Reaction-Induced Shearing Instabilities in High-Pressure Silicates, Germanates & Titanates: Implications for the Mechanics of Deep Earthquakes

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Outline

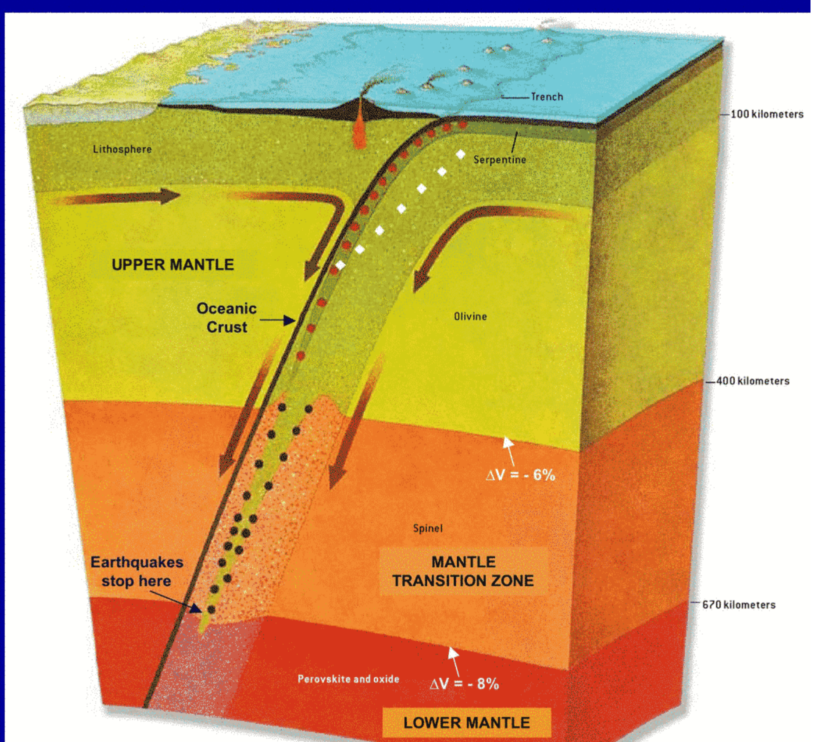
- Introduction
- Mode I features are key to shearing instability
- High-pressure shearing instabilities
  - Pore-pressure-induced faulting (Mode I cracks only)[1]
  - Transformation-induced faulting (Mode I cracks or anticracks)[2,3]
  - Dehydration of hydrous phases (Mode I cracks and anticracks)[4]
- Brief application to subduction zones

[1] Zhang, J., H.W. Green, K.N. Bozhilov, Z-M Jin, 2004. *Nature* **428**:633-636.
[2] Green, H. W., II and P. C. Burnley. 1989. *Nature* **341**:733-737.
[3] Green, H. W., II, T. E. Young, D. Walker and C. H. Scholz. 1990. *Nature* **348**:720-722.
[4] Jung, H., H.W. Green, II, L.F. Dobrzhinetskaya 2004. *Nature* **428**:545-549.

Introduction

- Brittle fracture/frictional sliding is limited to the upper ~30-50 km of Earth.
- Nevertheless, earthquakes occur to ~700 km in subduction zones and stop abruptly at the base of the upper mantle.
- Experiments show that generation of small amounts of low-viscosity "fluid" are required for failure at high pressure.
- The "fluid" can be a polycrystalline solid if it is superplastic at seismic strain rates
- In either case, P- and T- induced mineral reactions are central to enabling earthquakes at depth.

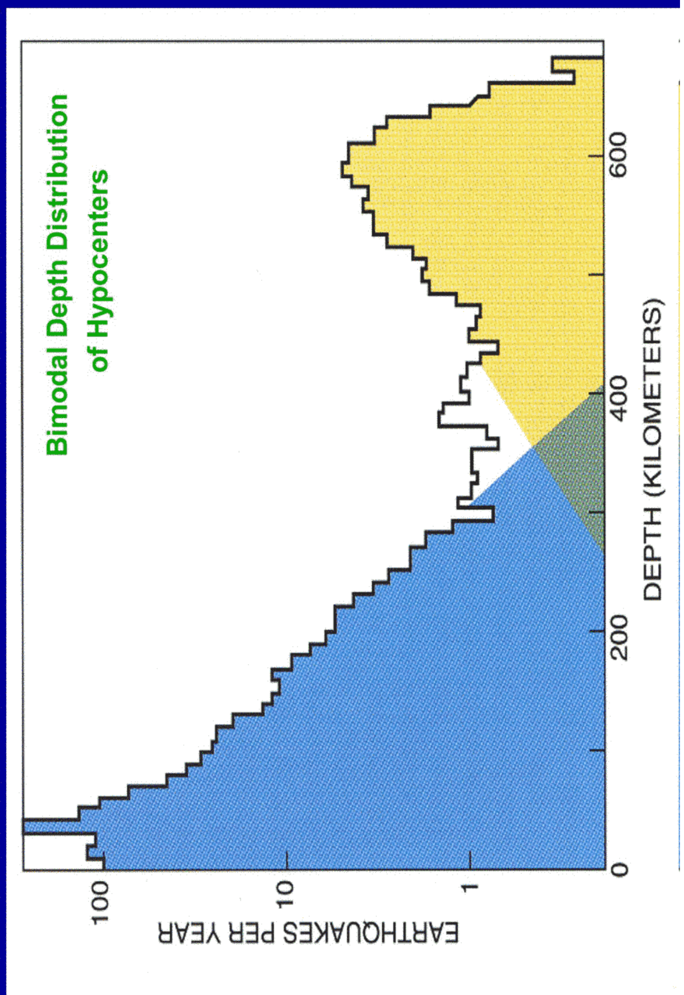
MANTLE PETROLOGY AND EARTHQUAKE SPATIAL DISTRIBUTION IN SUBDUCTION ZONES



(after Green, 2005)

EARTHQUAKE DEPTH DISTRIBUTION

After Frohlich (1989)



Earthquakes at Depth

- Like shallow earthquakes, those at depth involve movement across a fault.
- However, many observations suggest that subduction zone earthquakes involve breaking of virgin rock.
- Therefore, self-organizing failure mechanisms are probably necessary.
- We therefore start with analysis of brittle shear failure

