ESS2222H

Tectonics and Planetary Dynamics
Lecture 6 – Plate Tectonics & Habitability

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Plate Tectonics
A Crucial Component for the Habitability of the Earth

Plate tectonics

One of the **key factors** in the habitability and evolution of life (e.g., the stabilization the planet's **climate** by regulating the global **carbon cycle**)

Earth - The only known habitable planet with active plate tectonics

Habitability

In order a planet to be **habitable**, it should have a **suitable atmosphere** and **water** which is possible with the existence of **bio-elements** as **Carbon**, **Hydrogen**, **Oxygen**, and **Nitrogen**

Uncertainty

Even in the case of **Earth** for which we have **data** from **continents** and **cratons**, there is **no established mechanism** for the **initiation of subduction** and the **onset** which ranges from about **4 billion years ago** to about to about **700 or 800 million years ago.**

Tectonics Regimes

Stagnant-lid regime

The most common and **natural style** of mantle convection observed in our solar system where the heat is transferred by **advection** and **conduction** from the interior of planet to the **base of lithosphere** and radiated to space by **conduction** and **volcanism** through lithosphere.

Mars and **Venus** have no active tectonics (moving plates) and their present tectonic regime is a stagnant lid regime **(single plate planets).**

Mars

Mars is a **single-plate planet**. Stagnant-lid convection is a plausible mechanism for Mars to cool. Mars has the **solar system's largest volcano** (non-active) along with its **biggest canyon**. Present day crust of Mars is thick, so the molten rock from deep levels cannot reach the surface.

Venus

Present day Venus is in a **stagnant lid regime**, however, it is suggested that Venus had a **large resurfacing event in the past**.

Tectonics Regimes

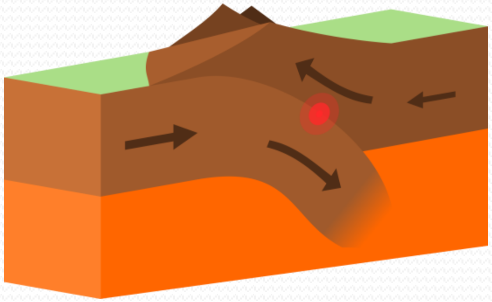
Mercury

Mercury is **one-plate planet** with no plate tectonics, Numerical models support a **weak mantle convection** supporting the outer core dynamo explanation of **Mercury's intrinsic magnetic field**. Some studies suggest that **major volcanic activity** on Mercury most likely ended about **3.5 billion years ago**.

Difficulty of Initiation

The difficulty is related to the mechanism responsible for the onset of plate tectonics from stagnant-lid convection regime.

So the **initiation** of plate tectonics is a **challenging** process where a buoyant highly viscous layer at the surface has to be pulled into the hot mantle.



Habitability

Optimistic Habitable Zone

The graph in the next slide is showing the **habitable boundaries** for some **solar system planets** and some **other exoplanets** in terms of the temperature of the host star and amount of light that the planet receives.

The rightmost boundary between **blue** and **yellow** lines is **conservative** habitable zone (a higher likelihood for life).

Earth – Mars -Venus

Here as you can see **Earth** and **Mars** are **inside the conservative habitable** zone but **Venus** is **outside of this boundary.**

Life Under Extreme Hot Conditions

Life could still exist within the left boundary (between **yellow** and **red** lines) but the **surface conditions are hot**.

Habitable Zones

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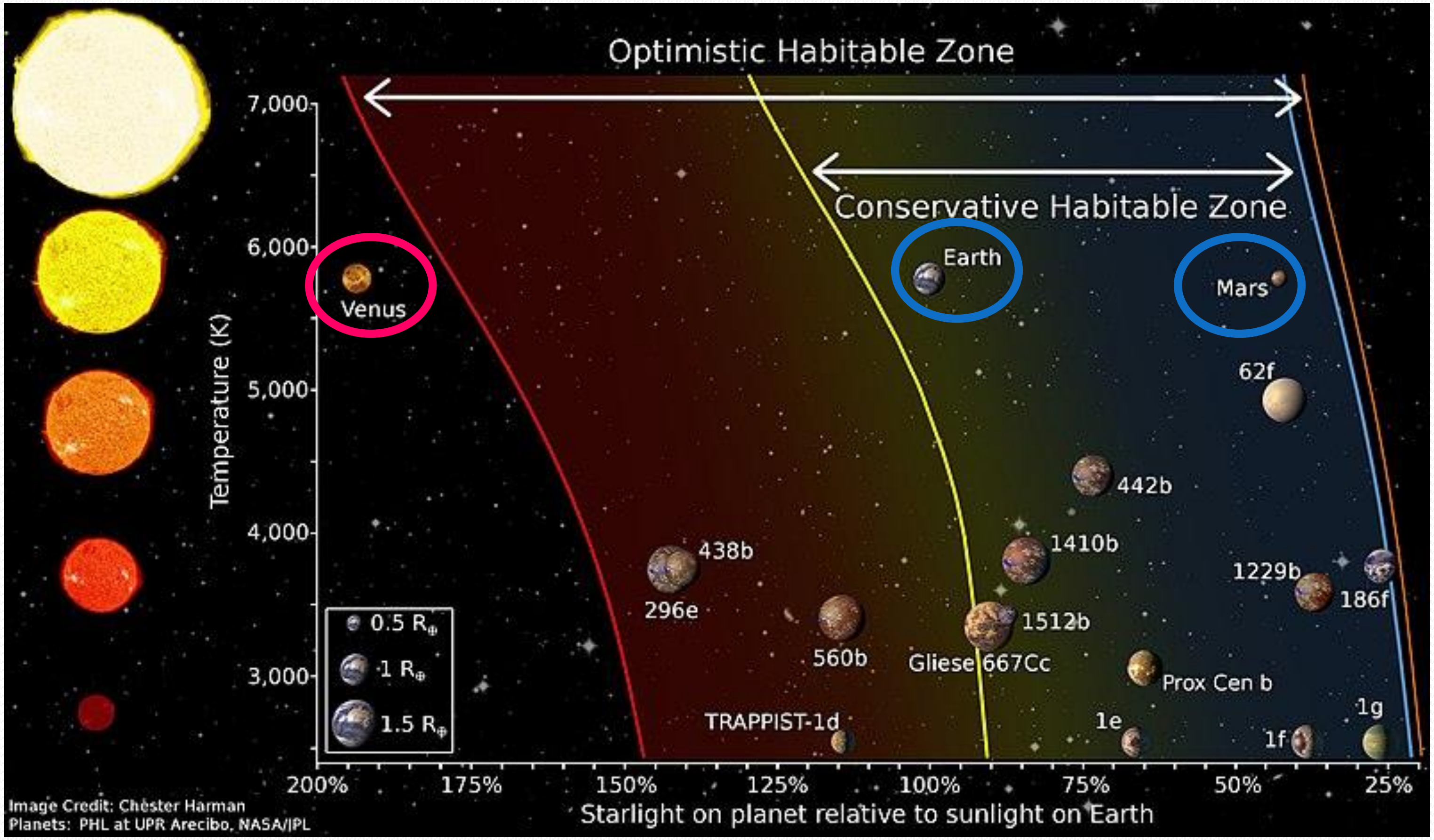
Star surface temperature



A diagram depicting the habitable zone boundaries around stars (Chester Harman).

Relative Starlight (~Distance)

Plate Tectonics on the Earth

Driving forces in plate tectonic

Convection Forces

Heat driven convection of mantle fluid exerts lateral forces at the base of lithosphere which can cause plate motion.

Slab pull

Slab pull is that part of the motion of a tectonic plate caused by its subduction. Plate motion is partly driven by the weight of cold, dense plates sinking into the mantle at oceanic trenches (strongest force among driving plate motion).

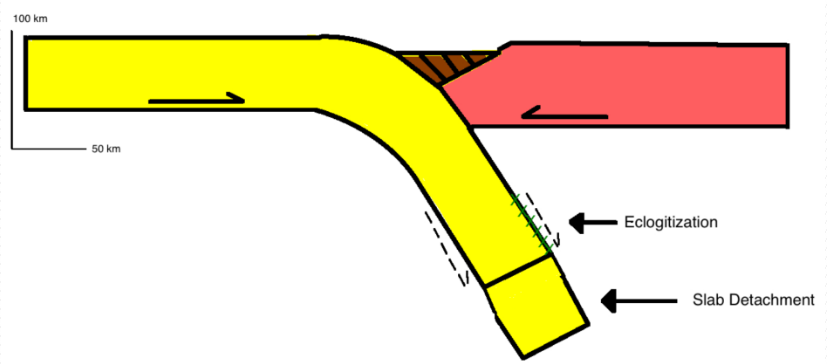


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Plate Tectonics on the Earth

Ridge Push

Ridge push (gravitational sliding) occurs at mid-ocean ridges as the result of the rigid lithosphere sliding down the hot, raised asthenosphere below mid-ocean ridges.

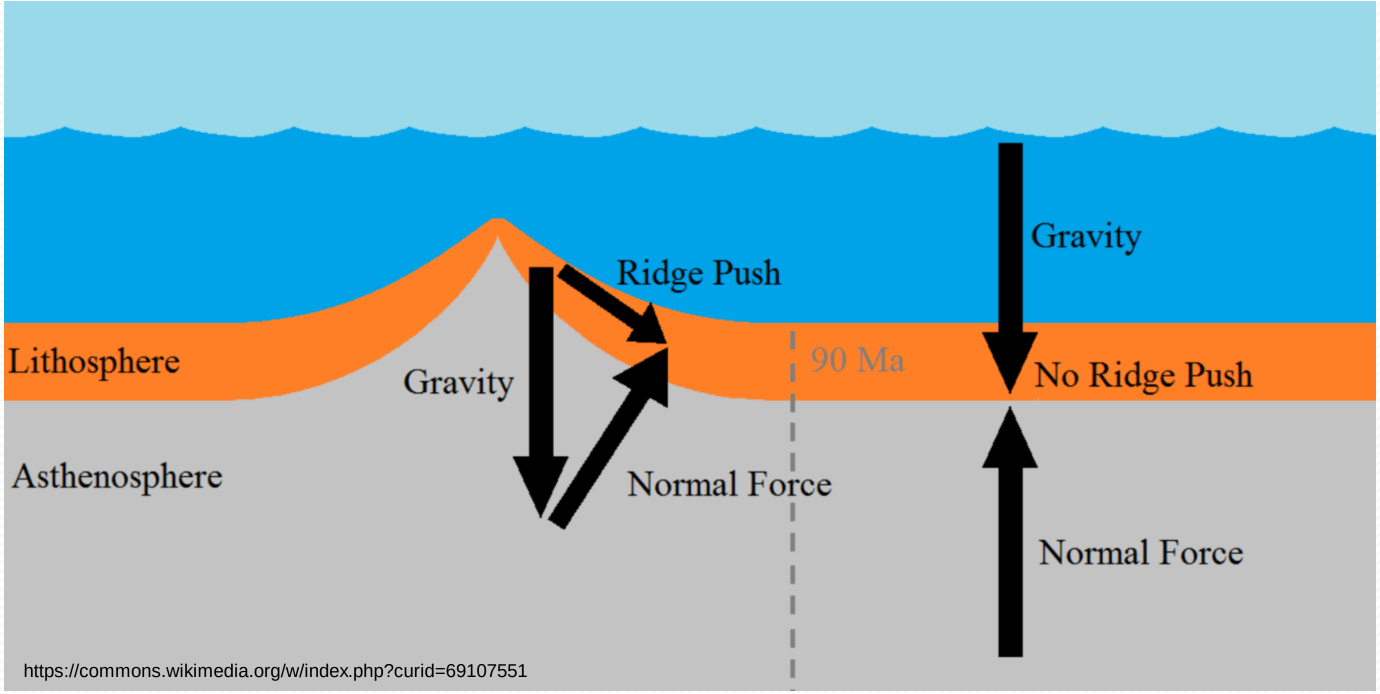


Plate Tectonics on the Earth

Slab Suction (Trench Suction)

Slab suction is one of the four main forces that drive plate tectonics. It creates a force that pulls down plates as they are subducting and speeds up their movement, creating larger amounts of displacement (Forsyth and Uyeda, 1975). Trench Suction can be created by a small-scale convection in the mantle wedge, driven by the subducting lithosphere.

