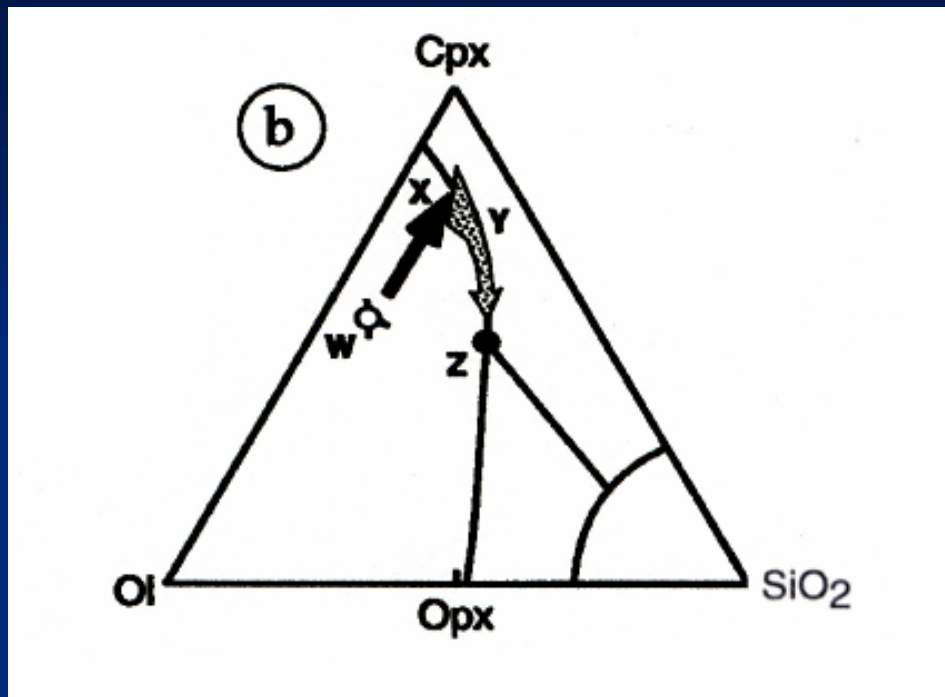
Particular attention will be dedicated to the field, structural-petrographic and petrological-geochemical features that allow to unravel these processes as they are recorded in mantle peridotites.

**Melts from the asthenosphere migrate through the lithospheric mantle via diffuse or focused porous flow percolation.**

**Asthenospheric melts are saturated in all the component mineral phases of the mantle source at the P-T conditions of formation / last equilibration with the melting source and became progressively oversaturated in olivine and undersaturated in pyroxenes as they migrate upwards (i.e. toward lower P conditions).**

**Depending on the physical/chemical characteristics of the percolated mantle and the migration mechanisms, the migrating melts can react with the host peridotites, modifying both the peridotite modal composition and the trace element budget and distribution of melts and host peridotite.**

**In the case of melt-rock interaction, percolating melts dissolve pyroxenes and precipitate olivine and interact with the mantle minerals tending to melt-mineral trace element equilibration.**

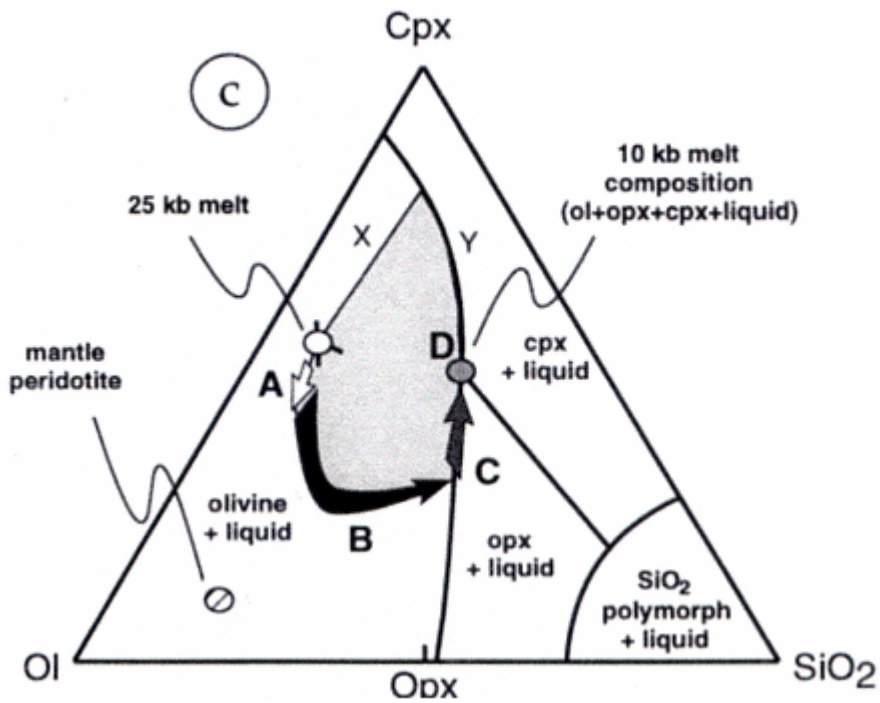


Schematic, pseudo-ternary phase diagram Ol-Cpx-SiO<sub>2</sub> at 0.5 GPa. It is assumed that at point W it ascends adiabatically a liquid formed by small degree partial melting of mantle lherzolite at 2.0 GPa. As the melt reaches its liquidus temperature at 0.5 GPa it is saturated in Ol. Crystallization of Ol drives the liquid composition to saturation in Cpx (X). Co-precipitation of Ol and Cpx drives the liquid along the path Y. Finally, saturation in Opx is reached at point Z. The liquid composition at Z is substantially different from a partial melt of lherzolite at 0.5 GPa, having a lower Mg/Fe ratio and lower Ni e Cr contents than a mantle primary melt formed at Z at 0.5 GPa.

Reaction from 2.0 to 0.5 GPa between mantle lherzolite and a liquid formed at 2.5 GPa.

The peridotite reactant is at its solidus T at 0.5 GPa and the liquid rising adiabatically is above its liquidus temperature.

The melt initially dissolves peridotites (path A) then crystallizes Ol and dissolve pyroxenes.

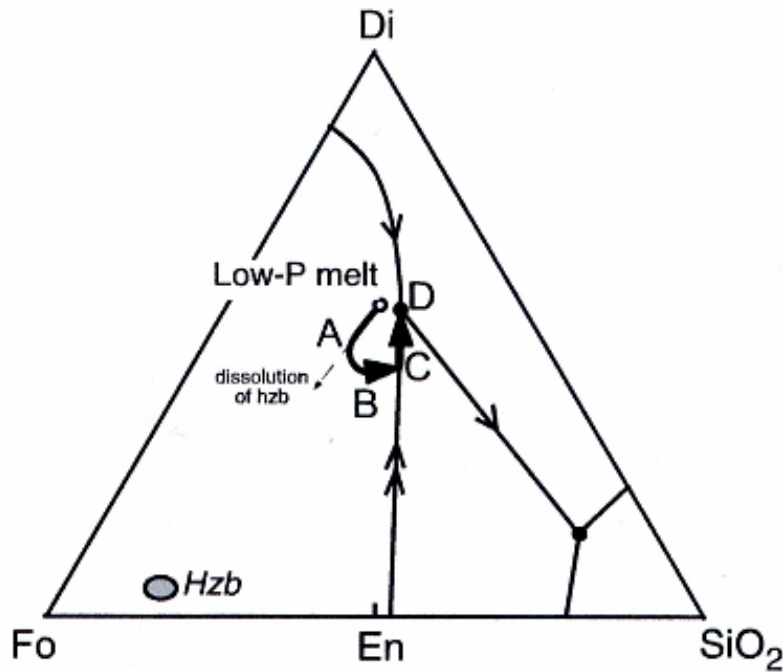


One possible liquid path is the vector B, that eventually leads to saturation of the melt in Opx as well as Ol (C). Continued reaction and cooling will consume Cpx, will crystallize Ol+Opx along the path C-D and finally the liquid will be saturated also in Cpx at D.

More rapid cooling, or slower pyroxene dissolution, would produce liquid paths within the shaded area.

The liquid composition at point D will be similar in major element composition (Mg/Fe, Ni, Cr, SiO<sub>2</sub>) to a small degree primary melt of mantle lherzolite at 0.5 GPa, although its trace element characteristics may preserve a "memory" of its open system provenance.

Low-pressure melt fractions  
reacting with harzburgitic wall-rock



A = Peridotite (Hzb) dissolution

B = Peridotite (Hzb) dissolution + olivine fractionation

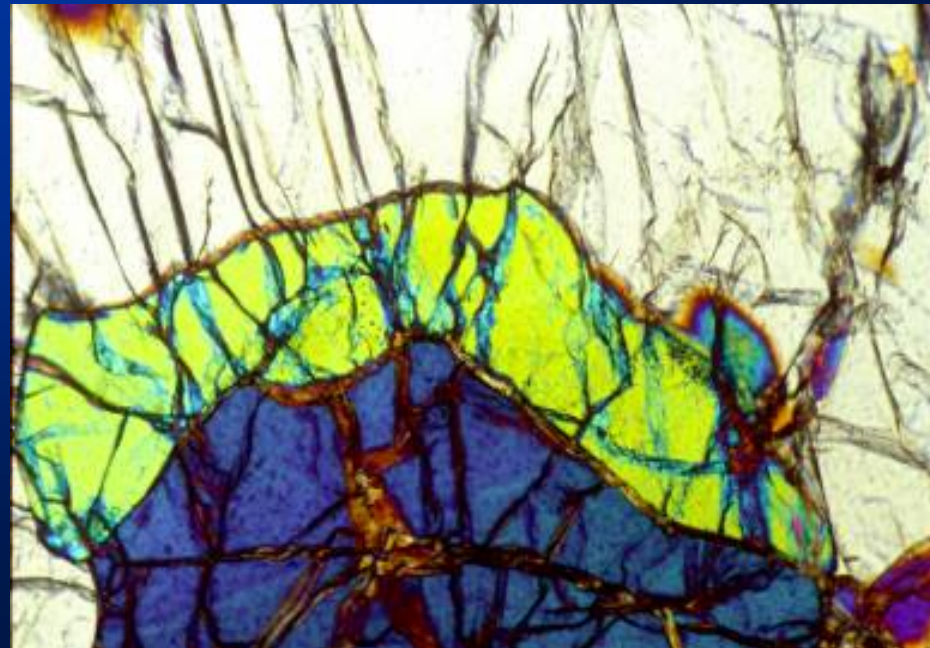
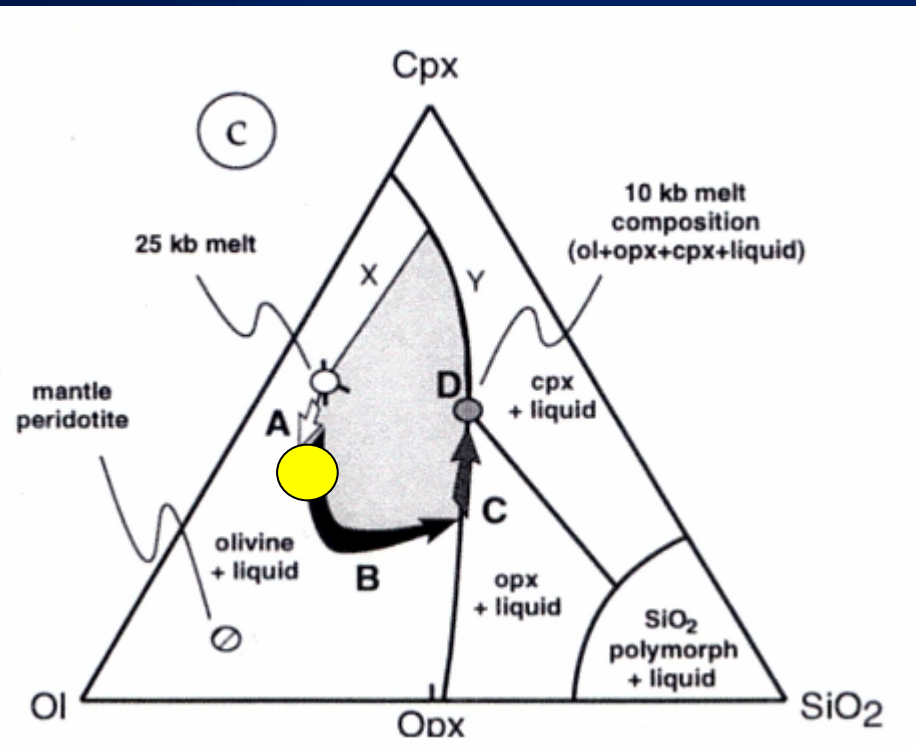
C = Reaction:  $\text{Fo} + \text{SiO}_2(\text{melt}) \rightarrow \text{En}$