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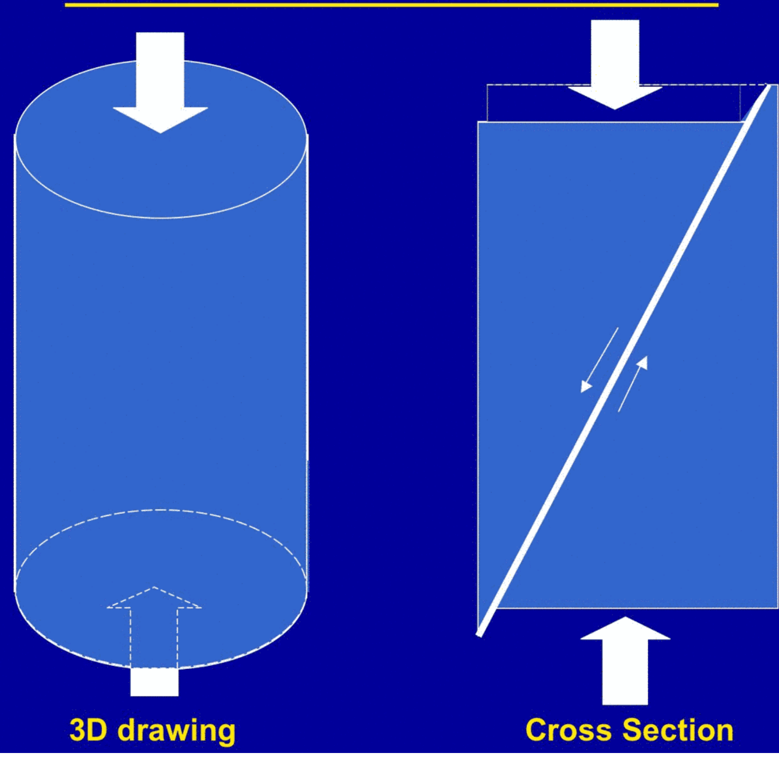
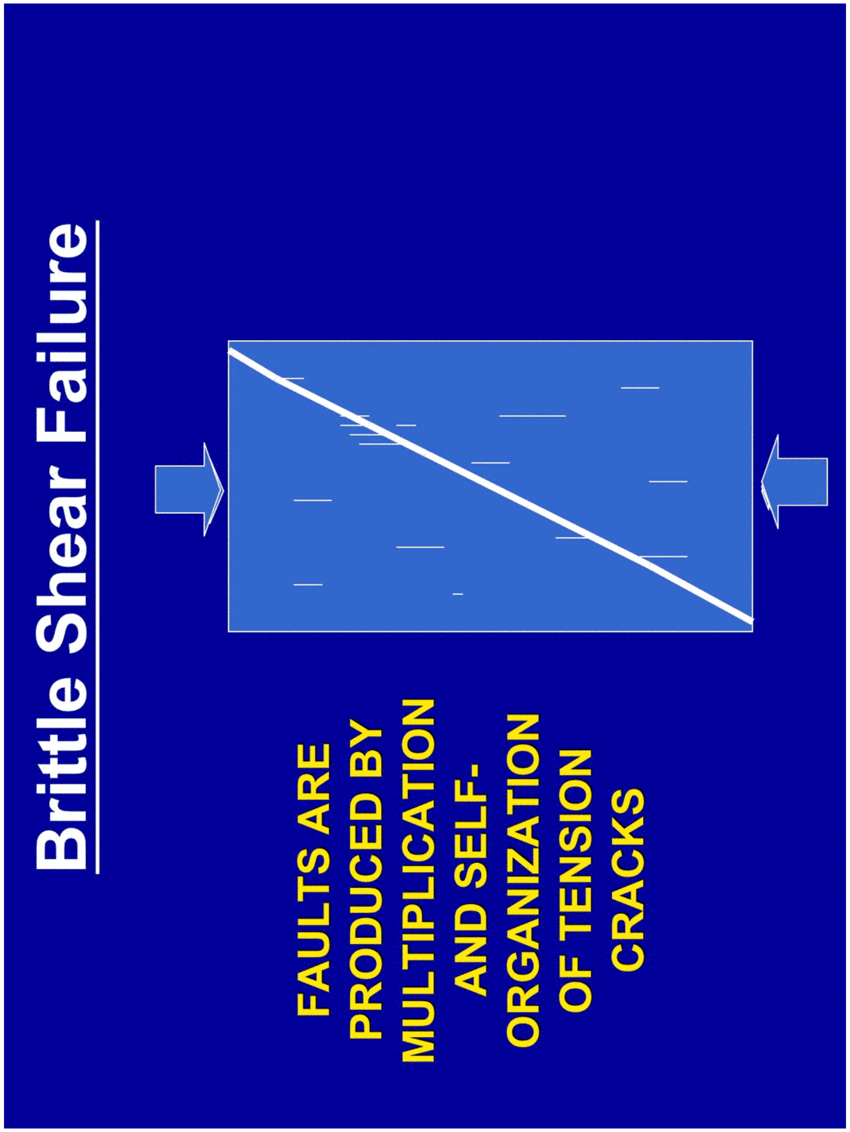
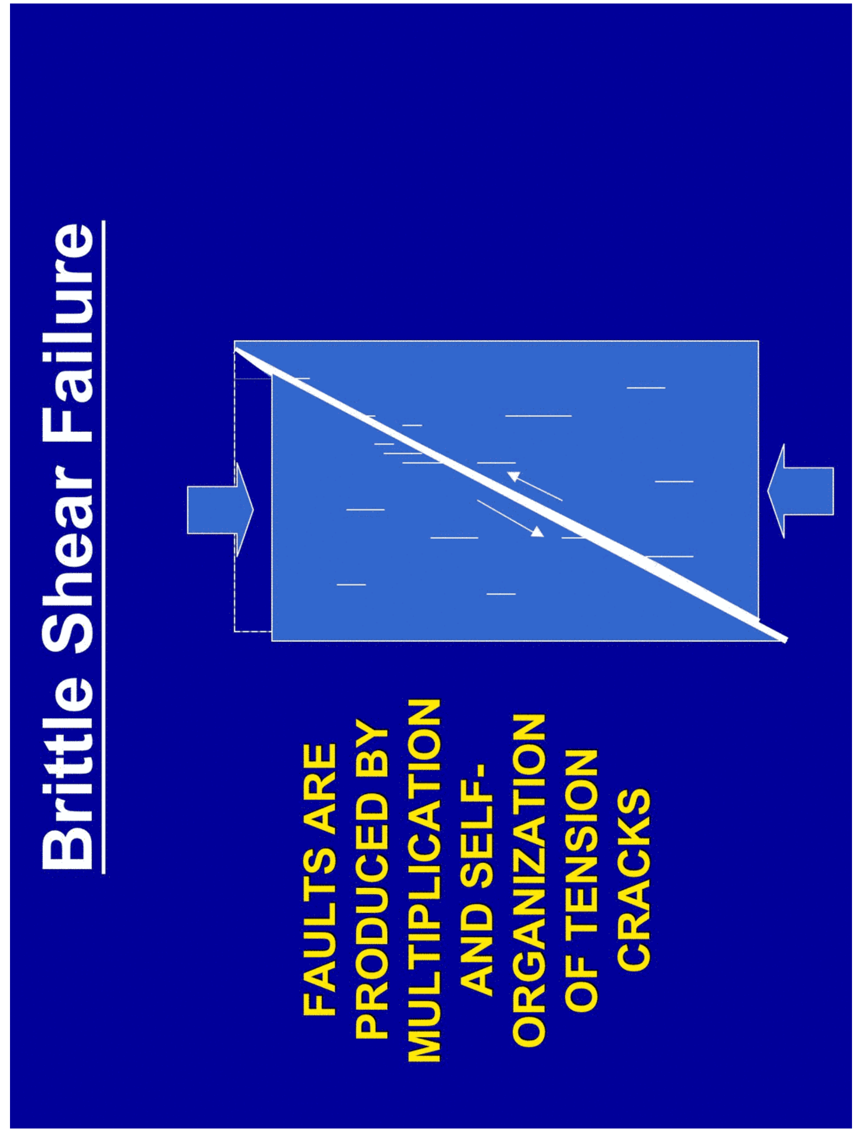
Brittle Shear Failure




