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Strength contrast between plagioclase and olivine and its significance on rheological structure of Earth and Venus

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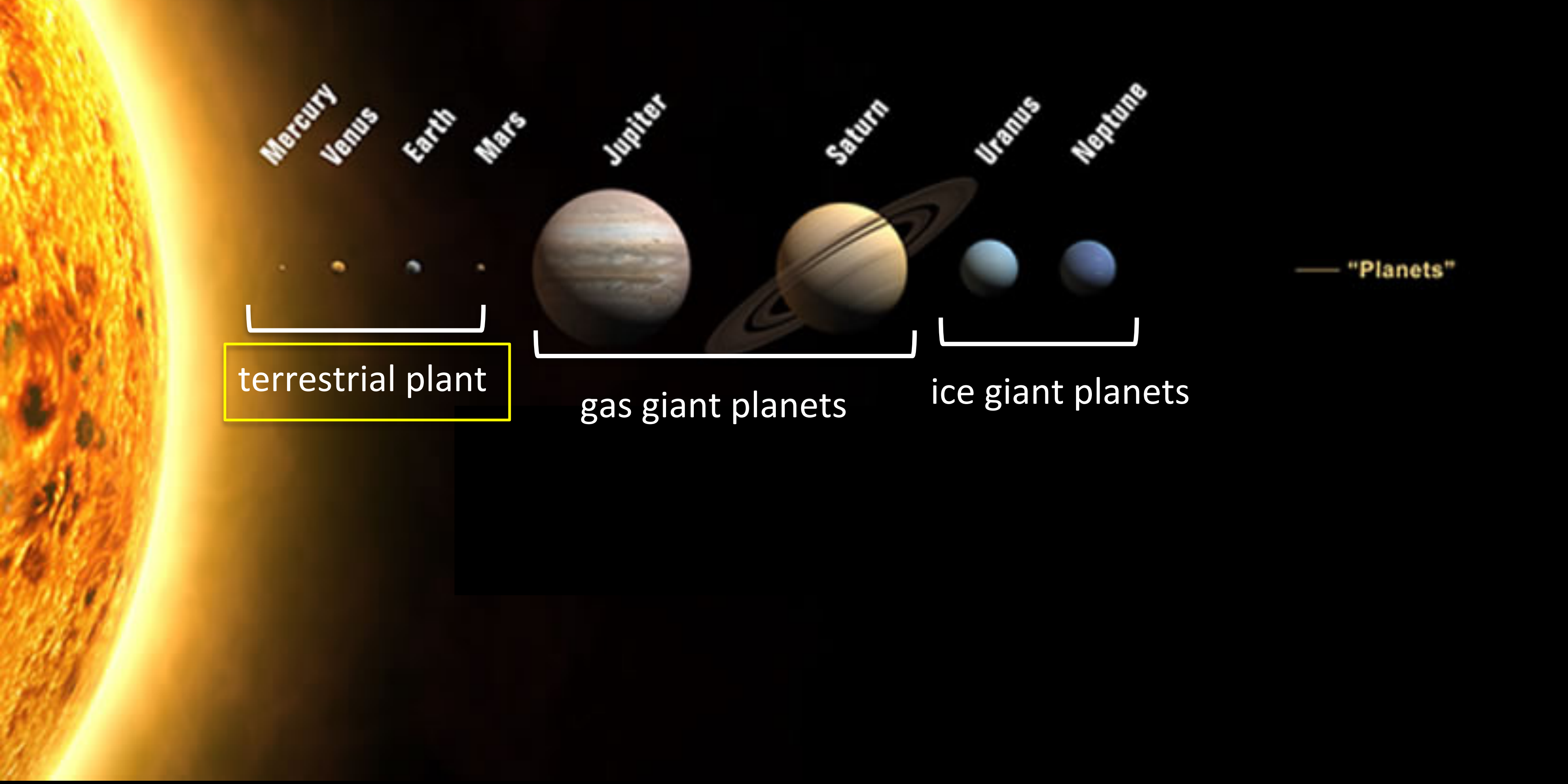
- Solar system

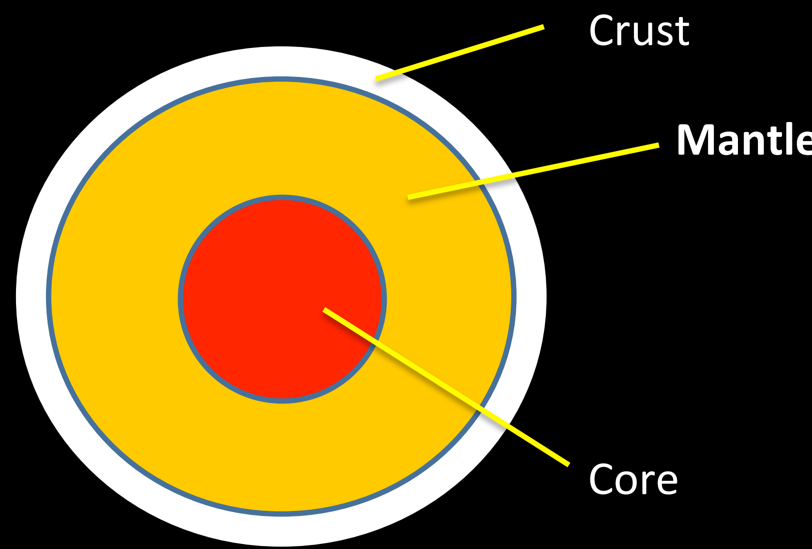


Terrestrial planet : These planets are composed mainly of rock and metal. In solar system, Earth, Venus, Mercury, Mars correspond to this kind of planet.

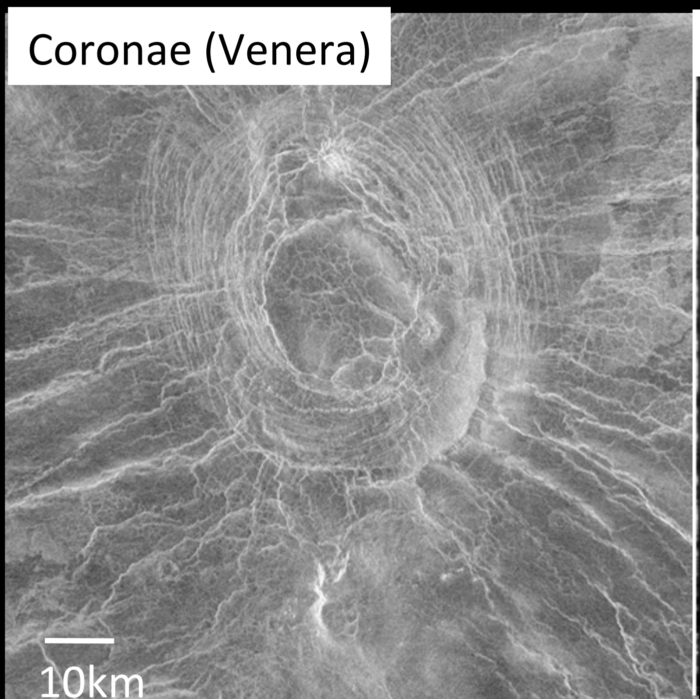
Gas giant planets : On this type of planet, the core that composed of refractory substance is surrounded by liquid or gas of hydrogen and helium

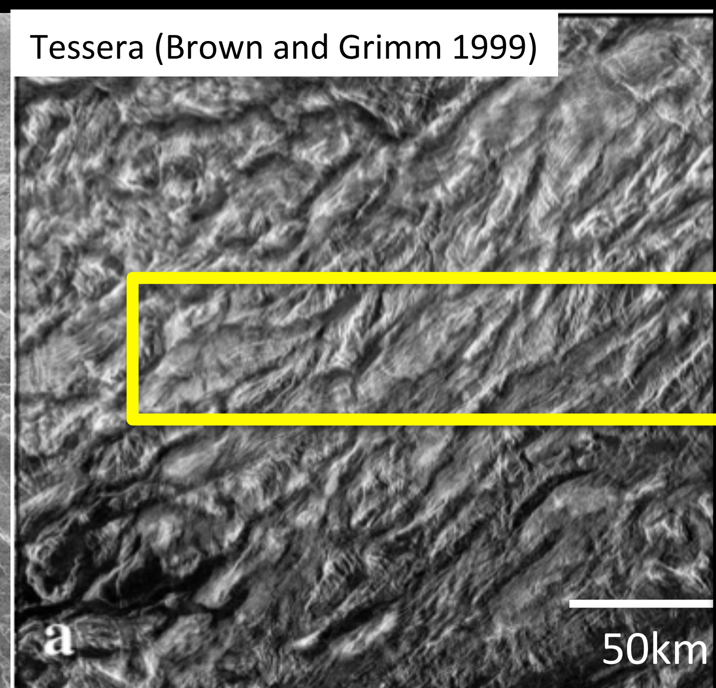
Ice giant planets : These planets are based on clotted ice of water, methane, ammonium.

• Earth and Venus …twin planets!?



Because of density, mass, size and distance from the Sun,
Venus has been regarded as a “twin planet” with the Earth.



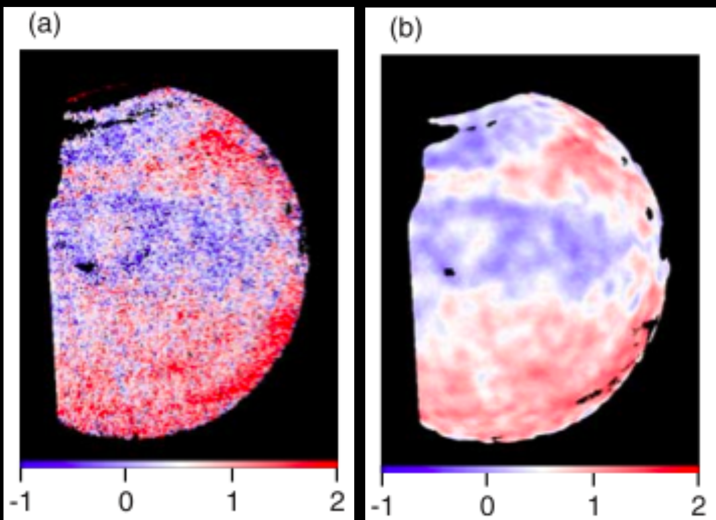


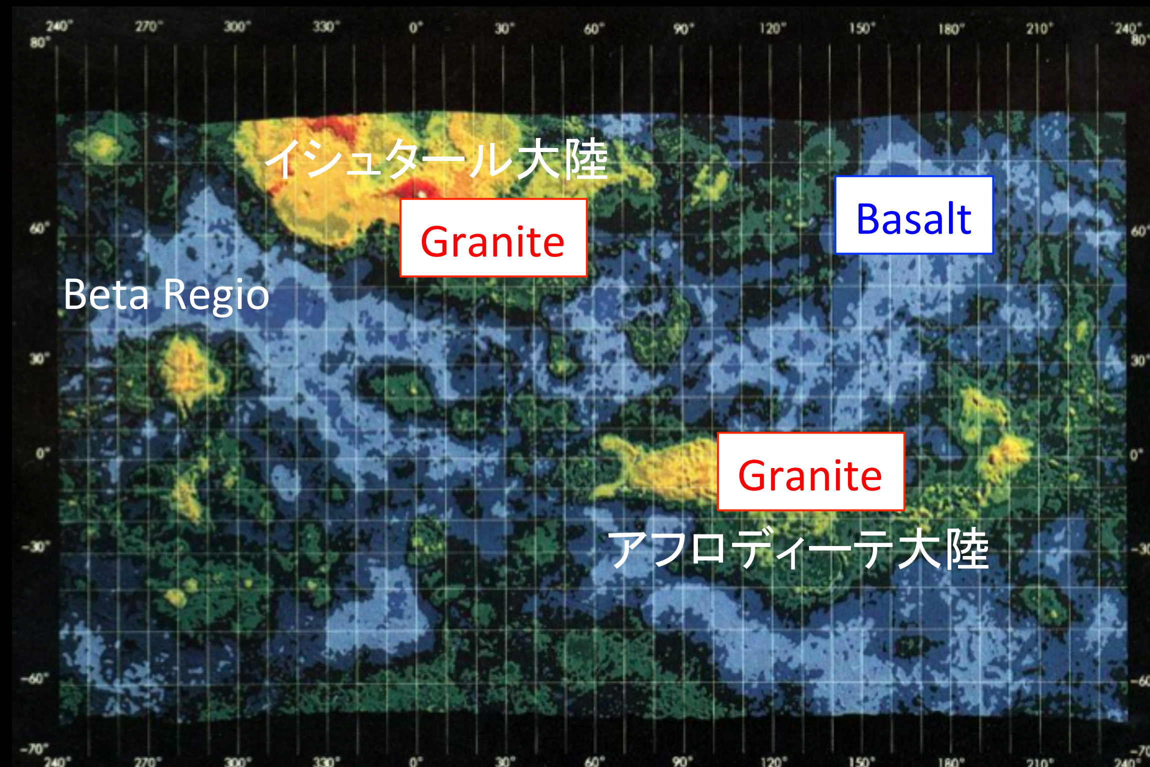
tmosph re	Water
2、N_2 013hPa	abur dance
O_2 3290hP	nothing?

en E (NASA data)

・How was plate tectonics in the past??

Galileo spacecraft the spatial variation of Venusian surface emissivity at 1.18μm wavelength.
（by NIMS)





Lowlands → High emissivity

Highlands → Low emissivity

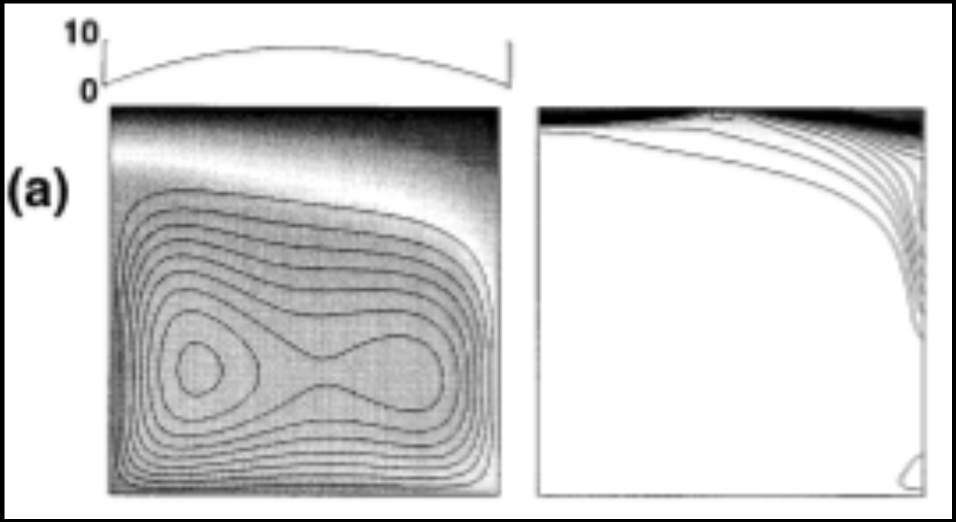
Generation of granitic magma requires the abundance water and subduction processes.

↓

The presence of granitic rocks would imply that Venus had have an ocean and subduction in the past.

(Hashimoto et al., 2008)

What stopped plate tectonics?



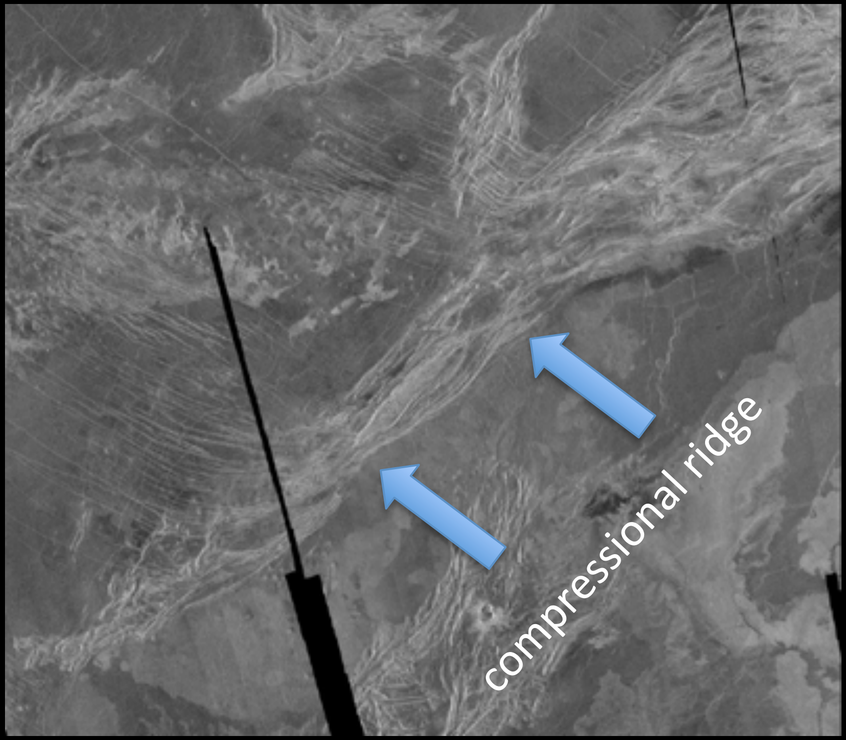
(Moresi and Solomatov, 1998)

Stagnant lid type (thick lithosphere)

↓

Lithosphere is separated from mantle convection.

Thick lithosphere = 150〜200km,
or more than 200km
(e.g., Solomatov and Moresi 1995)

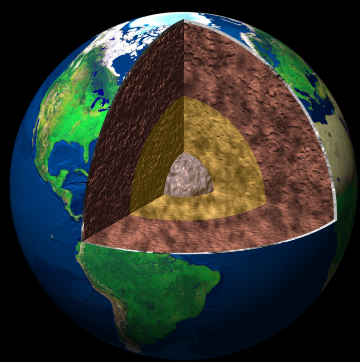


Compressional ridge on down welling of mantle convection and large coronae.

↓

Thin lithosphere = 50〜100km
(e.g., Sandwell and Schubert 1992, McKenzie 1994)

• What is the importance?? ……Rheology!!!



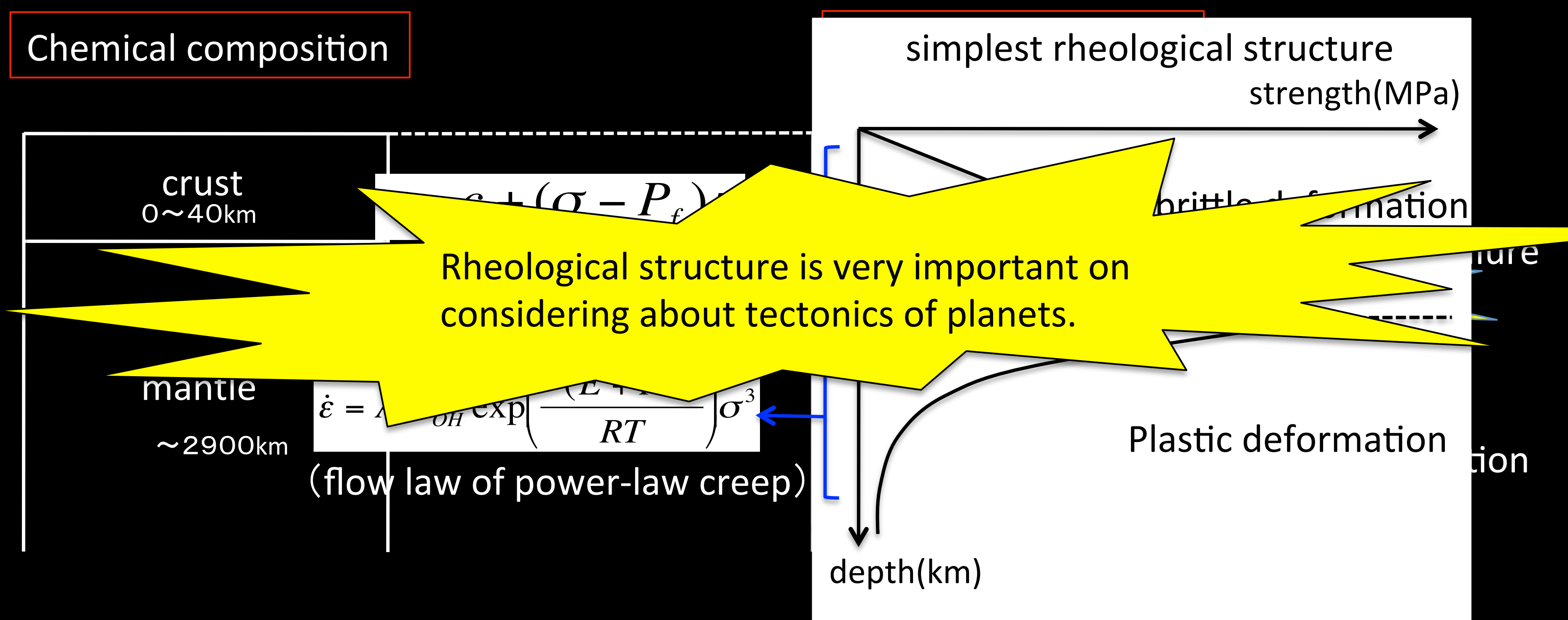
Earth

Venus

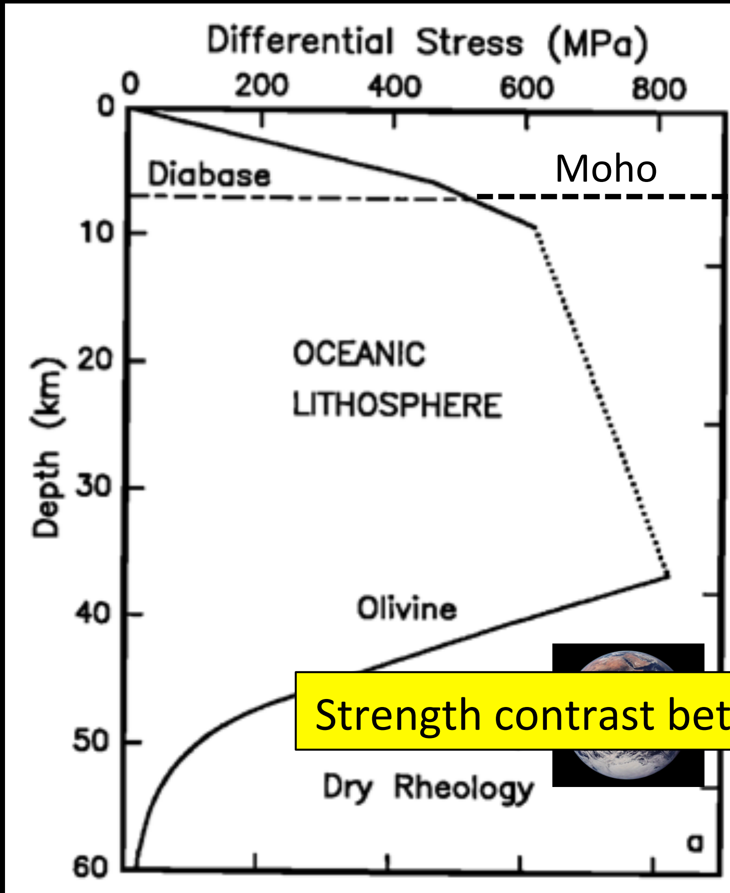
Inner structure of planet is heterogenius, it is layer structure!!!

