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Rejuvenation of lithospheric mantle by thermal erosion and igneous refertilisation

Case studies in Lherz and Ronda orogenic lherzolites

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MARIE CURIE ACTIONS

Crystal2Plate First Training Session
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Lherzolite?

• Fertile mantle rock with a composition not far from Primitive Mantle.

(Spinel field: about 50-60 olivine, 25-30% opx, 12-17% cpx, 2-3% spinel.)

Orogenic lherzolite?

• Fertile subcontinental mantle exhumed at continental margins during lithospheric thinning (mantle denudation), then tectonically emplaced in the crust.

Lherz?

- A small (~ 1 km^2) orogenic lherzolite in Pyrénées;
- the « lherzolite » type locality;
- considered to be pristine for decades;
- recently revisited and now viewed as a case study for lithosphere refertilization due to melt ingress at near-solidus temperature.

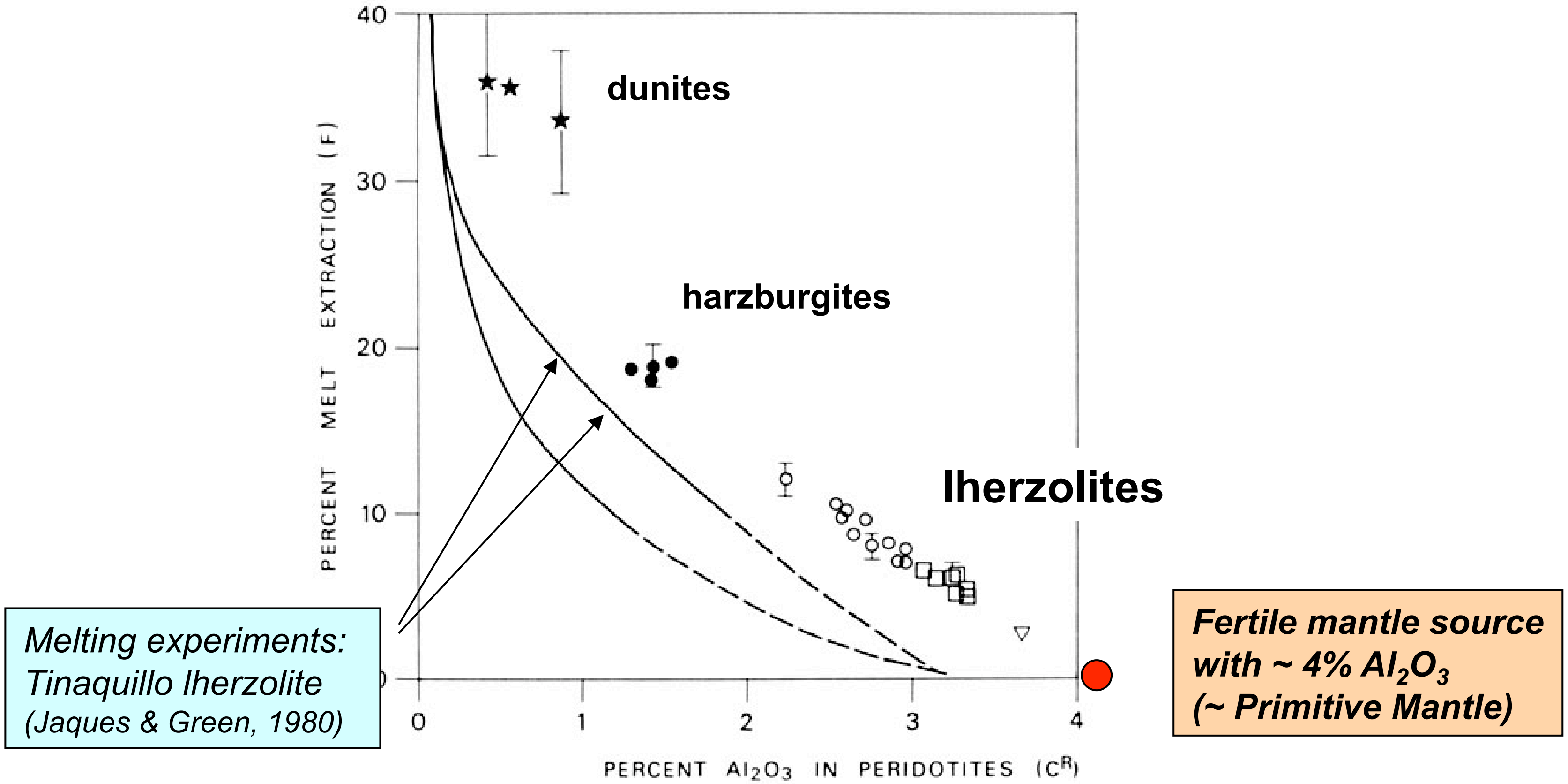
(Le Roux et al., 2007, 2008, 2009 – EPSL)

Ronda?

- A much larger (> 350 km^2) orogenic lherzolite in southern Spain;
- A case study for lithosphere thermal erosion and related features:
  - (fossil) moving lithosphere-asthenosphere boundary,
  - lithospheric melting (« asthenospherization »),
  - feed-back between melt infiltration and deformation.

Van der Wal & B., 1996 – CMP;
Garrido & B., 1999 – JPet;
Lenoir et al. 2001 – JPet;
Vauchez & Garrido, 2001 – EPSL;
Soustelle & al., 2009 – JPet.

Lherzolites: widely and for long considered as pristine mantle,
only weakly affected by partial melting and melt extraction



Mass-balance (peridotite-melt) model for the Lanzo orogenic lherzolite, constrained by experimental data (Bodinier, 1988).

However, for long, the melting model has been challenged by field observations and geochemistry:

(1) « Melt impregnation » textures in plagioclase lherzolites

Lanzo (Boudier & Nicolas,1972)

The most 'impregnated' lherzolites have 'Primitive Mantle' compositions (Al_2O_3 ~ 4%)

Also:

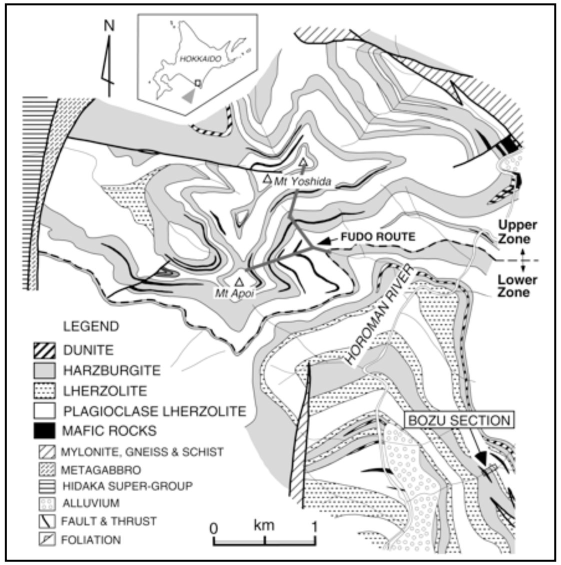
Othris (Menzies, 1973; Dijkstra et *al*., 2001),

New Caledonia (Nicolas & Dupuy, 1984)

Liguria-Corsica (Rampone *et al*., 1994).

(2) lherzolite- harzburgite layering (meter to tens of meters thick)

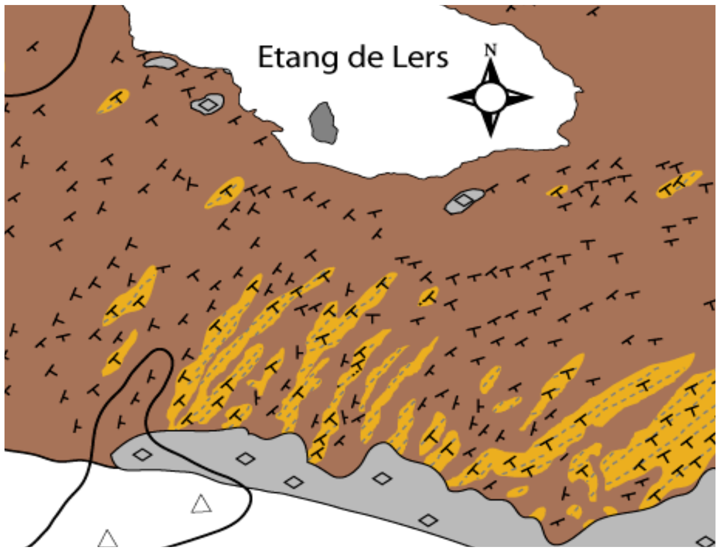
Horoman (after Takazawa et al., 1996)



The melting model implies irrealistic, small-scale thermal gradients in the mantle:

Suggested alternatives :

- frozen compaction-decompaction waves (Obata & Nagahara, 1987);
- folding and stretching of larger structures (Toramaru *et al.*, 2001);
- chanelled, fluxed melting (Takazawa et al. , 1992);
- mingling of lithospheric strips with convecting asthenosphere (Bodinier & Godard, 2003).

