Co-evolution of the atmosphere, oceans, interior, and life on Earth

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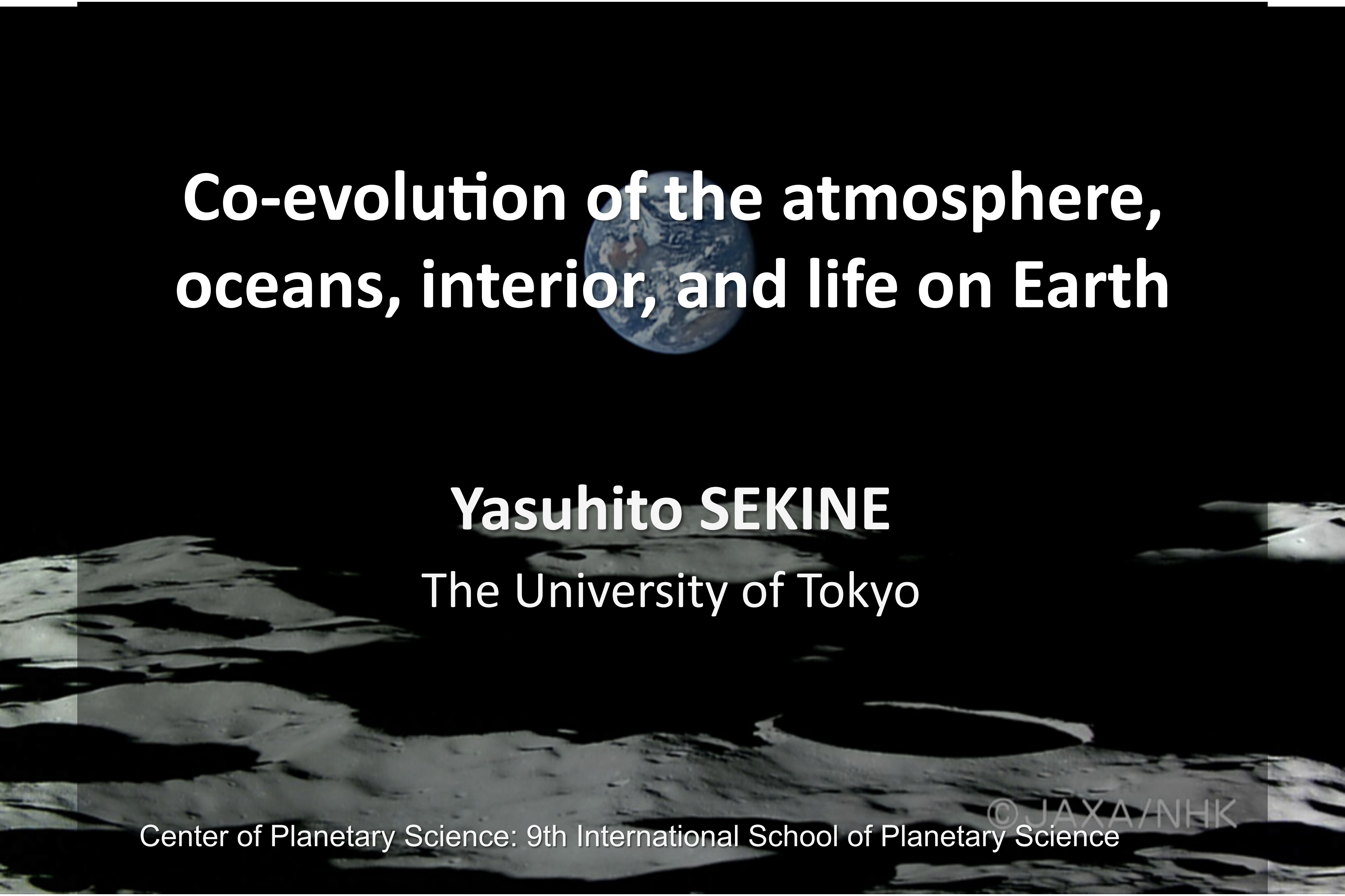

Center of Planetary Science: 9th International School of Planetary Science


Earth: a habitable planet
• Ocean, Atmosphere, & Life
Are there any other
habitable planets in space?
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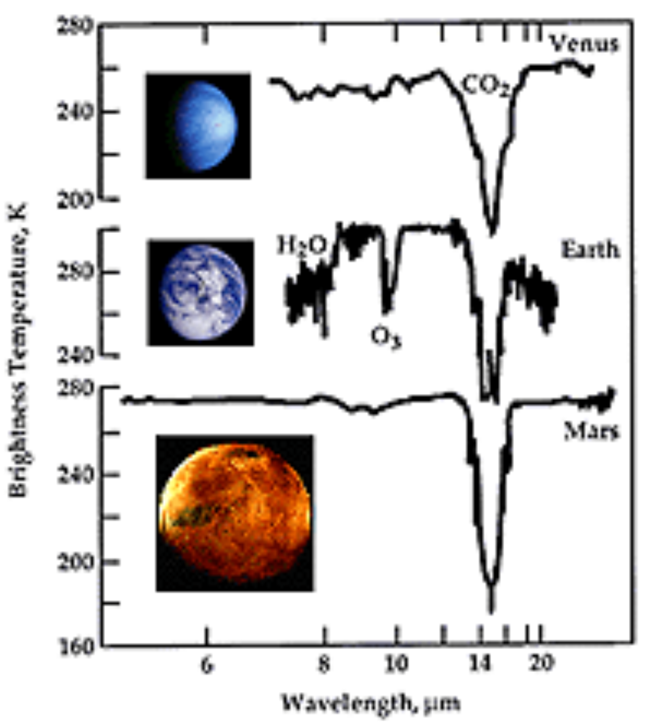
Challenge for finding habitable planets

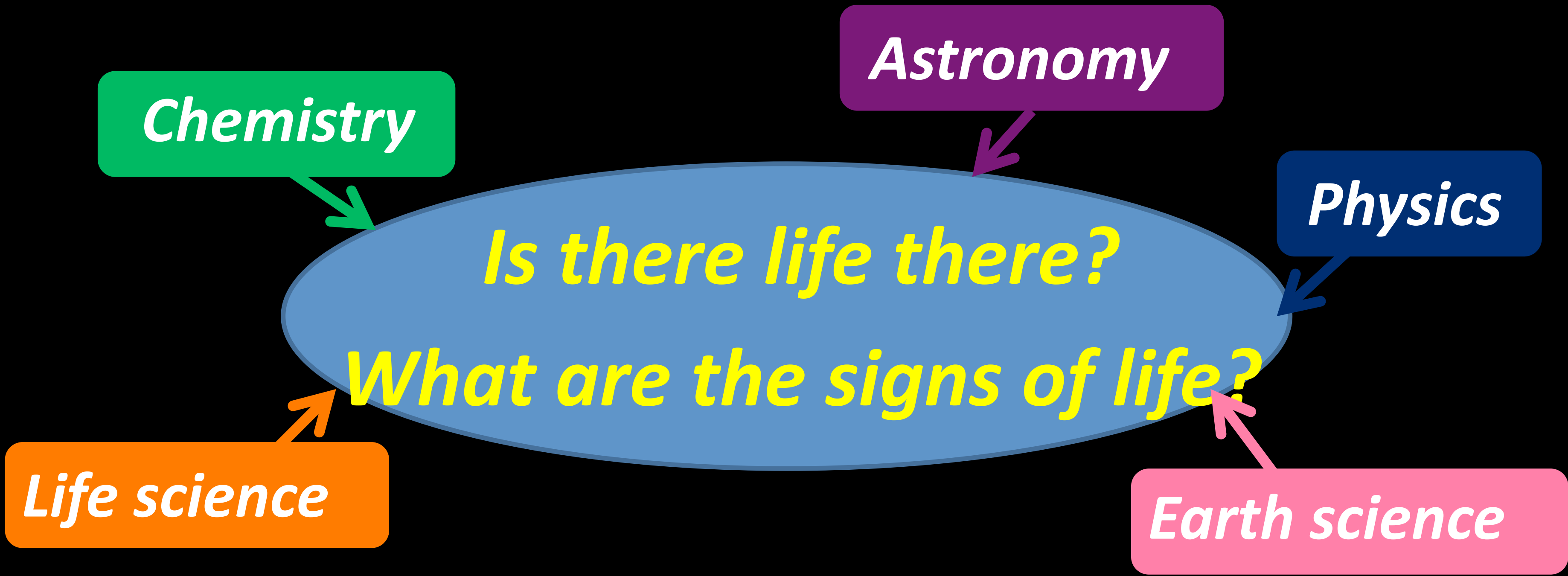
- Kepler space telescope (2009-)
- Terrestrial Planet Finder (2020?)
- Darwin mission (2020?)



The Launch of the Kepler space telescope on March 6, 2009

The first Earth-sized habitable planet is expected to be found soon!

Today's topic



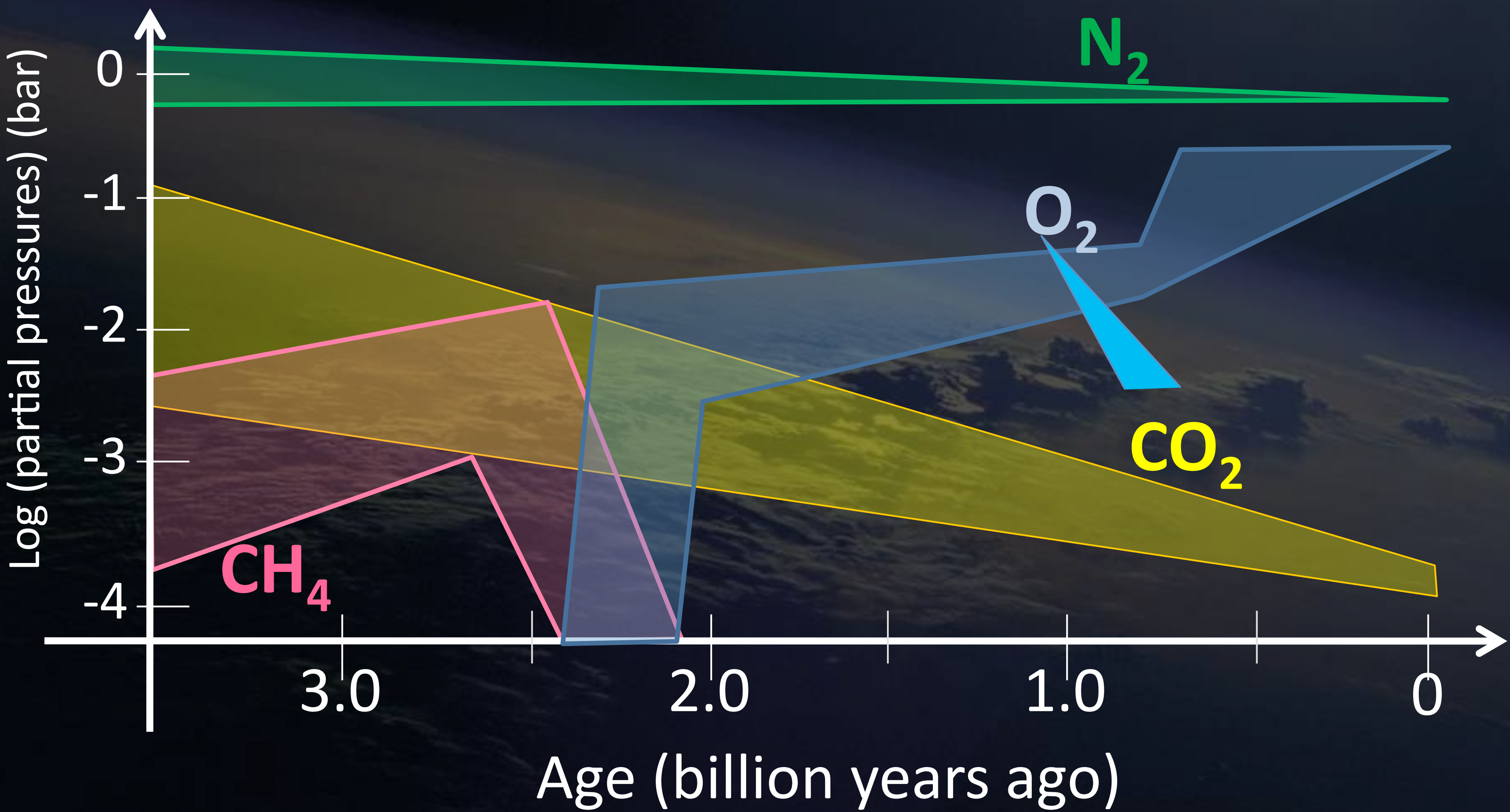
Earth is the only known habitable planet so far.

We need to know from Earth's archive how the atmosphere, oceans, interior, and life have interacted over its history.