Brittle Shear Failure
FAULTS ARE PRODUCED BY MULTIPLICATION AND SELF-ORGANIZATION OF TENSION CRACKS


Brittle Shear Failure
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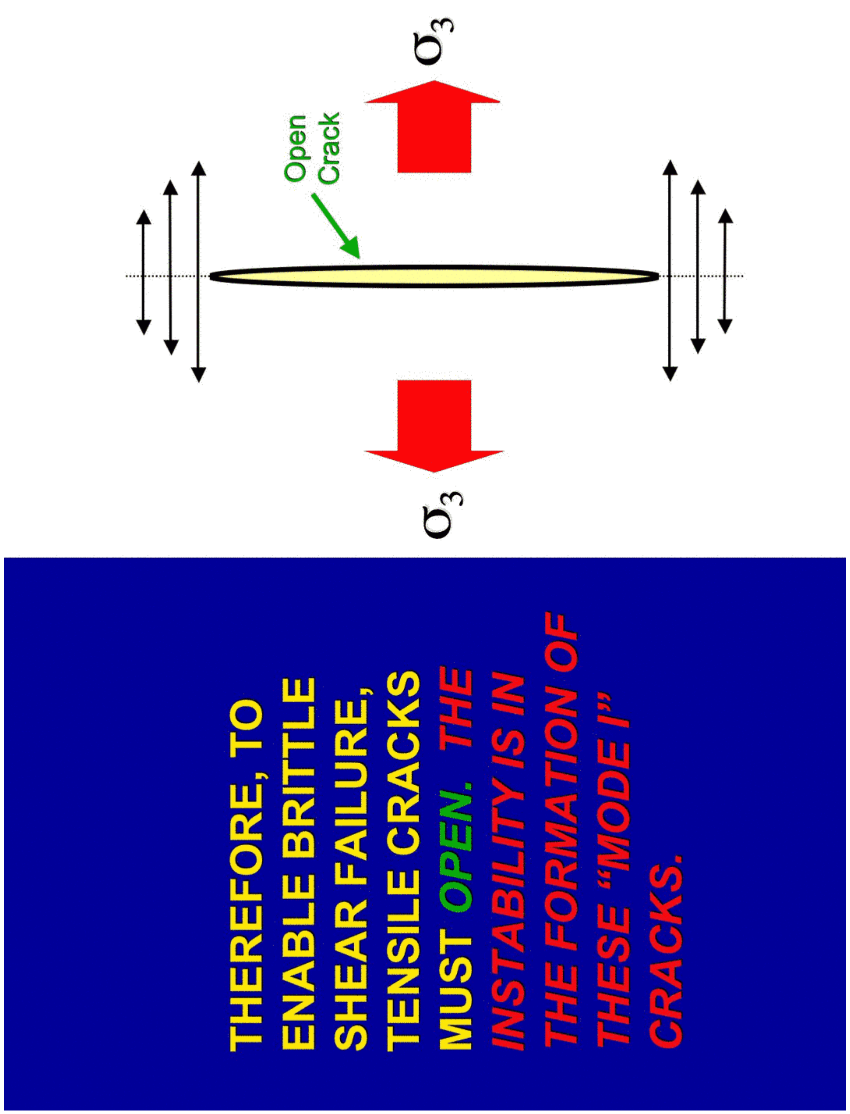
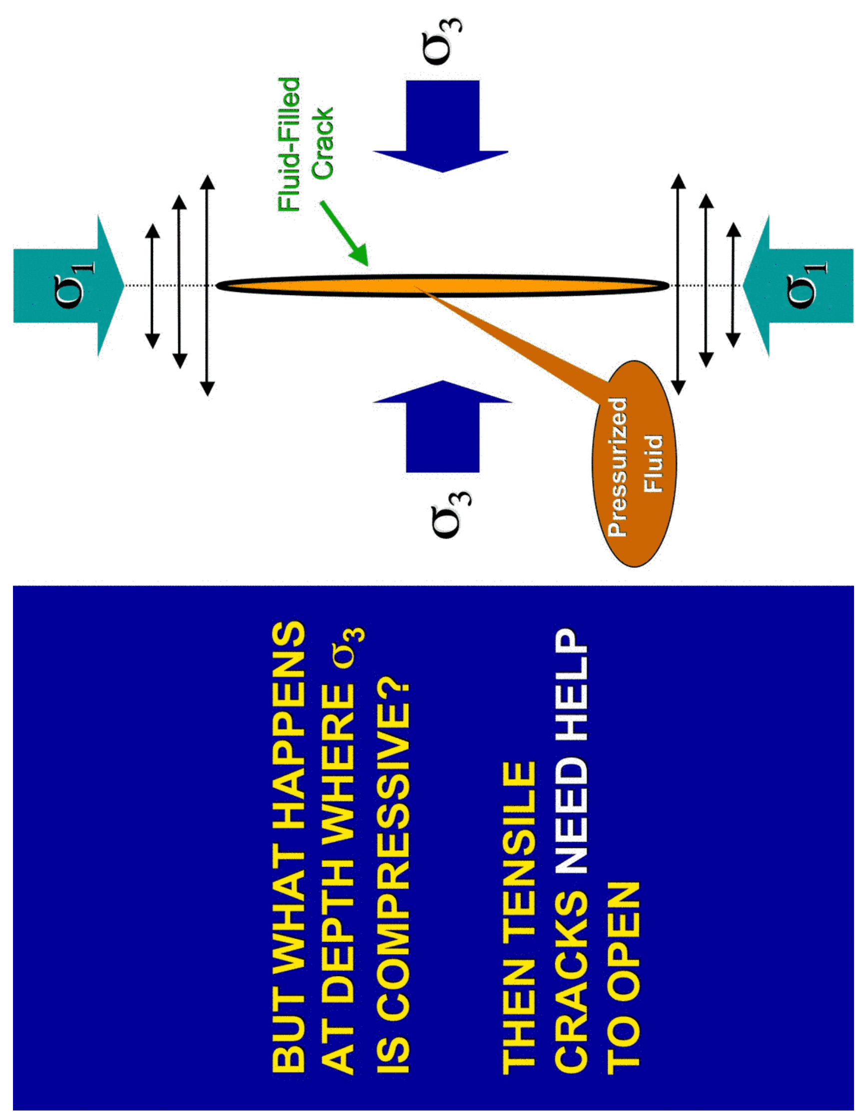
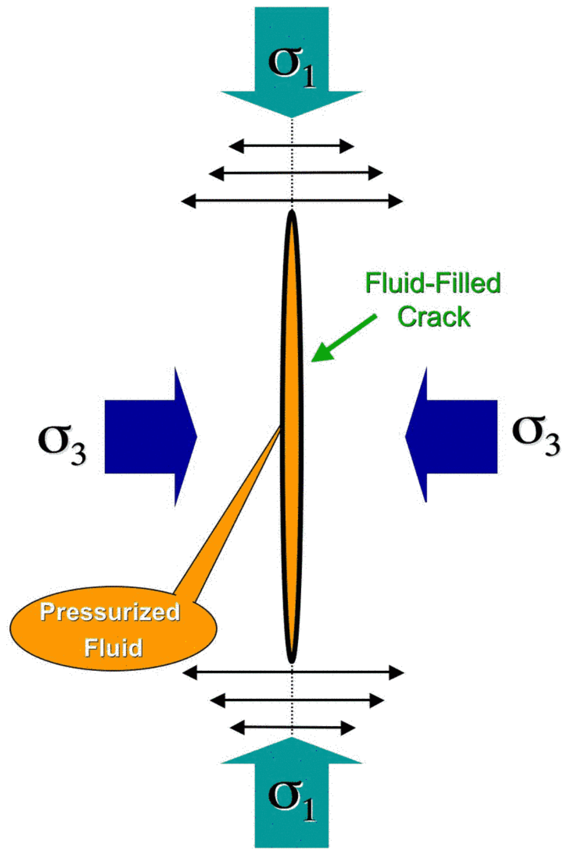

