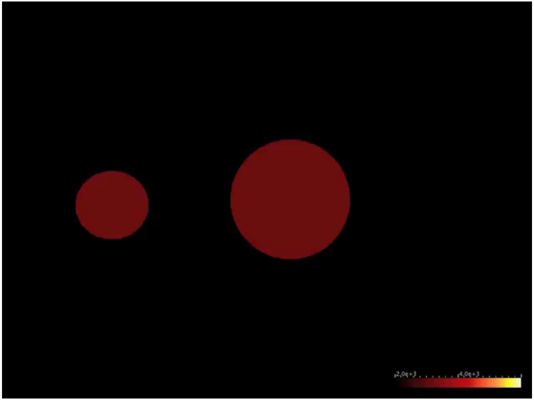
Earth's formation & core-mantle differentiation

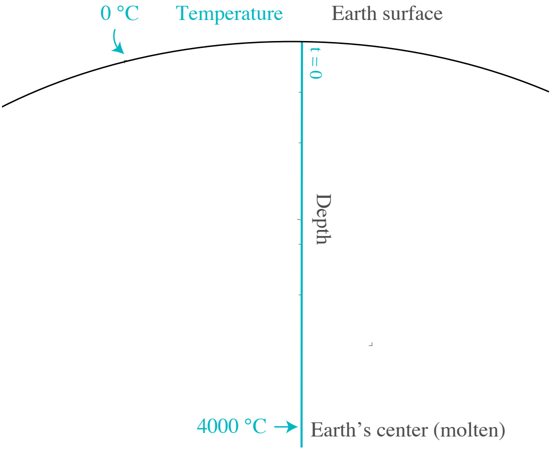
Maylis Landeau[1],

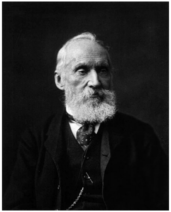
[1] Institut de Physique du Globe de Paris,



The age of the Earth

Lord Kelvin, 1863, *On the secular cooling of the Earth*, Philos. Mag. 4th series, Vol. 25, 1-14.





Cooling by conduction of a semi-infinite half-plane

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

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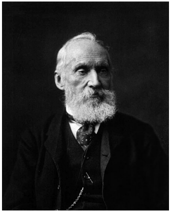

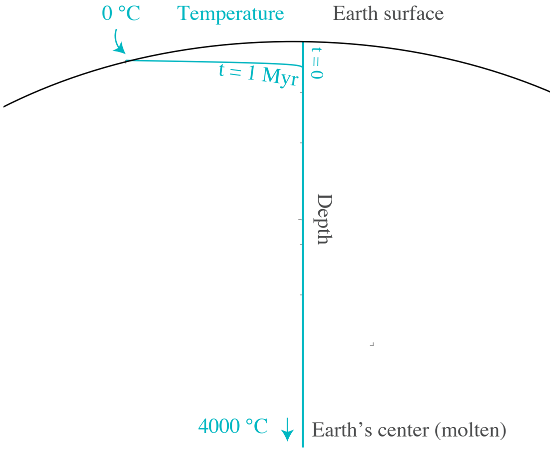

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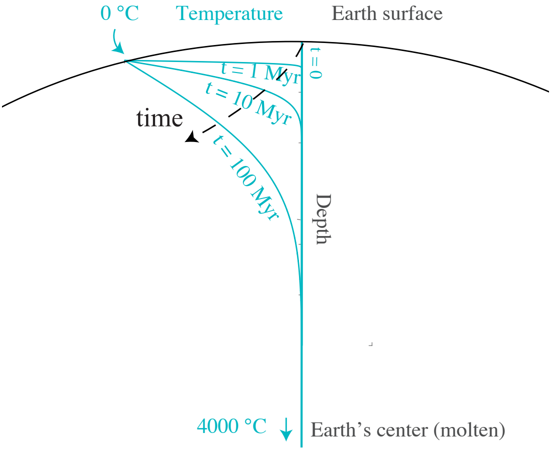

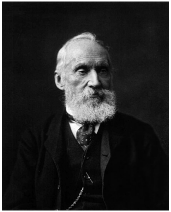

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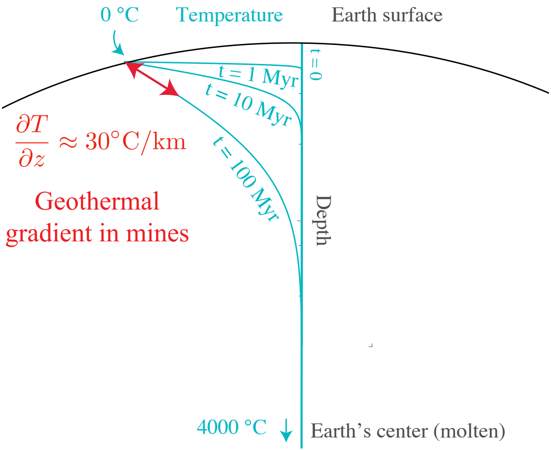
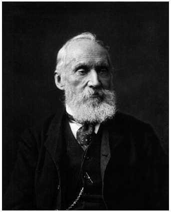


$$\frac{\partial T}{\partial z} \approx 30°\mathrm{C/km}$$

Geothermal gradient in mines



Cooling by conduction of a semi-infinite half-plane

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}$$

Age of the Earth
~ 100 Myr...

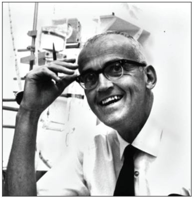
The age of the Earth: Using radiogenic isotopes

The Pb^{207}/Pb^{206} ages of some stone meteorites

CLAIRE C. PATTERSON
California Institute of Technology, Pasadena, California

(*Received* 10 *January* 1955)

ABSTRACT
The isotopic compositions have been determined for the leads isolated from three stone meteorites. Based upon certain assumptions, Pb^{207}/Pb^{206} ages of about $4 \cdot 5 \times 10^9$ years are calculated for the meteorites. The lead data indicate that the concentrations of uranium should be about 0·1 p.p.m. and the concentrations of thorium should be about 0·5 p.p.m. in stone meteorites.



Claire Patterson

Patterson, 1955, Geochimica et Cosmochica Acta

Age of solar system ~ 4.57 Gyr

The age of the Earth: Using radiogenic isotopes

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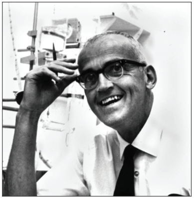

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Age of solar system ~ 4.57 Gyr

Carlson & Lugmair, 1988, EPSL

Lee & Halliday, 1995, Nature

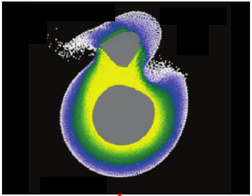
Earth formed in ~ 100 Myr

Earth formation: A young field !

Earth formation controls core & mantle evolution

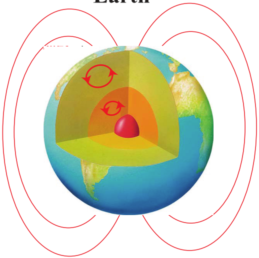
- 4.5 - 4.4 0 Time (Gyr)

Earth formation & differentiation



Initial **temperature**
& composition
for core & mantle

Present-day Earth

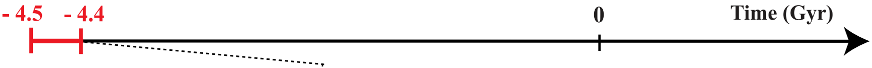


Geodynamo & magnetic field

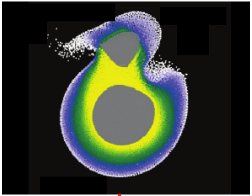
Inner core age

Mantle convection & plate tectonics

Earth formation controls core & mantle evolution

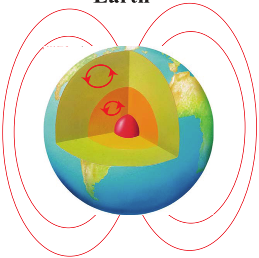


Earth formation & differentiation ?



Initial **temperature** & **composition** for **core & mantle**

Present-day Earth



Geodynamo & magnetic field

Inner core age

Mantle convection & plate tectonics

What constraints on Earth formation?

Geo & cosmochemistry

Isotopes
& radioactivity
Hf/W

Core-loving
elements
Ni, Co, ...

→

Earth's differentiation

Timing < 100 Myrs

Yin et al. 2002
Rudge et al., 2010

Depth ~ 1000 km
& Temperature ~ 3000 K

Wade & Wood, 2005, 2016;
Siebert et al., 2012, 2013;

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Astrophysics

Accretion in the
planetary disk

Mineral physics

Core-mantle
partition coefficients

Fluid dynamics

Mixing & chemical transfers
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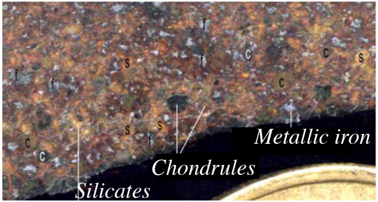
Extinct radioactivity: timing of core formation

$^{182}\text{Hf} \rightarrow {}^{182}\text{W}$

Key properties:

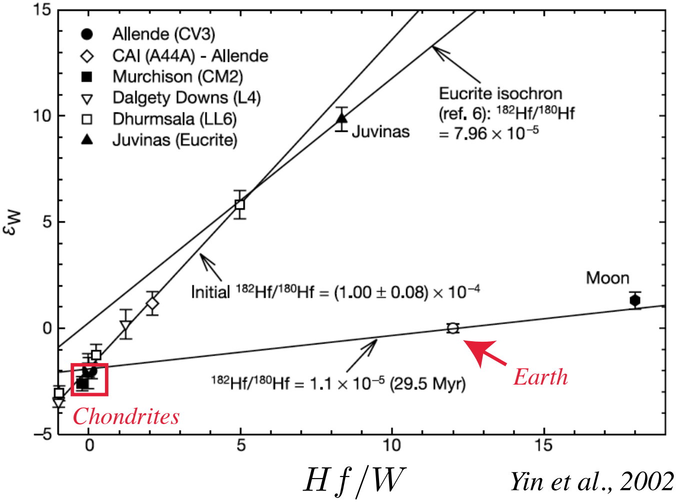
Both Hf and W are **refractory**.
Hf is **lithophile** while W is **siderophile**.
Half-life of 8.9Myrs.