- ***Generalize! Understand what events are common/particular***

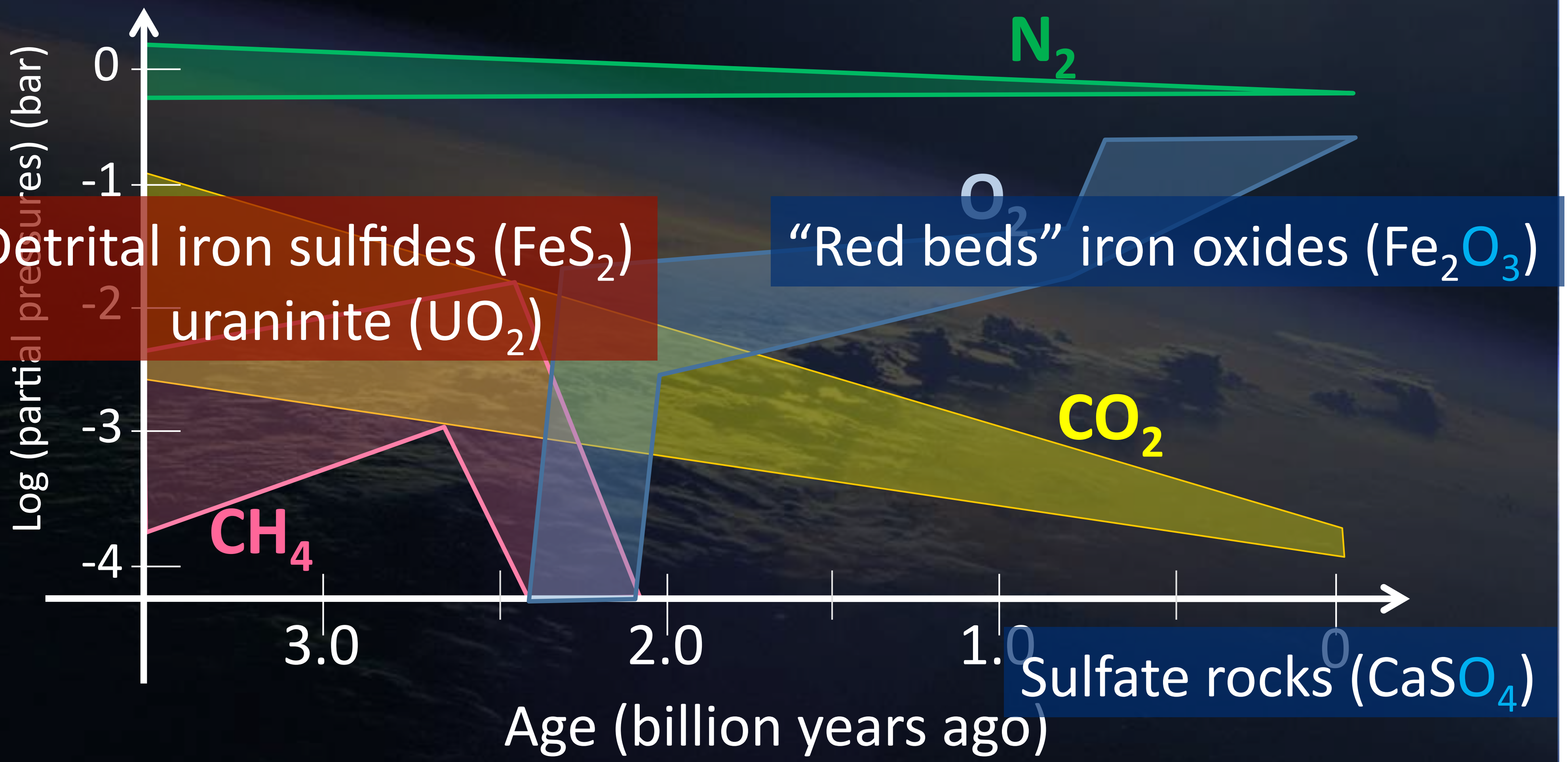
Overview of chemical evolution of Earth's atmosphere, oceans, and life

Evolution of Earth's atmosphere



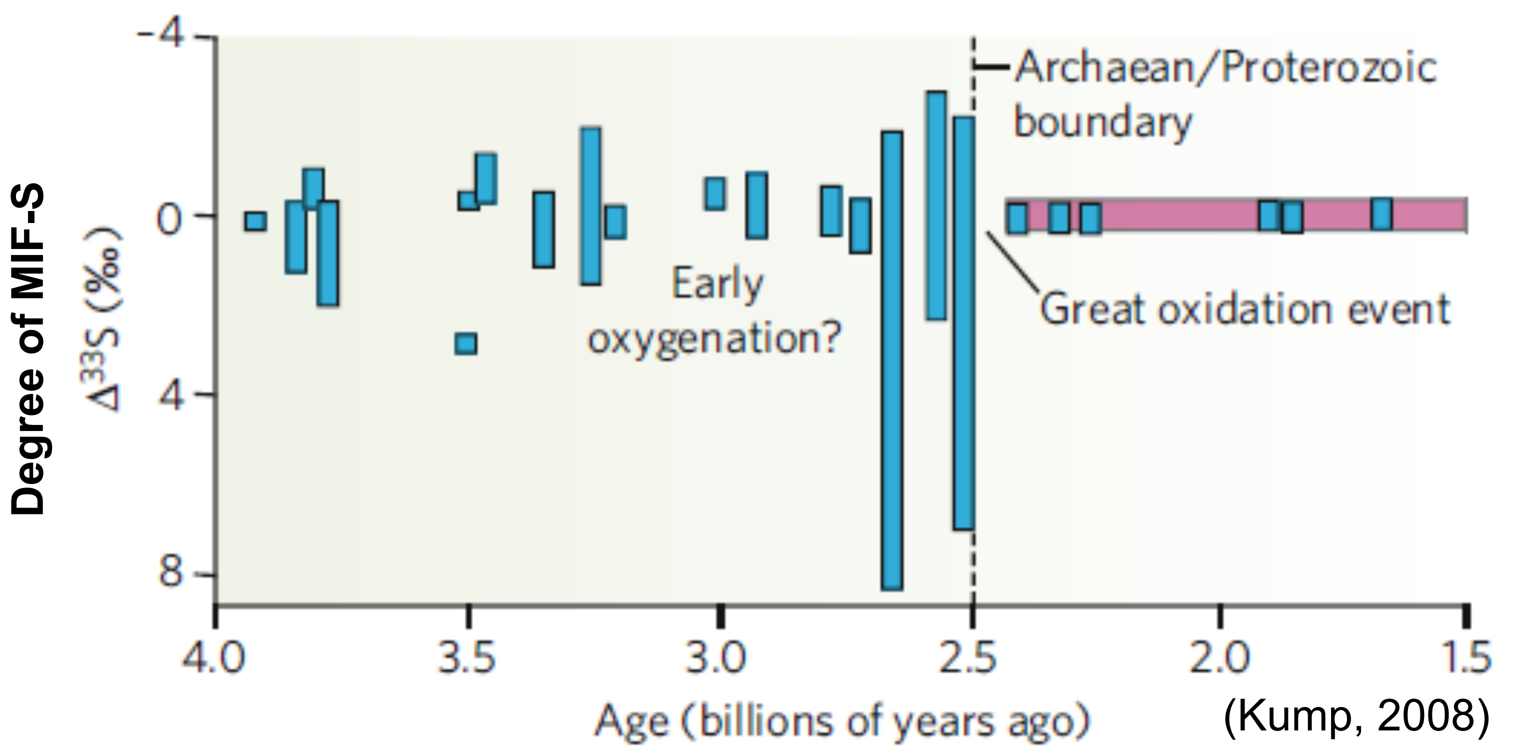
(Holland, 1984; Tajika & Matsui, 1992; Kasting, 1993;
Rye & Holland, 1998; Farquhar et al., 2000; Pavlov et al., 2001; Hoffman & Schrag, 2000; Zahnle et al., 2006)

Evolution of Earth's atmosphere



(Holland, 1984; Tajika & Matsui, 1992; Kasting, 1993;
Rye & Holland, 1998; Farquhar et al., 2000; Pavlov et al., 2001; Hoffman & Schrag, 2000; Zahnle et al., 2006)

Mass-independent fractionation of sulfur isotopes (MIF-S)



Farquhar et al., 2000;
Pavlov and Kasting, 2003;
Ono et al., 2004;
Bekker et al., 2004
Etc…

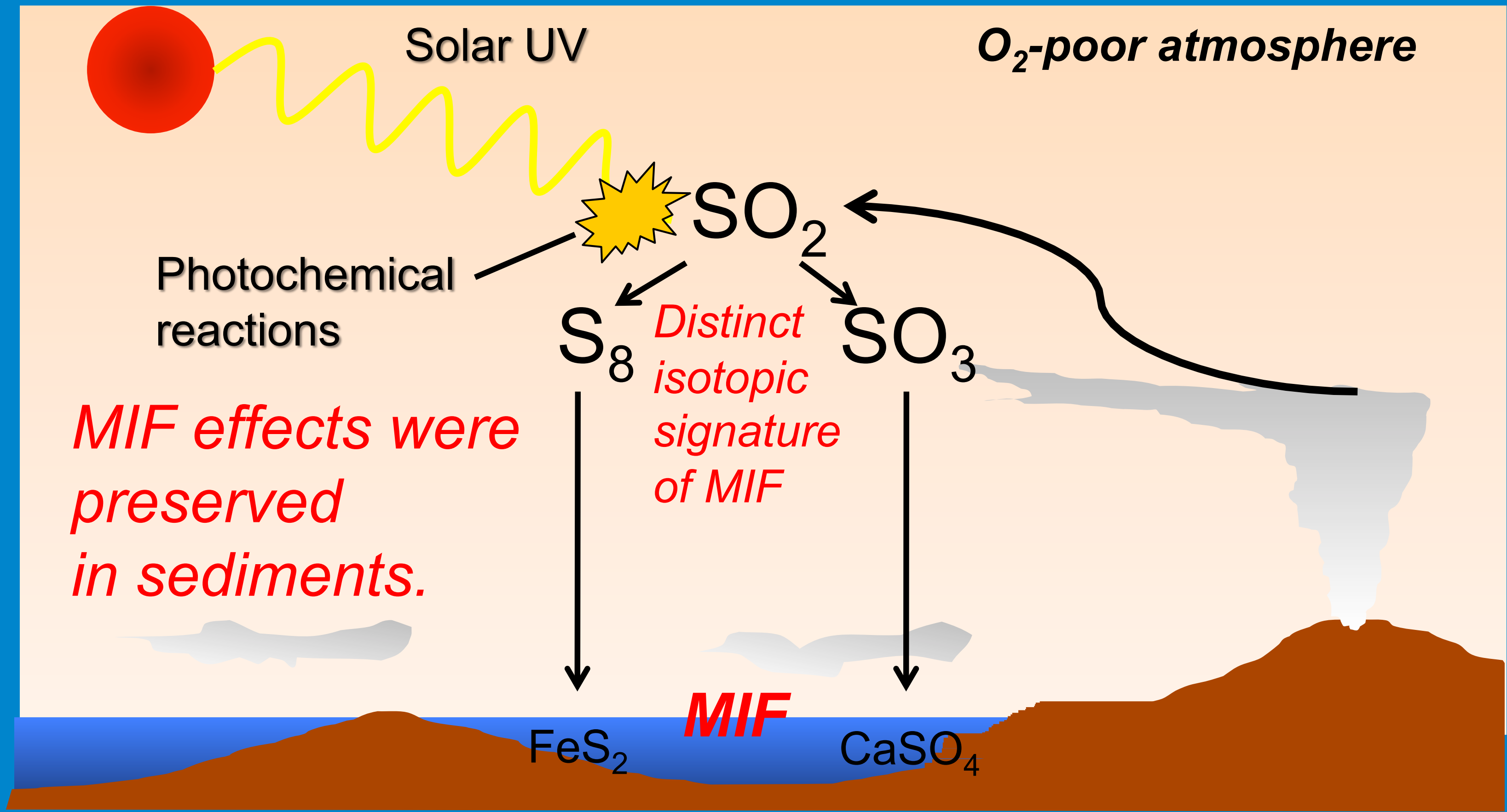
- Sedimentary rocks **> 2.45 Ga: large MIF-S**
  < 2.32 Ga: essentially no MIF-S
- Fractionation of isotopes usually depends on the mass
- Large MIF-S are produced by photochemical reactions

Sulfur cycle in the atmosphere-ocean

Reducing atmosphere

⇒ contrasting MIF between reducing & oxidizing sulfur

- Sulfur isotopes: ^{32}S, ^{33}S, ^{34}S, and ^{36}S



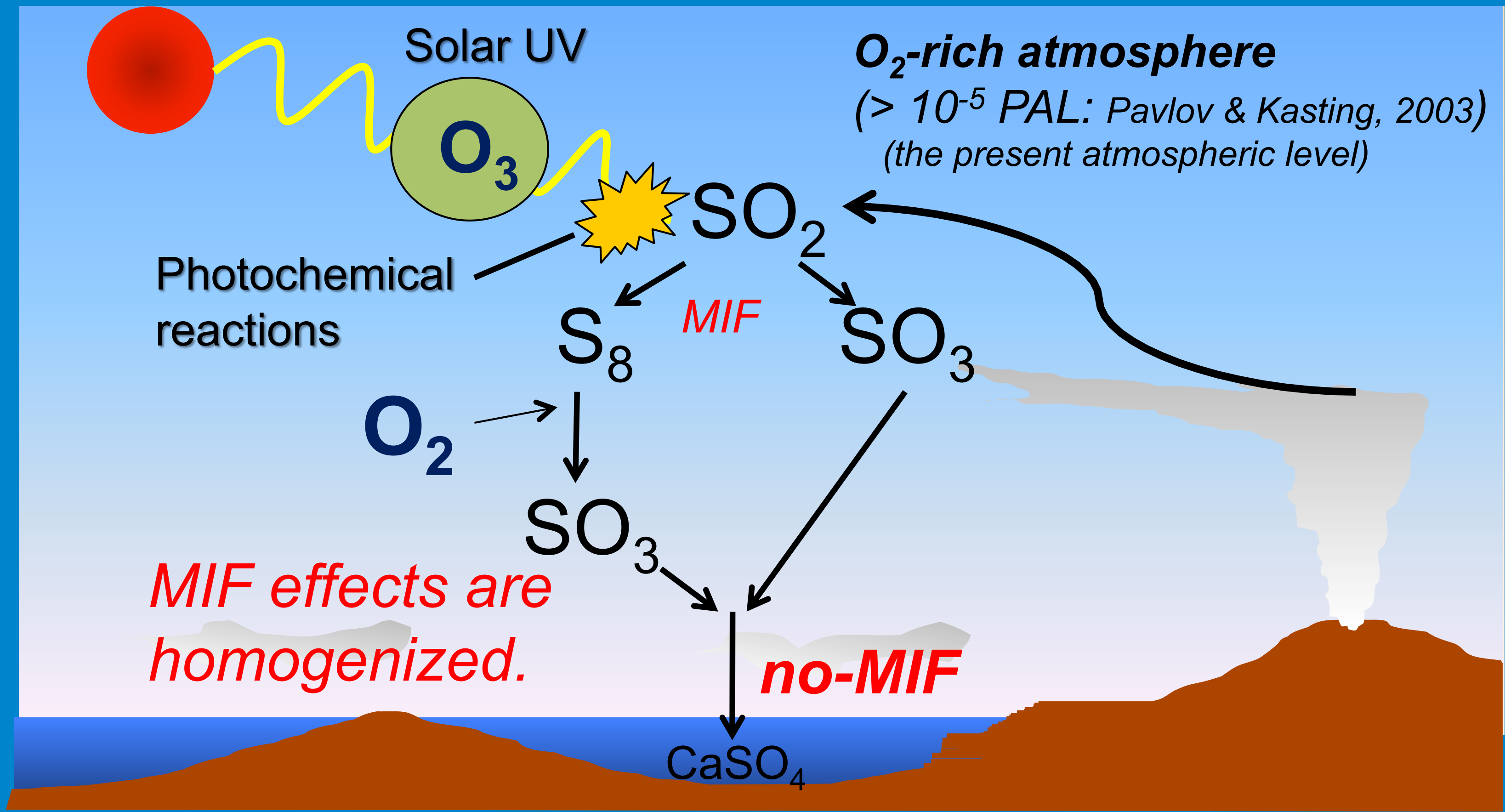
(Farquhar et al., 2000; Pavlov and Kasting, 2003; Ono et al., 2004; Bekker et al., 2004)