THEREFORE, TO ENABLE BRITTLE SHEAR FAILURE, TENSILE CRACKS MUST OPEN. THE INSTABILITY IS IN THE FORMATION OF THESE "MODE I" CRACKS.
σ_3
σ_3
Open Crack


BUT WHAT HAPPENS AT DEPTH WHERE σ_3 IS COMPRESSIVE?
THEN TENSILE CRACKS NEED HELP TO OPEN
σ_3
σ_3
σ_1
σ_1
Fluid-Filled Crack
Pressurized Fluid

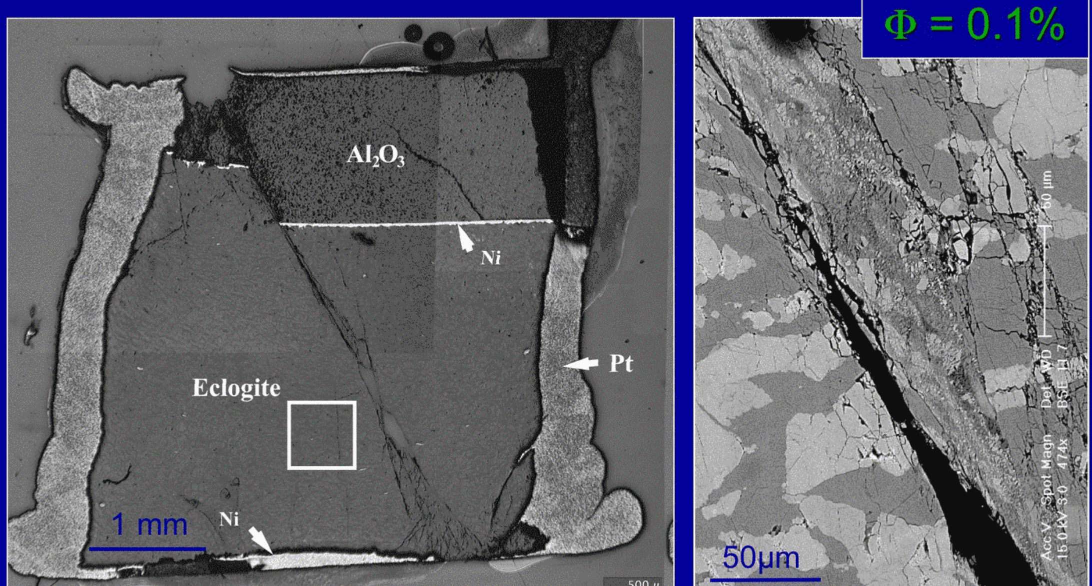
BUT WHAT HAPPENS AT DEPTH WHERE σ_3 IS COMPRESSIVE?

THEN TENSILE CRACKS NEED HELP TO OPEN



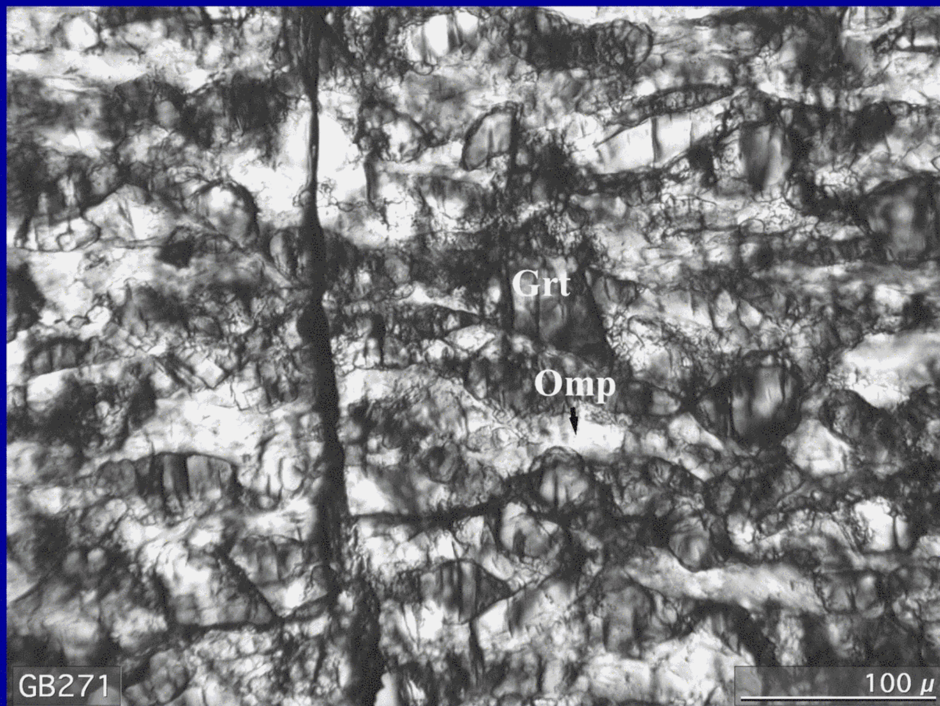
Faulting Associated with Melting at High Pressure

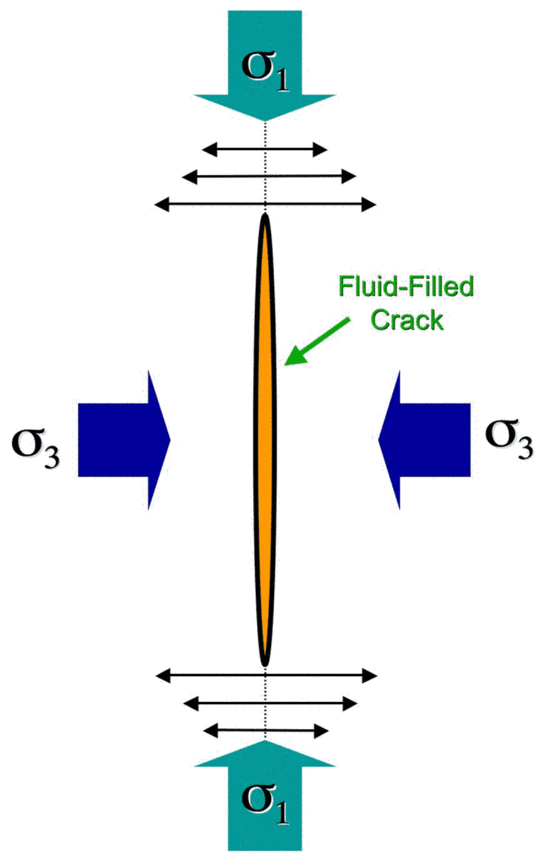
P = 3 GPa
Φ = 0.1%



Current PhD Dissertation Project (Zhang et al., *Nature*, 2004)