Main two ways to separate inner structure

① Classification according to chemical composition
② Classification based on mechanical behavior

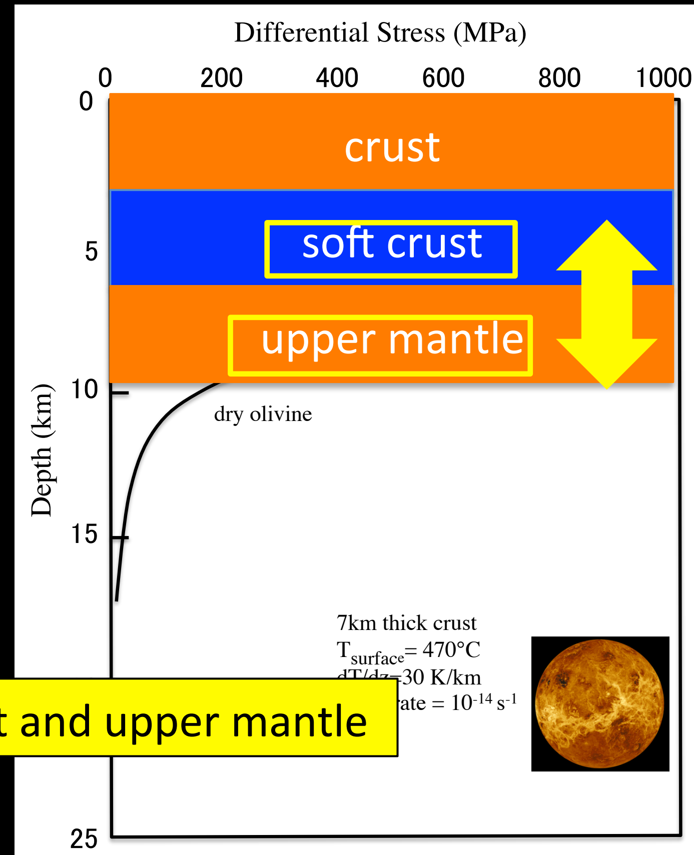


- Previous Study（Why no plate tectonics on Venus）



(Kohlstedt et al., 1995)

Strength contrast between crust and upper mantle



(Mackwell 1998)

$$\dot{\varepsilon} = AC_{OH}^{r} \exp\left(-\frac{H}{RT}\right)\sigma^{3}$$

（Power-law creep）

Decoupling ?? This strength contrast prevent plate tectonics in Venus????

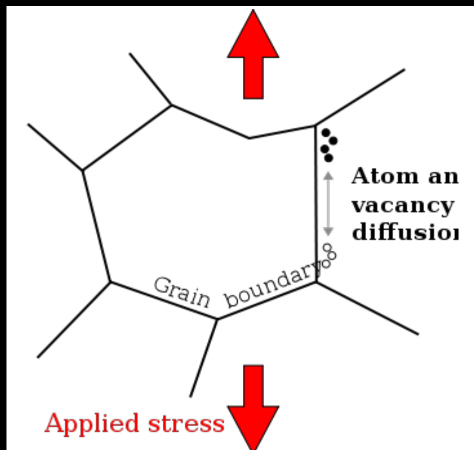
In any previous study, model of rheological structure have been inferred by extrapolating power-law creep.

However Power-law creep cannot be useful for applying to every condition (Tsenn and Carter 1987).

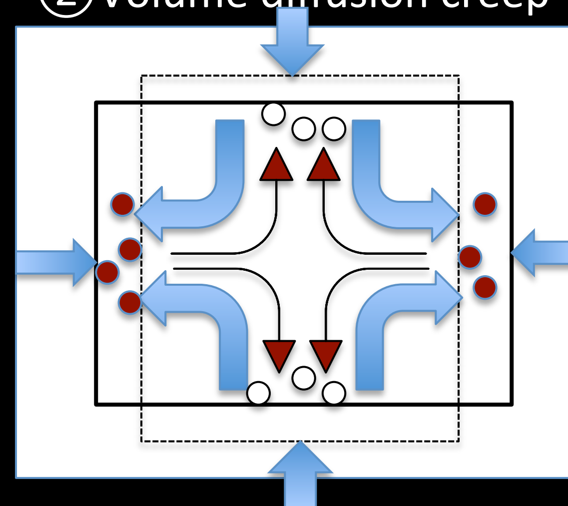
Deformation mechanism of rock

- Diffusion creep

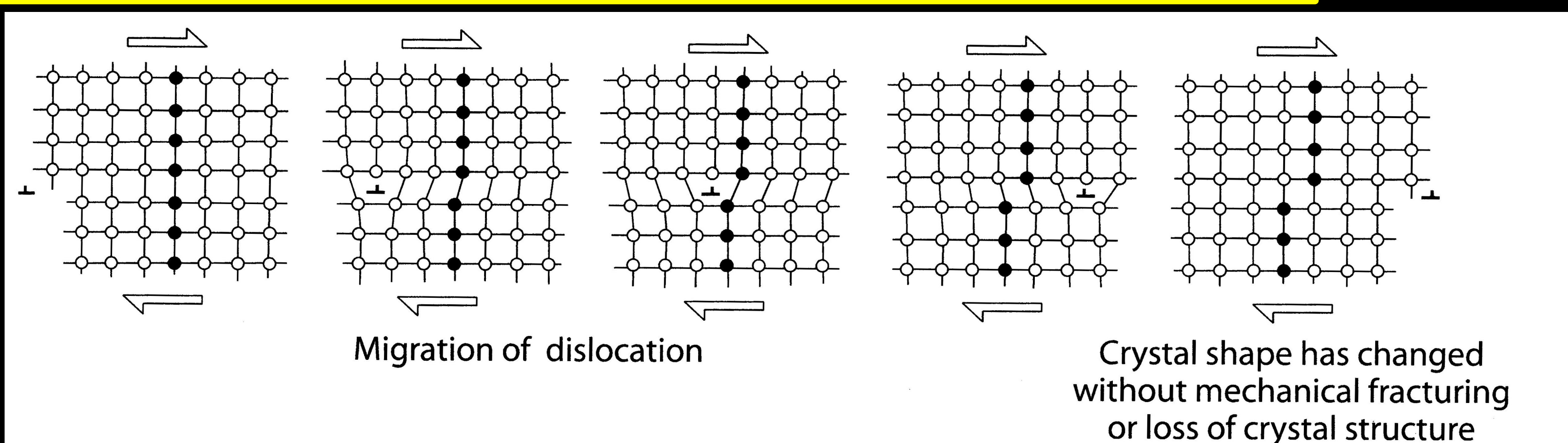
①Grain boundary diffusion creep



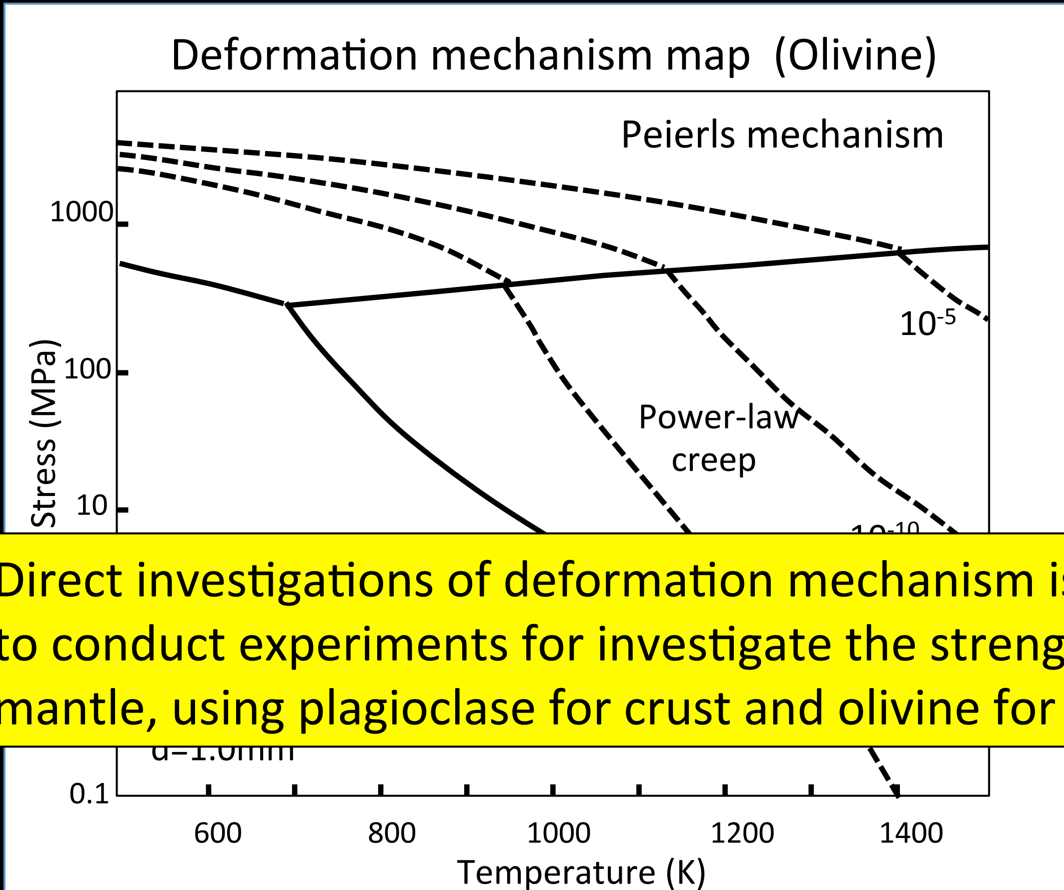
②Volume diffusion creep



- Dislocation creep → ①Dislocation climb (Power-law creep) ②Dislocation glide (Peierls mechanism)



・Power-law creep is suitable?? (Problematic point of previous study)



(Change of deformation mechanism)

high Temp. Power-law (dislocation climb)

Direct investigations of deformation mechanism is complicated!! Therefore, we tried to conduct experiments for investigate the strength contrast between crust and mantle, using plagioclase for crust and olivine for mantle.

Power-law creep

$$\dot{\varepsilon} = AC_{OH}^{r}\sigma^{3}\exp\left(-\frac{H}{RT}\right)$$

(Karato and Jung, 2003)

(A; const. σ; stress ε; strain rate H; activation enthalpy
R; gas const. T; temperature C; water contents)

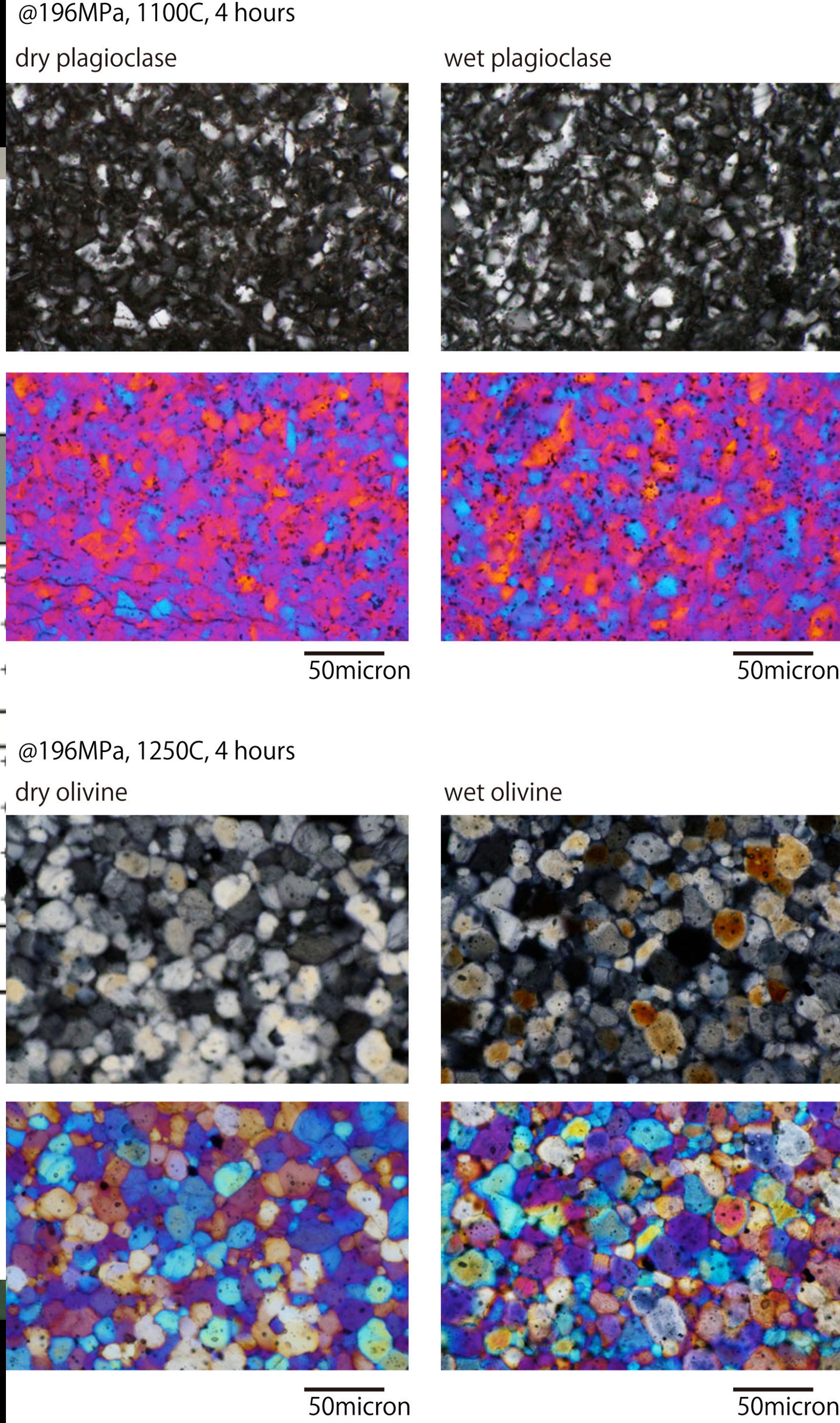
Peierls mechanism

$$\dot{\varepsilon} = AC_{OH}^{r}\sigma^{2}\exp\left\{-\frac{H}{RT}\left(1-\frac{\sigma}{\sigma_p}\right)^{2}\right\}$$

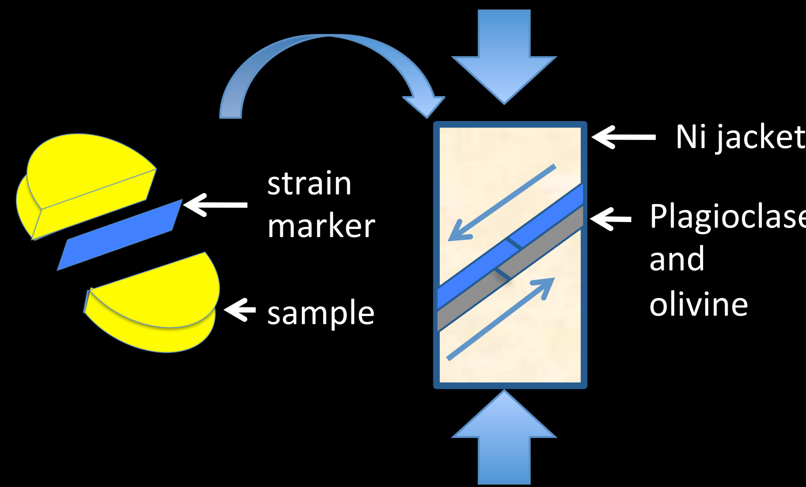
(Katayama and Karato, 2008)

(A; const. σ; stress H; activation enthalpy ε; strain rate
R; gas const. T; temperature C_{OH}; water contents σ_P; Peierls stress)

Tsenn and Carter (1987) reported that Peierls mechanism becomes dominant at low temperatures in materials with a relatively strong chemical bonding such as silicates.



We investigate the strength contrast between crust and mantle in Venus indirectly by utilizing two-phase deformation experiment of plagioclase and olivine.