Principles on the blackboard for a two stage accretion model.



Chondrite *(P. Thomas)*

Extinct radioactivity: timing of core formation



Yin et al., 2002

Two-stage time scale of Earth's core formation ~ 30 Myr

Extinct radioactivity: timing of core formation

Hoba iron meteorite, Namibia, > 60 tonnes

Two-stage time scale of most iron meteorites < 1.5 Myr after CAI

Kleine et al. 2005

Siderophile elements: Temperature & pressure

Principles :

- Partition coefficient of element i between metal and silicates:

$$D_i = \frac{C_i^{\text{metal}}}{C_i^{\text{silicates}}} \tag{1}$$

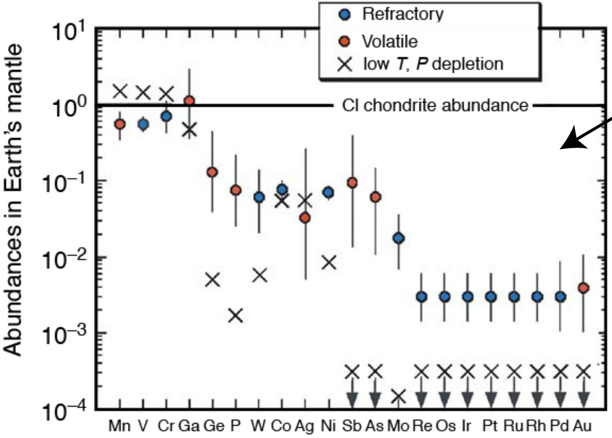
- Composition of the global Earth from chondrites
  - Mantle composition from upper mantle rocks (Bulk Silicate Earth)

  $\rightarrow$ Composition of the core

$$D_{i,Earth} = \frac{C_i^{\text{core}}}{C_i^{\text{mantle}}} \tag{2}$$

- $D_i = D_i(\text{Pressure}, \text{Temperature}, \text{Oxygen fugacity})$

Siderophile elements: Temperature & pressure

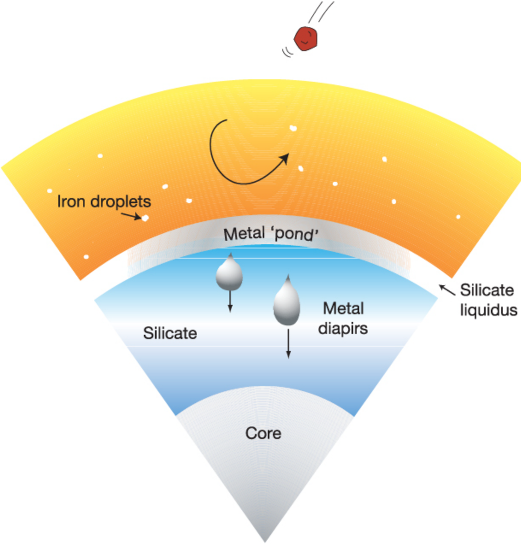


from Walter et al. 2000

Excess in refractory siderophile elements in Earth mantle

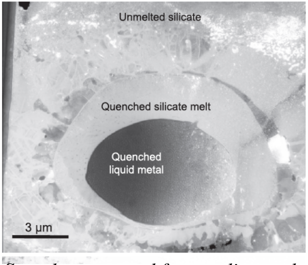
Evidence for **high P/T equilibration** in a **magma ocean**

Siderophile elements: Temperature & pressure

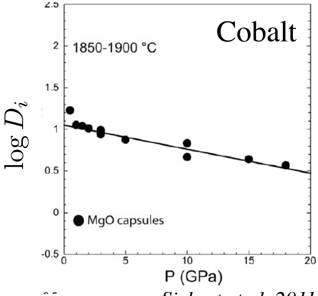


Siderophile elements: Temperature & pressure

- 1 - Obtaining partition coefficient $\log(D_i) = a + \frac{b}{T} + \frac{cP}{T}$, where a, b and c are estimated from high-pressure experiments.



Sample recovered from a diamond cell (57 GPa, 4440 K) Fischer et al. 2015

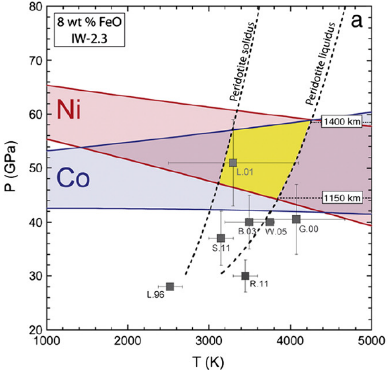


Siebert et al. 2011

- 2 - Finding pressure & temperature such that $D_i = D_{Earth}$.

Siderophile elements: Temperature & pressure

Siebert et al. 2012



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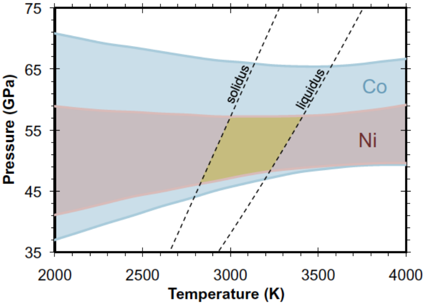
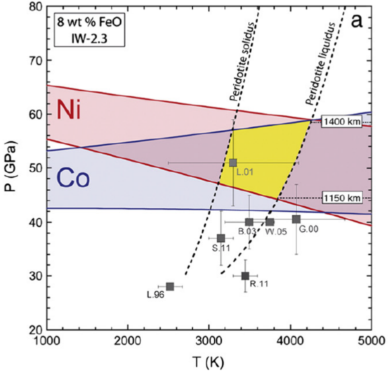


Chemical equilibration at
~ 3000 K, 40 - 60 GPa
in a 1000-1500 km **deep magma ocean**

Siderophile elements: Temperature & pressure

Siebert et al. 2012



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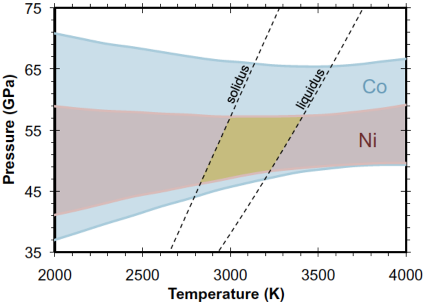


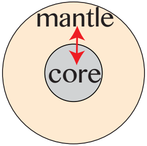
Chemical equilibration at
~ 3000 K, 40 - 60 GPa
in a 1000-1500 km **deep magma ocean**

Assuming full equilibration between metal and silicates !

What if **partial equilibration** *?*

Partial metal-silicate equilibration

$$^{182}Hf \rightarrow ^{182}W$$



Degree of equilibration

$$= \frac{\text{Mass exchanged}}{\text{Max. mass exchanged}}$$

Partial metal-silicate equilibration

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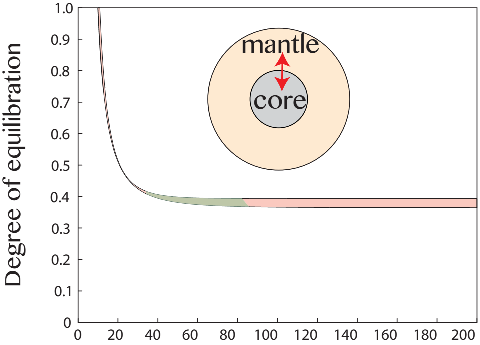

Duration of core formation from Hf/W isotopic data
Rudge et al., 2010, Nature

Degree of equilibration

$$= \frac{\text{Mass exchanged}}{\text{Max. mass exchanged}}$$

The **duration of core formation,** deduced from isotopic observations, strongly **depends** on the assumed **degree of equilibration**

What constraints on Earth formation?

Geo & cosmochemistry

Isotopes
& radioactivity
Hf/W

Core-loving
elements
Ni, Co, ...