GLASS-FILLED MODE I CRACKS





In addition to a pre-existing pore pressure enabling cracks to open, a dehydration reaction can cause a fluid-filled Mode I crack to form spontaneously under stress by rapid-fire bubble nucleation

INSTABILITY

- Once again, the instability is in the formation and self-organization of the Mode I features.

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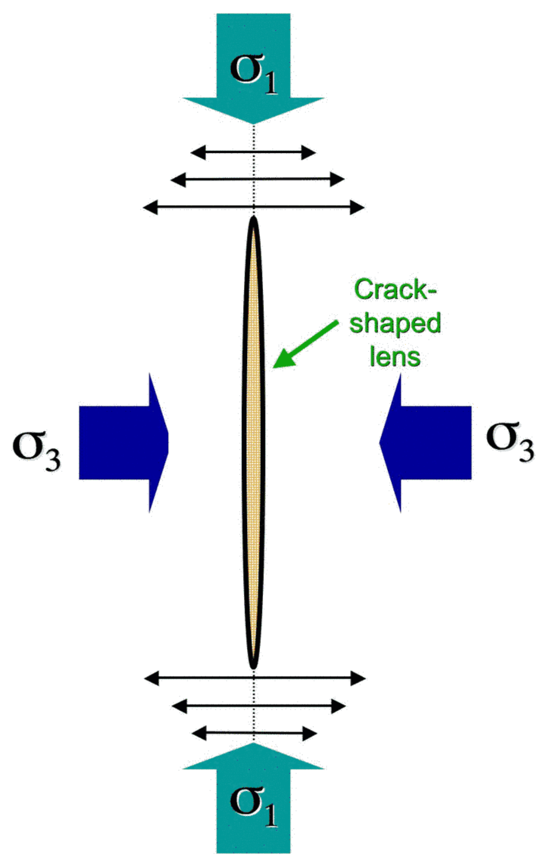
TRANSFORMATION-INDUCED FAULTING

- What if the new phase is a solid instead of a fluid?
- Same story if the nucleation rate is fast enough and $\Delta V > 0$.
- Example: $CdTiO_3$ perovskite → ilmenite

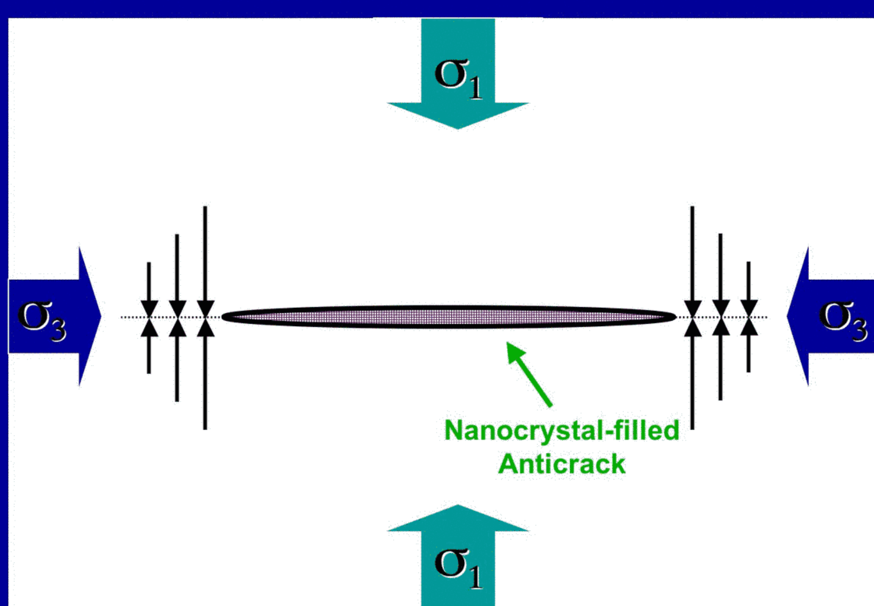
A solid-state reaction with $\Delta V>0$ can yield a crack-shaped Mode I lens under stress spontaneously by rapid-fire nucleation



TRANSFORMATION-INDUCED FAULTING

- What if $\Delta V < 0$?
- Same story if the nucleation rate is fast enough, but the lenses form normal to σ_1 rather than parallel, resulting in Mode I anticracks.
- Example: olivine → spinel

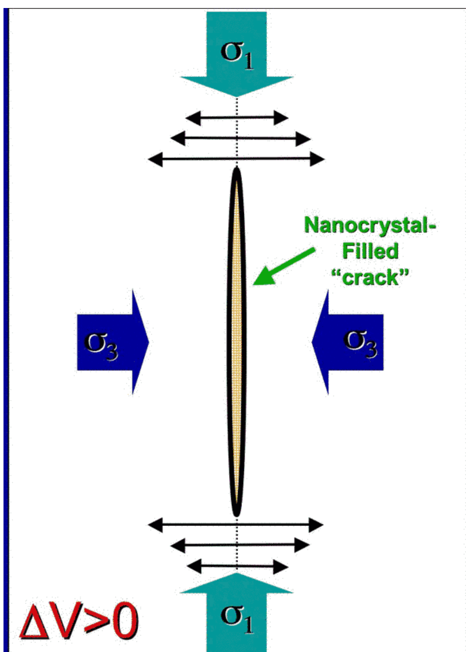
WHAT ARE ANTICRACKS?