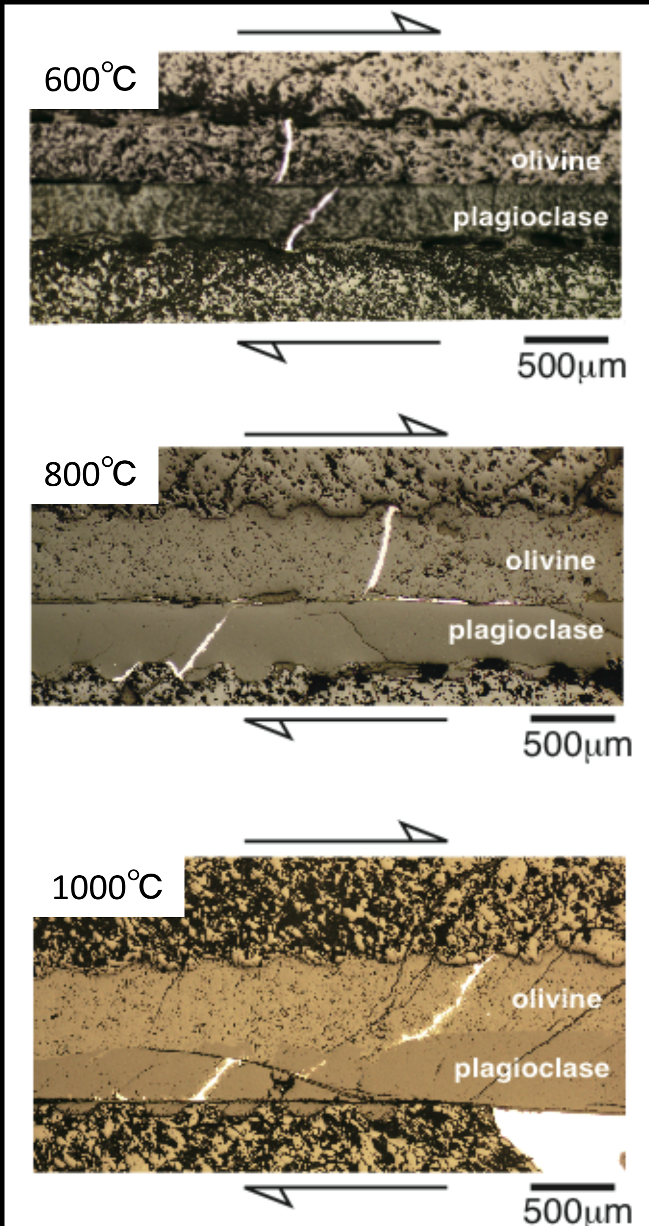


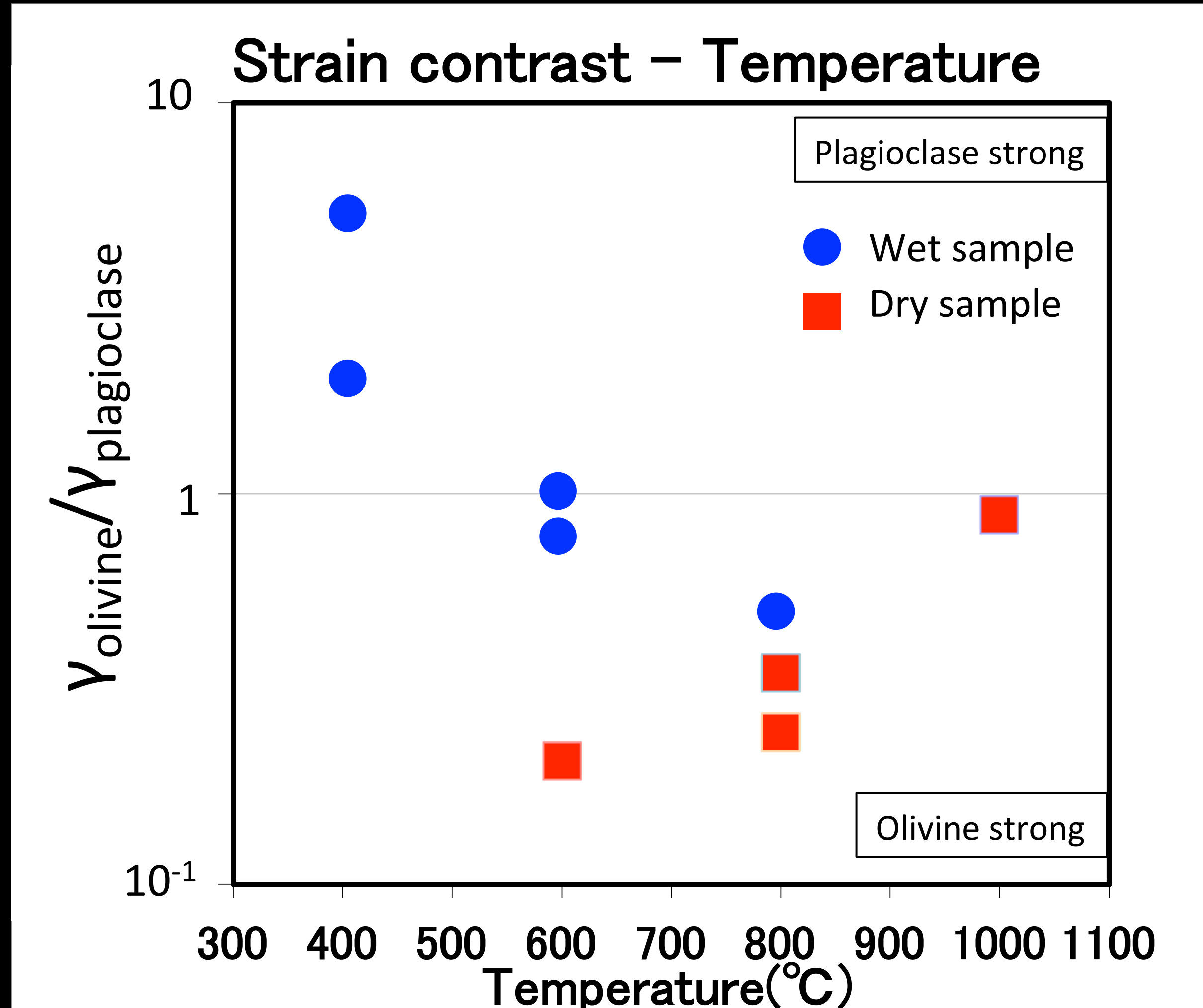
(Temperature) 600-1000°C
(Pressure) 1GPa
(Piston velocity) 500μm/hr (～10^{-5} /s)
(Sample thickness) ~450μm
(Condition) dry

The olivine (mantle) and plagioclase (crust) samples were sandwiched together between the alumina pistons, which are cut at 45° from the maximum compression direction.

・Experimental results

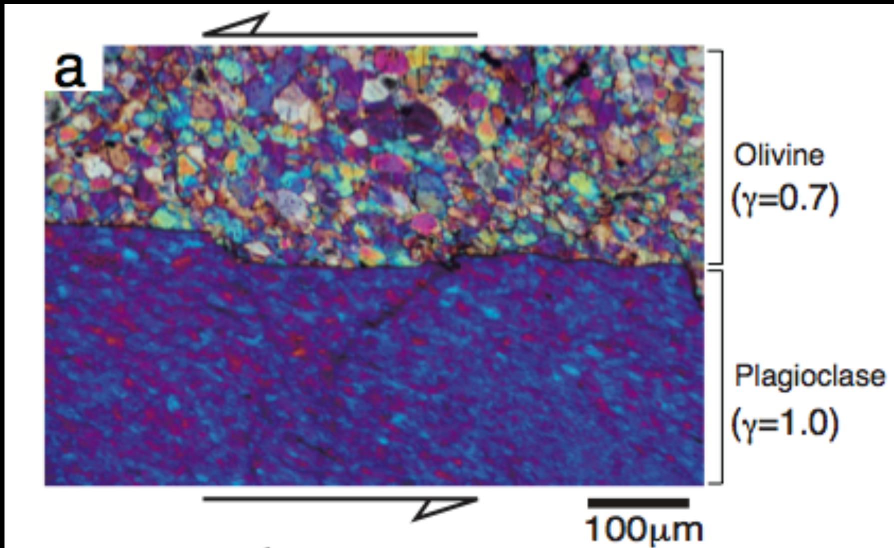
(Dry condition)





(Dry)
Olivine ＞ Plagioclase

・Deformation mechanism



（T=600℃, P=1GPa）

（before）dislocation density ~1.4×10^{12}(m^{-2})
（after） dislocation density ~1.5×10^{13}(m^{-2})

↓

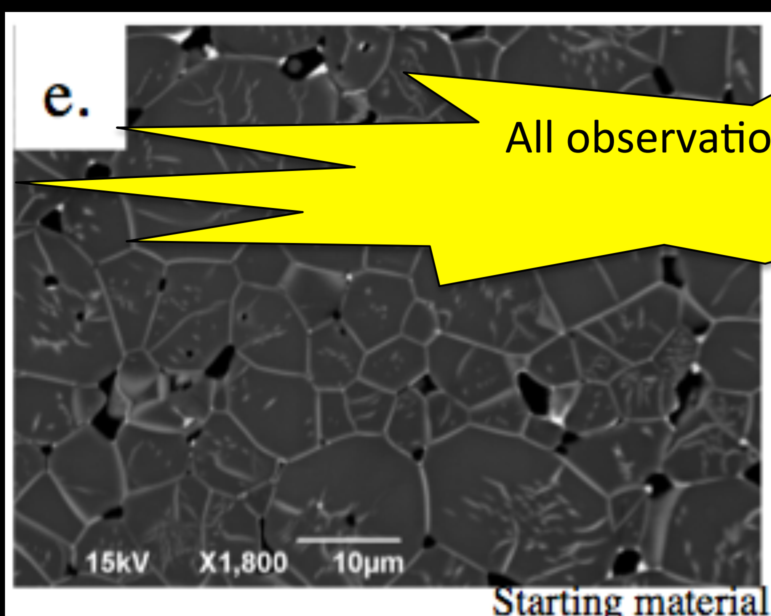
Dislocation creep dominant

LPO is observed.

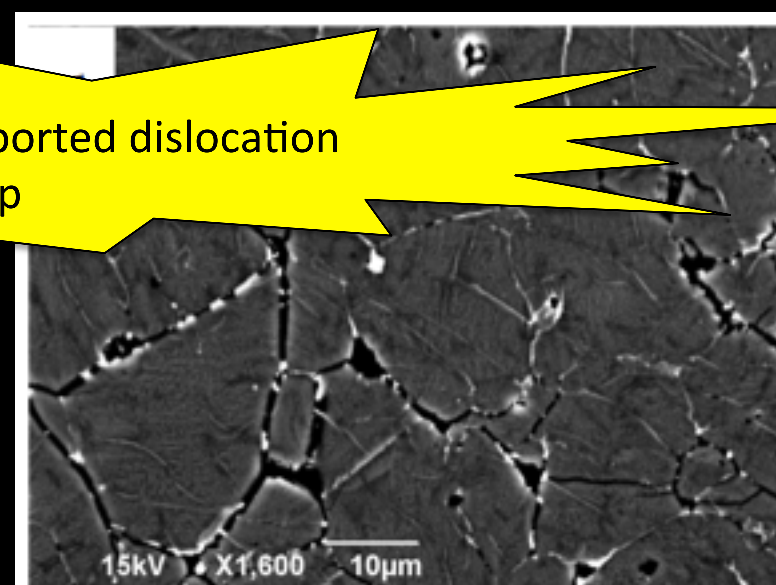
↓

Dislocation creep dominant

All observations supported dislocation creep

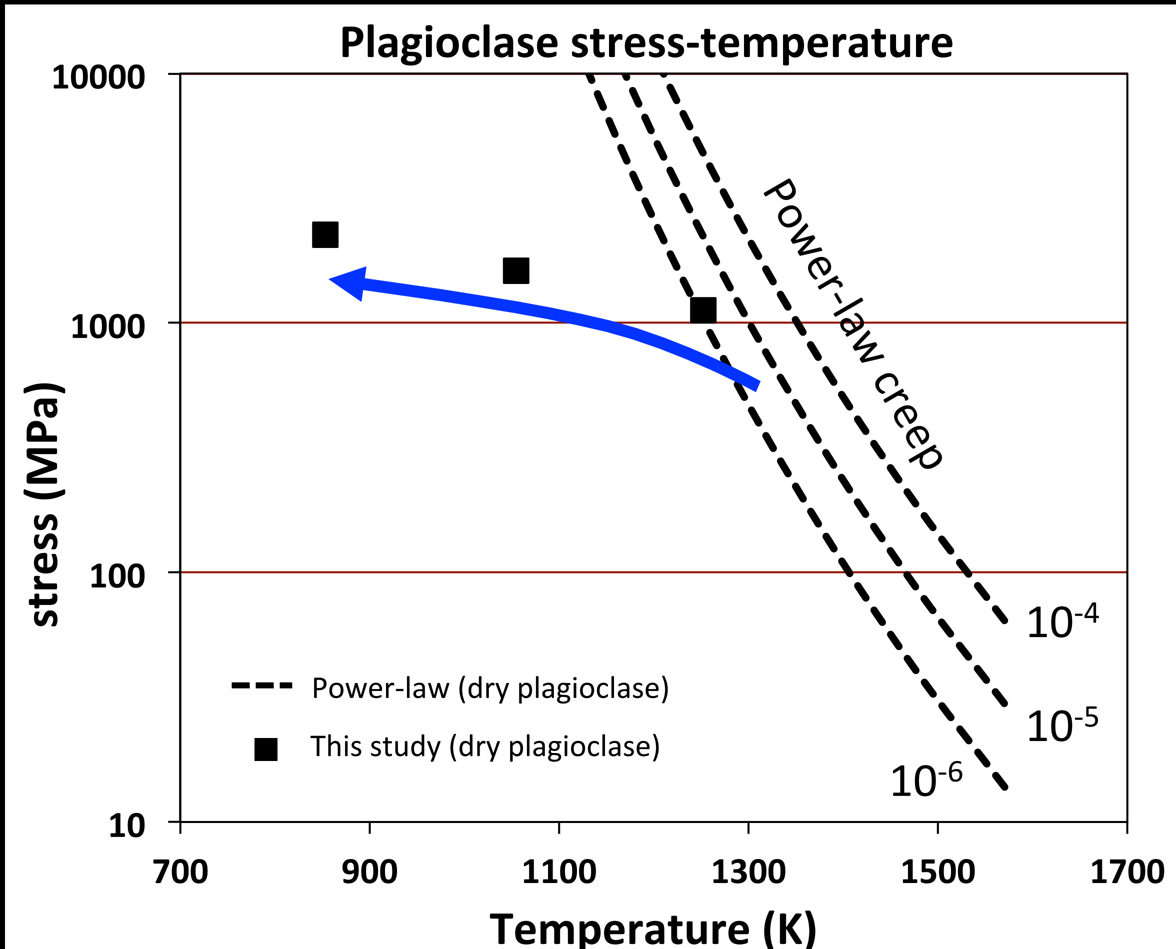


Before experiment (under SEM)



after experiments (under SEM)

･Power-law?? or Peierls mechanism??



Stress in our experiments is plotted and compared with Power-law.

Our results is deviated from the power-law clearly.

The peierls mechanism dominates the deformation mechanism in our experimental conditions.
Not power-law!!!!

Power-law

$$\dot{\varepsilon} = A C_{OH}^{r} \exp\left(\frac{-(E+PV)}{RT}\right)\sigma^{3}$$

(Karato and Jung, 2003)

A; const. σ; stress E; activation energy P; pressure
ε; strain rate R; gas const. T; temperature C; water contents
V; activation Volume

Peierls mechanism

$$\dot{\varepsilon} = A C_{OH}^{r} \sigma^{2} \exp\left\{-\frac{E+PV}{RT}\left(1-\frac{\sigma}{\sigma_p}\right)^{2}\right\}$$

(Katayama and Karato, 2008)

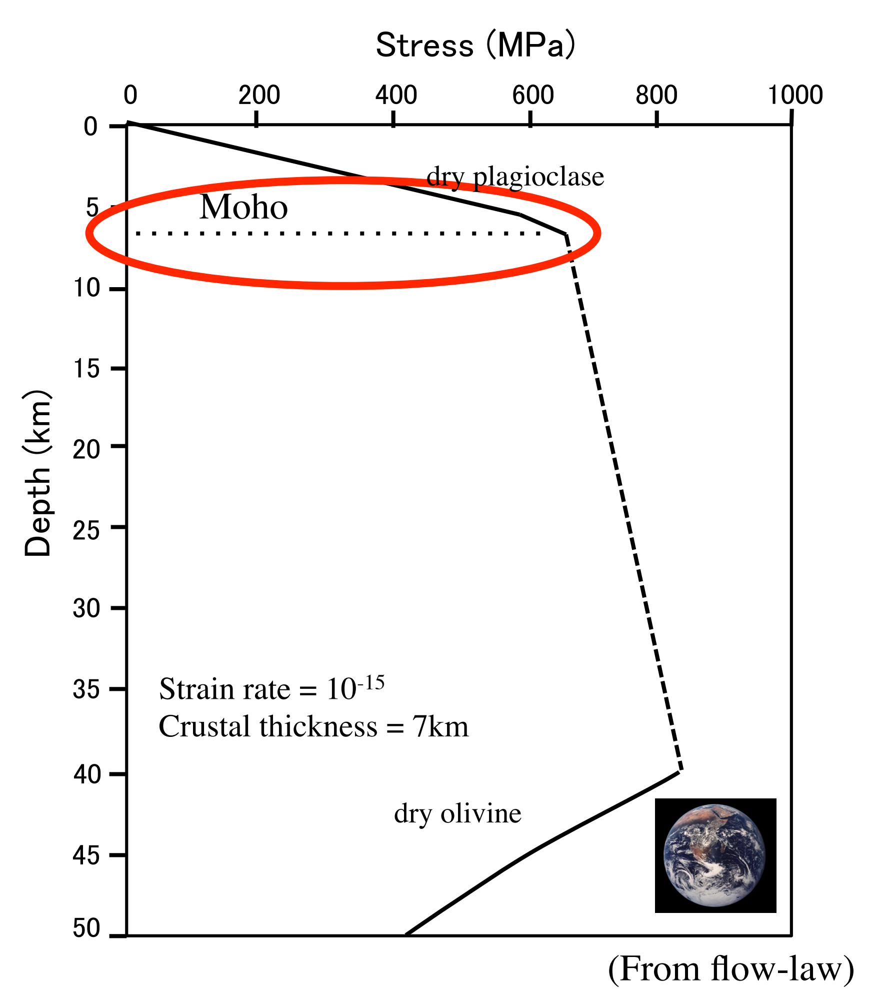
A; const. σ; stress H_0; activation enthalpy P; pressure
ε; strain rate R; gas const. T; temperature
C_{OH}; water contents σ_P; Peierls stress

・Comparison between Earth and Venus

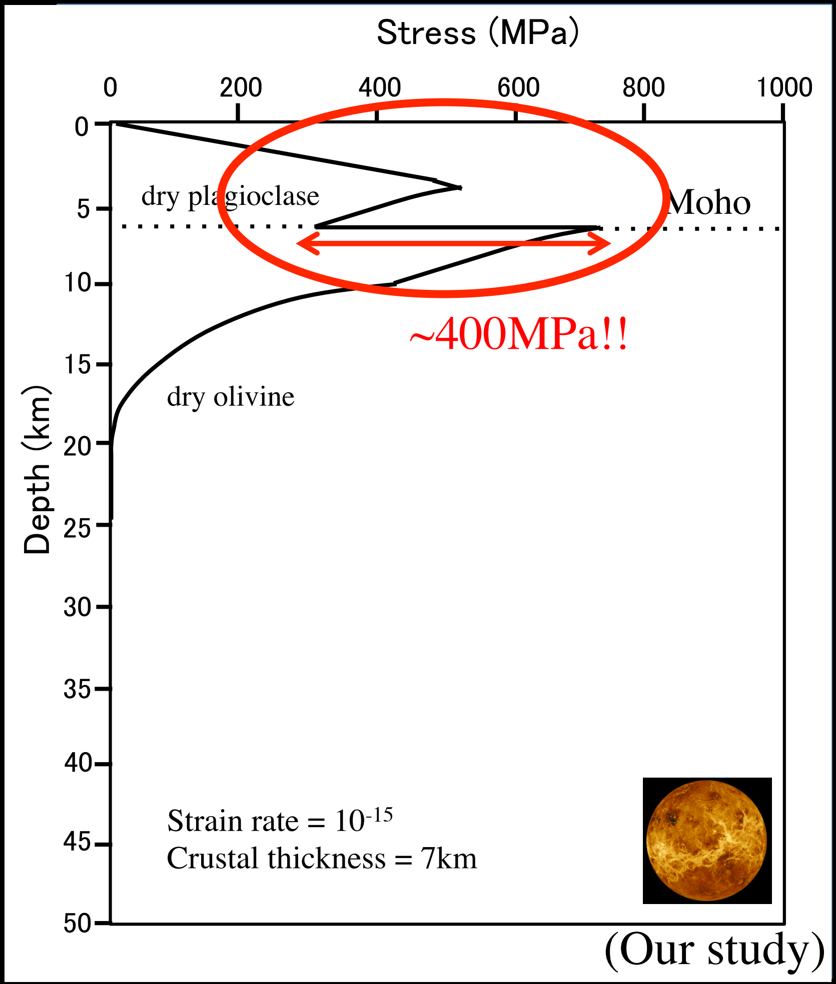
(Earth) Moho is brittle deformational range because of lower temperature. It means that lower crust and upper mantle is strongly coupled. Therefore, crust and mantle could move together.

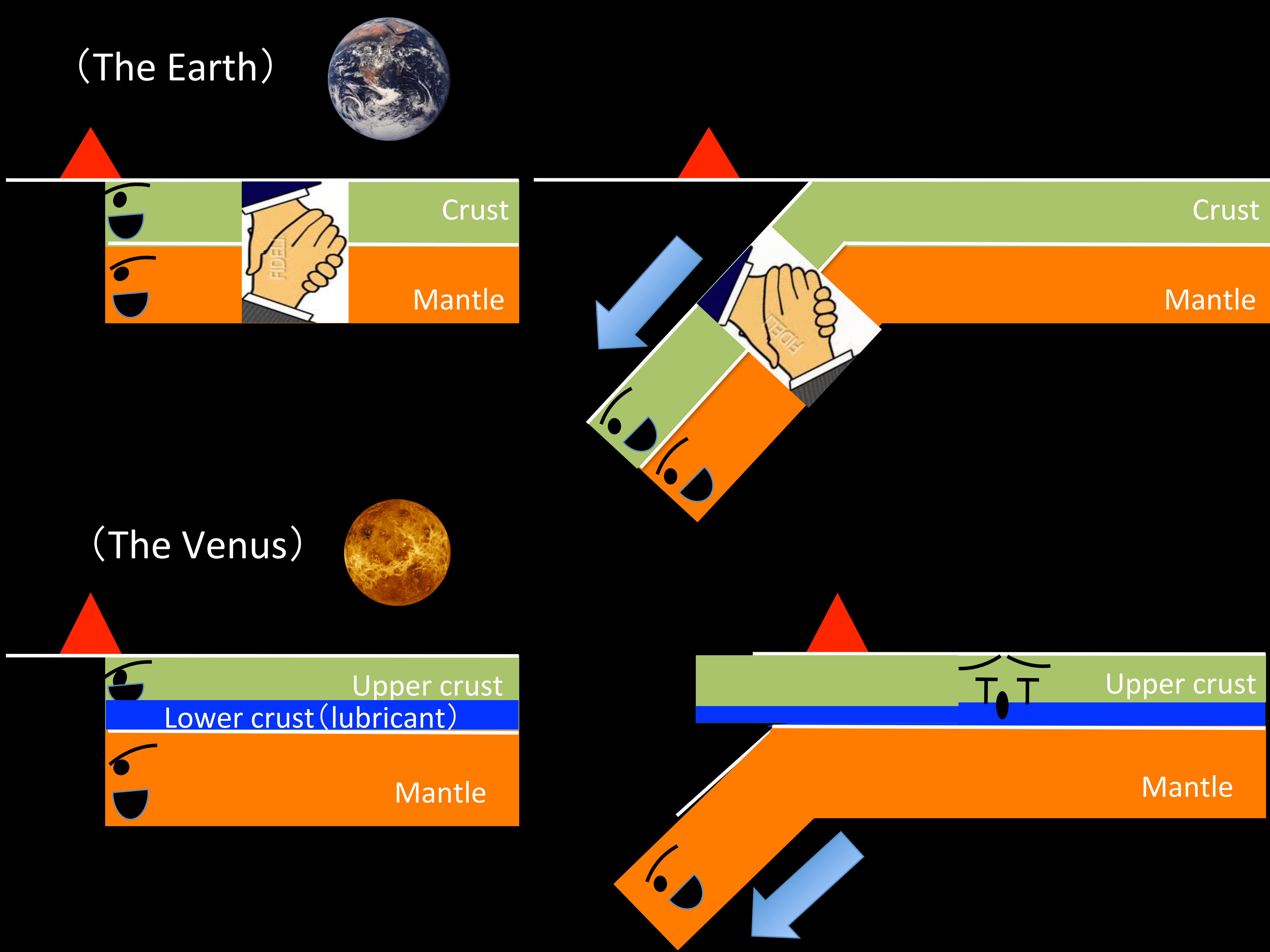
(Venus) Strength contrast between lower crust and upper mantle is significantly large due to high temperature, so it is possible that lower crust and upper mantle might be decoupled.