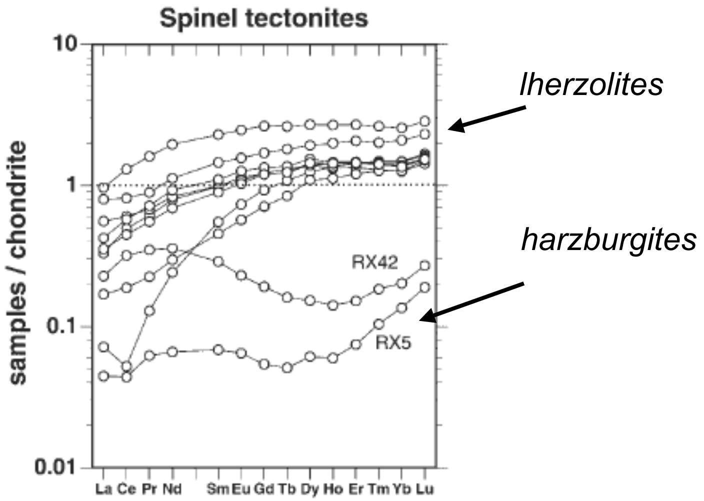


Lherz (after Le Roux et al., 2008)

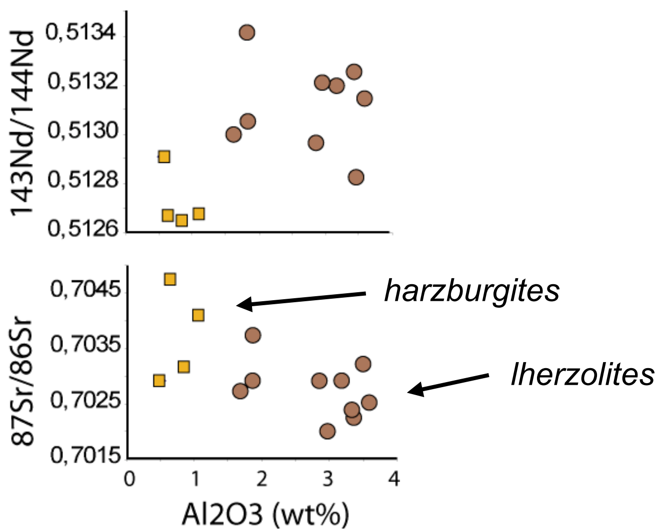
(3) harzburgites are more enriched in LREE than lherzolites

(also true for Nd-Sr isotopes, suggesting time-integration)

Ronda (Lenoir et al., 2001)



Lherz (Downes et al., 1991)



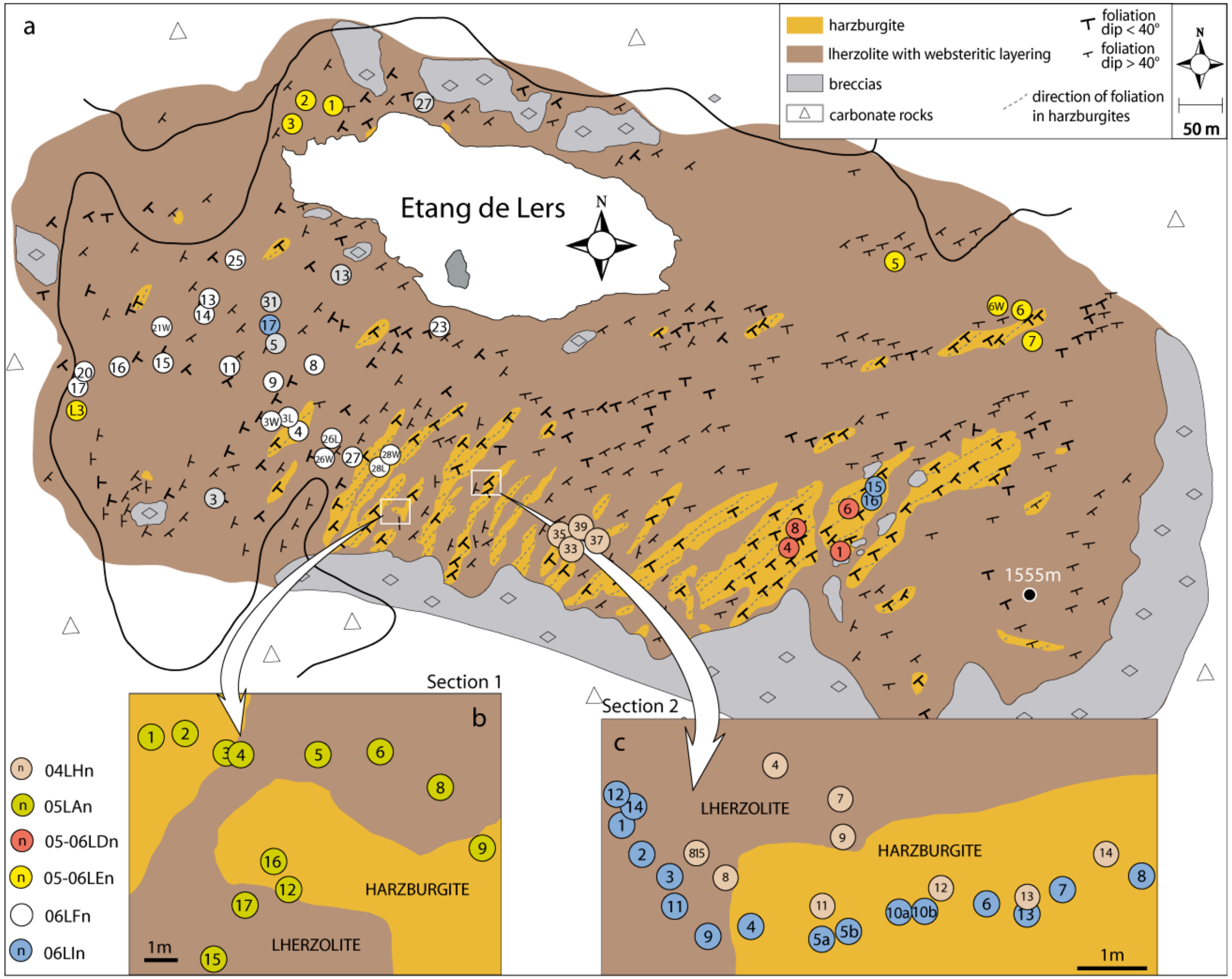
A widespread feature (also observed in xenoliths)

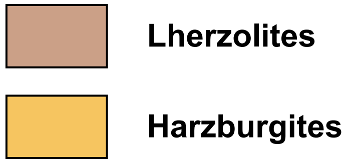
- harzburgites more permeable to enriched melts/fluids, based on Toramarau & Fujii (1986) (Bodinier *et al.*, 1988);

- harzburgites formed by fluxed melting, or (chanelled) reactive porous flow, based on Kelemen's model for dunites (Takazawa et al. , 1992);

- mingling of SCLM strips with convecting asthenosphere (Bodinier & Godard, 2003).