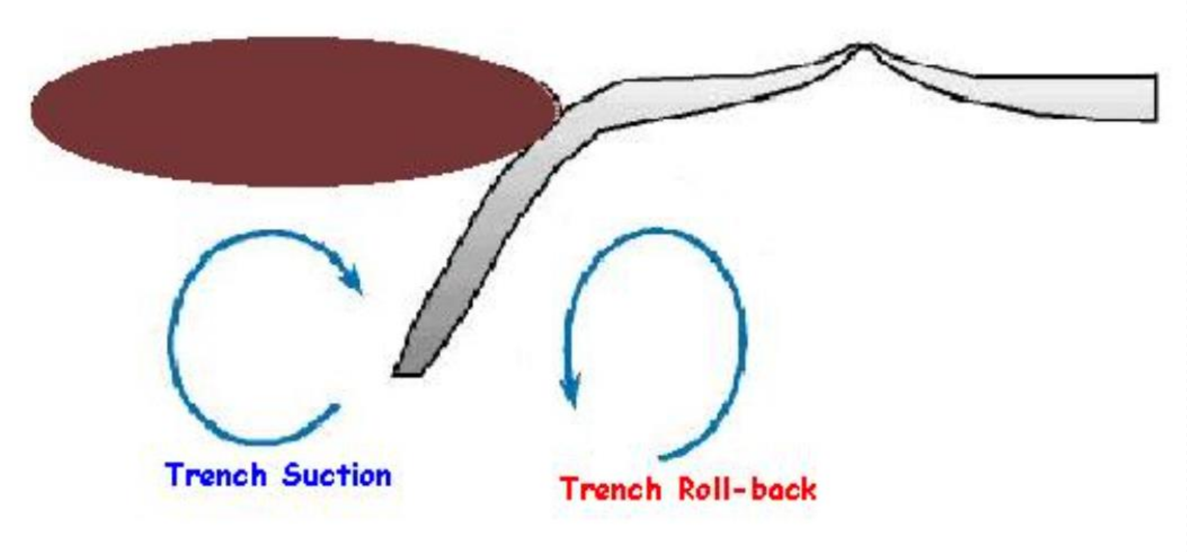
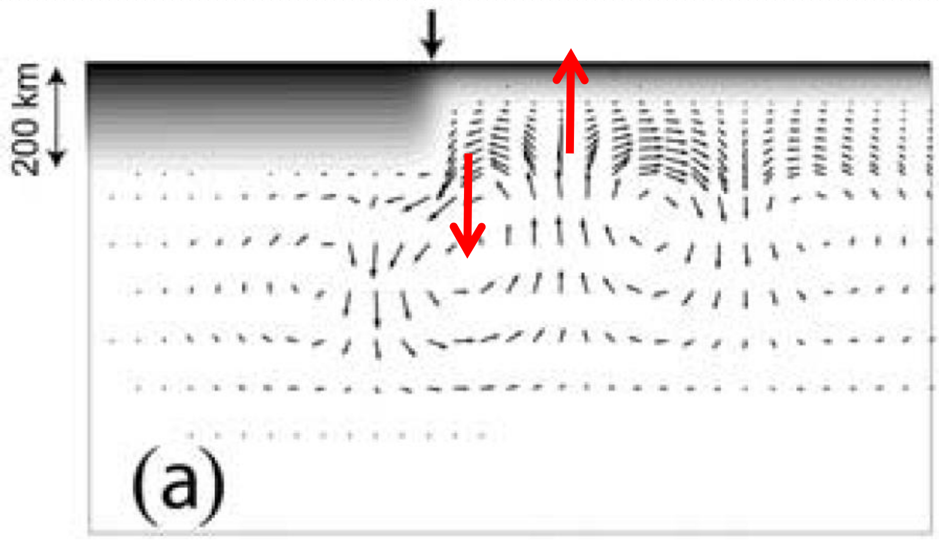


Plate Tectonics on the Earth

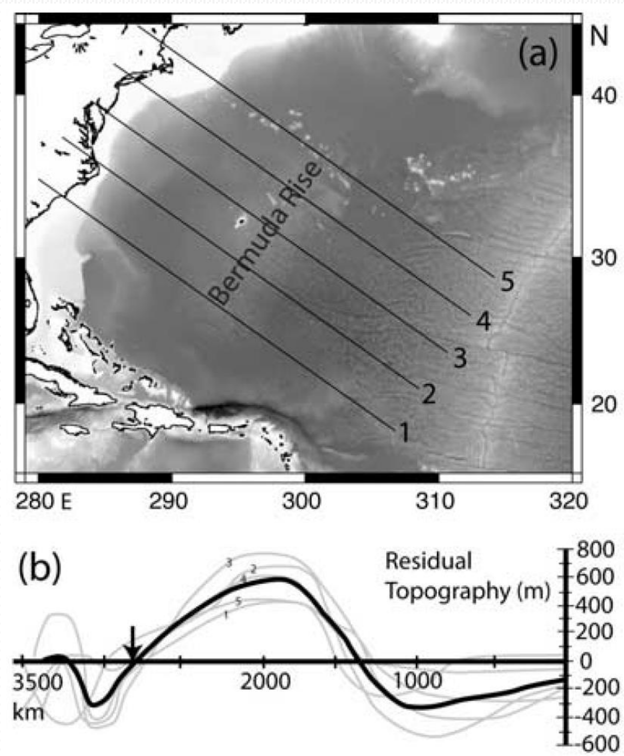
Edge Driven Convection

Edge-driven convection (EDC) is a **small scale convection** in the **upper mantle** at locations of **lithosphere thickness gradients**, e.g., craton edges, as a consequence of **thermal flow** at the edge.



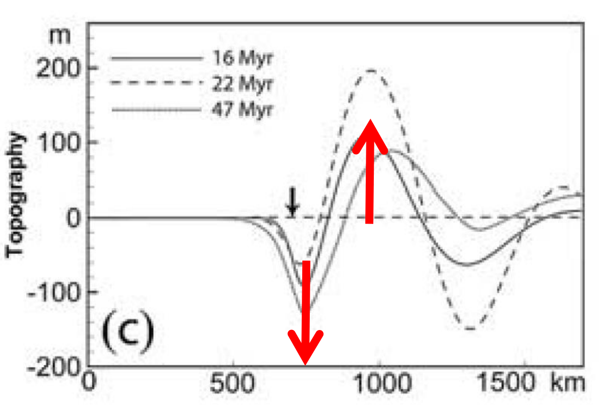
. Temperature fields and flow velocity vectors

(Shahnas & Pysklywec, 2004)



a) Bathymetric map of the western North Atlantic region. (b) Profiles of residual topography across the sections shown in (a) and an averaged section (bold solid line).

Plate Tectonics on the Earth



Profiles of surface topography at time intervals as indicated. Arrow marks the location of the continent-ocean boundary (Shahnas & Pysklywec, 2004).

The western Atlantic region contains a long wavelength intraplate topography anomaly that is defined by the NE-SW trending Bermuda Rise and two adjacent topography lows. Numerical experiments suggest that the anomalous topography may be the surface response to edge-driven convection (Shahnas & Pysklywec, 2004). King and Ritsema (1998) speculate that such convection cells may explain the occurrence of **seafloor volcanism** in intraplate environments on the South American and African plates. Conrad et al. (2004) proposed that an anomalously deep region off the coast of Nova Scotia may be caused by the downgoing portion of a potential edge-driven mantle convection cell.

Initiation of Plate Tectonics on the Earth

ABEL Theory

The initiation of plate tectonics is triggered during the **ABEL** ((advent of bioelements) Bombardment, which delivered **oceanic** and **atmospheric components** on a completely dry reductive Earth, originally comprised of **enstatite chondrite-like materials.**

The Shift from Stagnant-lid Tectonics to Modern Plate Tectonics

- The Earth was formed as a **dry reductive planet** at 4.567 Ga. The early Hadean was dry rocky planet with no ocean and atmosphere.
- ABEL Bombardment occurred in the **middle Hadean** (4.37-4.20 Ga) by bombardment of **carbonaceous Chondrites** as a result of the gravitational disturbance of asteroid belt caused by Jupiter, Saturn, and another missing gas giant (Maruyama et al., 2018).

Initiation of Plate Tectonics on the Earth

- Initially a region of **1000 km across** impactor impacted and the rigid continental lithosphere (stagnant lid: ~ 100-150 km thick) was destroyed. A **Pacific Ocean size crater** (10000 km) was created, and oceanic lithosphere was generated on the surface.

- Through the ABEL Bombardment, **Volatiles** including **water** were delivered from outer asteroid belts and accumulated as ocean gradually, as well as **penetrated** into the **interior** of the Earth through bombardments.

- **Eclogitization** started after volatiles were delivered by ABEL Bombardment. ABEL Bombardment caused **eclogitization** of **primordial continental crust** at both upper and lower levels.

- The presence of **volatile** is very **critical** factor for the **phase transition** as **eclogitization**.

- **Eclogitization facilitated** to **initiate the operation** of **plate tectonics** at bi-modal lithosphere (continental curst and oceanic crust).

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Initiation of Plate Tectonics on the Earth

- Plate tectonics was initiated by generation **of slab-pull force through eclogitization** of thick KREEP lower crust (100 km) together with **anorthositic** upper crust (21 km thick)

- Associated with **the development of trench line** along the continental margin, mantle upwelling by **plumes made topographic highs** to push up primordial continents, **which generated ridge pull force**.

This is the **ABEL scenario** to shift from stagnant lid tectonics to modern plate tectonics.

Hadean Eon

a) The early Hadean (4.57-4.37 Ga) - From the formation age of dry Earth until the beginning of ABEL Bombardment)

b) The middle Hadean (4.37e4.20 Ga) - Period of ABEL Bombardment

c) The late Hadean (4.20e4.00 Ga) - After ABEL Bombardment and the period to biotic life

Initiation of Plate Tectonics on the Earth

Requirements for Plate Tectonics

a) Presence of **lubricants** in the lithosphere (fluids like H_2O). Water (hydrogen) increases the concentration of **intra-crystalline point defects** and the rock **viscosity decreases** (e.g., Karato and Wu, 1993; Hirth and Kohlstedt, 2003), by a factor of 2-3, suggesting the presence of ocean on Hadean Earth. H_2O is the **most critical factor** for plate tectonics (Maruyama et al., 2018). Water plays an important role in plate tectonics by **reducing the viscosity** of plate (required for **bending** in subduction zone) and acting as **lubricant**.

b) Moderate strength of lithosphere is required to preserve the lithosphere's identity at plate boundaries and in subduction.

c) The existence of a **driving force**.

d) Unlike Earth, there is no active plate tectonics on Venus which is due to the domination of Co_2 in Venues and the **absence of water oceans**.

Initiation of Plate Tectonics on the Earth

Eclogitization

A tectonic process in which the high-pressure, **metamorphic facies, eclogite** (a very dense rock), is formed which **facilitates subduction** of the lithosphere at subduction zones (due to having a higher density).

By **ABEL** Bombardment, **volatiles** were circulated within the interior of the Earth down to mantle depth**, facilitating continuous eclogitization** (Bjørnerud, 2002).