D = Crystallisation of Fo, En, Cpx (and An) at ternary peritectic

**A similar trajectory is followed by a low pressure melt fraction rising through and reacting with a peridotite matrix at low pressure. The melt begins to dissolve the matrix (A), then precipitates Olivine (B). At (C), on the peritectic curve, Ol reacts with the liquid forming Opx (Ol + silica(liquid) = Opx), while Cpx is dissolved along the path C-D. At the ternary peritectic (D) the liquid is multiple saturated in all the component phases and crystallizes Olivine + Orthopyroxene + Clinopyroxene (+ Plagioclase).**

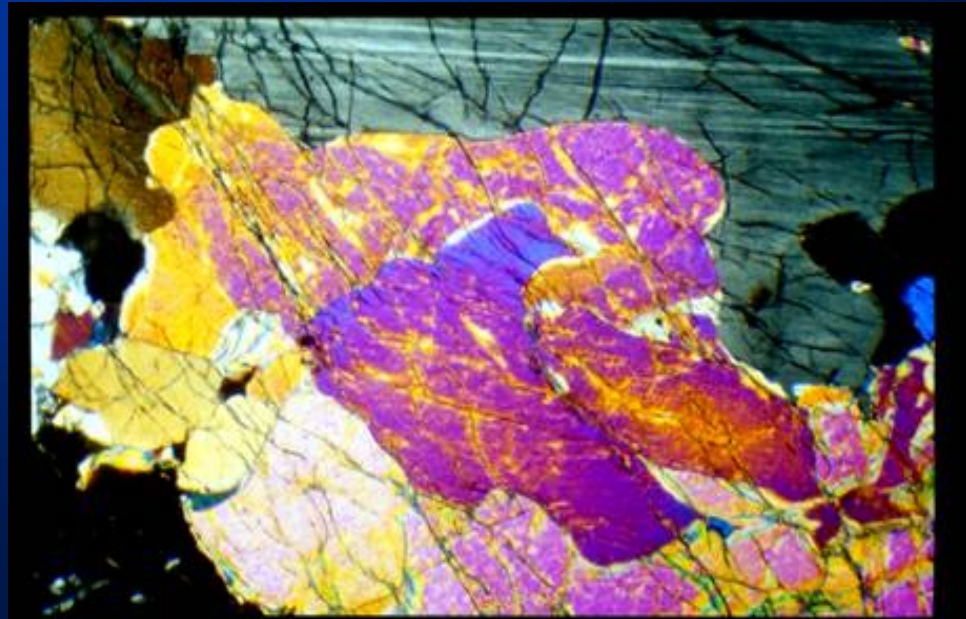
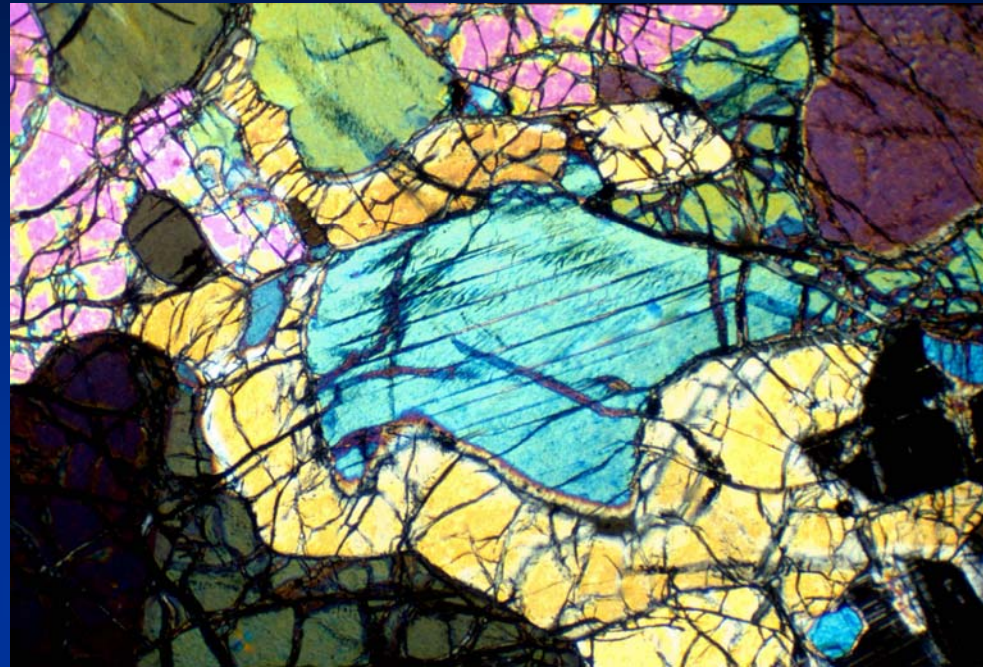
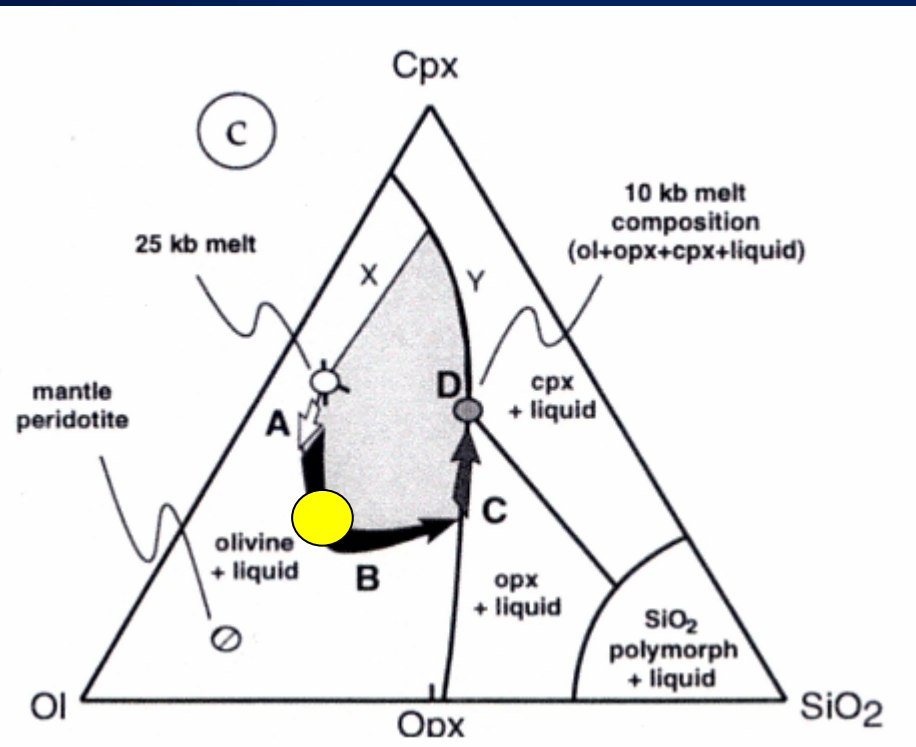
**RECOGNITION OF  
MELT/PERIDOTITE INTERACTION  
PROCESSES**