Earth's differentiation

Timing < 100 Myrs

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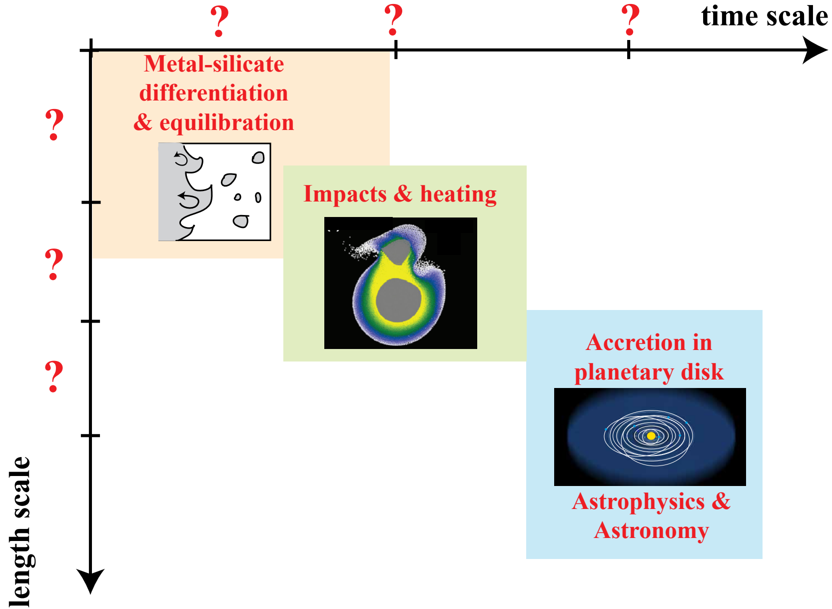
Physical processes: length & time scales



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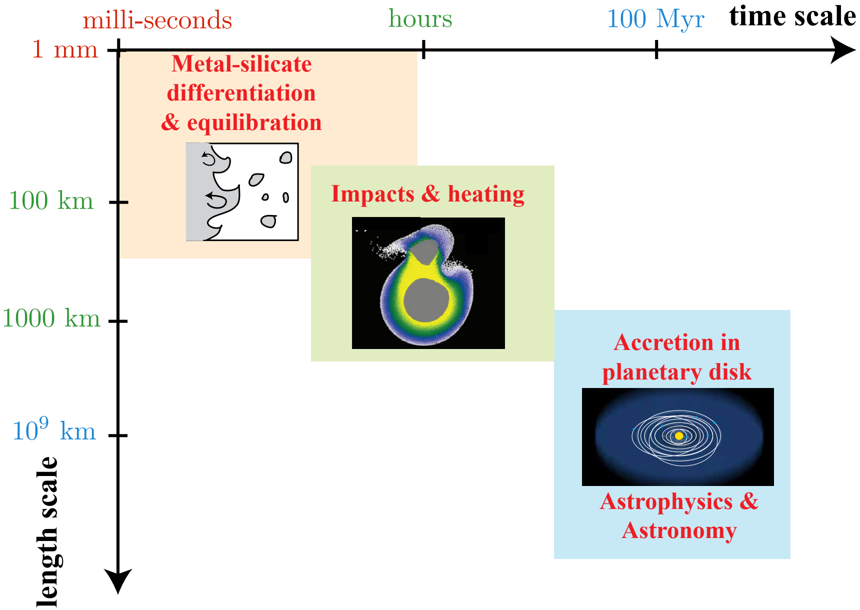

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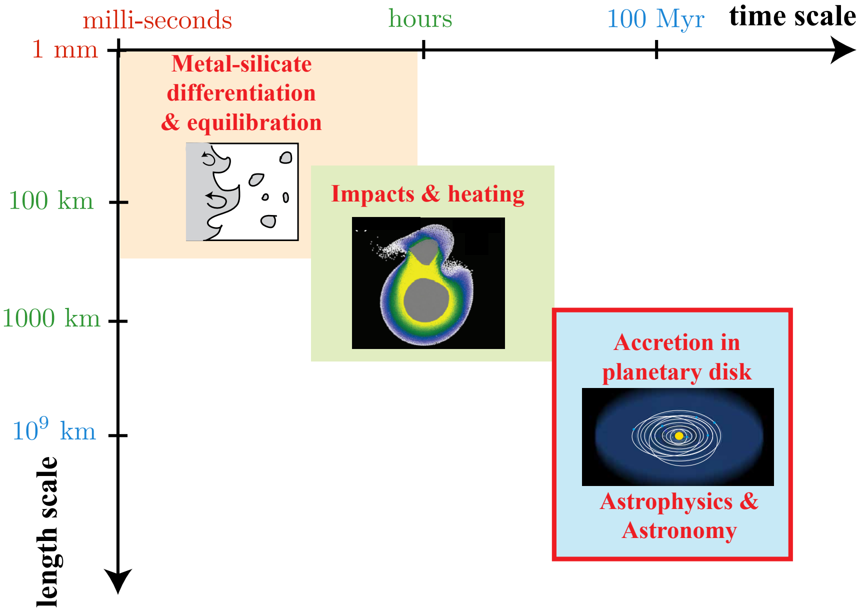
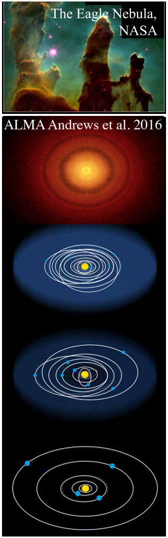


At the disk scale : Accretion stages



0 Myr — Cloud of dust and gas collapses to form a **protoplanetary disk**

↓ **Gravitational instabilities ?** — *Johansen et al. 2007*

Planetesimals (km-sized bodies)

↓ **Successive collisions** between planetesimals

Accretion of pebbles (cm)

Kokubo & Ida, 1996, 1998
Chambers 2006
Weidenschilling, 1997
Lambrechts et al. 2019

~ 1 Myr — **Planetary embryos (~1000 km-sized)**

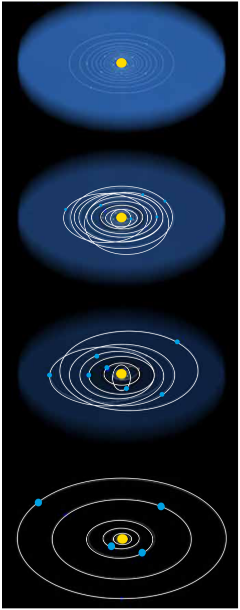
↓ **High-energy, giant collisions**

Chambers & Wetherill, 1998
Agnor et al., 1999
Walsh et al. 2011
O'Brien et al. 2014

~ 100 Myr — **Earth & other terrestrial planets**

time

Protoplanetary disk scale : planetesimals to planets



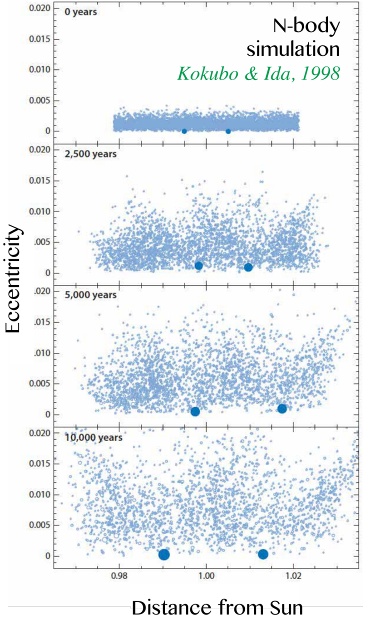
Planetesimals

Gravitational interactions
cause collisions
and merging

Recent models (Grand Tack):
Raymond & Morbidelli 2014
Walsh et al. 2011

Terrestrial planets

time



Protoplanetary disk scale : planetesimals to planets

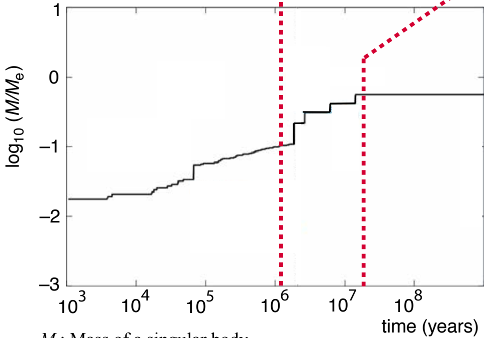
km-sized planetesimals → **Mars-sized embryos** → **Earth-sized planets**

Runaway & oligarchic growth

~ 1 Myr

Large impacts
80-90 % of Earth mass

~ 10-100 Myr

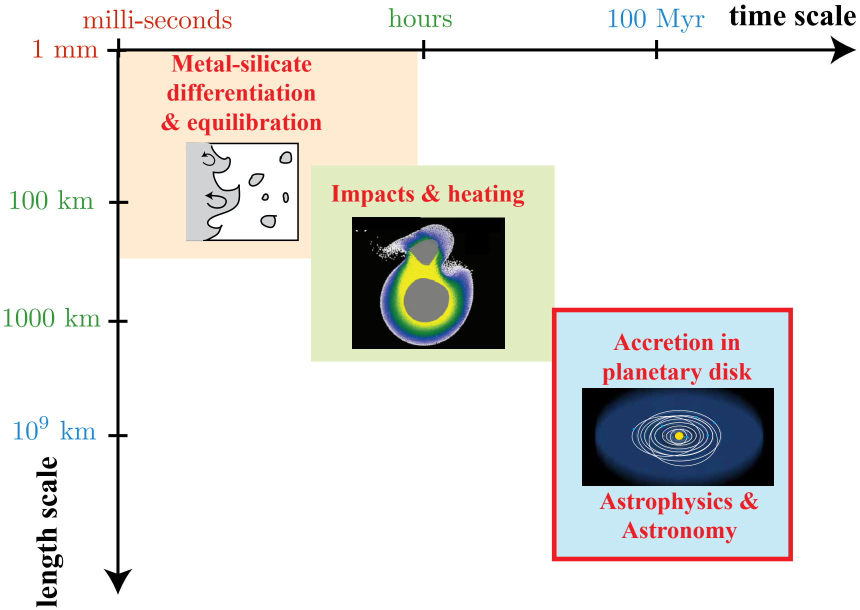


M : Mass of a singular body

Me : Final mass of the Earth

(modified from Rubie et al. 2007)