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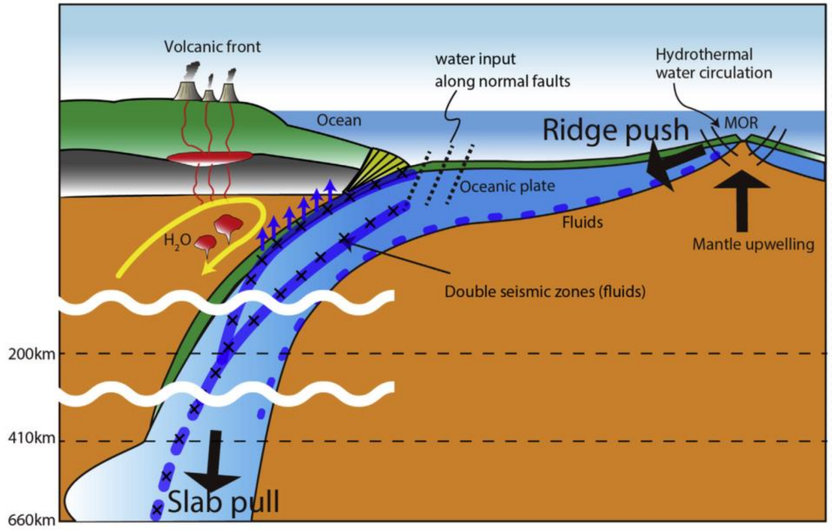

Dehydrated fluid is removed to the upper seismic zones. Fluids released during progressive dehydration play a critical role as lubricant and imparts a slippery top surface of the down-going plate (Maruyama et al., 2018)

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Initiation of Plate Tectonics on the Earth

The eclogite facies form at very high pressures. The impact itself **created high thermal and pressure conditions** which made possible large amount of **eclogitization at the surface**.

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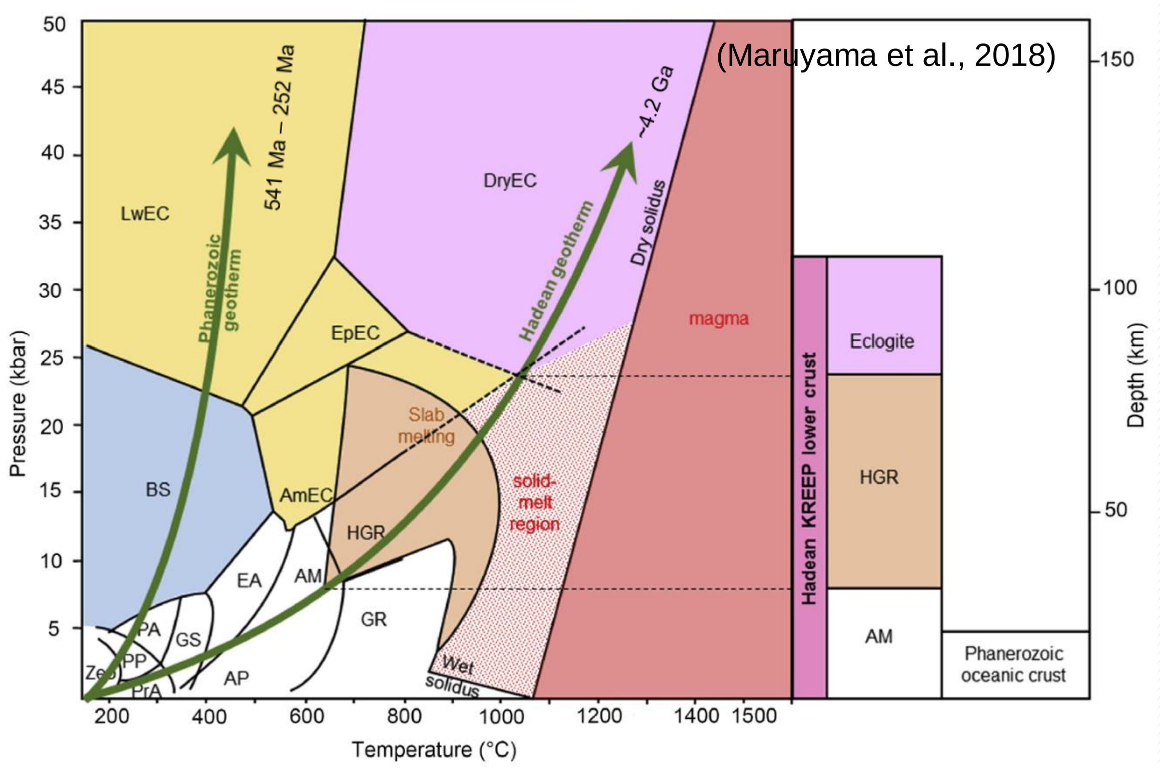
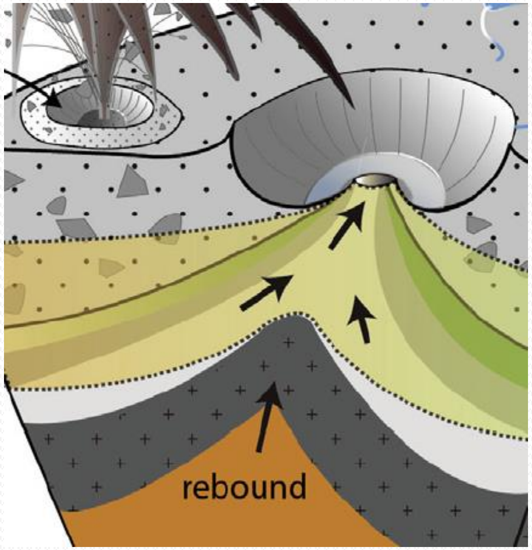




Phase diagram of MORB þ H2O system to explain eclogitization (modified after Maruyama et al., 1996; Okamoto and Maruyama, 2004).

Initiation of Plate Tectonics on the Earth

Plume Induced Subduction

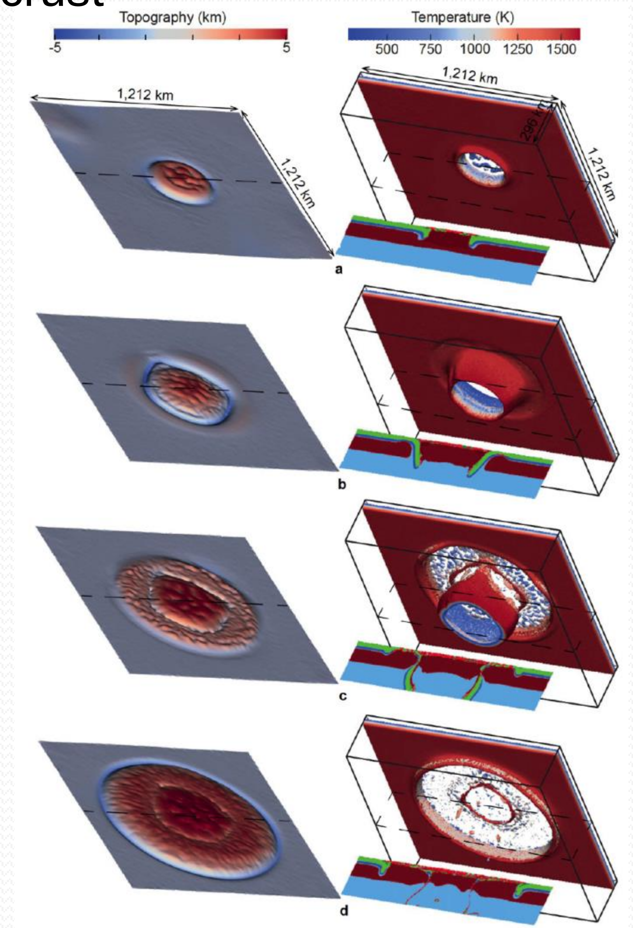
Key factors in triggering self-sustained subduction

a) **Strong, negatively buoyant oceanic lithosphere**
b) **Focused magmatic weakening** and thinning of lithosphere above the plume
c) **Lubrication of the slab interface** by hydrated crust

Dynamics of plume-induced lithospheric drips

a) **Oceanic plateau development**
b) Formation of a circular **eclogitic crustal drip** at the plateau margins
c) **Detachment** of the circular eclogitic drip
d) **Broadening of the plateau and nucleation** of the subsequent circular eclogitic drip

(Gerya et al., 2015)

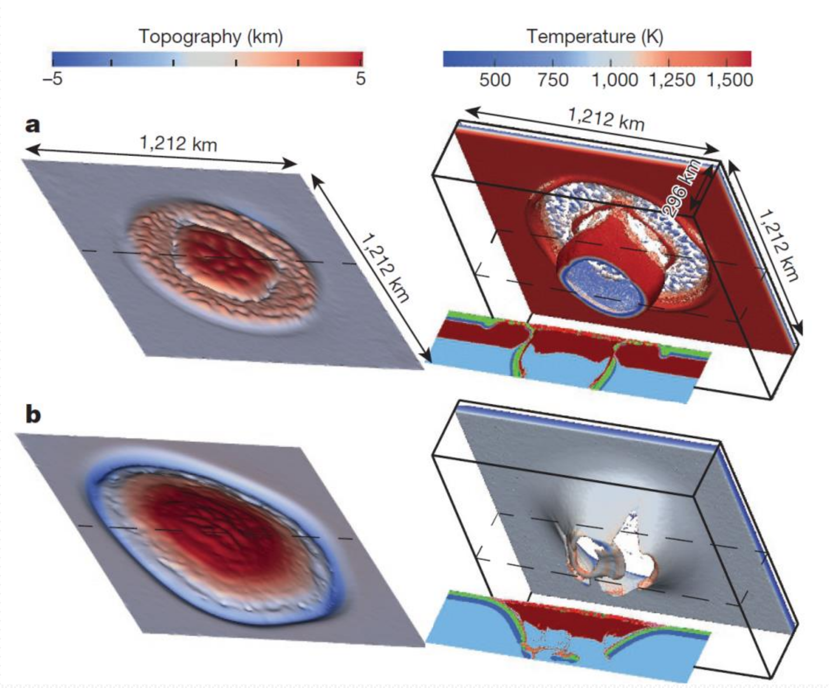


Initiation of Plate Tectonics on the Earth

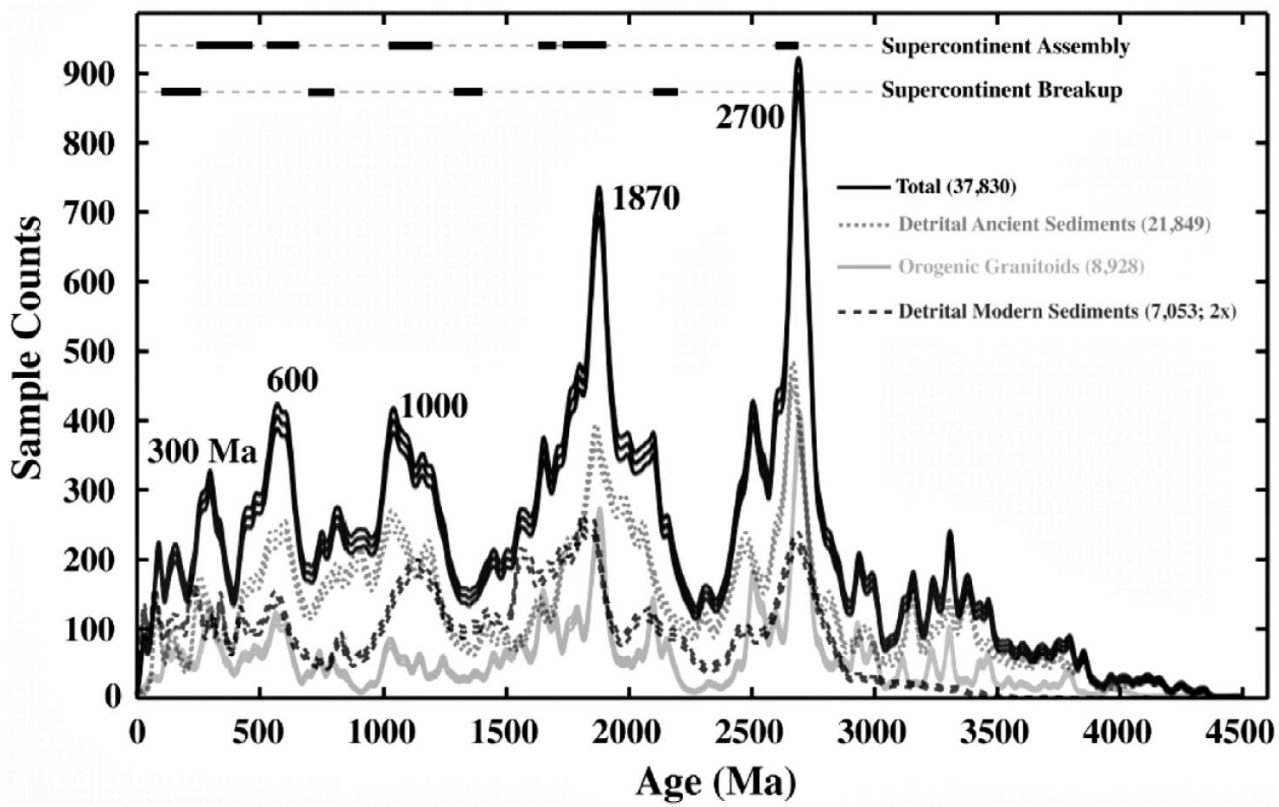
Plume–Induced Subduction for the hot mantle and thick oceanic crust

a) Development of plume-induced lithospheric drips for **20-Myr old** oceanic plate with **30-km-thick** crust at 0.34 Myr.
b) Development of plume-induced self-sustaining subduction for **80-My rold** oceanic plate with **20-km-thick** crust at 2.50 Myr.

