Mechanics of intermediate and deep earthquakes: field and experimental evidences

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Thanks to:
@ ENS: Sarah Incel (U. Oslo), Thomas Ferrand (ERI), Julien Gasc, Damien Deldicque
@ Isterre Grenoble: Fabrice Brunet
@ UMET Lille: Nadège Hilairet
@ U. Besançon: Olivier Fabbri
@ Saint Louis U.: Lupei Zhu
@ GSECARS, Argonne II.: Feng Shi; Yanbin Wang
@ UC. Riverside: Harry W. Green II
Earthquakes at depth

Herbert Hall Turner, 1861-1930

Kiyoo Wadati, 1902 - 1995

Hugo Benioff, 1889-1968

Frohlich 1987
Earthquakes at depth

The Times of Transmission and Focal Depths of Large Earthquakes.
By Harold Jeffreys, M.A., D.Sc., F.R.S.

(Received 1927 September 17.)

8.1. First, we know definitely that the upper layers of the earth are strong enough to support the weight of the Himalayas and other great mountain ranges. On the other hand, the evidence of isostasy is clear that this strength is confined to a comparatively thin layer, and that at some distance down the materials are too weak to resist the stress-difference due to the weight of about 200 metres of uncompensated material. Barrell, when he put this view forward originally, suggested that the transition took place at a depth of about 300 km., and I was originally prepared on this ground to entertain Prof. Turner's theory.† But further work on the mechanism of isostasy has led me to the conclusion that Barrell's estimate was much too great. Difficulties about the production of compensation within a mountain range ‡ made me consider a lithosphere only 100 km. thick, and later one of 70 km. § A recent attempt || to use the conventional depth of compensation of geodesists to determine the thickness of the strong layer has shown that it is most probably about 30 km., agreeing with the thickness of the two upper layers of seismology. Thus if the focal depth exceeded this amount the focus would be in the asthenosphere.
There is a theoretical possibility which should be kept in mind. There is no thermodynamic reason why [polymorphic] transitions should not occur under shearing stress ... No examples of phenomena which have been positively identified as being of this character have yet been found . . .
Earthquakes at depth
MOTIVATION

The Okhotsk, May 24th 2013, Mw=8.3, 620km deep EQ

Ye et al. Science 2013
MOTIVATION

Link between Intermediate seismicity and slab hydration

Shillington et al. Ngeo 2015
MOTIVATION

Intermediate seismicity and slab hydration

Shillington et al. Ngeo 2015
MOTIVATION

Deep focus seismicity and metastable olivine

Kawakatsu and Yoshioka 2012
OLIVINE PHASE TRANSITIONS in the mantle transition zone

OLIVINE: $\text{Mg}_2\text{SiO}_4$
orthorhombic

And its high pressure form
RINGWOODITE: $\text{Mg}_2\text{SiO}_4$
cubic
PHASE TRANSITION MODEL

The Green model

Harry W. Green 1940-2017
PHASE TRANSITION MODEL

The Green model

Harry W. Green 1940-2017

Science Times
The New York Times
TUESDAY, APRIL 11, 1983
C1

Bolivia Shakes, and So Does Theory on Deep Quakes

By WILLIAM J. BROAD

Experts thought they had a pretty good idea of what caused deep earthquakes. These upheavals, which occur 300 to 400 miles below the earth's surface, are puzzling in that they ought to be impossible. The pressures and temperatures at that depth are so great that rock should undergo no fractional shifting, the weakest of garden-variety earthquakes near the surface. So most geologists gave to believe that the squeezing pressures and increasing heat below a certain depth caused the rock into forms that were suddenly denser, causing huge cracks that developed into big earthquakes.

No more. As extraordinary and big earthquakes 300 miles beneath Bolivia last June not only shattered records by piling crimes as far away as Toronto but also left the squeeze theory shaken.

A new analysis of shock waves from that earthquake, which had fault area was 30 miles long and 20 miles wide, too big to be explained by the leading theory. In fact, experts say, the quake bears a disturbing resemblance to big areas that occur near the earth's surface.

"It's embarrassing," said Dr. Paul G. Silver, a geologist at the Carnegie Institution of Washington who questioned the old theory. "It looks and acts and talks like these shallow earthquakes. But it shouldn't exist."

In place of the squeeze theory, Dr. Silver and his colleagues are proposing a new one that says that they say better its evidence gathered by global arrays of detectors that track subtle ground movements over great distances.

"Even if they're right about the size of the faulting, it's not dead," said Dr. Harry W. Green, a geologist at the University of California at Riverside. "Death knell is their favorite term. But that's greatly over-Continued on Page C9"
OUTLINE

• A frozen mantle EQ in the field
• HP experimental set-up
• Dehydrations and intermediate depth seismicity
• Deep focus EQ and the olivine transf.
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A frozen mantle EQ in Balmuccia, It.