(Earth's oceanic lithosphere)



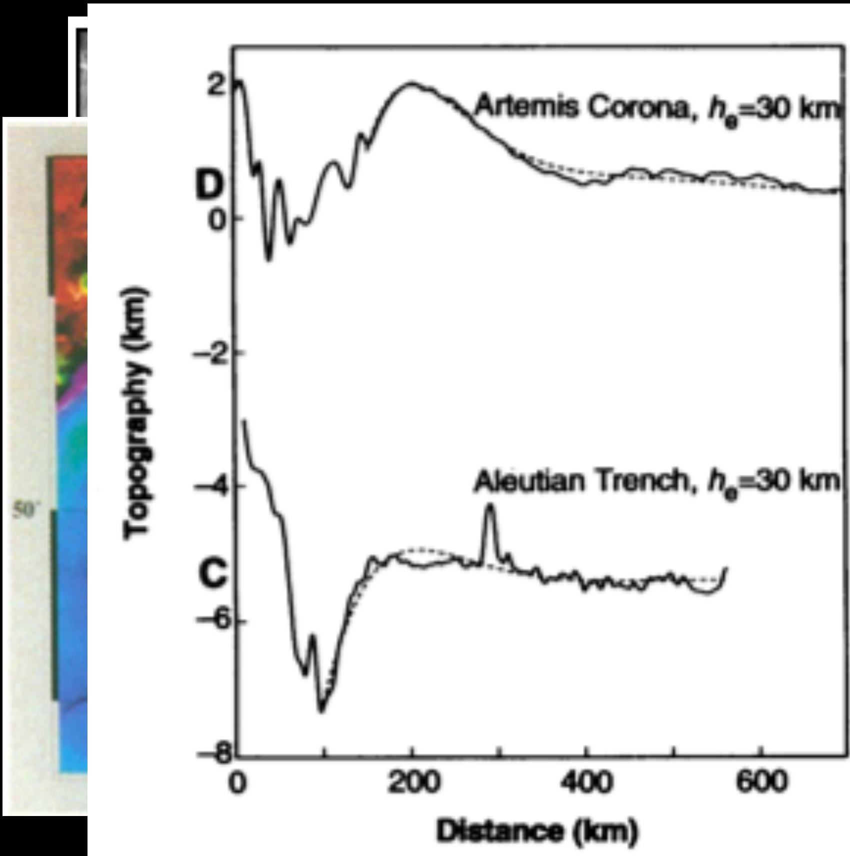
(Venus's lithosphere)

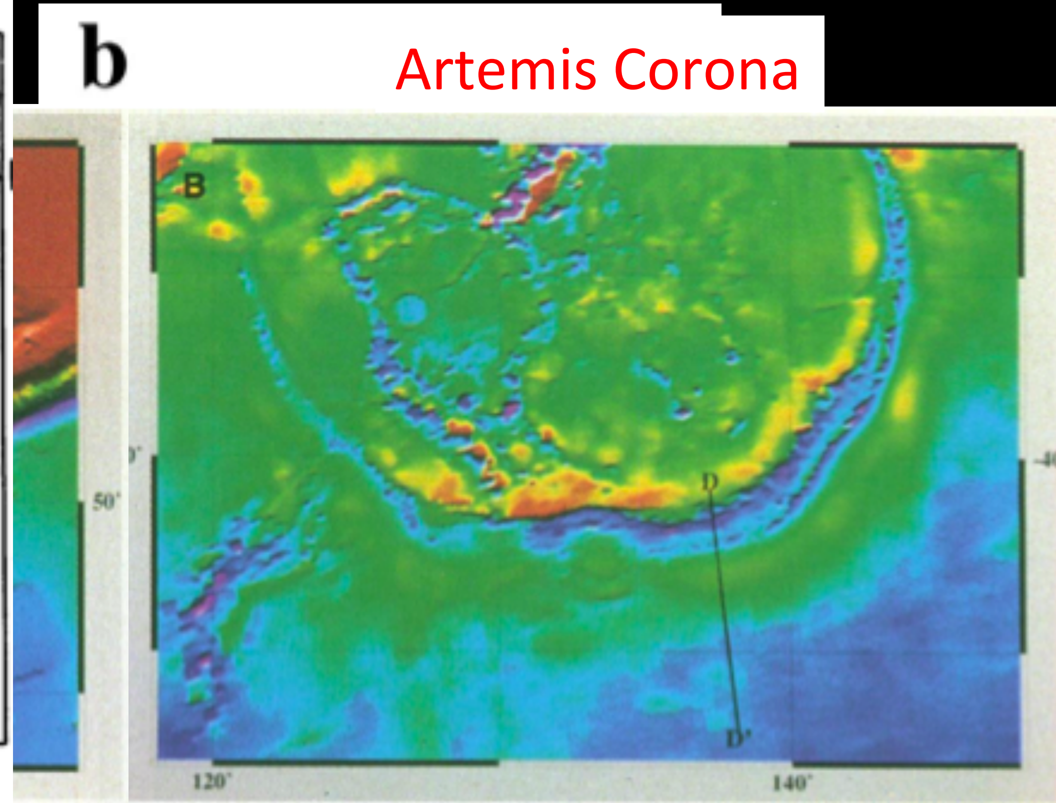




(The Earth)
Crust
Mantle
Crust
Mantle
(The Venus)
Upper crust
Lower crust (lubricant)
Mantle
Upper crust
Mantle

- Artemis Chasma





erthrust of lithosphere. This landform is analogous to terrestrial subduction zone. (Brown and Grimm 1999)

Due to weak lower crust….

- Crust is free from the circulations of mantle.
- Weak crust can not subduct into hard mantle.

Subduction has been stopped??

We conclude that the strength contrast in moho can be a factor which prevents plate tectonics in Venus.

Conclusion

Strength contrast between plagioclase and olivine

(Dry)

Olivine is always stronger than plagioclase in low T conditions (< 1000).
The peierls mechanism dominates deformation mechanism at relative low temperature.

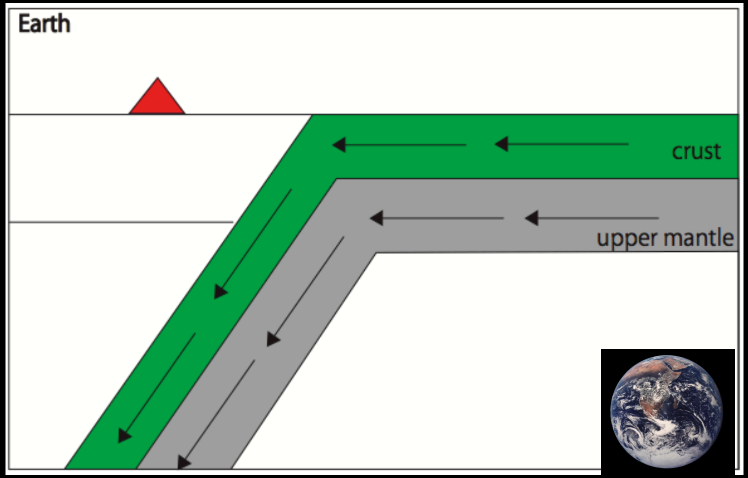
Rheological structure of the Earth

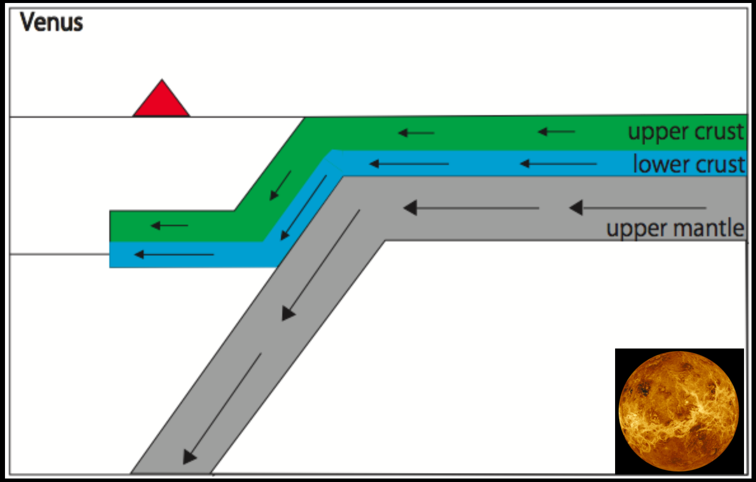
（Oceanic lithosphere）

Moho is still in brittle deformational range, hence weak strength contrast and the coupling between crust and mantle in the Earth can be observed.

Rheological structure of Venus

Since strength contrast between lower crust and upper mantle is significantly large, lower crust plays a role as a lubricant. Therefore lower crust cannot move with horizontal motion of mantle and also cannot subduct into the mantle. In conclusion, the weaker crust to compare to the mantle interrupt plate tectonics on Venus.





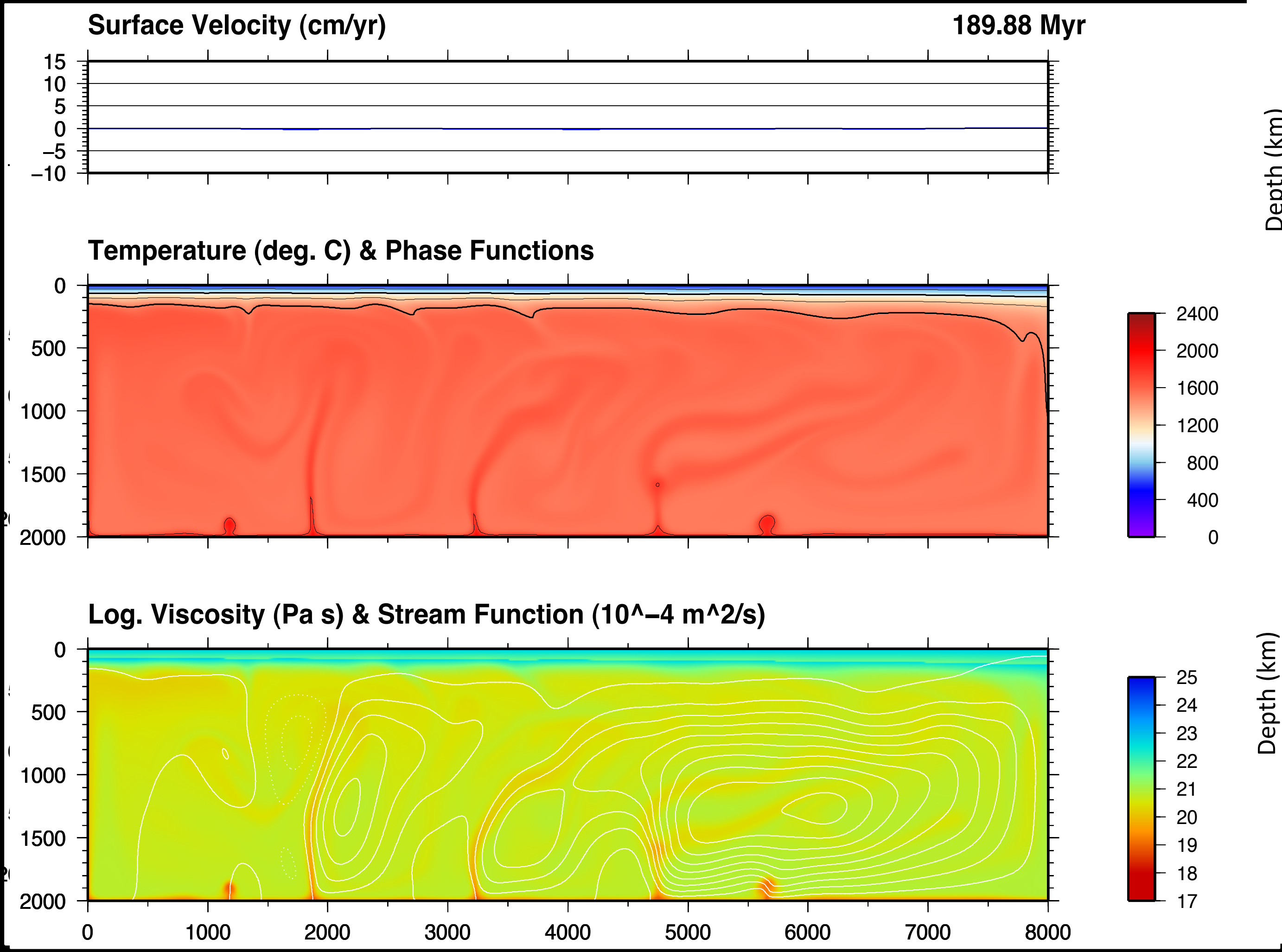
Numerical simulation feat. Dr. Nakakuki

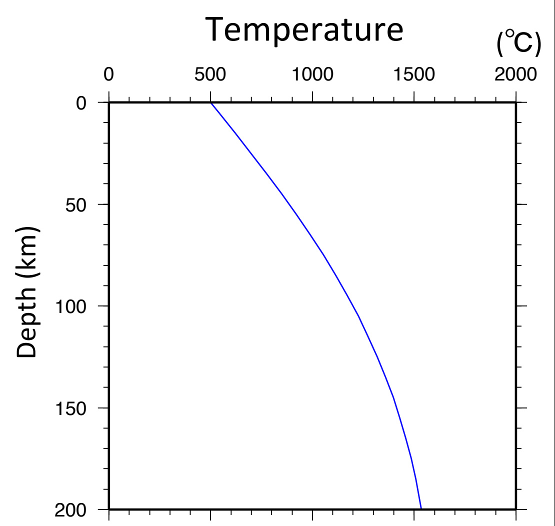
(Run a20120112)

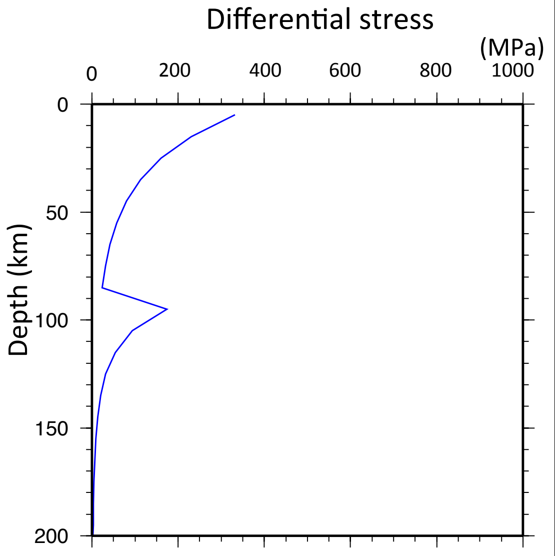
Crust thickness = 100km

Surface viscosity = 1×10^{23} Pa･s

Mantle viscosity = 10^{21} Pa･s







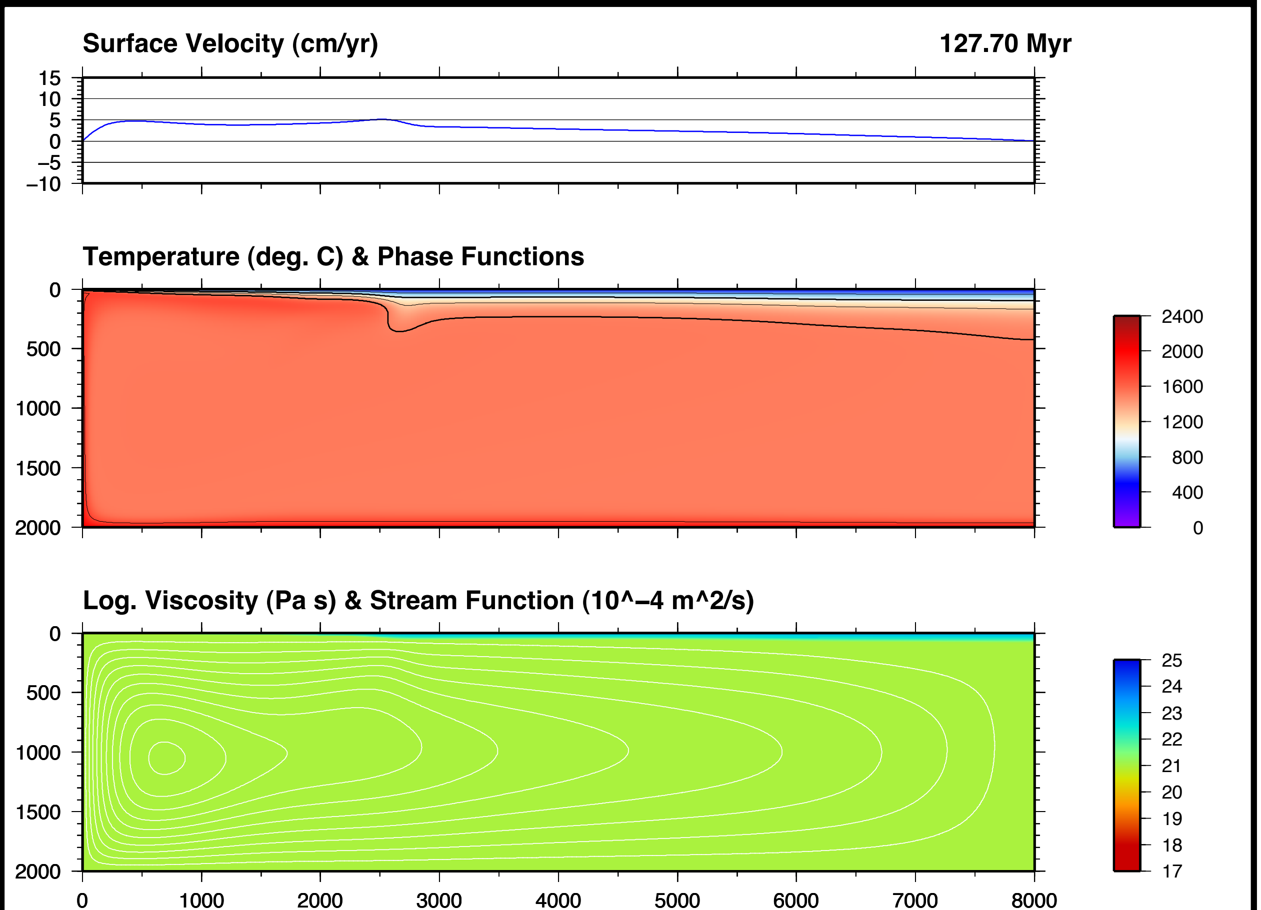
Numerical simulation feat. Dr. Nakakuki

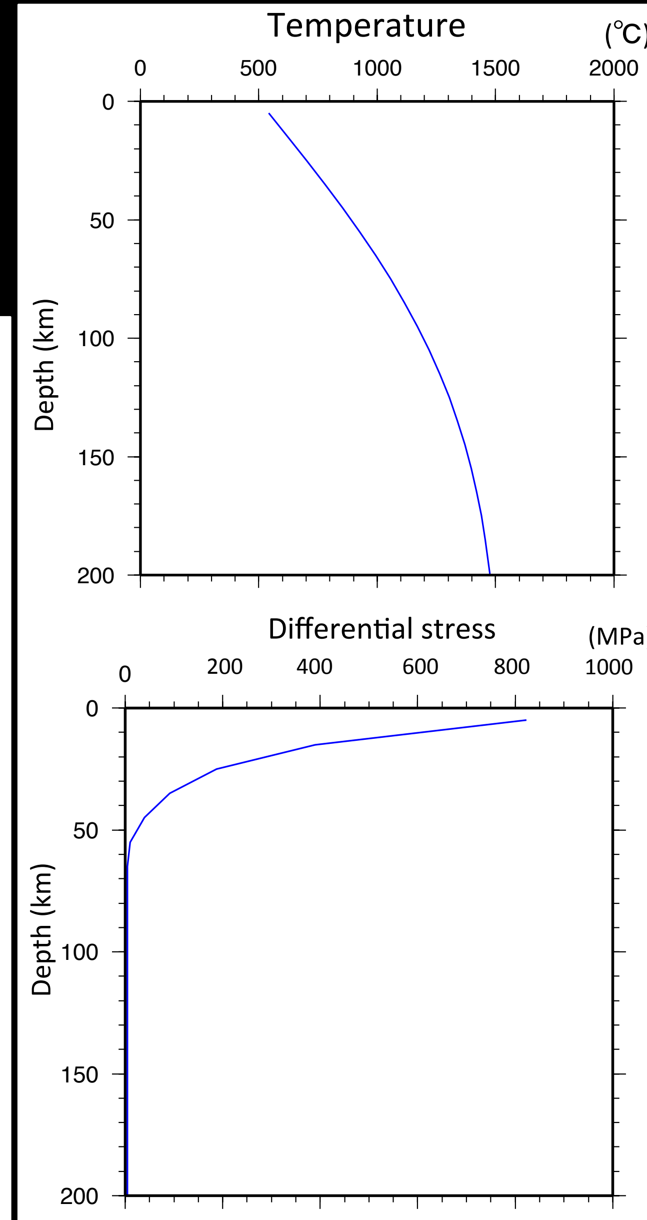
(Run a20120126)