(Gerya et al., 2015)



Initiation of Plate Tectonics on the Earth



U/Pb zircon age distribution in orogenic granitoids and two types of detrital zircon data sets for the past 4.5 Gyr [Condie et al., 2009b]. Distribution peaks are labeled with time estimates in Myr. The multiple lines in each spectrum represent error bounds of one standard deviation. The detrital modern sediment database is multiplied by 2 for clarity. Numbers of zircon sample ages in each data set are indicated in the legend. The supercontinent assembly and breakup periods are indicated at top (reproduced from Condie and Aster [2009c]).
(Shahnas & Peltier, 2010)

Propensity of Plate Tectonics on Super-Earth Planets(SEP)

Propensity of Plate Tectonics on SEP

Mantle convection a driving mechanism for plate tectonics

The vigour of convection is determined by the **Rayleigh number**

$$Ra = \frac{\rho g \alpha T d^3}{\eta \kappa}$$

As the size (mass) of a planet increases, **pressure increases** in deep mantle

a) **Density increases** with depth
b) **Thermal expansivity decreases** with depth
c) **Thermal diffusivity increases** with depth
d) **Viscosity increases with depth (traditional view)**

Propensity of Plate Tectonics on SEP

Challenging Results from the Numerical Models

Different studies suggest **different scenarios** and **likelihood** for **active plate tectonics** (a key factor for the habitability) on the planets of different sizes and masses.

One-Dimensional Convection Model Results

One-dimensional convection model with **strong dependence of mantle viscosity on pressure ($\eta(P)$)** were used to investigate the possibility of volcanism and plate tectonics in super-Earth planets (Stamenkovic´ et al., 2012).

Propensity of Plate Tectonics on SEP

Their model results suggest that:

As **m** → **m** (1 $M_\oplus$ –10 $M_\oplus$)

a) For initially **molten planets** (hot) the convection becomes **sluggish** in **massive planets.**

b) The convection in deep mantle changes from **sluggish** convection to **stagnant CMB-lid** conductive layer in cooler planets.

a) **Full** mantle convection becomes **impossible or less likely** and heat to the surface is mainly transferred by **conduction**.

b) And an interesting result of this study is that the **stagnant CMB-lid** becomes thicker in the models **with plate tectonics**

Propensity of Plate Tectonics on SEP

e) These model results also suggest that the **thermostat effect** or **self-regulation** which is the consequence of temperature dependence of mantle viscosity **is not efficient** with **strong t viscosity $\boldsymbol{\eta(P)}$.**

f) Also the **duration** of **melt production** and **volcanism decreases** by **mass.**

Prediction

The **propensity of plate tectonics**, **volcanism, intrinsic magnetic field decreases** with **depth increasing viscosity** in **massive** rocky planets.

Propensity of Plate Tectonics on SEP

Two-Dimensional Convection Model with strong $\eta(P)$

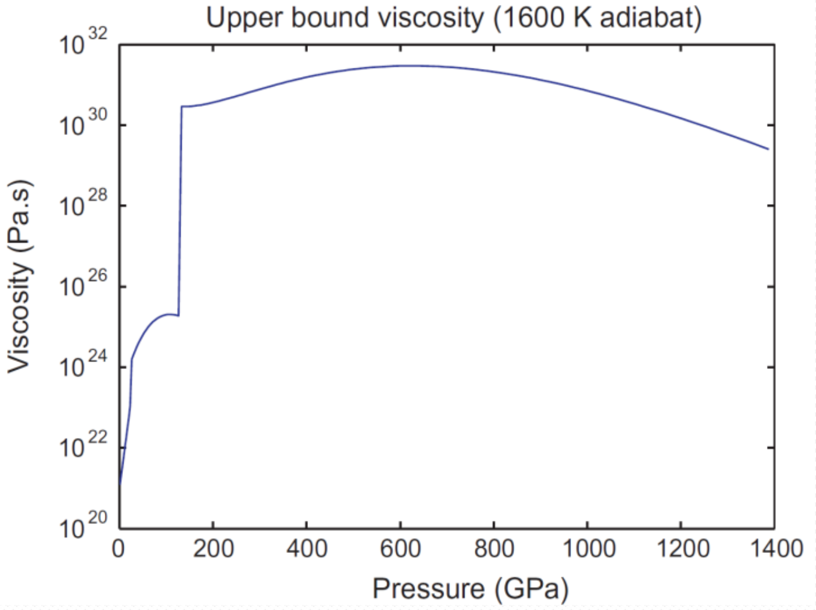
Paul Tackley's group used two-dimensional convection models, again with **strong mantle viscosity** (Tackley et al., 2013).

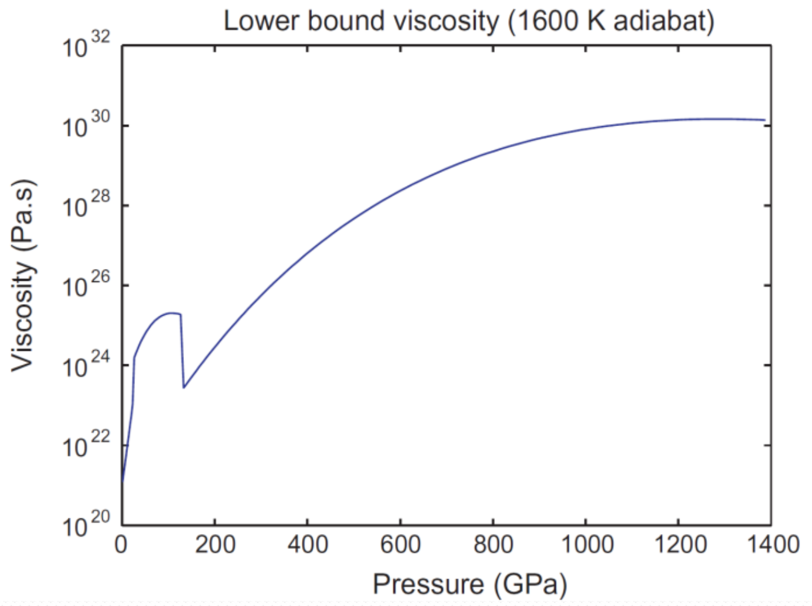
Based on density functional theory (DFT) calculations for pv and extending to ppv at higher pressures (Ammann et al., 2008, 2010), they assumed **two different rheologies** for **post-Perovskite** (ppv)

a) **Slowest diffusion** (upper-bound)
b) **Fastest diffusion** (lower-bound), with plastic yielding induced plate-like lithospheric behaviour

Propensity of Plate Tectonics on SEP

Based on density functional theory (DFT) calculations for pv and extending to ppv at higher pressures (Ammann et al., 2008, 2010), Paul Tackley et al. (2013) calculated **two different rheologies:**





Slowest diffusion

Fast diffusion

Propensity of Plate Tectonics on SEP

Prediction:

- **Deep mantle** of 7–10 $M_{\oplus}$ **convects** (despite high deep mantle viscosity) due to the internal heating **(self-regulation)**
- Convection in massive super-Earths: **Large upwellings**, and **small downwellings**
- For a **hot** (molten after formation) super-Earth, its **deep interior** may be extremely **hot** after **billions of years** (molten with a **super basal magma ocean**)

Suggestion

Their study suggests the **likelihood** of plate tectonics for planets with **Earth-like surface conditions** (temperature and water) for **all sizes.**

Their model results **unlike** the results obtained by Stamenkovic´´s group suggest that **the deep mantle of massive planets is convective** due to the **internal heating** and **self-regulation process.**

Propensity of Plate Tectonics on SEP

Influence of Initial Conditions

2D-finite volume convection model with **strong $\boldsymbol{\eta(P)}$** and **pseudo-plastic rheology** **-** Noack and Breuer (2014)

Two rheologies are assumed

a) Wet rheology: E=240 kJ/mol $\sigma_y = \mu\rho gz + P_0$ *(E: Activation energy)*

b) Dry rheology: E=300 kJ/mol $\sigma_y = \mu\rho' gz + P_0$

Perditions for large exoplanets (~10 $M_\oplus$)

- **Temperature** has **first order** influence on the **likelihood of the plate tectonics**
- Plate tectonics is **less likely** than the Earth for **standard** temperature conditions
- Plate tectonics is **more likely** than the Earth for **warm** temperature conditions
- **Wet** rheology **does not necessarily increase** the likelihood for plate tectonics

Habitability with the Stagnant-lid Regime

Habitability with the Stagnant-lid Regime

Some studies suggest that a **planet may be habitable** even with **stagnant-lid convection regime**

A stagnant-lid regime in Earth-like rocky planets may also **maintain** volcanic outgassing of CO_2 and HO_2 **suitable for habitability** over geological time scales (Tosi et al, 2017; Foley and Smye, 2018; Foley, 2019)

Similar studies also **explore the conditions** under which the Earth-like rocky planets can have suitable atmosphere within boundaries of the habitable zone (HZ) (Dorn et al., 2018; Höning et al, 2019)

Habitability with the Stagnant-lid Regime

Prediction Results from Coupled Models

In a study Tosi et al, (2017) used a **joined models** of:

a) **Simple convection** for the evolution of **melt generation** and water carbon dioxide build-up in the atmosphere and
b) **A simple model** for the **evolution of atmosphere** over a geological time

That is:

1D-Parameterized Convection: Evolution of melt generation and H_2O + CO_2 build-up over 4.5 Gyr

+

1D-Radiative-Convective Atmosphere: Evolution of the global atmospheric temperature and the boundaries of the habitable zone (HZ)

Habitability with the Stagnant-lid Regime

Predictions

- As the atmospheric **pressure grows**, the **release of H_2O** becomes **more difficult** (due its high solubility in surface lavas) → After **4.5 Gyr, no more than a few tens** of bars **H_2O** can be outgassed → **an Earth-sized ocean cannot be built up**

- For Earth-size planet at **similar distance from the host star** and **lower values of oxygen fugacity** the **amount of volatiles** outgassed to the atmosphere keeps the surface temperatures **suitable for liquid water over ~4.5 Gyr.**