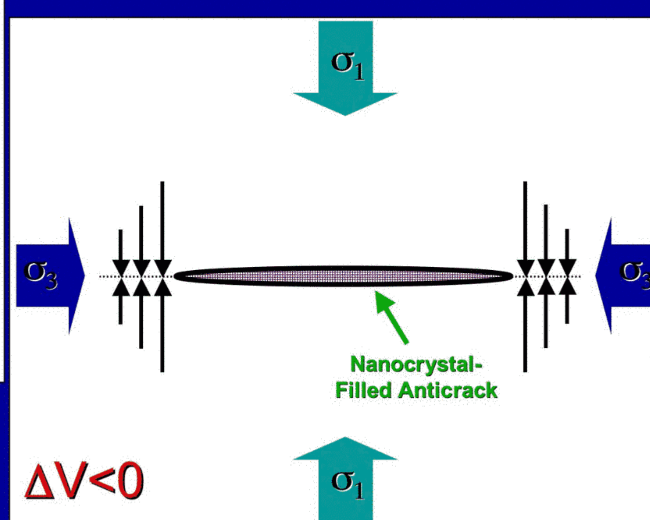


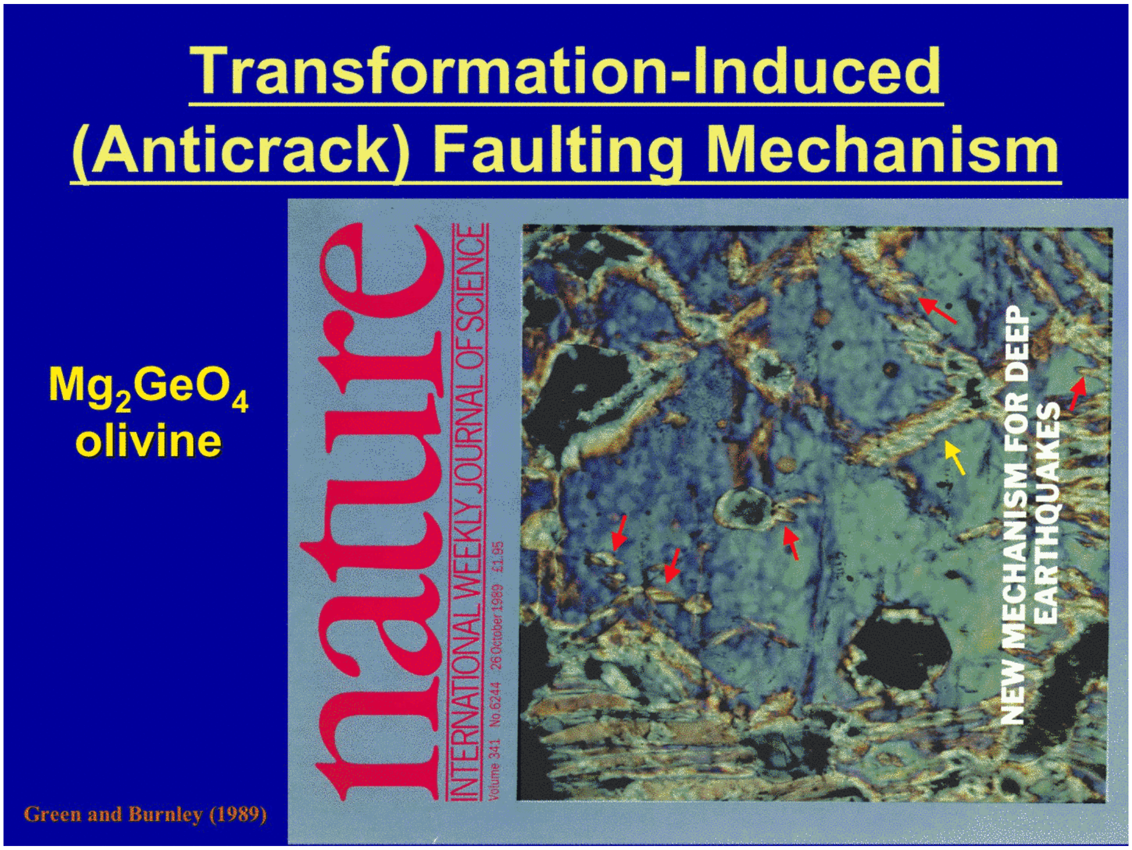
How do anticracks & cracks differ?

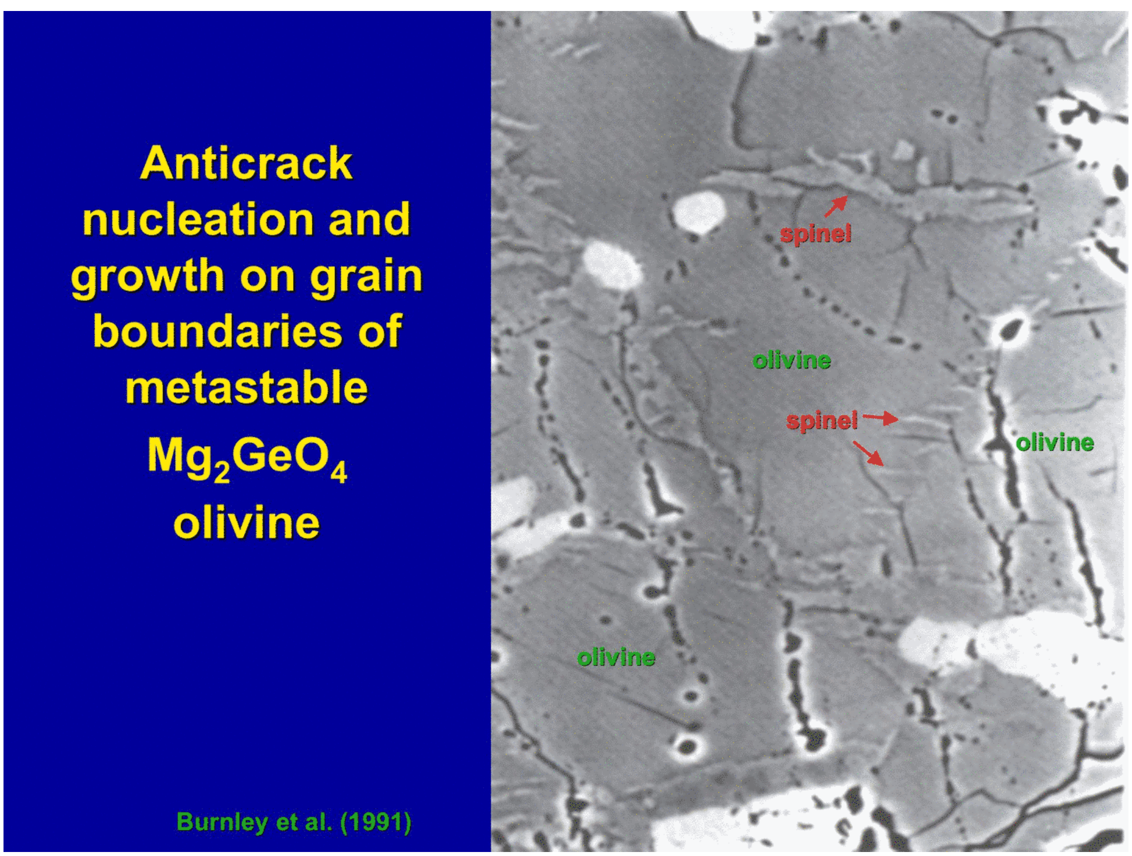
- Both are Mode I -- the displacements are perpendicular to the plane of the feature.
- However, in cracks, $\Delta V>0$ so displacements are outwards and dev. stress at tips is tensile; in anticracks, $\Delta V<0$ so displacements are inwards and dev. stress at tips is compressive.