Sulfur cycle in the atmosphere-ocean

Oxidizing atmosphere

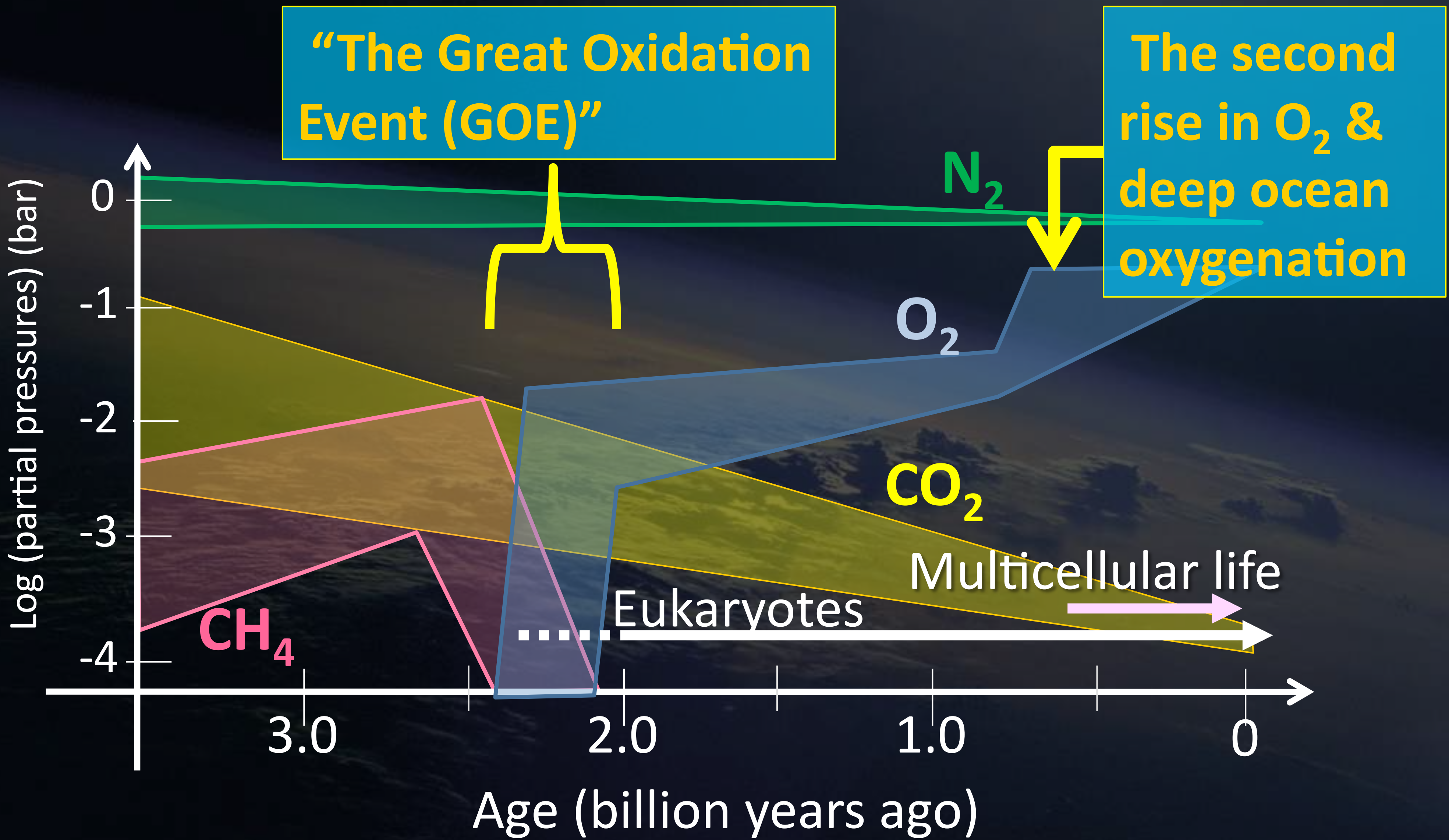
Reducing sulfur is oxidized ⇒ No MIF-S is preserved

・Sulfur isotopes: ^{32}S, ^{33}S, ^{34}S, and ^{36}S



(Farquhar et al., 2000; Pavlov and Kasting, 2003; Ono et al., 2004; Bekker et al., 2004)

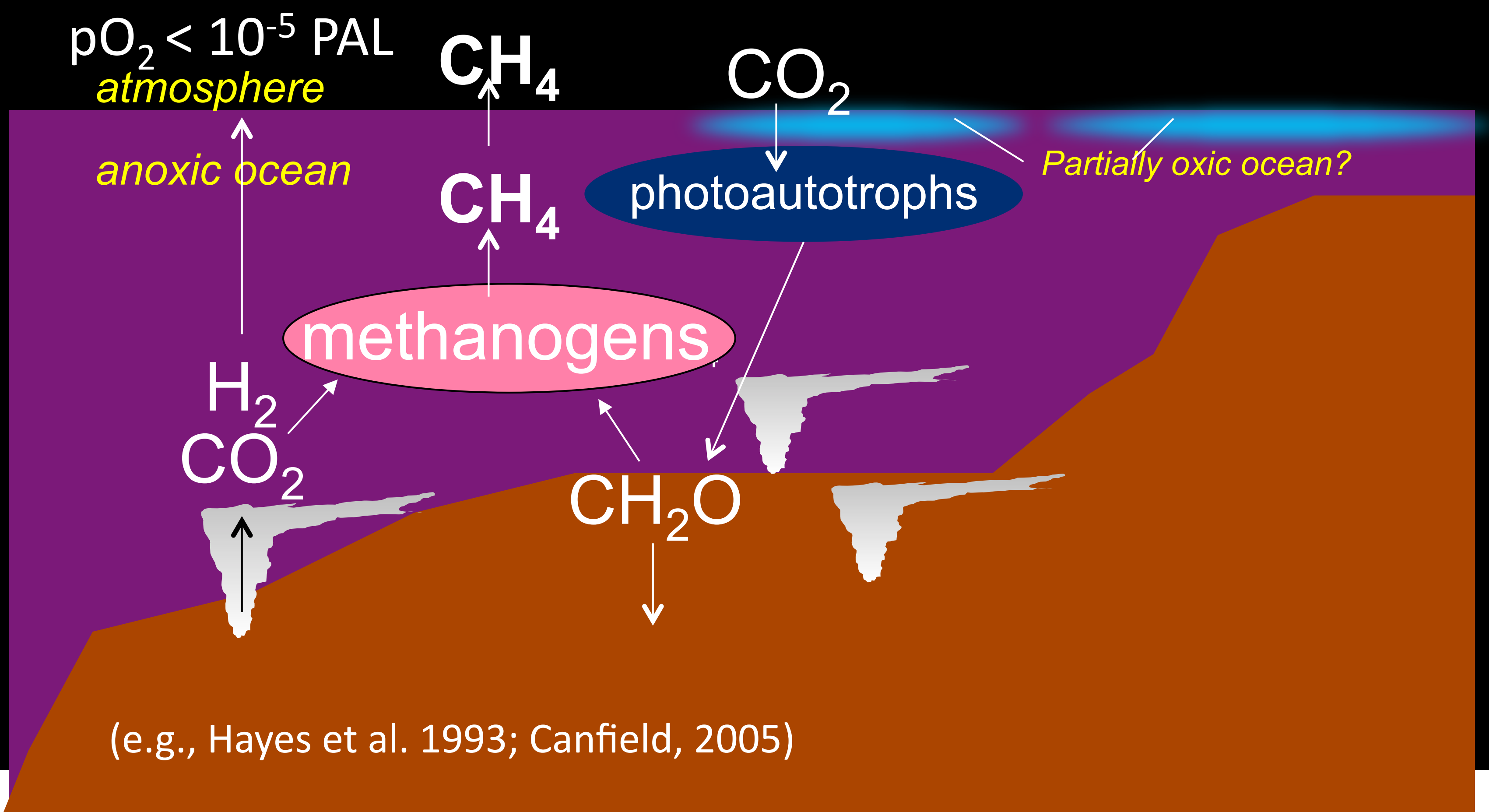
Evolution of Earth's atmosphere



(Holland, 1984; Tajika & Matsui, 1992; Kasting, 1993;
Rye & Holland, 1998; Farquhar et al., 2000; Pavlov et al., 2001; Hoffman & Schrag, 2000; Zahnle et al., 2006)

Before the rise in O_2: Archean (> 2.5 Ga)

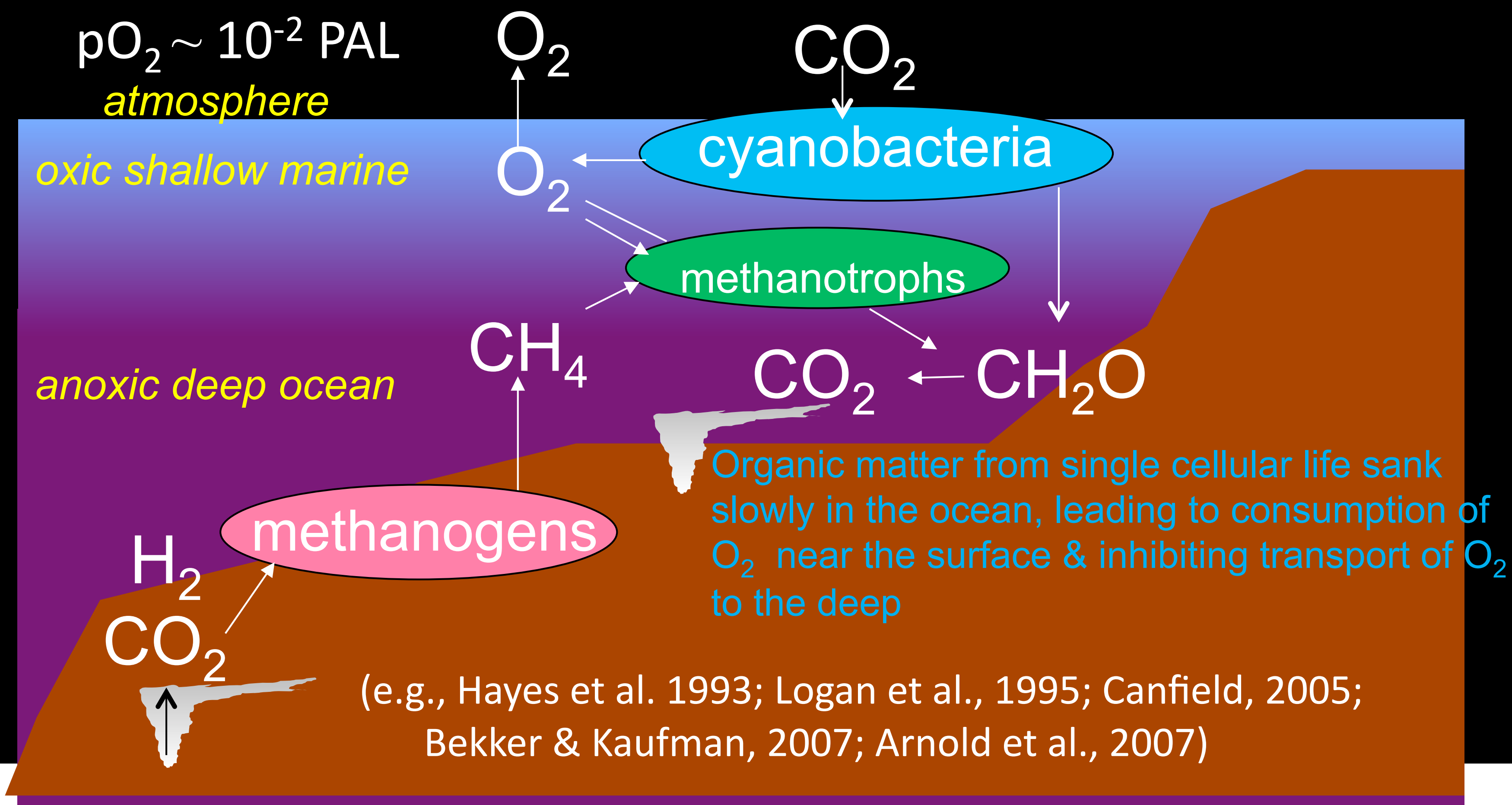
- Methanogens: ancient & sensitive to O_2 (Woese & Fox, 1977)
- Before 2.5 Ga, they would have been important primary producer & decomposer in the ecosystem (Hayes et al., 1993)



(e.g., Hayes et al. 1993; Canfield, 2005)