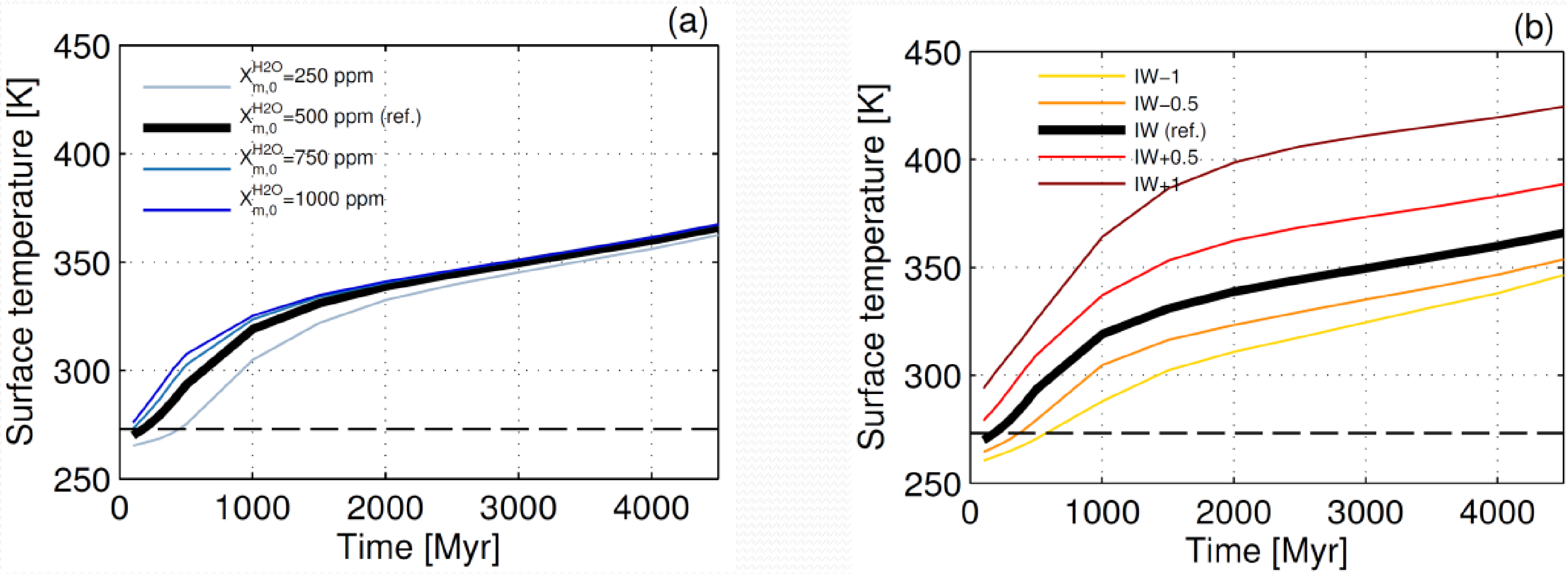
- The **width** of the **HZ:** is **controlled** by the **amount of outgassed CO2**, which in turn is determined by the **mantle oxygen fugacity** (**not** much **sensitive** to the **amount of water**)

Habitability with the Stagnant-lid Regime

- $D_{HZ}(Co_2(f_{O2}= IW + 1), 1000\ ppm\ H_2O)$ = **~ 0.2 -1.2 S_{sun}**   Solar radiation
- $D_{HZ}(Co_2(f_{O2}= IW - 1), 1000\ ppm\ H_2O)$ = **~ 0.7 -1.15 S_{sun}**

f_{O2} :Oxygen fugacity
IW: Iron wustite buffer

Tosi et al, (2017)



Evolution of the surface temperature for **(a)** an oxygen fugacity at the IW buffer and different initial mantle concentrations of water, **(b)** an initial mantle concentration of water of 500 ppm and different oxygen fugacities.

Habitability with the Stagnant-lid Regime

Fugacity

A measure of the **tendency** of a component of a liquid mixture to **escape**, or vaporize, from the mixture (unit: mol/m^3). In general, higher oxygen fugacity means there's a higher ratio of $Fe3+$ to $Fe2+$ (particularly in melts).

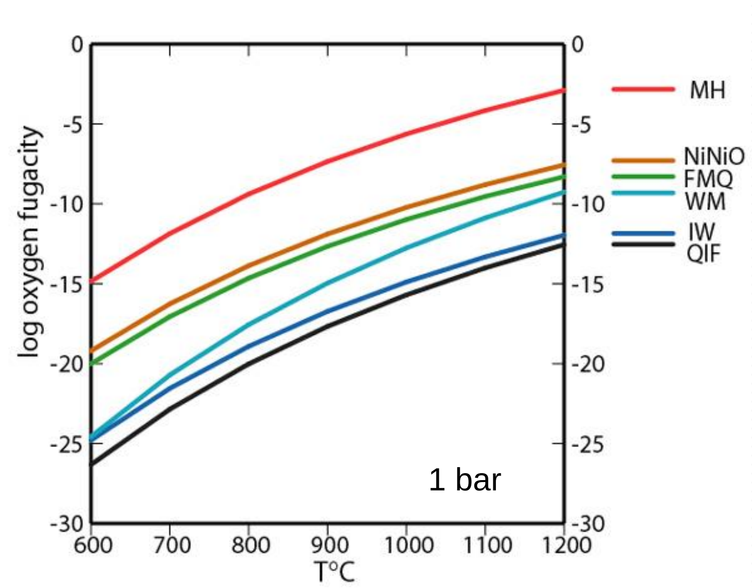
Redox Buffer

In geology, a redox buffer is an **assemblage** of minerals or compounds that **constrains oxygen fugacity** as a function of temperature (in laboratory experiments).

Common redox buffers

Iron wustite buffer (IW) -

MH, magnetite-hematite;
NiNiO, Nickel-nickel oxide;
FMQ, fayalite-magnetite-quartz;
WM, wustite-magnetite;
IW, iron-wustite;
QIF, quartz-iron-fayalite



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Habitability with the Stagnant-lid Regime

Outgassing

Using **2D-spherical annulus** convection model Dorn et al. (2018) studied **stagnant-lid regime** in planets in the mass range of **1–8 $M_{\oplus}$**

- **2–3 $M_{\oplus}$** Outgassing most **efficient**
- **5–7 $M_{\oplus}$** Outgassing very **inefficient** (**due to the increasing pressure gradient** that limits melting to shallower depths)
- Outgassing **decreases** with **increasing viscosity**
- **Interior structure and composition** only **moderately affect** outgassing rates
- The **majority** of outgassing occurs before **4.5 Gyr,** especially for planets below **3 $M_{\oplus}$**

Suggestion

Habitability with volcanic activities **restricted** to:

a) Small planets **<5 $M_{\oplus}$**

b) Planets younger than **5 Gyr.**

Habitability with the Stagnant-lid Regime

Coupled Models
A stagnant-lid regime in Earth-like, Earth-sized rocky planets

In a study Foley and Smye (2018) used a **coupled models** of:

a) **Simplified coupled** models of thermal evolution
b) **Crustal production**
c) **CO_2 cycling**

Assumptions
1) H = 100–250 TW (RG)
2) $CO_{2\ Outgas}$ = 0.01-1 times Earth's estimated CO_2 budget

Predictions

- **Suitable for habitability** for **~1–5 Gyr**
- $CO_{2\ Outgas}$ **> 1** Earth's budget → **Hot climate**
- $CO_{2\ Outgas}$ **< 0.01** Earth's → **Global glaciation**
- **H_{High}** → Sustains volcanism **(favour habitability, longer outgassing)**

Habitability with the Stagnant-lid Regime

Coupled Models
A stagnant-lid regime in Earth-like, Earth-sized rocky planets

Foley (2019) used **coupled models** of:

a) Mantle thermal evolution
b) Volcanism
c) Outgassing
d) Weathering
e) Climate evolution for **Earth-like** (size and composition)

Suggestion

- CO_2 budgets: ~3 OOM Earth's < budget < ~1 OOM Earth's → **Habitable climates lasting 1–5 Gyr.**

Propensity for Plate Tectonics in Massive Super-Earths

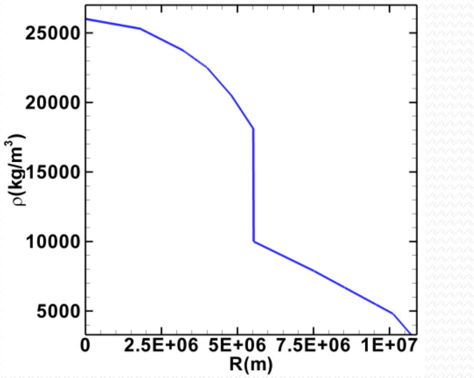
New Results Based on the Most Recent Theoretical Predictions

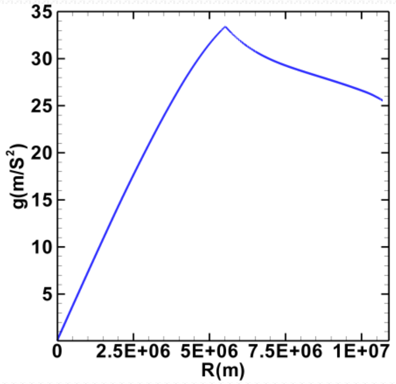
Propensity for Plate Tectonics on SEP
Results from 3D-Compressible Convection Models

Our focus: GJ 876 d-size super-Earth

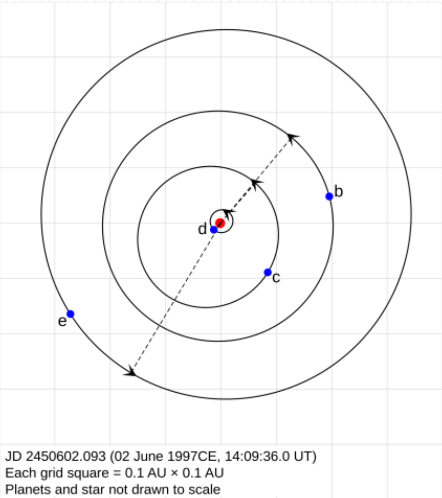
- GJ 876 d discovered in 2005 (Rivera et al., 2005)
- Estimated mass: $\mathbf{7.5 \pm 0.7 M_{\oplus}}$
- Estimated surface temperature: **430 -650 K**
- With a period of 1.938 days at 0.021 AU from the host star orbiting closely around the red dwarf GJ 876 (Gliese 876),
- Approximately **15 light-years** away from our solar system.
- An **Earth-like structure** is within the constraints (Valencia et al., 2006)

- The large planets of this size appear to be **rare**.





$7.3\ M_{\oplus}$

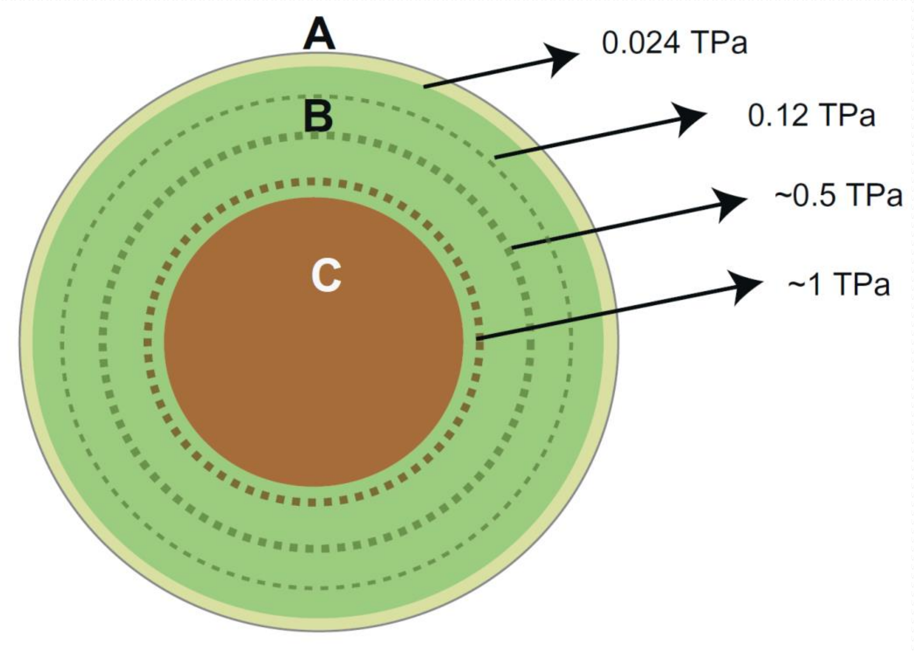


Shahnas et al. (2018)

Propensity for Plate Tectonics - GJ 876 d
Mantle Transitions

Recent Studies

Recent theoretical studies suggest that unlike traditional notion, the mantle viscosity decreases with pressure at higher pressures.