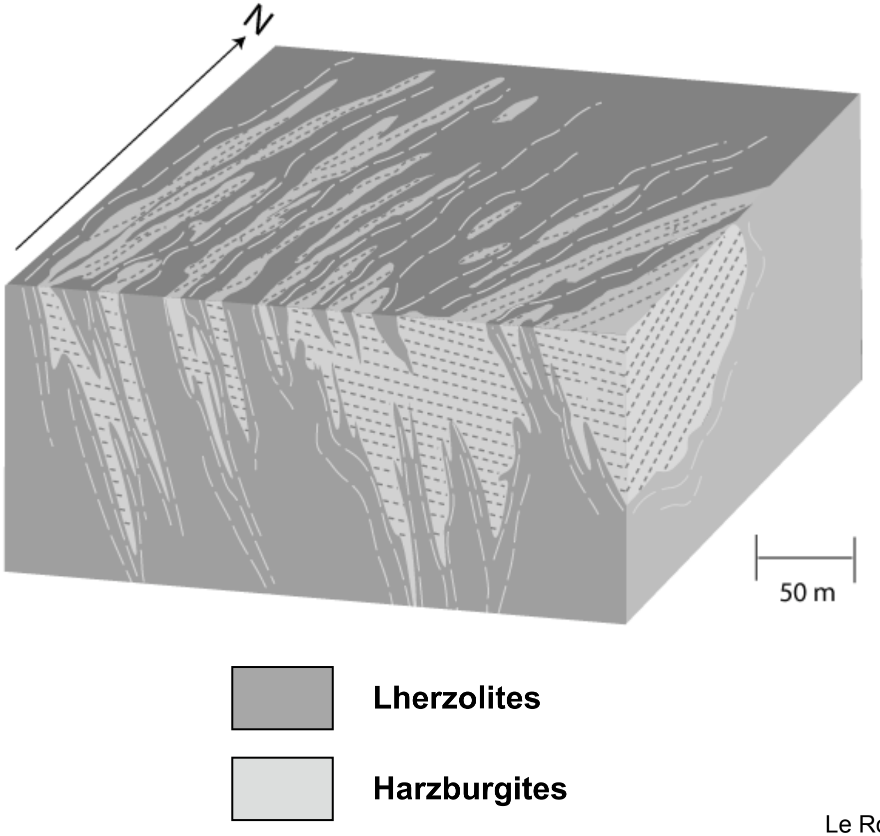
The Lherz massif





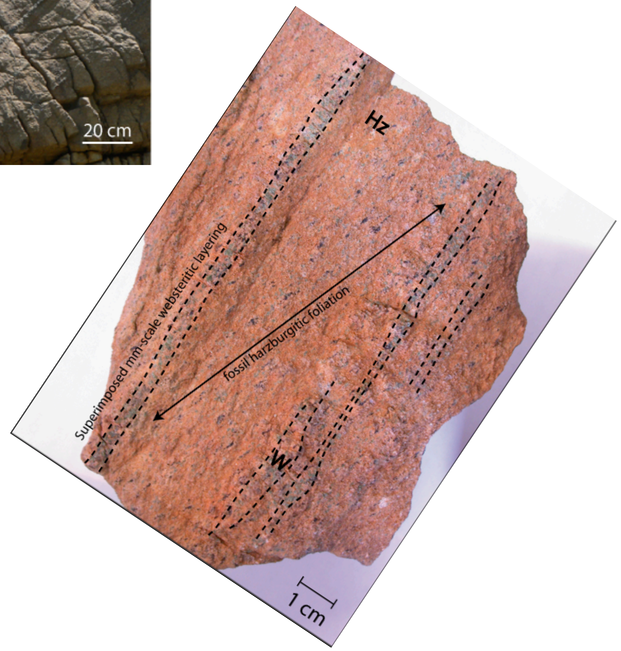
Le Roux et al. 2007, *The Lherz spinel lherzolite: refertilized rather than pristine mantle. EPSL, 259: 599-612.*

Refertilization in Lherz: structural evidence



Harzburgites: **relics** of the protolith

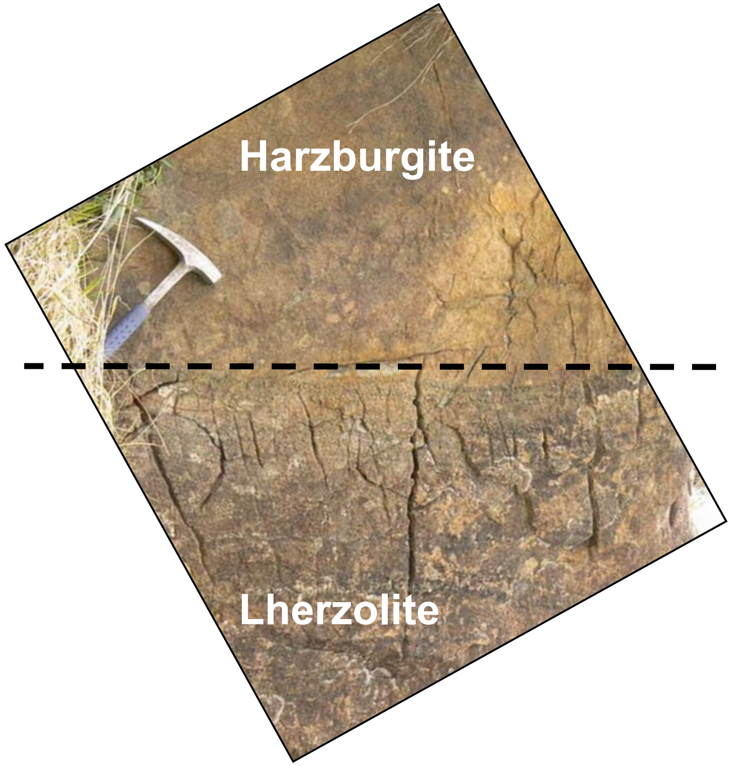
Lherzolites: **secondary** and formed at the expense of the harzburgites

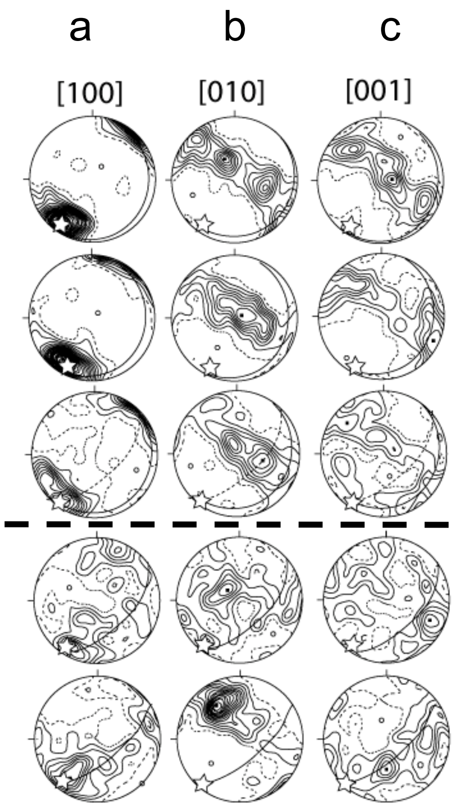


Le Roux et al. 2007 - *EPSL*

Refertilization in Lherz: structural evidence

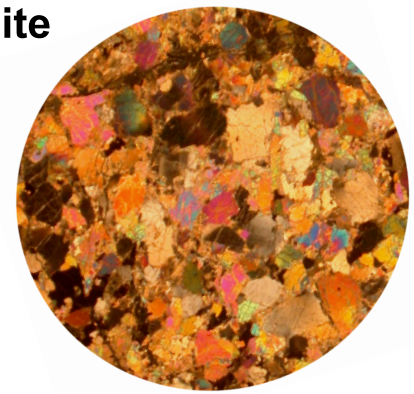
At the contact





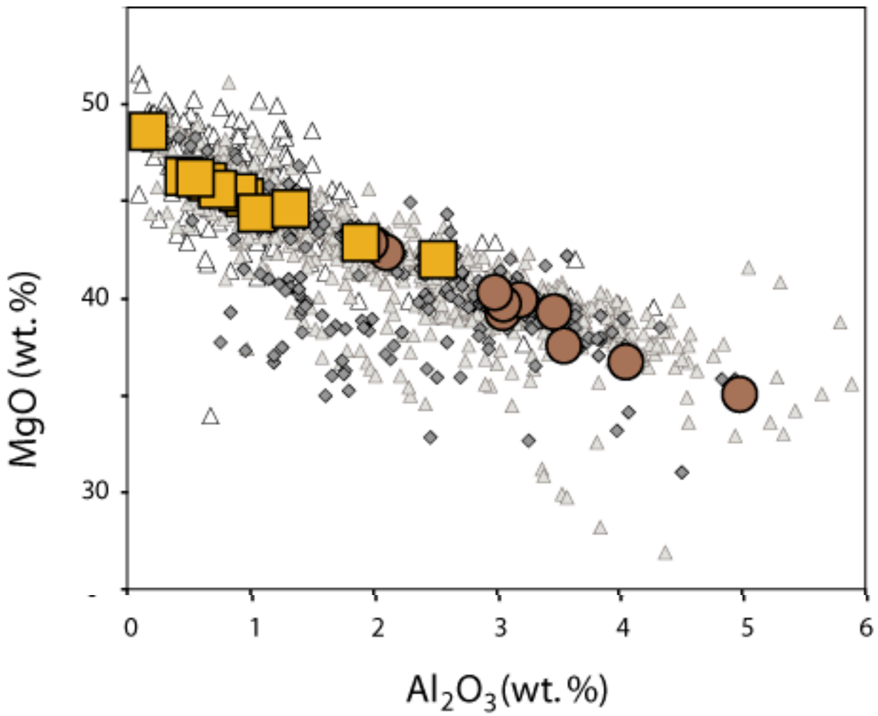
Harzburgite

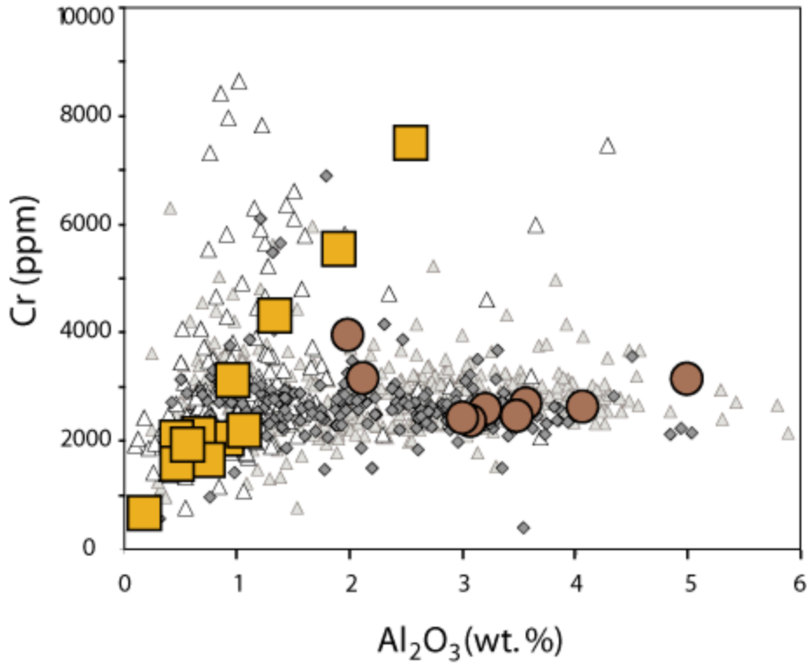
Lherzolite



Le Roux et al. 2007 - *EPSL.*

Refertilization in Lherz: geochemical evidence





Major elements: roughly consistent with partial melting (e.g. Al & Mg)

Some minor elements: not consistent (e.g. Cr).