ANALOGY BETWEEN CRACKS AND ANTICRACKS

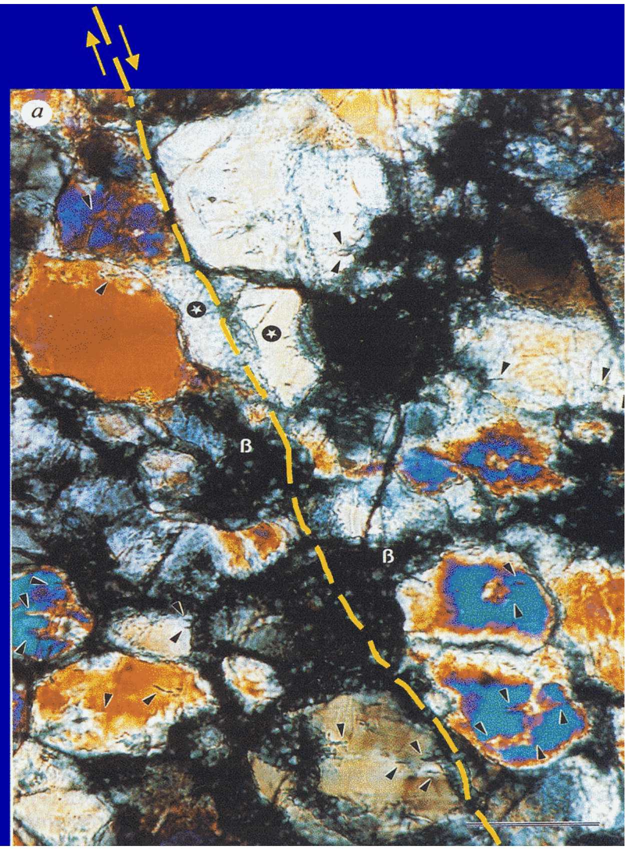





Transformation-Induced
(Anticrack) Faulting Mechanism
Mg_2GeO_4
olivine
nature
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Volume 341 No.6244 26 October 1989 £1.95
NEW MECHANISM FOR DEEP
EARTHQUAKES
Green and Burnley (1989)


Anticrack
nucleation and
growth on grain
boundaries of
metastable
Mg_2GeO_4
olivine
spinel
olivine
spinel
olivine
olivine
Burnley et al. (1991)

TRANSFORMATION-INDUCED FAULTING IN MANTLE OLIVINE -- $(Mg,Fe)_2SiO_4$ -- AT 14 GPa (~450 km)



Arrowheads point to anticracks

Green et al., *Nature* (1990)

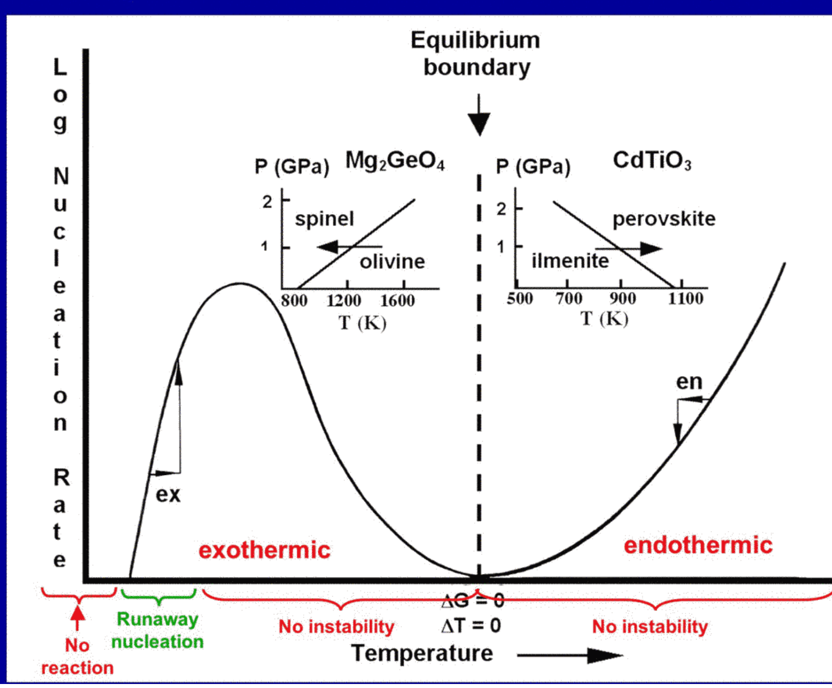
Why do anticracks self-organize?

- Just like open cracks and fluid-filled cracks, they talk to each other through the long-range stresses at their tips.
- The only difference is that the stresses are compressive rather than tensile.
- In both cases, self-organization deposits the “fluid” in the Mode I features into the growing fault zone, providing lubricant.
- The latter is analogous to the void space created by opening of cracks; that void space is available during frictional sliding after fault initiation.

Anticracks require an exothermic polymorphic transformation. Why?

- Runaway nucleation is required to yield the nanocrystalline filling of anticracks that enables fluid behavior and leads to crack-shaped lenses.
- What produces runaway nucleation?
- What special conditions are required?
- Is there a seismic signal during faulting?