# Some micro-structural evidence



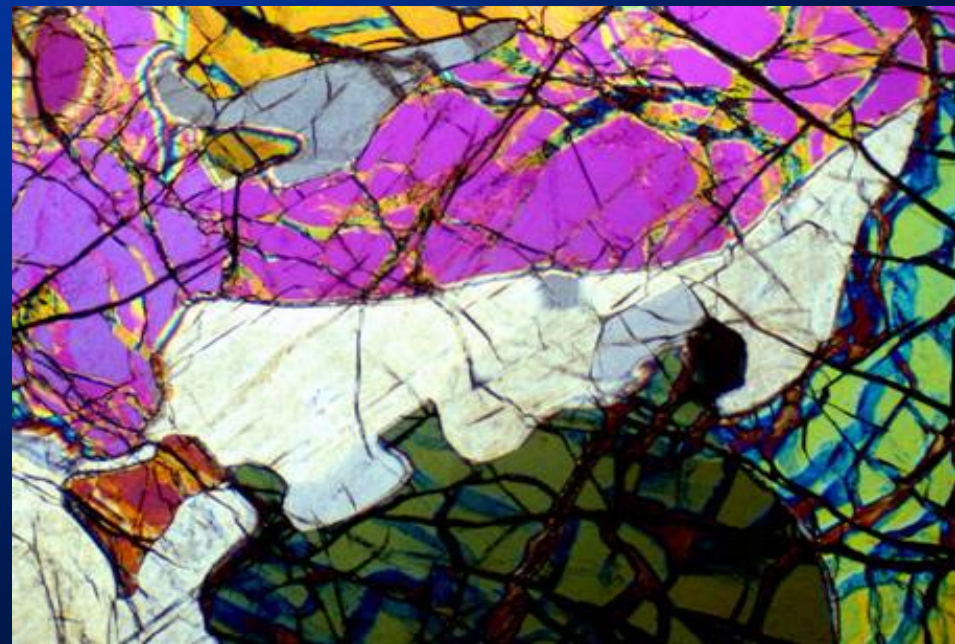
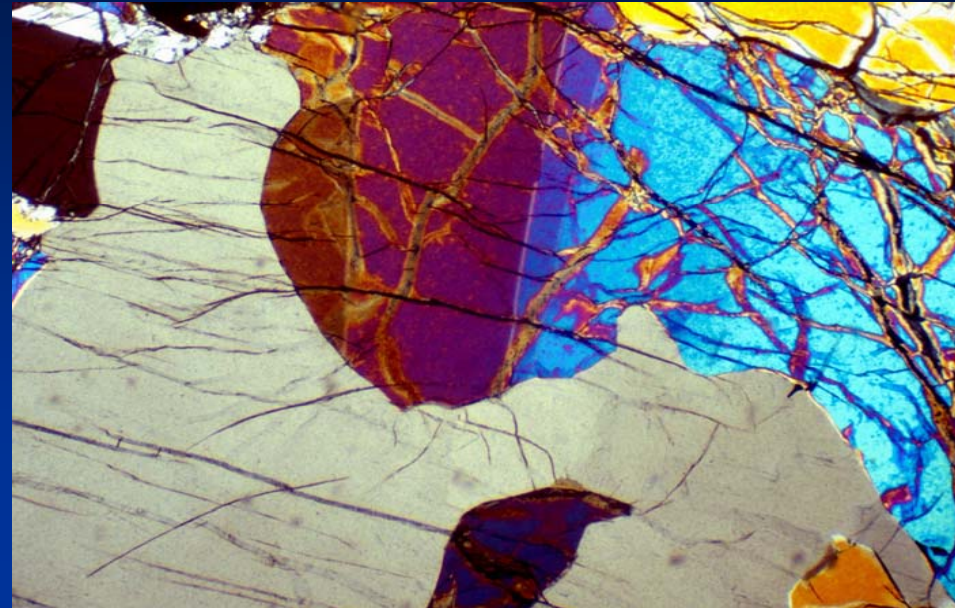
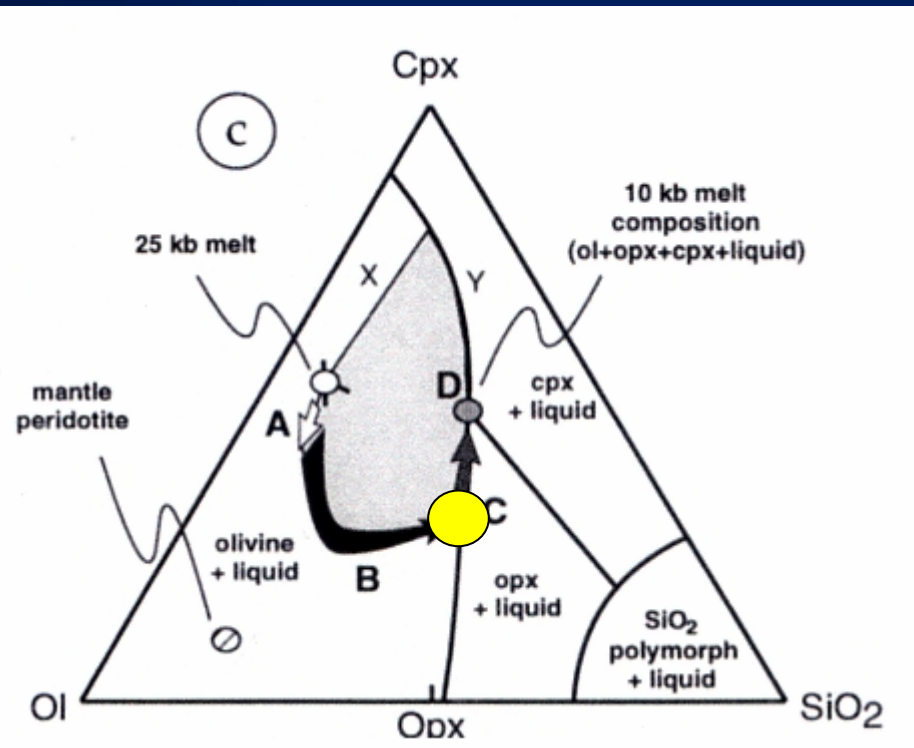
**New Olivine precipitation**

# Some micro-structural evidence



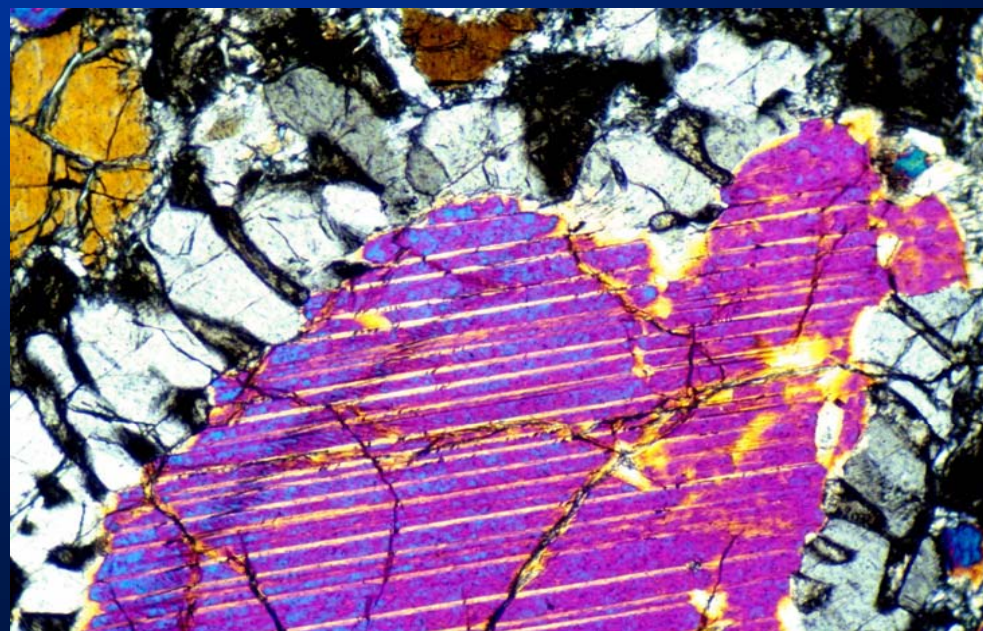
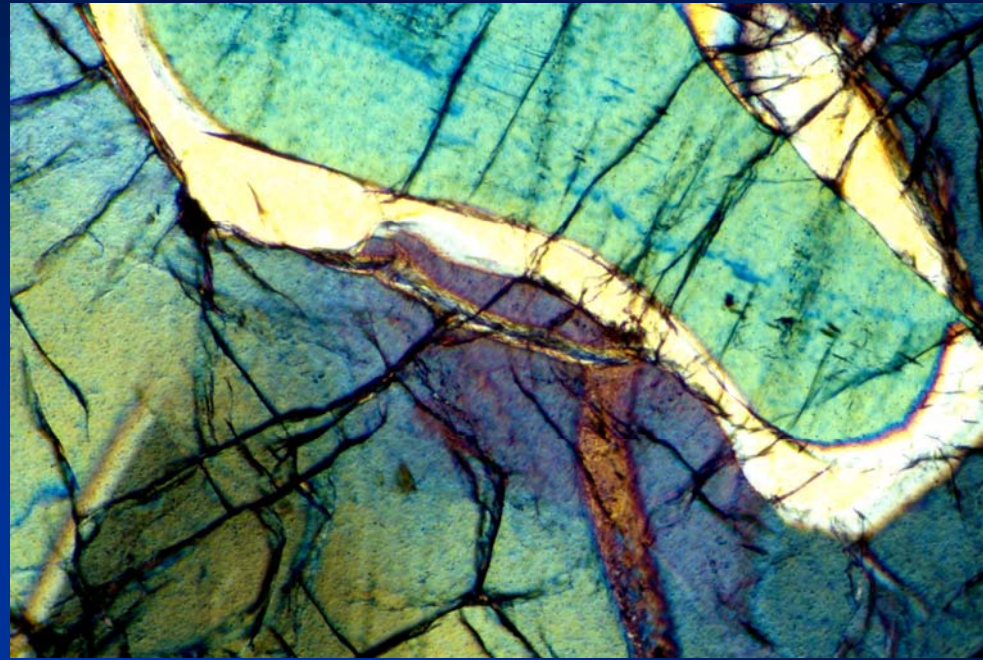
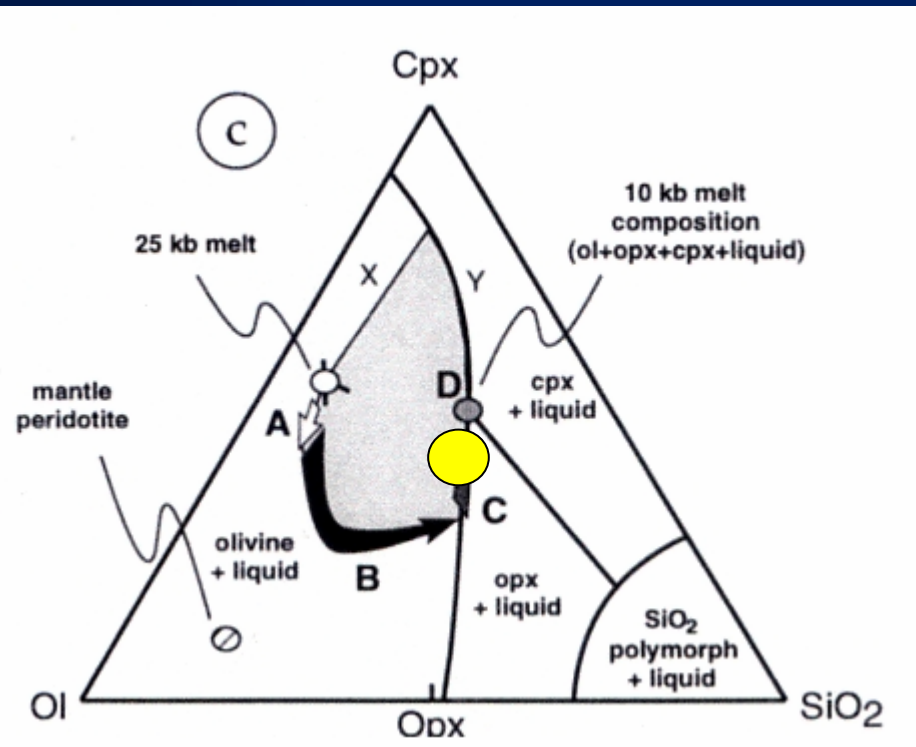
**Olivine precipitation and  
pyroxenes dissolution**