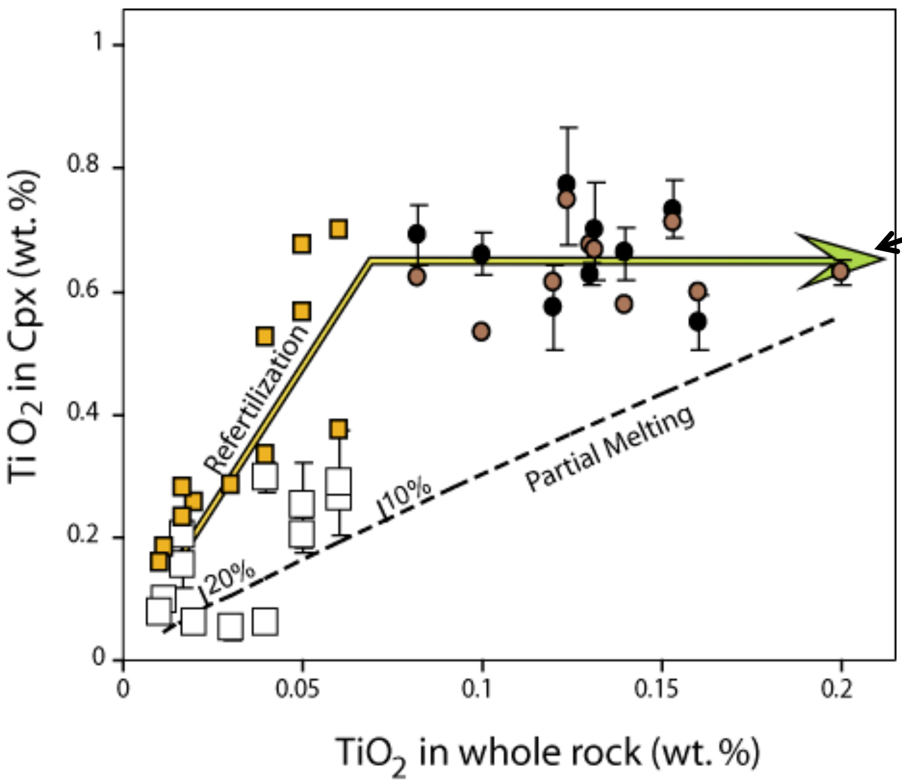
- Harzburgites
- Lherzolites

Le Roux et al. 2007 - *EPSL, 259.*

Refertilization in Lherz: geochemical evidence

Harzburgites

Lherzolites



Numerical simulation of refertilization reaction

Le Roux et al. 2007 - *EPSL*.

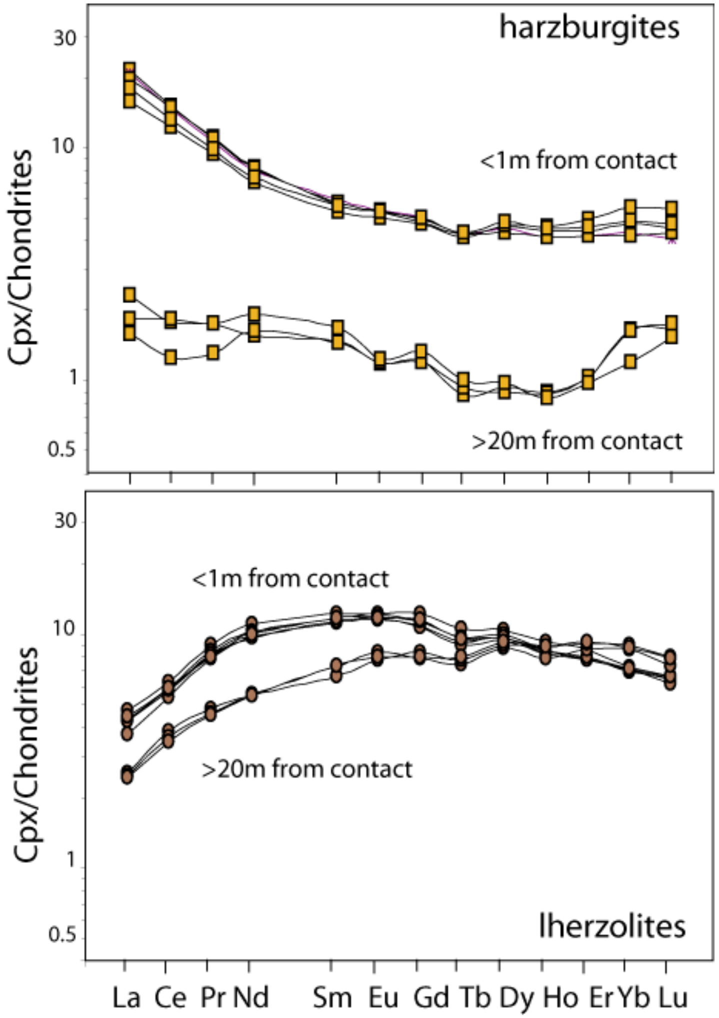
Mineralogical compositions of the lherzolites are almost constant (and governed by incoming melt).

In a melting process, they are expected to vary with mineral proportions.

Refertilization in Lherz: geochemical evidence

Harzburgites

Lherzolites



REE: enrichments at the contacts

Le Roux et al. 2007 – *EPSL.*

REE enrichment at the contacts explained by combining:

(1) the 'fractional cristallisation' effect of the refertilisation reaction (pyroxene-forming reaction at decreasing melt mass),

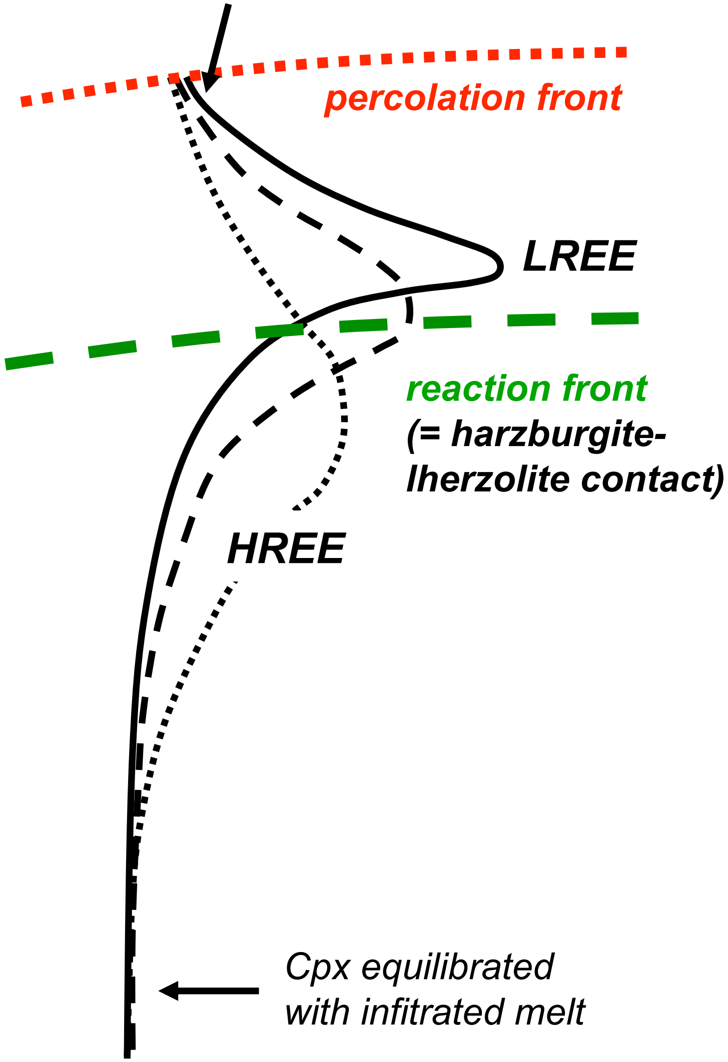
→ **REE enrichment in residual melt.**

(2) the 'chromatographic' effet of porous melt flow:

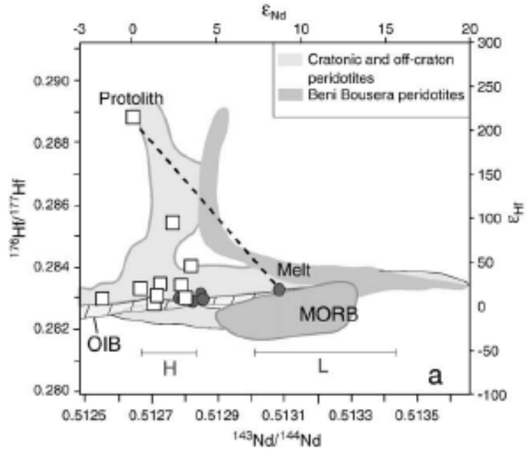
→ **concentration of REE enrichment at percolation front**

→confirms that the harzburgite-lherzolite contacts are reaction fronts,

→traces melt percolation fronts.



