Coupling between Partial Melting, Melt Transport, and Deformation at the Lithosphere/Asthenosphere Boundary: Observations and Models

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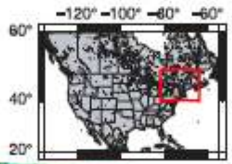
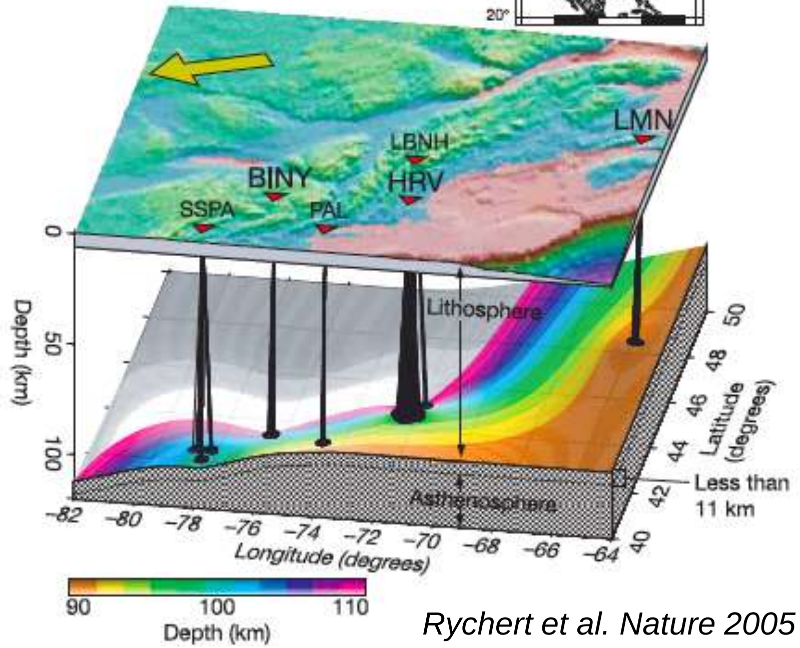
Geophysical observations:
Sharp velocity decrease at the base of the lithosphere

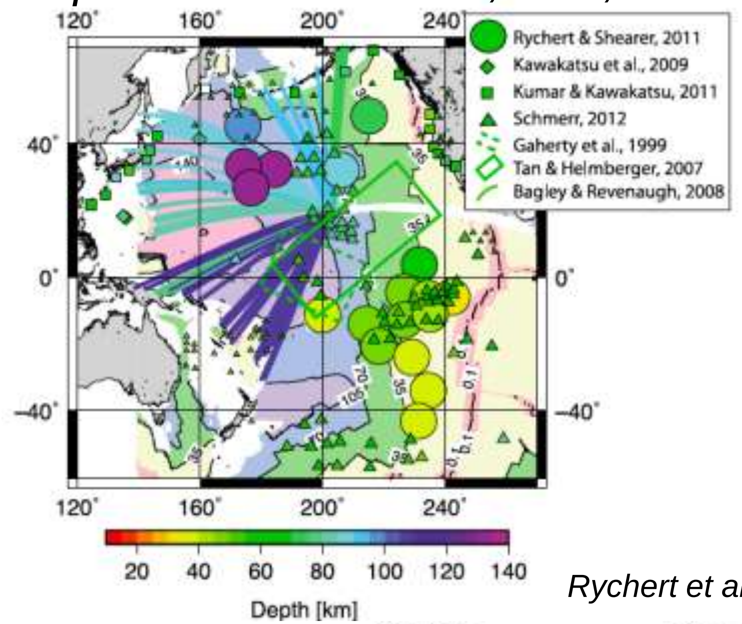
Eastern USA
Receiver functions



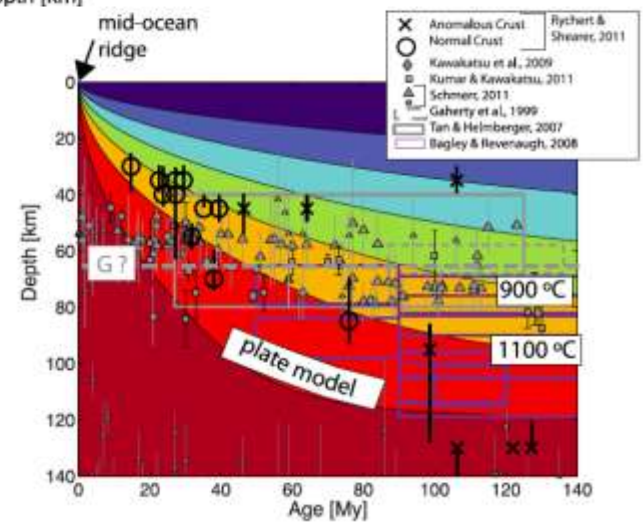


Rychert et al. Nature 2005

Pacific
Sp receiver functions, ScS, SS data



Rychert et al. G3 2012

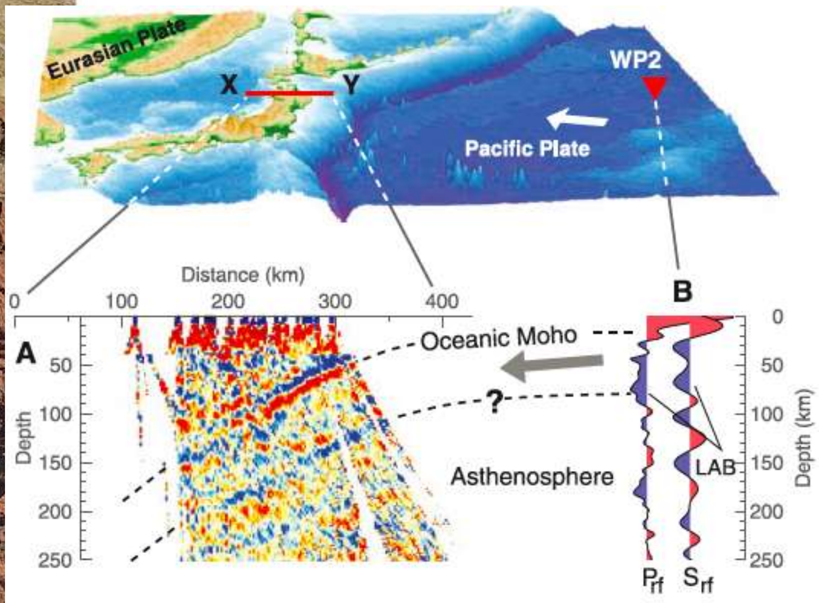


- ➢ *presence of small melt fractions in the asthenosphere*
- ➢ *depth-dependent mantle hydration + attenuation (e.g., Olugbuji et al. G3 2013)*

Seismic Evidence for Sharp Lithosphere-Asthenosphere Boundaries of Oceanic Plates

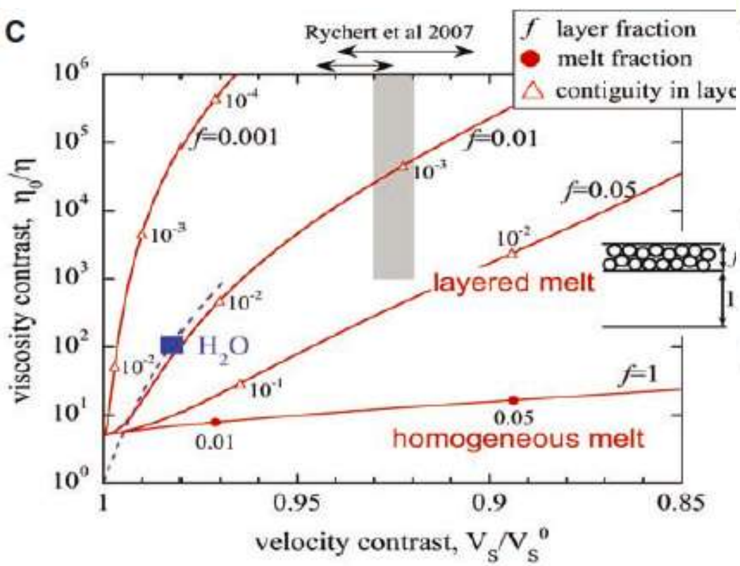
Hitoshi Kawakatsu,[1*] Prakash Kumar,[1†] Yasuko Takei,[1] Masanao Shinohara,[1] Toshihiko Kanazawa,[1] Eiichiro Araki,[2] Kiyoshi Suyehiro[2]

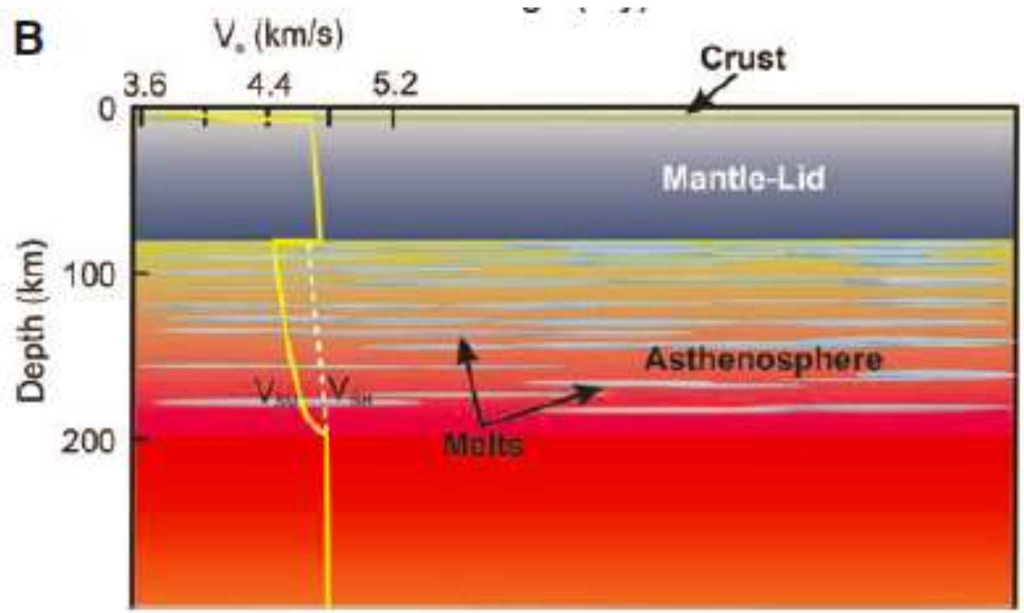
Science, 2009



Melt organized in lenses // LAB

- *Stronger velocity contrasts at lower melt fractions*
- *Also explains the seismic anisotropy*



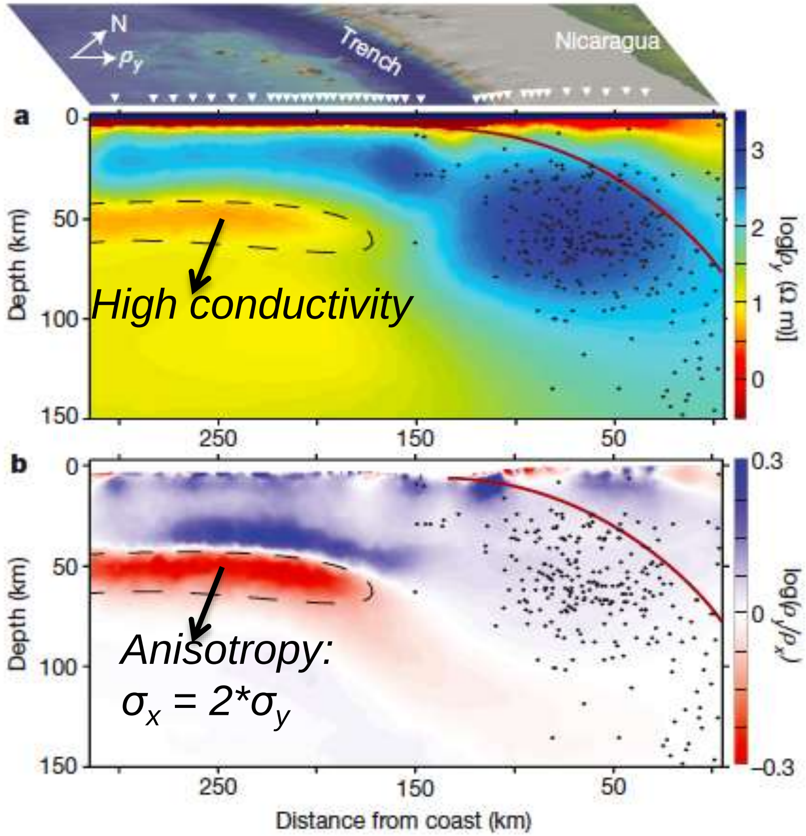


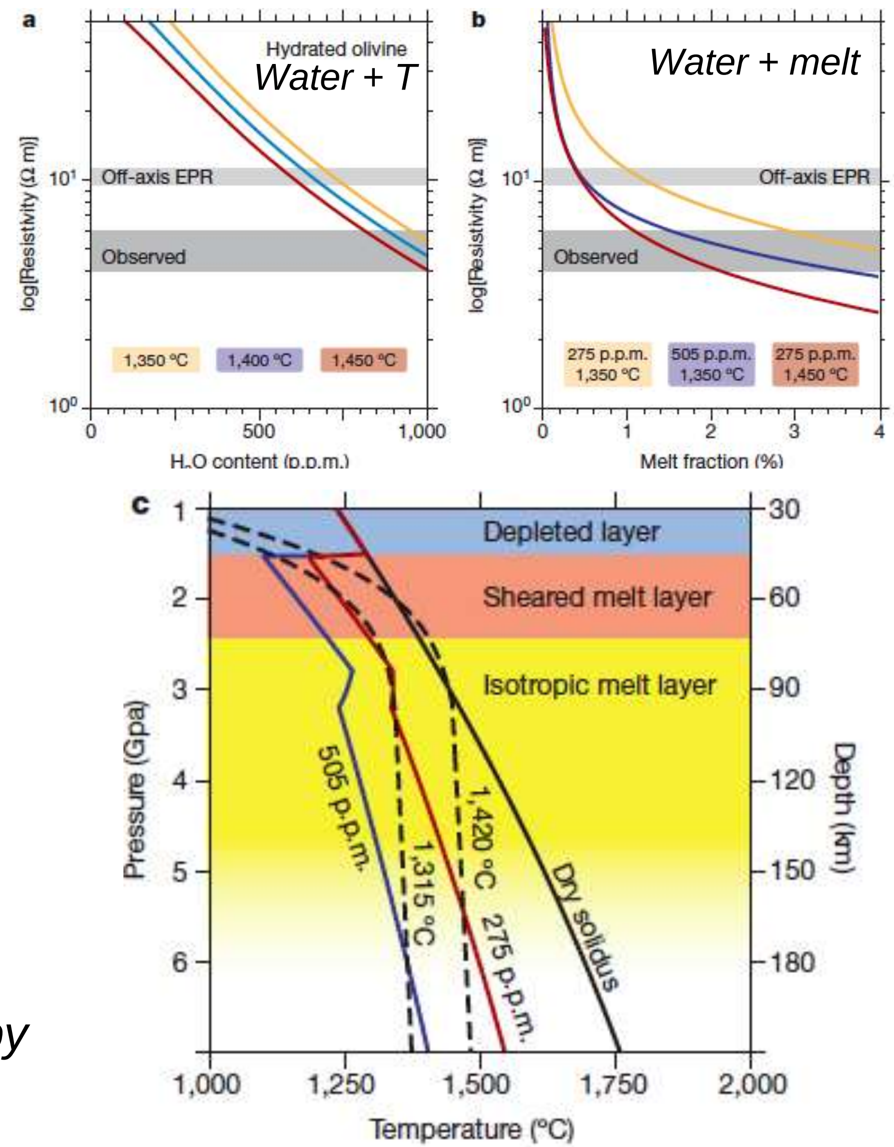
Electrical conductivity data:
Magnetotelluric soundings

Melt-rich channel observed at the lithosphere–asthenosphere boundary

S. Naif[1], K. Key[1], S. Constable[1] & R. L. Evans[2]

| NATURE | VOL 495 | 21 MARCH 2013

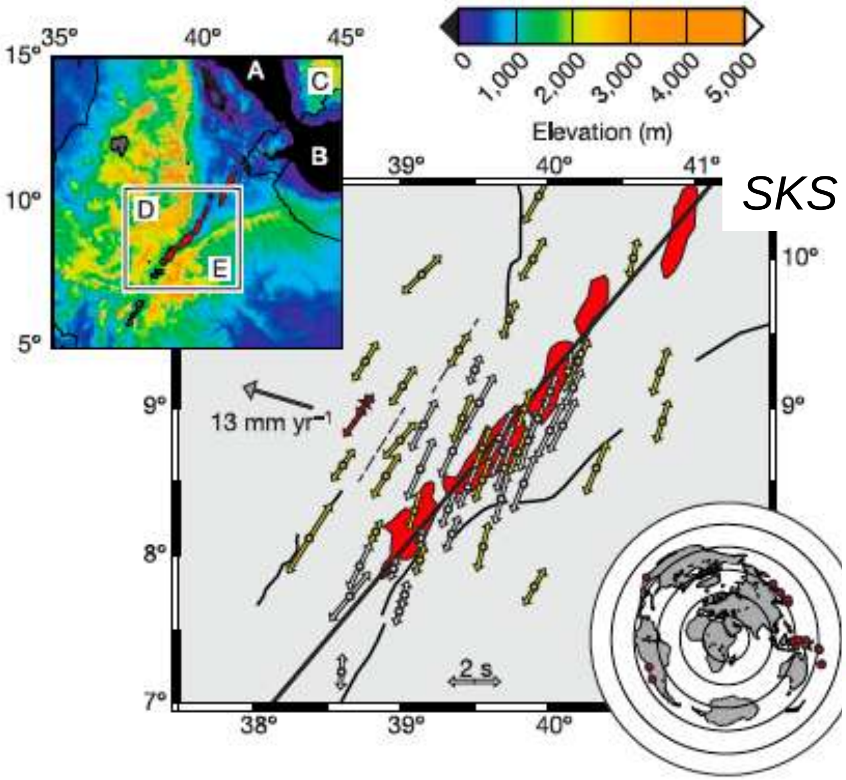




- *High mantle potential temperatures & water contents to produce melting*
- *Shearing required to explain anisotropy*

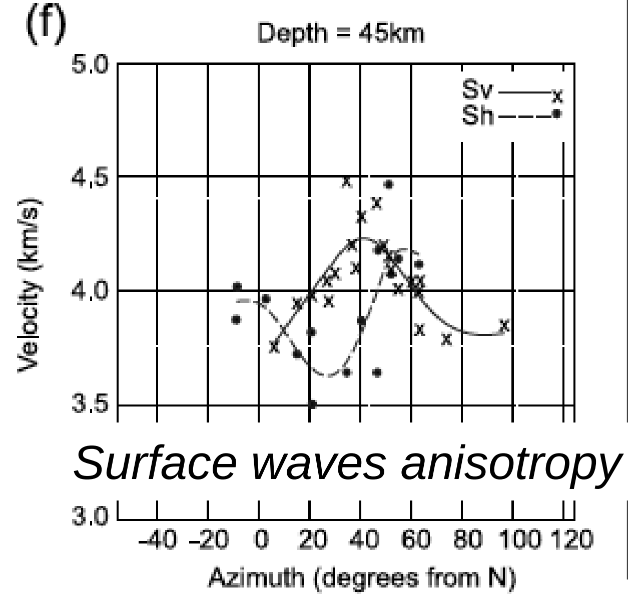
Similar processes also occur beneath active plate boundaries…