At the planetary scale : Impacts & heating



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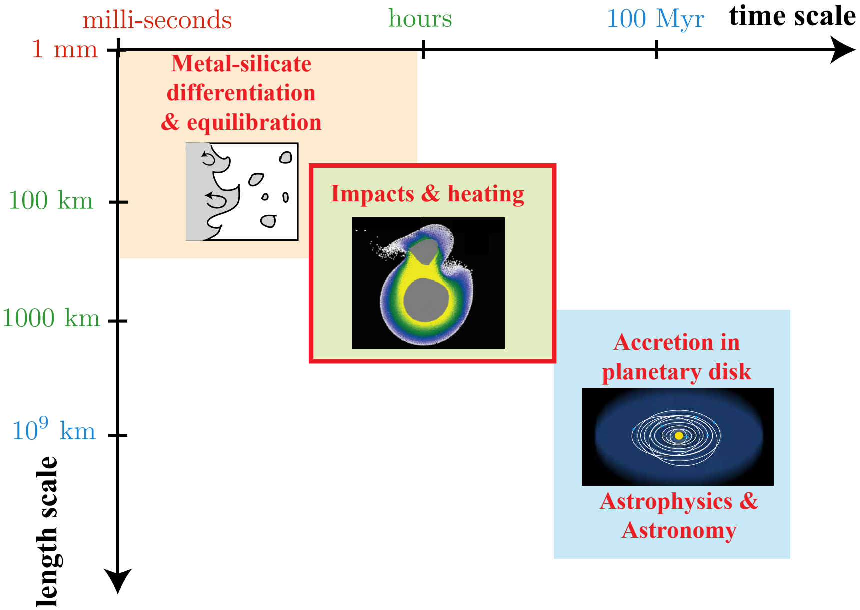
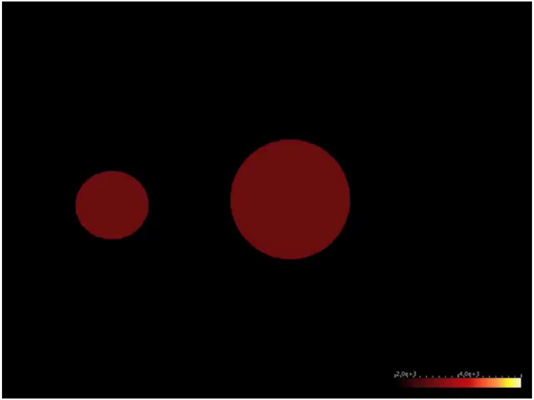


At the planetary scale : Impacts

Formation of the Moon

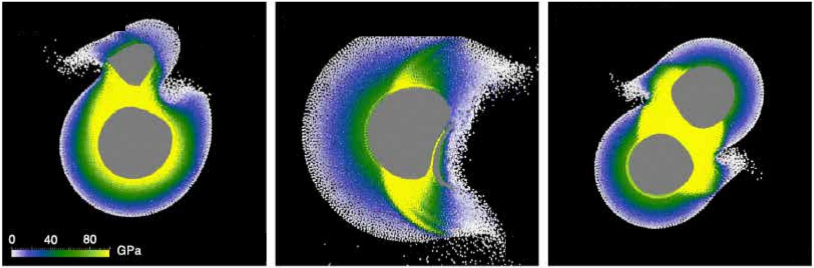
Courtesy of Miki Nakajima, Univ. of Rochester



At the planetary scale : Impacts

Standard Moon-forming scenarios do not easily explain :
the **angular momentum** of Earth-Moon.
& the high **isotopic similarities** of Earth & Moon. *Zhang et al. 2012*

Canup, 2004	*Cúk & Stewart, 2012*	*Canup, 2012*
Mars-sized impactor	*Fast-spinning Earth*	*Equal-sized impactors*



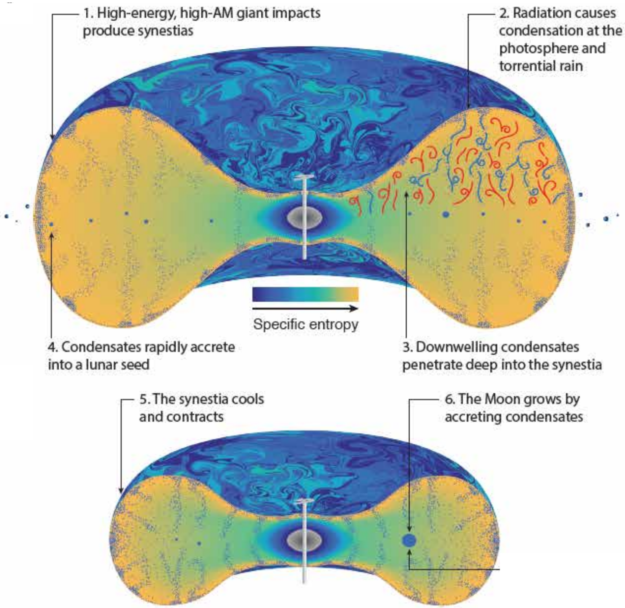
Proposed Moon-forming impact scenarios *Nakajima & Stevenson, 2015*

At the planetary scale : Impacts

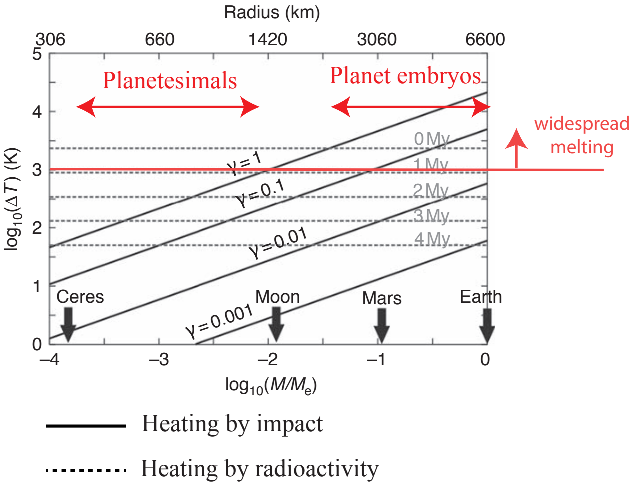
Alternative Moon-forming scenario :

Synestia

Lock et al. 2018



At the planetary scale : Heating & melting



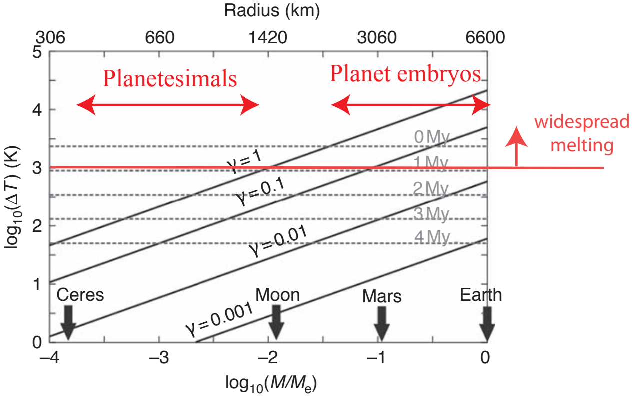
Rubie et al., 2007

Small planetesimals : melting by **radioactivity**

Planetary **embryos** : melting by **impacts**

Magma oceans are unavoidable !

At the planetary scale : Heating & melting



——— Heating by impact

········· Heating by radioactivity

Rubie et al., 2007

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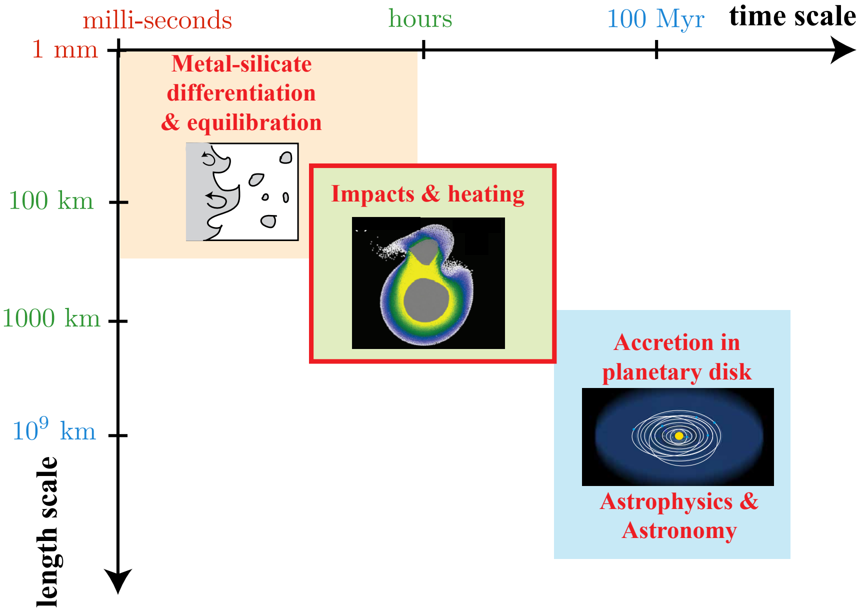
NB: See Tonks & Melosh, 1993 for scalings on heating by impacts