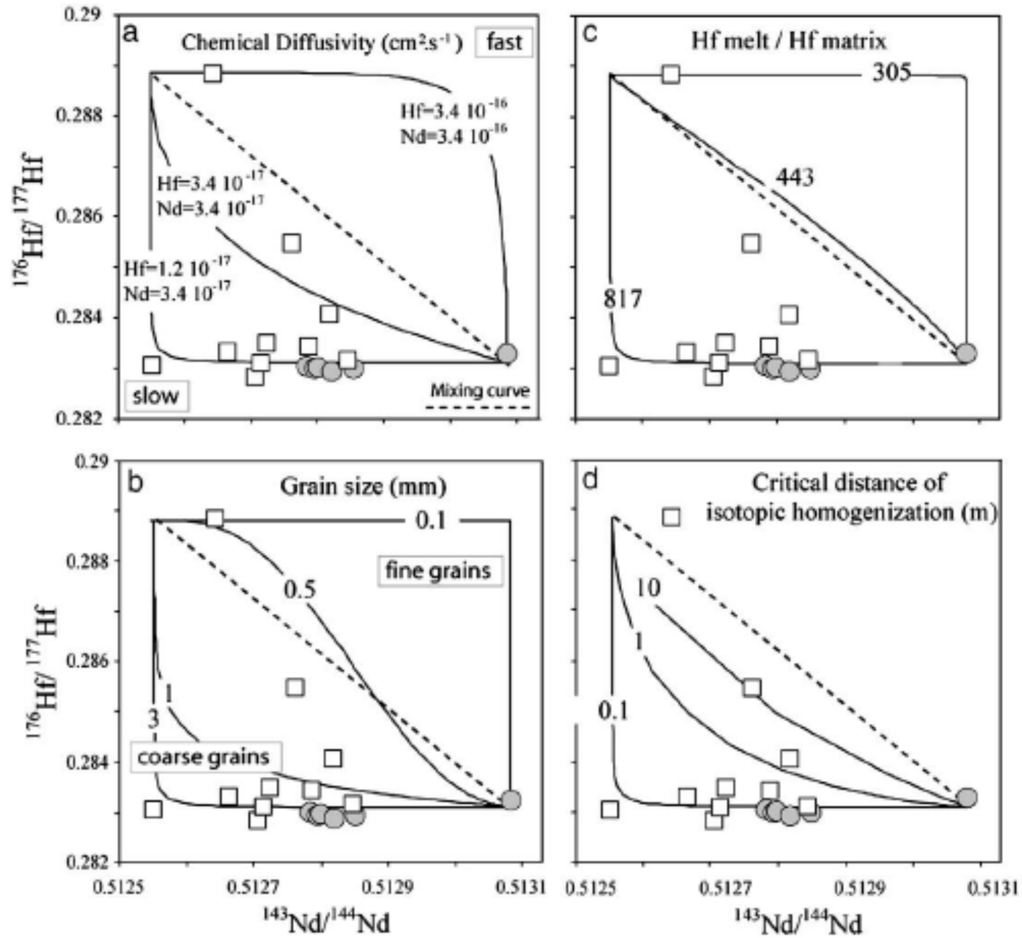
Melt percolation and isotopic variations



Lherz: almost the whole range of mantle variations at meter scale!

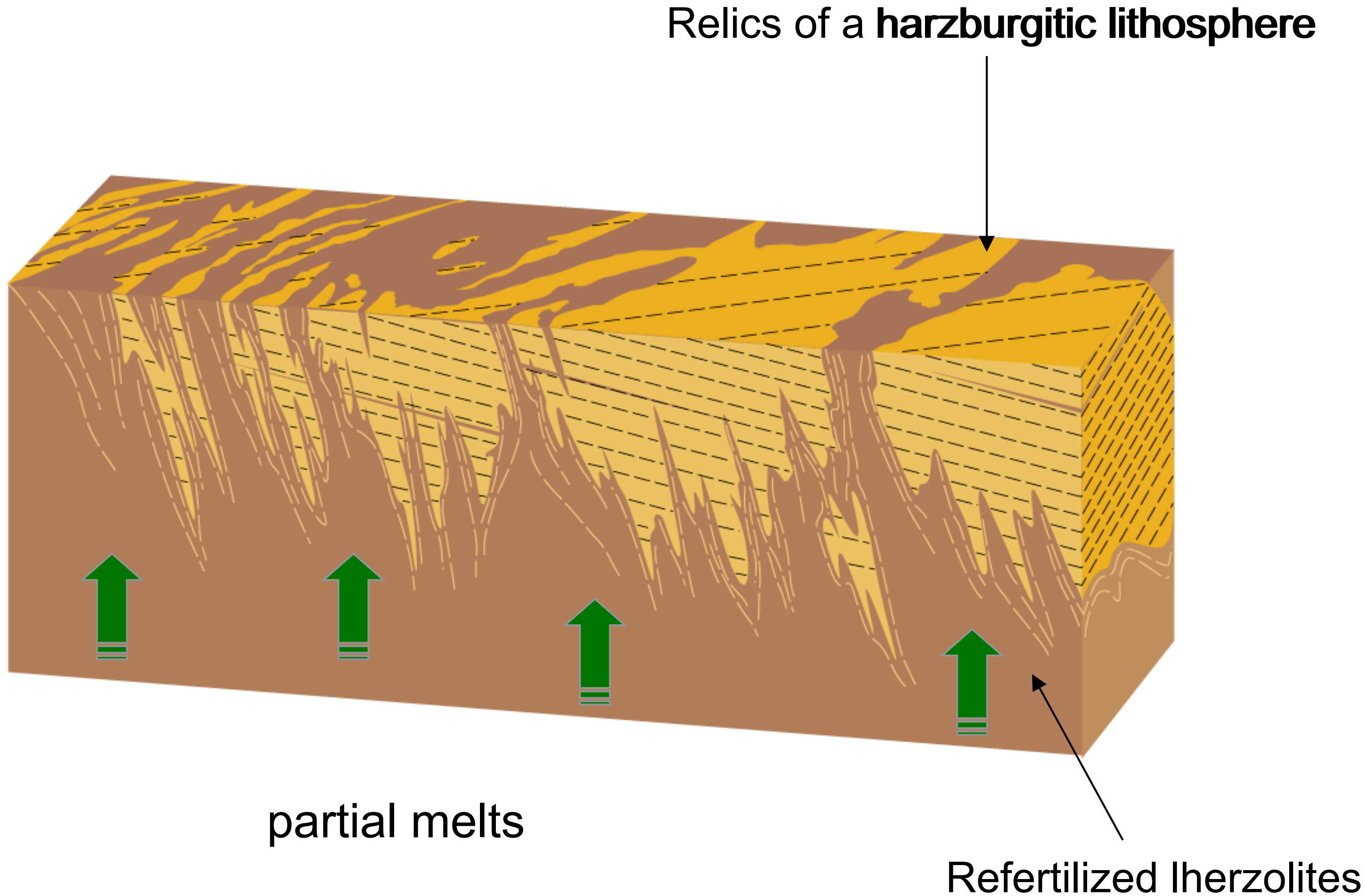
BUT: no inference on (convective) mantle heterogeneity can be retrieved from isotope systematics in orogenic peridotites.

Their (wide) range is governed by:
- daughter-daughter fractionation due to percolation-diffusion processes,
- time-integration of parent-daugher fractionation.