East African Rift

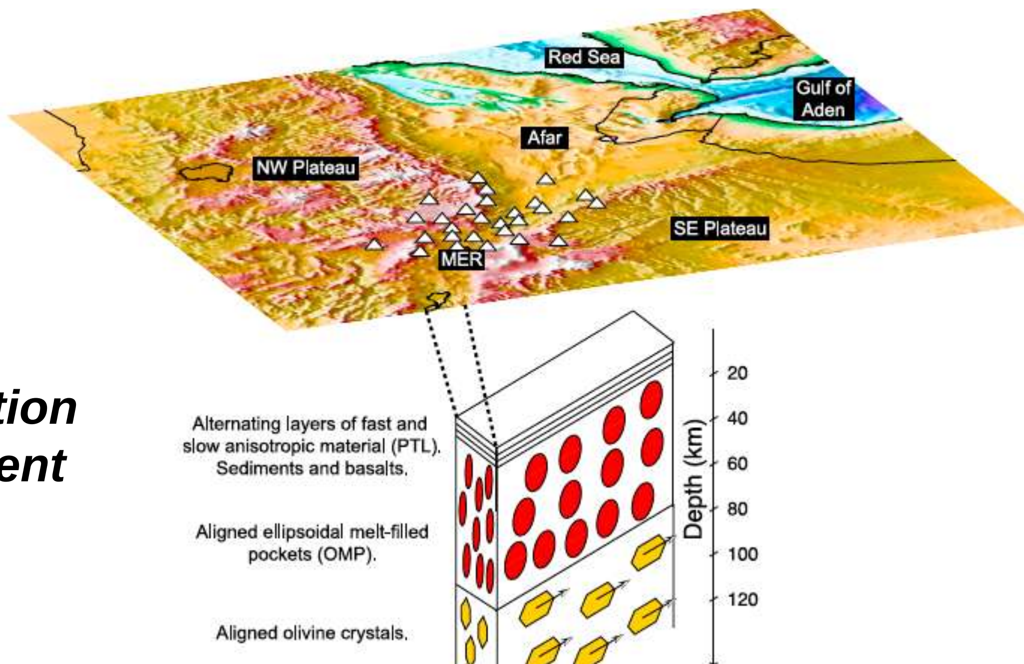


SKS splitting

Kendall et al. Nature 2005



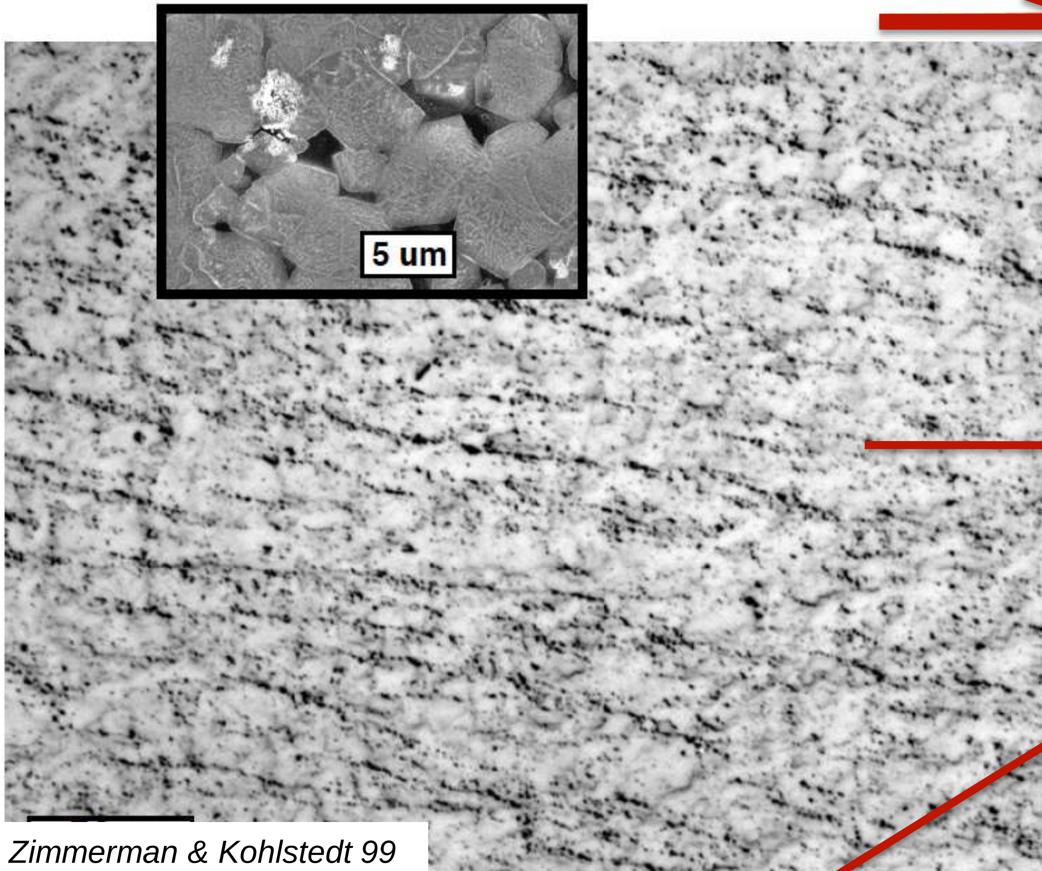
Surface waves anisotropy



Bastow et al. G3 2005

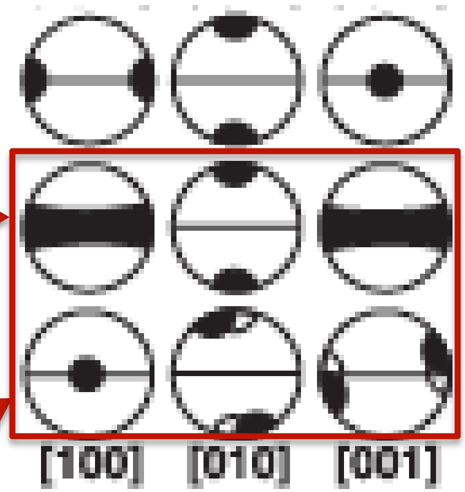
Records both olivine crystal preferred orientations (deformation in the solid mantle) AND alignment of melt lenses or dykes (spatial scale?)

Simple shear experiments in 2-phase systems:



Zimmerman & Kohlstedt 99

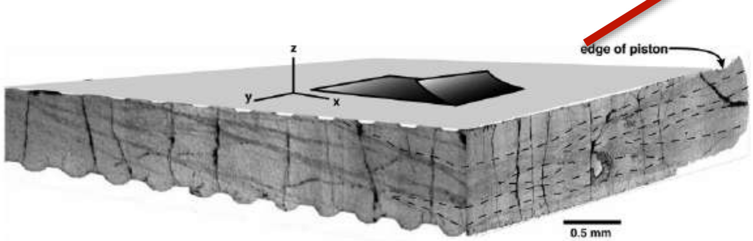
- melt distribution controlled by stress

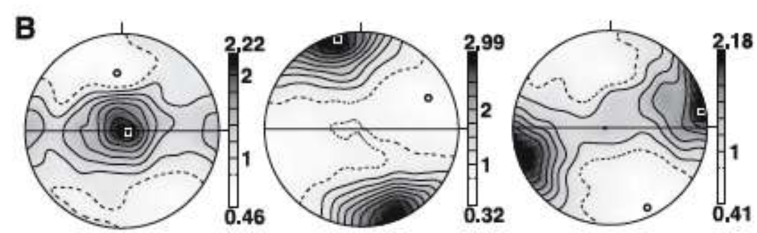


dry

Ol + melt

- change in olivine CPO





Holtzman et al. Science 2003

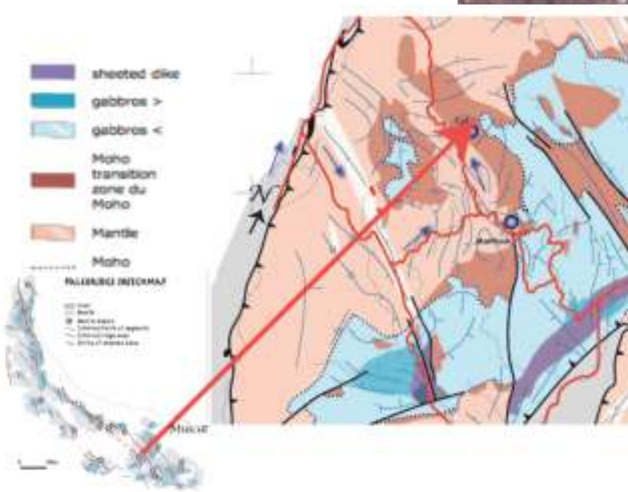
Evidence of such feebacks in nature? Structural & microstructural data on mantle peridotite outcrops

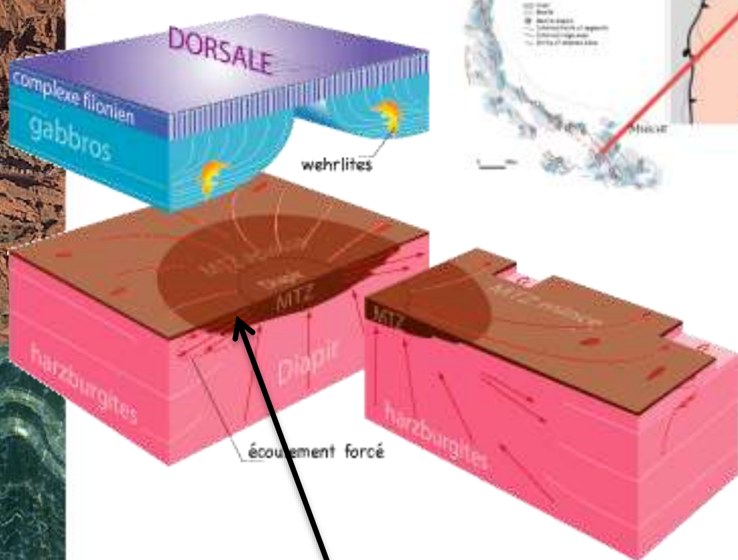



Melt organization in a mantle deforming by simple shear

K. Higgie, Ph.D. ITN Crystal2Plate

Oman MTZ (uppermost mantle)



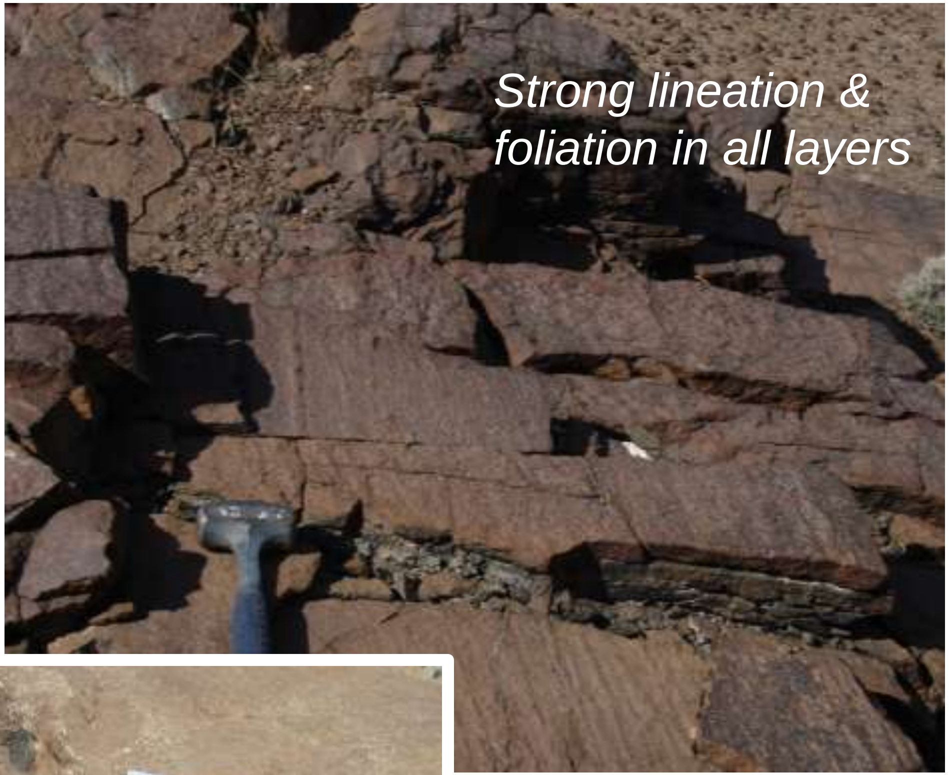


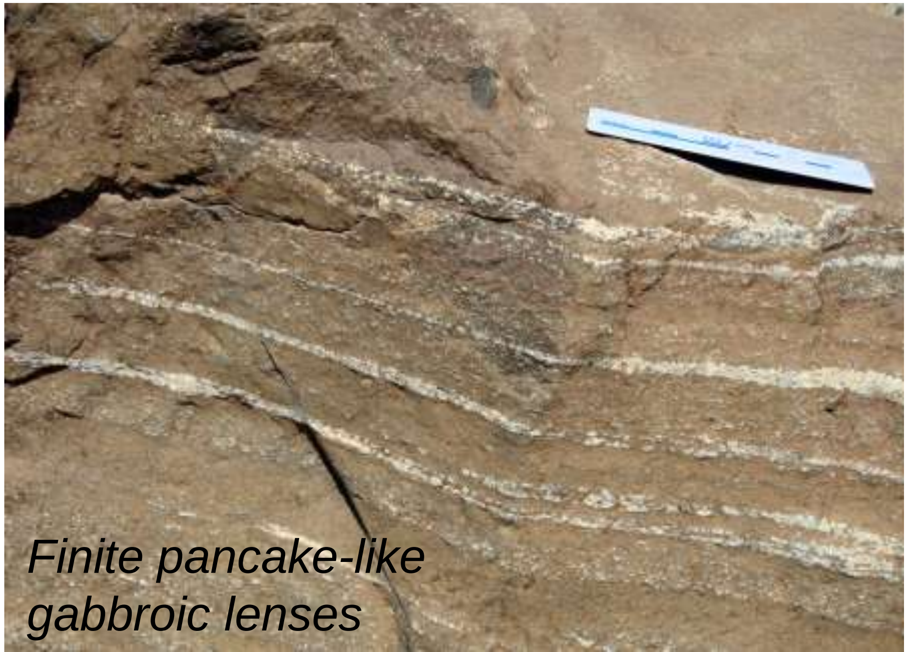
~ 55 Oriented samples along a ~100m section just below the Moho

Layering // Foliation // Moho = subhorizontal

Higgie & Tommasi EPSL 2012

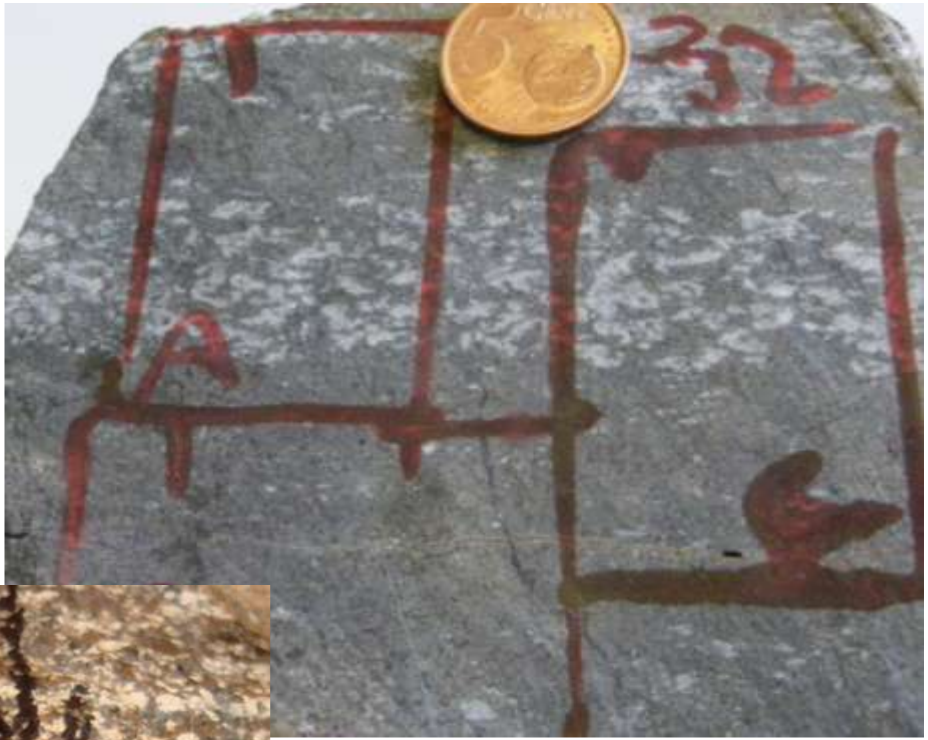
Melt organization in a mantle deforming by simple shear





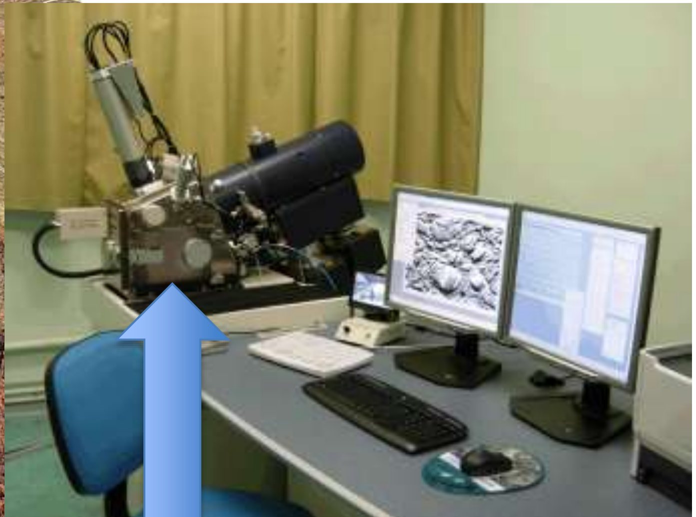
Higgie & Tommasi
EPSL 2012

Compositional layering @ cm to mm-scale

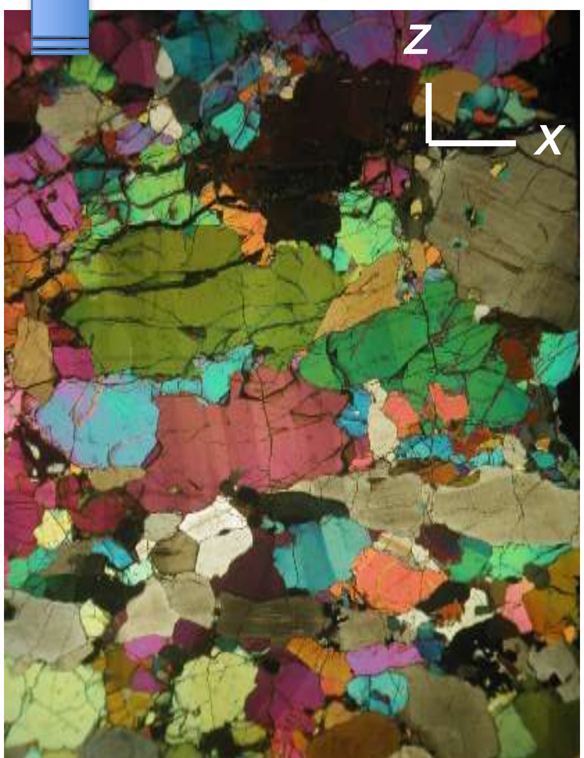


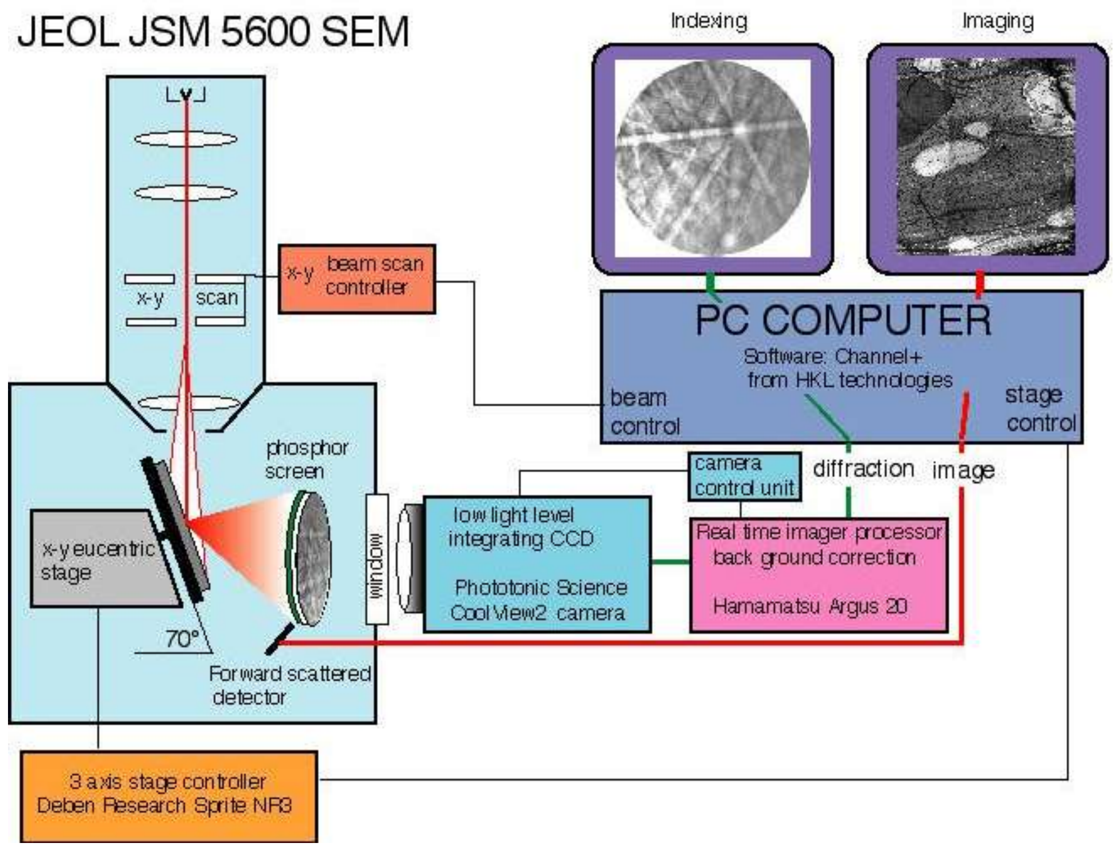
- *Layers limits = diffuse*
- *Continuous variations in composition from impregnated dunites to gabbroic levels with ol-rich lenses*