After the first rise in O_2: Proterozoic (2.3–1.0 Ga)

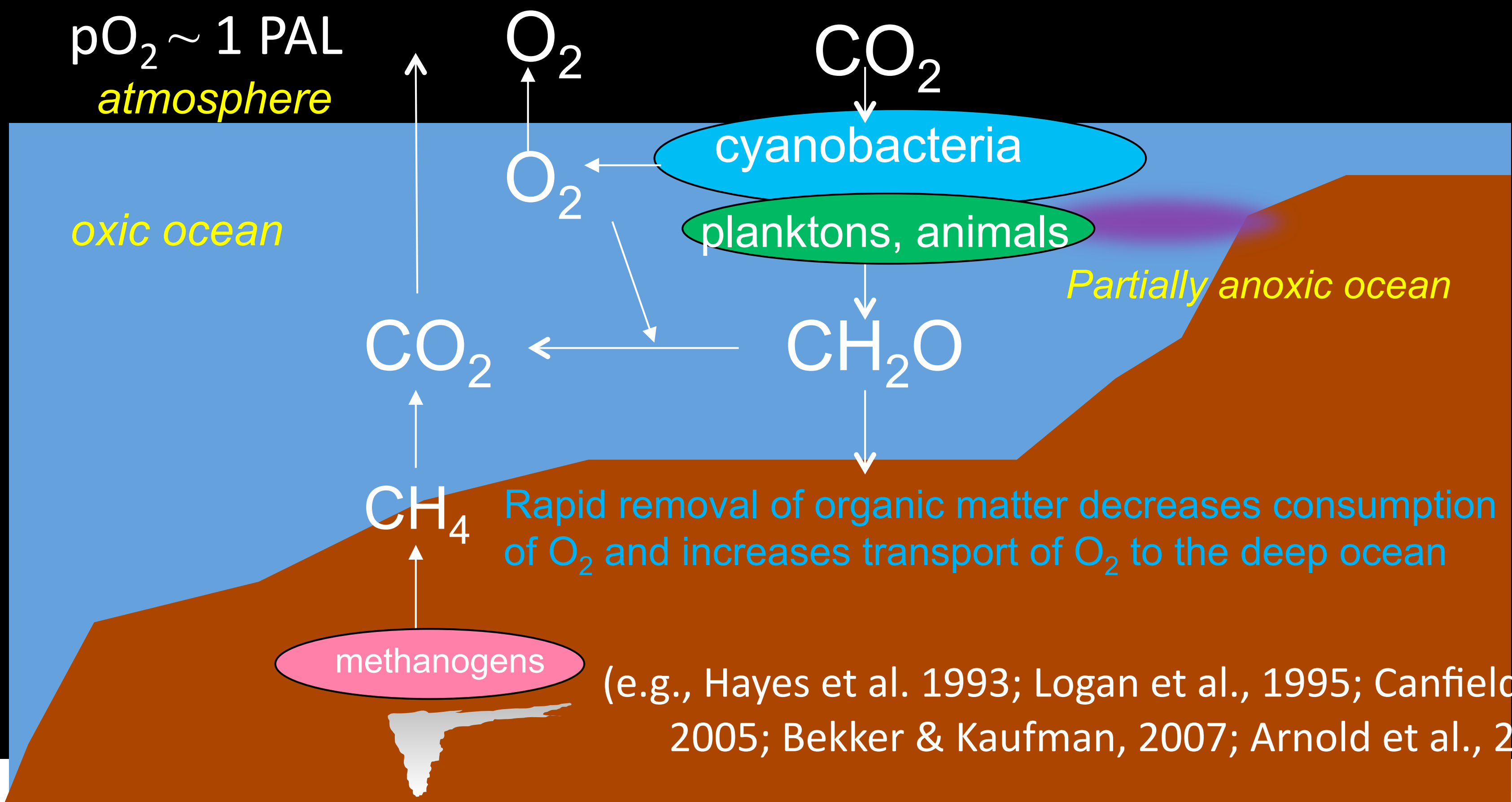
- **Ocean would have been stratified with respect to O_2**
- **Methanogens:** anoxic deep oceans and sediments
- **Cyanobacteria:** oxic shallow marine, producing O_2



(e.g., Hayes et al. 1993; Logan et al., 1995; Canfield, 2005; Bekker & Kaufman, 2007; Arnold et al., 2007)

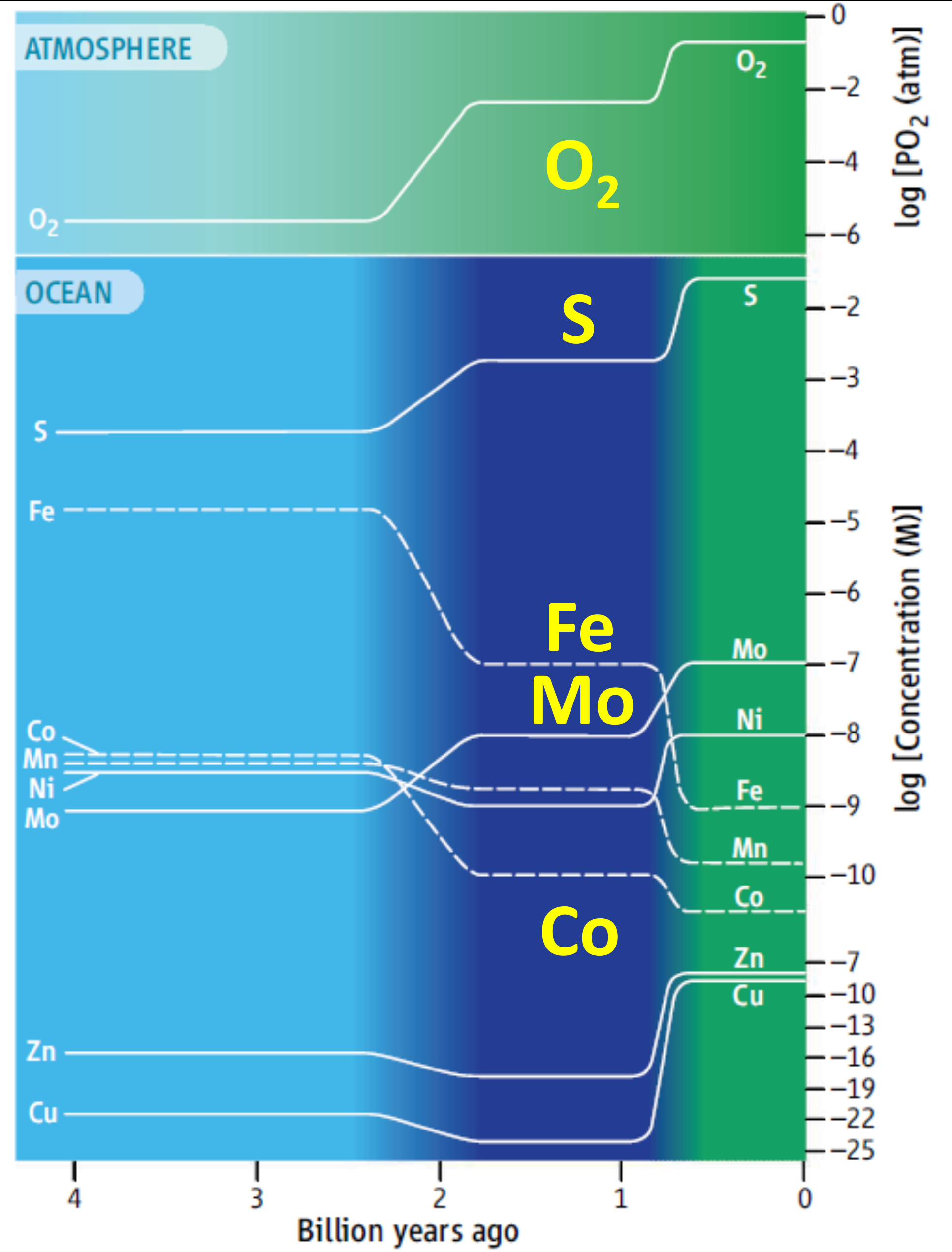
After the second rise in O_2: Phanerozoic (0.5 Ga-now)

- **Whole of the ocean has been oxidized**
- Evolution of multicellular life at 0.6 Ga: some parts of large organic matter (e.g., pellets) escape from dissociation due to fast sinking in the ocean.



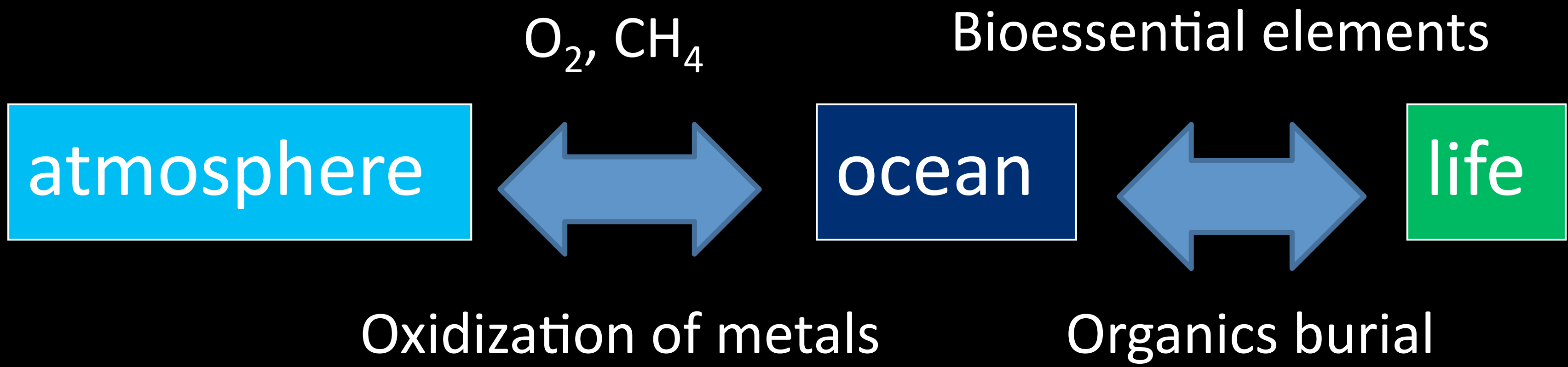
(e.g., Hayes et al. 1993; Logan et al., 1995; Canfield, 2005; Bekker & Kaufman, 2007; Arnold et al., 2007)

Elements & life evolution (Anbar, 2008)



- As O_2 levels increased, element abundances in the ocean also changed.
  - $Fe^{2+} \rightarrow Fe_2O_3$ $Mo \rightarrow MoO_4^{2-}$
- Change in availability of bioessential elements
  - Eukaryotes require more Mo & Zn, whose abundances increase

  Diversification of eukaryotes coincided with availability of bioessential elements (Knoll et al., 2006)



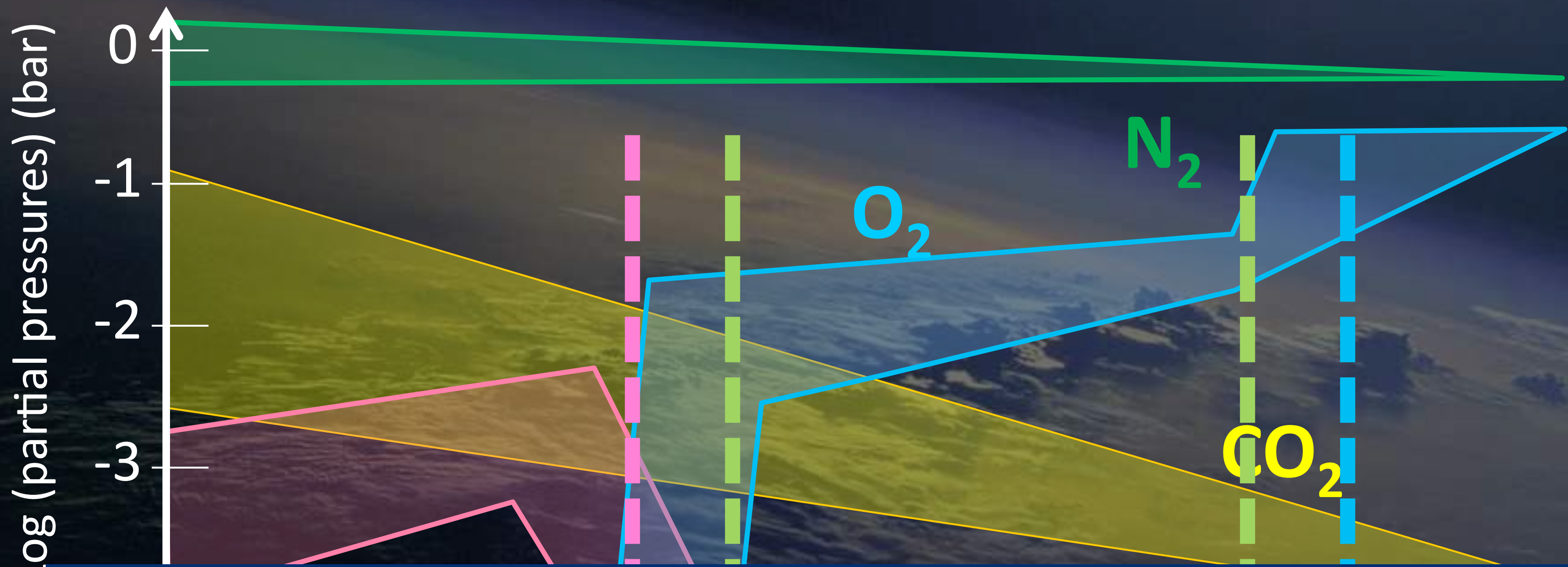
Too complicate to generalize!