A schematic model of the structure of a super-Earth with Earth-like composition (R = 11000 km, 7 $M_{\oplus}$) (Karato, 2011)

Propensity for Plate Tectonics - GJ 876 d
Mantle Transitions

A: Upper mantle (olivine-rich)

B: Lower mantle (pv + MgO, ppv + MgO, MgO + SiO_2),

Mantle Transitions

1- The α to β-spinel transition of olivine (~0.02 TPa, ~170 km depth)

2- Spinel to perovskite (~0.024 TPa, ~270 km depth)

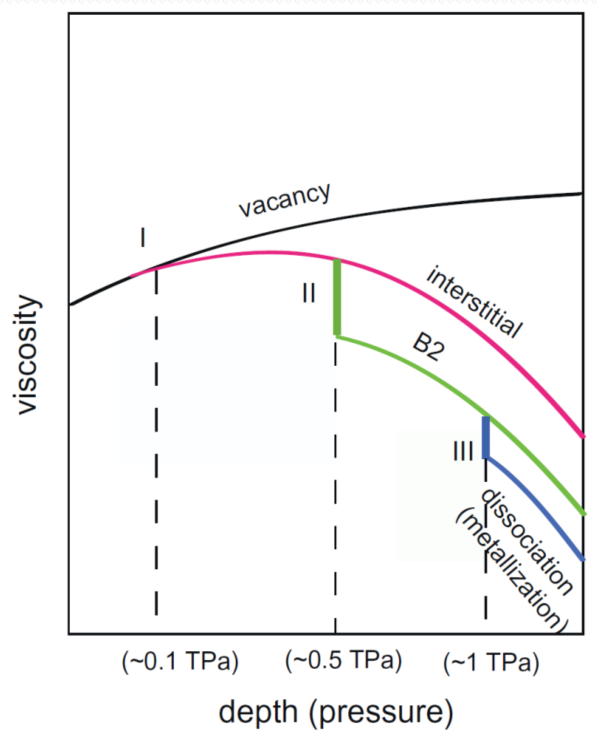
3- Perovskite to post-perovskite (~0.12 TPa, 1070 km depth)

4- B1 → B2 structural transition (~0.5 TPa, 3080 km depth)

5- $MgSiO_3$-ppv → MgO + $MgSi_2O_5$ (~0.9TPa, 4640 km depth)

6- Metallization of oxides (> 1 TPa)

Propensity for Plate Tectonics - GJ 876 d
Mantle Rheology



A schematic diagram of Mantle viscosity in super-Earth (7 $M_{\oplus}$) (Karato, 2011)

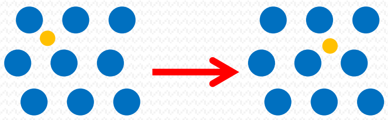
Mantle processes influencing mantle viscosity

Mechanism I (0.1 TPa): Transition in diffusion mechanism, Vacancy → interstitial (continuous)

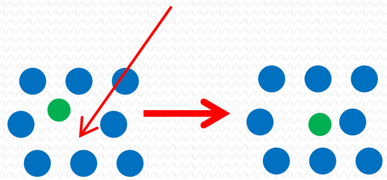
Mechanism II (0.5 TPa): B1→B2 transition in MgO (~2 orders of mag.)

Mechanism III (0.9 TPa): Dissociation of post-perovskite into oxides (factor of 3))
MgSiO3-pPv → MgO + $MgSi_2O_5$ at ~0.9 TPa (Umemoto & Wentzcovitch, 2011)

Mechanism IV (1 TPa or higher): Metallization of oxides.

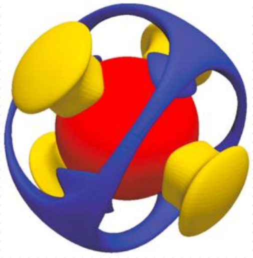


Interstitial diffusion



Vacancy diffusion

Propensity for Plate Tectonics - GJ 876 d
3D-Compressible Control Volume model



$$\nabla \cdot \left(\bar{\rho}\vec{V}\right) = 0$$

$$-\nabla P + \nabla \cdot \bar{\bar{\sigma}} - \rho g \hat{r} = 0$$

$$C_P \bar{\rho} \frac{DT}{Dt} - \alpha T \frac{DP}{Dt} = \nabla \cdot (K \nabla T) + \phi + \bar{\rho} H + \rho l_i \frac{D\Gamma_i}{Dt}$$

$$\bar{\bar{\sigma}} = \eta \left[\nabla \vec{V} + (\nabla \vec{V})^T\right] - \frac{2}{3}\eta\left(\nabla \cdot \vec{V}\right)\bar{\bar{I}}$$

$$\rho = \bar{\rho}\left[1 - \alpha(T - T_r) + \frac{1}{K_T}(P - P_r)\right] + \Delta\rho_i(\Gamma_i - \Gamma_{ri})$$ *i=1,2,3,4*

$$\Gamma_i = \frac{1}{2}[1 + \tanh(\pi_i)]$$

$$\pi_i = \frac{d_i - d - \gamma_i (T - T_i)}{h_i}$$

$r_{Surf} = 10700\ km,\ r_{CMB} = 5532\ km$

$T_{Surf} = 500\ K,\ T_{CMB} = 5000\ K, 6000\ K$

Grid resolution $2 \times \theta \times \varphi \times r = 2 \times 130 \times 400 \times 201$

Shahnas et al. (2015)

Propensity for Plate Tectonics - GJ 876 d
3D-Compressible Control Volume model

Model Parameters – Thermal Conductivity

$$K(P,T) = K_{lat} + K_{rad} + K_{el}$$

Lattice Contributions (due toe lattice phonon collisions)

$$K_{lat}(P,T) = k_0 \left(\frac{T_{surf}}{T}\right)^a \times exp\left[-\left(4\gamma + \frac{1}{3}\right)\alpha(P)(T - T_{surf})\right] \times \left(1 + \frac{K_0' P}{K_0}\right)$$

Radiative Contribution

$$K_{rad}(T) = \sum_{i=0}^{3} b_i T^i$$

Electron Contribution

$$K_{el}(T) = k_{ep} exp\left(-\frac{E_{el}}{k_B T}\right)$$

Hofmeister, (1999; 2019), Umemoto et al. (2006)

Propensity for Plate Tectonics - GJ 876 d
3D-Compressible Control Volume model

Lattice Contributions

Lattice contribution to the thermal conductivity arises from phonon oscillation in lattice which is temperature and pressure dependent (Hofmeister,1999; 2019).

Radiative Contribution

Radiative contribution to the thermal conductivity is due to the heat transfer as radiation at high temperatures Hofmeister,1999; 2019).

Electron Contribution

At high pressures and high temperatures ~1000 GPa and ~10,000 K, cotunnite-type SiO_2 is expected to have thermally activated electron carriers and thus higher electrical conductivity (close to metallic values). Electrons will give a large contribution to thermal conductivity (Umemoto et al., 2006).

Propensity for Plate Tectonics - GJ 876 d
3D-Compressible Control Volume model

Thermal Expansivity

$$\alpha(z) = \frac{(c_0 + 1)^3}{[c_0(1 - z) + 1]^3}$$

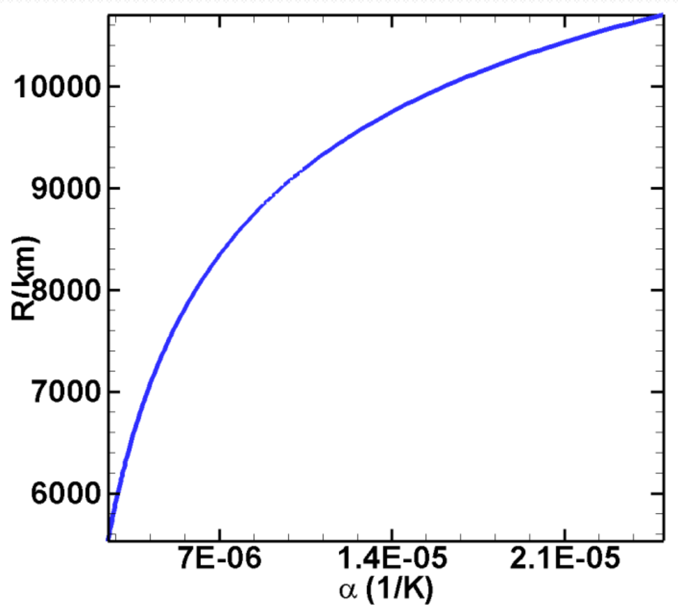
van den Berg et al. (2010),

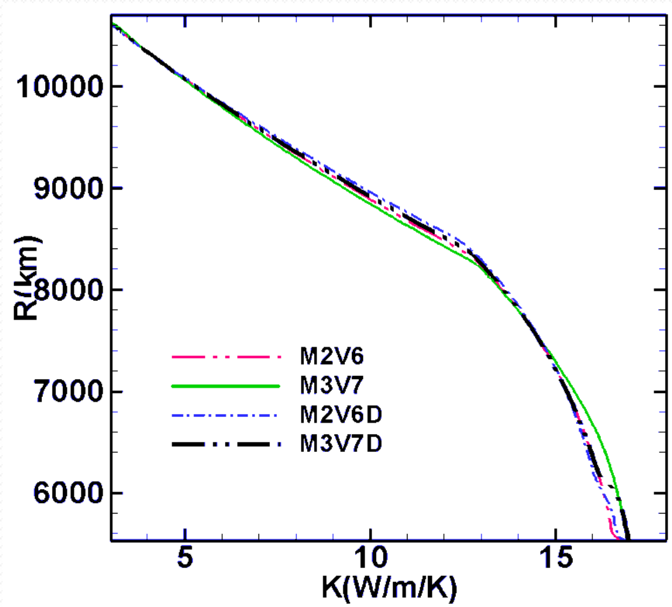
ppv - Dissociation Transition

$MgSiO_3$ post-perovskite → $MgSi_2O_5$ + MgO

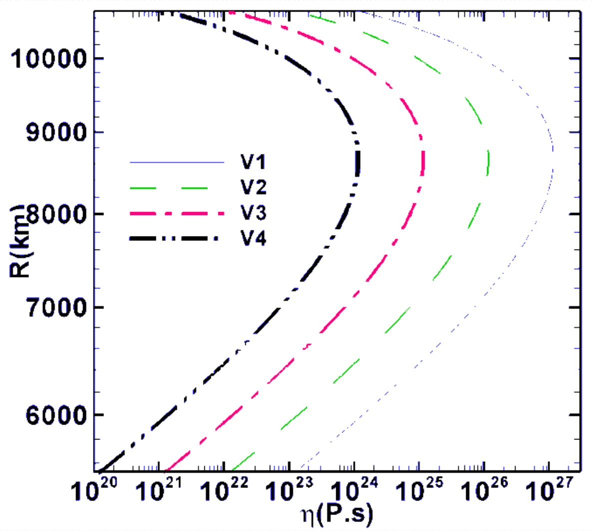
$\gamma = -18\ MPa/K$ Clapeyron Slope
$\Delta\rho = 80\ kg/m^3$ Density Change
$d = 4640\ km\ (0.9\ TPa)$ Transition Depth

Propensity for Plate Tectonics - GJ 876 d
Thermal Conductivity – Thermal Expansivity