Sub-planetary scale: Metal-silicate differentiation



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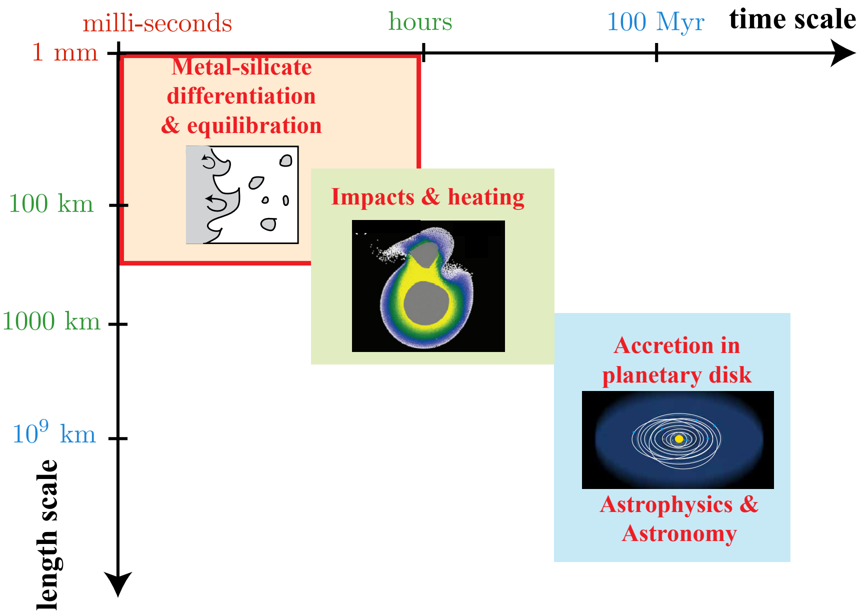
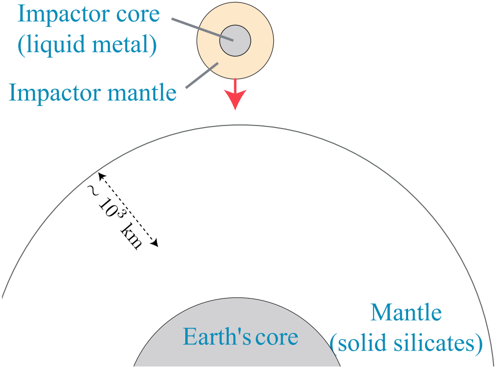
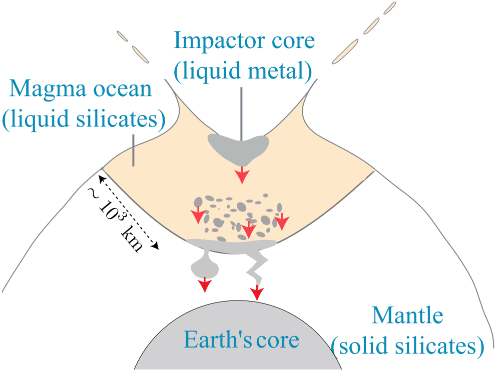


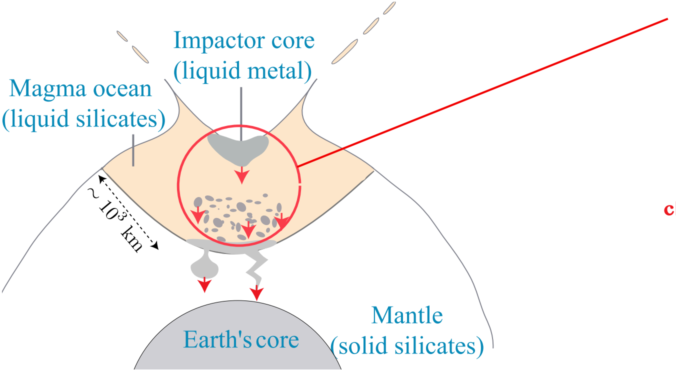
Sub-planetary scale: Metal-silicate equilibration



Sub-planetary scale: Metal-silicate equilibration



Sub-planetary scale: Metal-silicate equilibration



Turbulent mixing

How much metal & silicates mix?

Drop size?

↓

Metal-silicate chemical equilibration

↓

Composition of core & mantle

Duration of core formation from isotopic data

Sub-planetary scale: Metal-silicate equilibration

Nakajima & Stevenson, 2015

Metal-silicate equilibration: numerical simulations

Length scale 1000 km 1 cm

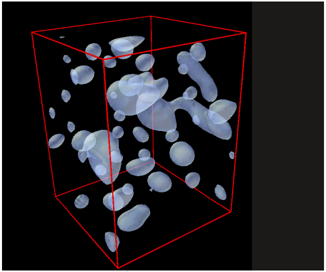
Planetary scale **Chemical equilibration**

Giant impact

time ~ hours

Cameron, 2000
Canup, 2004, 2012
Nakajima & Stevenson, 2015

Iron rain in magma oceans



Ichikawa et al. (2010)

Samuel, 2012
Rubie et al. 2003
Ulvrová et al. 2011
Lherm & Deguen 2018

Metal-silicate equilibration: numerical simulations

Length scale 1000 km 1 cm

Planetary scale ⟷ **Chemical equilibration**

Coupling
large & small scales

Turbulence!

↑

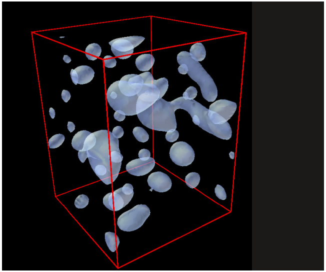
What is missing?

Giant impact

time ∼ hours

Cameron, 2000
Canup, 2004, 2012
Nakajima & Stevenson, 2015

Iron rain in magma oceans



Ichikawa et al. (2010)

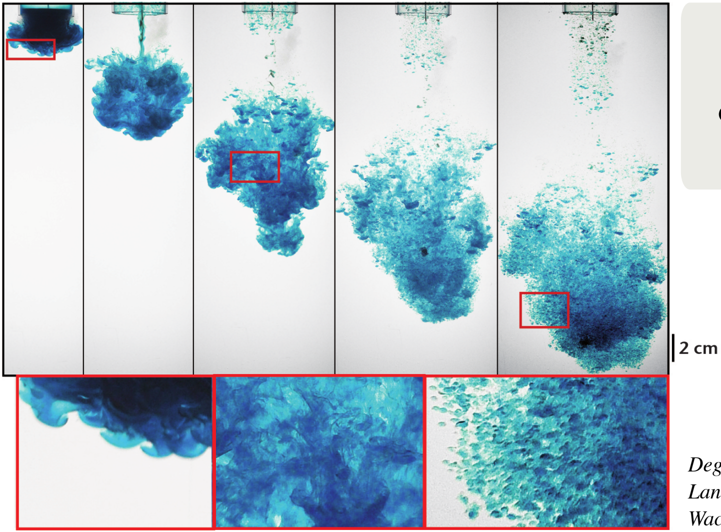
Samuel, 2012
Rubie et al. 2003
Ulvrová et al. 2011
Lherm & Deguen 2018

Metal-silicate equilibration: lab experiments

Turbulent plume, $We =$ inertia / surface tension $\sim 2 \times 10^3$

Deguen et al. 2014, Landeau et al. 2014

Metal-silicate equilibration: Turbulent plume



Sudden breakup of the **entire volume**

Deguen et al. 2014
Landeau et al. 2014
Wacheul & Le Bars 2018

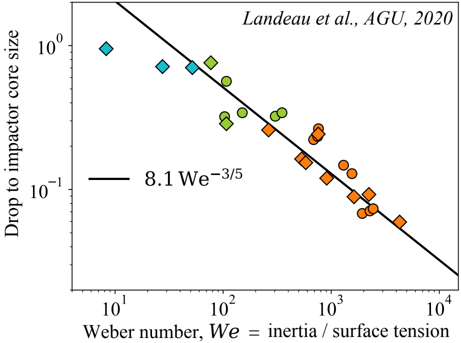
Metal-silicate equilibration: Drop size

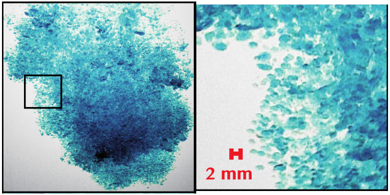
Turbulent plume, $We =$ inertia/surface tension $\sim 10^3$

Landeau et al. AGU 2020

Metal-silicate equilibration: Drop size

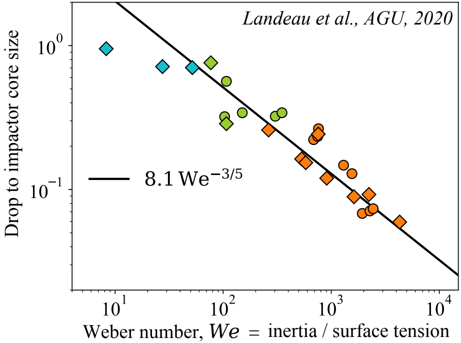
- Drop size $\sim We^{-3/5}$ for homogeneous turbulence. *(Hinze, 1955)*

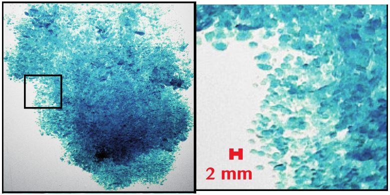




Metal-silicate equilibration: Drop size

- Drop size $\sim We^{-3/5}$ for homogeneous turbulence. *(Hinze, 1955)*
- Metal in magma ocean: Drops $\lesssim$ **1 mm**. Diffusion length ~ 10 mm.





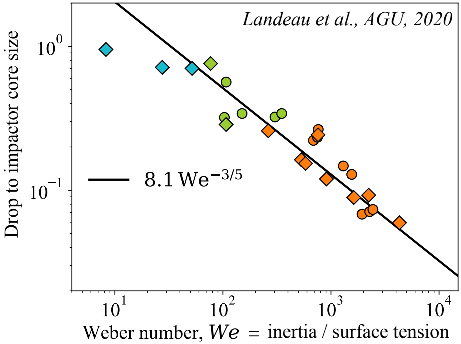
Metal-silicate equilibration: Drop size

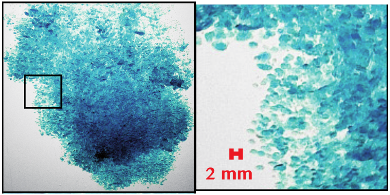
- Drop size $\sim We^{-3/5}$
  for homogeneous turbulence.
  (Hinze, 1955)

- Metal in magma ocean:
  Drops $\lesssim$ **1 mm**.
  Diffusion length ~ 10 mm.