These components can influence on each other
→ ***there should be some feedback mechanisms***

If a feedback is negative, the system would be stabilized
If positive, this can be a trigger for a runaway transition

Overview: evolution of Earth's atmosphere

- Irreversible oxidization of the atmosphere & ocean
- Major transitions & long periods of relative stability



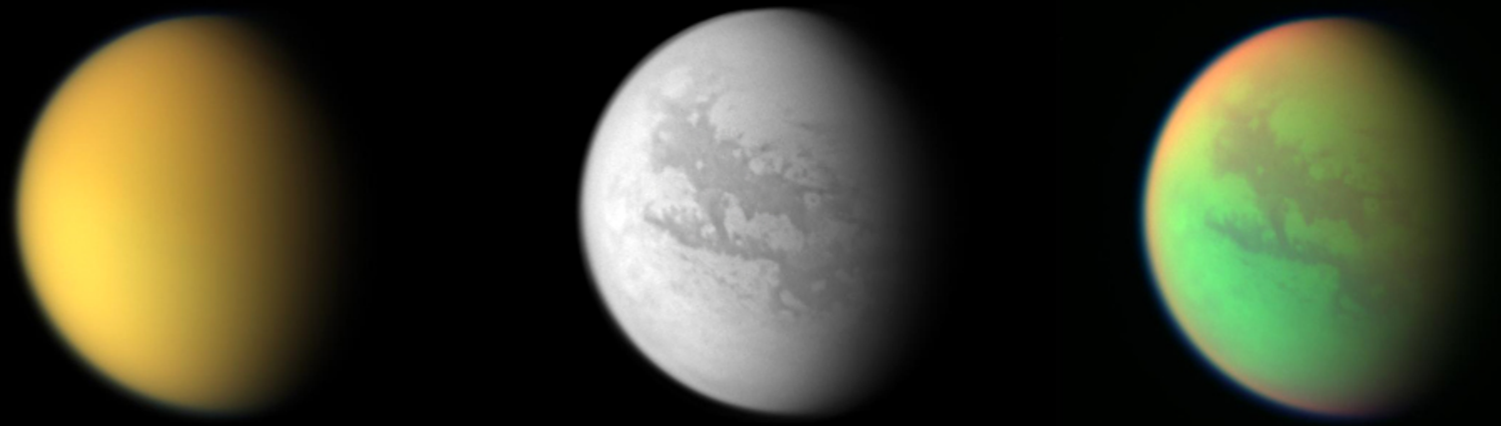
Primary questions

Why are the steady states stable?

How and why did the transitions occur?

(Holl… &
Kasting, 2002; Canfield, 2005; Hoffman & Schrag, 2002; Kump, 2008; Holland, 2006)

1. reducing atmosphere on early Earth & implications for exoplanets



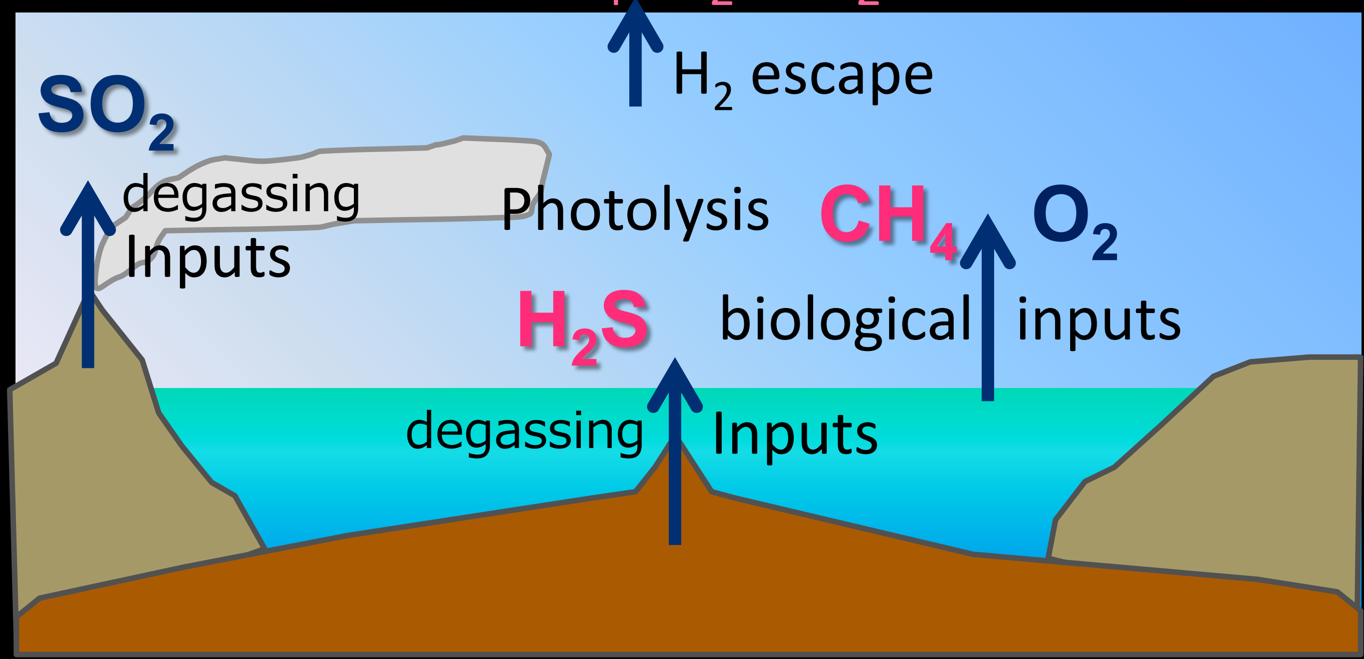
How was a CH_4-rich atmosphere maintained?

Why was Archean Earth habitable?

How was a reducing atmosphere maintained?

Redox (reducing-oxidizing) states of atmosphere:

- Inputs of oxidants (O_2, SO_2, OH, etc)
- Inputs of reductants (CH_4, H_2S, H_2, Fe^{2+}, etc)



Input sources: volcanic degassing (SO_2/H_2S, CO_2/CH_4)
biological activities (O_2/CH_4)

appearance of cyanobacteria may have occurred by 2.7 Ga

→ *Inputs of reductants may have been higher in Archean?*

How was a reducing atmosphere maintained?

1. Highly reducing early mantle? (Kasting et al., 1993; Holland, 2002)

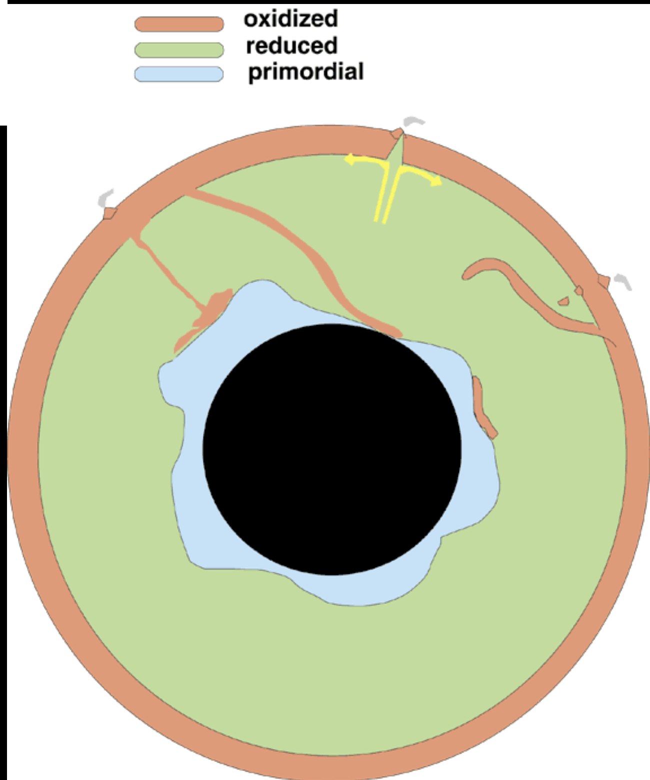
→ Supplying reducing volcanic gas species, CH_4, H_2, and H_2S

$$H_2O + 2FeO \rightarrow Fe_2O_3 + H_2$$

Earth's mantle may have been oxidized due to H_2 escape

→ Change in oxidation state of mantle induce the rise in O_2?

Model of late Archean mantle structure [Kump et al., 2001]



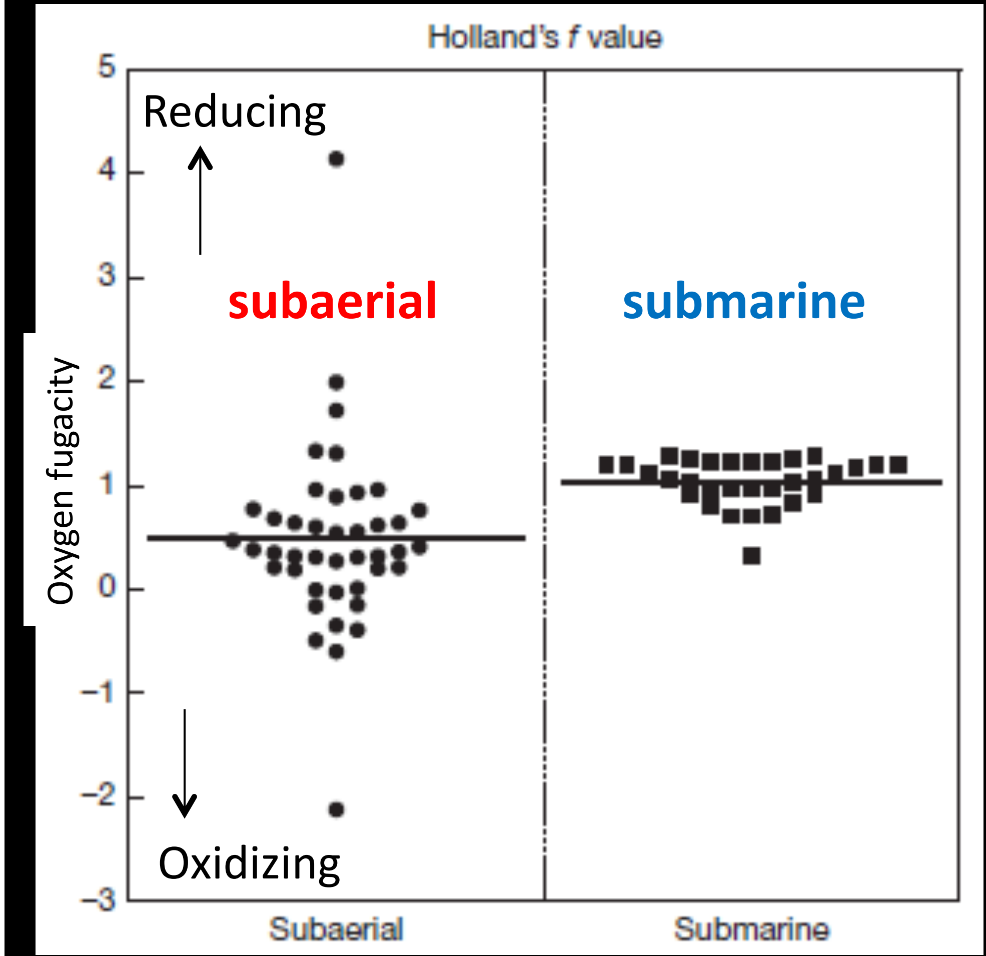
Unlikely: Oxidation states of basalts and their mantle sources remained constant since 3.5 Ga (Canil, 2002; Li & Lee, 2004).

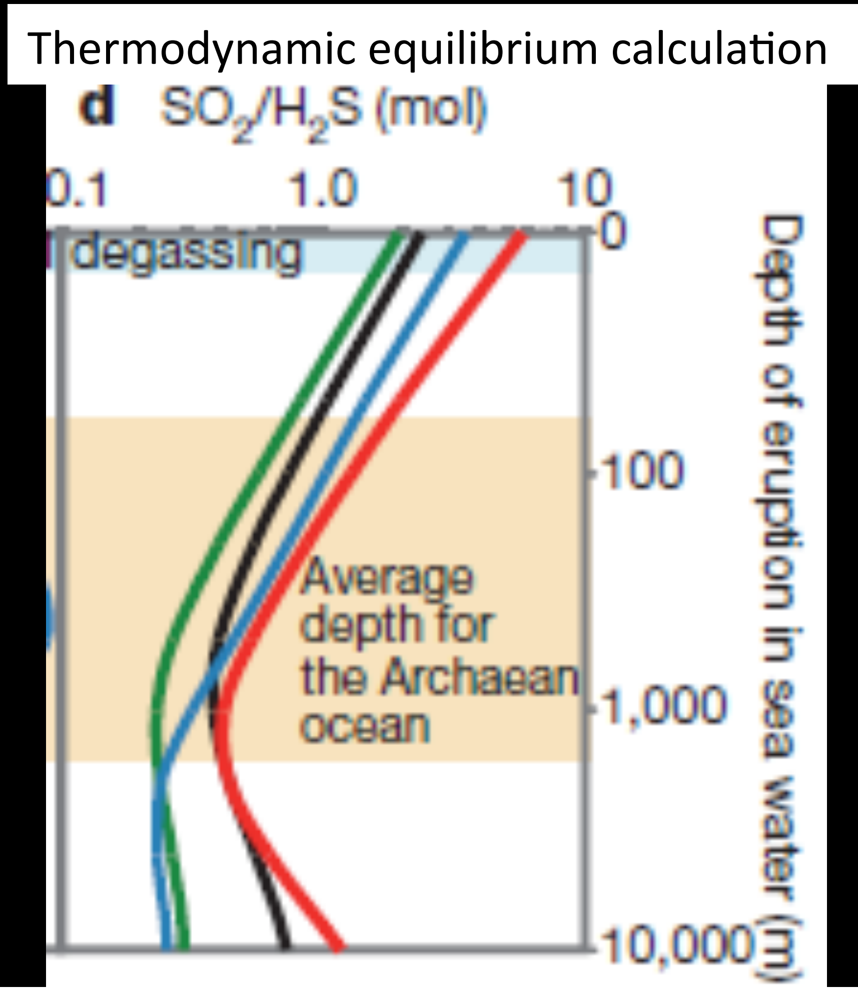
How was a reducing atmosphere maintained?

