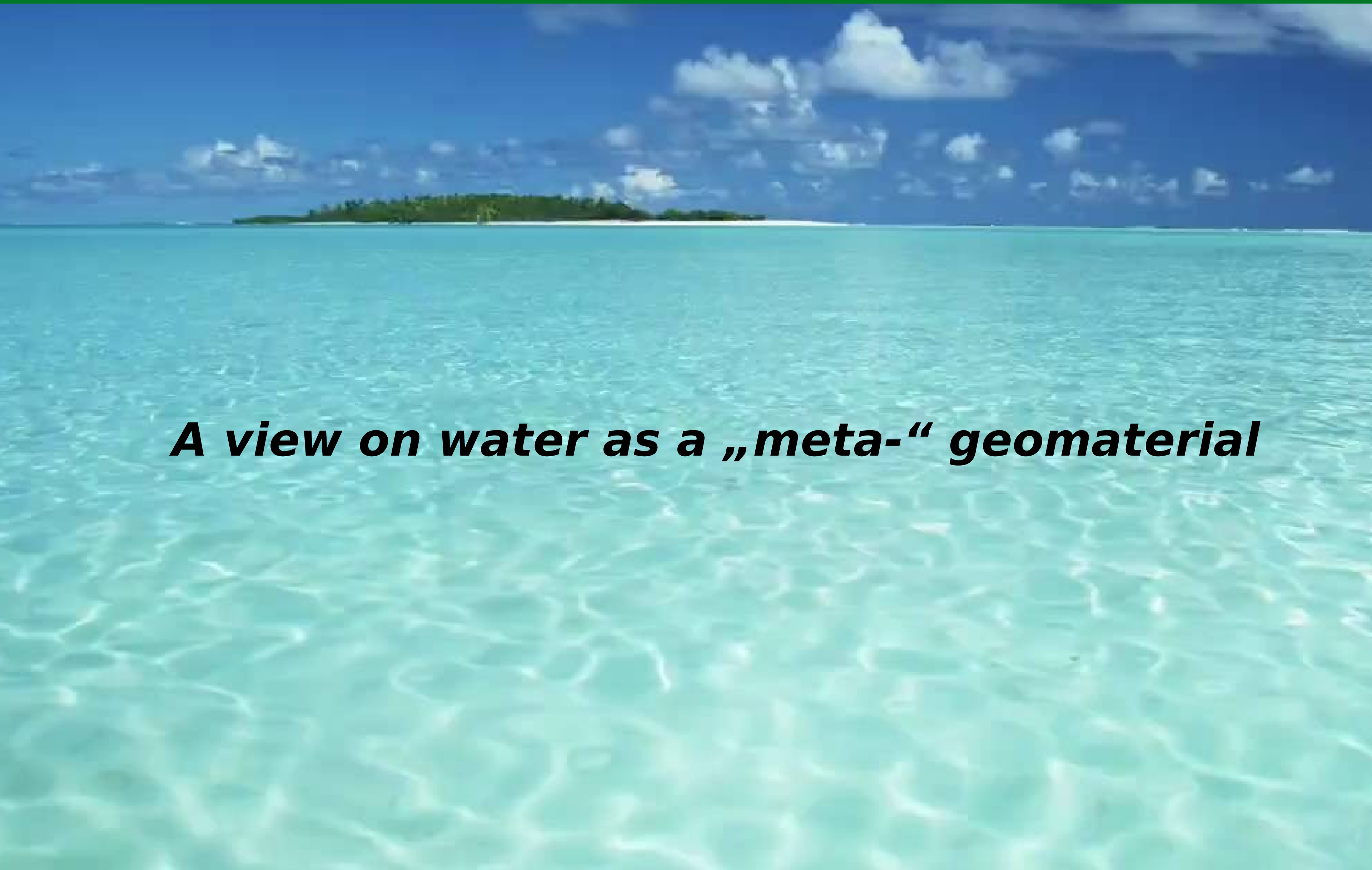
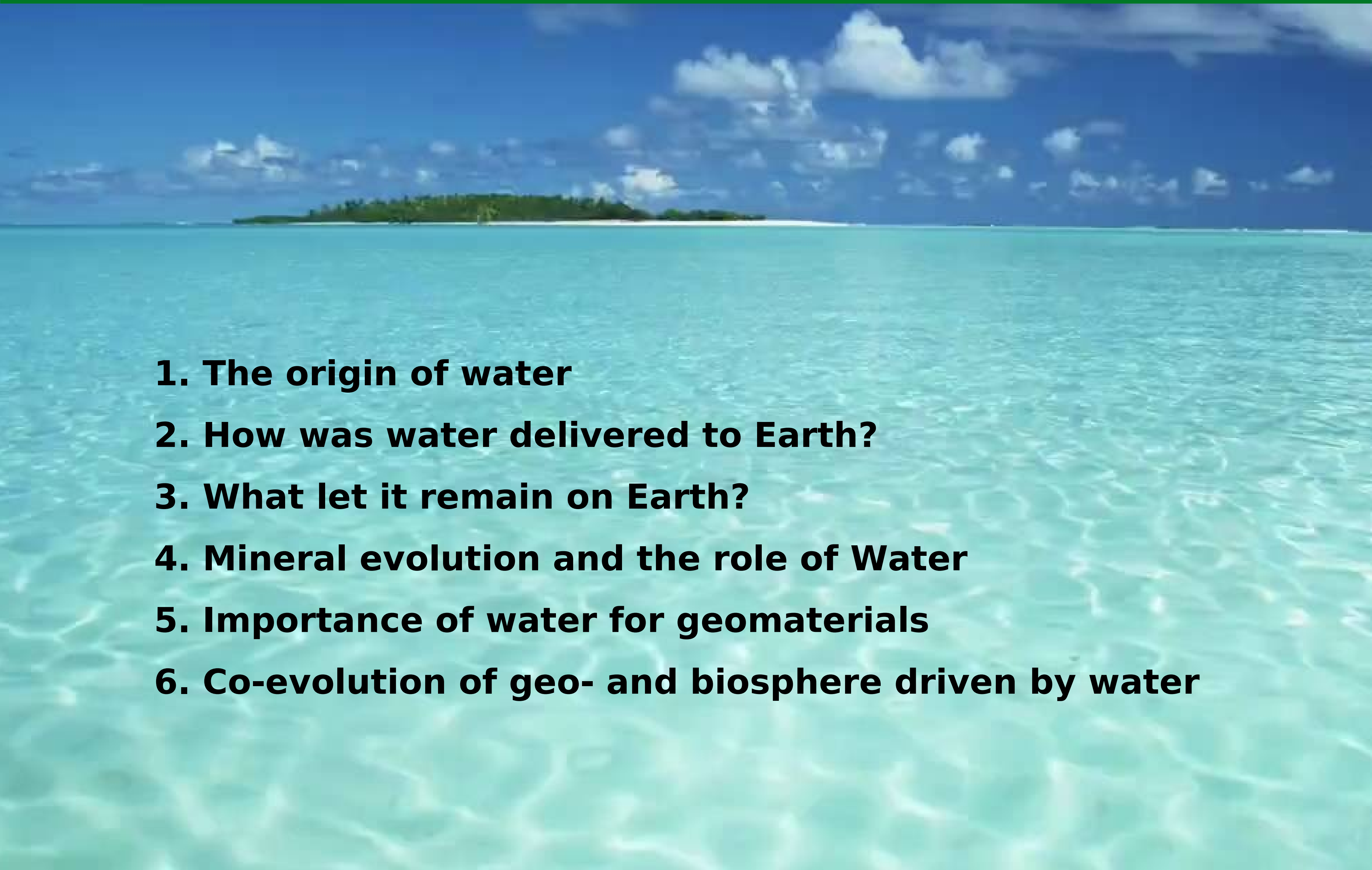
Water as „meta“-geomaterial
(F. Trixler)



A view on water as a „meta-“ geomaterial

Water as „meta“-geomaterial

(F. Trixler)



1. **The origin of water**
2. **How was water delivered to Earth?**
3. **What let it remain on Earth?**
4. **Mineral evolution and the role of Water**
5. **Importance of water for geomaterials**
6. **Co-evolution of geo- and biosphere driven by water**

1. Origin of Water

1. The origin of water

1. Origin of Water

Interstellar Medium (ISM)

Lynd 1251 (c) A. Jerahian

- Mainly H and He
- 0,1 % C, N, O, Mg, ... Fe
  → from stellar nucleosynthesis
  → Injected into the ISM via stellar outbursts, stellar winds, red supergiant stars
  → crystallization from gas phase (e.g. outer atmosphere of Red Giants) generates refractory component of nm/ µm size **dust particles:**
  Silicates (Olivine, Pyroxene), Carbides, Diamond, Graphite, PAHs...