  $\rightarrow$ Chemical **equilibration**
  of the entire impactor core.

  $\rightarrow$ But only with **entrained silicates**.

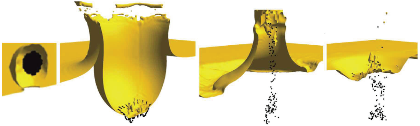




How much entrained silicates during impact?

Landeau et al., EPSL, 2021
Lherm et al., submitted

How much entrained silicates during impact?



Kendall & Melosh, 2016

Landeau et al., EPSL, 2021
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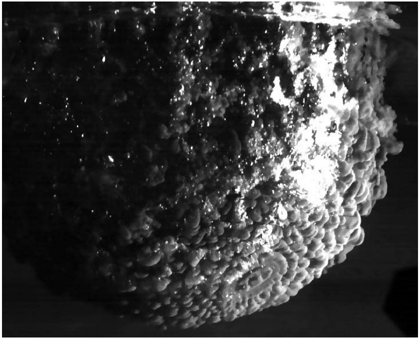
How much entrained silicates during impact?



Landeau et al., EPSL, 2021
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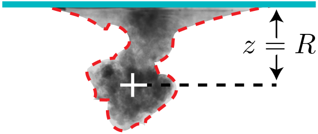
Entrained silicates by impact



Total volume, V

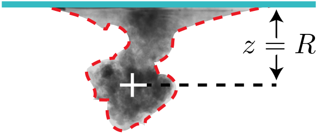
$\downarrow$

Entrained dimensionless volume,

$$V_e = \frac{V - V_0}{V_0}$$

V_0 : impactor volume

Entrained silicates by impact



Total volume, V

↓

Entrained dimensionless volume,

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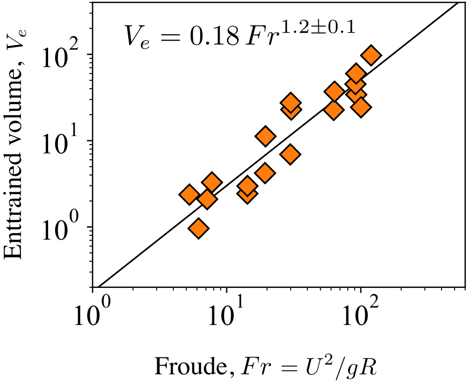
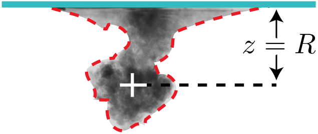


Entrained silicates by impact



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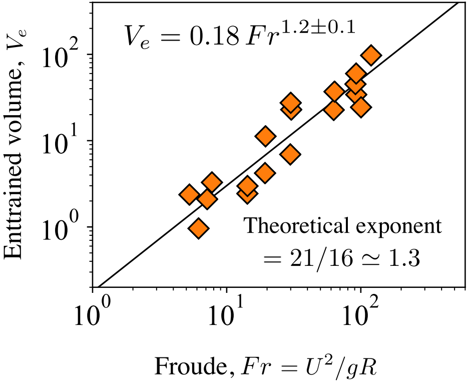
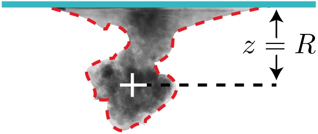


Entrained silicates by impact



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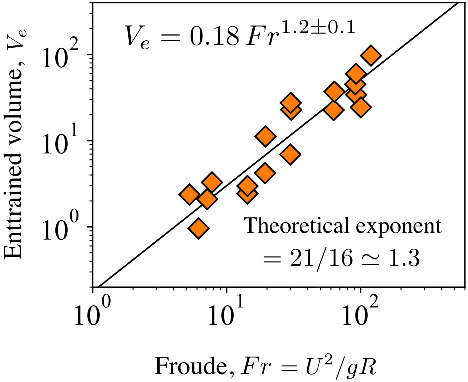
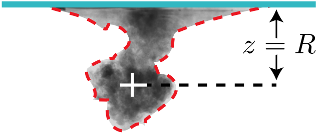


Metal-silicate mixing as a function of **impact velocity** & **impactor size**

Entrained silicates by impact



Total volume, V

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Entrained dimensionless volume,

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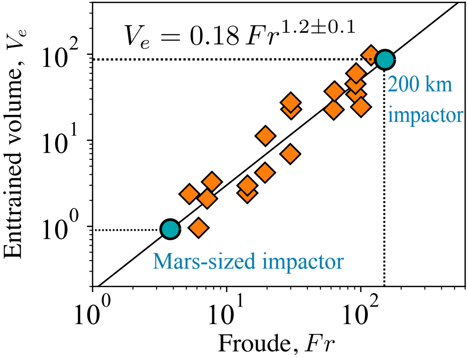
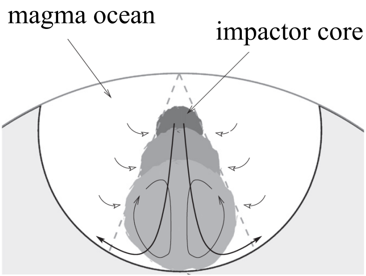


$U^2 \sim g R_p$

$Fr = U^2/gR \sim$ planet/impactor size

Metal-silicate mixing as a function of **impact velocity & impactor size**

Entrained silicates following impact



Deguen et al. 2014

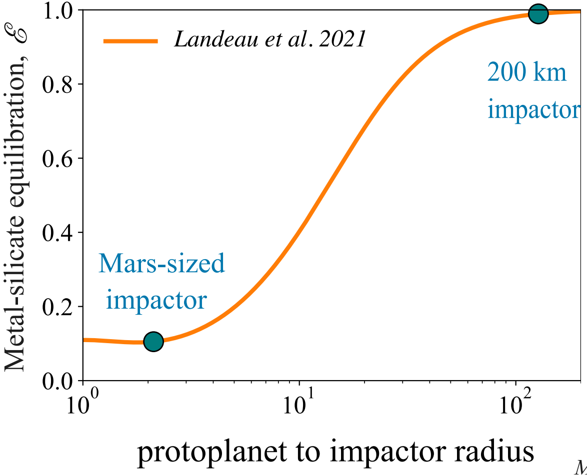
plume radius

$$r = r_0 + \alpha\, z$$

post-impact radius

depth of magma ocean

From entrained silicates to the degree of metal-silicate equilibration



$$\mathscr{E} = \frac{\text{Exchanged mass}}{\text{Max. exchanged mass}}$$

$$= \frac{1 + 2\,D/V_{\text{mantle}}}{1 + 2\,D/V_e}$$

D partition coefficient

V_e entrained silicates

Magma ocean = 40% mantle depth

Metal-silicate partition coeff = 30

Summary: Earth formation, a young field that needs geochemistry & physics

Geo & cosmochemistry

Isotopes
& radioactivity
Hf/W

Core-loving
elements
Ni, Co, ...

Earth's differentiation

Timing < 100 Myrs

Yin et al. 2002
Rudge et al., 2010

Depth ~ 1000 km
& Temperature ~ 3000 K

Wade & Wood, 2005, 2016;
Siebert et al., 2012, 2013;

Physics

Astrophysics

Accretion in the
planetary disk

Mineral physics

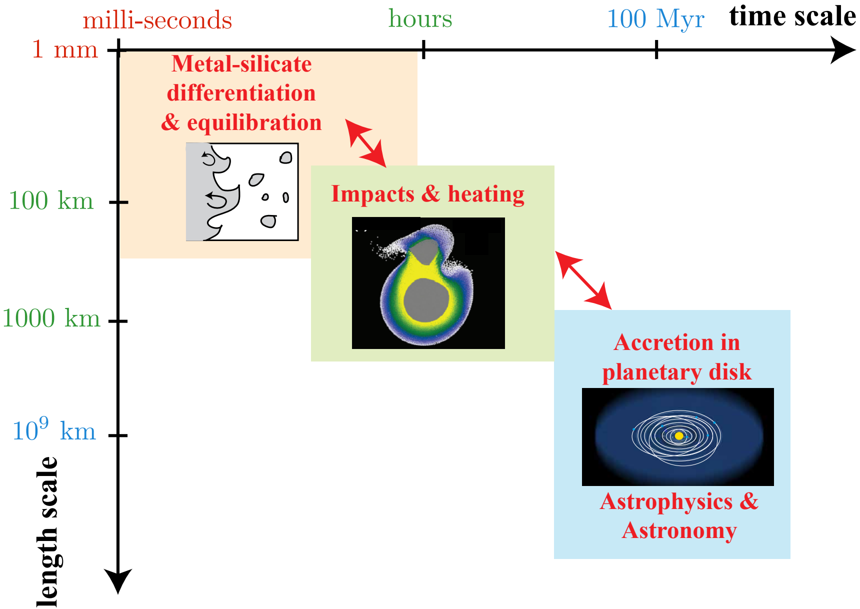
Core-mantle
partition coefficients

Fluid dynamics

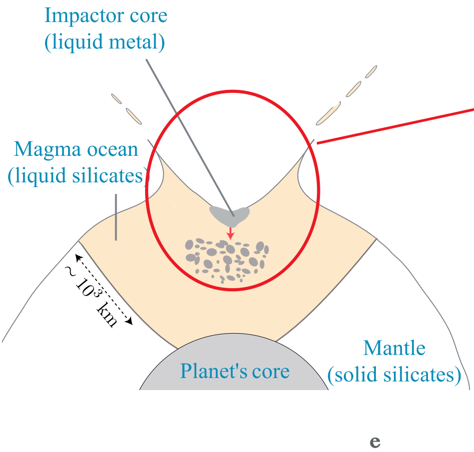
Mixing & chemical transfers
between core & mantle

Rudge et al., 2010
Fischer et al. 2017, 2018

Coupling a wide range of time and length scales



Open questions & next steps on Earth formation



Impactor core fragments into drops, but at what depth? During the impact? **?**

Poster by Augustin Maller

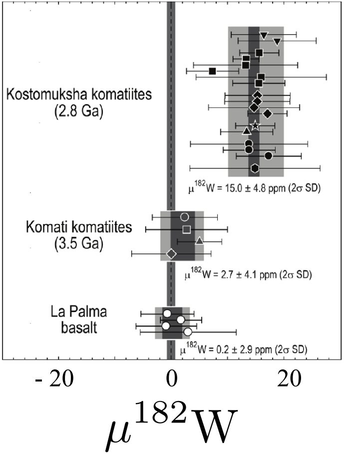
meteor crater (Arizona, USA)

Open questions & next steps on Earth formation

- Magma ocean: Origin of **primordial heterogeneities** in Earth's mantle?
  Impacts?