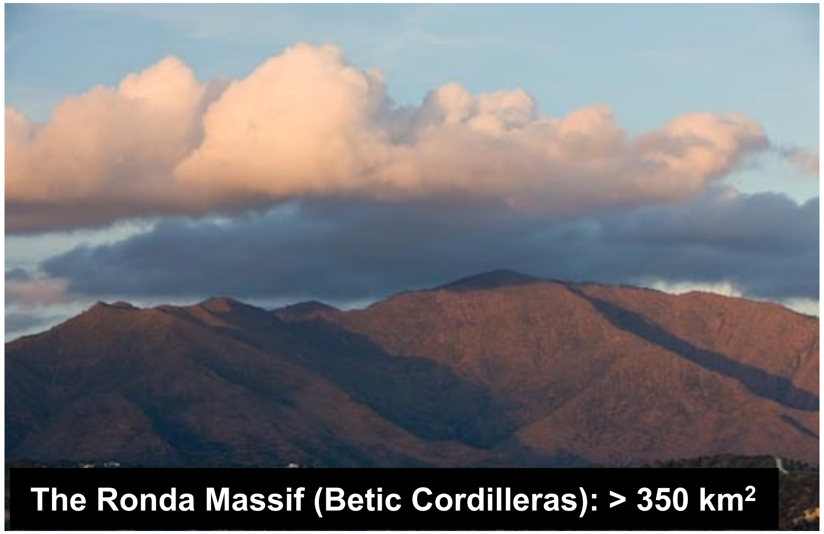
Le Roux et al. 2009 - *EPSL.*

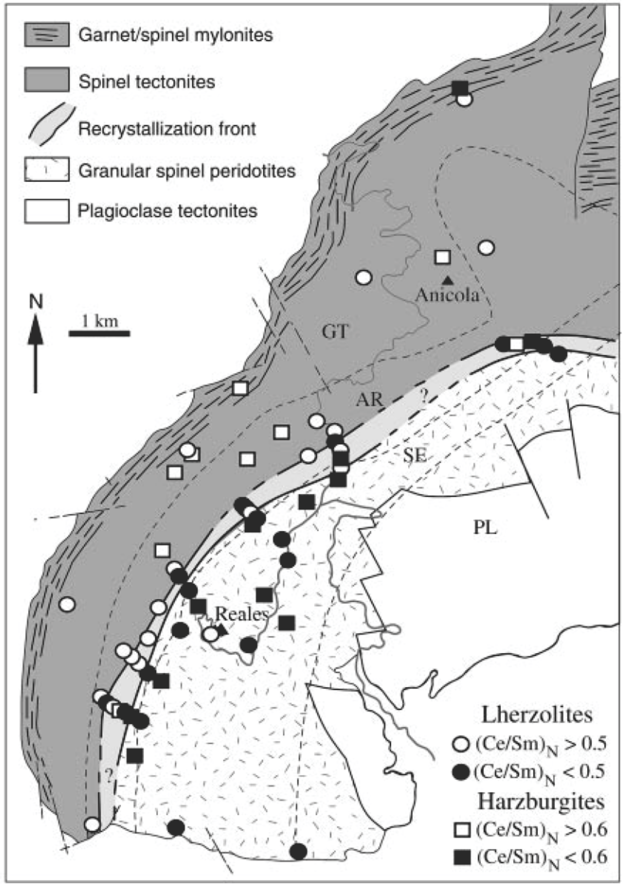
Lherz: refertilization of a ~2Ga (?) harzburgitic lithosphere



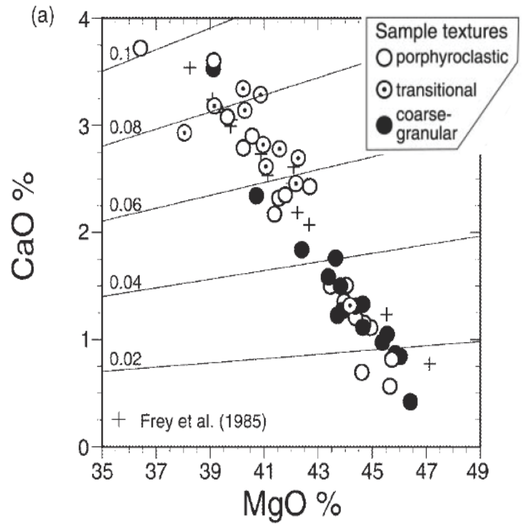
Ronda: a « frozen » asthenosphere- lithosphere boundary

- recrystallization front (Van der Wal & Vissers,1993),
- percolation front (Van der Wal & Bodinier, 1996),
- **melting front at regional scale** (Lenoir et al., 2001).



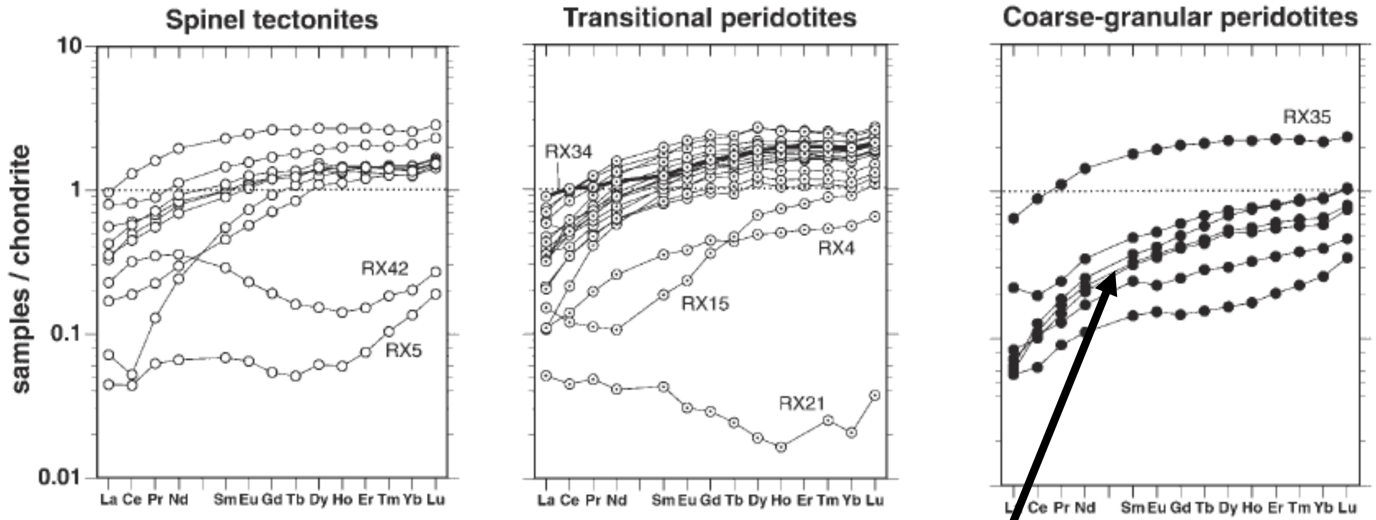


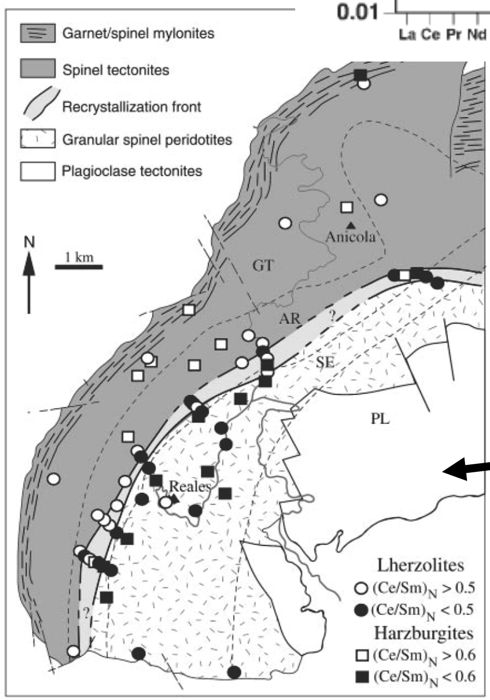
Spinel tectonites: lithospheric protolith