Peridotite body exhumed along the Insubric line
A frozen mantle EQ in Balmuccia, It.

Peridotite body exhumed along the Insubric line

Modified from Quick et al. 2003
A frozen mantle EQ in Balmuccia, It.

Fault trace // to Insubric line, along the river, approx. 100m long
A frozen mantle EQ in Balmuccia, It.

1.2m horizontal offset, 5mm wide

Ferrand et al., JGR 2018
A frozen mantle EQ in Balmuccia, It.

PSZ – recrystallized olivine, but HT (>1200°C) fabric
Alumina spinel stable P>1.2GPa
Updip component to slip

Ferrand et al., JGR 2018
A frozen mantle EQ in Balmuccia, It.

Presence of fossil (hydrated) glass at the tip of injection veins
Close to 2w% H2O in the glass - Origin of water?

Ferrand et al., JGR 2018
A frozen mantle EQ in Balmuccia, It.

Energy balance reconstruction (from melt production and displacement)
Dynamic friction $<< 0.1$, Mw 6+

$$\eta = \frac{E_R}{E_{tot}} \approx 1 - \frac{Q_f}{E_{tot}}$$

$$\bar{\tau} = \frac{\rho \cdot [H + C_p \cdot \Delta T] \cdot w}{(1 - \eta) D}$$

and

$$\Delta \tau \approx (GD)^{3/2}/Mo^{1/2}$$

Ferrand et al., JGR 2018
A frozen mantle EQ in Balmuccia, It.

low viscosity (<10 Pa.s) melt

→ High strain rates and possible ultralocalization (Platt, Rudnicki and Rice, 2014)

-->melt injection may induce restrengthening

\[ f_d = \nu \frac{\dot{\gamma}}{\sigma_n} \]
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What is the role played by MINERAL transformations?

Deformation experiments at in-situ PT conditions
HP Deformation devices

Griggs, Heard, Paterson...

Multi-anvils in relaxation

Diamond-anvil cells

Deformation-DIA (mostly pure shear)

Rotational Drickamer (simple shear)
Experimental set-up

The DDIA – controlled pressure, stress and strain under HP-HT conditions

D-DIA
HP-HT + deviatoric stress

Sintered diamond rear-anvils (Debye rings)

**Experimental set-up**

The **Richter continuous acoustic recording system**

- 6 sensors in total (One behind each anvil - Possibility of AE location)
- Continuous acoustic recording (ie complete AE catalogue) + Triggered systems
- Focal mechanisms inversion

![Diagram of experimental set-up](image)
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Serp. peridotite dehydration under stress

Hot pressed San Carlos olivine + 5, 10, 20, 50 vol% Antigorite (Corsica)

Strain rate $= 5 \times 10^{-5}/s$; $dT/de \approx 1000$ AEs, even for 5% serp.

Ferrand et al., Nat. Comm 2017
Serp. peridotite dehydration under stress

Hot pressed San Carlos olivine + 5, 10, 20, 50 vol% Antigorite (Corsica)

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Ferrand et al., Nat. Comm 2017
Serp. peridotite dehydration under stress

Corner frequency $f_c \approx V_r/L$

$V_r \approx 4\text{km/s}$

$\Rightarrow L \approx 2\text{mm}$
Serp. peridotite dehydration under stress

SEM (Backscattered) evidence of HP-faulting

Ferrand et al., Nat. Comm 2017
Serp. peridotite dehydration under stress

TEM – fault zone nanostructure

Ferrand et al., Nat. Comm 2017
Serp. peridotite dehydration under stress

TEM – fault zone nanostructure
Serp. peridotite dehydration under stress

TEM – evidence of melting?
Serp. peridotite dehydration

Dehydration stress transfer model

Ferrand et al., Nat. Comm 2017
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Ge-olivine-spinel transition

Sintered Mg$_2$GeO$_4$ – 30µm grain size
Effective mean stress $(\sigma_1{+}2\sigma_3)/3 = 4\text{GPa }{+/-}0,25$
Strain rate $= 10^{-4}/\text{s}$

Stress – strain curve

Schubnel et al. Science 2013
Ge-olivine-spinel transition

Two complete AE catalogues
D1247 Effective mean stress \((\sigma_1+2\sigma_3)/3 = 4\text{GPa} +/-0,25\)
D1253 Effective mean stress \((\sigma_1+2\sigma_3)/3 = 5\text{GPa} +/-0,25\)
Strain rate = \(10^{-4}/\text{s}\)

Sonification:
courtesy to Ben Holtzman
LDEO, U. Columbia NY
Visiting prof. ENS 2015

Schubnel et al. Science 2013
Ge-olivine-spinel transition
Correlating X-ray tomography and AE locations

Double difference relocation (Waldhauser and Ellsworth 2000)

Wang et al., Sci. Ad. 2017
Ge-olivine-spinel transition
Correlating X-ray tomography and AE locations