1. Origin of Water

Interstellar Medium (ISM)

Lynd 1251 (c) A. Jerahian

Density of dust clouds can be so high that it is opaque for most electromagnetic radiation of nearby stars

→ low temperature (<30 K): **inefficient** gas phase synthesis
→ rich chemistry takes place; **high abundance** of H_2, H_2O, ...

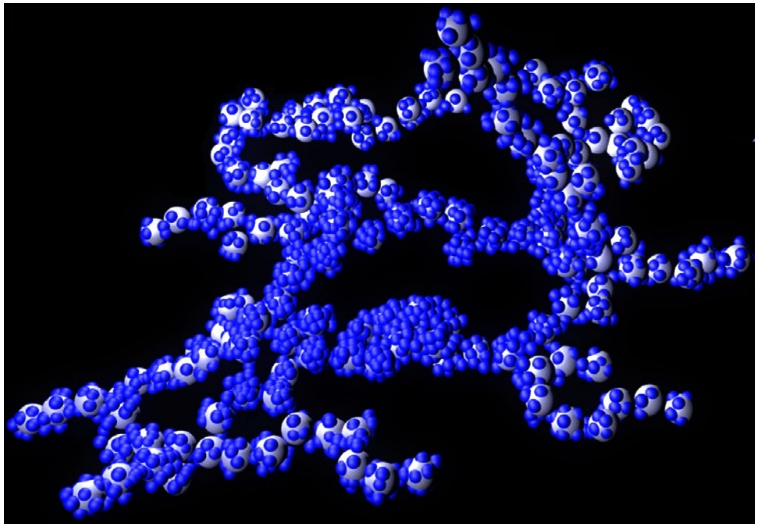
} **paradox**

1. Origin of Water

→ **surface of interstellar dust grains catalyzes H_2 / H_2O formation**

↓

H adsorption → exchange energy with surface → diffusion →
→ combination with other adsorbed H → **H_2** ... (+ OH → **H_2O** + H)



Phys. Rev. Lett. 124, 221103 (2020).

1. Origin of Water

Dark Clouds in ISM

→ Low temperature: T < 20 K

- Physisorption (without fast desorption)
- But low mobility for diffusion!
- However: high efficiency in $\mathbf{H_2}$ production

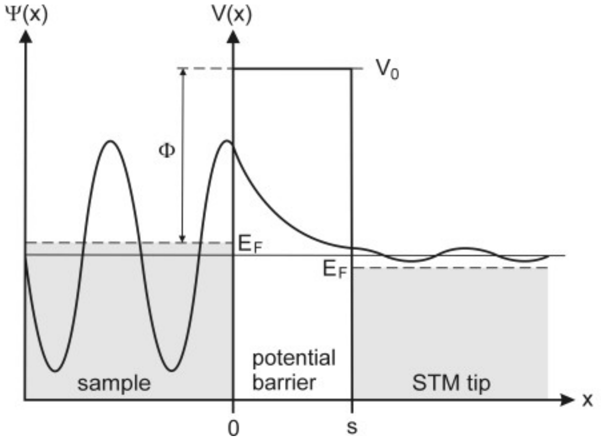
Dark Clouds in ISM

→ Low temperature: T < 20 K

- Physisorption (without fast desorption)
- But low mobility for diffusion!
- However: high efficiency in **H_2** production

↓

Quantum Tunneling



Curr. Org. Chem. 17 (2013), 1758

1. Origin of Water

→ Icy mantles around interstellar dust particles (T < 20 K)

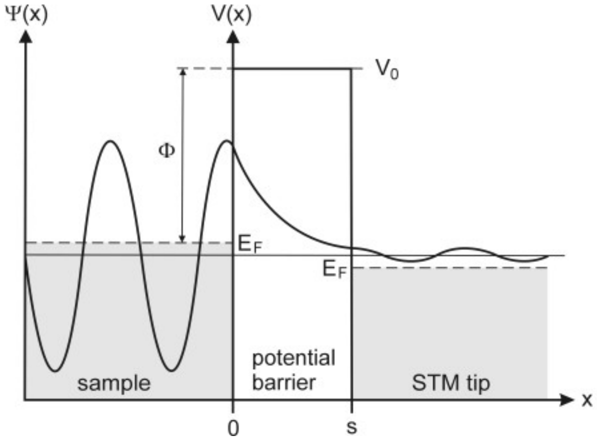
- Most abundant: H_2O
- Considered as most common surface reaction:
  $OH + H_2 \rightarrow H_2O + H$
- Large activation barrier: at T> 20 K
  → reaction via thermal activation: very low probability

1. Origin of Water

→ Icy mantles around interstellar dust particles (T < 20 K)

- Most abundant: H_2O
- Considered as most common surface reaction:
  $OH + H_2 \rightarrow H_2O + H$
- Large activation barrier: at T> 20 K
  → reaction via thermal activation: very low probability
  but:

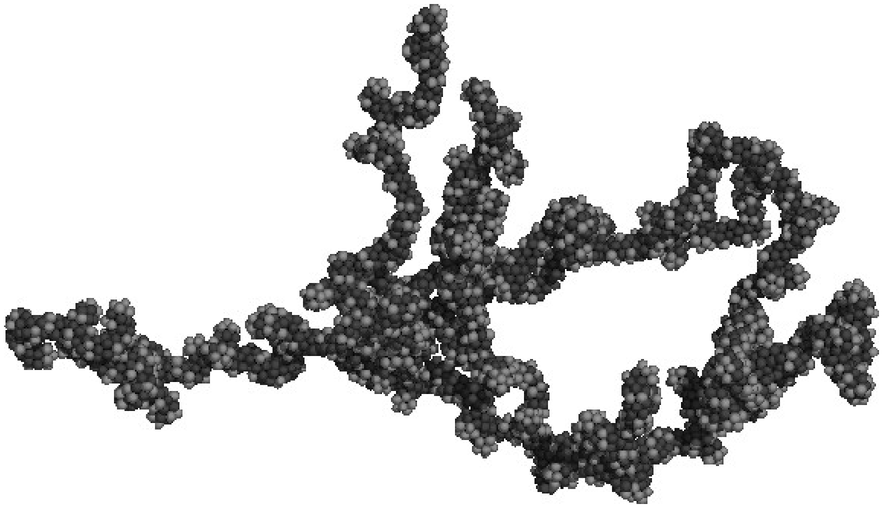
Quantum Tunneling



Curr. Org. Chem. 17 (2013), 1758

1. Origin of Water

origin of water is linked to mineral particles



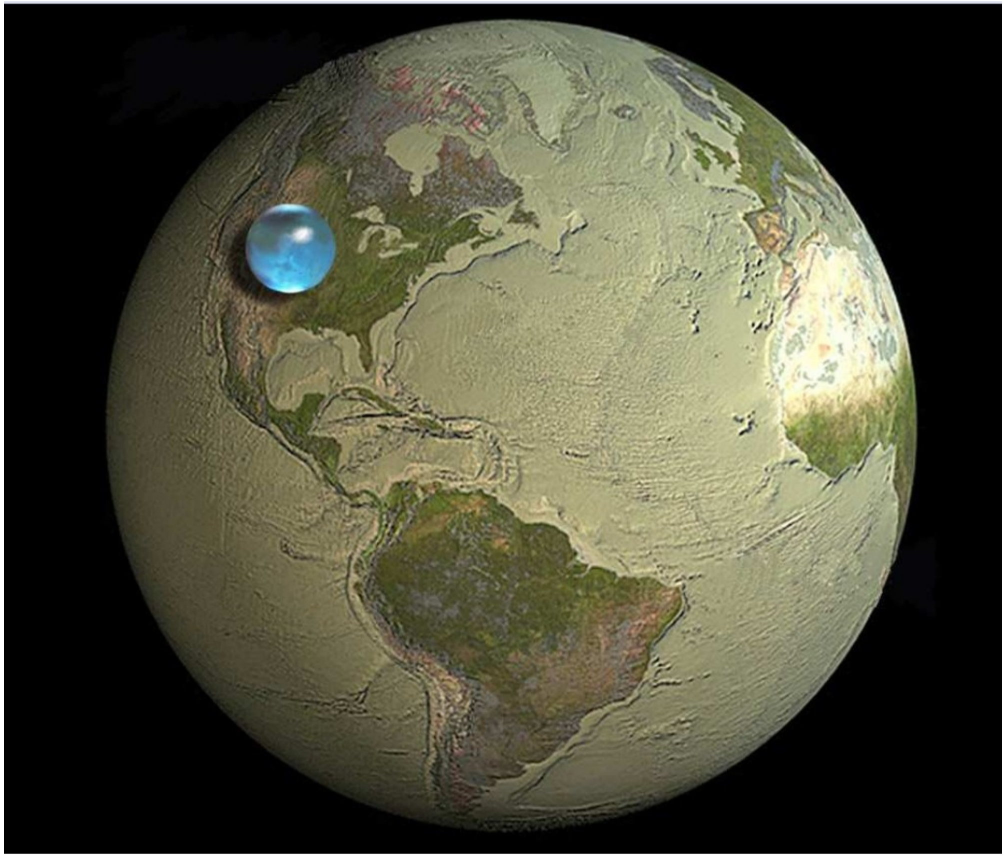
chm.bris.ac.uk

2. How was water delivered to Earth?

2. How was water delivered to Earth?

2. How was water delivered to Earth?

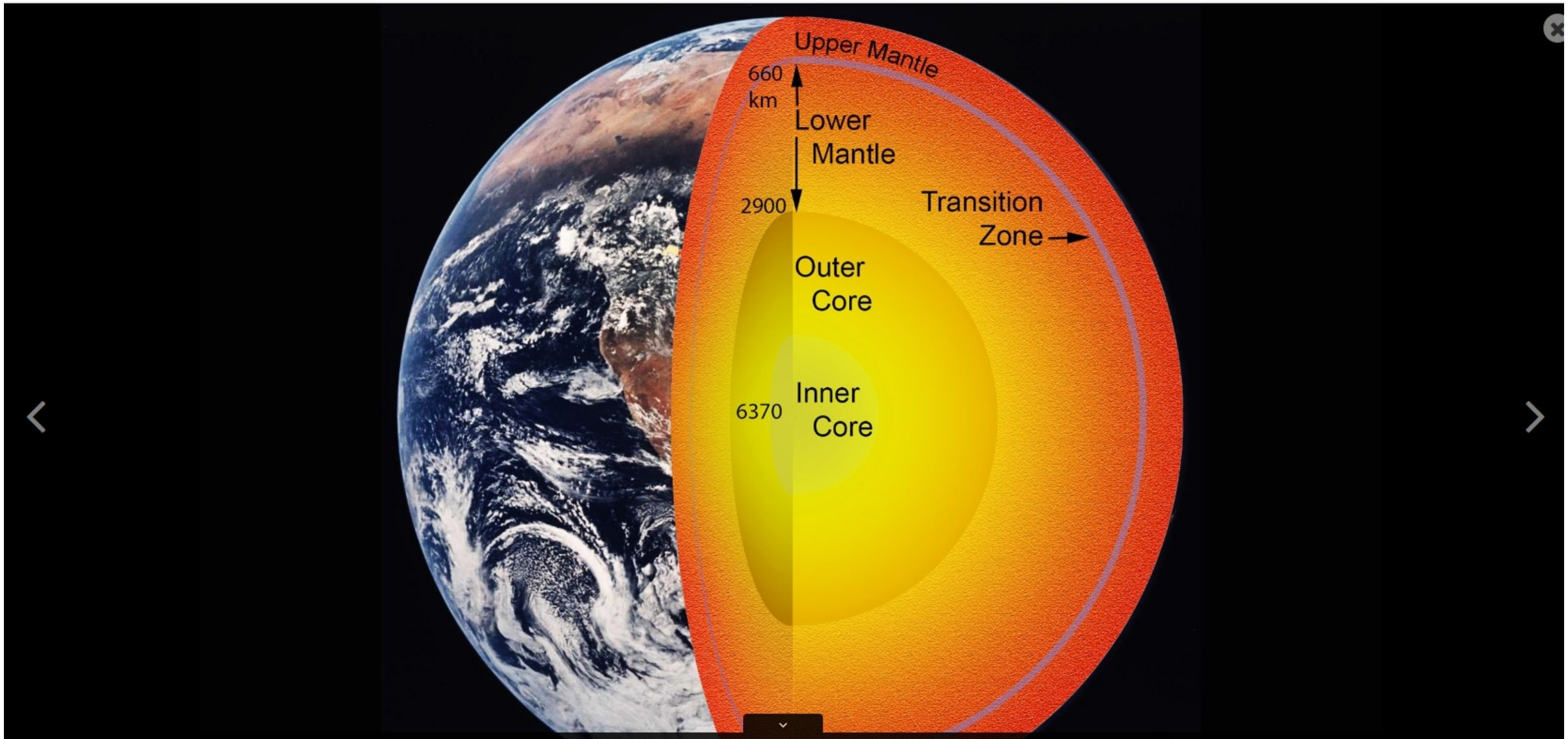
Amount of water on/near surface



All the Water on Planet Earth
Illustration Credit & Copyright: Jack Cook, Woods Hole Oceanographic Institution, Howard Perlman, USGS

2. How was water delivered to Earth?

Hydration of mantle transition zone: 1 – 1.5 w% H_2O
→ in sum may ~ equal oceanic water