2. Submarine volcanisms were predominated?

(Kump & Barley, 2007; Gaillard et al., 2011)

Submarine volcanoes emit more reducing gas species than subaerial ones due to higher pressure and lower temperature





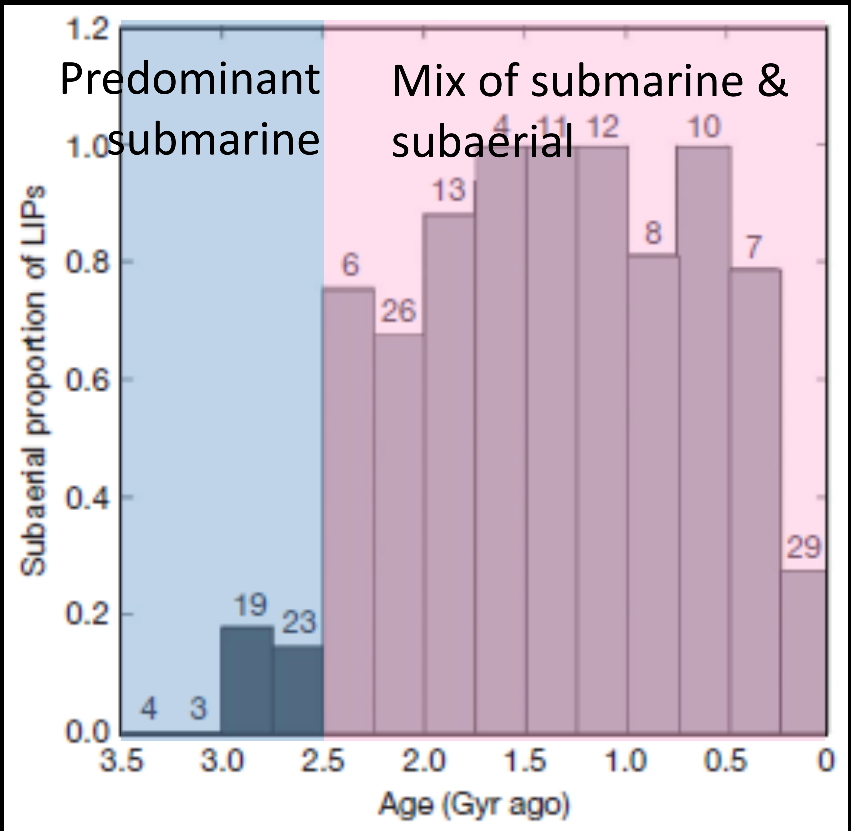
How was a reducing atmosphere maintained?

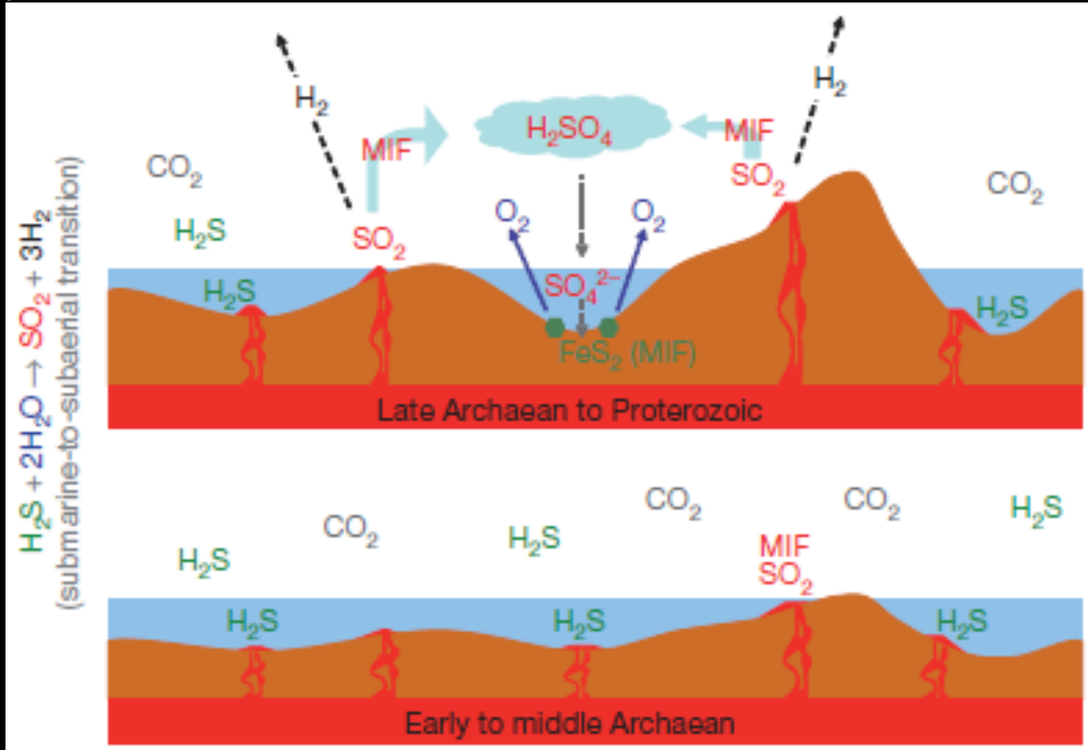
2. Submarine volcanoes were predominated?

(Kump & Barley, 2007; Gaillard et al., 2011)

Absence of substantial continents in the early Archean may have played an important role to provide lots of reductants?

Subaerial LIPs (large igneous provinces)

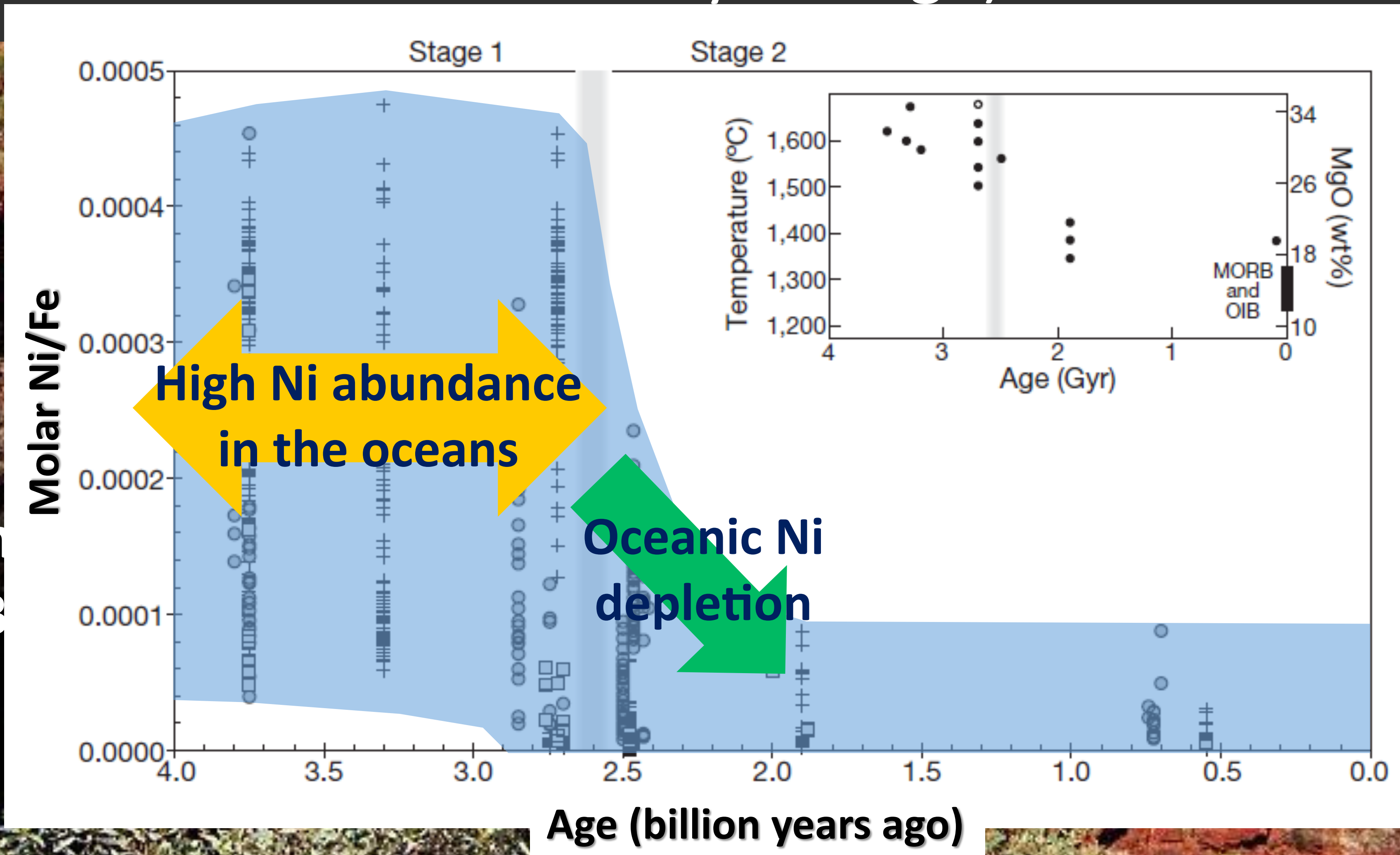




How was a reducing atmosphere maintained?

3. High levels of Methanogen activities? (Konhauser et al., 2009)

Ocean composition (High Ni concentration in the oceans before 2.5 billion years ago)

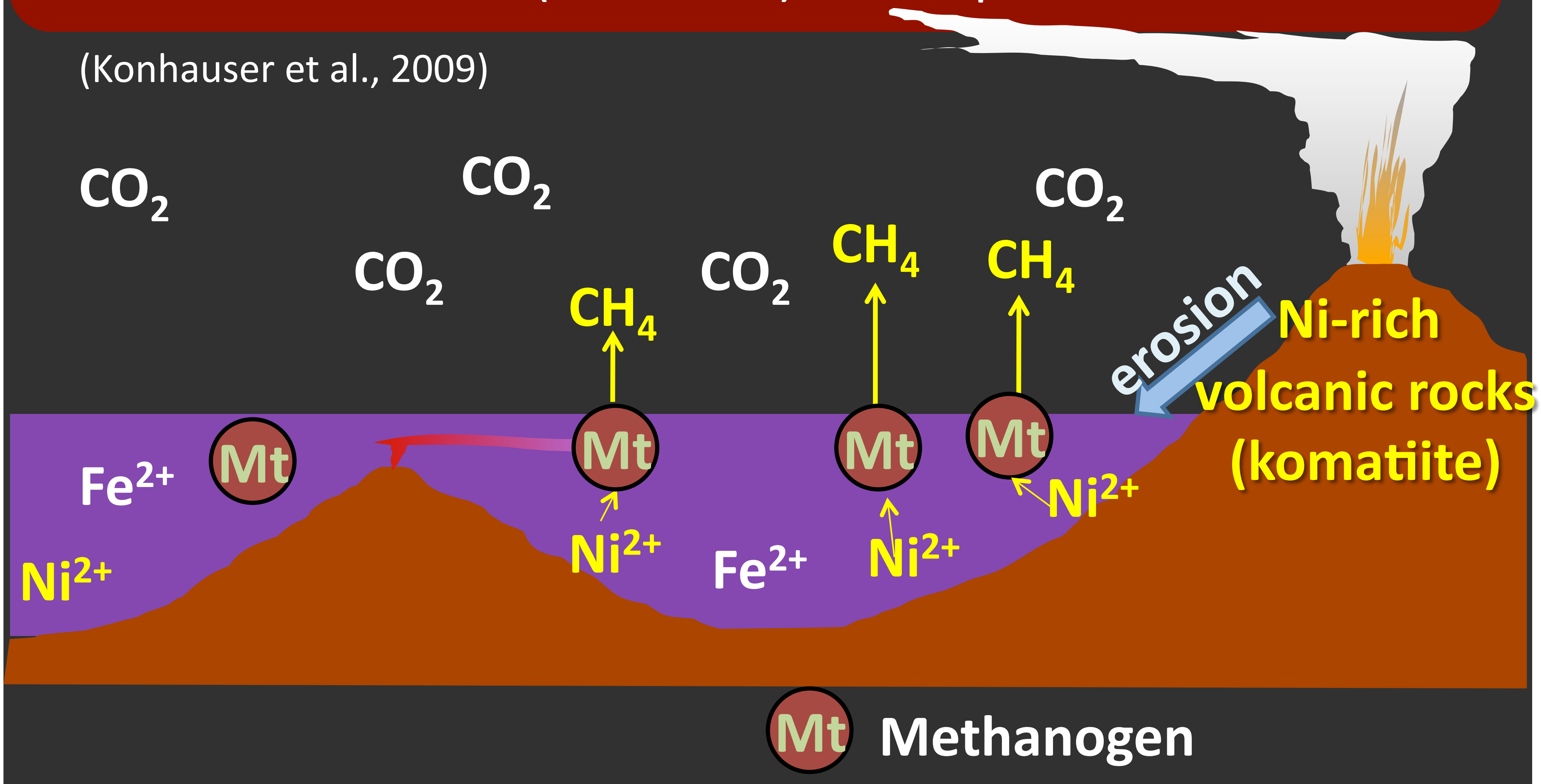


High methanogen activities in Archean

Before 2.5 Ga: Archean

Hot early Earth's mantle ⇒ Eruption of ultlamafic Ni-rich volcanic rocks (komatiite) & Ni input to the oceans

(Konhauser et al., 2009)