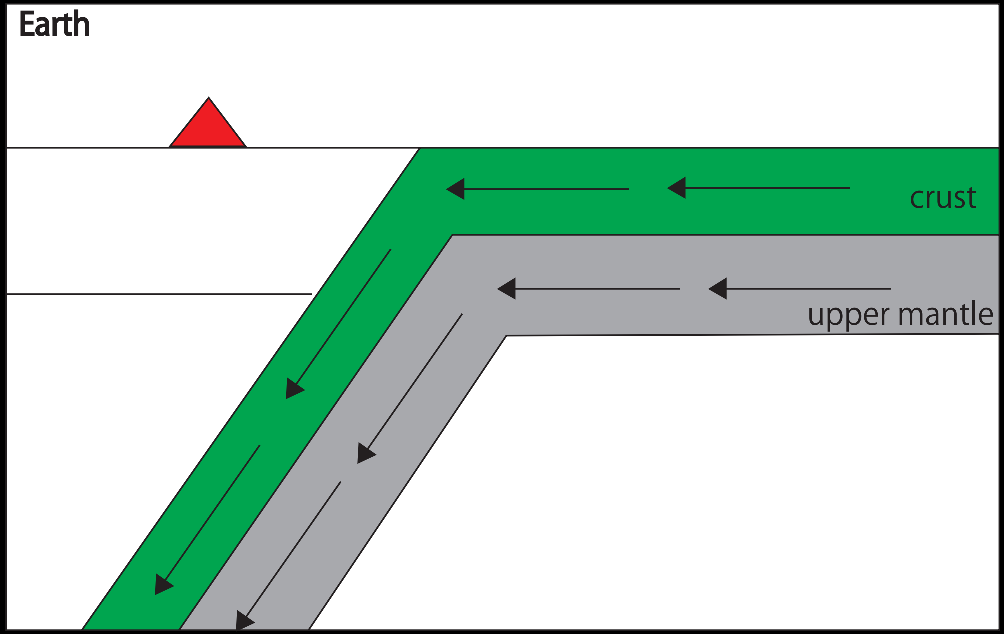
Crust thickness = 40km

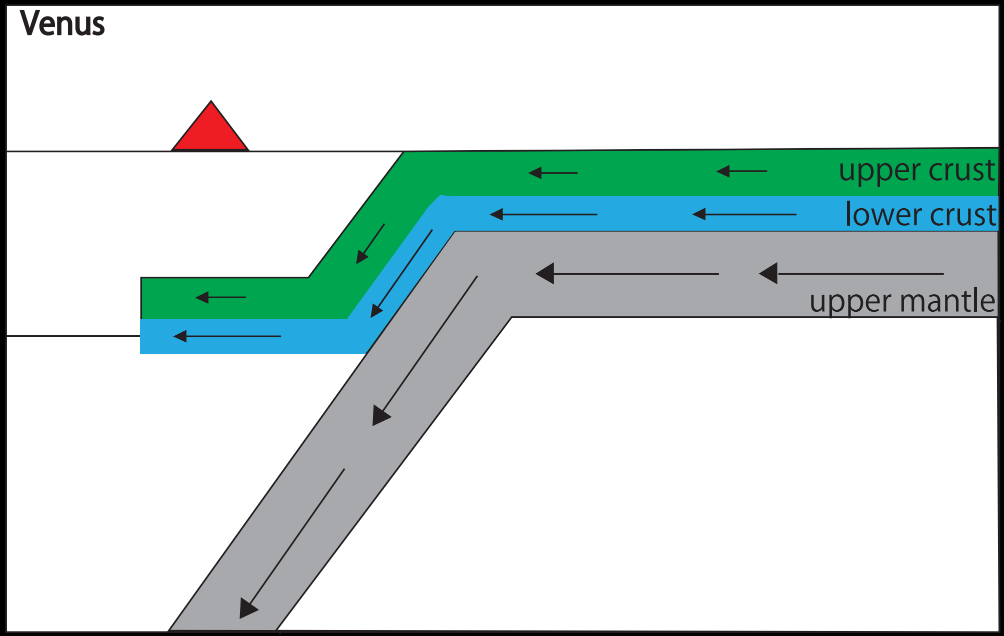
Surface viscosity = 3×10^{23} Pa･s

Mantle viscosity = 10^{21} Pa･s






Earth
crust
upper mantle

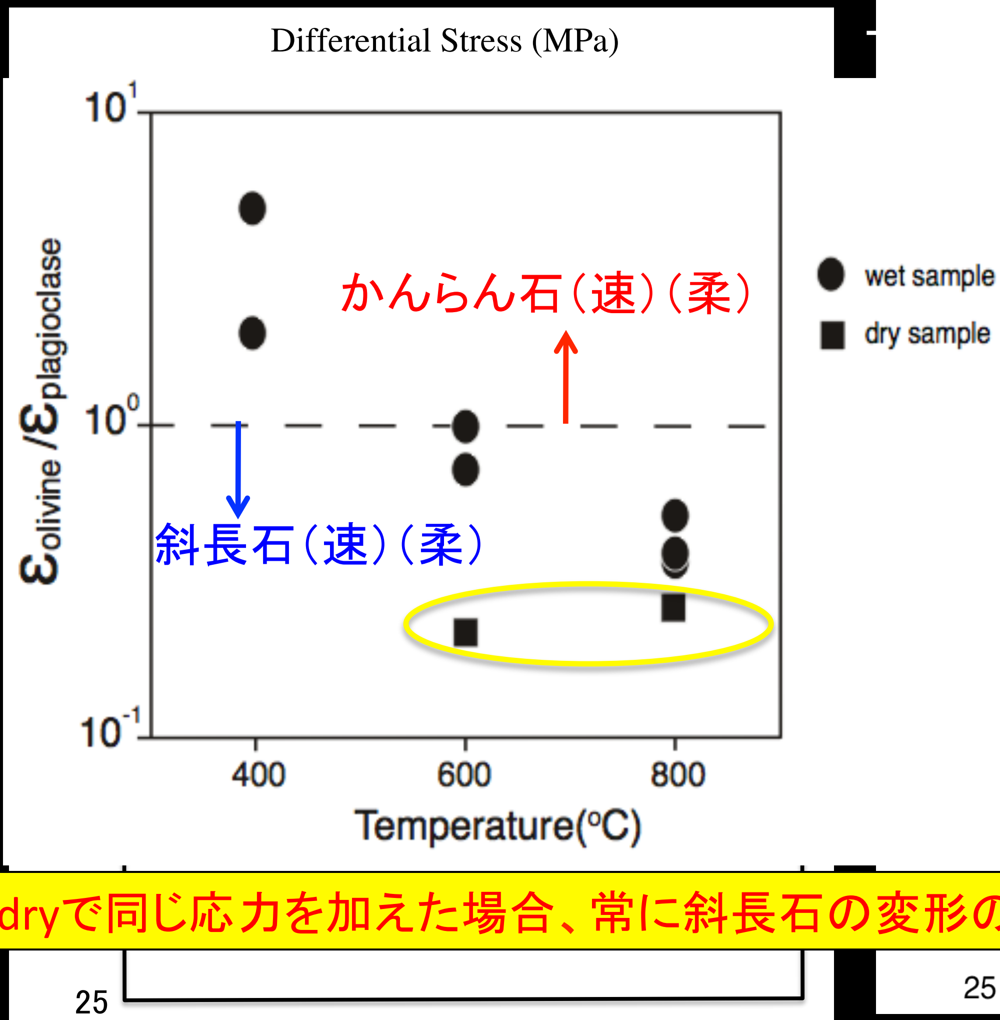

Venus
upper crust
lower crust
upper mantle

・金星

金星の表面温度470℃ ➡ かなりdryな惑星と考えられるため、dry実験の結果を外挿

地殻の厚さ=7km、地温勾配=30K/km、strain rate=10^{-14}一定と仮定。

（金星の過去の内部構造を想定）



dryで同じ応力を加えた場合、常に斜長石の変形の方が早い！つまり柔らかい！！

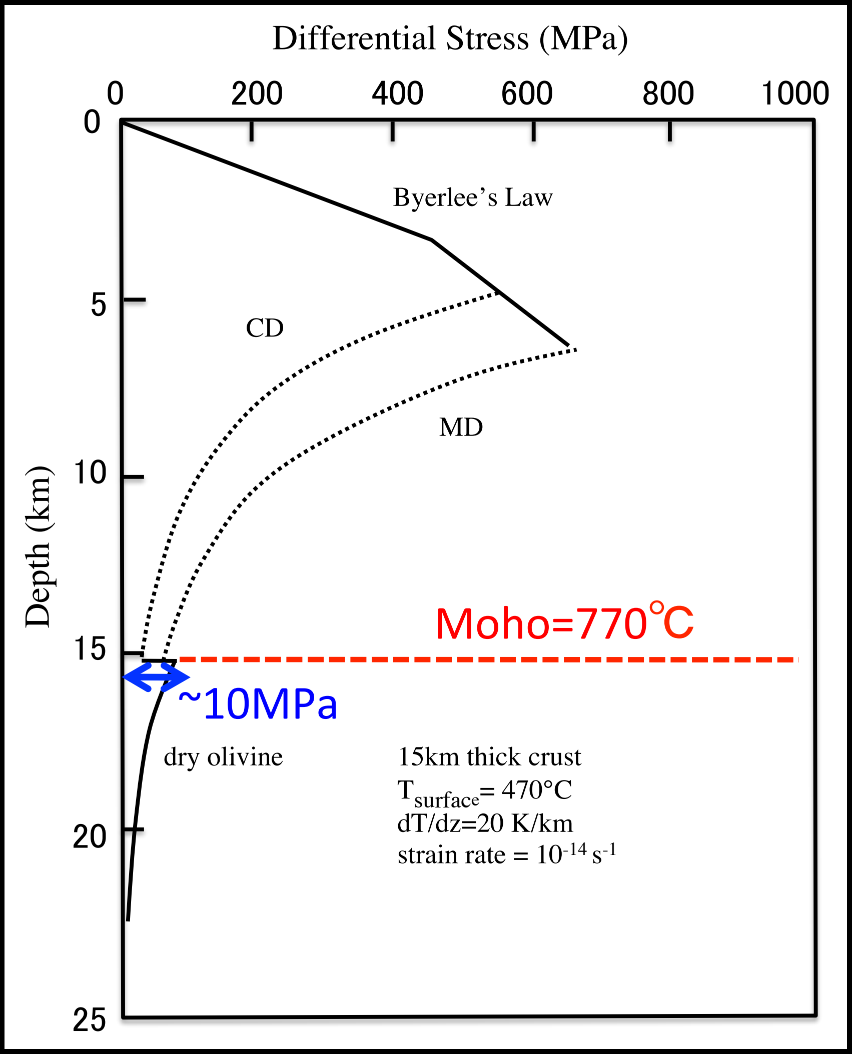
(Mackwell 1998)

（本実験結果からの推察）

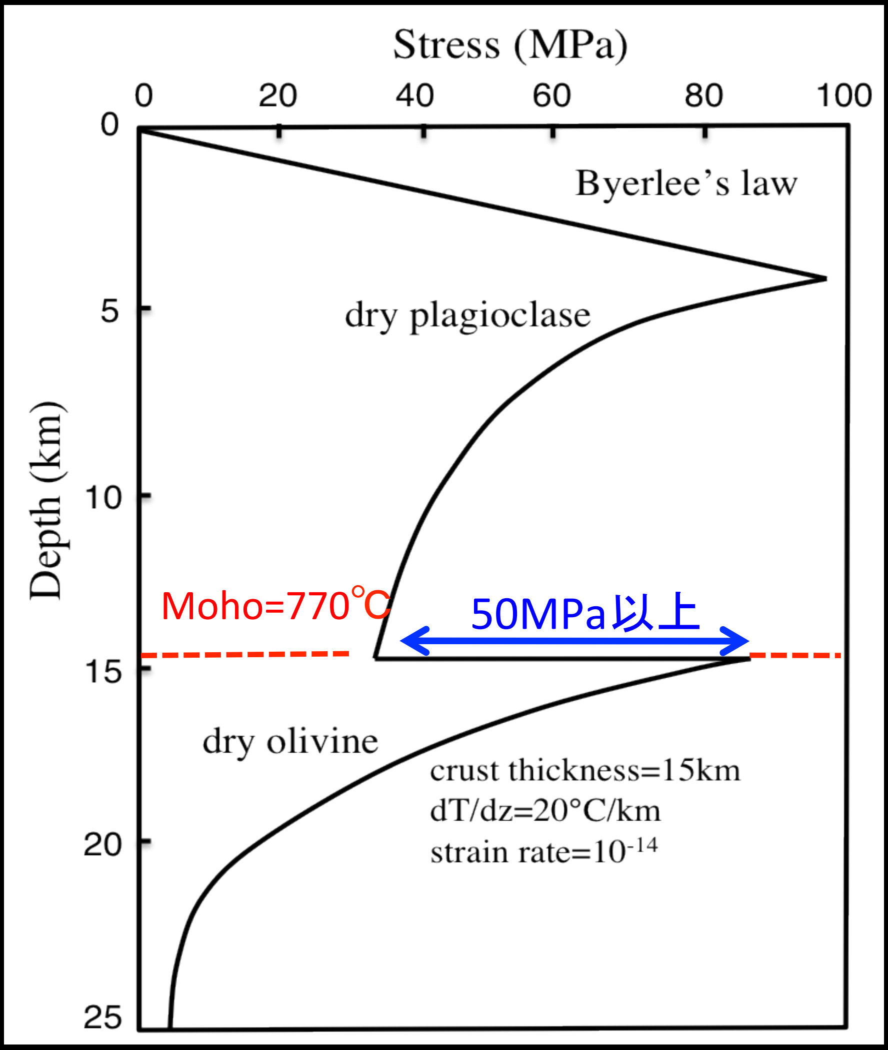
・金星

地殻の厚さ=15km、地温勾配=20K/km、strain rate=10^{-14}一定と仮定。

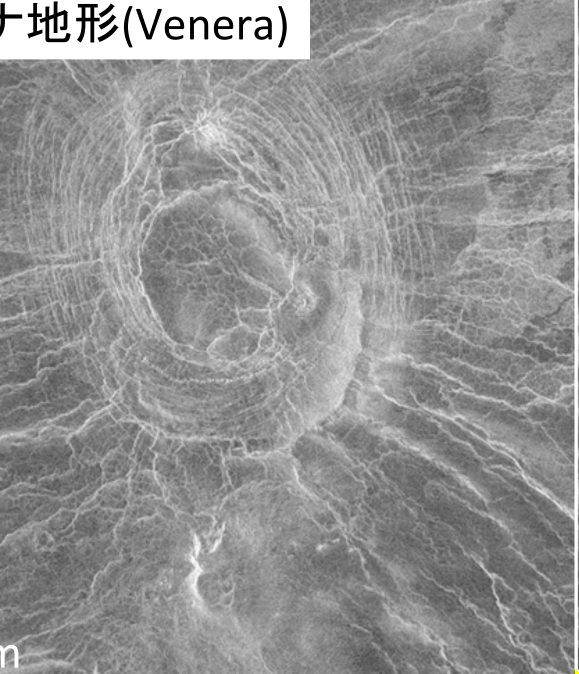
（金星の現在の内部構造を想定）

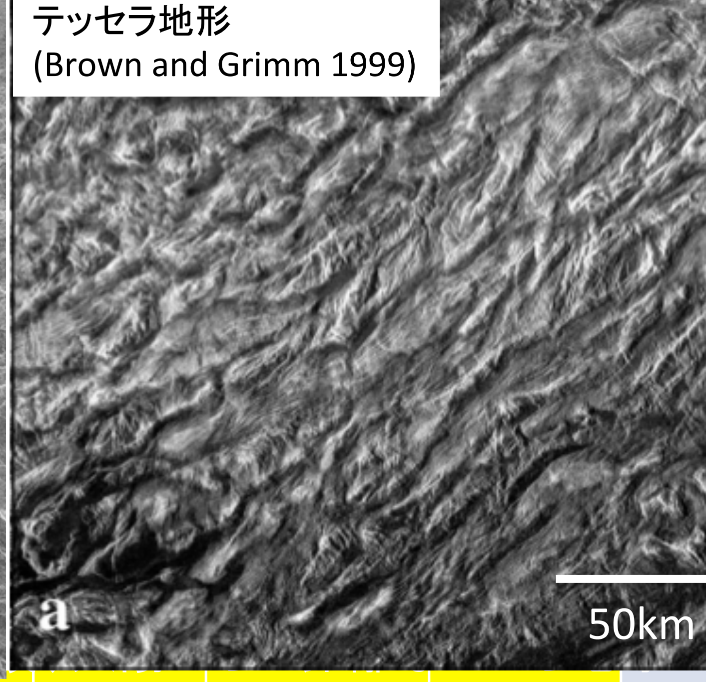


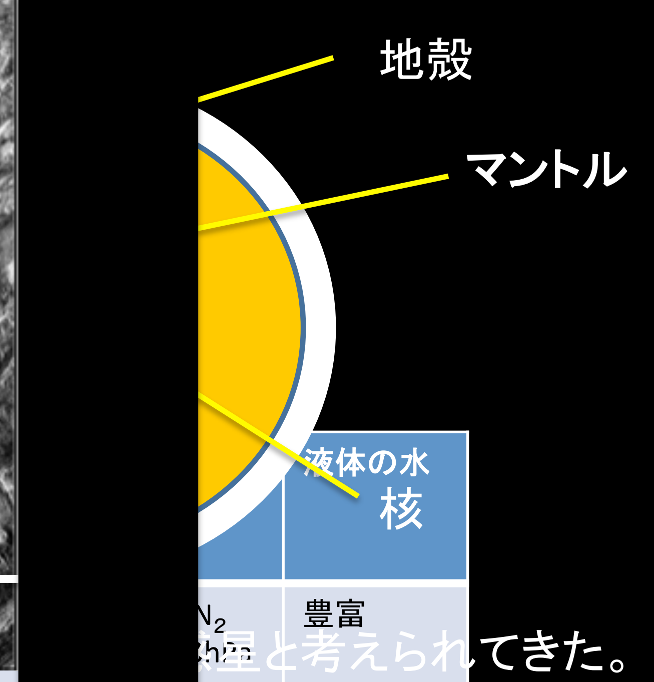
(Mackwell 1998)



（本実験結果からの推察）







星と考えられてきた。

								液体の水
（斜長石）							N_2	豊富
ダイアベース （斜長石）	カンラン石	5.20g/cm^3	12103km	0.72AU	8.87m/s2	460℃	CO_2 93290hPa	無し