# Some micro-structural evidence



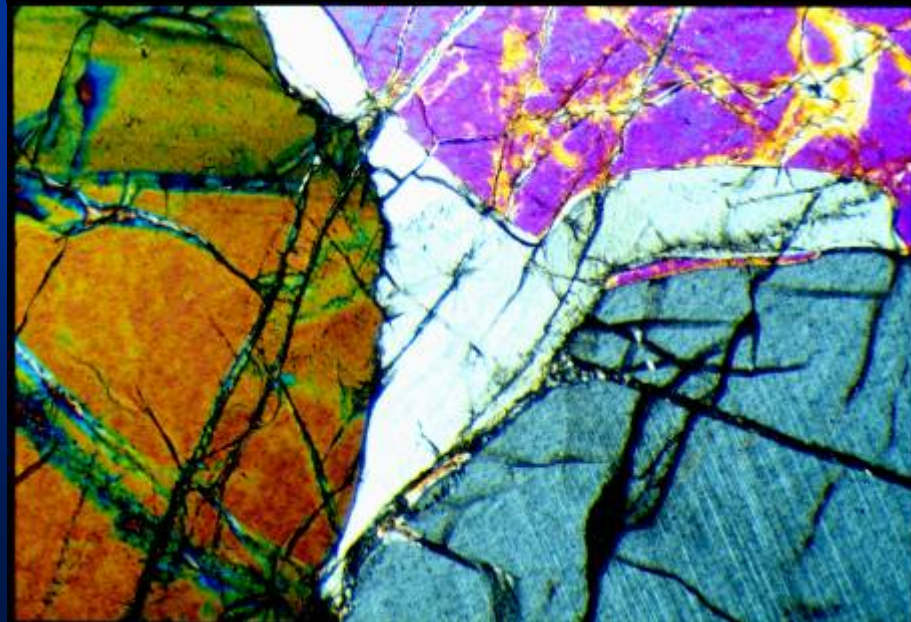
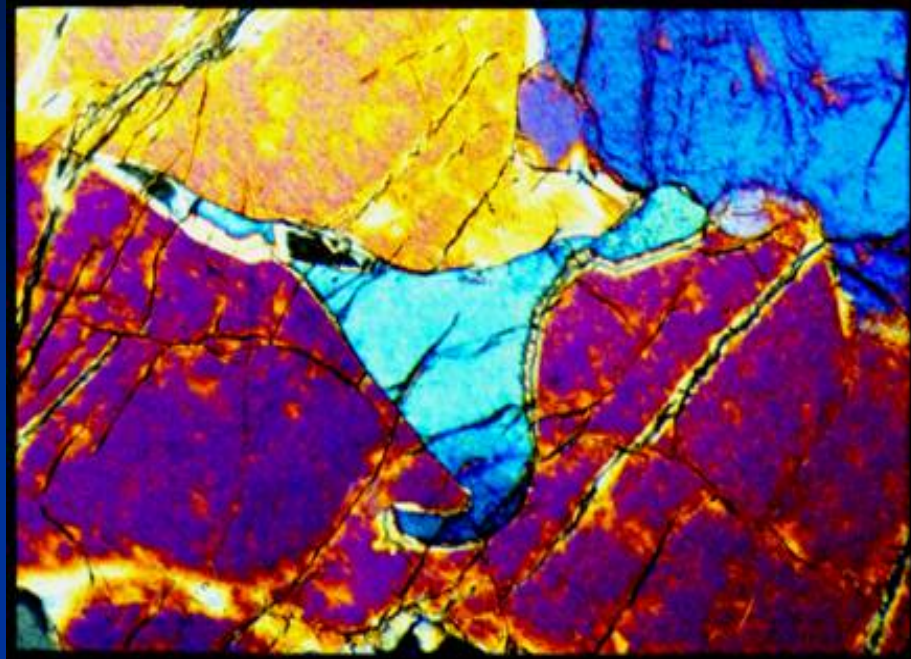
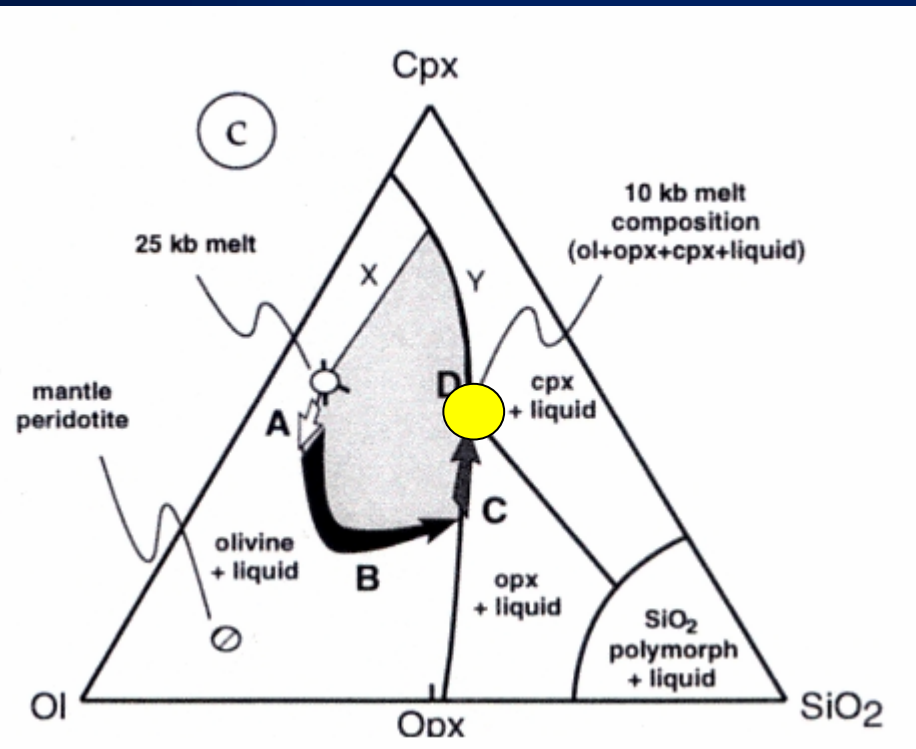
As the liquid becomes saturated in Orthopyroxene (silica) it reacts with Olivine forming Orthopyroxene  
 $Ol + \text{silica}(\text{liquid}) = \text{Opx}$

# Some micro-structural evidence



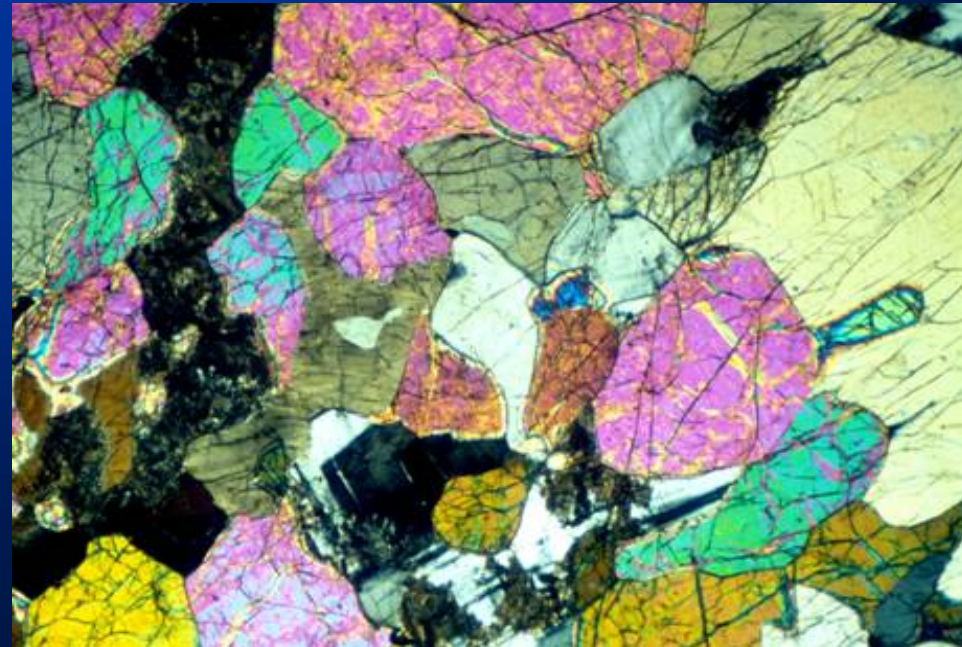
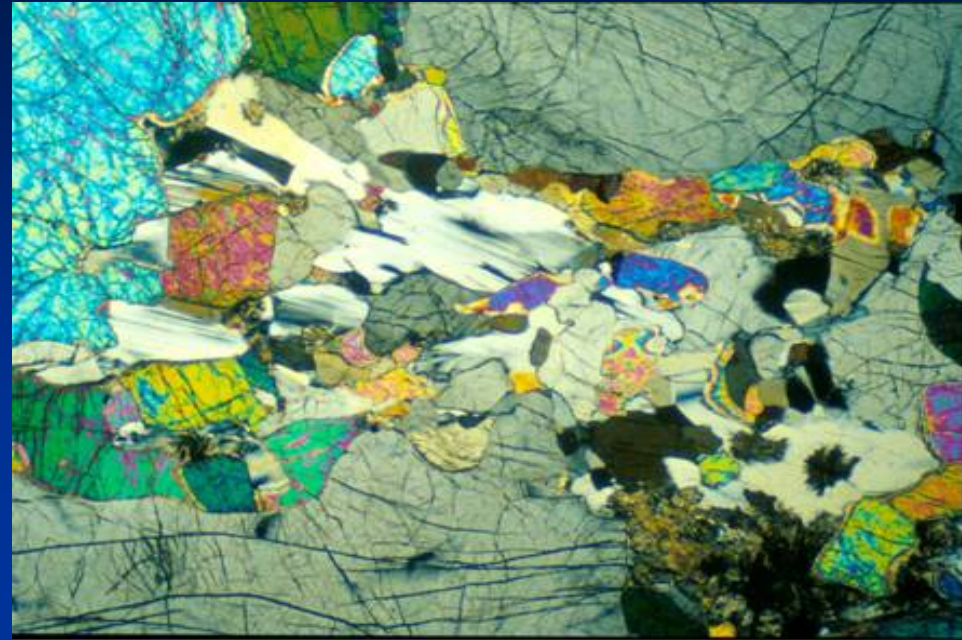
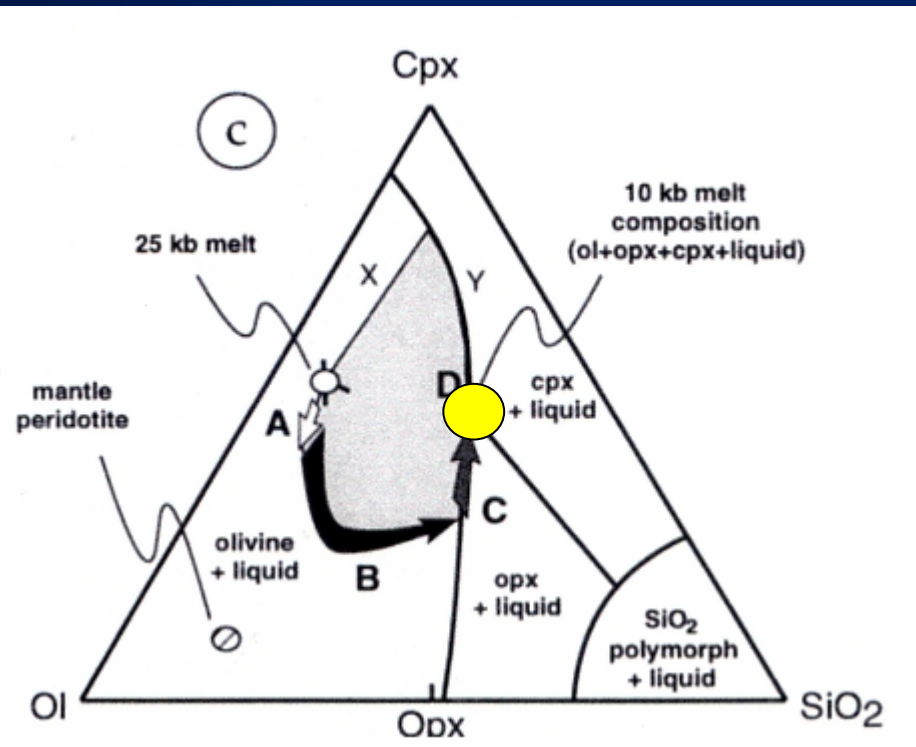
**Orthopyroxene saturation  
Clinopyroxene dissolution and  
orthopyroxene (+ plagioclase)  
crystallization**