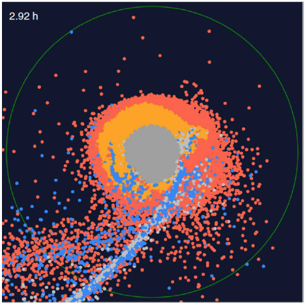
Mundl et al. 2020

Touboul et al. 2012



Open questions & next steps on Earth formation

- **Moon-formation**: impact scenario that explains **compositional similarity** between Earth & Moon?



Hosono et al. 2019

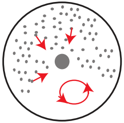
Open questions & next steps on Earth formation
Composition of Earth-forming impactors?

Planetesimals formed before 1 Myr

↓

Melting of silicates by radioactivity (Al^{26}, Fe^{60})

Kaminski et al. 2020

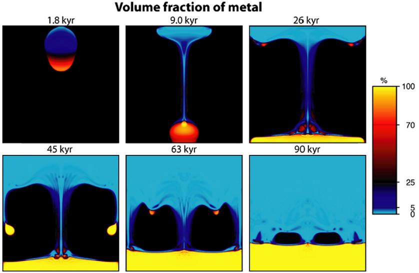


Chemical equilibration

Planetesimals formed after 2 Myr

↓

Partially-solid silicates



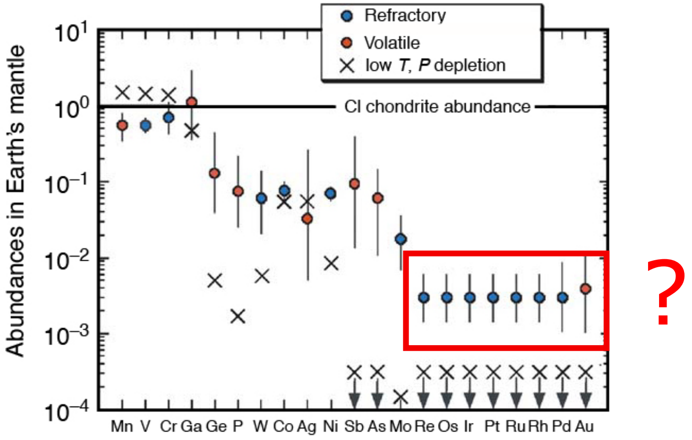
Ricard et al., 2009

Differentiation in ~ 10 000 yr

Chemical equilibration ?

?

Open questions & next steps on Earth formation
Addition of highly-siderophile elements by impacts



from Walter et al. 2000

References:

Books & reviews on Earth formation:

Treatise of geophysics, chapter 9.01 to 9.11, Earth formation & evolution, 2007, Elsevier.

Morbidelli et al. 2012. Building terrestrial planets, Annual Review of Earth and Planetary Sciences.

Melosh, 1989. Impact cratering: A geologic process. Oxford monographs on geology and geophysics.

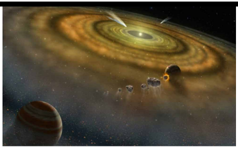
Extra slides

From a uniform nebula to a differentiated planet

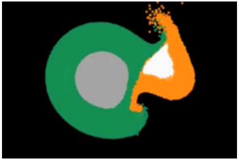
Uniform cloud of dust & gas

Differentiated Earth

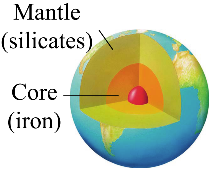
The Eagle Nebula, NASA



Protoplanetary disk



Impacts



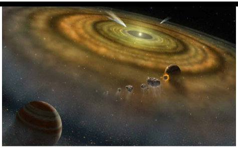
From a uniform nebula to a differentiated planet

Uniform cloud of dust & gas

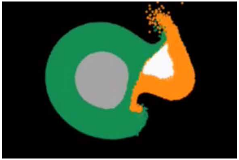
?

Differentiated Earth

The Eagle Nebula, NASA



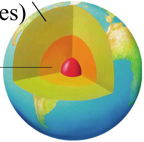
Protoplanetary disk



Impacts

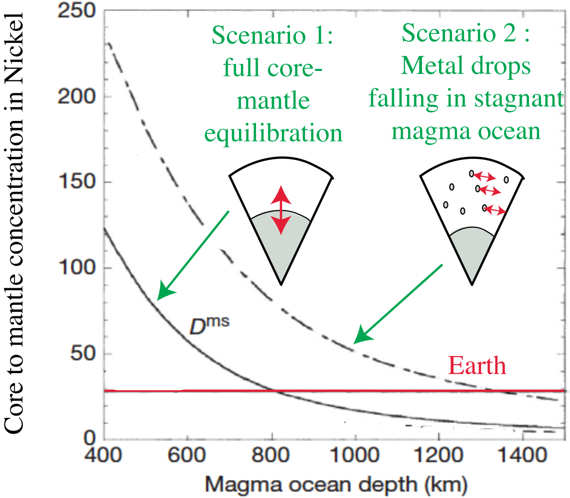
Mantle
(silicates)

Core
(iron)



Partial metal-silicate equilibration

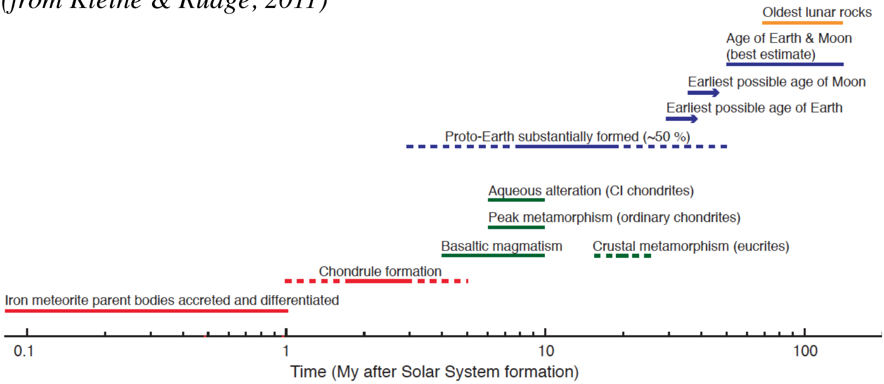
Rubie et al. 2003



Depth of magma ocean deduced from siderophile elements depends on assumed **physics of metal-silicate equilibration !**

Extinct radioactivity: timing of core formation

Summary : Timescales for the formation of inner Solar System planets as determined from isotopic dating *(from Kleine & Rudge, 2011)*



Protoplanetary disk scale: dust to planetesimals

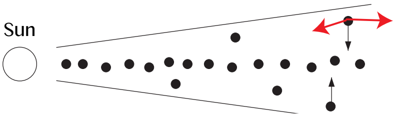
0 Myr

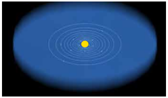
Nebula, Cloud of dust and gas

Angular momentum conservation
+ centrifugal force

Chambers 2004

Protoplanetary disk





~ 1 Myr **Planetesimals (km-sized bodies)**

time

Protoplanetary disk scale: dust to planetesimals

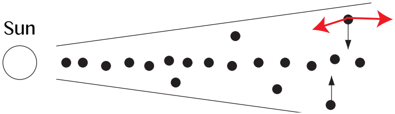
0 Myr

Nebula, Cloud of dust and gas

Angular momentum conservation
+ centrifugal force

Chambers 2004

Protoplanetary disk



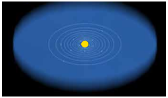
Main problem to overcome :
Gas drag causes **inward migration** of
meter-sized objects in **~1000 yrs**

?

Gravitational instabilities ? *Goldreich & Ward, 1973*
Requires too high concentrations of solid particles...

Helped by **turbulence ?** *Johansen et al. 2007*
High-pressure regions concentrate particles.