Wang et al., Sci. Ad. 2017
Ge-olivine-spinel transition
Nano-seismicity time-series analysis
(template matching of continuous wfms)

Wang et al., Sci. Ad. 2017
Ge-olivine-spinel transition
Nano-seismicity time-series analysis
(after template matching of continuous wfms)

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Ge-olivine-spinel transition
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Wang et al., Sci. Ad. 2017
Ge-olivine-spinel transition

Microstructure - Sintered Mg$_2$GeO$_4$ – 30µm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10$^{-4}$/s
Ge-olivine-spinel transition

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Ge-olivine-spinel transition

Microstructure - Sintered Mg$_2$GeO$_4$ – 30$\mu$m initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10$^{-4}$/s
Ge-olivine-spinel transition

Microstructure - Sintered Mg$_2$GeO$_4$ – 30µm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10^{-4}/s
Ge-olivine-spinel transition

Microstructure - Sintered Mg$_2$GeO$_4$ – 30µm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = $10^{-4}$/s

FIB Section
Ge-olivine-spinel transition

Microstructure - Sintered Mg$_2$GeO$_4$ – 30µm initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = 10$^{-4}$/s

≈ XRPD of spinel phase

≈ 100nm thick
Shear strain ≈ microns
>>
Volumetric strain ≈ 10nm
Ge-olivine-spinel transition

Microstructure - Sintered $\text{Mg}_2\text{GeO}_4$ – 30$\mu$m initial grain size
Effective mean stress = 5GPa +/-0.25, Strain rate = $10^{-4}$/s

Fully crystalline, no melt!
Ge-olivine-spinel transition

Frictional sliding?

Shear heating: w/o diffusion:

$$\Delta T = f \sigma_n D / (h \rho c)$$

$5 \times 10^9 \text{Pa}$

$3 \times 10^{-6} \text{m}$

$100 \times 10^{-9} \text{m}$

$3 \times 10^6 \text{Pa/K}$

$f \approx 0.01$, $\Delta T = 6000 \degree \text{C}$

Shear heating: w diffusion:

$$\Delta T = f \sigma_n D / (\rho c \sqrt{\pi kt})$$

$10^{-6} \text{m}^2/\text{s}$

$f \approx 0.1$, $\Delta T = 6000 \degree \text{C}$

This is neglecting latent heat $\Delta rH$ (transformation is exothermic)
Ge-olivine-spinel transition

So what mechanism? Superplastic flow for olivine?

\[ \dot{\varepsilon} = \Lambda \sigma^n d^p \]

\[ n \approx 2.3 \text{ and } p \approx -1.5 \]

10^{-5}s^{-1} at 1500 K and 20 MPa

In our experimental conditions,

\[ \sigma \approx 5.10^9\text{Pa}, \quad d \approx 10\text{nm} \text{ yields } \dot{\varepsilon} \approx 10^4\text{s}^{-1} \]

*Hiraga et al, Nature 2010*
But what becomes that energy budget, if above a given pressure or temperature (that of the reaction) the system liberates / consumes mineral heat or work?
Olivine $\alpha \rightarrow \gamma$

$\Delta rH \approx -50-500 \text{ MJ/m}^3$

For comparison, the fracture energy of Tohoku EQ $\approx 30-60 \text{ MJ/m}^2$ Fulton et al. 2014
Conclusions

- Energy balance of a deep lithospheric EQ (Mw 6+) can be unraveled in Balmuccia, It. Dynamic friction <<0.1, role of injection veins in re-strengthening. Recrystallized ol. is a marker of the afterslip (Ferrand et al. JGR 2018).

- During dehydration of partially serpentinized San Carlos olivine under stress, “dehydration embrittlement” was observed for serpentine ratio as low as 5% (@ 1 GPa), and as high as 50% (@ 3 GPa), including within ΔV<0. Dehydration stress transfer model (Ferrand et al. Nat. Com., 2017)

- During Ge-olivine – spinel phase transformation under stress, faults propagate dynamically (rapid enough to radiate AEs) – NO FLUIDS! Evidence of a nucleation phase (Wang et al. Sci. Ad, 2017)
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• Similar experimental observations during:
  - Qz-Coes transformation
  - Eclogitization of CO and CC:
    Blueschist under stress: glaucophane breakdown → Omphacite (Incel et al. EPSL 2017)
    Dry granulites: Ab-An breakdown (Shi et al., Nat. Comm. & Incel et al., Geology, under rev.)! UWP and deep continental Eqs.
  - OPx – HP-CPx (Shi et al., AGU 2018), EQs nests at 200-300km depth like Bucaramanga?
Mineral transformation not to be neglected in the overall energy balance, because reactions are:

1) heat sinks or source
2) pressure sink or source
3) produce extremely fine grain-size – weak material and
4) possible stress transfer

(LARGE AMOUNTS OF) FLUIDS ARE NOT NEEDED!