# Some micro-structural evidence



**Melt Orthopyroxene and Clinopyroxene saturation and interstitial crystallization at triple junction in peridotite**

# Some micro-structural evidence



**Interstitial crystallization of Olivine, Orthopyroxene, Clinopyroxene + Plagioclase**

# THE PERIDOTITE PERSPECTIVE

# THE REACTIVE PERIDOTITES

## Some bulk rock features

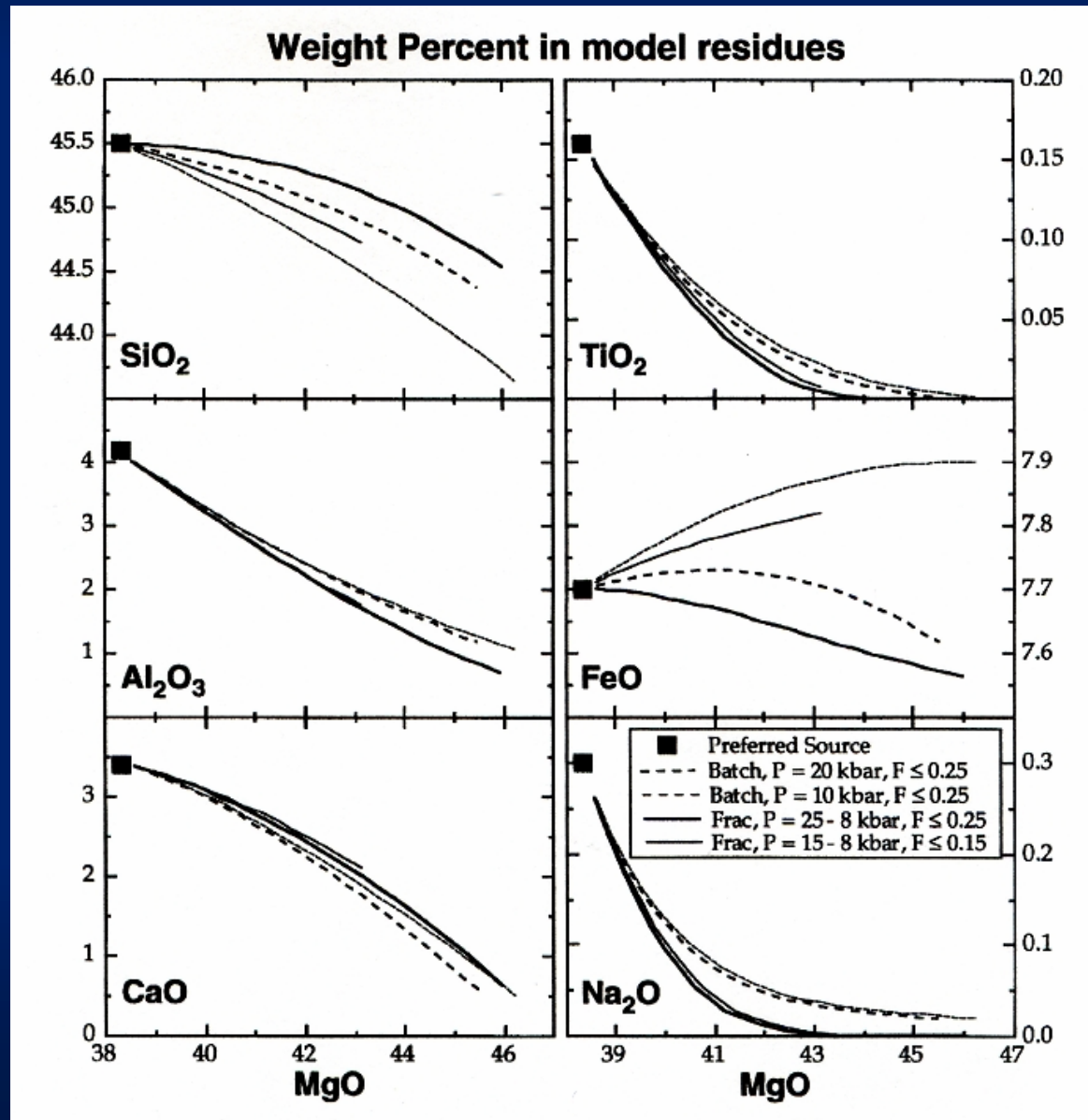
In an early stage of peridotite interaction with an Ol-oversaturated / Pxs-undersaturated liquid, new olivine crystallizes and mantle pyroxenes are dissolved in peridotite.

The mantle protoliths undergo significant modal changes being progressively enriched in modal olivine and are transformed into pyroxene-poor spinel peridotites.

The bulk rock major element compositions of these reactive peridotites are, accordingly, strongly modified toward MgO enriched and  $\text{SiO}_2$  ( $\text{CaO}$ ,  $\text{Al}_2\text{O}_3$ ) depleted compositions.

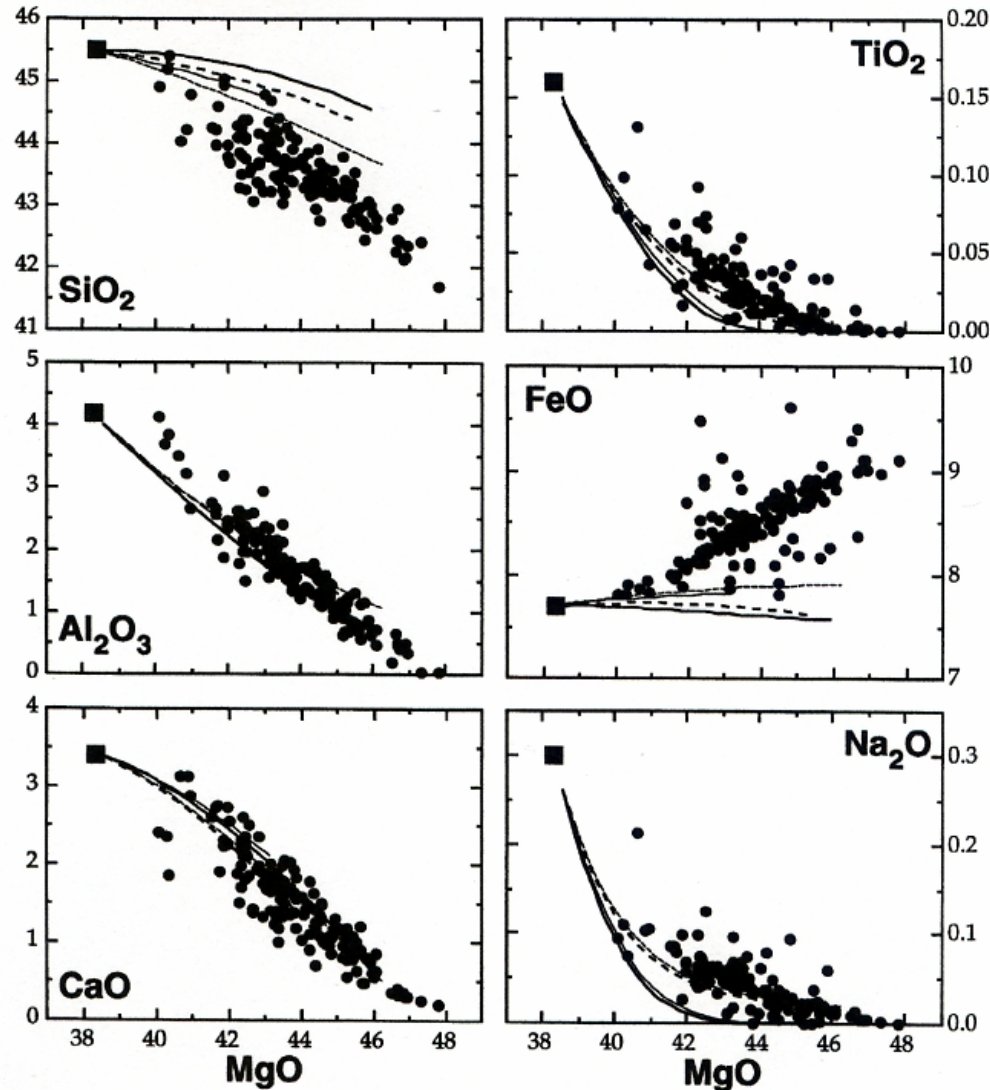
The reactive process (i.e., pyroxene dissolution and olivine precipitation) significantly modify the peridotite bulk rock major element compositions in a distinct way with respect to those of refractory residua after any kind of partial melting.

