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

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

Pacific
Sp receiver functions, ScS, SS data

Rychert et al. Nature 2005

Rychert et al. G3 2012
Melt organized in lenses // LAB

- Stronger velocity contrasts at lower melt fractions
- Also explains the seismic anisotropy
Electrical conductivity data: Magnetotelluric soundings

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

Melt-rich channel observed at the lithosphere–asthenosphere boundary

S. Nafi, K. Key, S. Constable & R. L. Evans

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- High conductivity
- Anisotropy: $\sigma_x = 2\sigma_y$
- Water + melt
Similar processes also occur beneath active plate boundaries...

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

Kendall et al. Nature 2005

East African Rift

SKS splitting

Surface waves anisotropy

Bastow et al. G3 2005
Simple shear experiments in 2-phase systems:

- melt distribution controlled by stress
- change in olivine CPO

Zimmerman & Kohlstedt 99

Holtzman et al. Science 2003
Evidence of such feedbacks in nature?

Structural & microstructural data on mantle peridotite outcrops
Oman MTZ (uppermost mantle)

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

Layering // Foliation // Moho = subhorizontal

Melt organization in a mantle deforming by simple shear
K. Higgie, Ph.D. ITN Crystal2Plate

Higgie & Tommasi EPSL 2012
Layering: ol-rich & plg-cpx rich levels // foliation

Melt organization in a mantle deforming by simple shear

Strong lineation & foliation in all layers

Finite pancake-like gabbroic lenses

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

Olivine Gabbro

[100] [010] [001]

[100] [010] [001]

AXIAL-[100]  AXIAL-[010]

Cpx  Plg

Higge & 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

Plg-rich layer: Axial-[010]

Dunitic layer: Axial-[100]

Higie & 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 alignment 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

Compositional layering // flow plane
✓ Melt distribution controlled by deformation
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
Melt migration and melt-rock reactions in the deforming Earth’s upper mantle: Experiments at high pressure and temperature


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**Abstract:** 

The study investigates melt migration and melt-rock reactions in the deforming Earth’s upper mantle through high-pressure and high-temperature experiments. The experiments were conducted using a sample assembly and deformation geometry diagrammed below.

**Sample Assembly and Deformation Geometry:**

- **Compressive Anvils**
- **Constant pressure Anvils**
- **Extensive Anvils**

**Materials:**

- Pyrophylite
- Mo electrode
- Porous Al₂O₃
- ZrO₂
- MgO
- Calibrated T°
- Re jacket
- Sample
- Hard Al₂O₃
- Graphite Furnace
- Porous Al₂O₃
- Mo electrode

**Experimental Conditions:**

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

**EDS Maps**

- **Silicium (Si)**
- **Potassium (K)**

**Binary Images**

- Processed by ImageJ

**Results:**

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

**Conclusion:**

The experiments reveal insights into melt migration and melt-rock reactions under high-pressure and high-temperature conditions, contributing to our understanding of the Earth’s upper mantle processes.
Grain size reduction drains melt (capillarity) + higher reaction rates

Stretching of the reaction products // to shear direction

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

Vincent Soustelle*, Nicolas P. Walte*, M.A. Geeth M. Manthilake*, and Daniel J. Frost*
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!
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

Relics of harzburgitic lithosphere

Refertilized lherzolites

Le Roux et al. (2007) EPSL

EPSL
**Lherz: feedbacks between melt percolation and deformation**

**at the contacts**

Lherzolites: incipient foliation // contact

Harzburgites: strong foliation & lineation often oblique to contact

coarse grains, coexistence of deformed & underformed phases

websterite layers // contact: melt accumulation horizons?

sp alignment + weak elongation ol

websterites

Contacts = changes in composition, grain growth + annealing, dispersion and reorientation of olivine CPO (delayed = ≥1m from the contact)

> Deformation "follows" the reaction/percolation front

*Le Roux V, Tommasi A, Vauchez A. EPSL, 2008*
**Lherz: feedbacks between melt percolation and deformation**

- **strain** ➔ with ➔ distance from harzburgites contact (percolation front)
- **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**

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

Ingo Wölblem and Georg Rümpker

12-24% Vs reduction

6-9% Vs reduction
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 reequilibration

Small-scale convection

Minimum depth of the 1300°C isotherm

Weak cold plumes

Strong hot plumes

30 km of thinning

Ra number for SSC (local Ra)

SSC onset time

Agrusta et al. GJI 2013

R. Agrusta PhD 2012
Bottom-up erosion of the lithosphere favored by partial melting in the asthenosphere?

- **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**

© C. Thoraval

Kohlstedt & Mackwell 2008
Viscosity reduction due to partial melting

- small-scale convection enhanced = more erosion

But... no melt extraction
Unrealistic instantaneous melt fractions - up to 40%

Anhydrous melting

\[ X_M = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \]

\[ T_{solidus} = 1085.7 + 132.9P - 5.1P^2 \]

\[ T_{liquidus} = 1780 + 45P - 2P^2 \]

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

R. Agrusta
PhD 2012
Rheology of a partially molten mantle

Which is the critical melt fraction for extraction & rheology?

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

Takei & Holtzman 2009
Instantaneous extraction of melt at a critical threshold (1%)

Depletion = cumulative melt production

Instantaneous melt fraction = $X_M - \text{depletion}$

\[
X_M = \frac{T - T_{\text{solidus}}}{T_{\text{liquidus}} - T_{\text{solidus}}}
\]

Depletion:
Changes density

Instantaneous melt fraction:
Changes viscosity

R. Agrusta
PhD 2012
Effect of melting on the composition (density) of the residue depletion in Fe = decrease in density = $F(\text{cummulated melting})$
Decrease in viscosity = $F(\text{instantaneous melt fraction})$
Thresholds for melt extraction = 1% & for viscosity decrease = 0.1%

200K plume; $V_p=7\text{cm/y}$

2 effects add up = earlier onset of small-scale convection

R. Agrusta – PhD 2012
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

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 alignment in the asthenosphere

On the role of anisotropic viscosity for plate-scale flow

T. W. Becker¹ and H. Kawakatsu²

Effect of melt-induced transverse anisotropy cannot be discriminated from an isotropic viscosity decrease in the asthenosphere
All observations in natural systems: shallow LABs <70 km depth! Partial melting is easy. Extrapolation to deeper depths?

The East African rift by B. Holtzman

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

Observations in natural systems:
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Models: coupling of deformation & melting => enhances upwelling of LAB anisotropy of viscosity => first results not conclusive

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