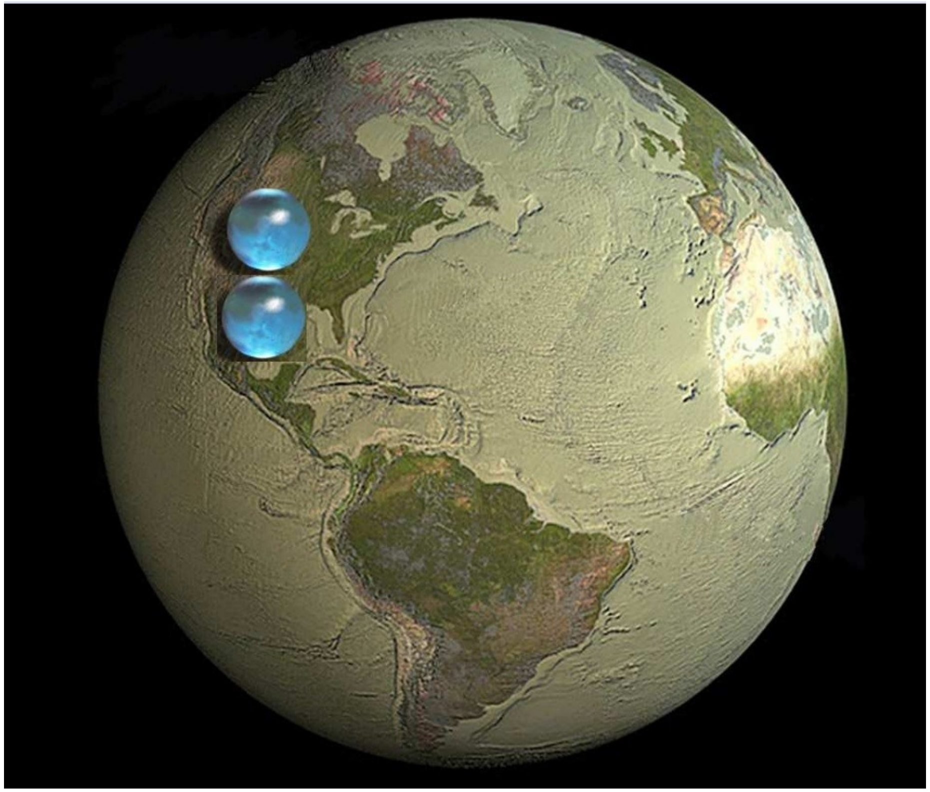
SCHEMATIC CROSS SECTION OF THE EARTH'S INTERIOR HIGHLIGHTING THE TRANSITION ZONE LAYER (LIGHT BLUE, 410-660 KM DEPTH), WHICH HAS AN ANOMALOUSLY HIGH WATER STORAGE CAPACITY. THE STUDY BY SCHMANDT AND JACOBSEN USED SEISMIC WAVES TO DETECT MAGMA GENERATED NEAR THE TOP OF THE LOWER MANTLE AT ABOUT 700 KM DEPTH. DEHYDRATION MELTING AT THOSE CONDITIONS, ALSO OBSERVED IN THE STUDY'S HIGH-PRESSURE EXPERIMENTS, SUGGESTS THE TRANSITION ZONE MAY BE NEARLY SATURATED WITH H2O DISSOLVED IN HIGH-PRESSURE ROCK. IMAGE CREDIT: STEVE JACOBSEN/NORTHWESTERN UNIVERSITY

B. Schmandt, et al., “Dehydration melting at the top of the lower mantle,” **doi: 10.1126/science.1253358**
D. G. Pearson, et al., “Hydrous mantle transition zone indicated by ringwoodite included within diamond,” **doi:10.1038/nature13080**

2. How was water delivered to Earth?

Total amount of water:
~ 0.02* (0.04 %) of total mass

* M. Willians, *Universe Today* (2014), 12



All the Water on Planet Earth
Illustration Credit & Copyright: Jack Cook, Woods Hole Oceanographic Institution, Howard Perlman, USGS

2. How was water delivered to Earth?

Snow line

(ice line, frost line)

- Is the distance to the sun where T °C low: volatiles condense (in space)
- Current snow line water: ~ 2.7 AU (Ceres: 2,77 AU)

→ Snow Line separates inner solar systems (rocky plantes) and outer solar systems (Gas Giants, Icy Moons, Ceres)

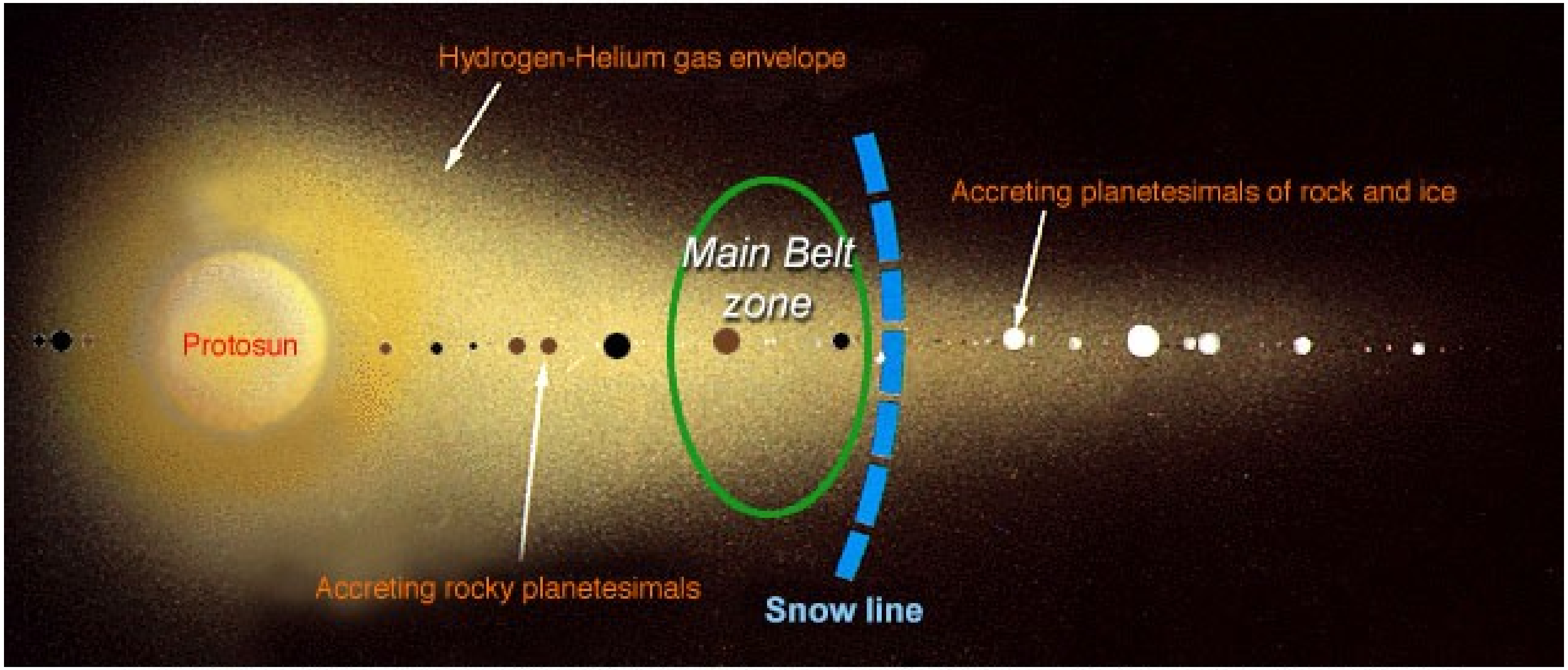
w% Water:
Earth: 00.04
Titan: 40.00
Rhea: 75.00

2. How was water delivered to Earth?

Snow line

(ice line, frost line)

Solar System Formation



(Background graphic courtesy of Windows to the Universe, www.windows.ucar.edu. Ellipse added for emphasis.)

psrd.hawaii.edu/WebImg/protoplanets-snowline.jpg

2. How was water delivered to Earth?

snow line → visible

Comet Hale-Bopp, 1997. F. Trixler

2. How was water delivered to Earth?

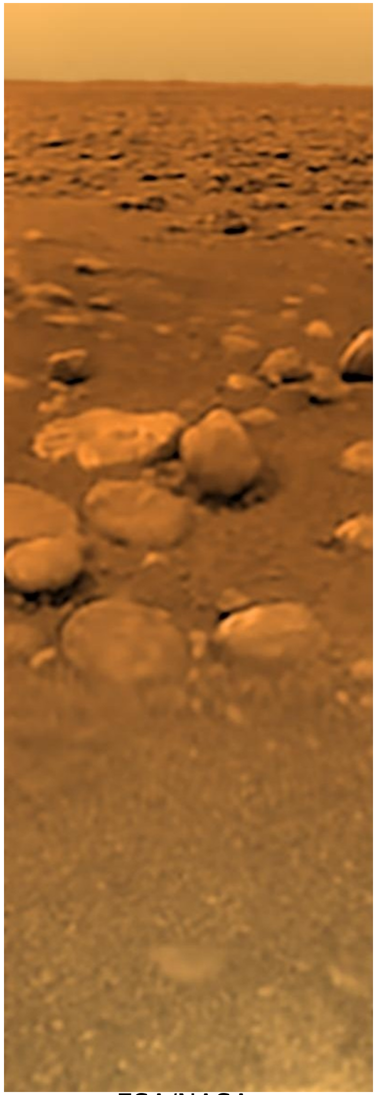
Snow line
(ice line, frost line)

↓

„Geomaterials in technology and environment“
would be very different on an icy planetary body
in the outer solar system.