Higgie & Tommasi EPSL 2012

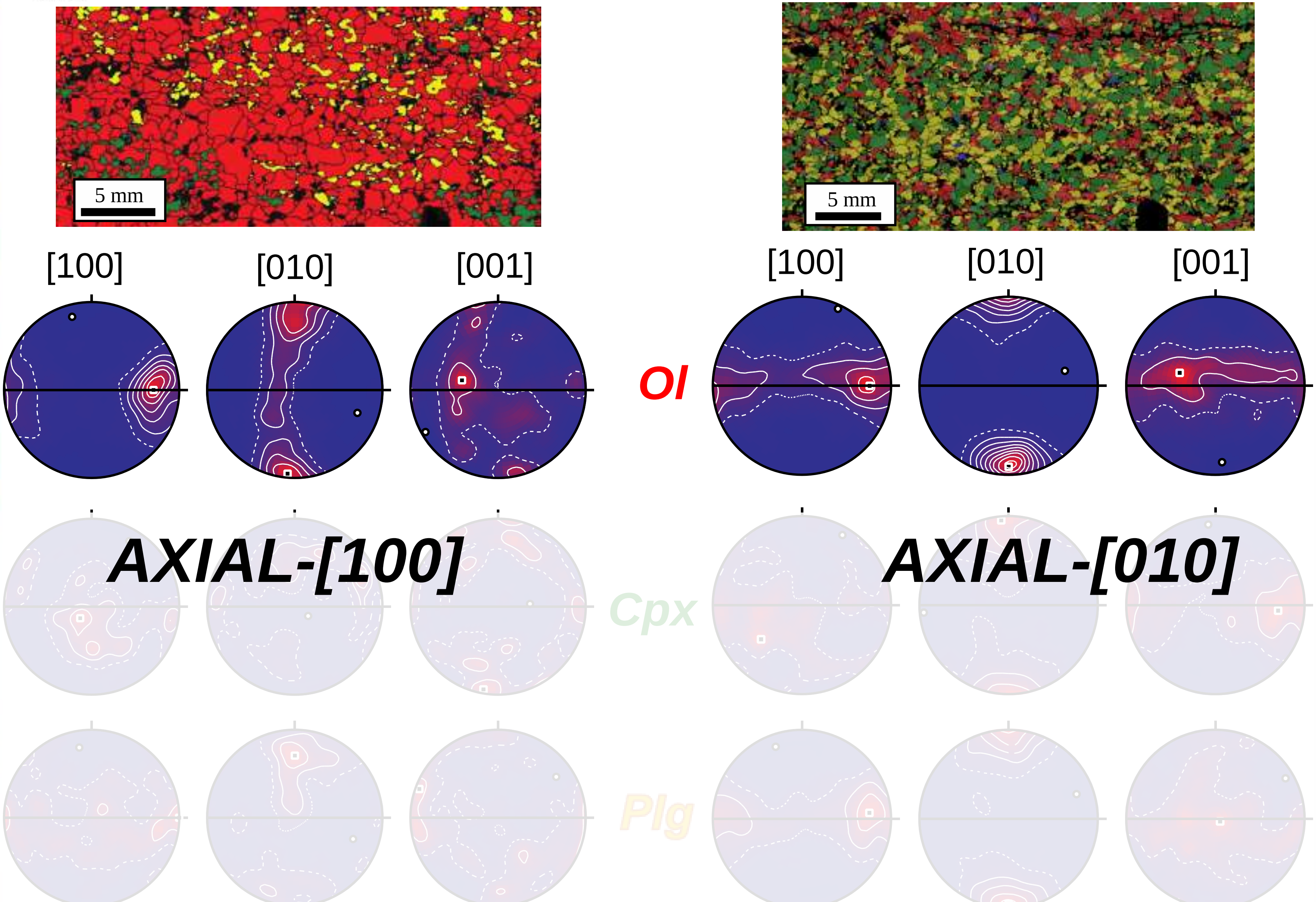


Measuring Crystal Preferred Orientations (CPO) by indexation of Electron BackScatered Diffraction (EBSD) patterns





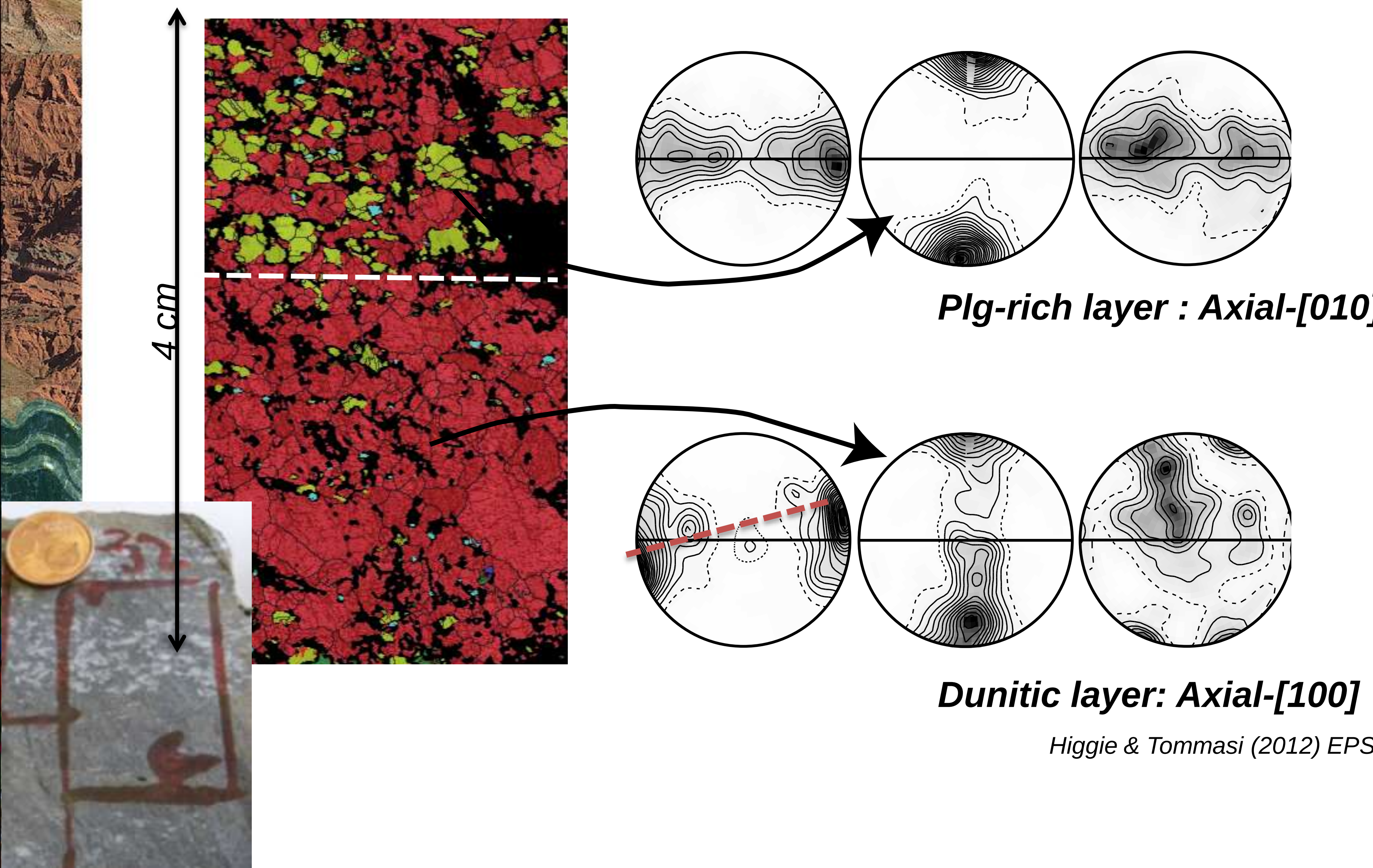
Impregnated Dunite / *Olivine Gabbro*



Higgie & Tommasi EPSL 2012

Changes in olivine fabric at the mm-cm scale

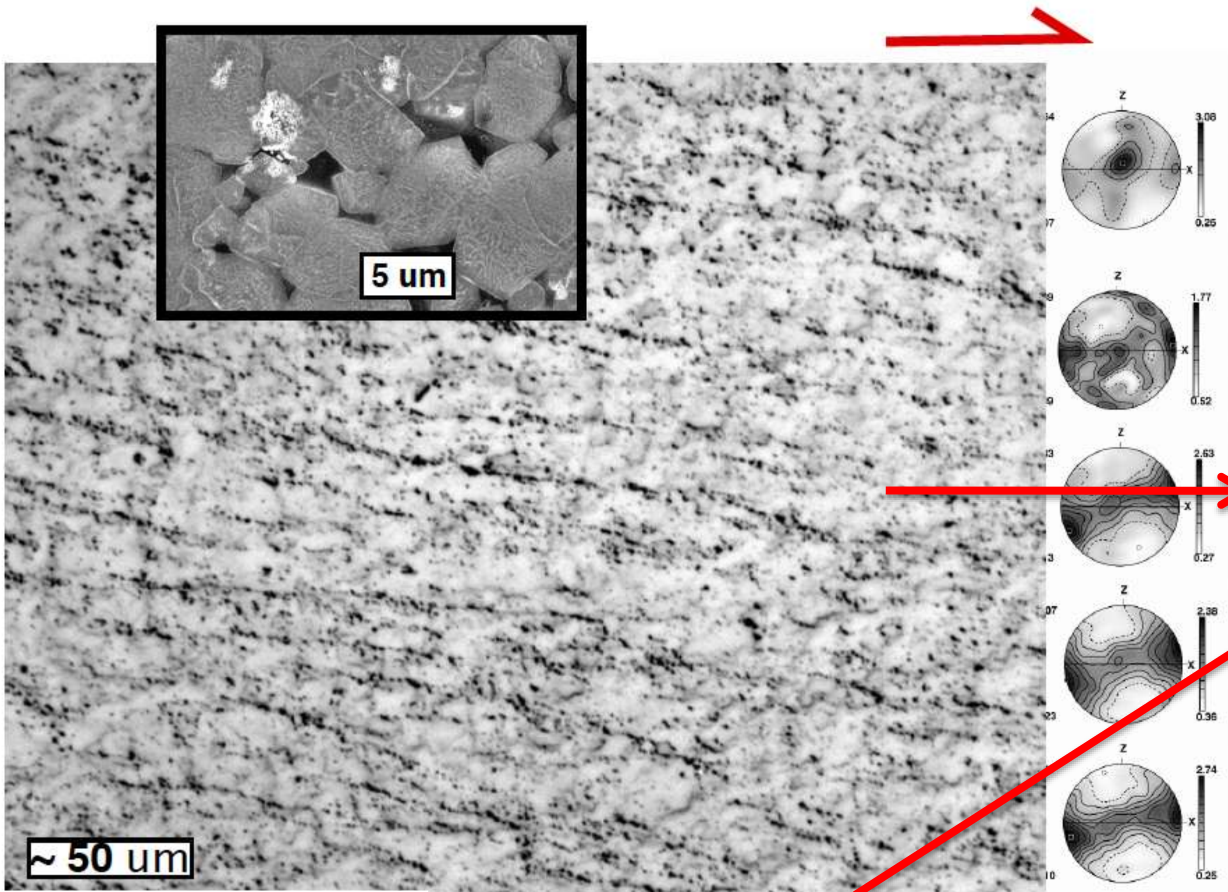
- ***deformation in presence of varying melt fractions***
- ***melt segregation in layers // shear plane***

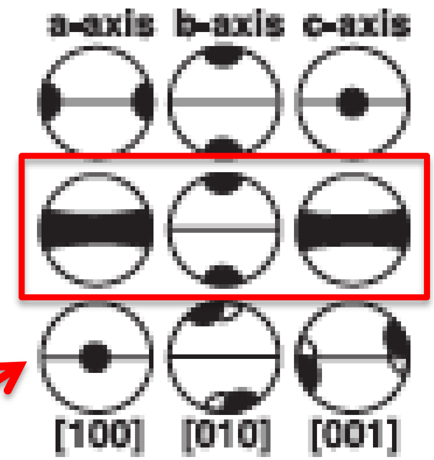


Higgie & Tommasi (2012) EPSL

Fabric change in olivine + MORB samples

Simple shear experiments



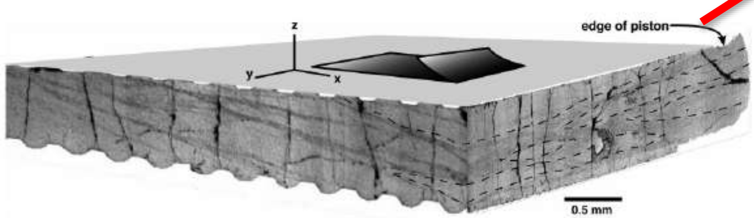


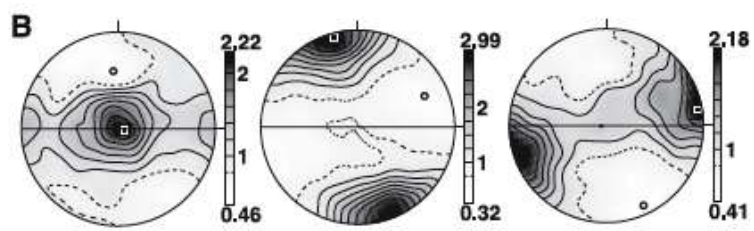
dry

Ol + melt

Ol + melt layers

Zimmerman & Kohlstedt 99





Holtzman et al. Science 2003

Shear results in alignement of melt-rich layers // shear plane

Presence of melt changes olivine CPO = dispersion of [100] in the foliation

Do these processes also occur in ‘normal’ asthenosphere ? (lower melt fractions)

Synkinematic reactive melt percolation

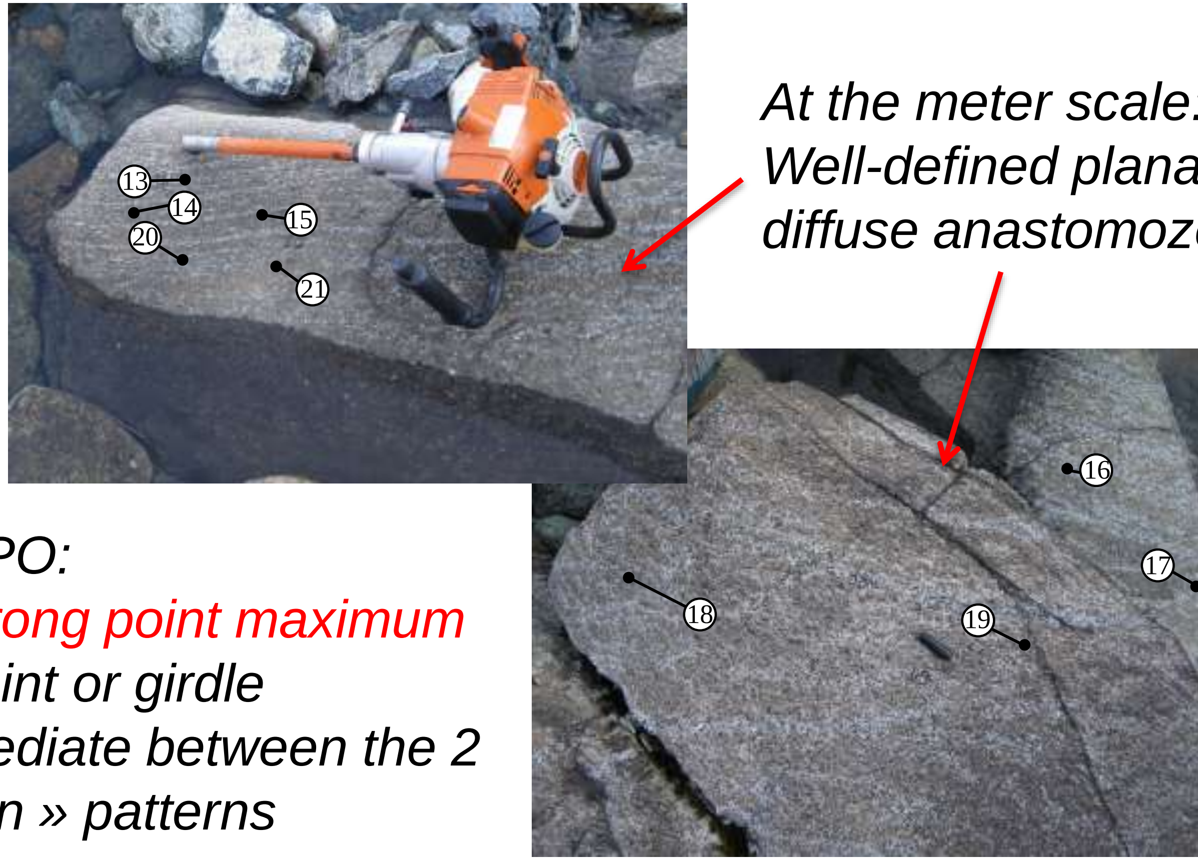
Plagioclase peridotites from Lanzo

Higgie & Tommasi Tectonophysics, submitted

Compositional layering // flow plane

- ✓ *Melt distribution controlled by deformation*

Lanzo



At the meter scale: Well-defined planar to diffuse anastomozed layering

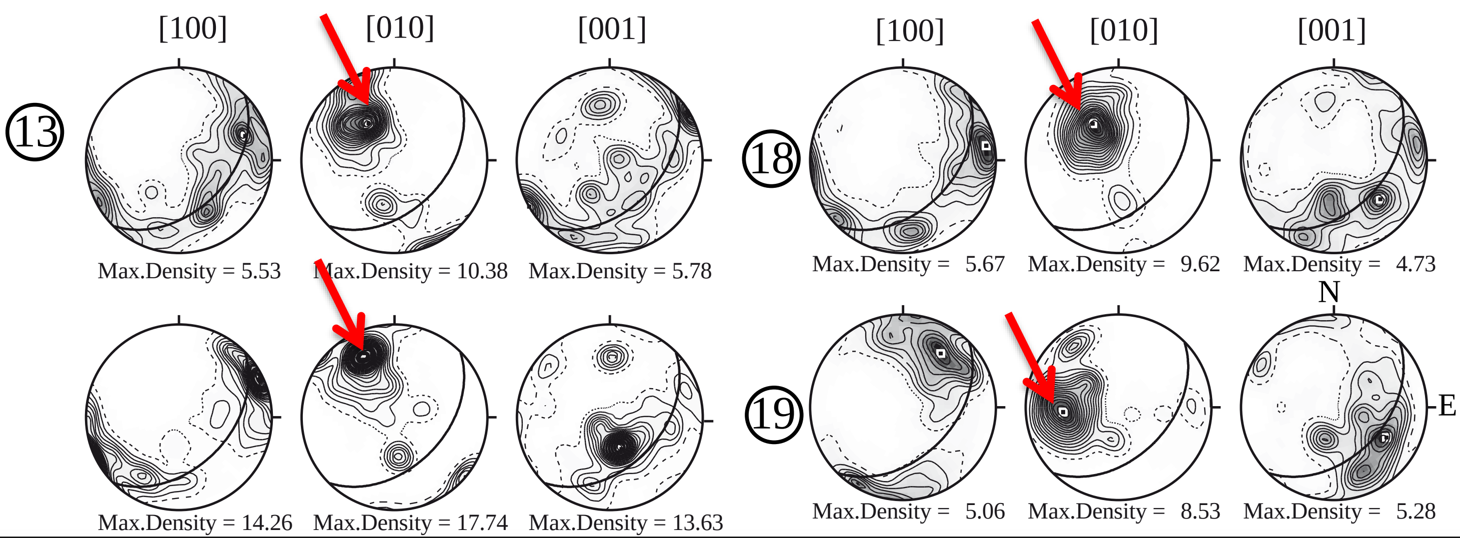
Olivine CPO:

[010] = strong point maximum

[100] = point or girdle

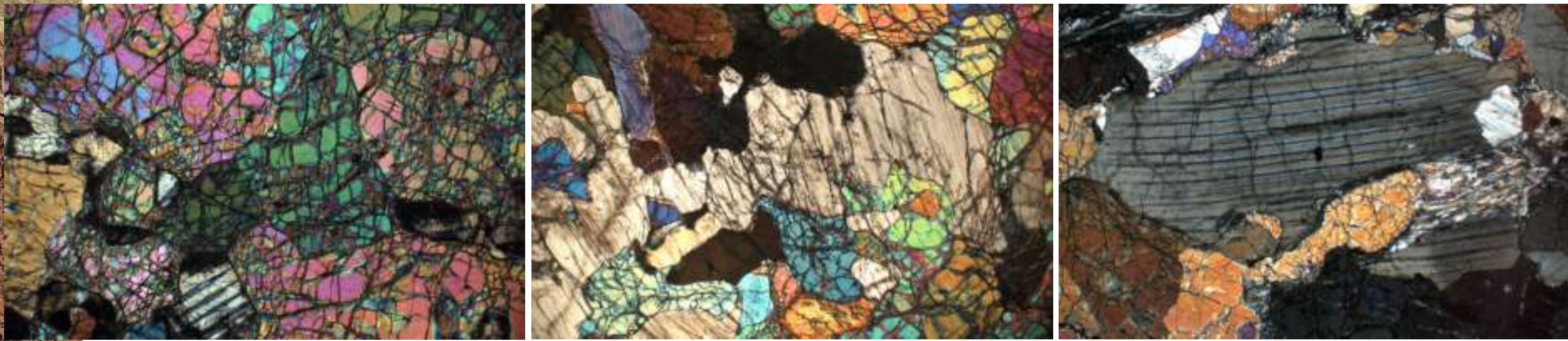
- *Intermediate between the 2 « Oman » patterns*

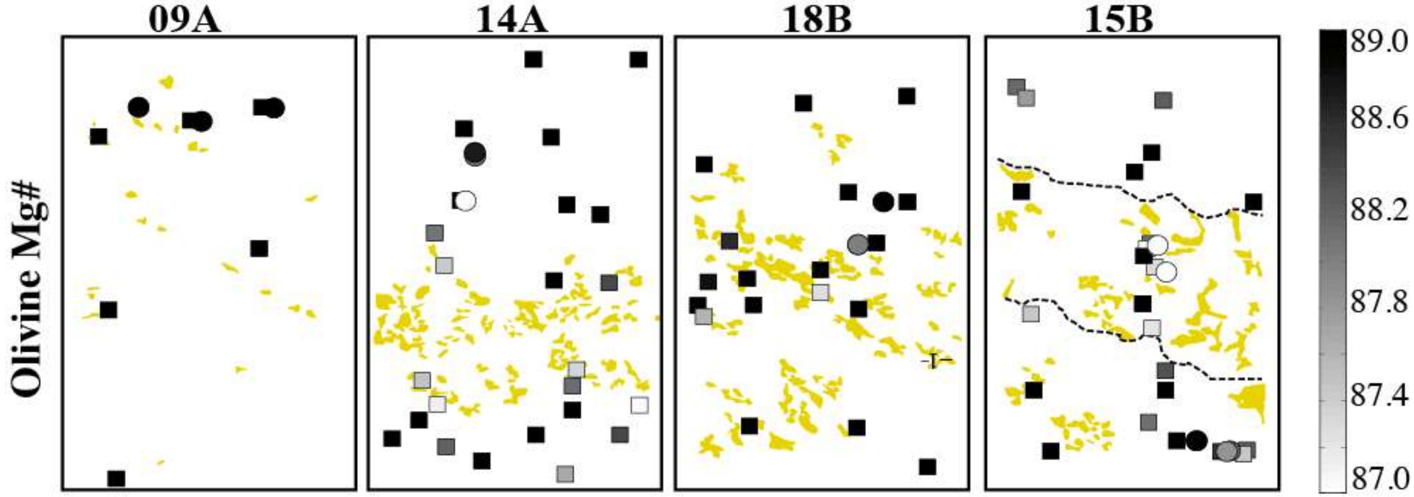
higher radial to azimuthal anisotropy



Synkinematic reactive melt percolation

Plagioclase peridotites from Lanzo





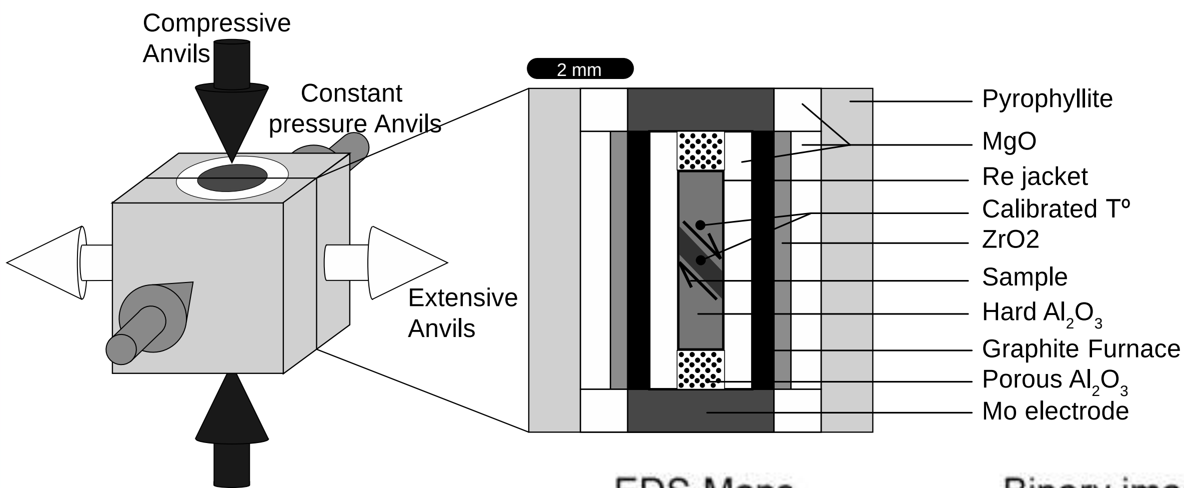
Fe-enrichment in olivine associated with cm-scale plg-rich bands

- ✓ *Variations in melt % at the scale of the layering*
- ➢ *Anisotropy of seismic & mechanical properties*

Higgie & Tommasi Tectonophysics, submitted

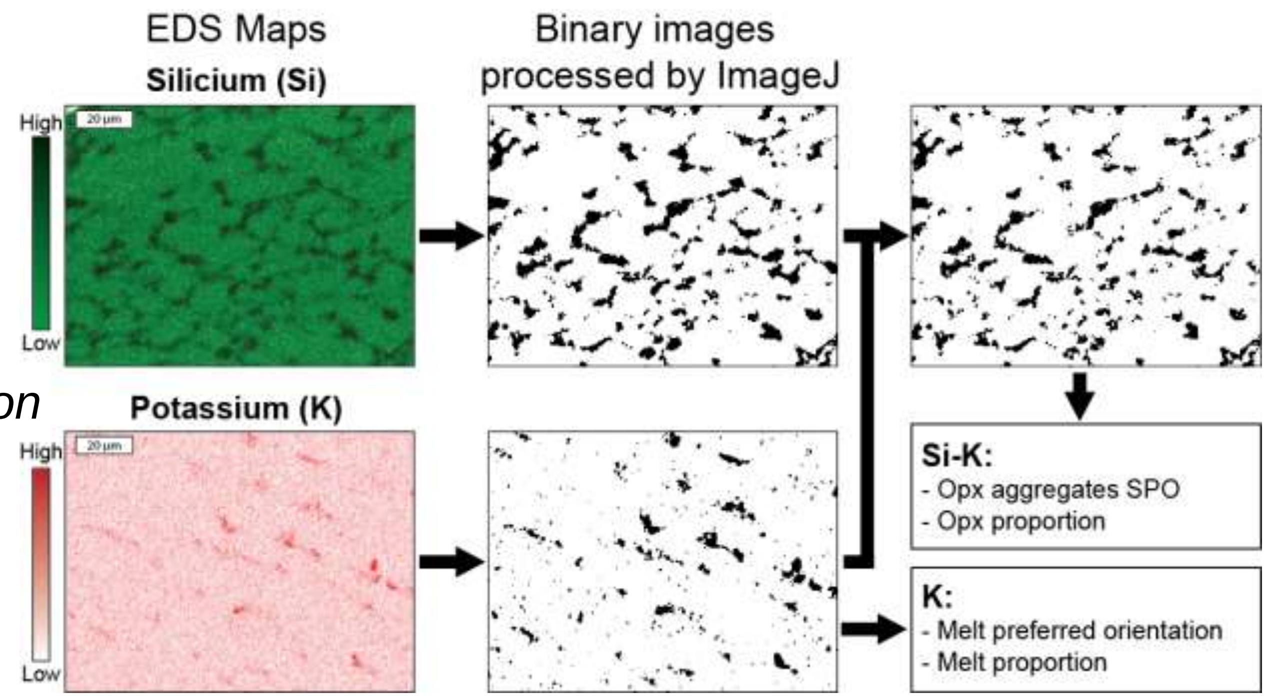
Melt migration and melt-rock reactions in the deforming Earth's upper mantle: Experiments at high pressure and temperature

Vincent Soustelle[1]*, Nicolas P. Walte[1]*, M.A. Geeth M. Manthilake[2]*, and Daniel J. Frost[1]*



2GPa
1150°C
Ol+10% Si-rich melt
Shear strain ≤ 2

Melt & melt-derived phases (opx) not //:
Melt @ -30° to SP
Opx aligned in foliation



Melt migration and melt-rock reactions in the deforming Earth's upper mantle: Experiments at high pressure and temperature

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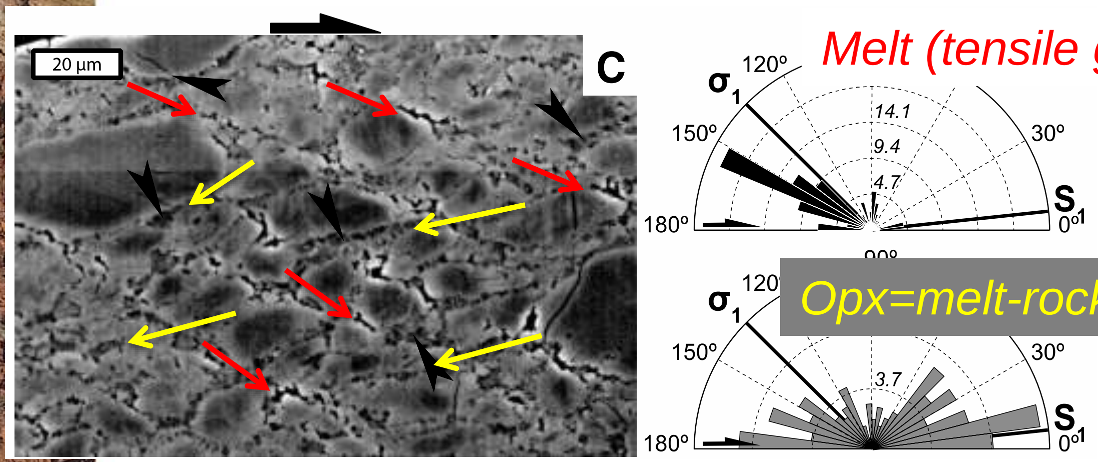
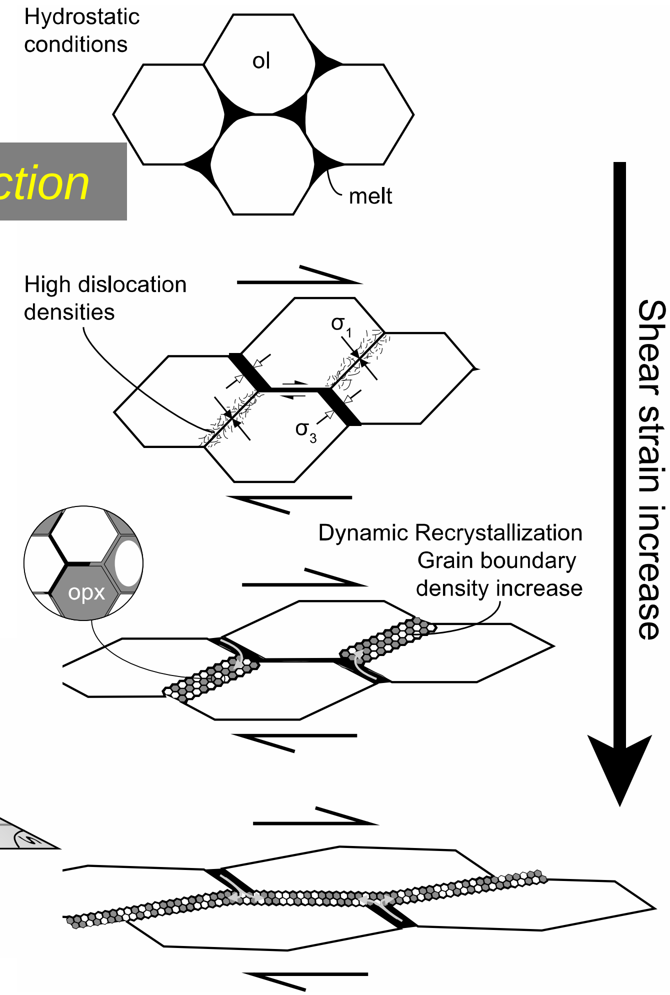
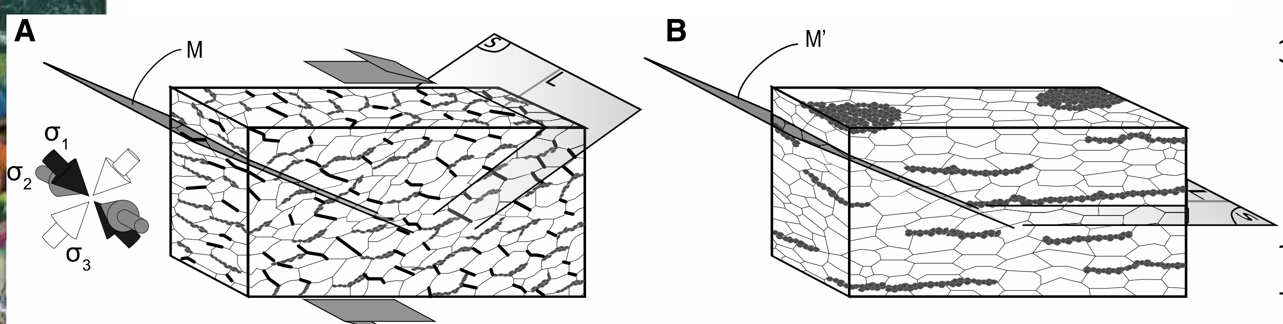




- *Grain size reduction drains melt (capillarity) + higher reaction rates*
- *Stretching of the reaction products // to shear direction*



≠ orientations of melt lenses and products of melt-rock reactions may explain the discrepancy between experiments & observations

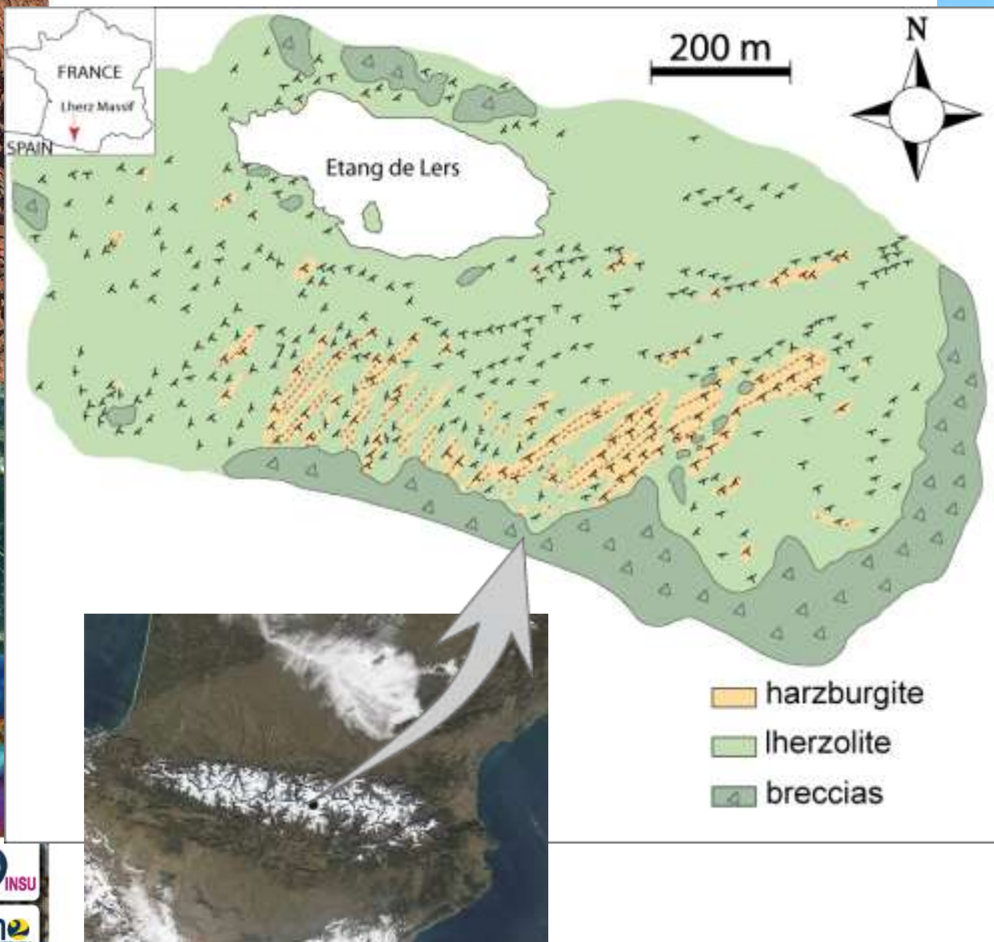
BUT, in crustal migmatites, “frozen” melt is often parallel to the shear plane!