# Major element variation during progressive partial melting of a fertile mantle source

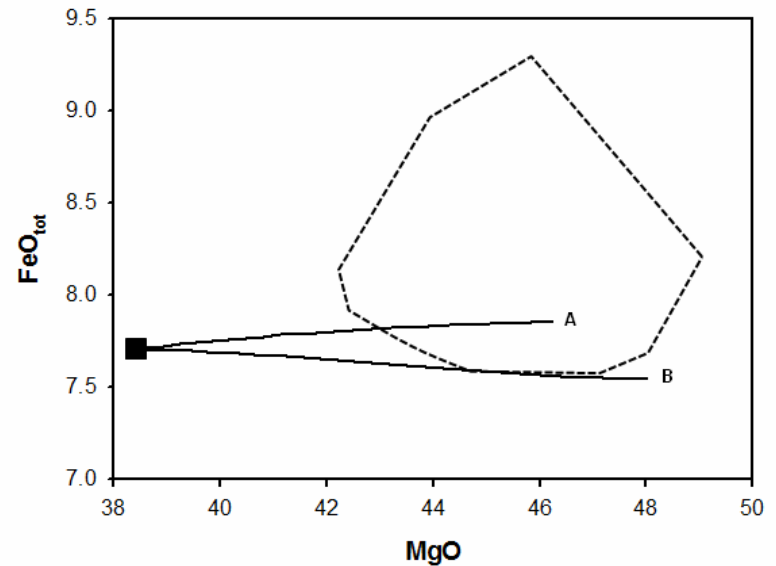
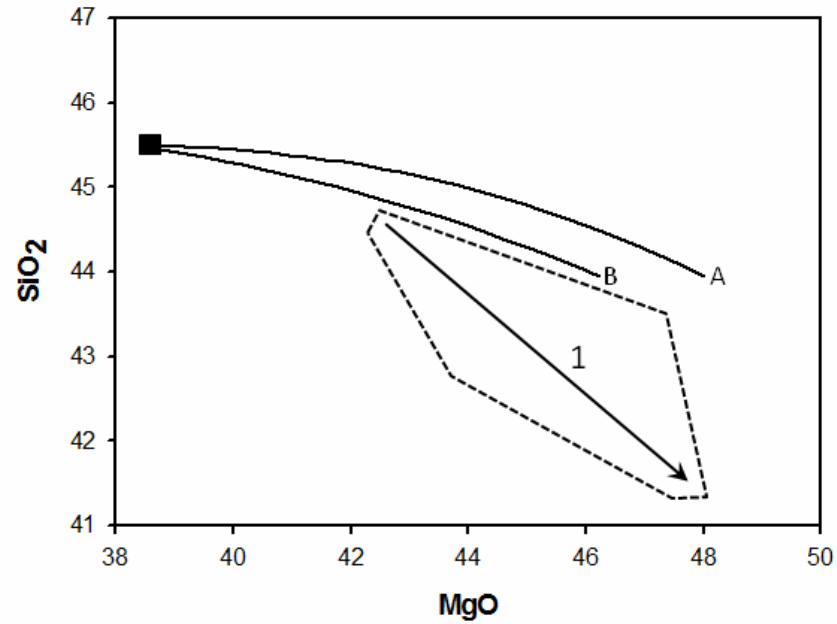
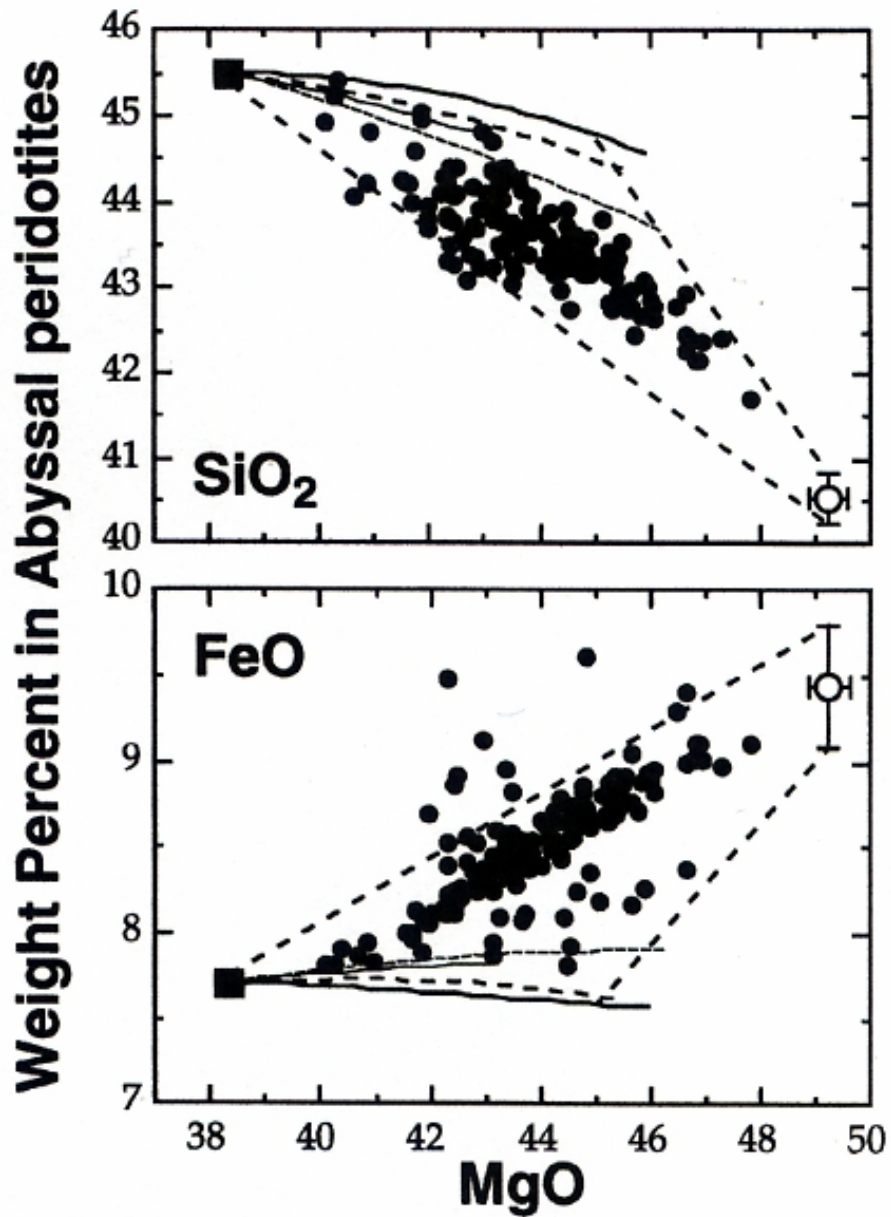


# Comparison with "typical" residua of oceanic MORB melting: the abyssal peridotites

Weight Percent in model residues and abyssal peridotites



# SiO<sub>2</sub> depletion and FeO enrichment



**On the MgO vs SiO<sub>2</sub> diagram, the reactive peridotites fall systematically at significantly lower SiO<sub>2</sub> at the given MgO values, when compared with refractory compositions after any kind of partial melting as calculated by Niu (1997).**

**Similarly, in the MgO vs FeO diagram, the reactive peridotites fall systematically at significantly higher FeO at the given MgO values, when compared with refractory compositions after any kind of partial melting as calculated by Niu (1997).**

**FeO enrichment in strongly depleted peridotites with respect to Fe content in fertile peridotite protoliths is a strong indication of interaction with a basaltic melt.**

**These evidence stress out that the petrogenetic process of the reactive peridotites cannot consist in a partial melting and melt extraction mechanism.**

# Micro-textural features

Under the microscope, characteristic and distinctive micro-textures of these depleted peridotites consist of:

- i) coronas and grain aggregates of new unstrained olivine surrounding and replacing deformed and exsolved pyroxene porphyroclasts;
- ii) crystallization of new olivine inside and/or along the contacts and at triple junctions between the deformed mantle porphyroclasts.

These micro-textures indicate that melt-mineral reaction caused pyroxenes' dissolution and olivine precipitation and that the percolating melt was silica(-pyroxene)-undersaturated. Sporadically, small interstitial grains of pyroxenes formed later along the porphyroclastic olivine rims and at triple junctions, suggesting that the percolating melts became silica(pyroxene)-saturated at the end of the melt-peridotite interaction process.

# THE REACTIVE PERIDOTITES

## Some trace element features

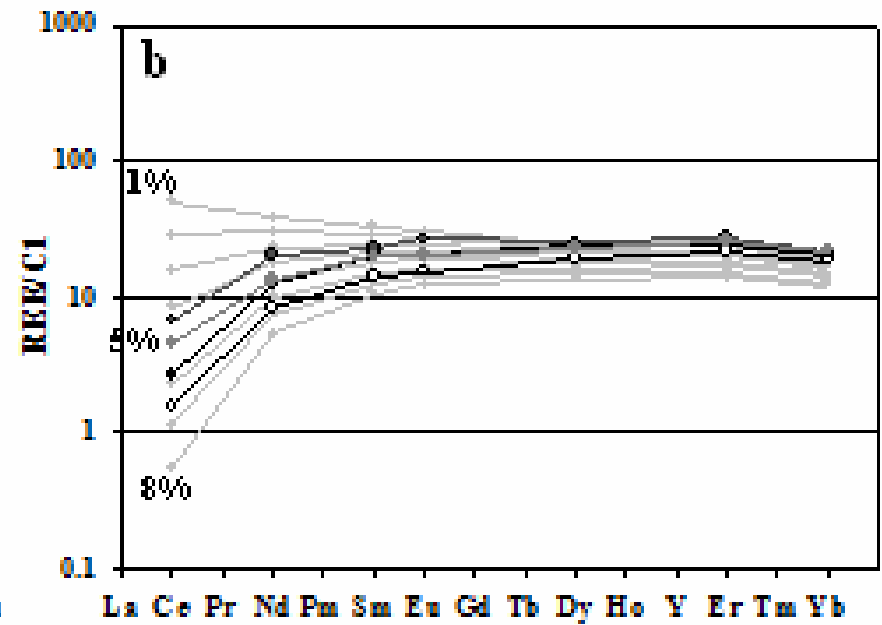
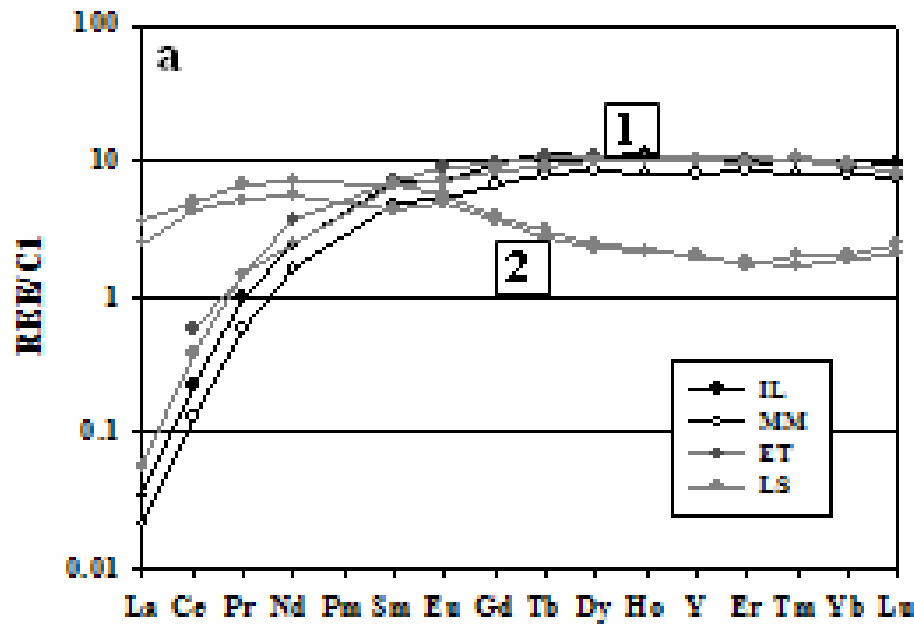
Host peridotite and percolating melt have distinct trace element budgets hosted in their component minerals.