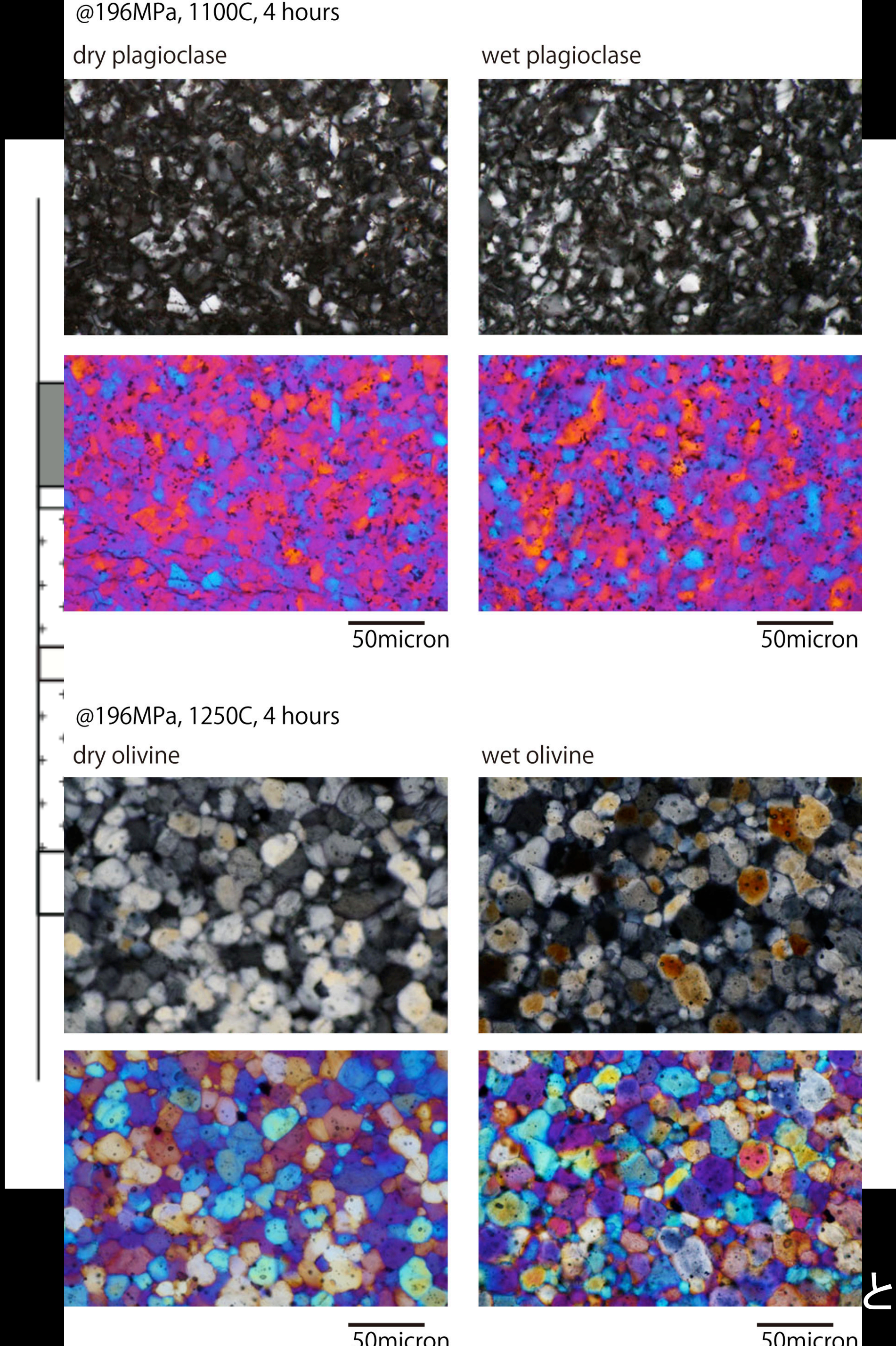
②金星の表面の年代は一様であり、とても古いわけでもなく、若いわけでもない。

なぜプレートテクトニクスがないの？？

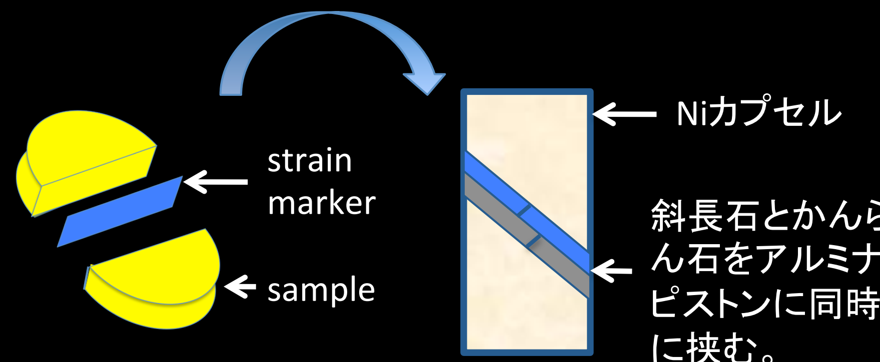
Plate tectonics is one of the most important material circulationプレートテクトニクスは惑

(e.g., NASA’s HP)

Therefore, it is inferred that existence and non-existence of this plate tectonics is one factor



流動則による外挿ではなく、広島大学設置の固体圧式実験装置（改良型Griggs）によって検証



（実験条件）

圧力　1GPa

温度　400～800℃

wet条件　各400p.p.m　H/Si (FTIR測定)

dry条件

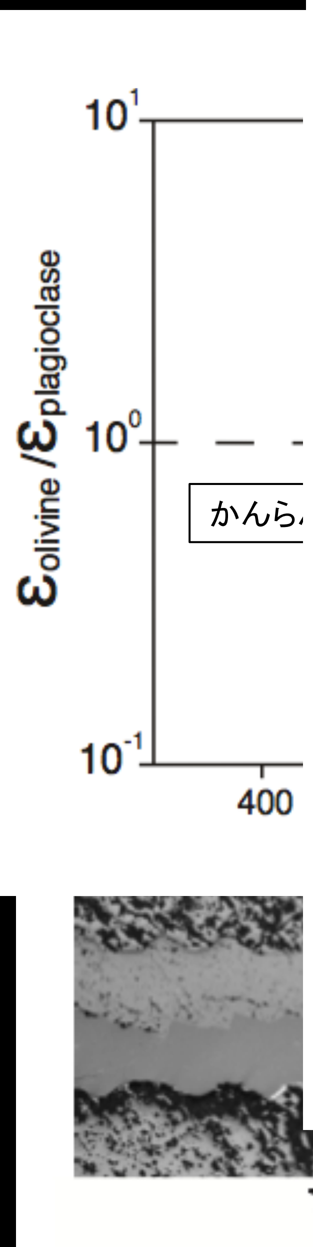
wet条件とdry条件でのモホ面における
斜長石vsかんらん石

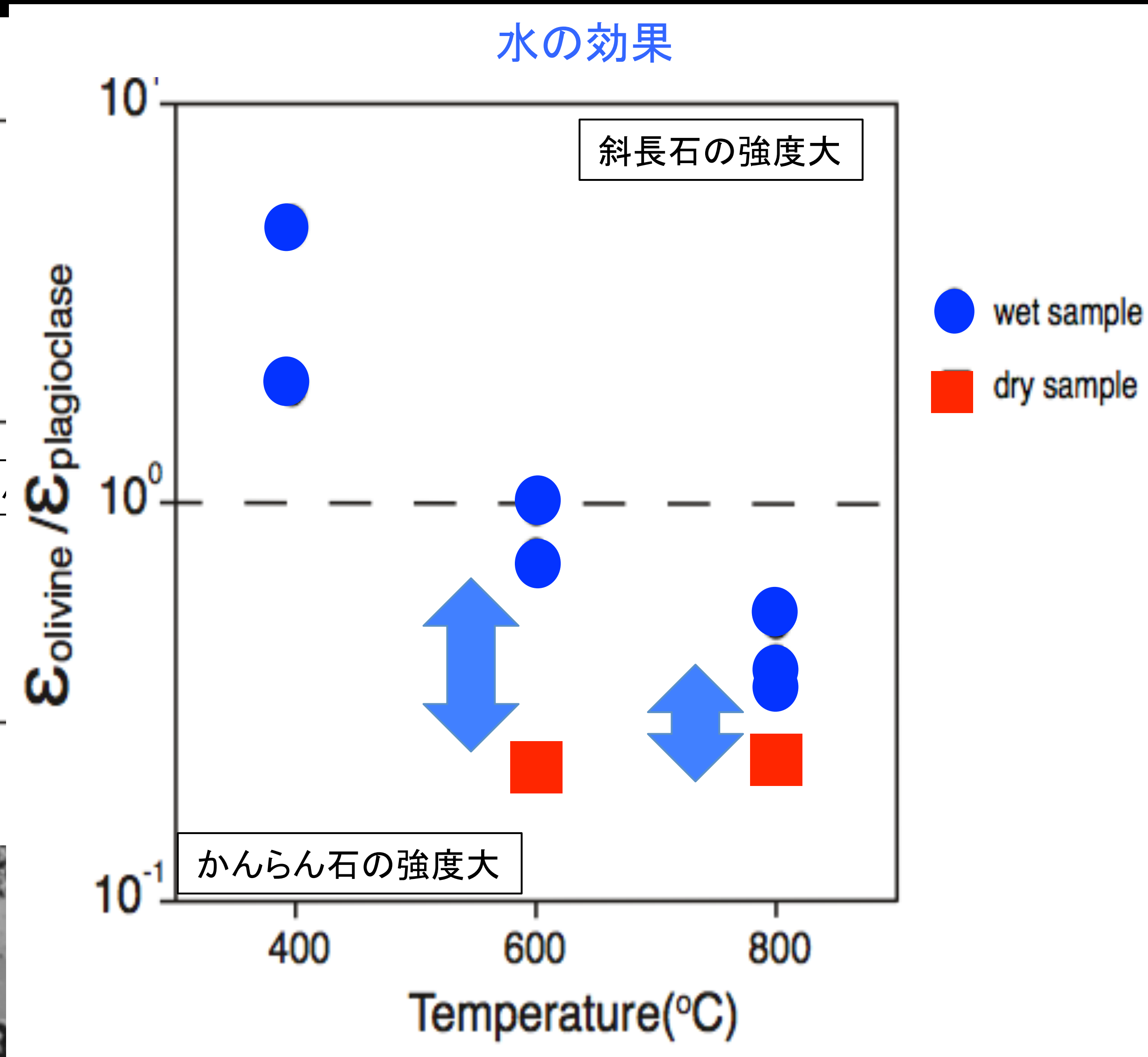
とかんらん石（マントル）の強度比を直接決定！！

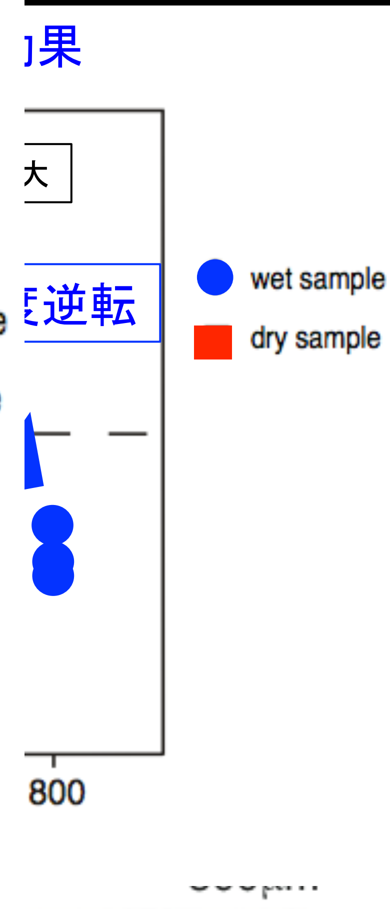
・斜長石とかんらん石の変形実験結果

(wet条件)

(dry条件)







(dry)
かんらん石＞斜長石

相対強度逆転

- Why is plate tectonics important??

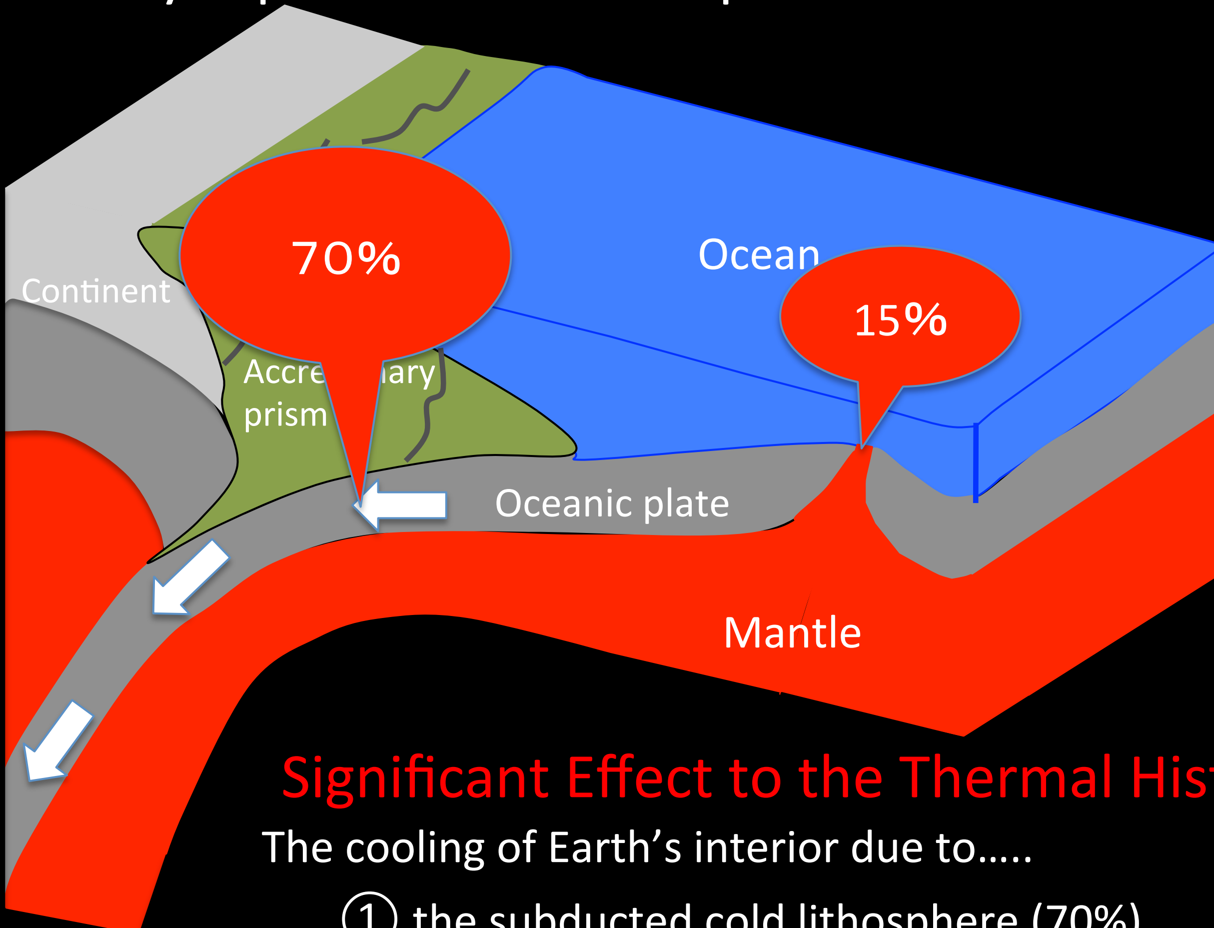


Plate tectonics induces.....

- Earthquake
- Accretionary prism
- Transport of water to the mantle
- Metamorphic rock
- Recycle of plate

etc.....

Significant Effect to the Thermal History of Earth

The cooling of Earth's interior due to.....

① the subducted cold lithosphere (70%)
② hot mantle plumes (15%)
③ delamination (partial subduction) of the lithosphere (15%)

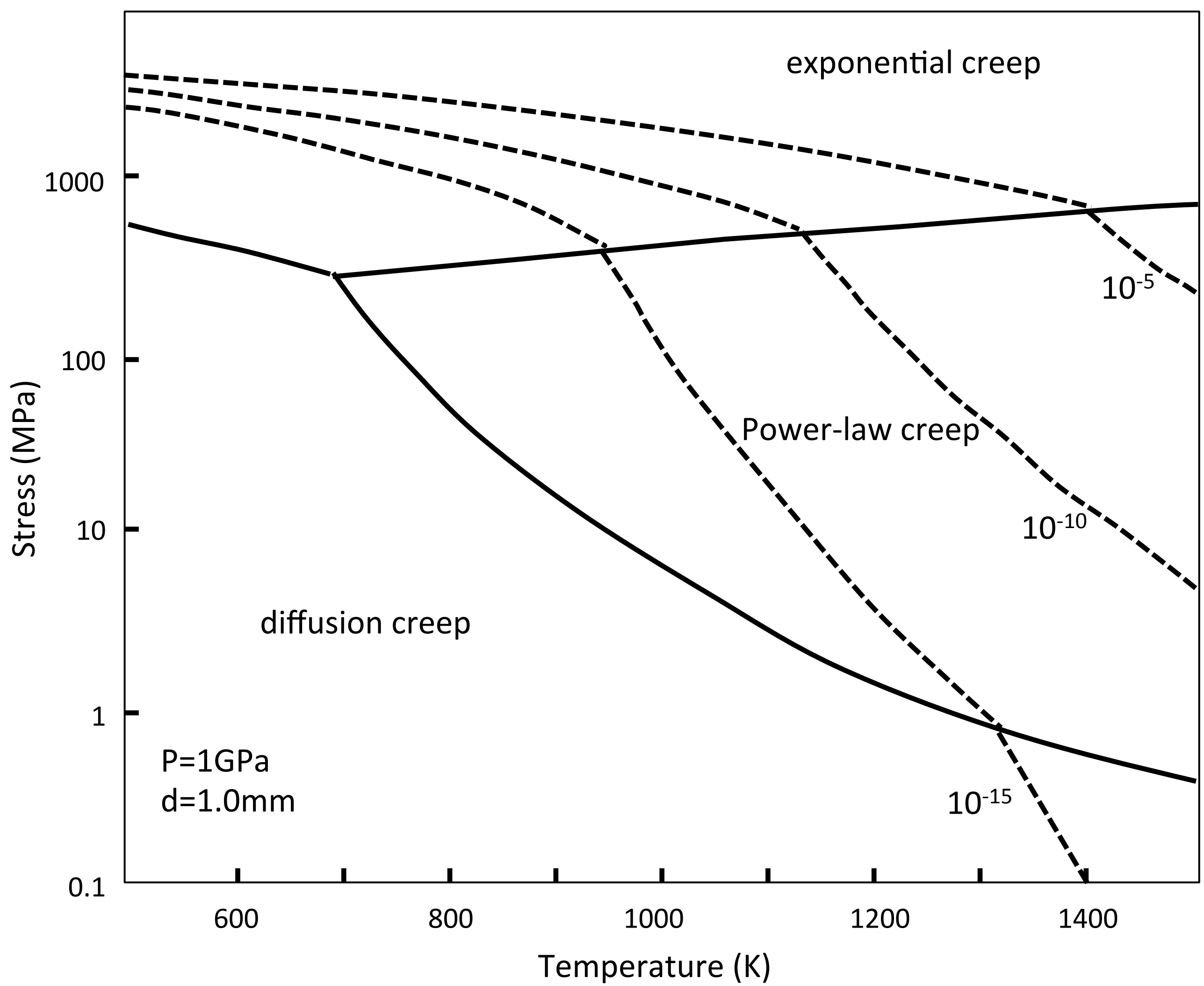
(Turcotte et al., 1999)

And plate tectonics is one of the most important material circulation on the Earth.

⇩

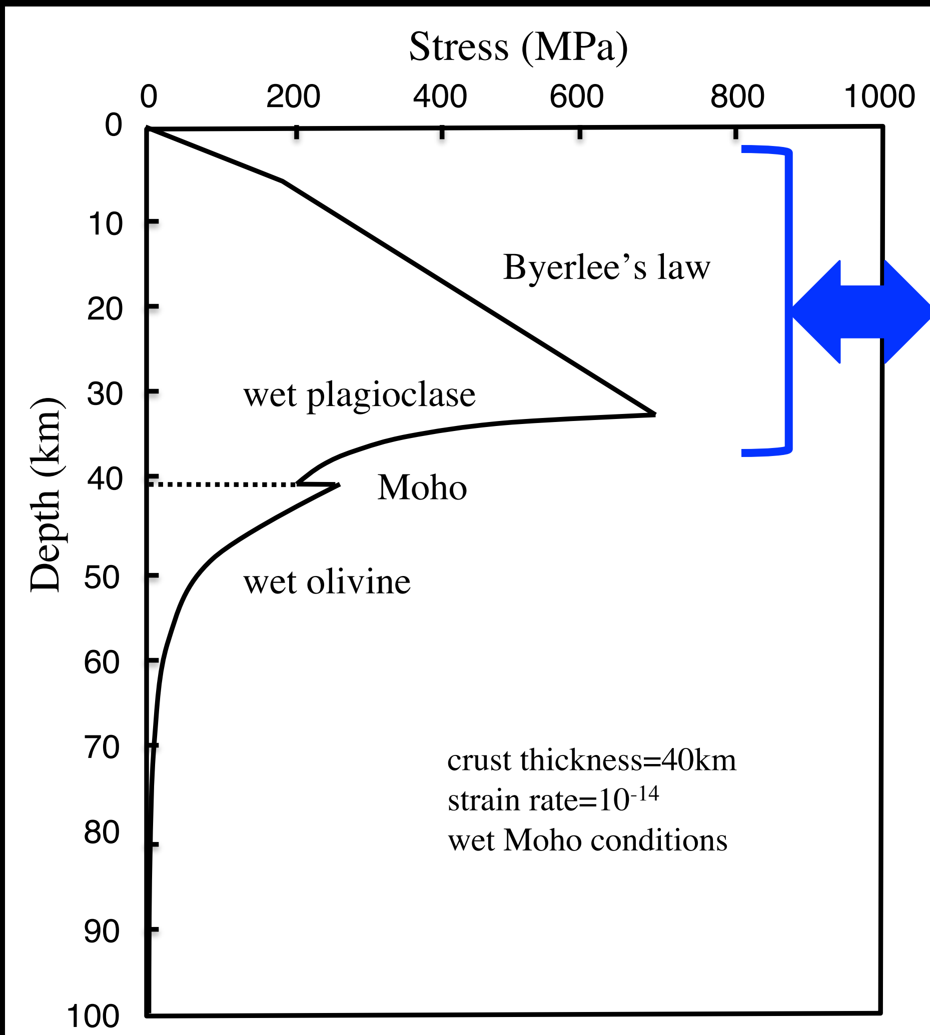
Plate tectonics is one of the most important factor to compare the history of planets.