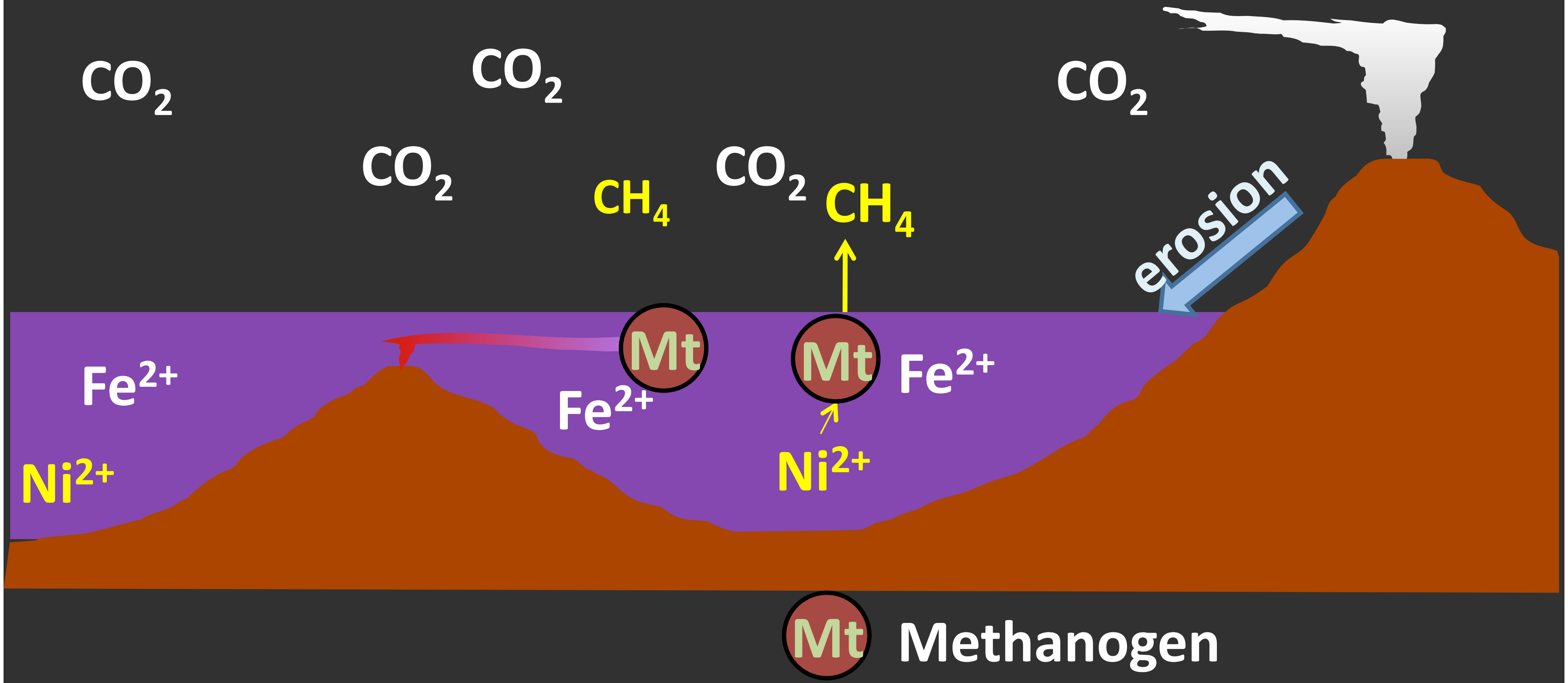
High methanogen activities in Archean

After 2.5 Ga: Cooling Earth's mantle

⇒ A decline in Ni concentration in the oceans at 2.5 Ga

⇒ a methanogen famine and a decrease in CH_4

(Konhauser et al., 2009)



How was a reducing atmosphere maintained?

Geological & biological ***inputs of reductants > 2.5 Ga*** *may have been* ***higher*** *than today because of* ***hot mantle and/or lack of substantial continents***

↓

Continuance period of reducing atmosphere on Earth

→ Interior activities: thermal evolution & continental growth

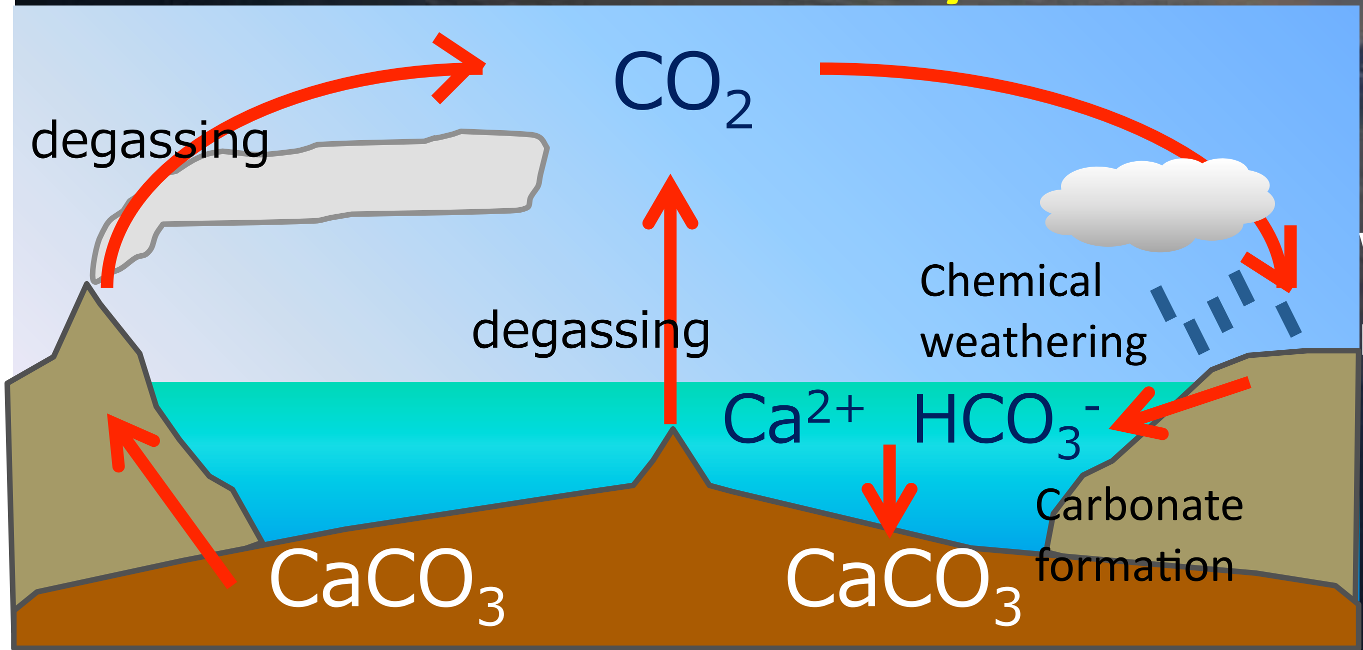
What types of atmosphere do exist on Earth-like exoplanets as functions of stellar age and planet mass?

Was early Earth with a CH_4-rich atmosphere climatically stable & habitable?

Why was early Earth habitable?

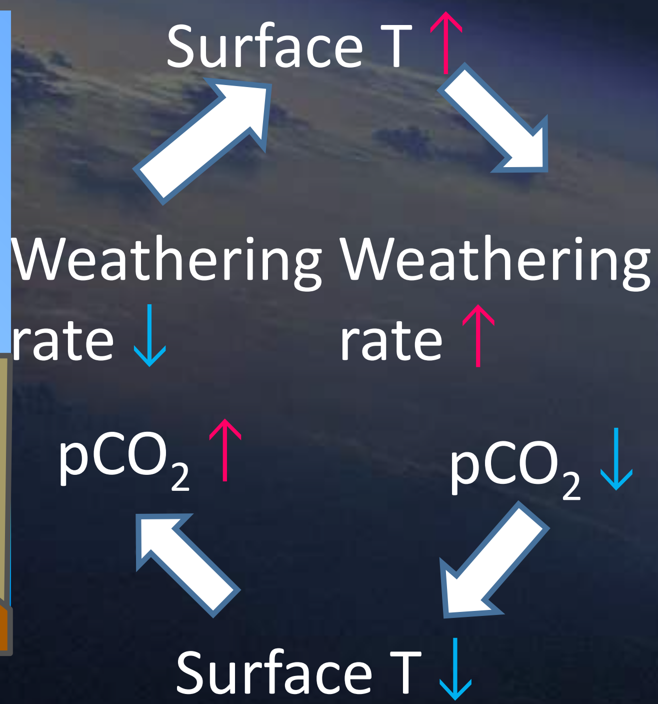
- On present Earth, CO_2 is essential greenhouse effect gas to stabilize climate on long time scales (Walker et al., 1981)
- Possible solution for the Young Faint Sun problem (Walker et al., 1981)

Carbonate-silicate cycle



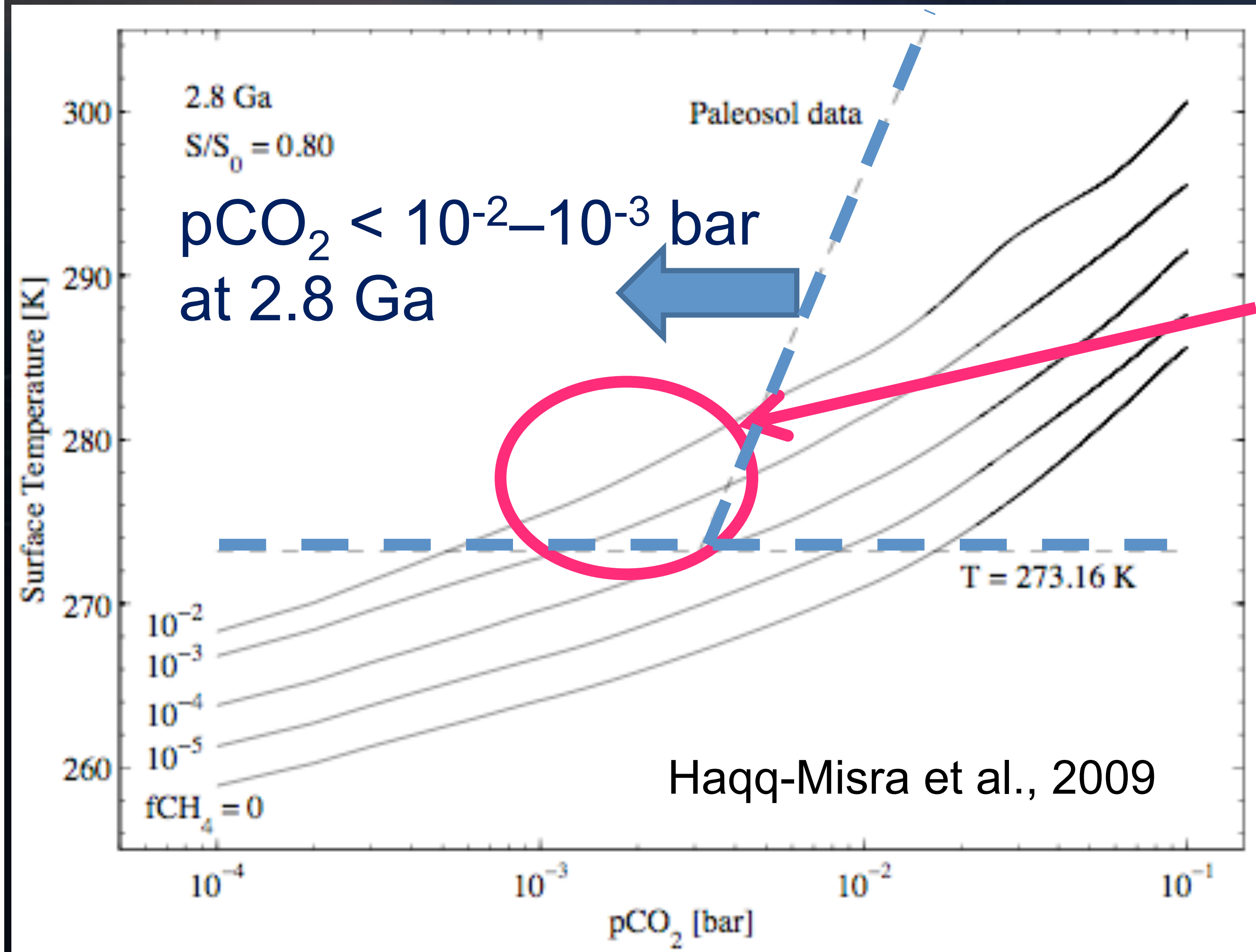
(e.g., Walker et al., 1980; Tajika & Matsui, 1992)

Negative feedback



Why was early Earth habitable?