Melt/peridotite interaction tend to the ideal trace element equilibration between the two reactant components.

Depending on the physical-chemical parameters governing the percolation, the low to high time-integrated melt-rock ratios, the peridotite minerals attain different trace element budgets.

Considering, in particular, mantle clinopyroxenes in reactive peridotites, their C1-normalized REE patterns are broadly divided into two different groups :

- 1) strongly fractionated in the LREE and almost flat in the MREE-HREE patterns, at  $\leq 10 \times C1$ , and
- 2) L-MREE enriched, HREE depleted sinusoidal patterns.



**Type-1 REE patterns are consistent with Cpx equilibrated with melts with MORB affinity formed by 5-7% fractional melting of a DM mantle source under spinel-facies conditions.**

**Type-2 sinusoidal REE patterns can be interpreted as induced by trace element equilibration with melts recording transient geochemical gradients attained during the melt-peridotite interaction process.**

# THE REACTIVE PERIDOTITES

## Concluding remarks

The reactive peridotites of the Alpine-Apennine ophiolitic peridotites describe a case of spinel peridotite interaction with rising melts formed in the asthenosphere under spinel-facies conditions (as suggested by the composition of melt in equilibrium with the totally melt-equilibrated Cpx).

The migrating melts were formed as single melt increments of asthenosphere fractional melting that survived unmixed and migrated isolated through the overlying lithospheric mantle.

As evidenced by the petrographic-structural features of the reactive peridotites, pyroxene dissolution led the melt composition to silica(-pyroxenes)-saturation.

# THE IMPREGNATED PERIDOTITES

## Some micro-textural features

These peridotites are enriched in plagioclase.

These Plg-enriched peridotites are moreover characterised by Opx-forming, Ol-dissolving micro-structures.

The most common micro-structural features are: i) the presence of widespread undeformed Plg crystals which are interstitial or crosscutting mantle minerals; ii) the replacement of mantle Ol by undeformed Opx patches; iii) the occurrence of mm-size Plg-rich gabbroic veins and pods, and symplectitic Px + Plg interstitial patches; iv) rims of Plg surrounding the Sp crystals.

These micro-textures indicate that the reacting melt, after precipitation of abundant Ol under low pressure conditions (i.e., Plg-peridotite facies) reached the Ol-Opx peritectic line (incongruent reaction boundary) and reacted with Ol [Ol + silica (liquid) = Opx] forming Opx (+ Plg).

These micro-textures are frequently coupled with Cpx-dissolving, Opx+Plg-forming reactions (i.e. symplectitic Opx+Plg coronas surrounding Cpx porphyroclasts) and interstitial crystallization of noritic microgranular aggregates.

The Cpx-dissolving/Opx+Plg forming microtextures indicate that the percolating melt is still undersaturated in Cpx, suggesting that the melt composition at low pressure conditions did not reach the composition of the melt that forms at the ternary peritectic of the Ol-Cpx-SiO<sub>2</sub> system.

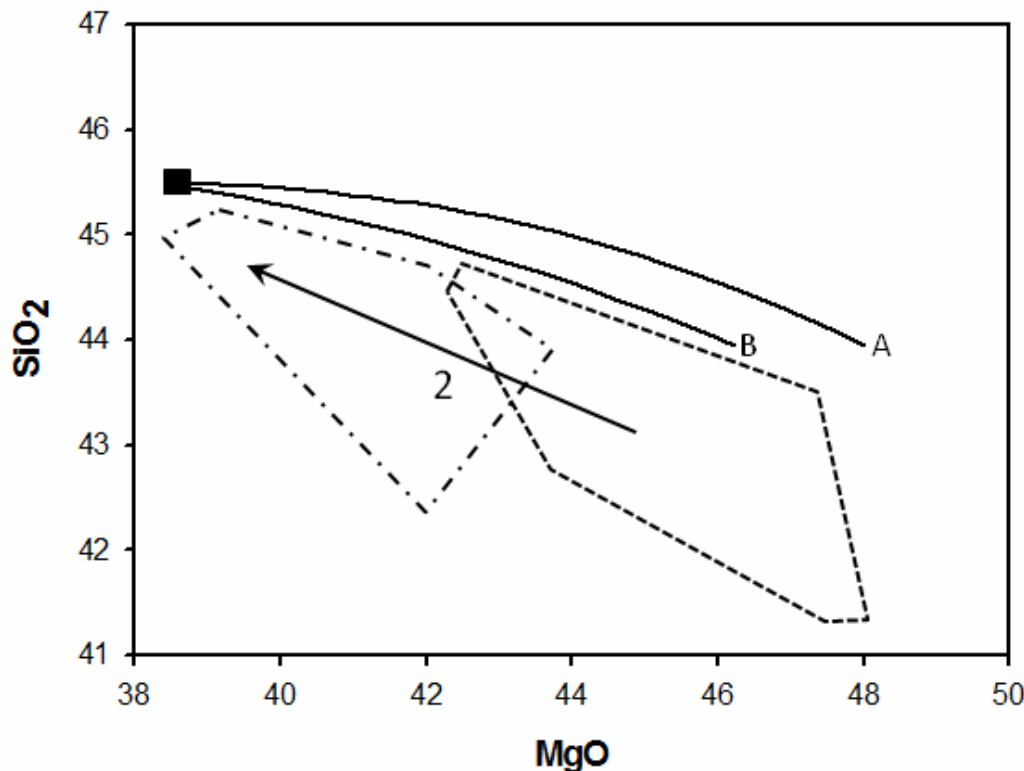
The subsequent interstitial crystallization of mm-size gabbro-noritic aggregates indicate that the melt reached the composition of the low pressure ternary peritectic, and crystallize all the equilibrium mineral phases.

It is worth noting that the liquid composition at the ternary peritectic will be similar in major element composition (Mg/Fe, Ni, Cr, SiO<sub>2</sub>) to the primary melt formed at 0.5 GPa.

# THE IMPREGNATED PERIDOTITES

## Some bulk rock features

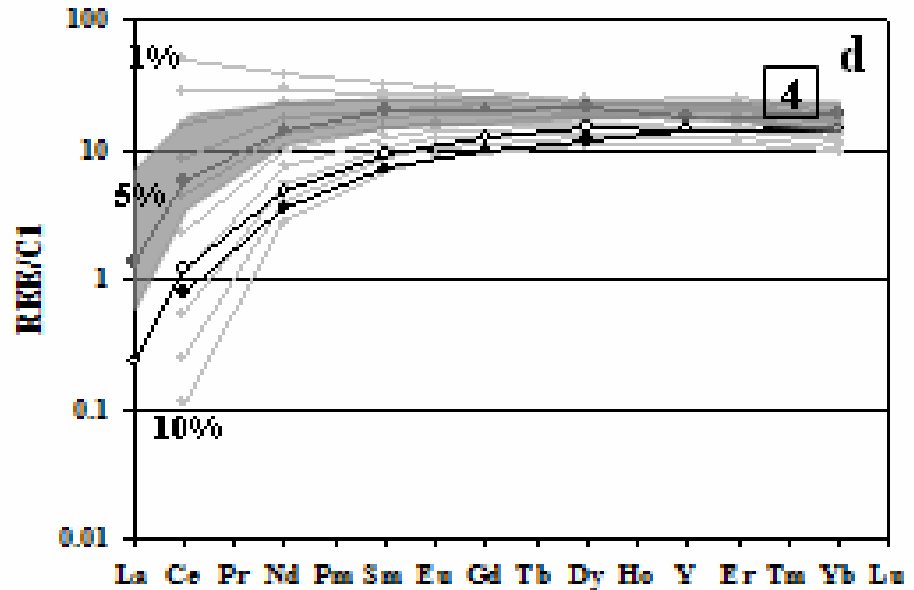
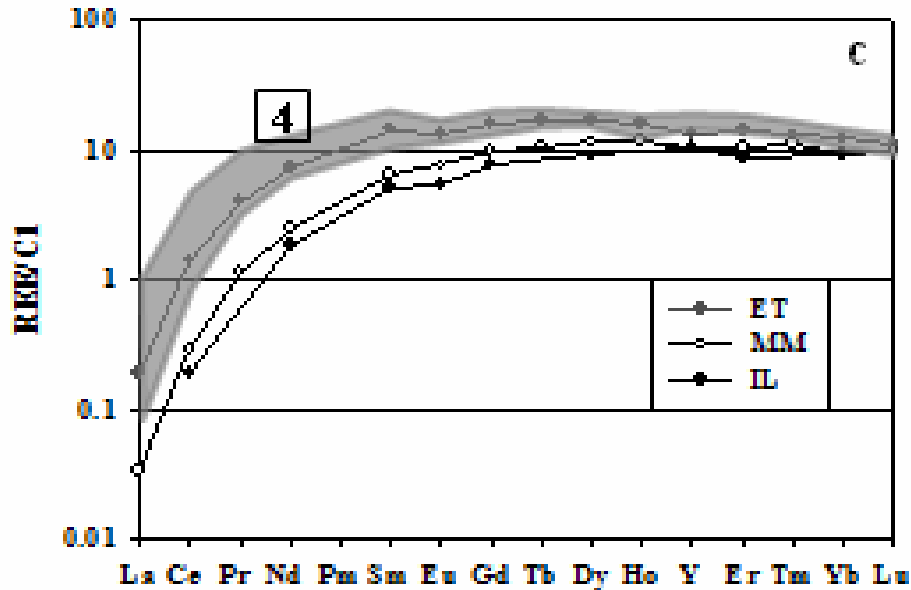
Their bulk rock major element compositions are depleted in  $\text{SiO}_2$  with respect to refractory residua after partial melting, at lower MgO and slightly higher  $\text{SiO}_2$  concentrations than the reactive peridotites.



Petrographic-structural features evidence that they were formed on previous reactive peridotites. Slight  $\text{SiO}_2$  increase and MgO decrease is fully consistent with addition to pristine reactive peridotites of a Plg-rich gabbroic assemblages.

# THE IMPREGNATED PERIDOTITES

## Some trace element features



Cpx C1-normalized REE patterns are relatively enriched in MREE and strongly fractionated in LREE.

Their trace element compositions preserve “a “memory” of its open system provenance”. Calculated equilibrium liquids indicate that they derive from single melt increments after 5-7% degree of fractional melting of DM spinel-facies mantle source.