Deformation mechanism map (Dry Olivine)



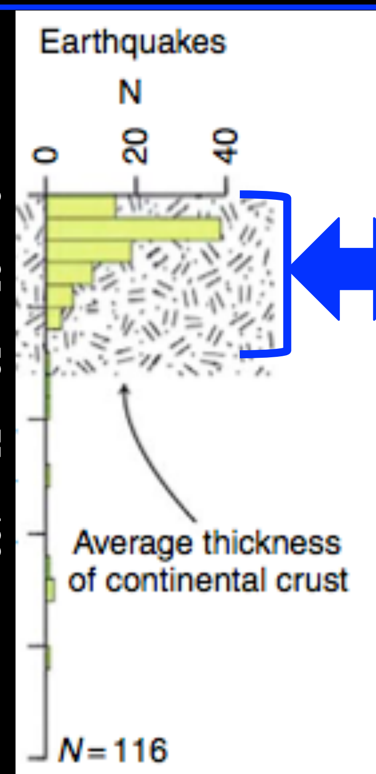
Earth

・What does happen in case of crème brulee????



（In case of crème brullee）
Strength of continental lithosphere reside in crust. Therefore occurrence of earthquake concentrates on crust.

Actually, earthquake often occurs in crust, and earthquake in mantle is very rare. (Watts and Burov, 2003)

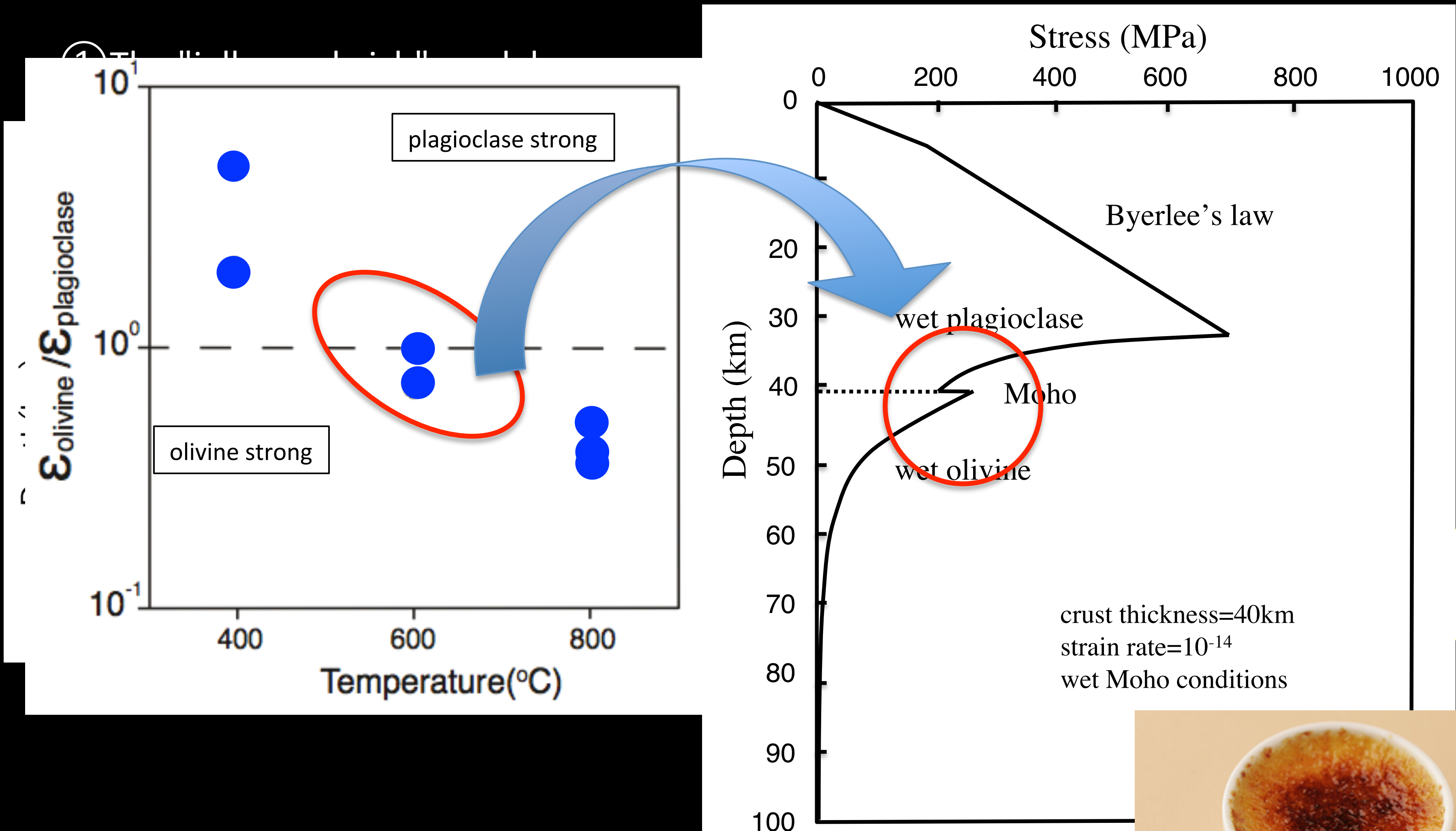


concentration of earthquake in crust

(Burov, 2007)

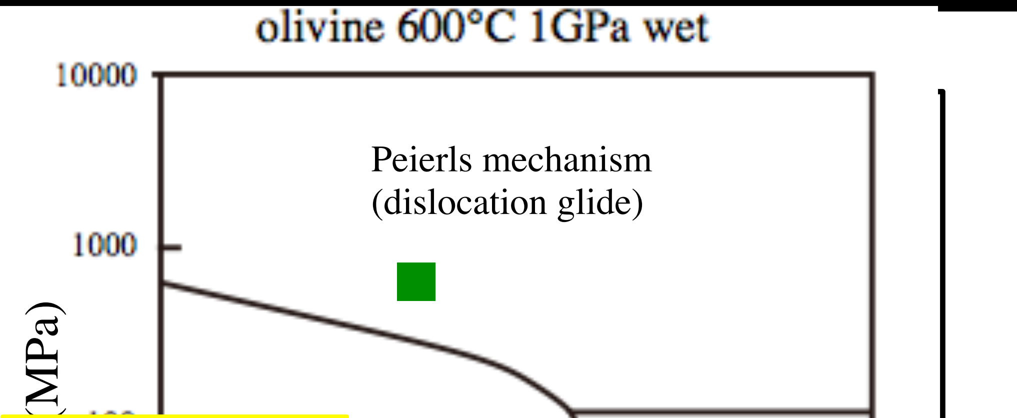
Earth

· The results of wet sample are applied on the Earth's Moho.



From our experimental results using wet sample, the creme brullee model is expected as structure of continental lithosphere.

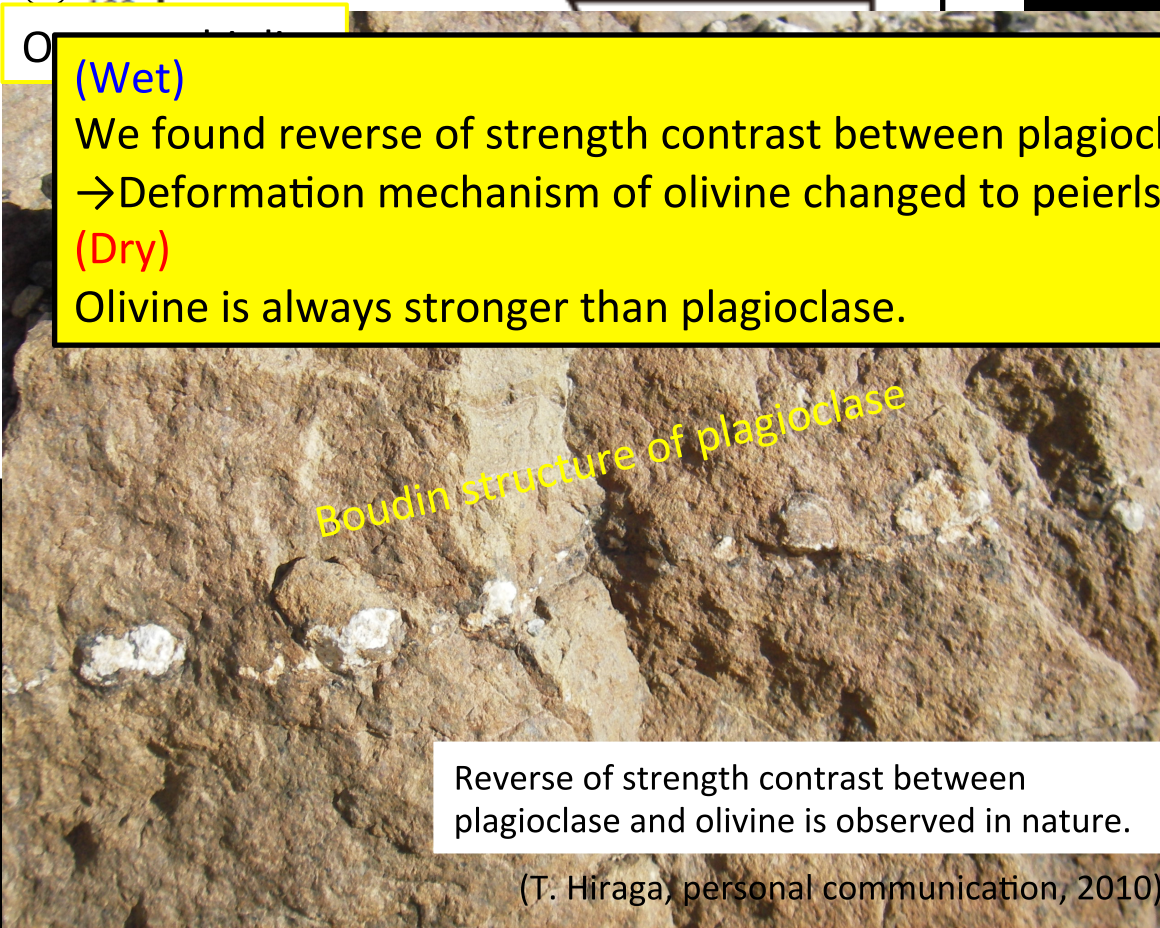
Reverse of strength contrast due to change of deformation mechanism



（Change of deformation mechanism of olivine）

high T		low T
Power-law (dislocation climb)	→	Peierls mechanism (dislocation glide)

(Wet)
We found reverse of strength contrast between plagioclase (lower crust) and olivine (mantle).
→Deformation mechanism of olivine changed to peierls mechanism at low temperature.
(Dry)
Olivine is always stronger than plagioclase.



Reverse of strength contrast between plagioclase and olivine is observed in nature.

(T. Hiraga, personal communication, 2010)

eierls mechanism

$$= AC_{OH}^{r}\sigma^{2}\exp\left\{-\frac{E+PV}{RT}\left(1-\frac{\sigma}{\sigma_p}\right)^{2}\right\}$$

(Katayama and Karato, 2008)

; stress H_0; activation enthalpy P; pressure ε; strain rate
T; temperature C_{OH}; water contents σ_P; Peierls stress

elatively strong chemical bonding such
emperatures.

Venus

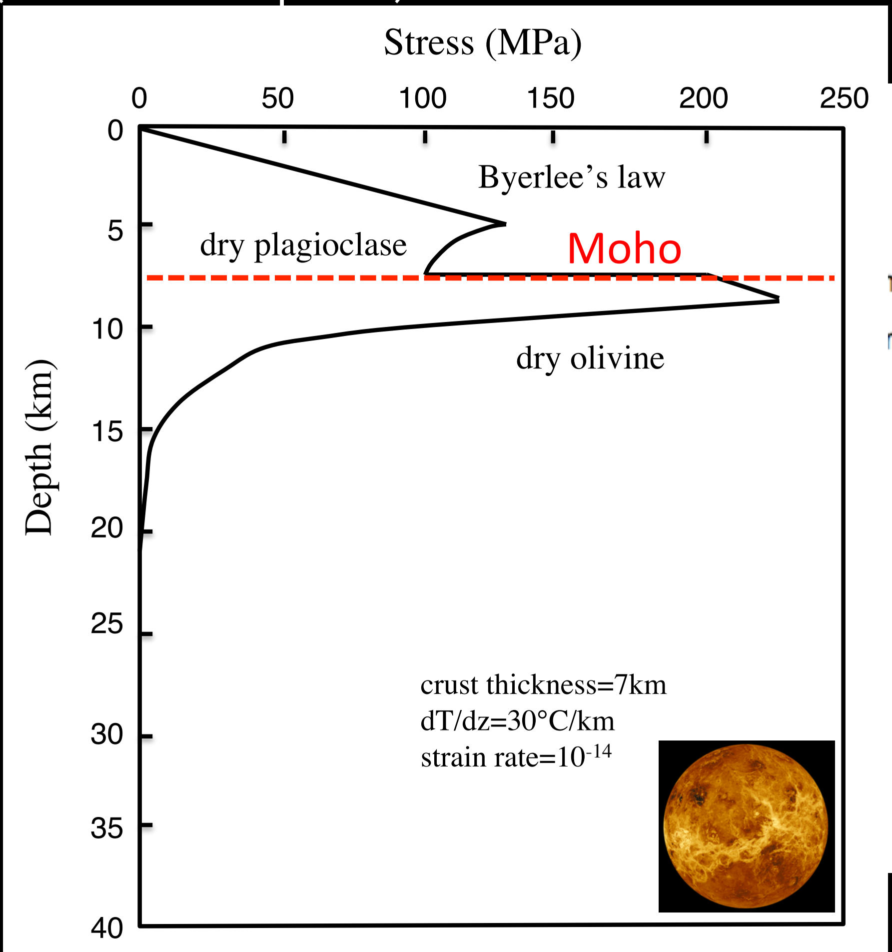
→ Very dry planet. So the results of dry sample are applied on Venus.

Surface temperature 470℃

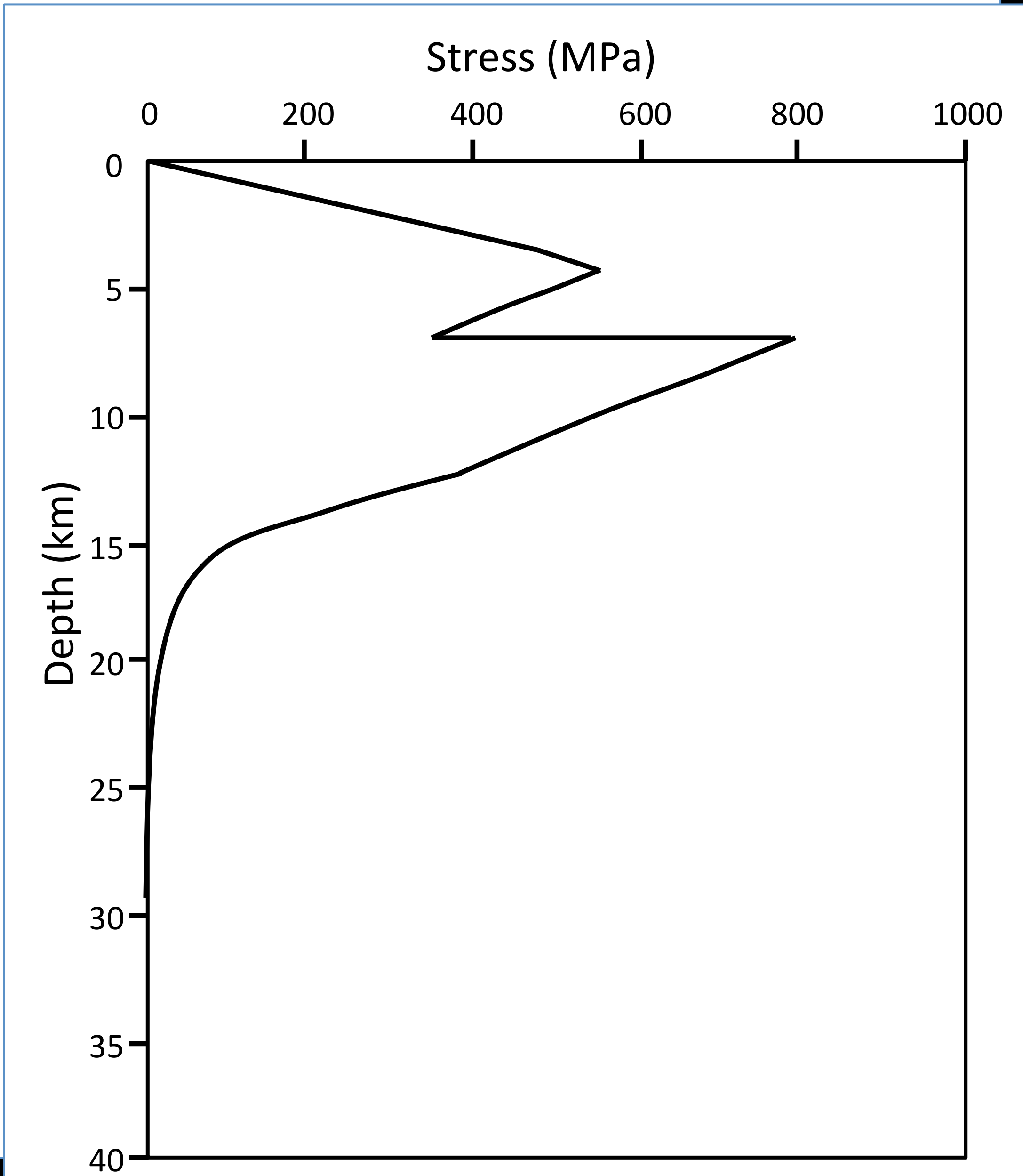
（Current Venus is assumed….）

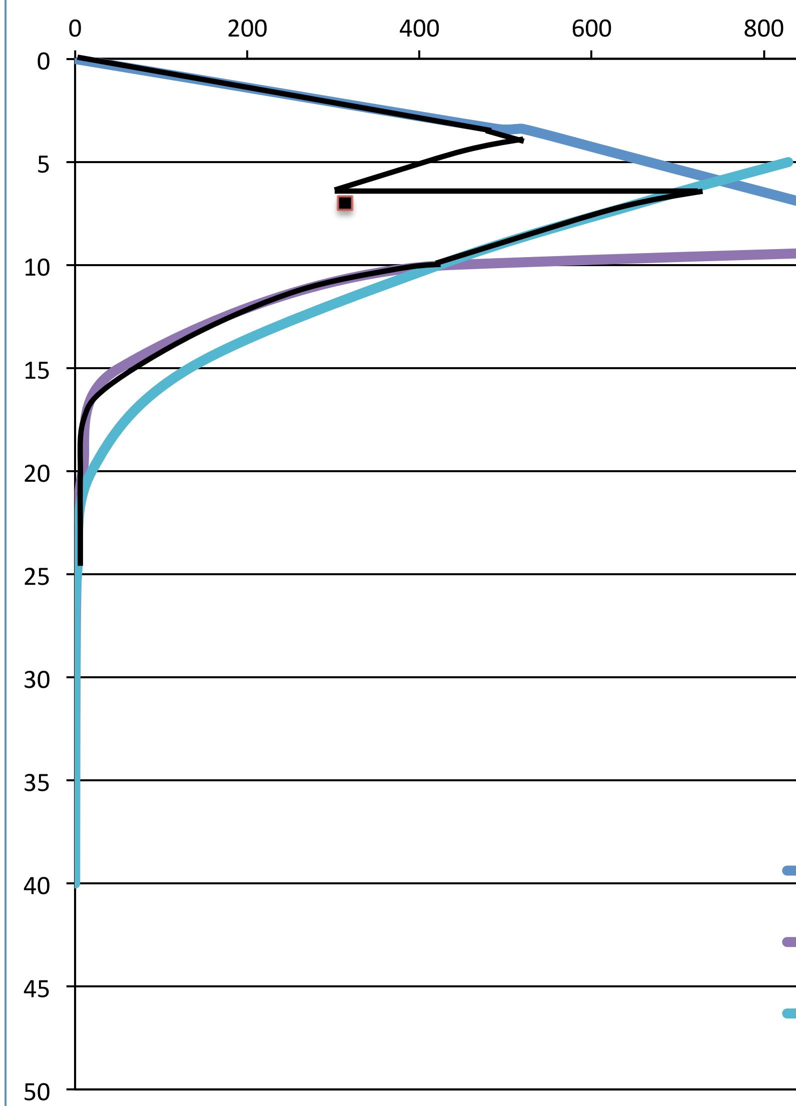
crustal thickness=7km、thermal gradient=20K/km、strain rate=10^{-14}

（Venus's lithosphere）

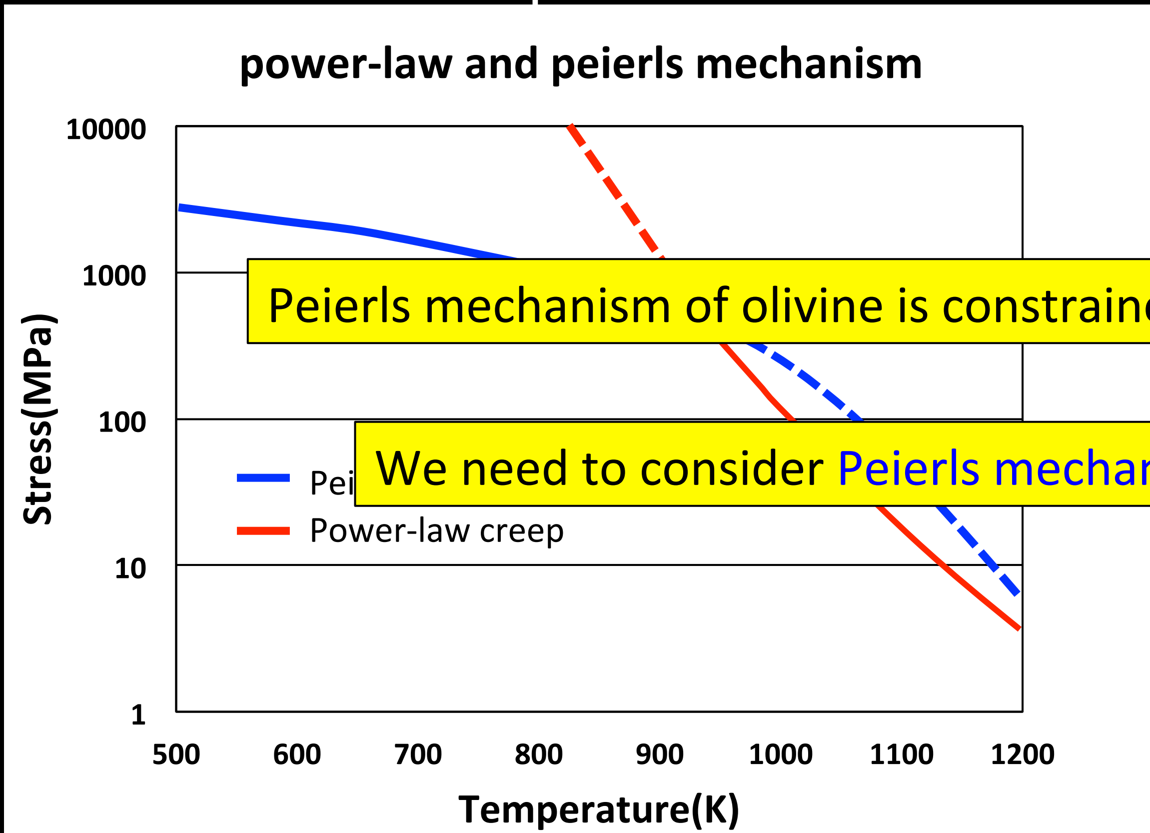


In case that same stress is applied, plagioclase is deformed faster than olivine. So very soft!!!