Question remains open…

At larger scale:
A moving lithosphere-asthenosphere boundary

Magmatic rejuvenation or "asthenospherization" of the lithospheric mantle

Lherz massif, France
(lherzolite type-locality)

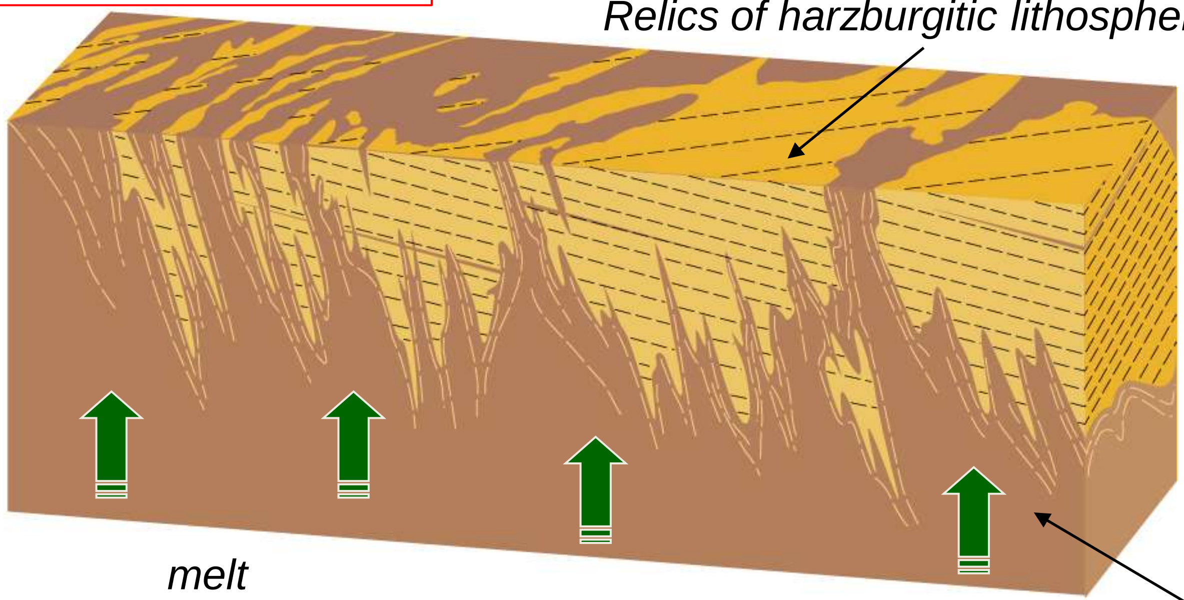


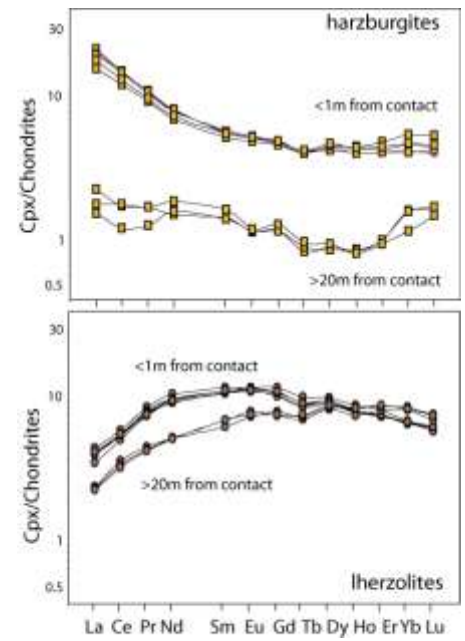
- ✓ *thermo-chemical "erosion" of an old subcontinental mantle lithosphere*
- ✓ *interactions between melt transport & deformation*

V. Le Roux – PhD 2008

Reactive melt percolation: Lherz

50-70 km depth

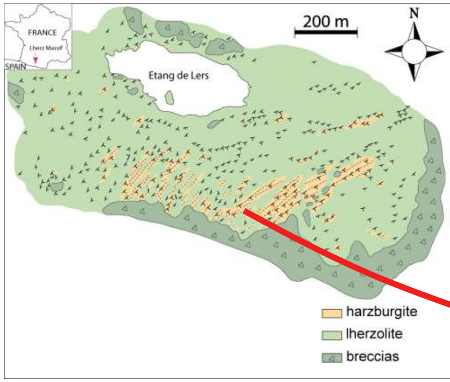




Le Roux et al. (2007) EPSL

Lherz: feedbacks between melt percolation and deformation

at the contacts



Harzburgites: strong foliation & lineation often oblique to contact

Lherzolites: incipient foliation // contact

sp alignment + weak elongation ol

websterites

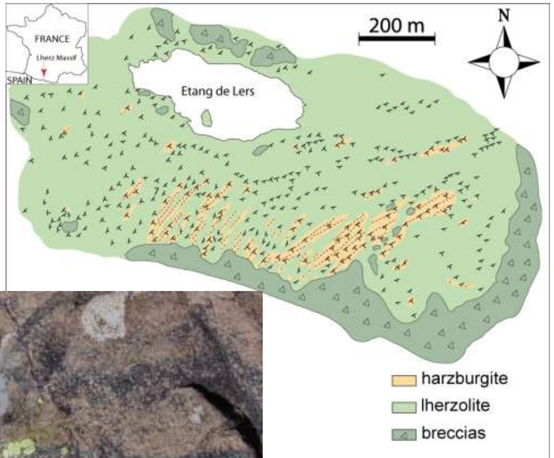
coarse grains, coexistence of deformed & underformed phases

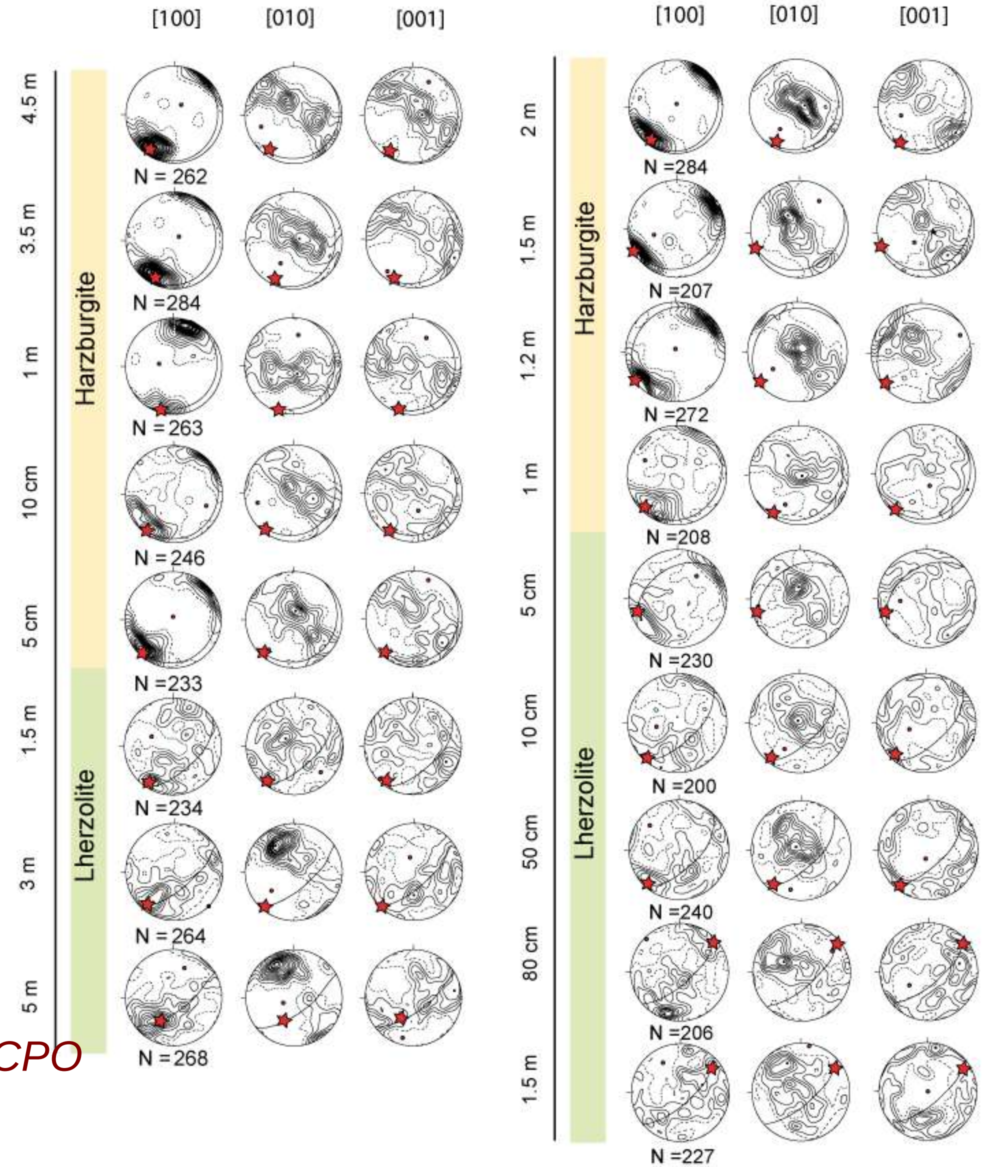
websterite layers // contact: melt accumulation horizons?

Le Roux V, Tommasi A, Vauchez A. EPSL 2008

Lherz: feedbacks between melt percolation and deformation

changes in olivine crystal preferred orientations at the contacts





Le Roux V, Tommasi A, Vauchez A. EPSL, 2008

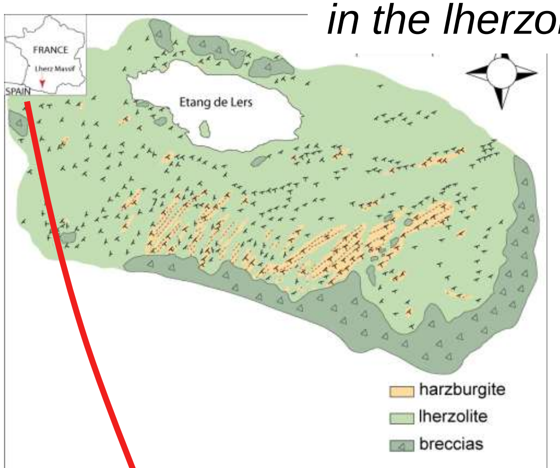
contacts = changes in composition,
grain growth + annealing

dispersion and reorientation of olivine CPO
(delayed = ≥1m from the contact)

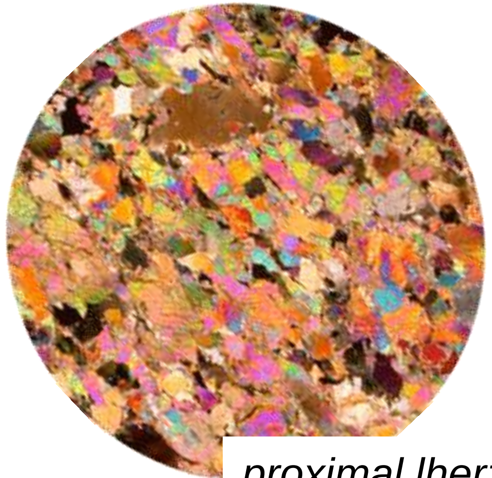
➢ ***deformation "follows" the reaction/percolation front***

Lherz: feedbacks between melt percolation and deformation

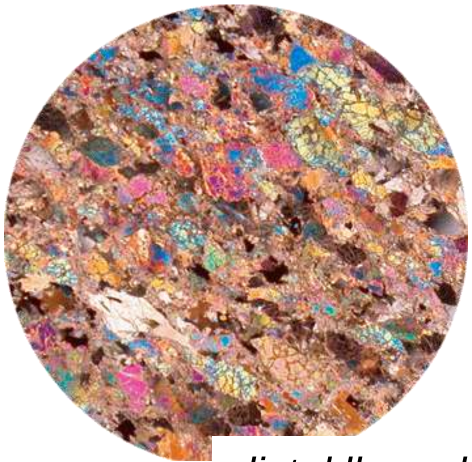
in the lherzolites



strain ↗ with ↗ distance from harzburgites contact (percolation front)



proximal lherzolite



distal lherzolite

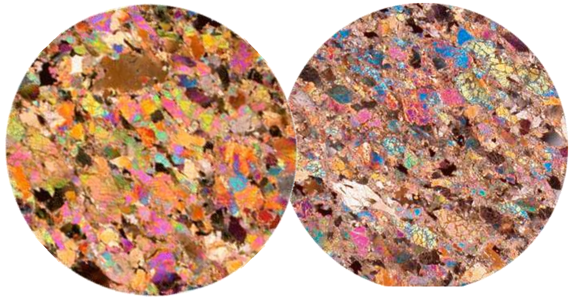
highest strains = most fertile lherzolites
boudinage of thick websteritic bands in layered lherzolites (>500m from contacts)

✓ ***melt-induced strain localization***

✓ ***layering = melt segregation due to shearing***

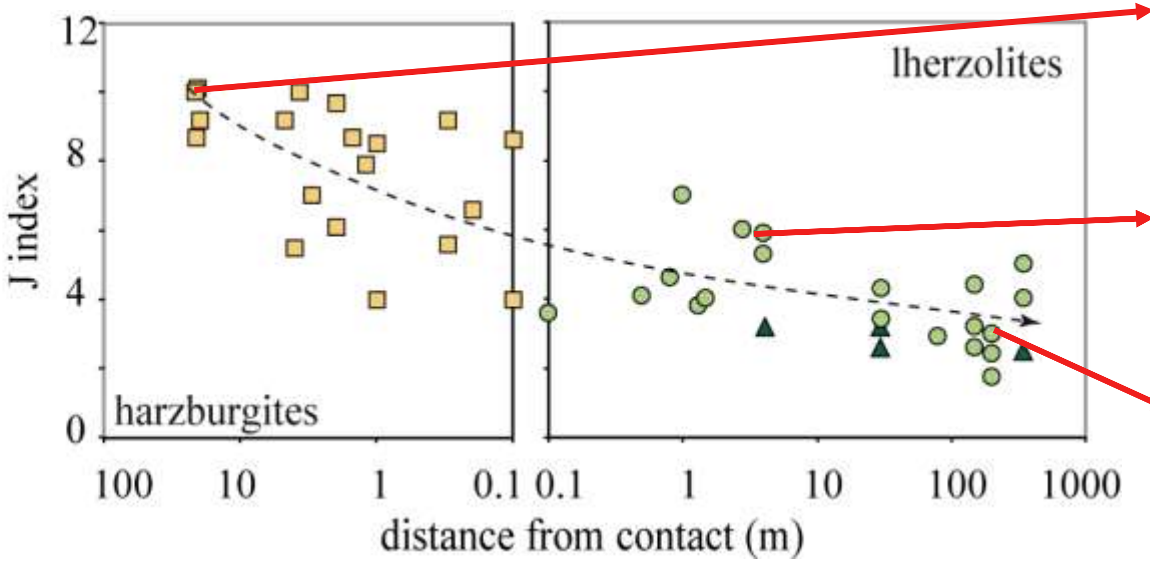
Similar to Oman & Lanzo, but only pyroxenes & spinel crystallization in the melt-rich bands = higher pressure

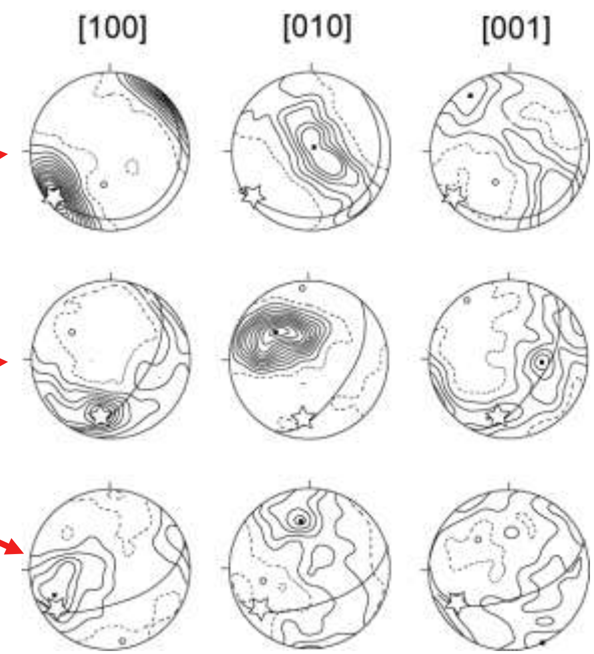
Lherz: feedbacks between melt percolation and deformation



strain in the lherzolites ↗ with ↗ distance from harzburgites contact (percolation front),