Surface of Titan (Saturn System):
- water ice rocks
- sand pebbles made of icy grains and Tholins
- pores of wet sand filled with liquid methane

Nature 438 (2005), 756


ESA/NASA

2. How was water delivered to Earth?

availability/ abundance of certain geomaterials on the surface also depends on the location relative To the snow line of water

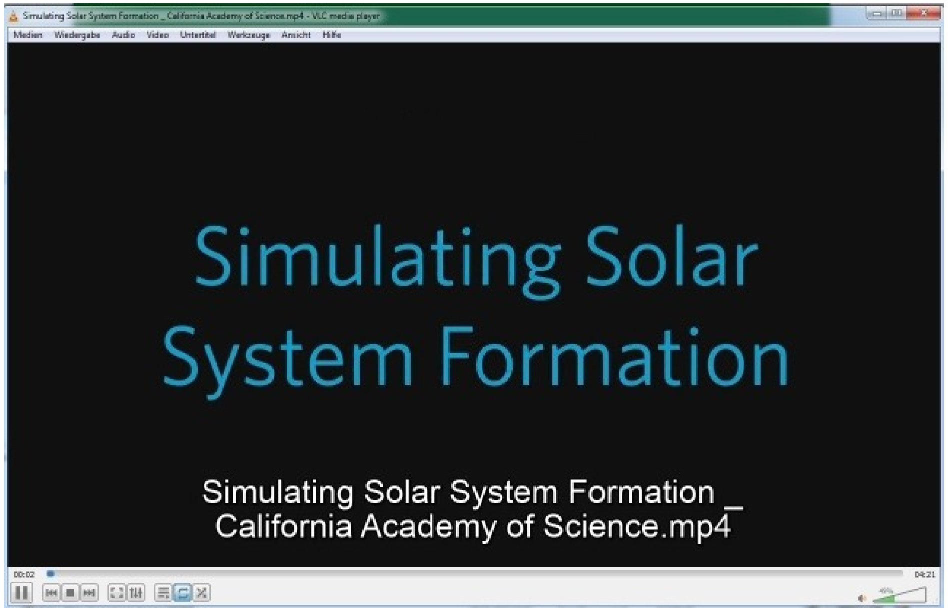
2. How was water delivered to Earth?

- Water abundant in the outer solar system beyond snow line
- Carbonaceous chondrites highest content of volatiles such as water
- aggregate in comets, asteroides, planetesimals
- Isotope geochemistry:
  → Mo:
  Earth accreted carbonaceous bodies late in its growth history, probably through the Moon-forming impact [http://dx.doi.org/10.5772/50172]
  → Se:
  signature of Se in Earths mantle matches nearly perfect with Se signature of carbonaceous chondrites [https://dx.doi.org/10.1038/s41561-019-0414-7]

↓

Most of water on Earth delivered by late accretion of carbonaceous chondrites from the outer solar system

2. How was water delivered to Earth?

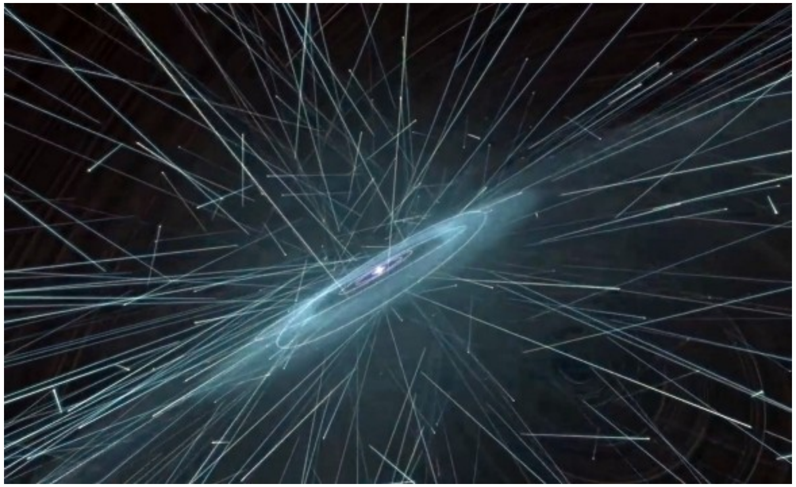


youtube.com/watch?v=yXq1i3HlumA

2. How was water delivered to Earth?

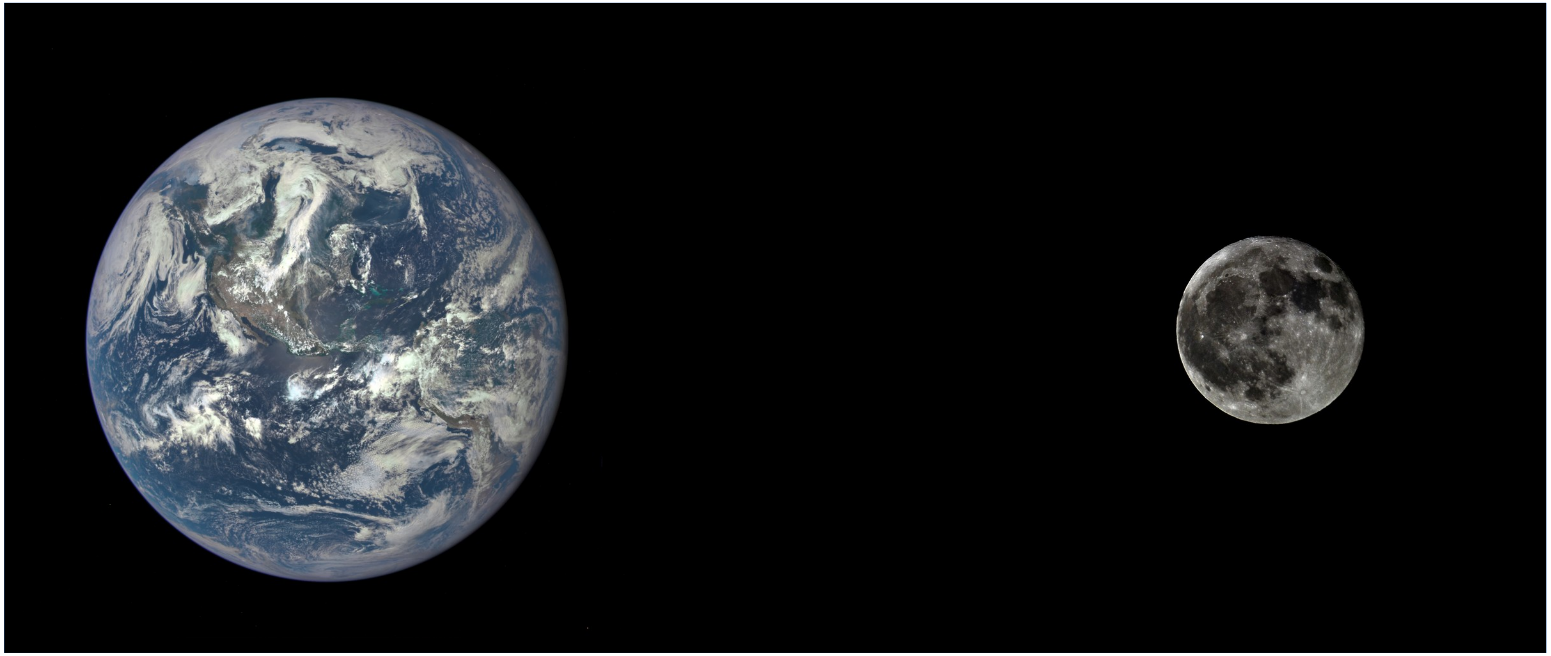
Water mainly delivered from outer solar system

→ **packing:** icy mantles on dust particles, aggregation
→ **transport:** C-type asteroides/planetesimals
(and a bit from comets)
→ **delivery service:** Jupiter and other gas giants



3. What let water remain on Earth?

What let water remain on Earth?