Fusion + solidification of ice during collisions ? *Wettlaufer 2010*

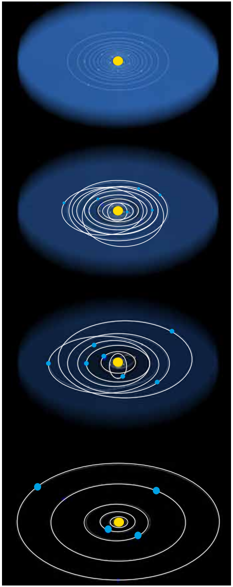


~ 1 Myr

Planetesimals (km-sized bodies)

time

Protoplanetary disk scale : planetesimals to planets



Planetesimals (km-sized bodies)

Inward, then outward **migration** of **Jupiter & Saturn** explains:

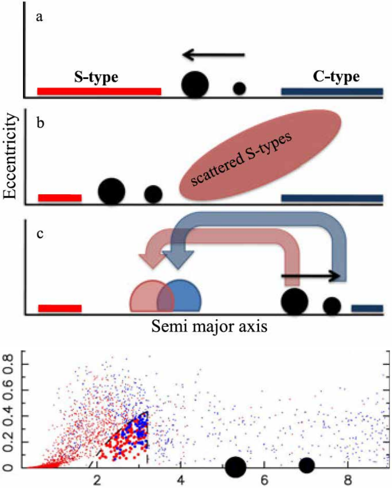
- **Size of Mars**
- **Water in inner solar system**
- **Distribution in asteroid belt**

Terrestrial planets

time

The Grand Tack scenario

Walsh et al. 2011



Core-mantle differentiation: large impacts

Villermaux and Bossa (2009)

Deformation of the initial object → Ligaments, filamentary structures → Drops

Core-mantle differentiation: large impacts

Villermaux and Bossa (2009)

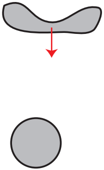
Deformation of the initial object → Ligaments, filamentary structures → Drops

Dimensionless number

$$\text{Weber} = \frac{\text{inertia}}{\text{surface tension}}$$

deformation

spherical shape

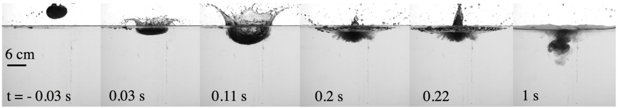


Core formation:

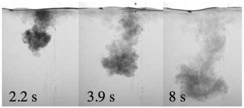
$We \gtrsim 10^{12}$

Entrained silicates: two main stages

Short times



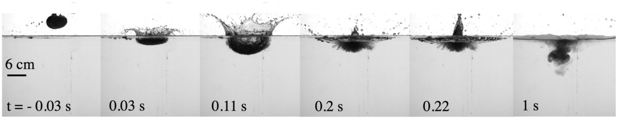
Long times



Froude = 18, U = 2.3 m/s

Entrained silicates: two main stages

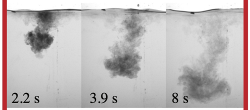
Short times



Froude = 18, U = 2.3 m/s

Long times

Turbulent plume

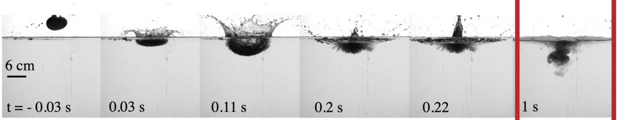


Landeau et al., 2014
Deguen et al., 2014
Wacheul & Le Bars, 2017

Entrained silicates: two main stages

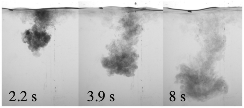
Short times

Long times



Froude = 18, U = 2.3 m/s

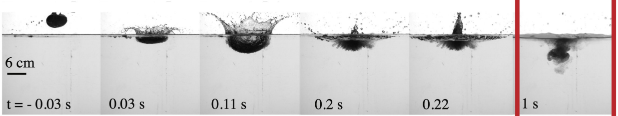
Turbulent plume



Landeau et al., 2014
Deguen et al., 2014
Wacheul & Le Bars, 2017

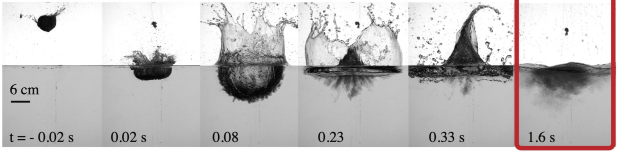
Entrained silicates: two main stages

Short times



Froude = 18, U = 2.3 m/s

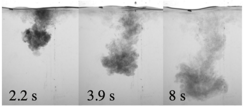
?



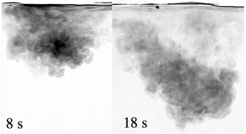
Froude = 130, U = 6.2 m/s

Long times

Turbulent plume

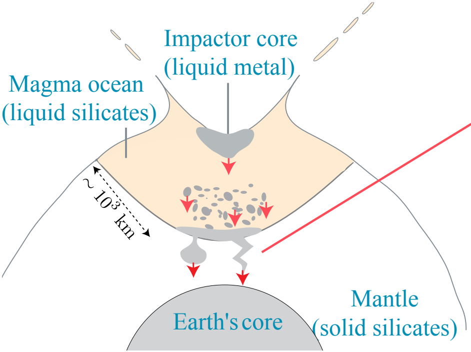


Landeau et al., 2014
Deguen et al., 2014
Wacheul & Le Bars, 2017



How much ambient fluid entrained & mixed with the impactor?

Metal-silicate differentiation: large impacts



Diapirs or dykes in solid mantle

Length $\gtrsim 1$ km

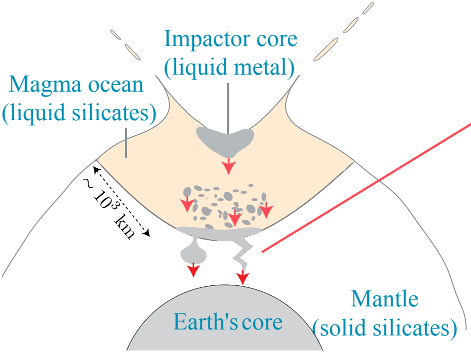
Karato & Murthy, 1997

Time $\gtrsim$ 3 yr

Length for chemical transfers $\sqrt{Dt} \sim 1$ m

No chemical equilibration

Metal-silicate differentiation: large impacts



Diapirs or dykes in solid mantle

Length $\gtrsim 1$ km

Karato & Murthy, 1997

Time $\gtrsim$ 3 yr

Length for chemical transfers $\sqrt{Dt} \sim 1$ m

No chemical equilibration

Thermal transfers ?

Metal-silicate differentiation: large impacts

Differentiation in solid mantle

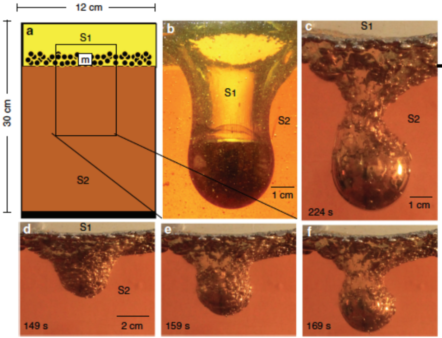
Mantle viscosity

$\lesssim 10^{12}$ Pa s

Diapir

$\gtrsim 10^{12}$ Pa s

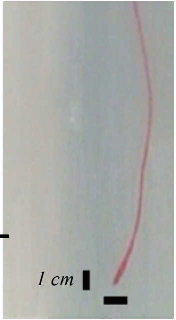
Dyke



Fleck et al. 2018

Deformation & heating in the mantle

Deformation & heating in the metal



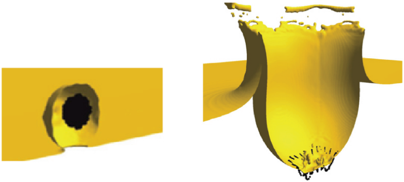
Sumita & Ota, 2011

Sub-planetary scale: Metal-silicate equilibration

Impact simulations

Nakajima & Stevenson, 2015

Canup, 2004, 2012



Kendall & Melosh, 2016

↓

Resolution ~ 100 km

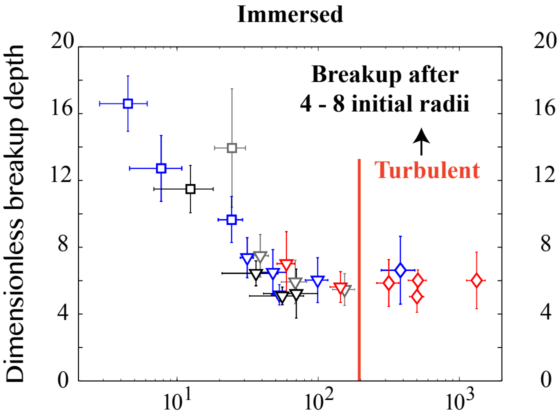
Scale of chemical transfers ~ 1 cm

Ichikawa et al. 2010

What is missing?

Small scales & Turbulence!

Core-mantle differentiation: large impacts
Turbulent plume



$$We = \frac{\text{inertia}}{\text{surface tension}}$$

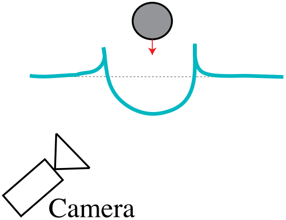
Breakup into drops after most impacts

(except the largest giant impacts)

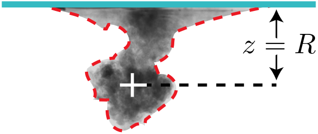
Landeau et al. 2014

Mixing?

Mixing?



Entrained silicates



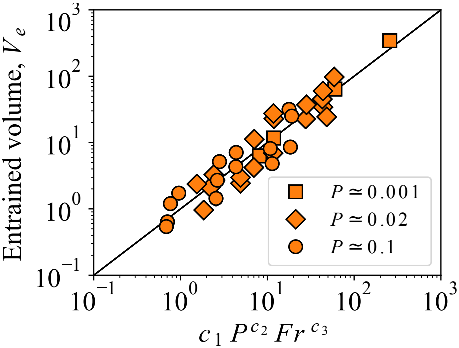
Total volume, V

$\downarrow$

Entrained dimensionless volume,

$$\boxed{V_e = \frac{V - V_0}{V_0}}$$

V_0 : impactor volume



$$c_1 = 0.024 \pm 0.007,$$
$$c_2 = -0.6 \pm 0.1,$$
$$c_3 = 1.2 \pm 0.1$$