BUT olivine CPO in lherzolites and websterites becomes progressively weaker





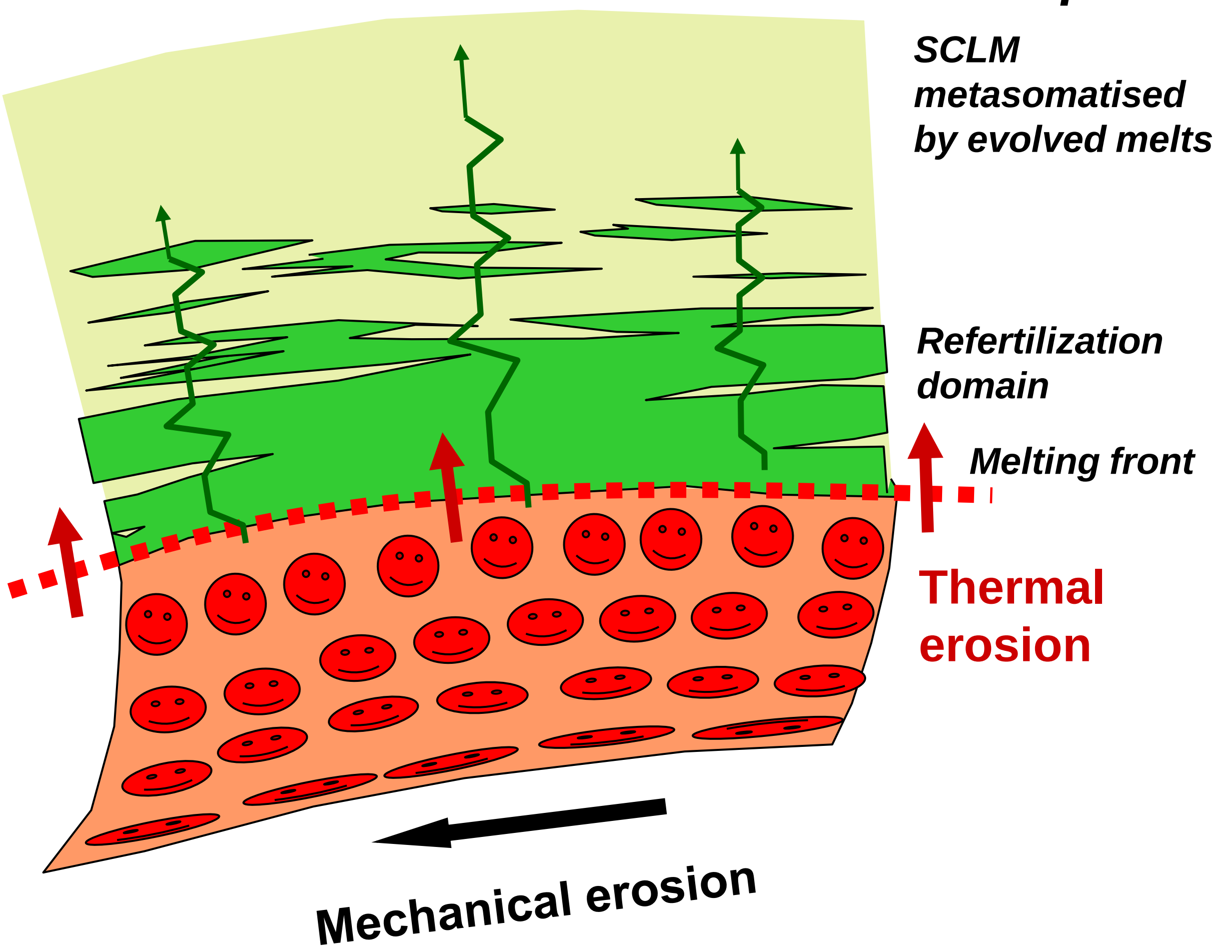
✓Olivine crystals preferred orientations similar to those in Oman & Lanzo

✓Weak CPO = higher contribution of diffusional processes to deformation in presence of melt

Le Roux V, Tommasi A, Vauchez A. EPSL 2008

Lherz (also Ronda!): melting, refertilization & deformation

➢ **thermo-mechanical erosion of mantle lithospheric**



➔ *the lithosphere is*

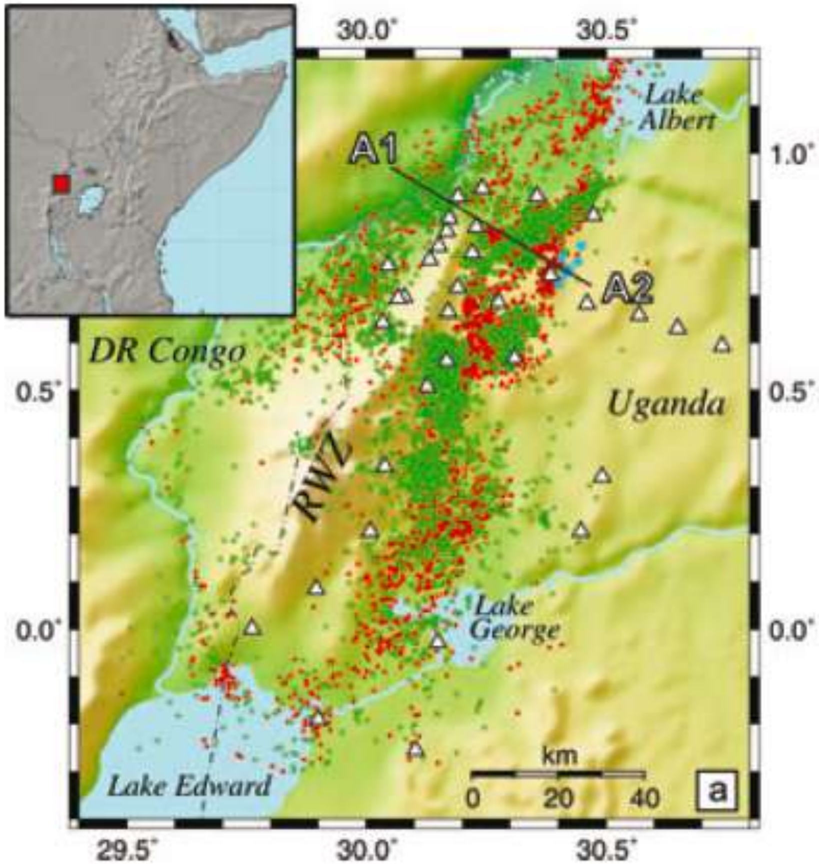
(1) refertilized

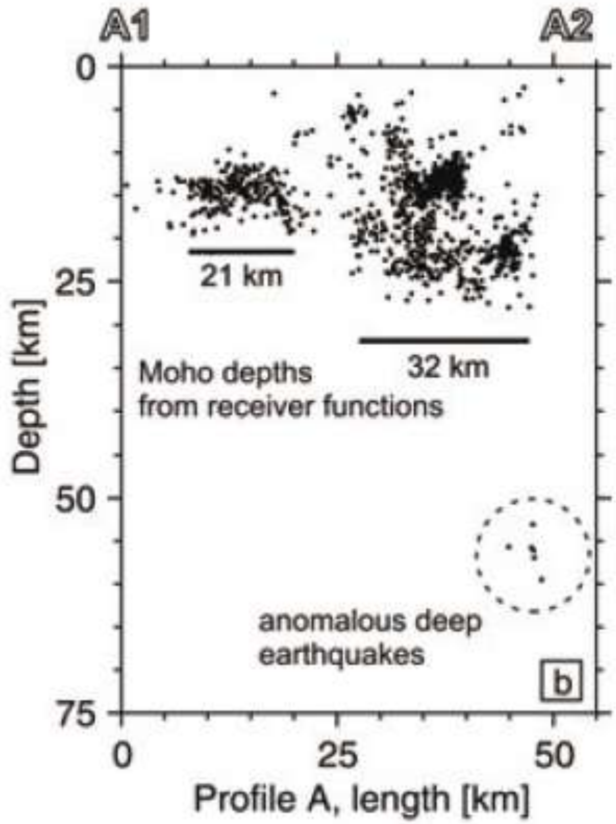
(2) molten & deformed

→ ***The melting domain is all but 'pristine'***

Do we see such melt percolation fronts in the geophysical data?

Earthquakes in the mantle lithosphere: tracers of magma motion?



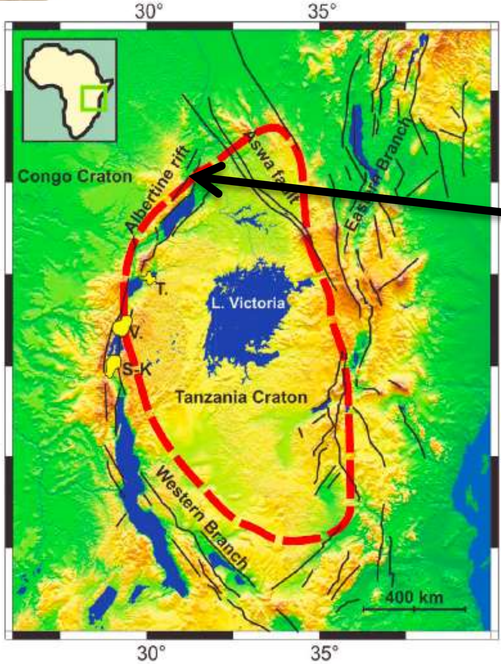


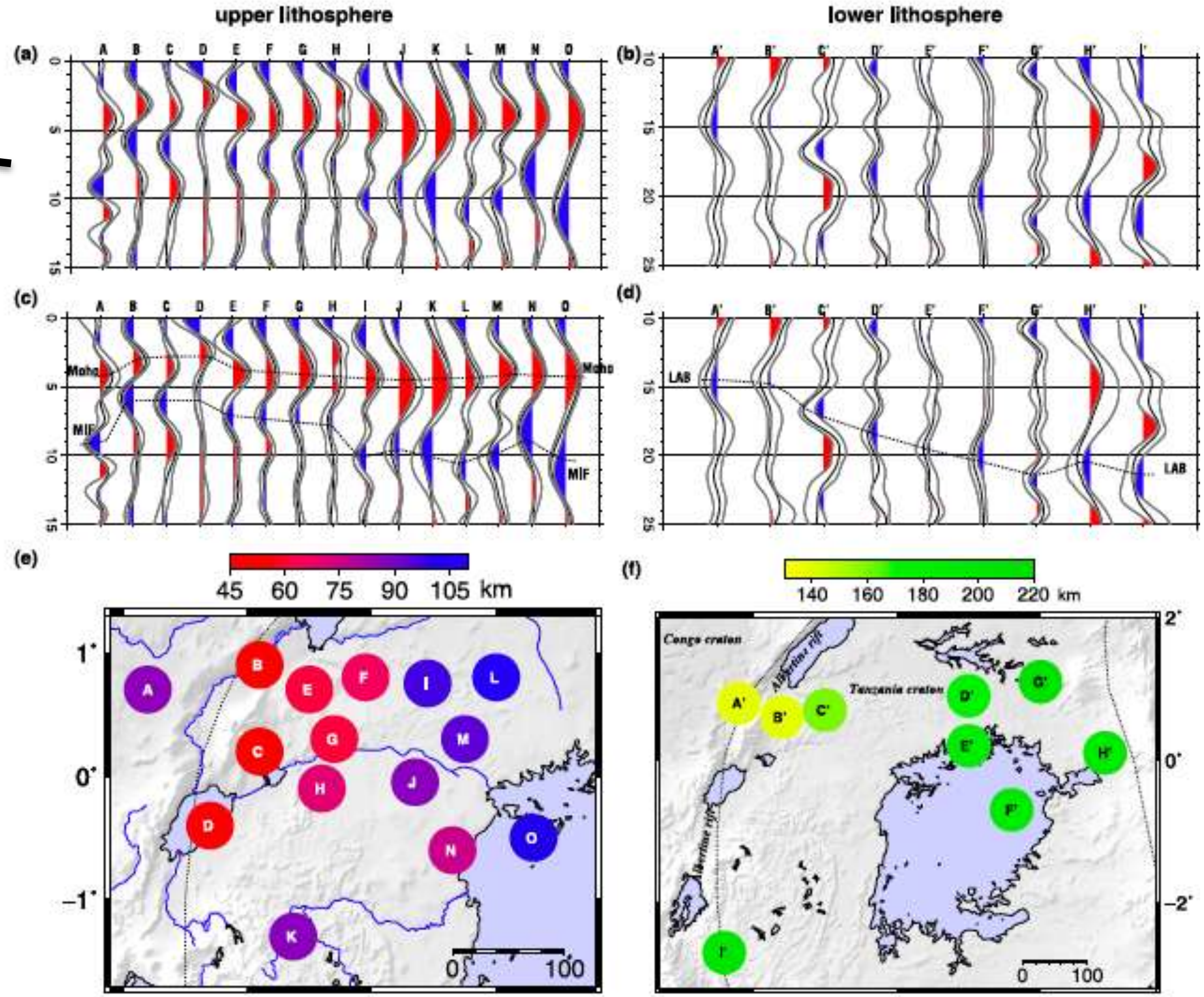
Lindenberg & Rümpker GJI 2011

Melt infiltration of the lower lithosphere beneath the Tanzania craton and the Albertine rift inferred from S receiver functions

Ingo Wölbern and Georg Rümpker

Geochemistry
Geophysics
Geosystems
G3

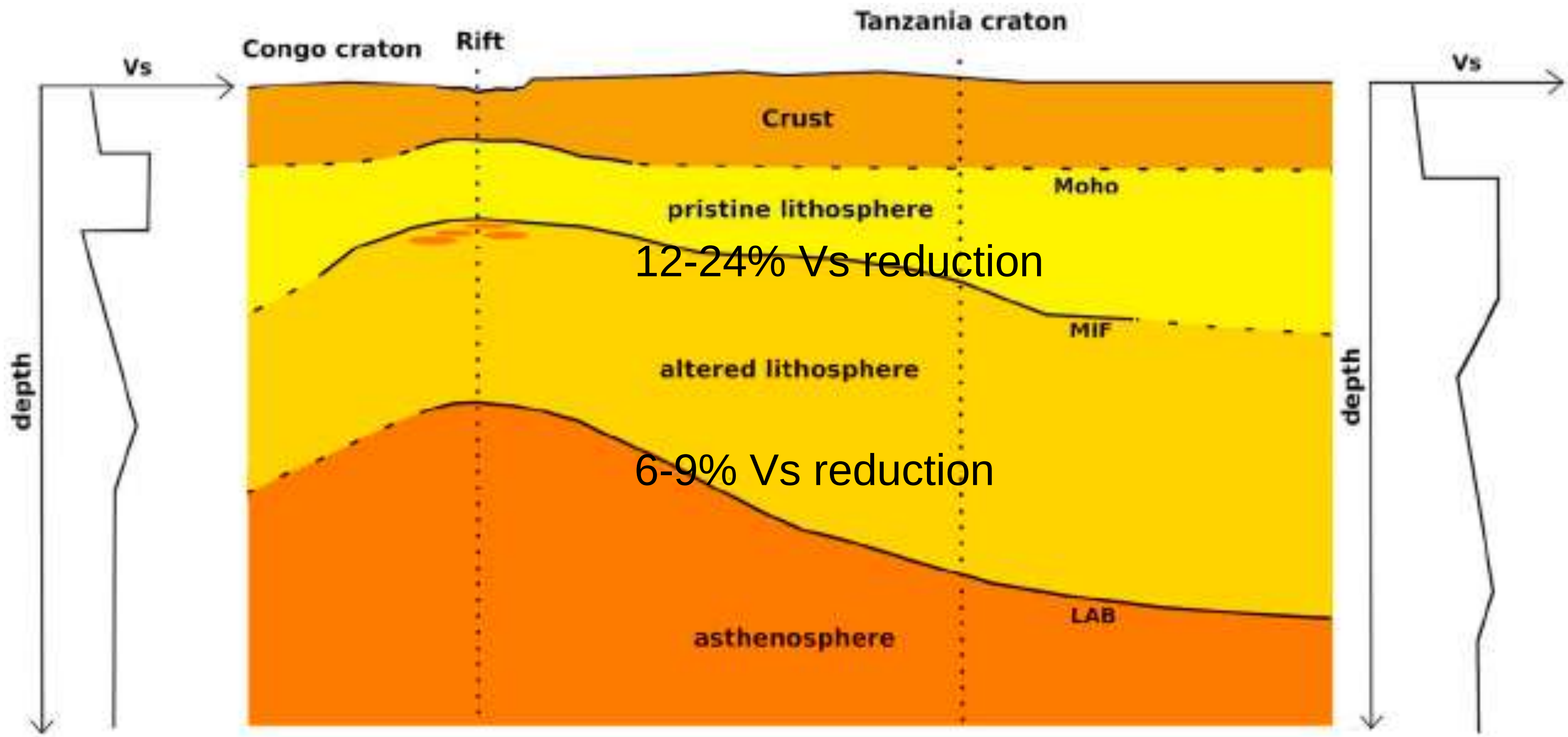


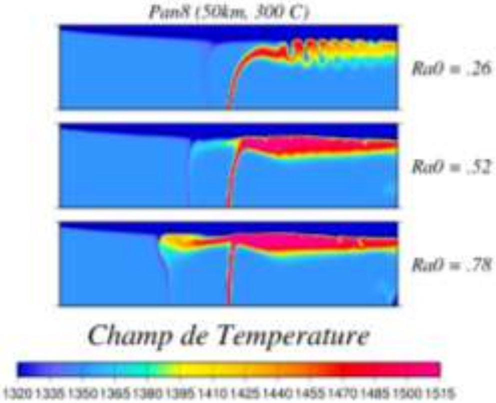


Melt infiltration of the lower lithosphere beneath the Tanzania craton and the Albertine rift inferred from S receiver functions

Ingo Wölbern and Georg Rümpker

Geochemistry Geophysics Geosystems G3



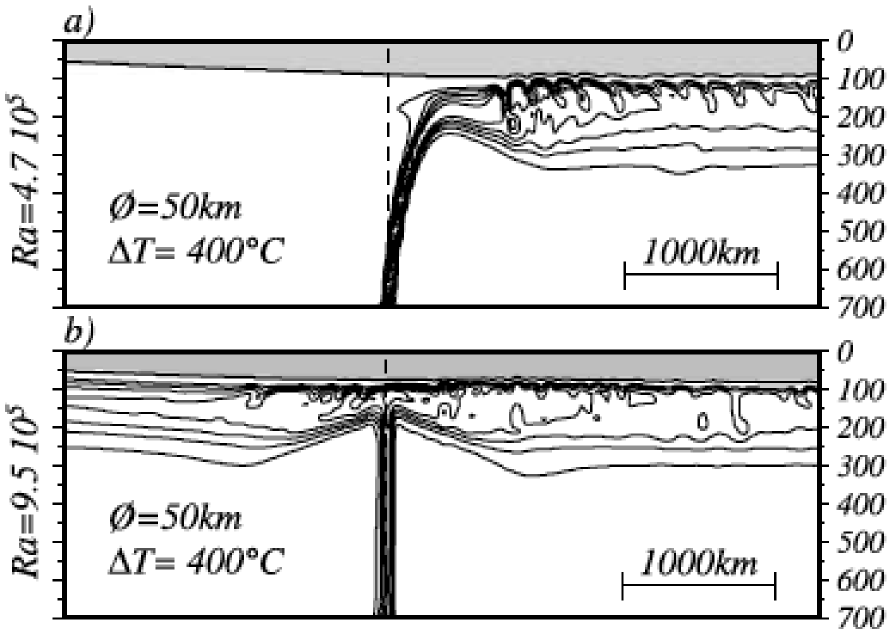


May such a process help bottom-up thinning of the mantle lithosphere?