Nucleation Kinetics in Polymorphic Phase Transformations

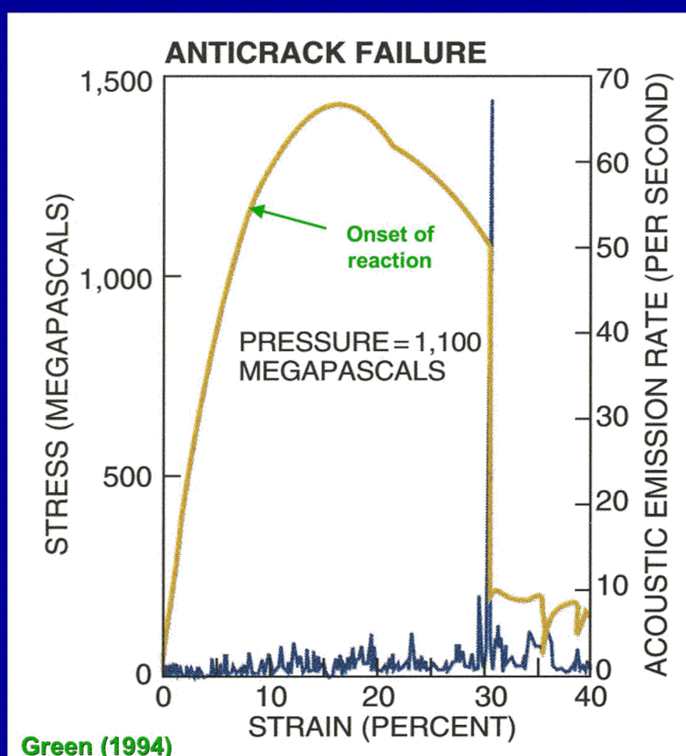


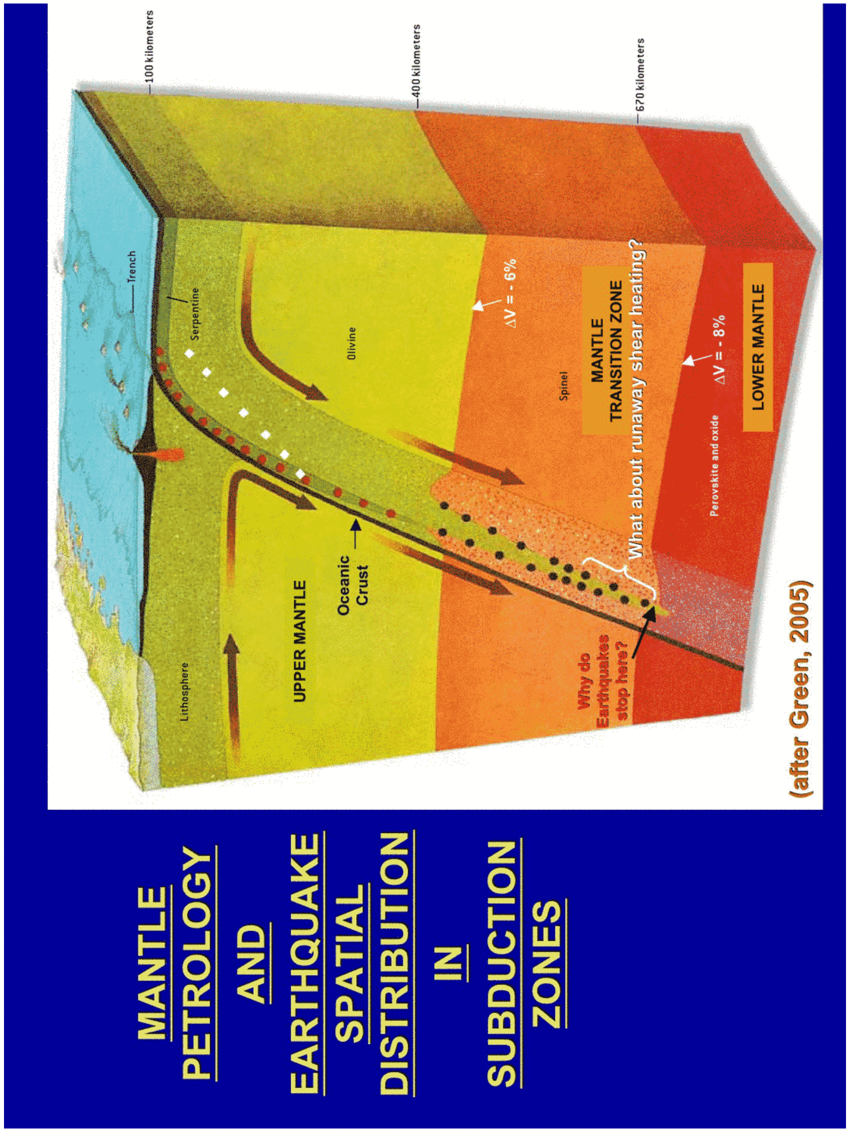
But why did I say the reaction had to be a polymorphic transformation?

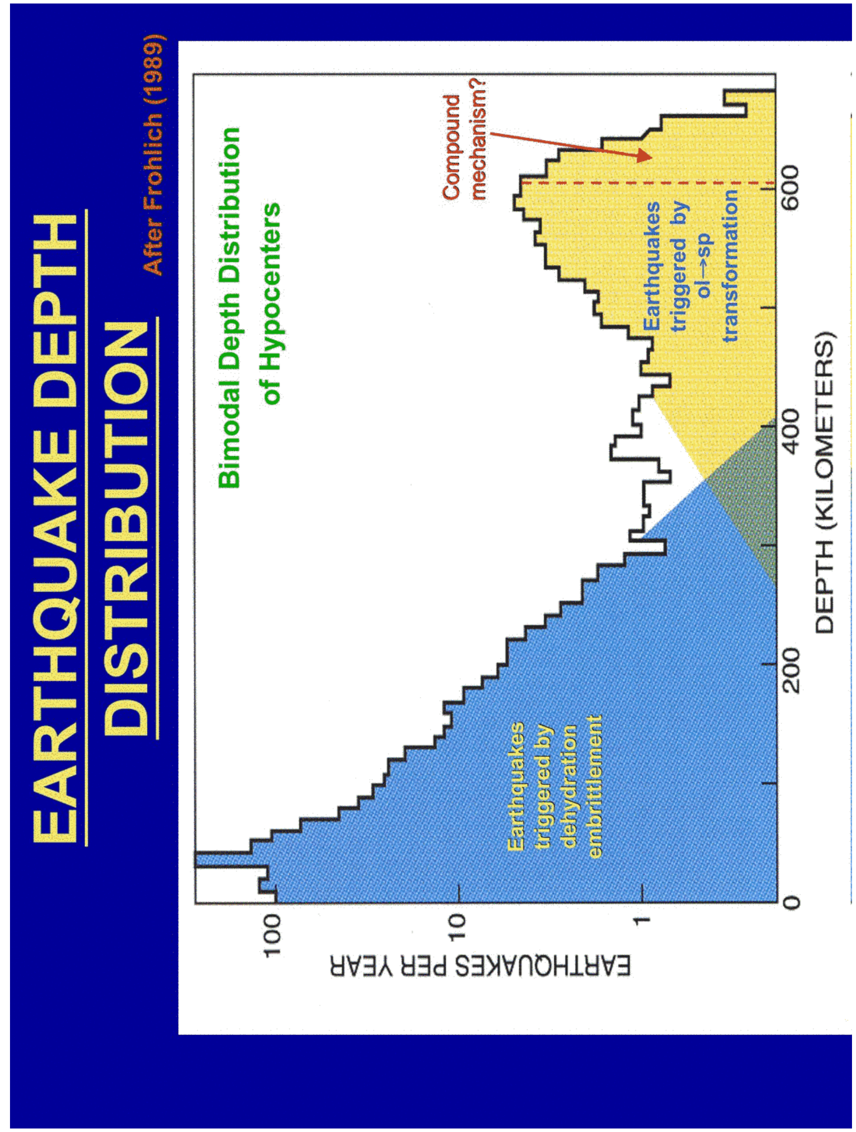
Because if two phases are involved as either reactant or product, the diffusive step to combine or separate components kills the runaway nucleation.

We demonstrated this using the decomposition reaction: Albite → Jadeite + Coesite, which has a v. large negative ΔV and is strongly exothermic.

ACOUSTIC EMISSIONS ACCOMPANYING ANTICRACK FAILURE




MANTLE PETROLOGY AND EARTHQUAKE SPATIAL DISTRIBUTION IN SUBDUCTION ZONES
100 kilometers
400 kilometers
670 kilometers
Trench
Serpentine
Olivine
Spinel
Lithosphere
UPPER MANTLE
Oceanic Crust
MANTLE TRANSITION ZONE
Perovskite and oxide
LOWER MANTLE
ΔV = - 6%
ΔV = - 8%
What about runaway shear heating?
Why do Earthquakes stop here?
(after Green, 2005)


EARTHQUAKE DEPTH DISTRIBUTION
After Frohlich (1989)
Bimodal Depth Distribution of Hypocenters
Compound mechanism?
Earthquakes triggered by ol→sp transformation
Earthquakes triggered by dehydration embrittlement
EARTHQUAKES PER YEAR
100
10
1
0
200
400
600
DEPTH (KILOMETERS)


Summer Solstice Eve in the
Western Norway UHPM Terrane
06.23.2003

The End