# THE IMPREGNATED PERIDOTITES

## Concluding remarks

The impregnated peridotites of the Alpine-Apennine ophiolitic peridotites describe a case of spinel-plagioclase peridotite interaction with rising melts formed in the asthenosphere under spinel-facies conditions that attained pyroxene(-orthopyroxene)-saturation during reactive rising.

Although saturated basaltic melts can be formed by low pressure peridotite partial melting, the field, micro-textural and compositional features and, particularly, the reaction relationships between melts and low pressure peridotite claim for reaction/crystallization processes for their formation.

Accordingly, migrating melts derive from pristine single melt increments of fractional melting that underwent melt-rock interaction during previous stage of reactive percolation.

# THE REPLACIVE PERIDOTITES

The replacive peridotites, mostly spinel dunites, represent the case of almost complete pyroxene dissolution from pristine mantle peridotites caused by reactive focused percolation within channels most probably represented by structural and compositional discontinuities in the host peridotite.

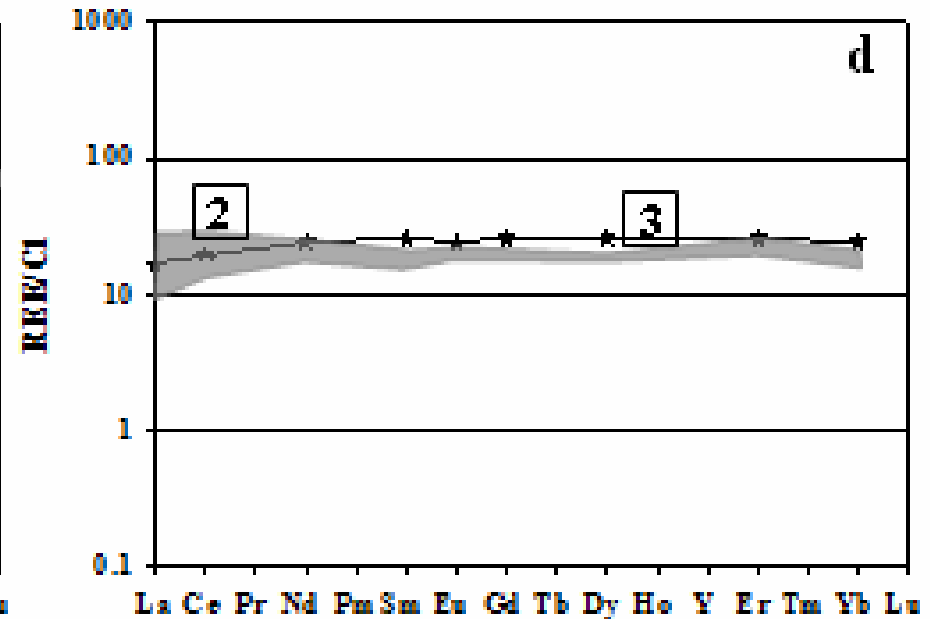
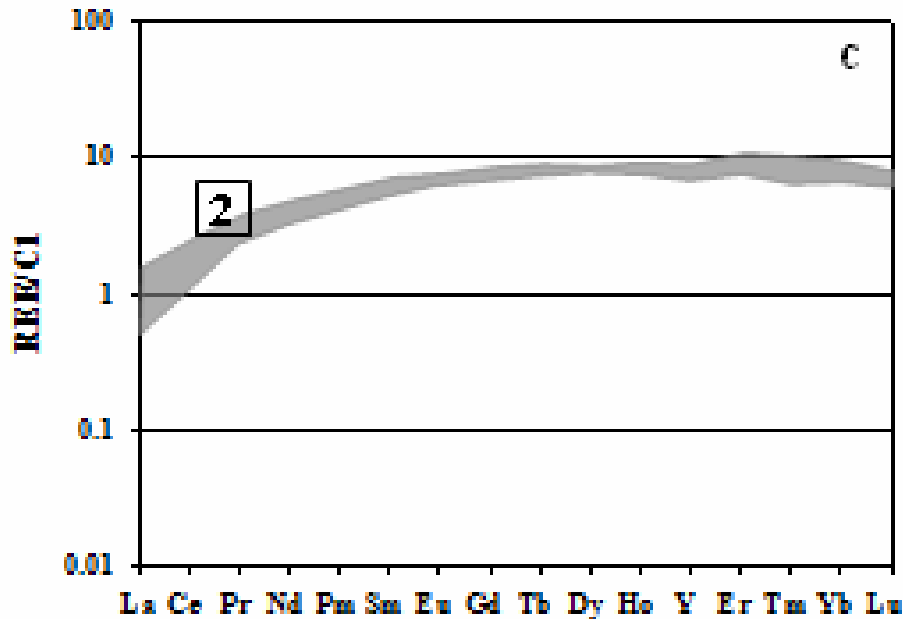
Field evidence suggest that strongly deformed tectonite-mylonite in shear zones are the preferential ways for the melt infiltration and represent suitable channels for melt migration.

As a rule, silica-undersaturated melts from the asthenosphere migrate under high melt/rock ratios and open system conditions, dissolving pyroxenes and precipitating olivine.

The migration channels are progressively transformed into high porosity, high permeability olivine-rich media that are, subsequently exploited for further delivery of primary, unreacted asthenospheric melts towards shallow levels.

# THE REPLACIVE PERIDOTITES

## Some trace element features



Cpx C1-normalized REE patterns (2) are slightly fractionated in LREE and almost flat in the M-HREE at less than 10xC1.

Calculated equilibrium liquids closely match with aggregate MORB liquids.

# THE REPLACIVE PERIDOTITES

## Concluding remarks

The replacive peridotites of the Alpine-Apennine ophiolitic peridotites describe a case of focused porous flow percolation of silica(-pyroxene)-undersaturated melts driven by structural or compositional discontinuities, when diffuse melt migration is no more permitted by the physical conditions (temperature, porosity etc.) of the host peridotite.

Rapid open-system reactive migration dissolve pyroxenes and precipitate olivine, forming suitable channels for further migration without any melt-rock reaction of subsequent melts, that can migrate preserving their primary characters.

Replacive dunite channels are believed to represent preferential pathways for MORB melt upwelling under mid-ocean ridges.

# DISCUSSION

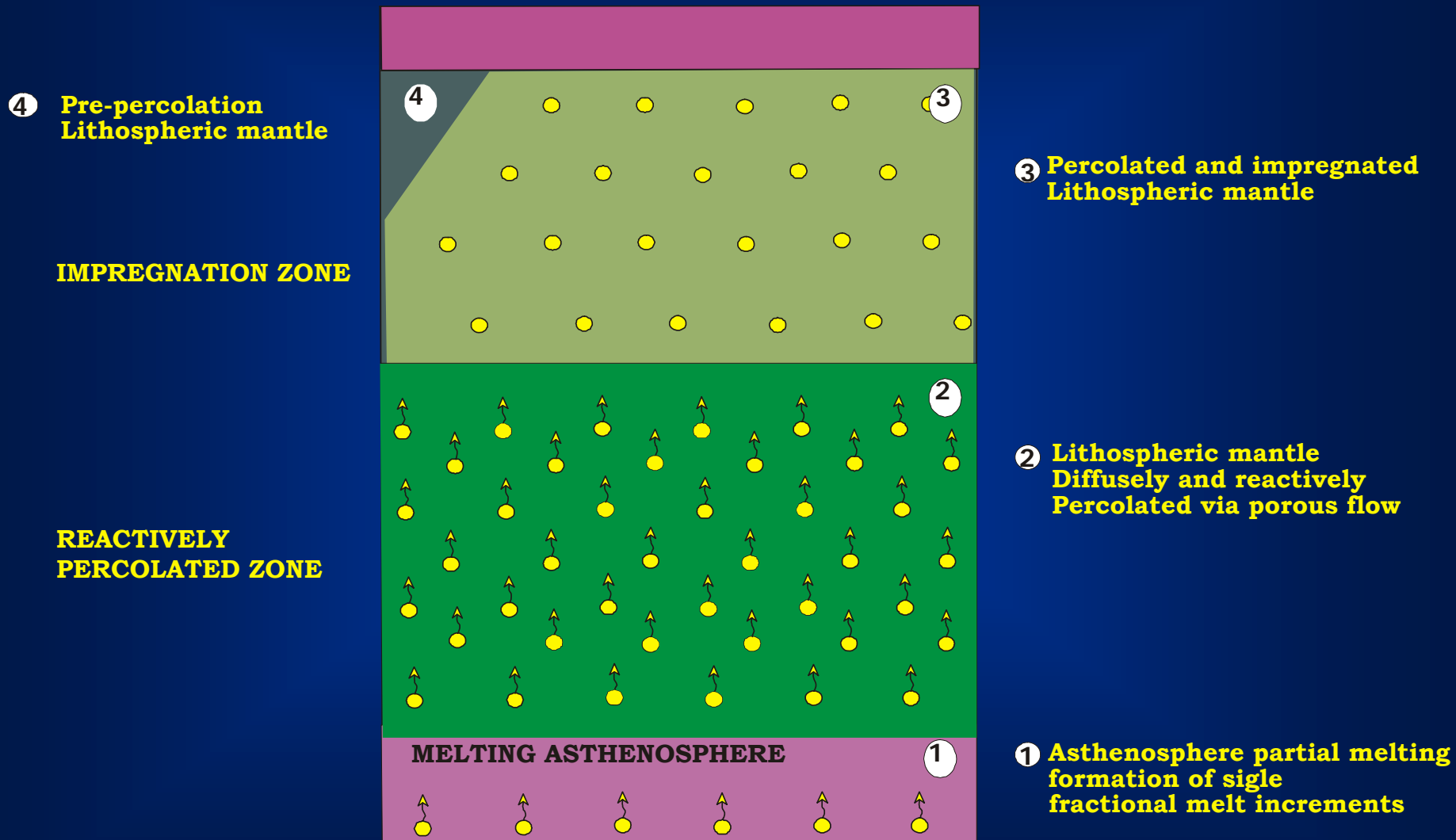
Field, structural and petrologic knowledge on the Alpine-Apennine peridotite massifs evidence the sequence of melt-rock interaction processes that were formed above the melting asthenosphere during continental extension and rifting.

The sequence of melt -rock reaction events occurred during extension and the different sections of lithospheric mantle were exhumed from Sp- to Plg-peridotite facies conditions.

Accordingly, every peridotite massif records the superimposed sequence of melt-rock interaction events from the early reactive percolation, to the subsequent impregnation to the later formation of the replacive channels.

This sequence describe the composite history of melts that migrated through the mantle lithosphere via diffuse porous flow percolation and reacted with the percolated peridotites.

# MELT MIGRATION IN THE MANTLE LITHOSPHERE



# MELT MIGRATION IN THE MANTLE LITHOSPHERE