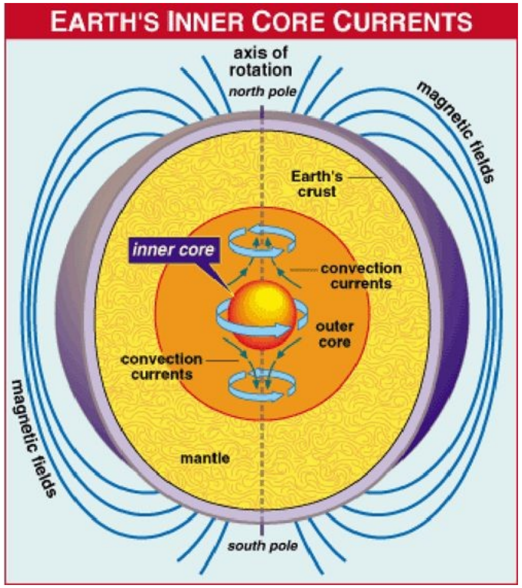


Water ◄—— (both received water) ——► virtually no water

3. What let water remain on Earth?

- Abundance of elements critical to geophysical development:
  → U, Th, Fe, H_2O

- Determine e.g.
  gravity, core size, internal temperature, **plate tectonics** and **magnetic field**



3. What let water remain on Earth?

Comparing Earth / Venus

- Earth models reach steady state carbon cycles after several hundred million years of degassing, weathering, and subduction.

- Faster **plate tectonic** speeds and erosion rates tend to dampen fluctuations in the carbon cycle via silicate weathering.

- Venus models evolve to runaway greenhouses with all volatiles in the atmosphere and rapid water loss to space.

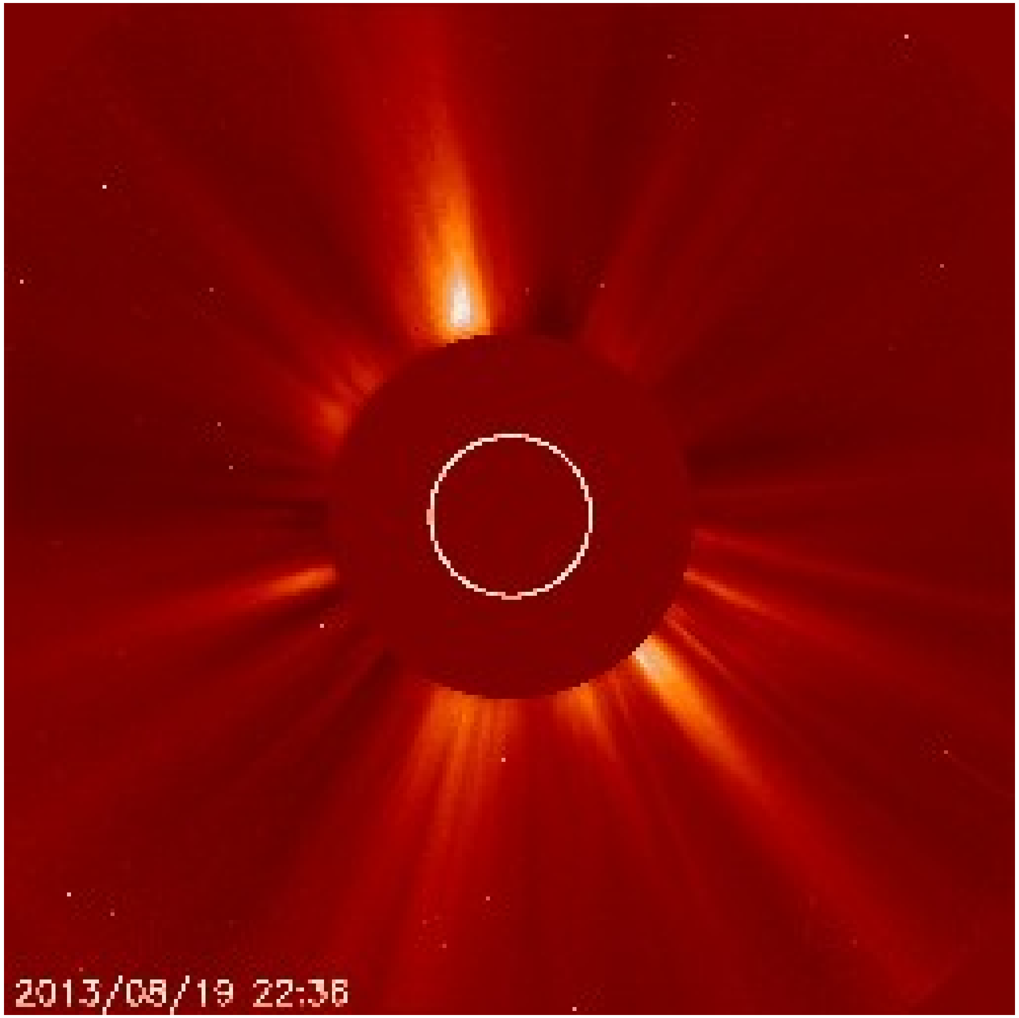
- A strong **magnetic field** at Venus would have prevented significant water loss.

P.Driscol, lD.Bercovici: Divergent evolution of Earth and Venus: Influence of degassing, tectonics, and magnetic fields