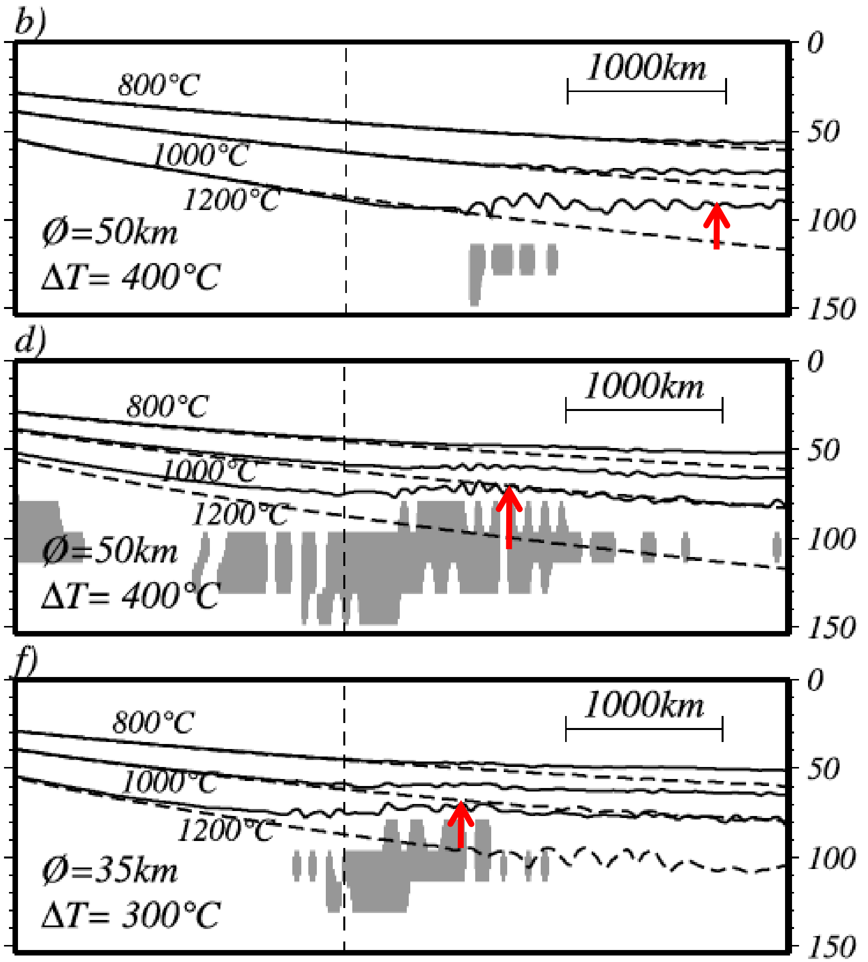
Numerical models: plume – lithosphere interaction:

small-scale convection enhanced in the plume wake

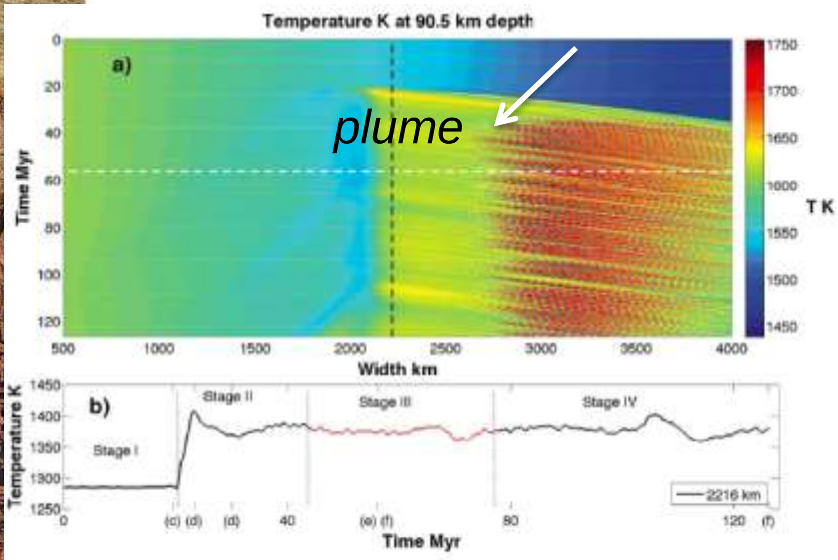
If partial melting is not considered : 1200° C isotherm raised by 10-30km, downstream of the plume impact point



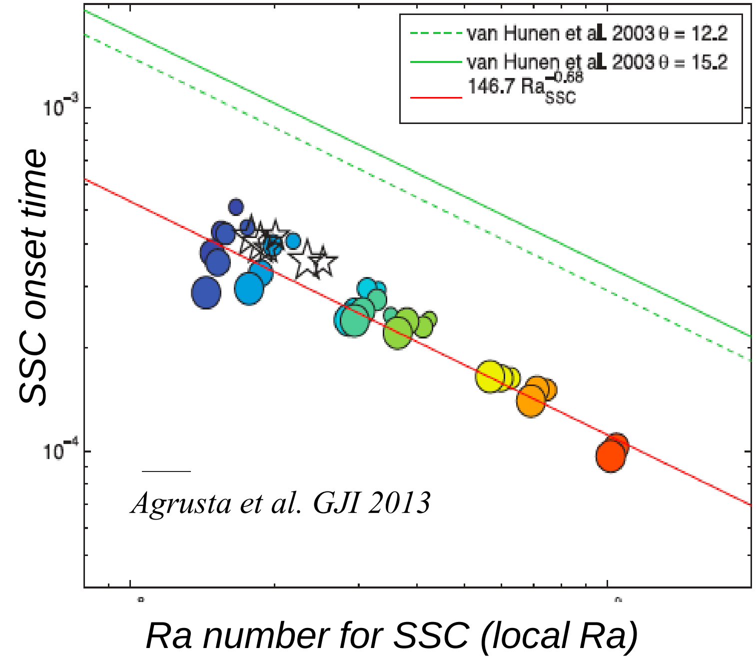
Thoraval et al. GRL 2006

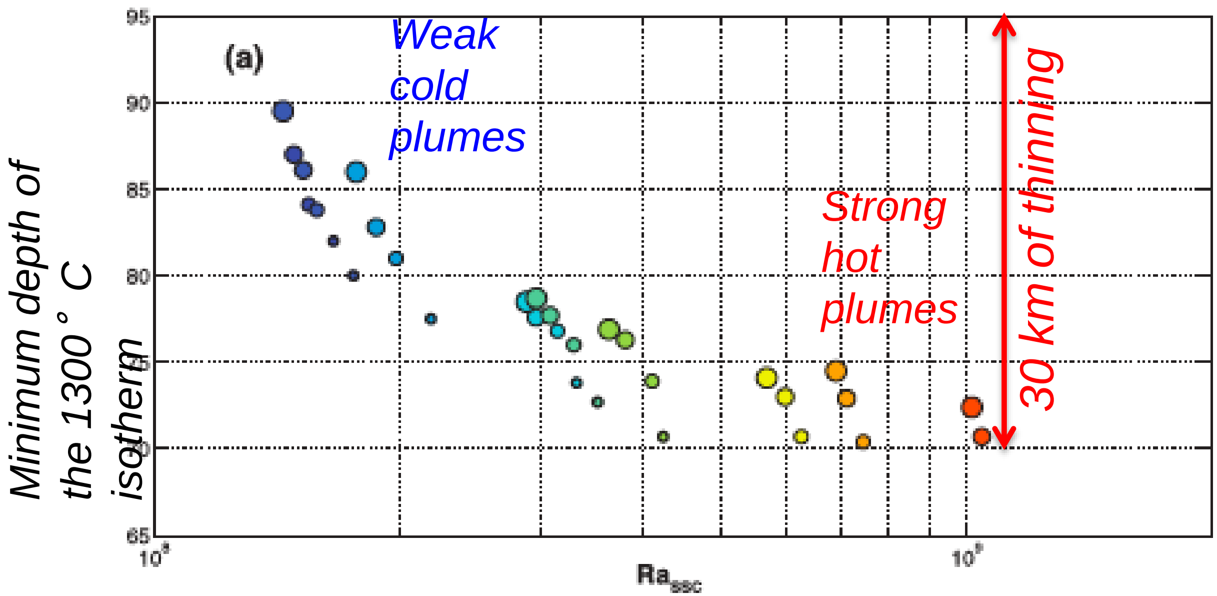


Dynamics of the small-scale convection in the plume-fed LAB



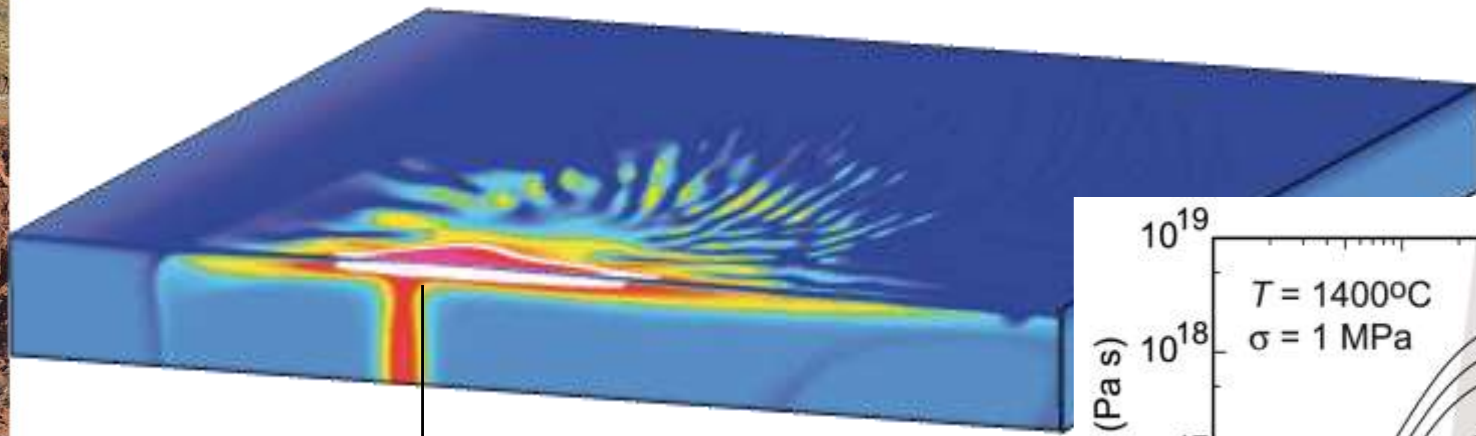
Plume impact | *Conductive reequilbration* | *Small-scale convection*



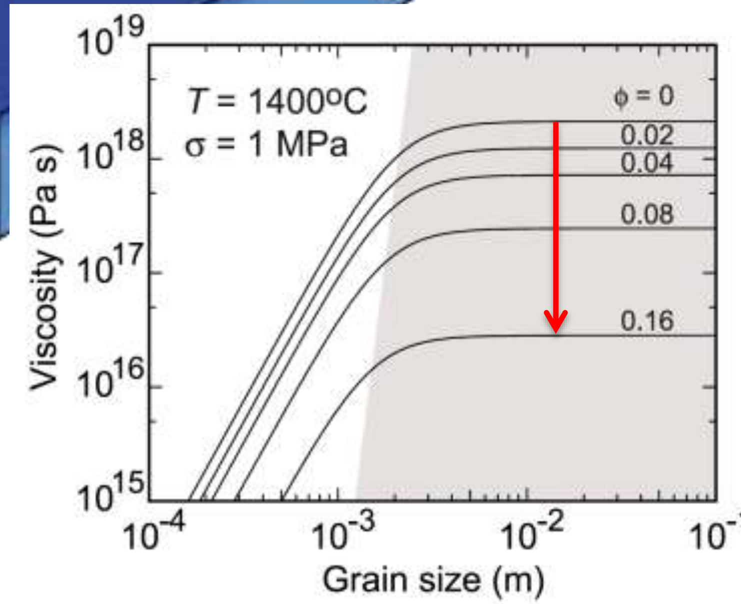


R. Agrusta PhD 2012

Bottom-up erosion of the lithosphere favored by partial melting in the asthenosphere?



© C. Thoraval



Kohlstedt & Mackwell 2008

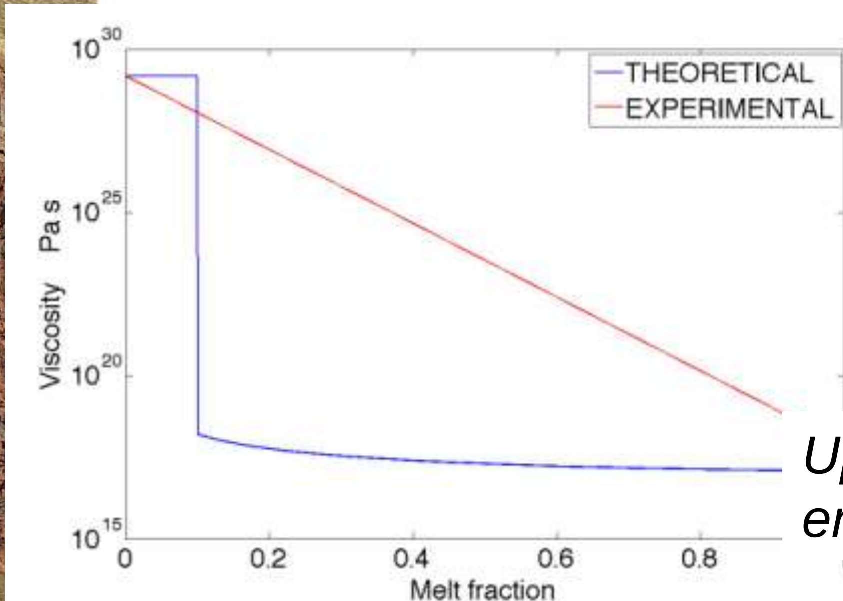
in experiments:

***presence of melt** => reduces the viscosity*

***melt extraction** => lowers the density of the residue*

- ***Partial melting may lead to more effective small-scale convection and lithosphere erosion atop a mantle plume***

Viscosity reduction due to partial melting
➢ *small-scale convection enhanced = more erosion*



Anhydrous melting

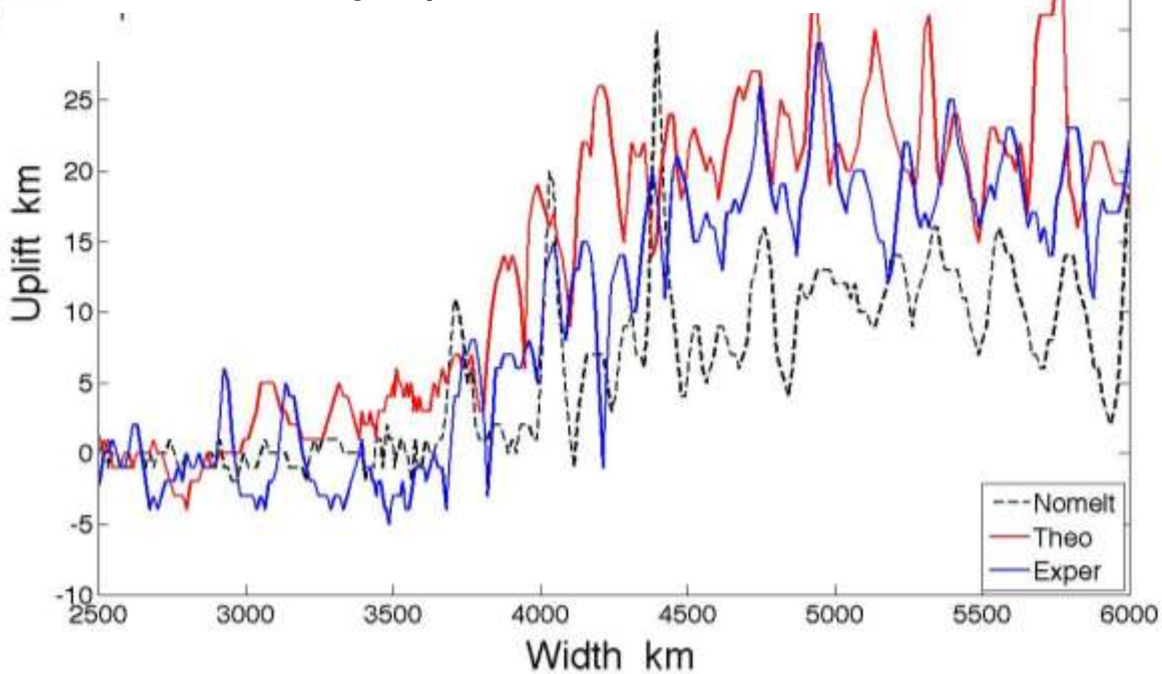
Katz et al. G3, 2003

$$X_M = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}$$

$$T_{solidus} = 1085.7 + 132.9P - 5.1P^2$$

$$T_{liquidus} = 1780 + 45P - 2P^2$$

Uplift of the 1200° C isotherm enhanced by up to 15 km



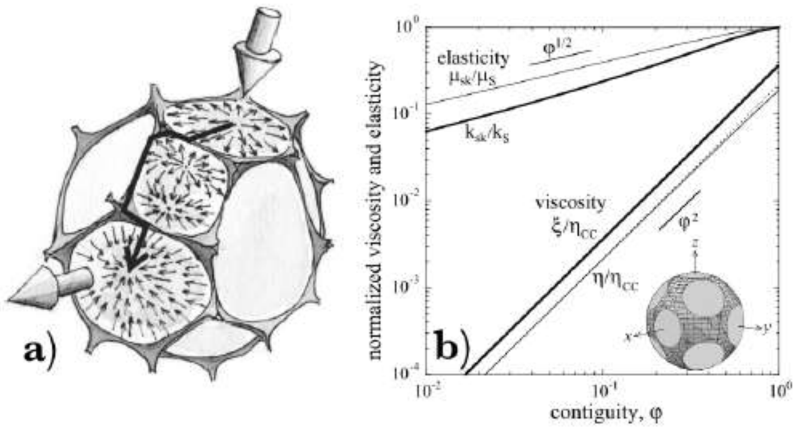
But… no melt extraction

Unrealistic instantaneous melt fractions - up to 40%

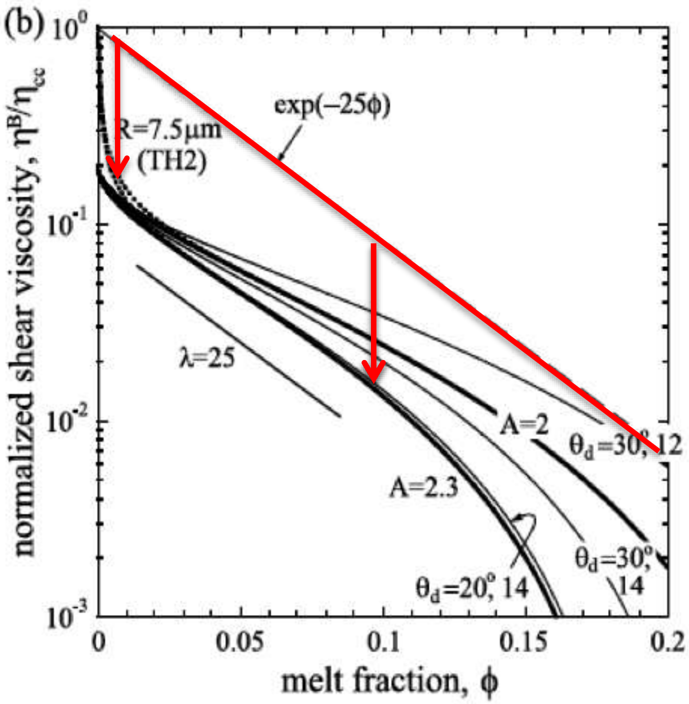
R. Agrusta PhD 2012

Rheology of a partially molten mantle

Which is the critical melt fraction for extraction & rheology ?