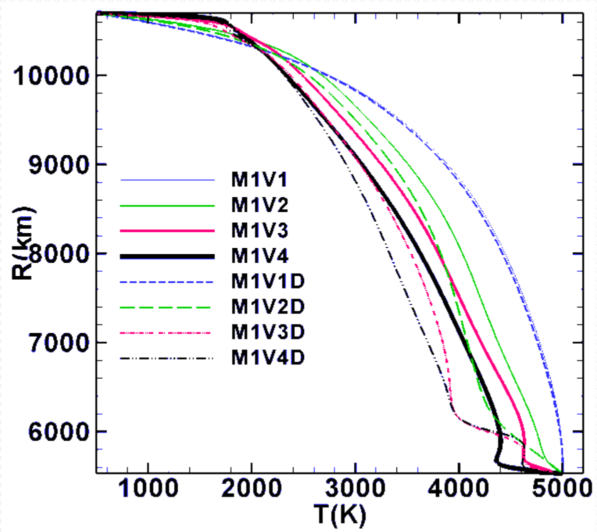


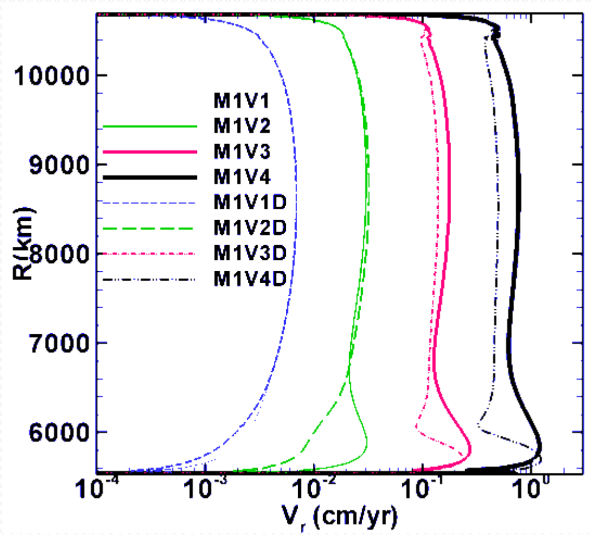
3D-Spherical Numerical Models
M1V1-M1V4D



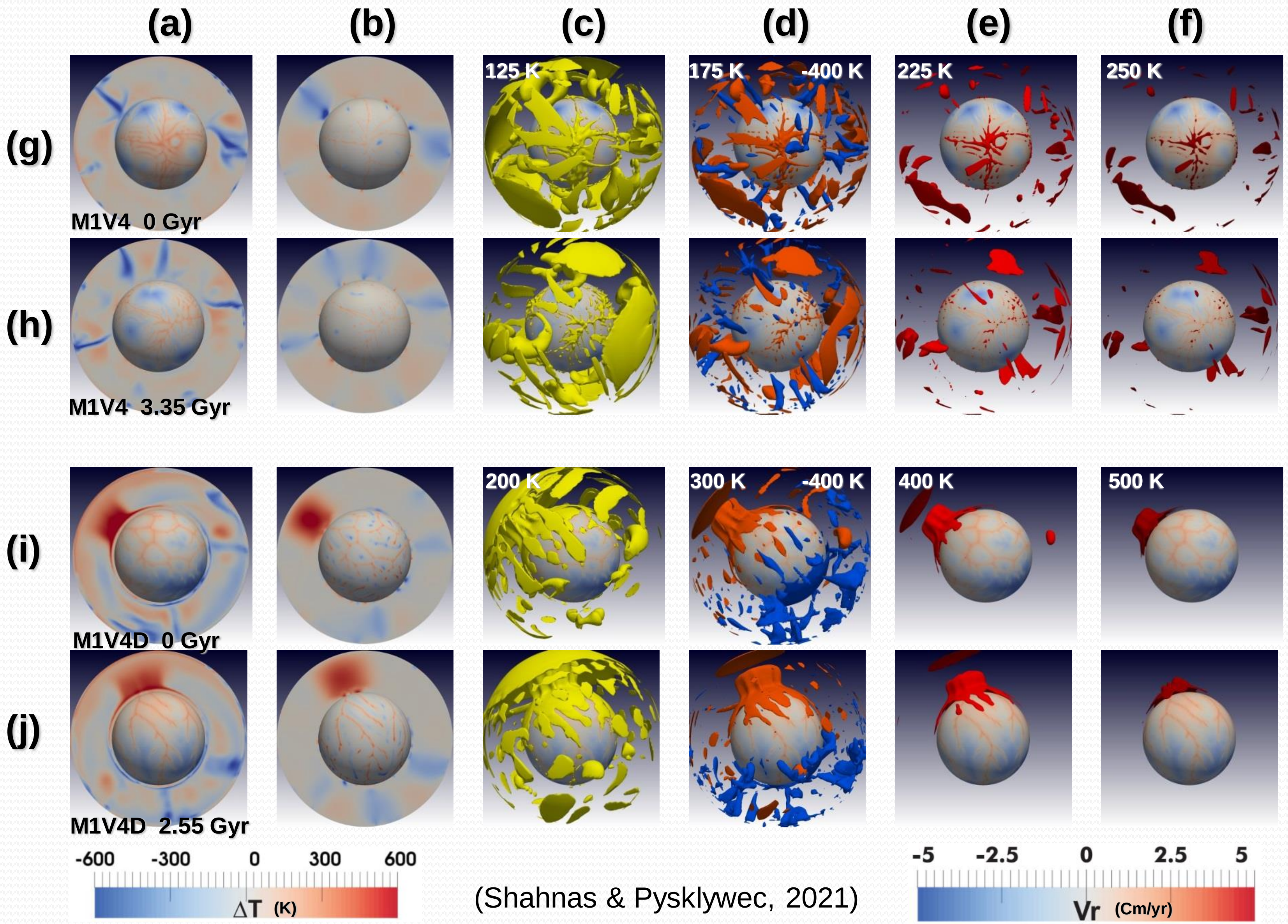
Depth-dependent viscosity models

$$T_{Surf} = 500\ K$$
$$T_{CMB} = 5000\ K$$



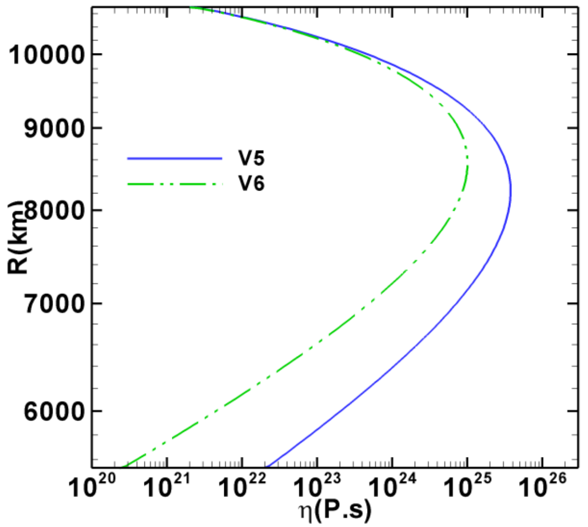


3D-Spherical Numerical Models
M1V1-M1V4D



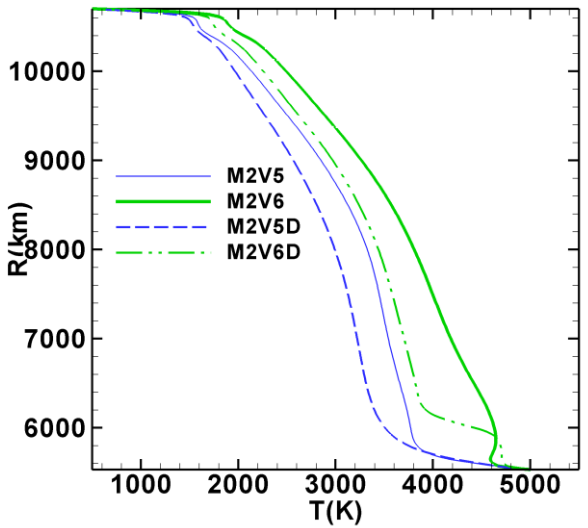
(Shahnas & Pysklywec, 2021)

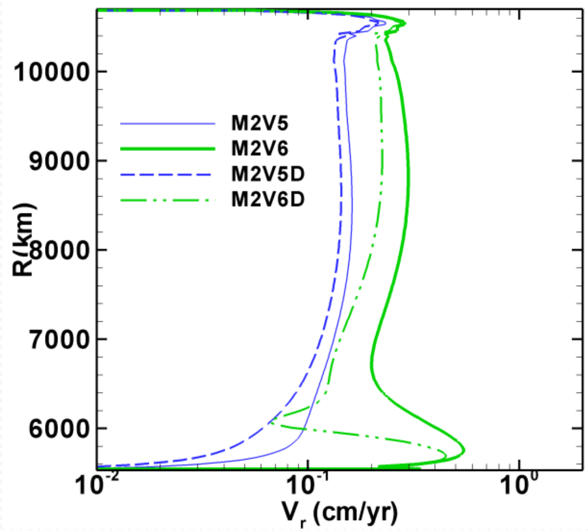
3D-Spherical Numerical Models M2V5-M2V6D



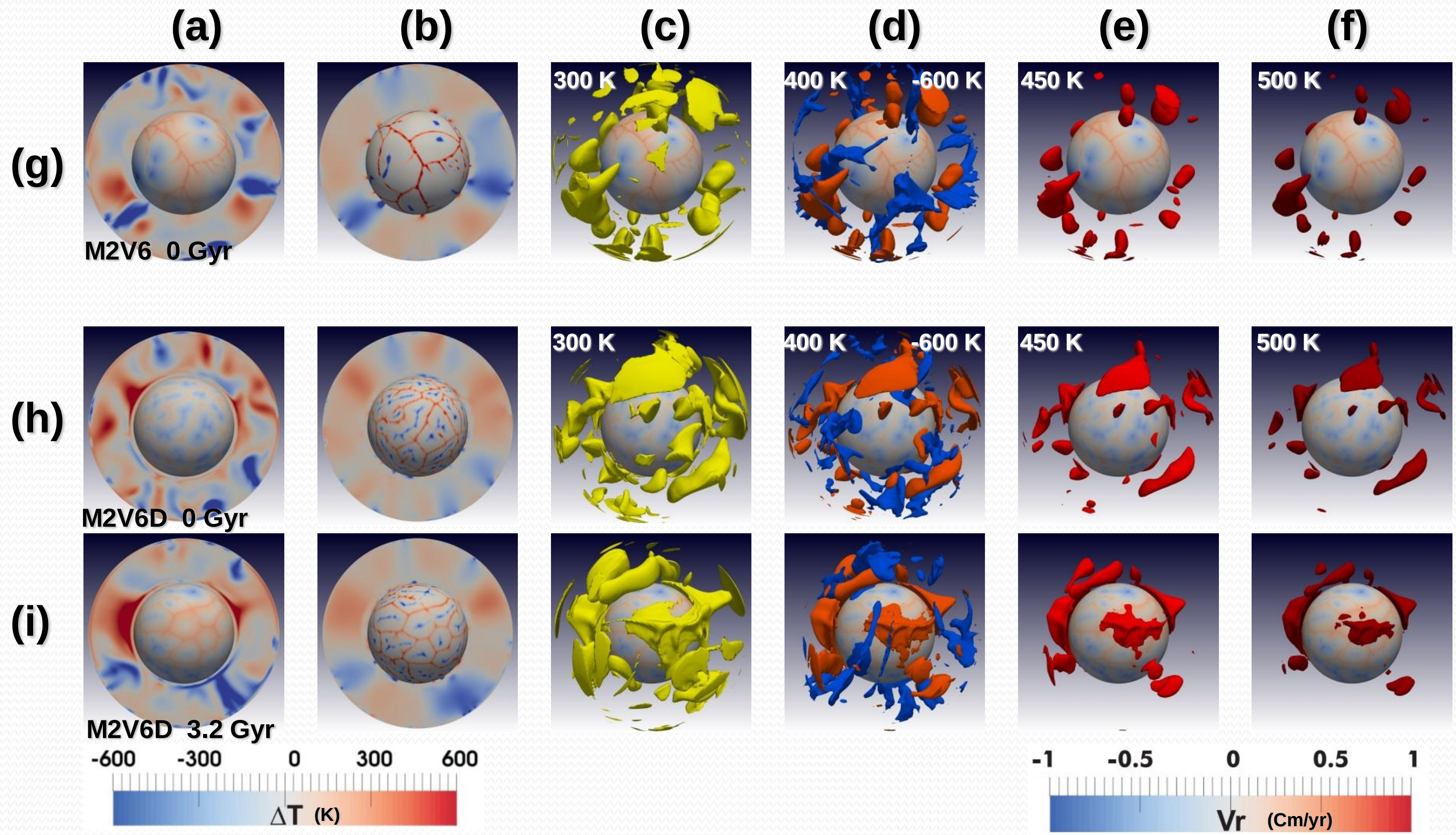
$T_{Surf} = 500\ K$
$T_{CMB} = 5000\ K$

The depth-dependent viscosity profiles (V5 and V6) used in our second sequence of models shown in Figure 3a have the same value at the upper boundary but different values at the lower boundary by two orders of magnitude.