Coarse-granular peridotites: recrystallized/molten mantle

Ronda: REE confirm the origin of the coarse-granular domain via partial melting

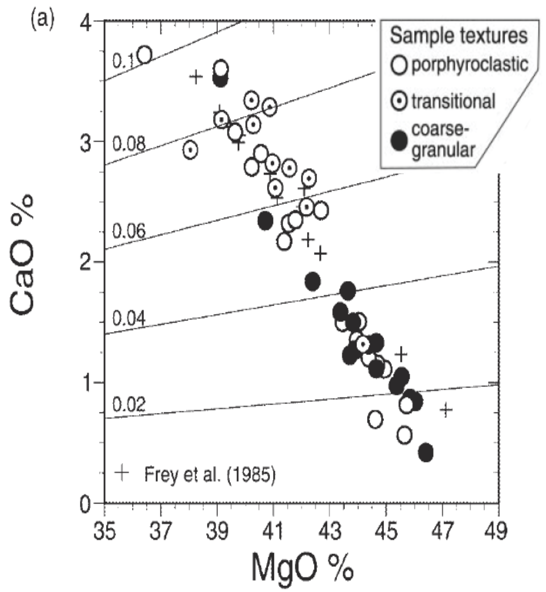


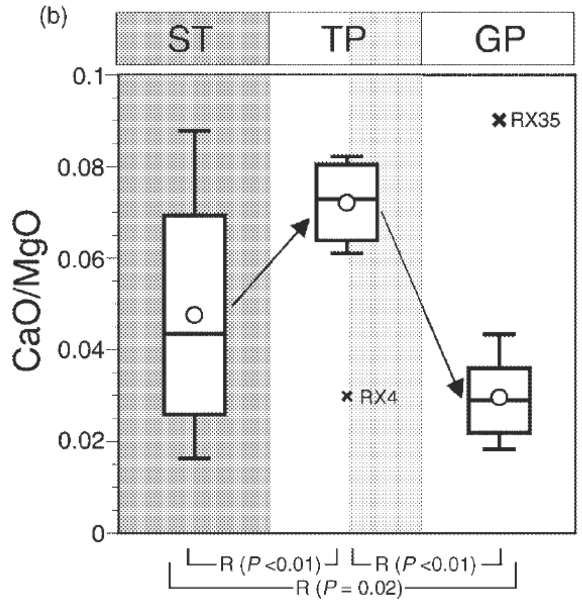


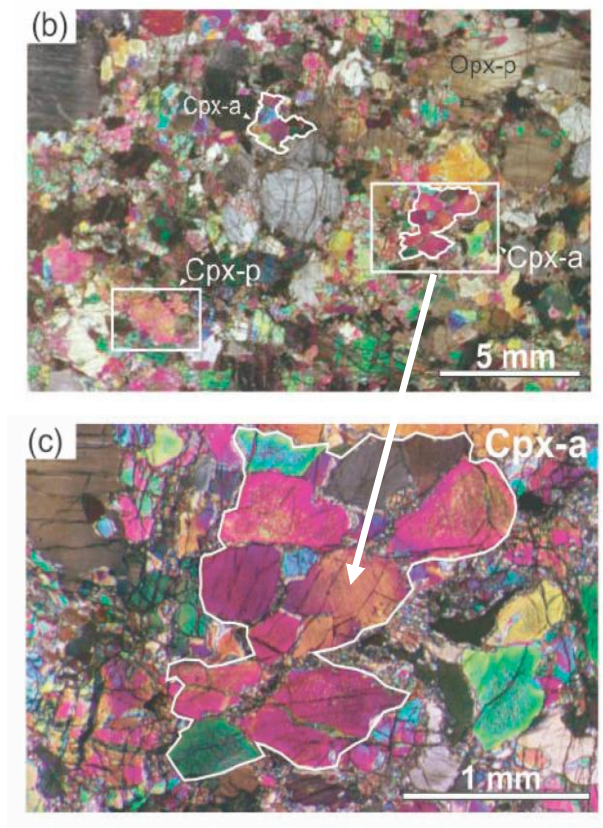
Compared with peridotites beyond the front, **the coarse-granular** cpx-harzburgite are:

- depleted in REE.
- depleted in LREE relative to HREE.

Refertilization in Ronda: downstream of the melting front





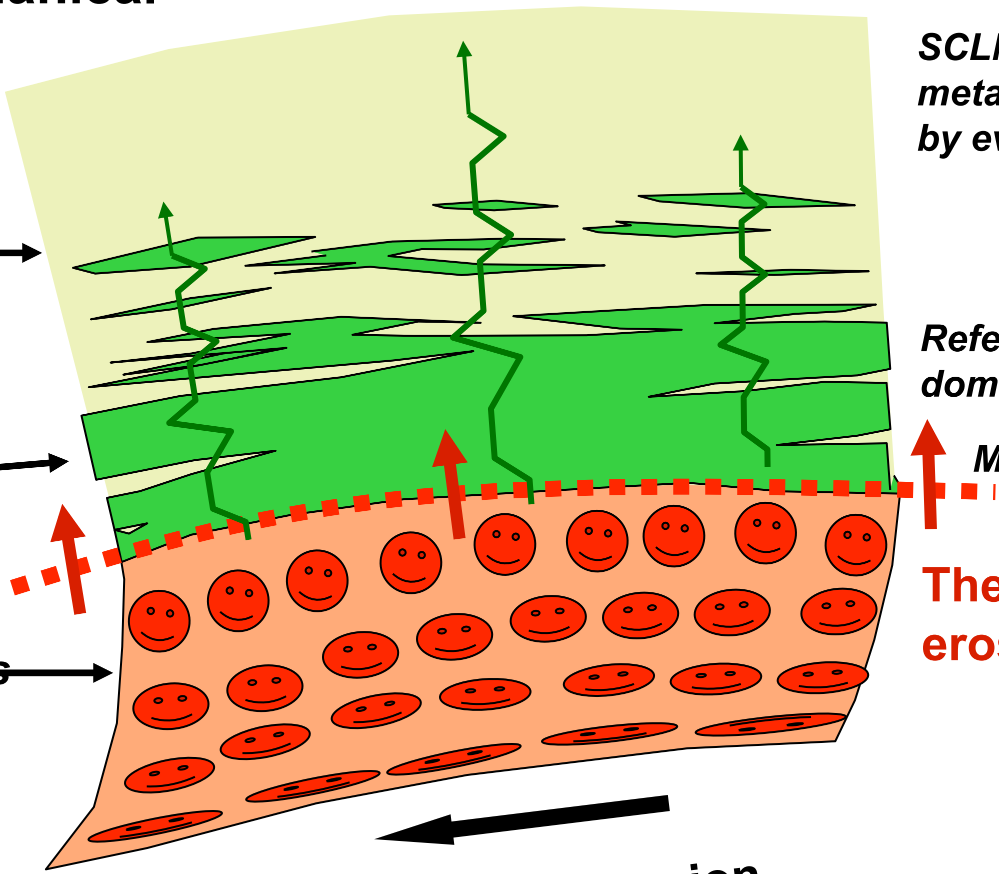


Downstream of the front, the 'transitional peridotites' are homogeneously fertile and contain undeformed cpx aggregates (Lenoir et al. , 2001)

→ **partial melts infiltrated beyond the front are 'frozen' and refertilize the lithospheric protolith;**

→**in addition: refertilization by partial melts from garnet pyroxenites** (Garrido & Bodinier, 1999).

Ronda: refertilisation + melting related to thermo-mechanical erosion of SCLM



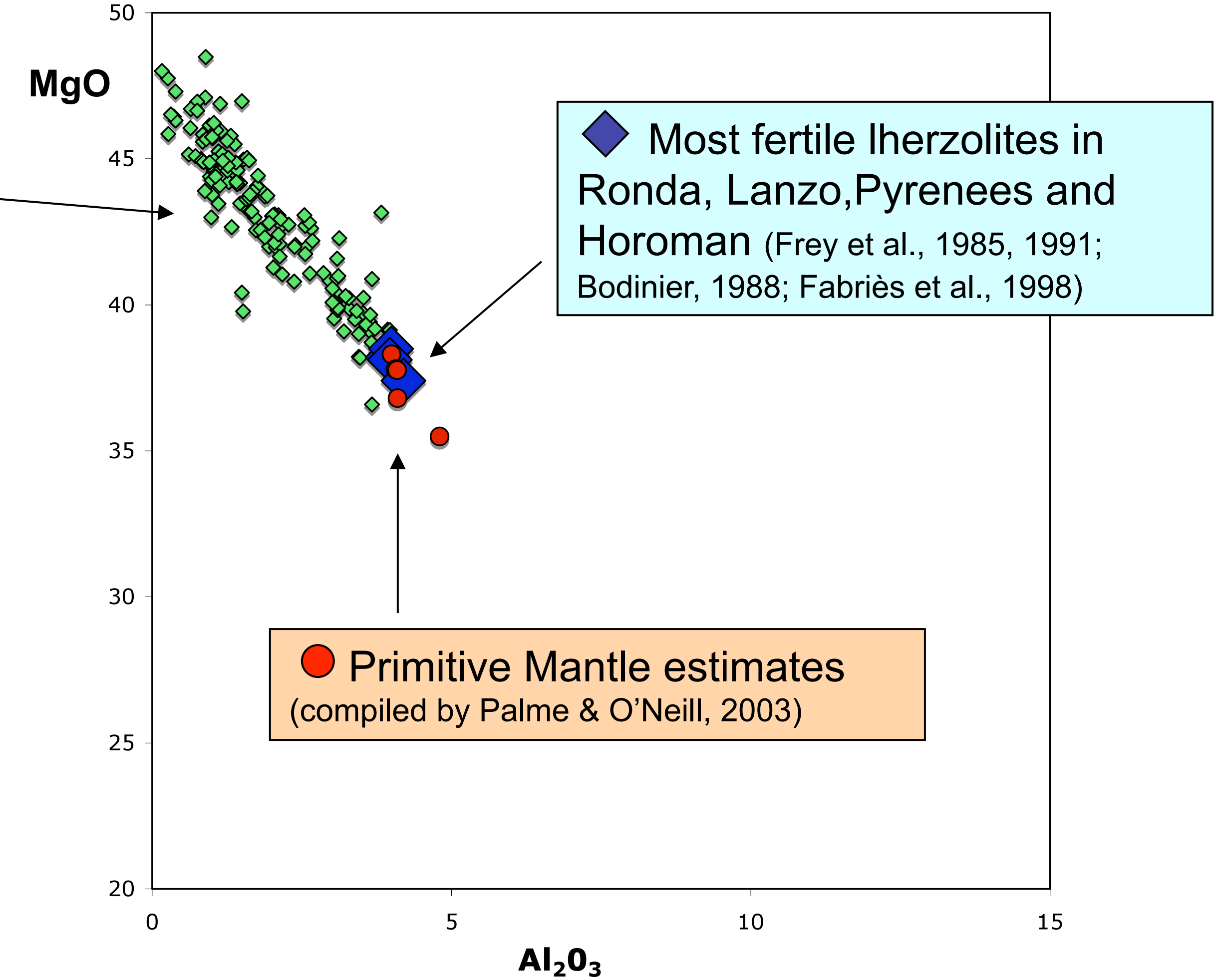
Suggest that the lithosphere is

(1) first refertilized,

(2) then, molten.