Stress (MPa)
0
200
400
600
800
1000
0
5
10
15
20
25
30
35
40
Depth (km)


0
200
400
600
800
0
5
10
15
20
25
30
35
40
45
50

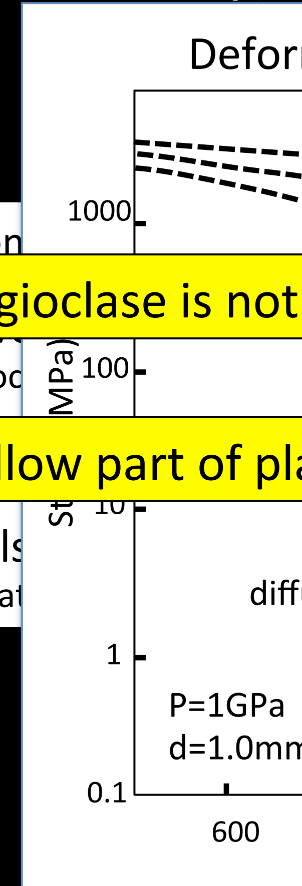
・Power-law creep is suitable?? （Problem point of previous study)



（Change of deformation

high Temp. Pow (disloc

low Temp. Peierls (dislocat



Peierls mechanism of olivine is constrained well. However plagioclase is not

We need to consider Peierls mechanism at relatively shallow part of pla

Power-law

$$\dot{\varepsilon} = A C_{OH}^{r} \exp\left(\frac{-(E+PV)}{RT}\right)\sigma^{3}$$

(Karato and Jung, 2003)

Peierls mechanism

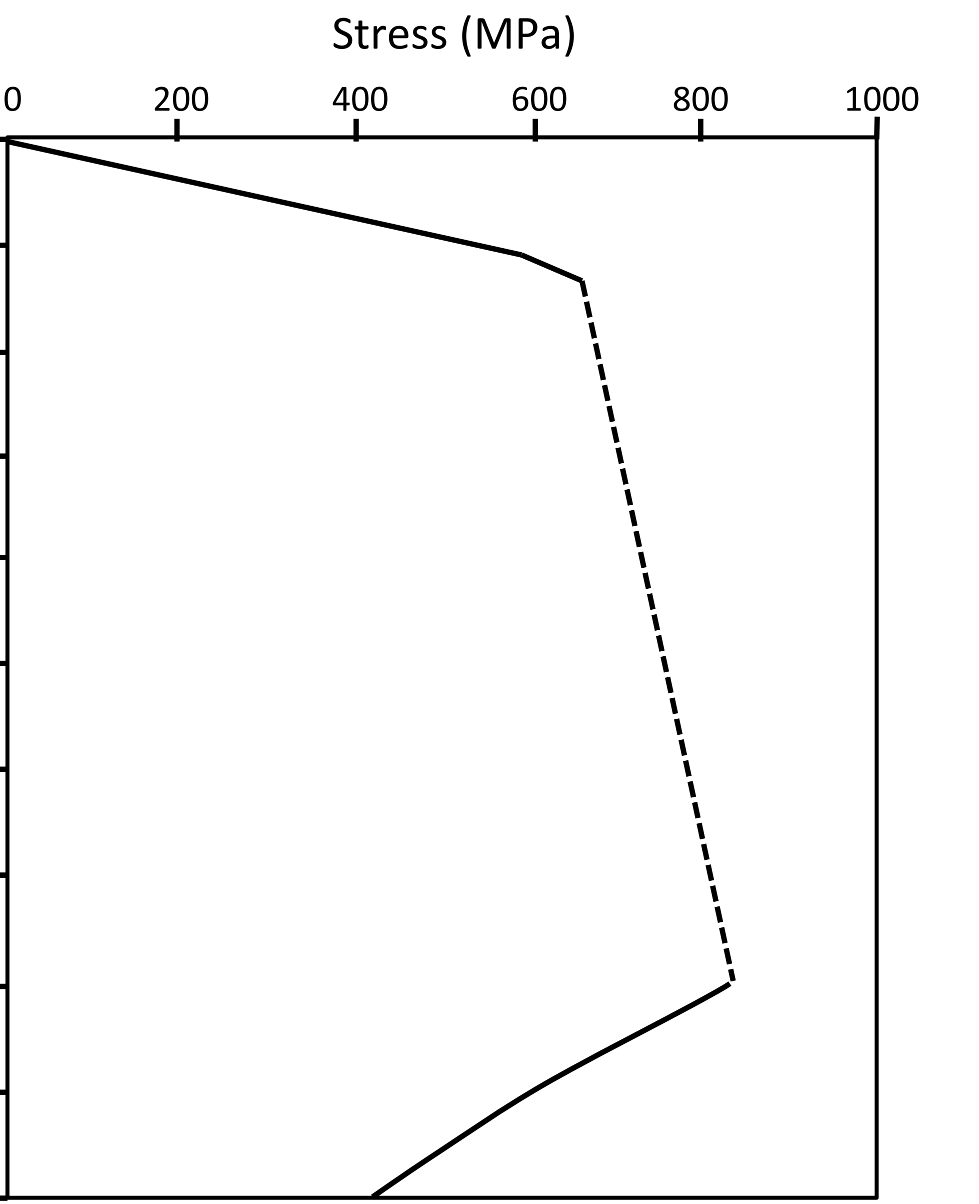
$$\dot{\varepsilon} = A C_{OH}^{r} \sigma^{2} \exp\left\{-\frac{E+PV}{RT}\left(1-\frac{\sigma}{\sigma_{p}}\right)^{2}\right\}$$

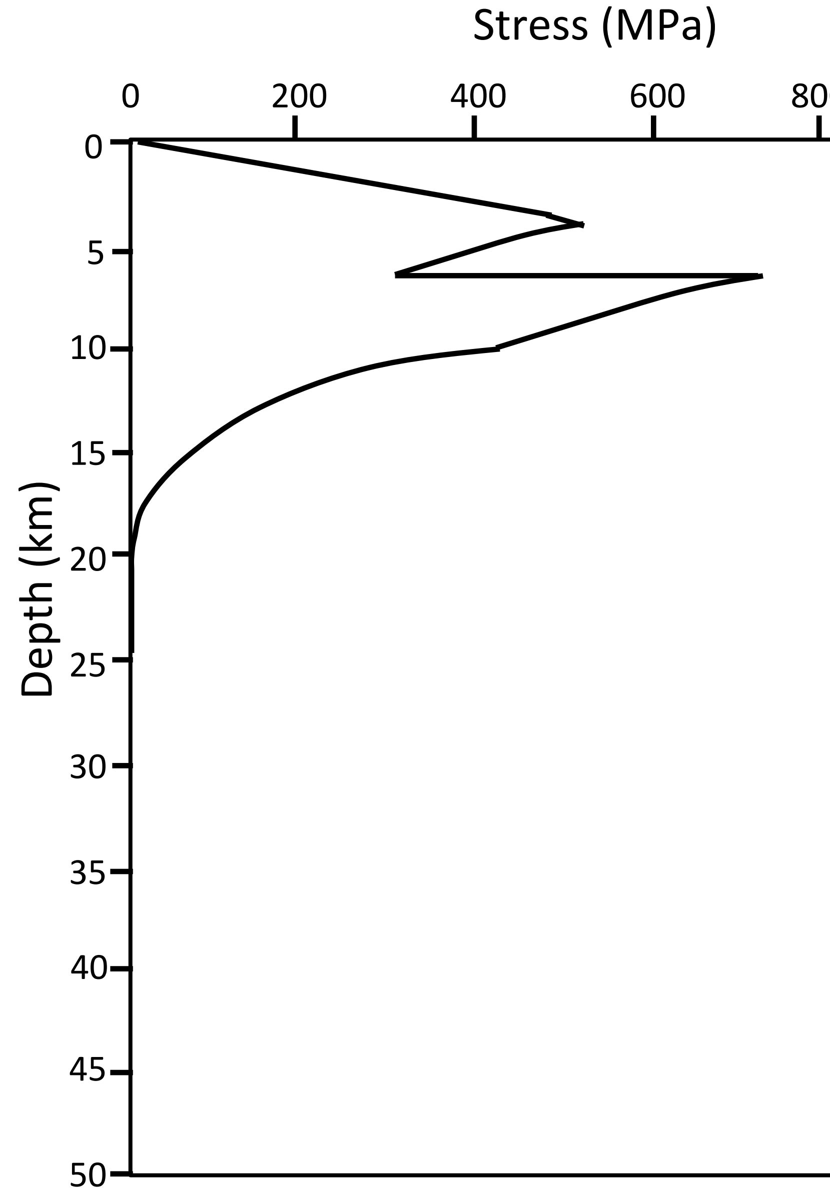
(Katayama and Karato, 2008)

(A; const. σ; stress E; activation energy P; pressure ε; strain rate
R; gas const. T; temperature C; water contents V; activation Volume)

(A; const. σ; stress H_0; activation enthalpy P; pressure ε; strain rate
R; gas const. T; temperature C_{OH}; water contents σ_P; Peierls stress)

Tsenn and Carter(1987) reported that in materials with a relatively strong chemical bonding such as silicates, Peierls mechanism becomes dominant at low temperatures.


Stress (MPa)
0
200
400
600
800
1000


Stress (MPa)
0
200
400
600
80
Depth (km)
0
5
10
15
20
25
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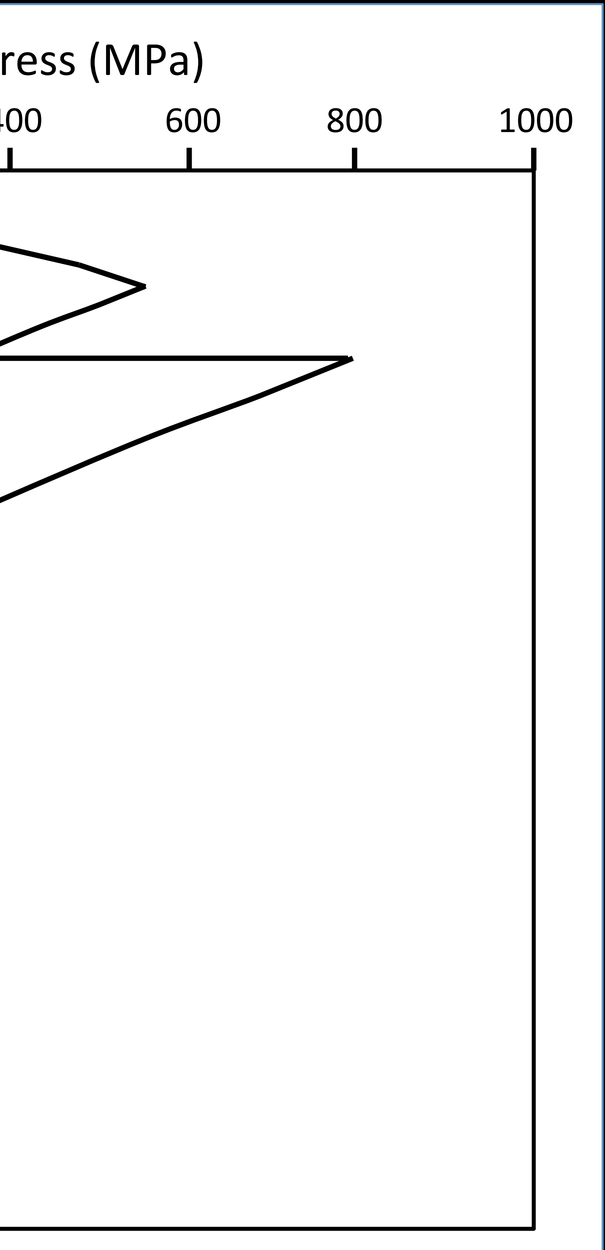
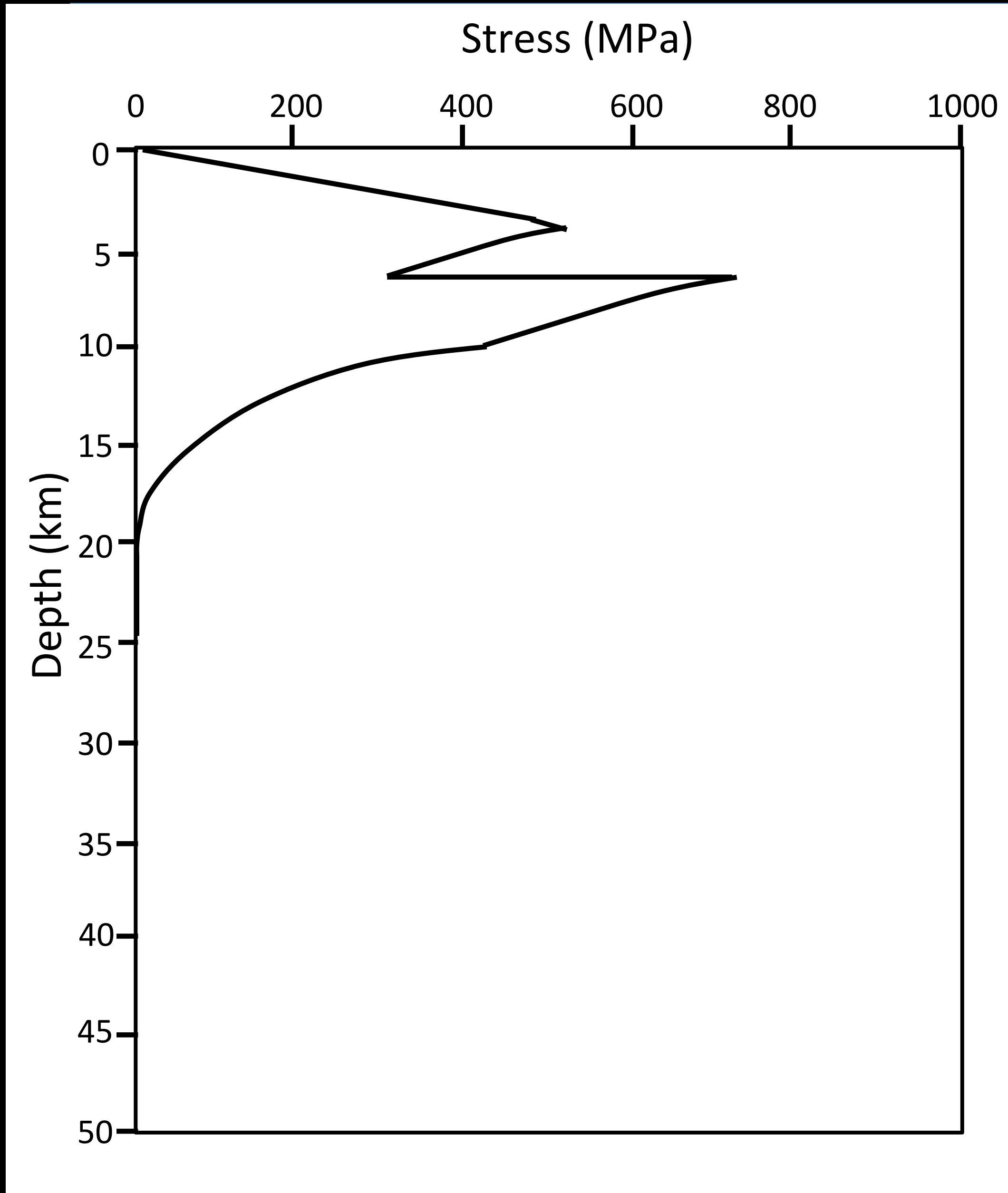
35
40
45
50



ress (MPa)
400
600
800
1000



Stress (MPa)
0
200
400
600
800
1000
Depth (km)
0
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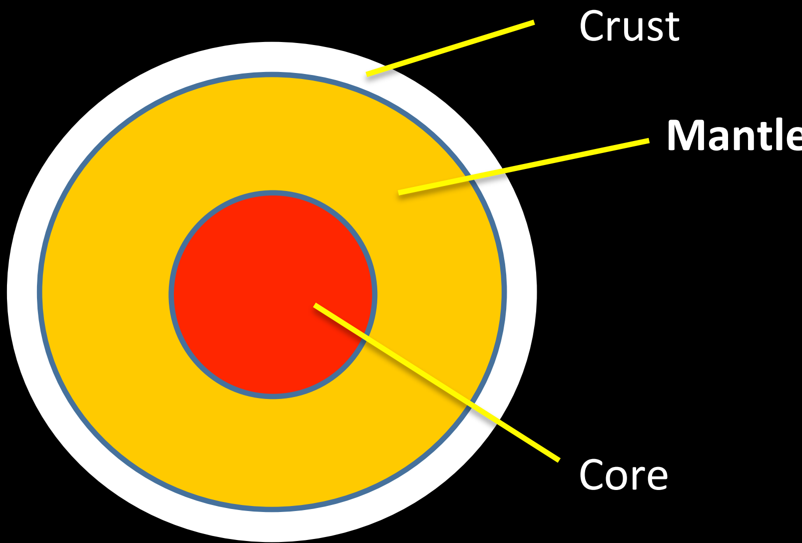
- Earth and Venus …twin planets!?



Because of density, mass, size and distance from the Sun,
Venus has been regarded as a "twin planet" to the Earth.

Magellan mission（1989-1994）reported two important results.

①No evidence for a global pattern of accretional plate margin and subduction zone.
②The age of surface of Venus is nearly uniform.

Water
abundance
nothing?

93290hP
a

(e.g., NASA's data)

➡ Why does plate tectonics not work on Venus??

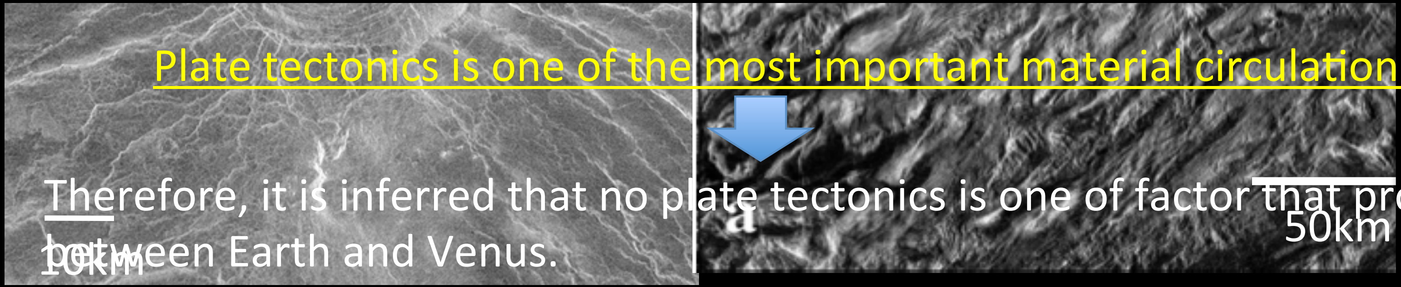


Plate tectonics is one of the most important material circulation.

Therefore, it is inferred that no plate tectonics is one of factor that produce the difference between Earth and Venus.