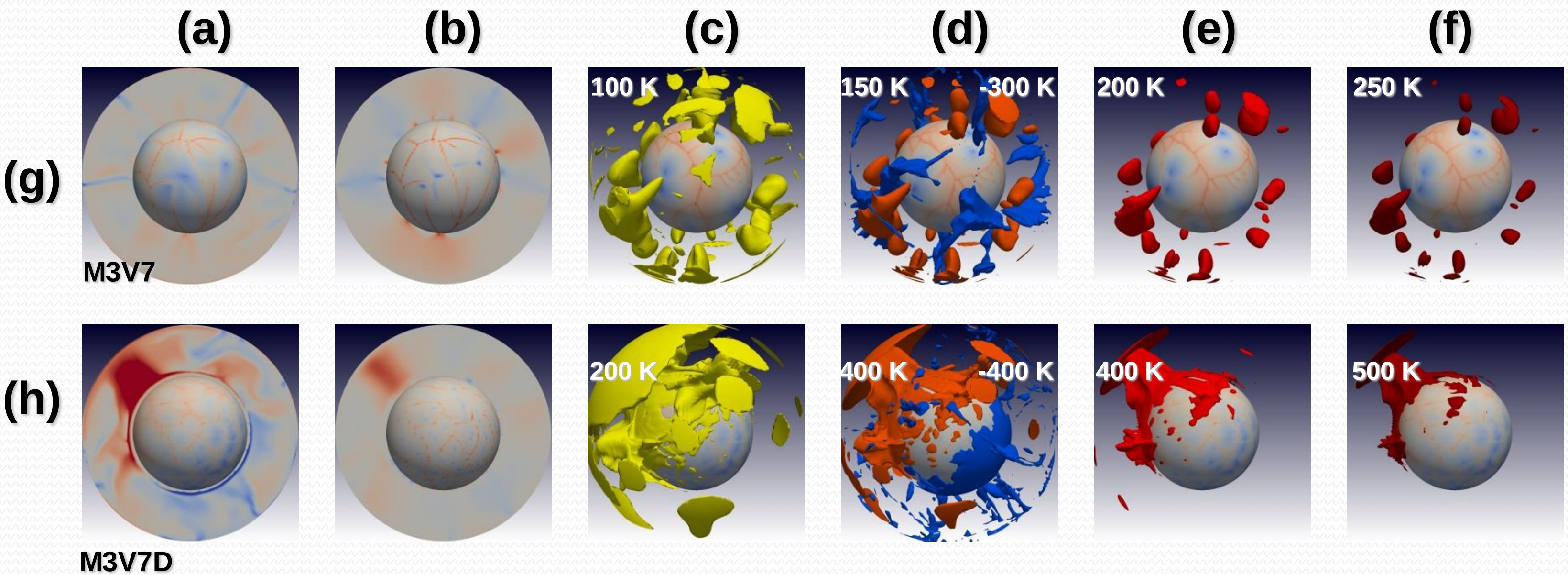


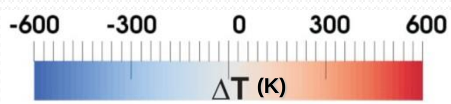


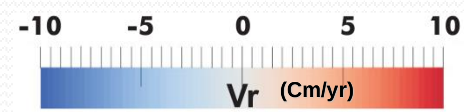
3D-Spherical Numerical Models
M2V5-M2V6D



3D-Spherical Numerical Models
M3V7-M3V7D



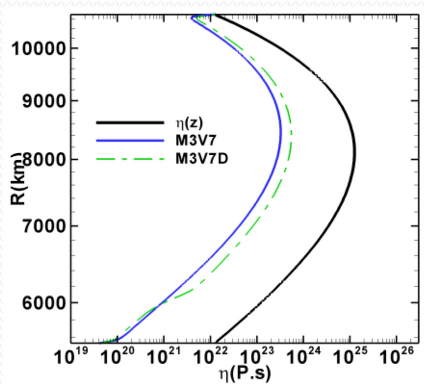


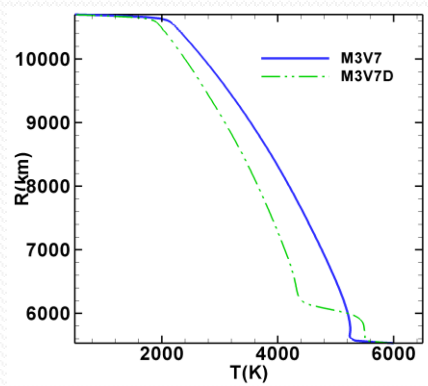


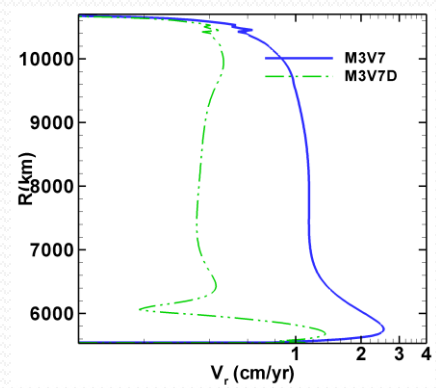
$$\boldsymbol{\eta(T,z) = \eta_i(z)\exp(-bT)}$$

$$T_{Surf} = 500\ K$$

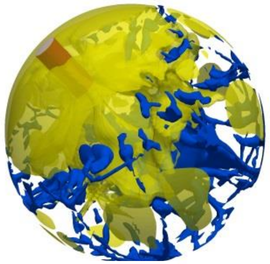
$$T_{CMB} = 6000\ K$$

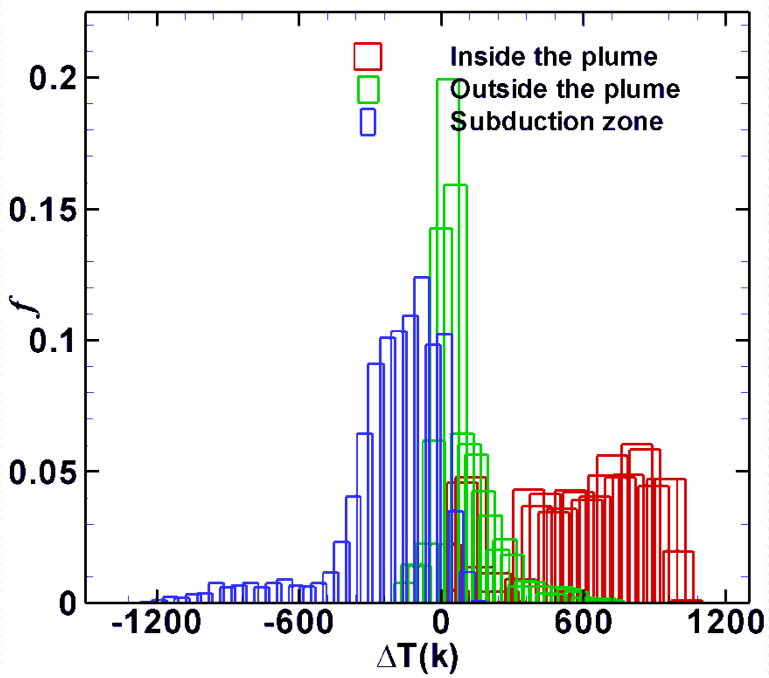


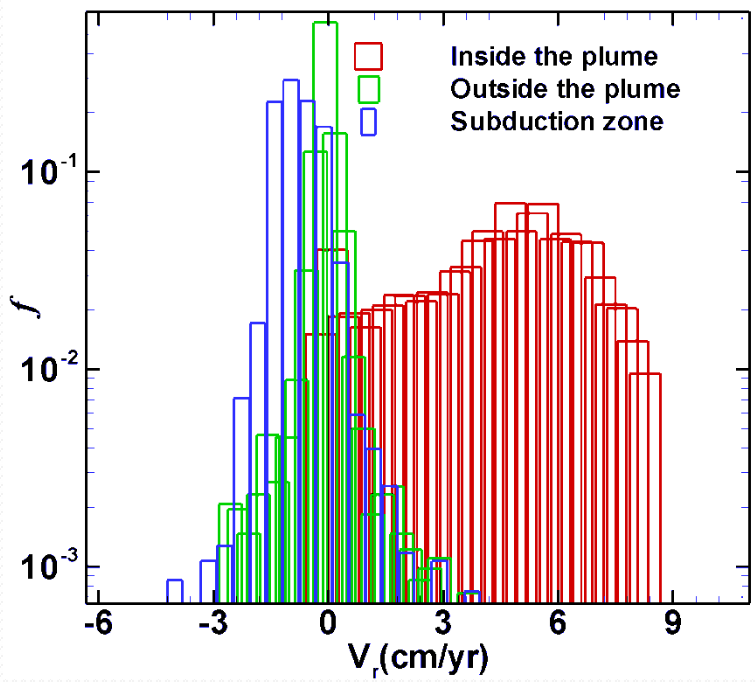




3D-Spherical Numerical Models
M3V7D







Histograms of relative distribution of the temperature anomalies and radial velocities taken within a 1000 km-diameter cylinder within the plume, adjacent to the plume and within a subduction zone

Possibility for Core Dynamo
M3V7-M3V7D

For an adiabatic core the threshold heat out-flux for convection in the outer core can be approximated by (Nimmo & Stevenson, 2000):

$$F = K_c \, \alpha_c \, g \, T_c / C_{Pc}$$

For nominal values of parameters ($K_c \sim 100$ Wm^{-1} K^{-1}, $\alpha_c \sim 2.5 \times 10^{-5}$ K^{-1}, $g \sim 34$ ms^{-2}, $T_c \sim 5000$ K and $C_{Pc} \sim 1250$ J kg^{-1} K^{-1}): $F \sim 0.34$ Wm^{-2}

	M3V7	M3V7D
HF_{Surf}(W/m^2)	0.112	0.087
HF_{CMB}(W/m^2)	0.419	0.328
T_{Mean}(K)	3643	3219

The models with CMB-heat fluxes exceeding $F \sim 0.34$ Wm^{-2} can potentially drive geodynamo in GJ 876 d size super-Earth.

Suggestions

- Our 3D-compressible control volume convection models suggest that in the massive super-Earth planets (>7 $M_\oplus$) dissociation of $MgSiO_3$-ppv to MgO + $MgSi_2O_5$ may cause deep mantle layering.

- Penetrative plumes from the layered deep mantle region can survive for billions of years without losing their vigour and without significant lateral migrations.

- While the mantle radial velocity on average is of order of 1 cm/yr or less, the velocity within the focused penetrative plumes (FPP) may exceed 10 cm/yr. This can potentially initiate and sustain plate tectonics in the massive super-Earths.