→ **the source of the melting domain is all but 'pristine'.**

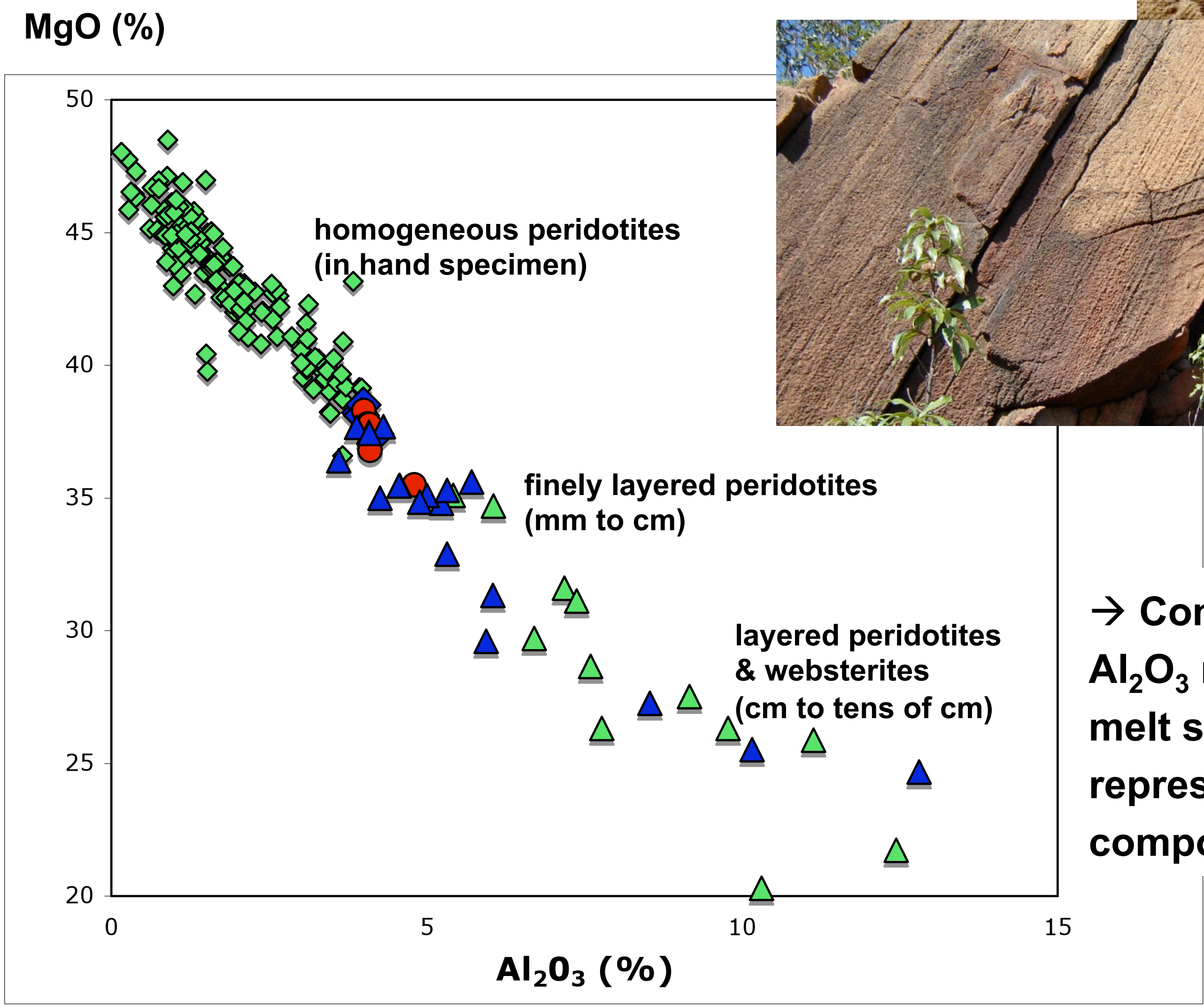
However, can the refertilization account for the observation that the most refertilized lherzolites have virtually the same composition in all orogenic peridotites worldwide ?

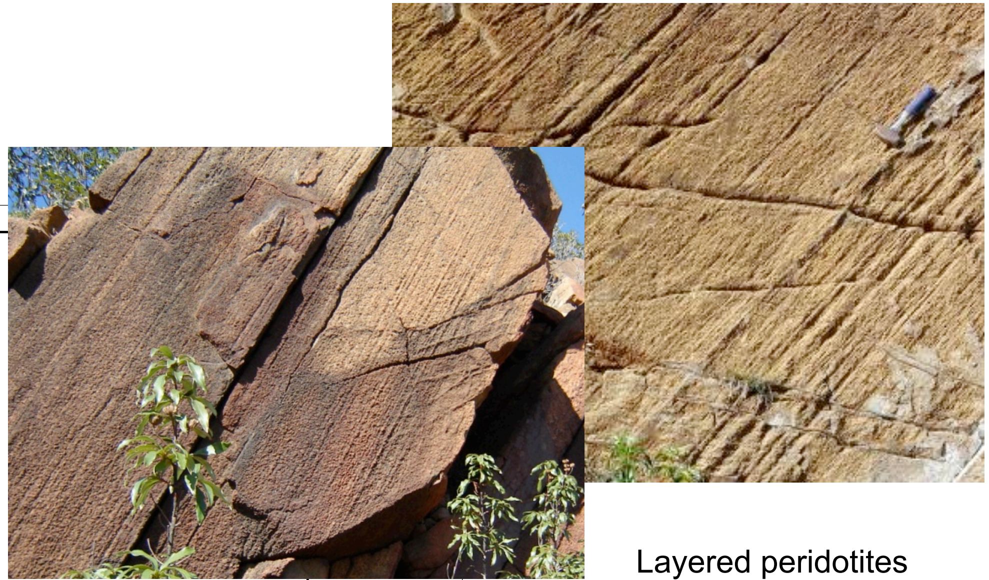


Ronda peridotites

Partial melting of homogeneous, pristine mantle is generally considered to be the only satisfactory explanation

just a sampling bias?…





Layered peridotites
in Ronda

→ Compositions around 4% Al_2O_3 might be a threshold for melt segregation rather than representing Primitive Mantle compositions?

Several studies now suggest the origin of lherzolites from tectonically-emplaced peridotites by igneous refertilization

- include spinel and garnet peridotites (Beyer et al., 2006), not only plagioclase peridotites:

→ **refertilization occurs at depth**: it is not restricted to melt accumulation at the Moho (e.g. impregnated dunites/harzburgites in ophiolites).

Refertilization affects km-scale lherzolite bodies

→ **occurs at regional scale**: not restricted to local melt redistribution due to compaction of molten peridotites.

Refertilization is **related to major events of lithospheric thinning and rejuvenation** associated with:

- oceanic or back-arc rifting (e.g. Lenoir et al., 2001; Müntener et al., 2004; Piccardo et al., 2004),
- post-orogenic lithosphere destabilisation (Lherz?).

Refertilization in Ronda connected with exhumation (most likely in a suprasubduction setting):

The melting front and related refertilization were developped in a late stage of Ronda evolution, just before mantle exhumation, in the Cenozoic.

Thermo-mechanical erosion of SCLM at the onset of Western Mediterranean back-arc opening (roll-back of an oceanic slab).

Refertilization in Lherz: when and why?

Unrelated to the Cretaceous, « Pyrenean » extensional events responsible for peridotite exhumation:

- low equilibrium temperatures (~ 800°C),
- Cretaceous veins and metasomatism overprint the refertilization front.

Possibly connected with the **late-Variscan thermal event** recorded by high-T granulites.