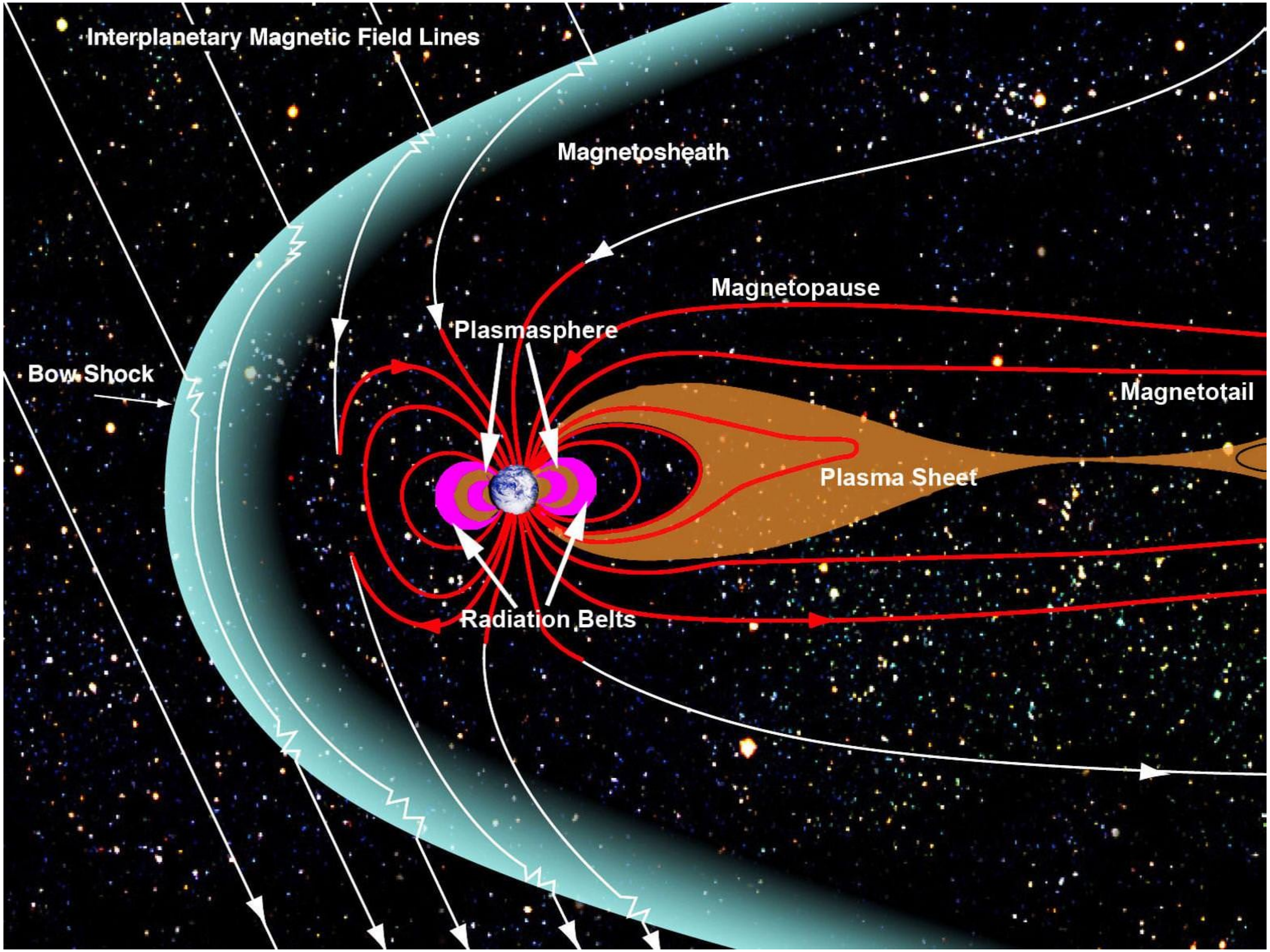
doi.org/10.1016/j.icarus.2013.07.025

3. What let water remain on Earth?

Coronal mass ejections (CMEs)



3. What let water remain on Earth?



3. What let water remain on Earth?

No plate tectonics → no oceanic ridges heat loss → planetary core stays hot

↓

inhibits development of magnetic field

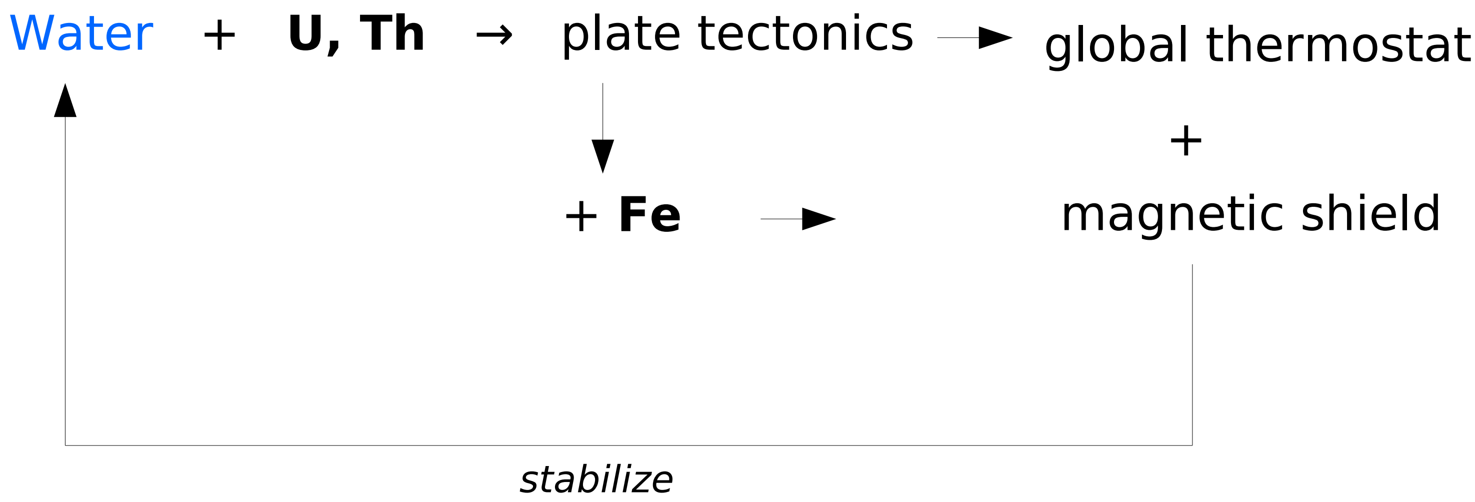
No magnetic field → no shielding against solar wind → atmospheric loss

Water instable when:

- Atmospheric loss
  (no magnetic shielding)

- Runaway greenhous effect
  (no negative feedback between atmospheric temperature, carbon dioxide weathering and surface tectonics)

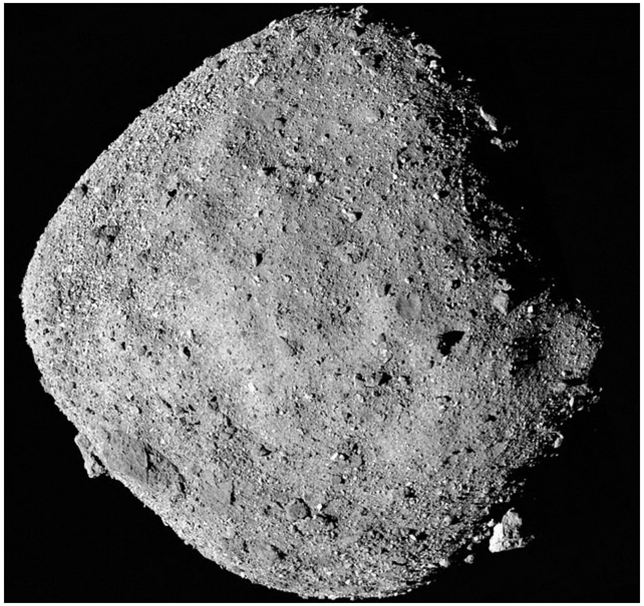
3. What let water remain on Earth?



3. What let water remain on Earth?

→ Indirect, but strong relationship between the geomaterials
U, Th and Fe, Ni with water
→ stabilize water on Earth via feedback loops (carbon cycle/ plate tectonics) and magnetic shielding

Mineral Evolution and the Role of Water



Asteroid „Bennu“: ~ 250 mineral species
(CI carbonaceous chondrite)

Earth: > ~ 4.300 mineral species

4. Mineral Evolution and the Role of Water

Hazen et al.: American Mineralogist 93, 1693–1720, 2008.

Stage	Age (Ga)	Examples of minerals	~ Cumulative no. species
The era of planetary accretion (>4.55 Ga)			
1. Primary chondrite minerals	>4.56 Ga	Mg-olivine/pyroxene, Fe-Ni metal, FeS, CAIs	60
2. Planetesimal alteration/differentiation	>4.56 to 4.55 Ga		250
a) aqueous alteration		phyllosilicates, hydroxides, sulfates, carbonates, halite	
b) thermal alteration		albite, feldspathoids, biopyriboles	
c) shock phases		ringwoodite, majorite, akimotoite, wadsleyite	
d) achondrites		quartz, K-feldspar, titanite, zircon	
e) iron meteorites		many transition metal sulfides and phosphates	
The era of crust and mantle reworking (4.55 to 2.5 Ga)			
3. Igneous rock evolution	4.55 to 4.0 Ga		350 to 500
a) fractionation		feldspathoids, biopyriboles (volatile-poor planets)	350
b) volcanism, outgassing, surface hydration		hydroxides, clay minerals (volatile-rich planets)	500
4. Granite formation	4.0 to 3.5 Ga		1000
a) granitoids		quartz, alkali feldspar (perthite), hornblende, micas, zircon	
b) pegmatites		beryl, tourmaline, spodumene, pollucite, many others	
5. Plate tectonics	>> 3.0 Ga		1500
a) hydrothermal ores		sulfides, selenides, arsenides, antimonides, tellurides, sulfosalts	
b) metamorphic minerals		kyanite, sillimanite, cordierite, chloritoid, jadeite, staurolite	
6. Anoxic biological world	3.9 to 2.5 Ga		1500
a) metal precipitates		banded iron formations (Fe and Mn)	
b) carbonates		ferroan carbonates, dolostones, limestones	
c) sulfates		barite, gypsum	
d) evaporites		halides, borates	
e) carbonate skarns		diopside, tremolite, grossularite, wollastonite, scapolite	
The era of bio-mediated mineralogy (>2.5 Ga to present)			
7. Paleoproterozoic atmospheric changes surface oxidation	2.5 to 1.9 Ga	>2000 new oxide/hydroxide species, especially ore minerals	>4000
8. Intermediate ocean	1.9 to 1.0 Ga	minimal mineralogical innovation	>4000
9. Neoproterozoic biogeochemical changes	1.0 to 0.542 Ga		>4000
a) glaciation		extensive ice deposition, but few new minerals	
b) post-glacial oxidation		extensive oxidative weathering of all surface rocks	
10. Phanerozoic Era	0.542 Ga to present		4300+
a) biomineralization		extensive skeletal biomineralization of calcite, aragonite, dolomite, hydroxylapatite, and opal	
b) bio-weathering		increased production of clay minerals, soils	