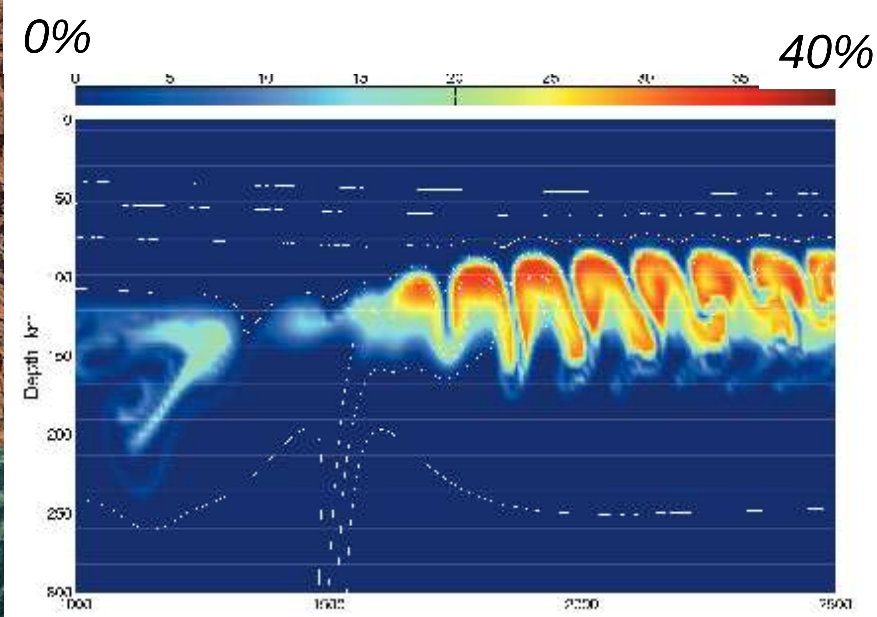
Takei & Holtzman 2009



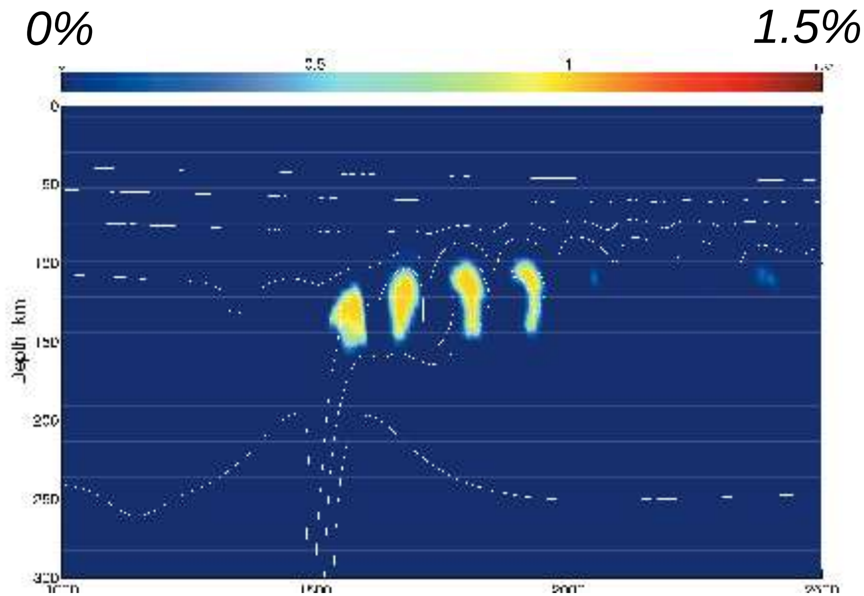
Melt interconnection & Strong decrease in shear viscosity (~10 times)
@ very low melt fractions
~0.1%

Instantaneous extraction of melt at a critical threshold (1%)
Depletion = cummulative melt production
Instantaneous melt fraction = X_M - depletion

$$X_M = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}$$



Depletion:
Changes density



Instantaneous melt fraction:
Changes viscosity

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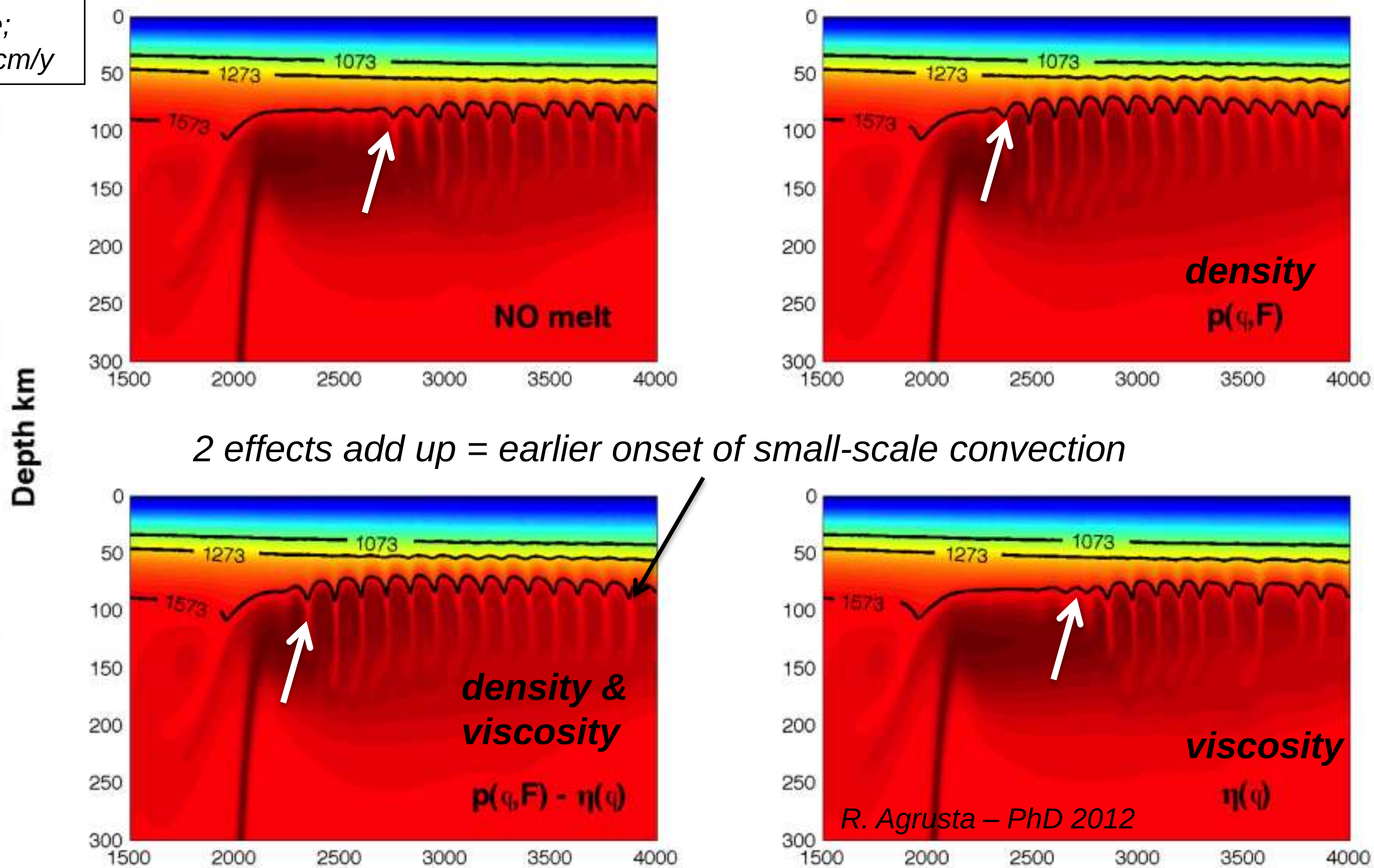
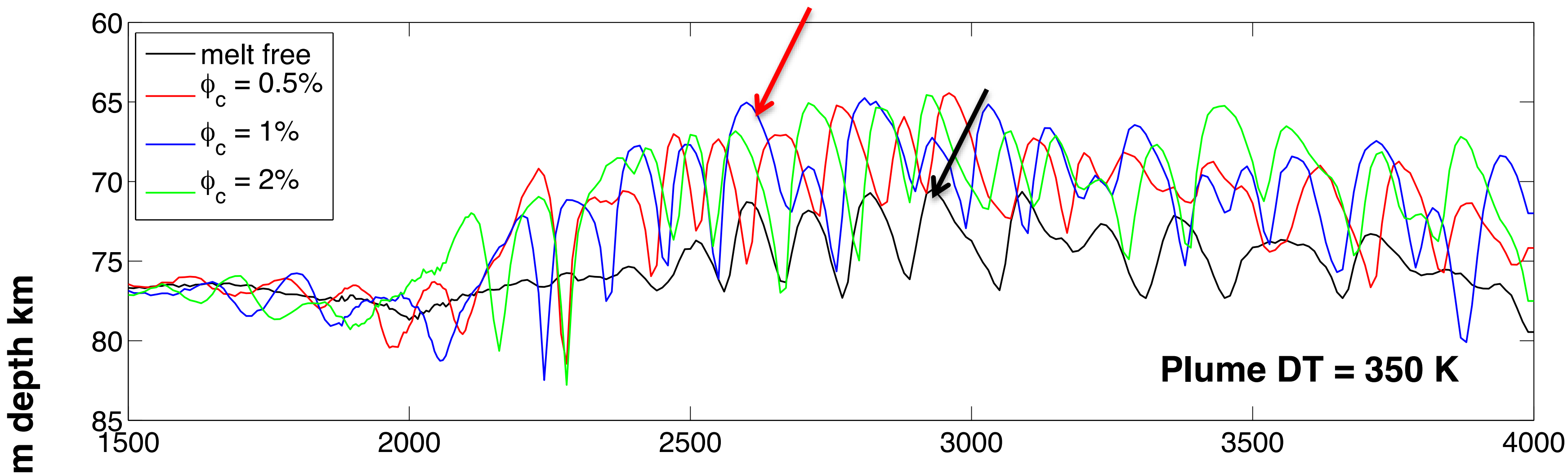
PhD 2012

Effect of melting on the composition (density) of the residue
depletion in Fe = decrease in density = F(cummulated melting)
Decrease in viscosity = F(instantaneous melt fraction)
Thresholds for melt extraction = 1% & for viscosity decrease = 0.1%

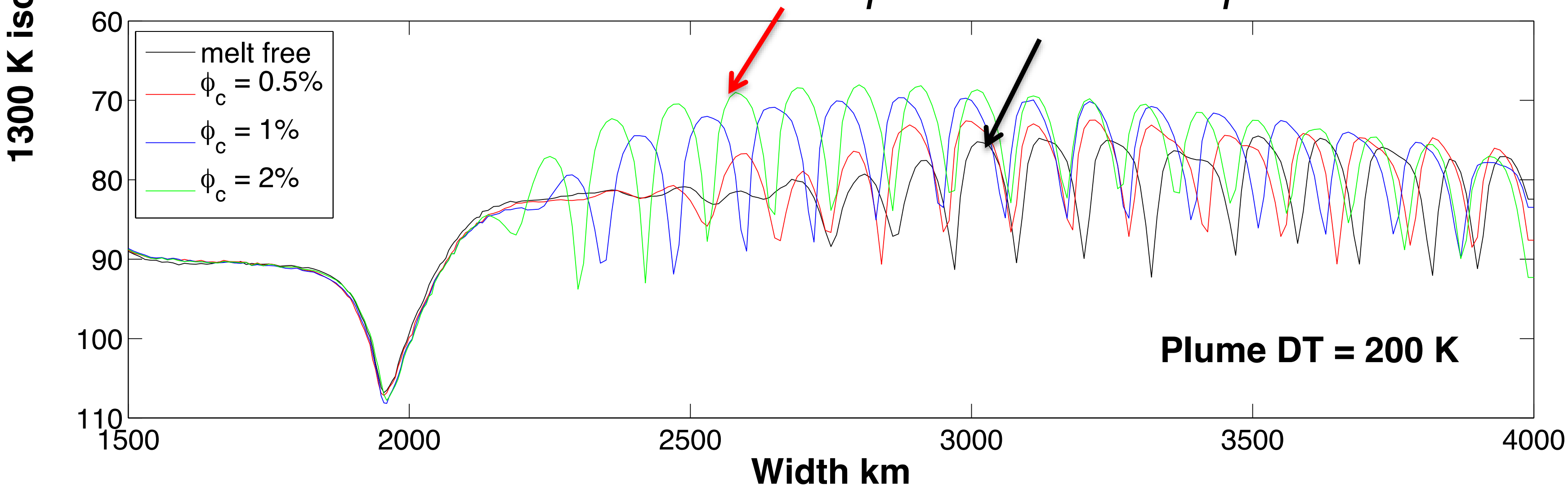
200K plume; Vp=7cm/y



Bottom-up erosion of the lithosphere accelerated & enhanced

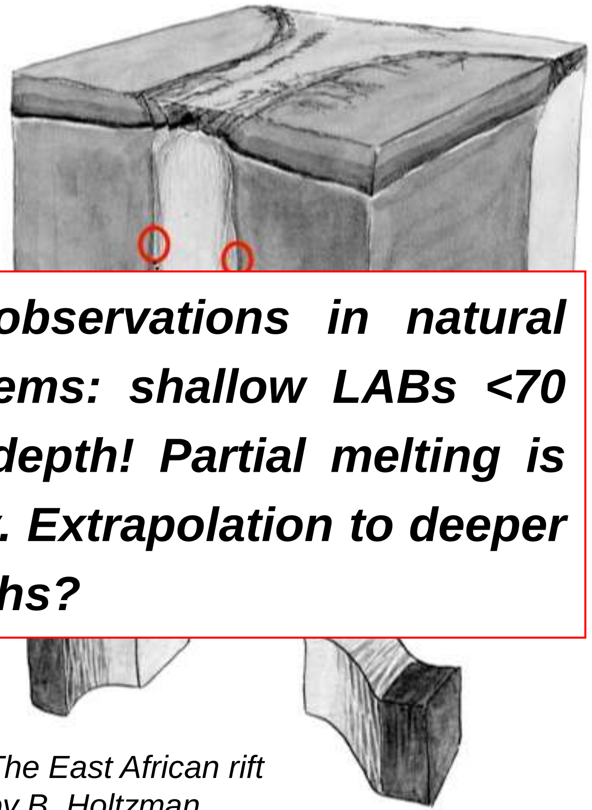


Melt extraction threshold : more important for small plumes



R. Agrusta – PhD 2012

Coupling between partial melting, melt transport and deformation in the LAB



The East African rift
by B. Holtzman

All observations in natural systems: shallow LABs <70 km depth! Partial melting is easy. Extrapolation to deeper depths?

Observations in natural systems *:*

- *melt percolation and refertilization reactions affect the lithosphere up to 1km ahead of the melting front*
- *melt migration precedes deformation, weakening & refertilising the base of the lithosphere*
- *strong interactions between melt transport and deformation: strain localisation + layering (anisotropy of physical properties)*

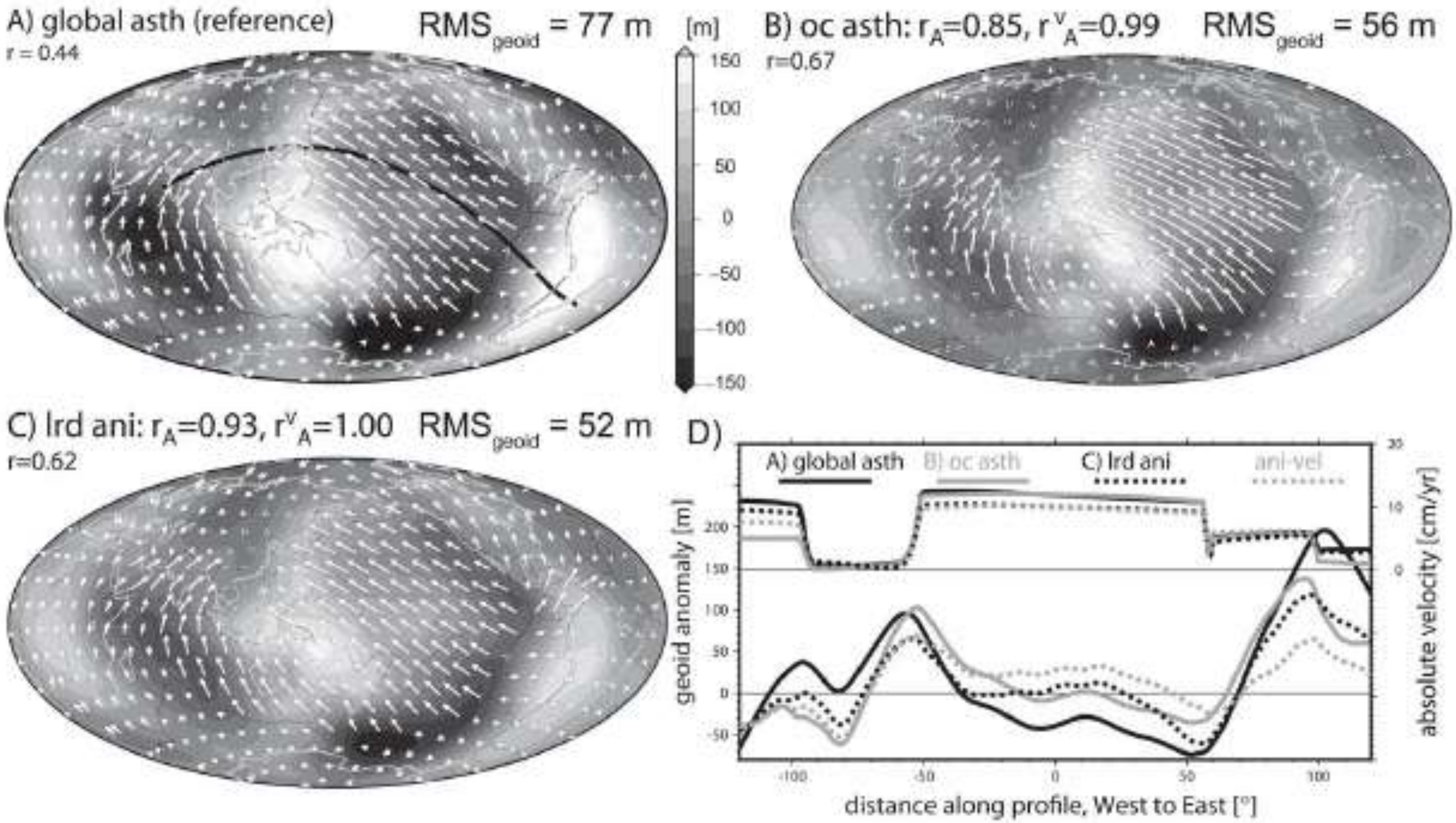
Models*: coupling of deformation & melting => enhances upwelling of LAB*
Geophysical data*: melts in the mantle lithosphere up to shallow depths. Distribution and composition?*

Open questions*: Differences between melt topology in experiments and natural systems? Melt migration processes? Thermodynamics of these biphasic systems?*

Viscosity anisotropy due to melt alignement in the asthenosphere

On the role of anisotropic viscosity for plate-scale flow

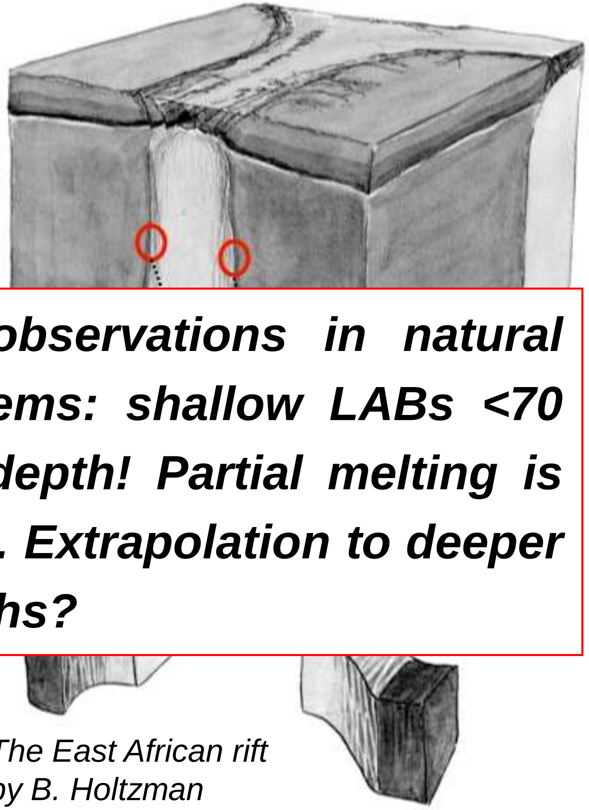
T. W. Becker[1] and H. Kawakatsu[2]



➢ *Effect of melt-induced transverse anisotropy cannot be discriminated from an isotropic viscosity decrease in the asthenosphere*

Coupling between partial melting, melt transport and deformation in the LAB

All observations in natural systems: shallow LABs <70 km depth! Partial melting is easy. Extrapolation to deeper depths?



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***Models**: coupling of deformation & melting => enhances upwelling of LAB*
anisotropy of viscosity => first results not conclusive
***Geophysical data**: melts in the mantle lithosphere up to shallow depths.*
Distribution and composition?

***Open questions**: Differences between melt topology in experiments and natural systems? Melt migration processes? Thermodynamics of these biphasic systems?*