Rheological properties of the mantle lid beneath the Mojave from xenoliths

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Constraints from natural rocks on rheology

We can quantify several variables in the classic creep equation in natural rocks...

\[ \dot{\varepsilon} = A f_{H_2O} \sigma^n d^{-p} e^{\left(\frac{-Q}{RT}\right)} \]

**Tools**

- Deformation mechanisms -- microstructural analysis
- Pressure-temperature estimates -- thermobarometry
- Stress estimates -- paleopiezometry
- Water contents -- FTIR spectroscopy
- Strain rate estimates -- field observations + geochronological data
Application to the Cima volcanic field

Cima xenoliths include deformed mantle rocks sourced from beneath the Moho in the Mojave region...

- What can they tell us about the strength of the Mojave mantle lithosphere?

- How does this compare to post-seismic relaxation models of rheology from Landers and Hector Mine?

- How localized is the deformation in the Mojave mantle lithosphere?
Application to the Cima Volcanic field

Map modified from Frankel et al., 2010
Why Cima xenoliths?

- Youthful volcanism ranging from 13 to less than 1 Ma, with most vents less than 3 Ma
- Well constrained Moho depth from receiver functions

Zhu & Kanamori (2000), JGR
• Youthful volcanism ranging from 13 to less than 1 Ma, with most vents less than 3 Ma
• Well constrained Moho depth from receiver functions
• Existing data on upper mantle flow and rheology from post-seismic relaxation following Landers (1992) and Hector Mine (1999) EQ's
Crosscutting relationships among the xenoliths indicate that originally nonfeldspathic spinel peridotites were partly to pervasively infiltrated by melts, which crystallized plagioclase in anastomosing and planar networks and along grain boundaries. More than half of these infiltrated peridotites were penetratively deformed and dynamically recrystallized subsequent to melt infiltration (Wilshire, 1990). Both the spinel and plagioclase peridotites are in turn cross-cut by mostly undeformed and unmetamorphosed, cm-scale dikes of the green-pyroxene and Al-augite-- these represent recent magmatic infiltration and crystallization near the crust-mantle transition zone at and above the Moho.
Cr-diopside group

more strongly deformed, showing recrystallization of both olivine and orthopyroxene
Cr-diopside group
Timing of deformation in the xenoliths

Very recent, based on:

- evidence for large-scale mantle deformation from post-seismic relaxation
- high heat flow beneath Mojave and lack of evidence for annealing/ grain growth

Grain growth curve for conditions of Cima xenoliths

T = 950 C
P = 1.2 MPa
d0 = 50 μm
What can we do with the deformation fabrics?

Quantify the following:

- Deformation mechanisms -- microstructural analysis
- Pressure-temperature estimates -- thermobarometry
- Stress estimates -- paleopiezometry
- Water contents -- FTIR spectroscopy
- Strain rate estimates -- GPS constraints

focus is on xenoliths from just below the Moho
Deformation mechanism = dislocation creep
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P-T conditions of plagioclase-bearing xenoliths

From two-pyroxene thermometry

Temperature range in plagioclase-bearing xenoliths from Cima spinel

Range of possible geotherms estimated for Mojave region from Yang & Forsyth (2008)

minimum
intermediate
maximum

MOHO
Stress magnitude

\[ d = K \sigma^{-p} \]

Paleopiezometry

van der Wal et al., 1993

Stipp et al., 2002
Stress magnitude

deformed porphyroclast
recrystallized grains

Grain Size (µm)
dehomed porphyroclast
recrystallized grains

Recrystallized Grain Size

Subgrain Spacing
Stress magnitude at Moho = 12-15 MPa
Water contents

FTIR Spectroscopy

Example spectrum for olivine grain: area under the curve scales with water concentration
Putting it all together

- Deformation mechanism = dislocation creep
- Pressure-temperature conditions = just below the Moho (~30 km) at 920-960 C
- Stress magnitude = 12-15 MPa
- Water contents = ~300 H/Si
Is the Mojave lithosphere ‘jelly sandwich’ or ‘creme brulee’?

\[ \mu = 0.65, \lambda = 0.4 \]

\[ \mu = 0.3, \lambda = 0.8 \]

Brittle-ductile transition
Peak stress in upper mantle measured in Cima xenoliths
MOHO

Differential Stress (MPa)

Depth (km)

Burgman & Dresen (2006)

Behr & Hirth (in prep)
How does this compare to Mojave post-seismic relaxation studies?

**letters to nature**

**Evidence of power-law flow in the Mojave desert mantle**

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Mobility of continental mantle: Evidence from postseismic geodetic observations following the 1992 Landers earthquake

Fred F. Pollitz

Department of Geology, University of California, Davis
How does this compare to Mojave post-seismic relaxation studies?

*Thatcher and Pollitz, 2008*
How does this compare to Mojave post-seismic relaxation studies?

Thatcher and Pollitz, 2008

Mojave Moho over long time scales
Localization in the mantle lithosphere?

Surface strain rate can be estimated from geodesy

\[ \dot{\varepsilon} = \frac{dV}{dx} \]
Localization in the mantle lithosphere?

But where is the strain accommodated at depth?

Surface strain rate

\[ \dot{\varepsilon} = \frac{dV}{dx} \]

Strain rate at depth

\[ \dot{\varepsilon} = Af_{H_2O}O'' d^{-\nu} e \left( -\frac{Q}{RT} \right) \]
Strain rates in the mantle lithosphere

Surface strain rate = 1.3 x 10^{-15} /s

Strain rate in the mantle calculated from xenoliths = min. 5.8 x 10^{-14} /s

An order of magnitude higher than surface strain rates

At least one order of magnitude higher strain rates recorded in the upper mantle (most conservative estimate).
While both of these ideas are interesting and provocative, the former one is unlikely for several reasons.
Freed et al. (2007) found poor fits to post-seismic relaxation data when modeling a ductile extension of ECSZ faults.

While both of these ideas are interesting and provocative, the former one is unlikely for several reasons.
Faults localized from surface to depth likely doesn’t work...

Local anisotropy in Cima region is not parallel to active faults or plate boundary

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Summary

- Stress in the Mojave upper mantle is consistent with a ‘creme brulee’ model of lithospheric strength in which the mantle is weaker than the crust.
- Deformation is localized into a relatively narrow shear zone in the lithospheric mantle-- could possibly reflect localized shear beneath a megadetachment?

Future work

- Examining spinel-facies peridotites derived from deeper in the mantle - comparison to geophysical models of LAB depth and sharp velocity contrast across the LAB.
- Correlation between olivine fabrics and local anisotropy to constrain shear zone orientations.