5. Importance of water for geomaterials

5. Importance of water for geomaterials

5. Importance of water for geomaterials

Water:

→ important in the *formation* of many geomaterials

↓

→ important for the *control* of these geomaterials

Lime
Slaking of burned lime (CaO) with water → hydrated lime $Ca(OH)_2$

Gypsum
Removal water of crystallisation → burned gypsum (plaster) → rehydrate dry plaster by adding water: $CaSO_4 \cdot 2H_2O + \mathit{heat} \rightarrow CaSO_4 \cdot 0.5H_2O + 1.5H_2O$

Clay
Adding water: processable via plastic ductility (swellable clay)
Burning: resilient ceramic.

6. Coevolution of geo- and biosphere driven by water

Minerals and the Origin of Life

↓

Life- mediated Origin of Minerals

6. Coevolution of geo- and biosphere

6.1. Minerals and the Origin of Life

- *Mineral surfaces:*
  - concentration of organic molecules (e.g. clay minerals) [dx.doi.org/10.5772/50172]
  - selection (chirality) of L-amino acids (e.g. calcite) [doi.org/10.1073/pnas.101085998]
  - stabilyzing amino acids (e.g. pyrite) [doi.org/10.1021/ja063295a]
  - catalyzing (bio)chemical reactions (e.g. pyrite) [doi.org/10.1038/344387a0]

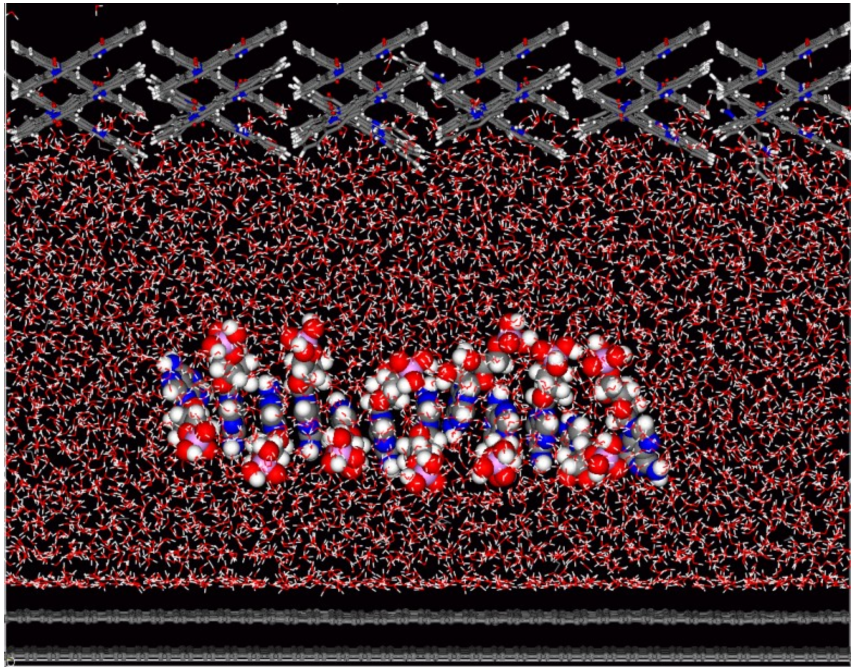
- *Mineral pores:*
  prebiotic reaction vessels (e.g. pumice) [doi.org/10.1089/ast.2010.0546]

- *Mineral nanoconfinements:*
  biopolymerization within aqueous particle suspensions (e.g. graphite, magnetite, silica)

6. Coevolution of geo- and biosphere driven by water

Mineral nanoconfinements:

→ biopolymerization within aqueous particle suspensions
(e.g. graphite, PHAs, magnetite, silica)



6.2. Life-mediated Origin of Minerals

- Great Oxidation Event (~ 2,5 Ga)
  After rise of oxygenic photosynthesis: no rise of atmosphereic O_2
  → oxidation of dissolved Fe and other oxidizable compounds (e.g. Methane gets oxidized to CO_2 (much weaker greenhouse gas) and H_2O → *Huronian Glaciation)* which are constantly resupplied via volcanism + erosion

  → numerous new mineral species and morphologies as oxidiation products (oxides, hydroxides)

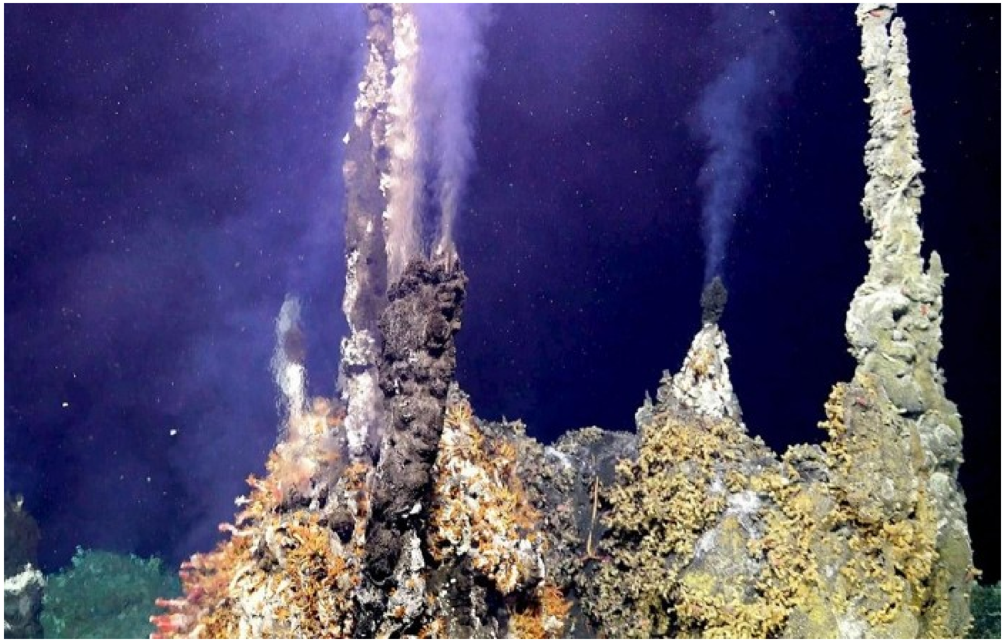
- Phanerozoic biomineralization (since ~ 0,54 Ga)
  „sudden“ rise of most prevalent biominerals (calcite, dolomite, aragonite, apatite).

  Limestone Alps: Part of geosphere, but material originated from biosphere. Biomineralization bound CO_2.

6. Coevolution of geo- and biosphere driven by water

Water + minerals → origin of life

Oxide minerals / biominerals ← water + life



Summary

Water as a Meta-Geomaterial:

→ Origin on mineral particles

→ Transport to Earth via chondrites

→ Remains on Earth due to Fe, U

→ Boosts evolution of mineral species and morphologies

→ Drives geobiology

→ Enables to control properties of geomaterials due to its role in their origin