- Paleosol evidence: CO_2 levels may not have been high sufficient to keep the surface warm (Rye and Holland, 1998)
- High levels of CH_4? But, CH_4 may not have been enough?



pCH_4 must have been several thousands ppm (10^{-2}–10^{-3} bar) ?
⇔ high CH_4 inputs

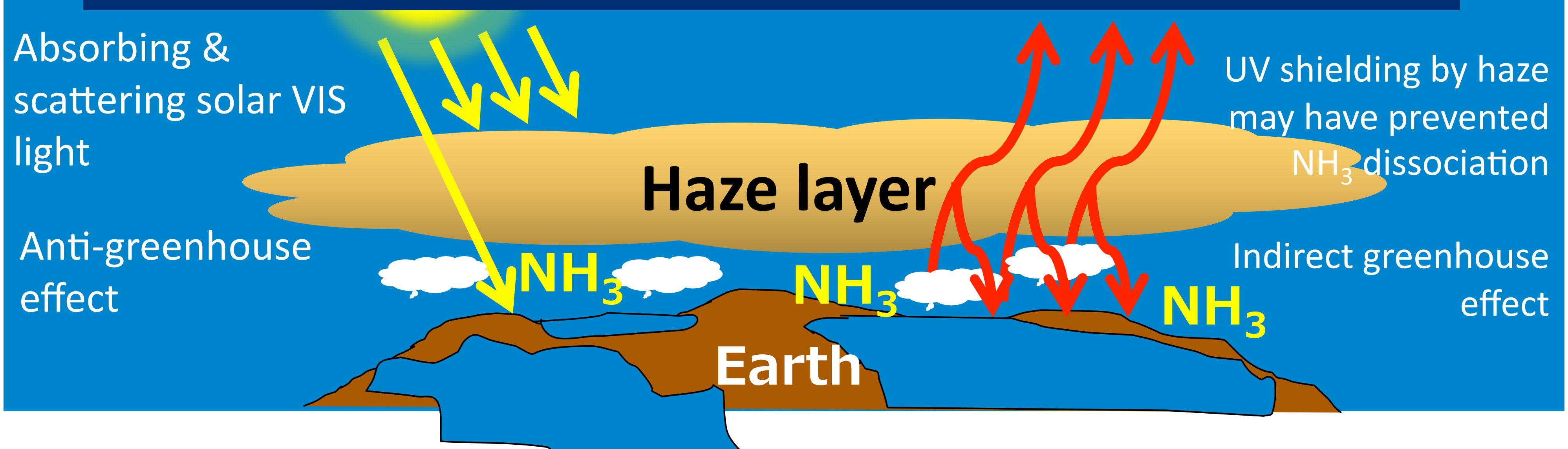
If so, a new question arises…

Organic haze on early Earth

- Haze production at CH_4/CO_2 > 0.1? (Zahnle et al., 1990; Sagan & Chyba, 1997; Pavlov et al., 2001; Trainer et al., 2006)
- Antigreenhouse effect cools the surface? (Haqq-Misra et al., 2009)

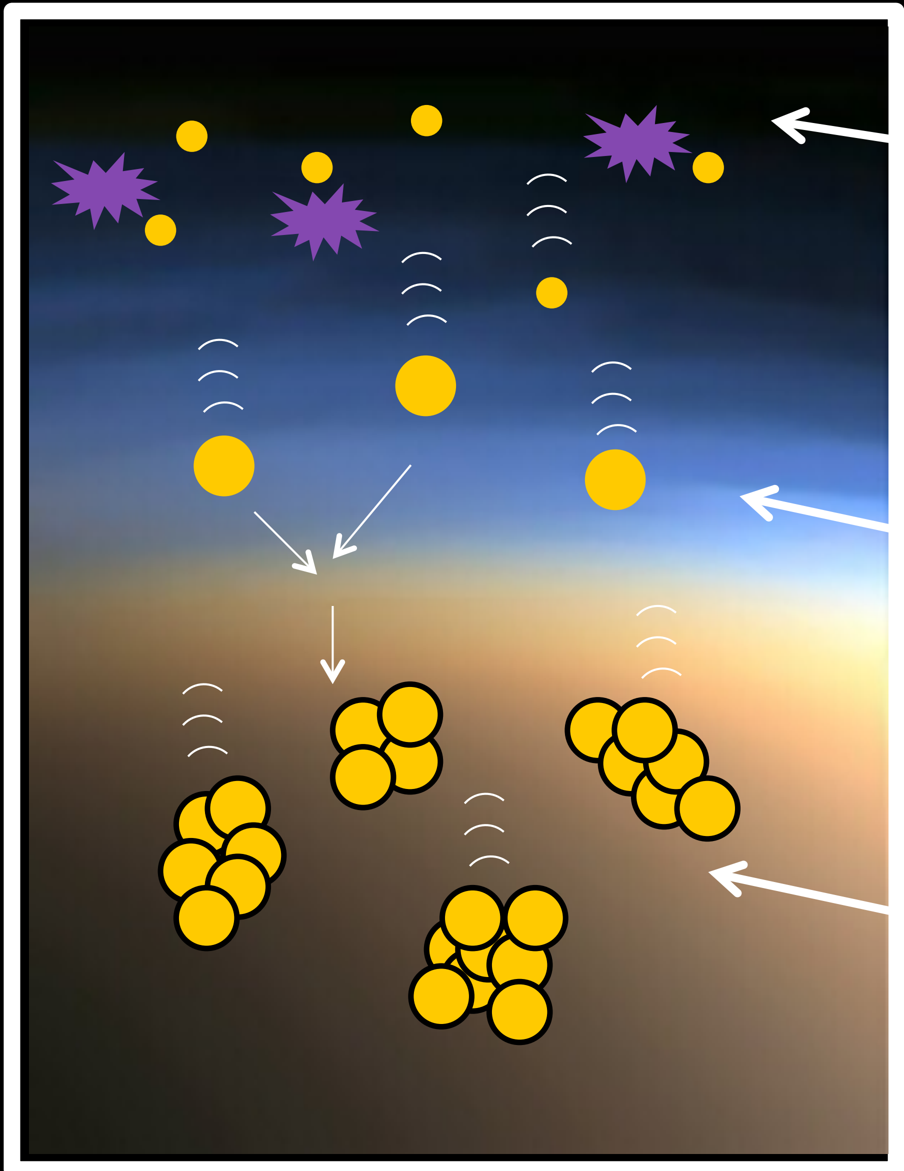
  e.g., Titan haze cools the surface about 9 K (McKay et al., 1991)
- Indirect greenhouse keeps the surface warm? (Sagan & Chyba, 1997; Wolf & Toon, 2010)

Strongly depending on optical properties and production rate of haze



Cassini-Huygens mission (2004-)

Insights from Cassini-Huygens



Formation of monomers (100-8000 Da) at high altitudes (1000 km) by EUV & Lyman α (Waite et al., 2007)

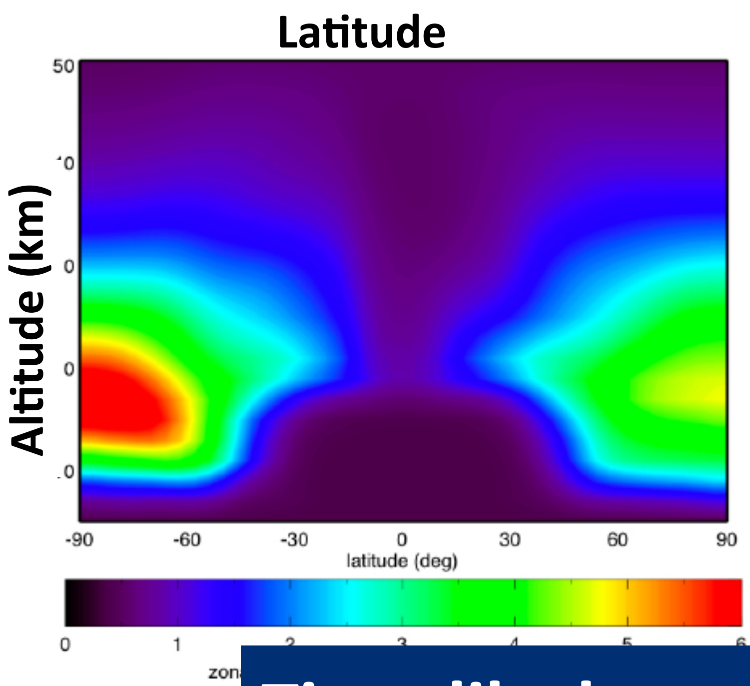
Growth of monomers (50-100 nm) by surface reactions with hydrocarbons (Lavvas et al., 2010)

Coagulation forming aggregates with fractal structure (200-1000 monomers: 1 μm) at 300-500 km (Niemann et al., 2005)

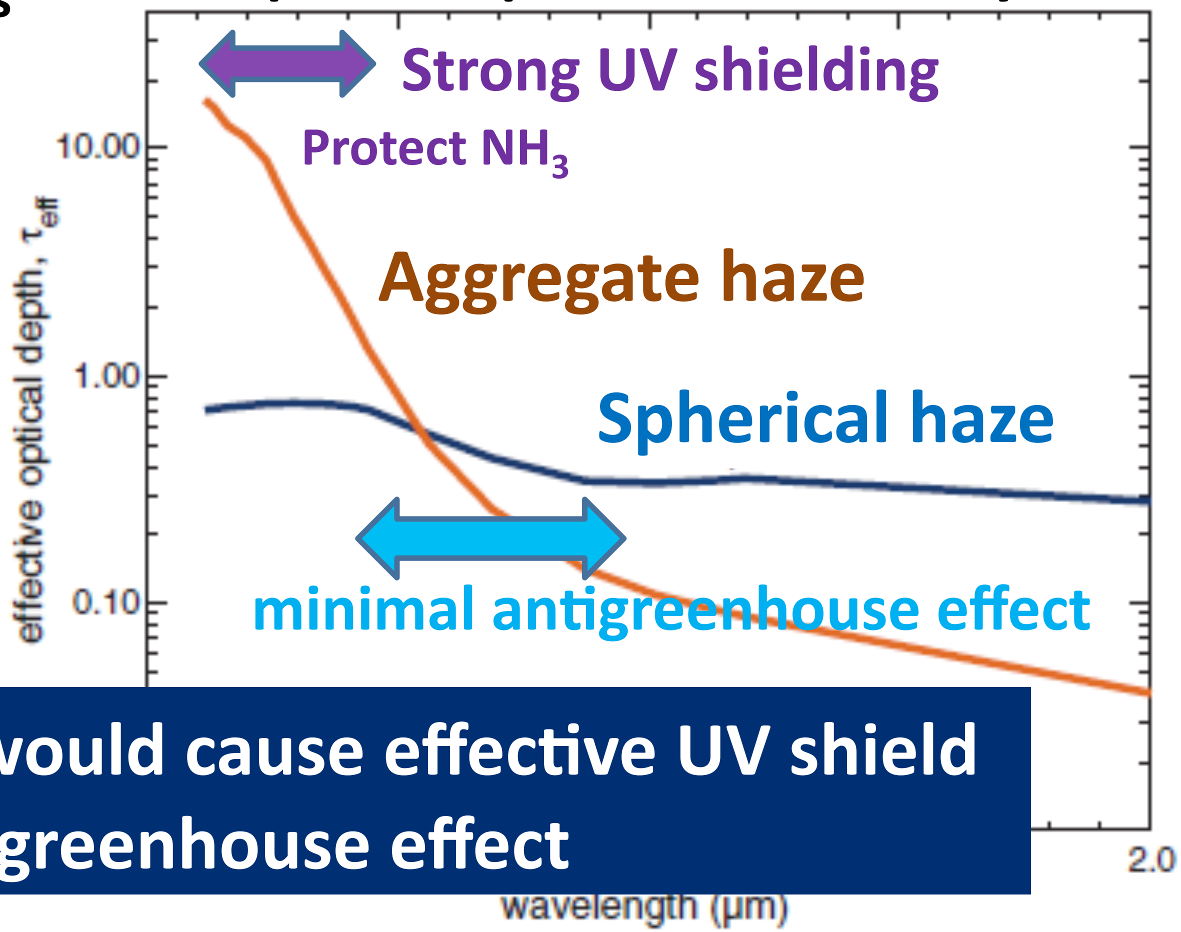
Applications to early Earth (Wolf & Toon, 2010)

- Fractal structure of aggregate has strong effect on radiative properties of haze
- Incorporating haze production & coagulation in a general circulation model (GCM) (Wolf & Toon, 2010)

Average haze mass concentrations



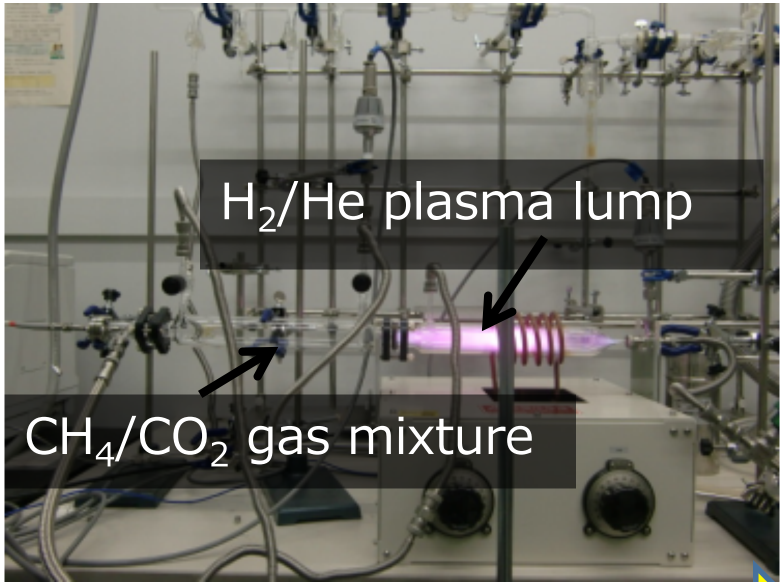
Optical depth due to haze layers

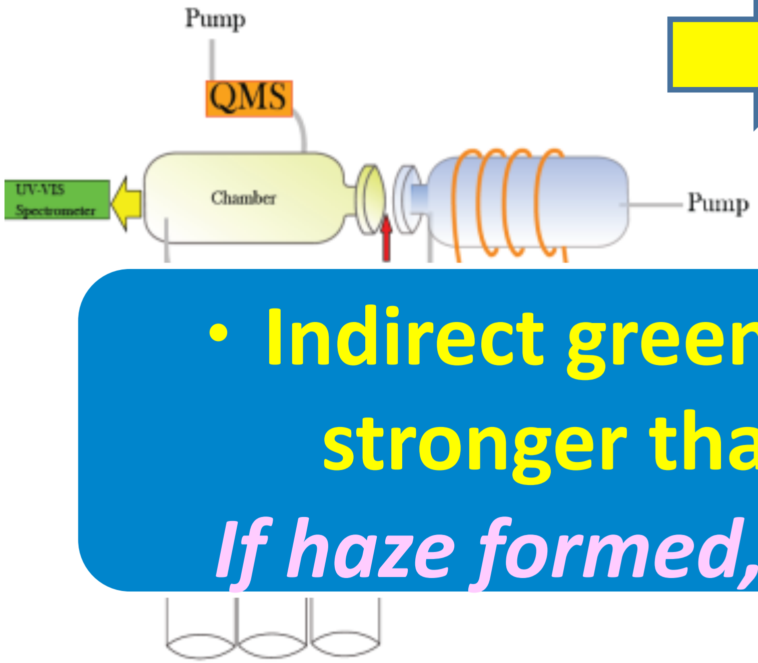


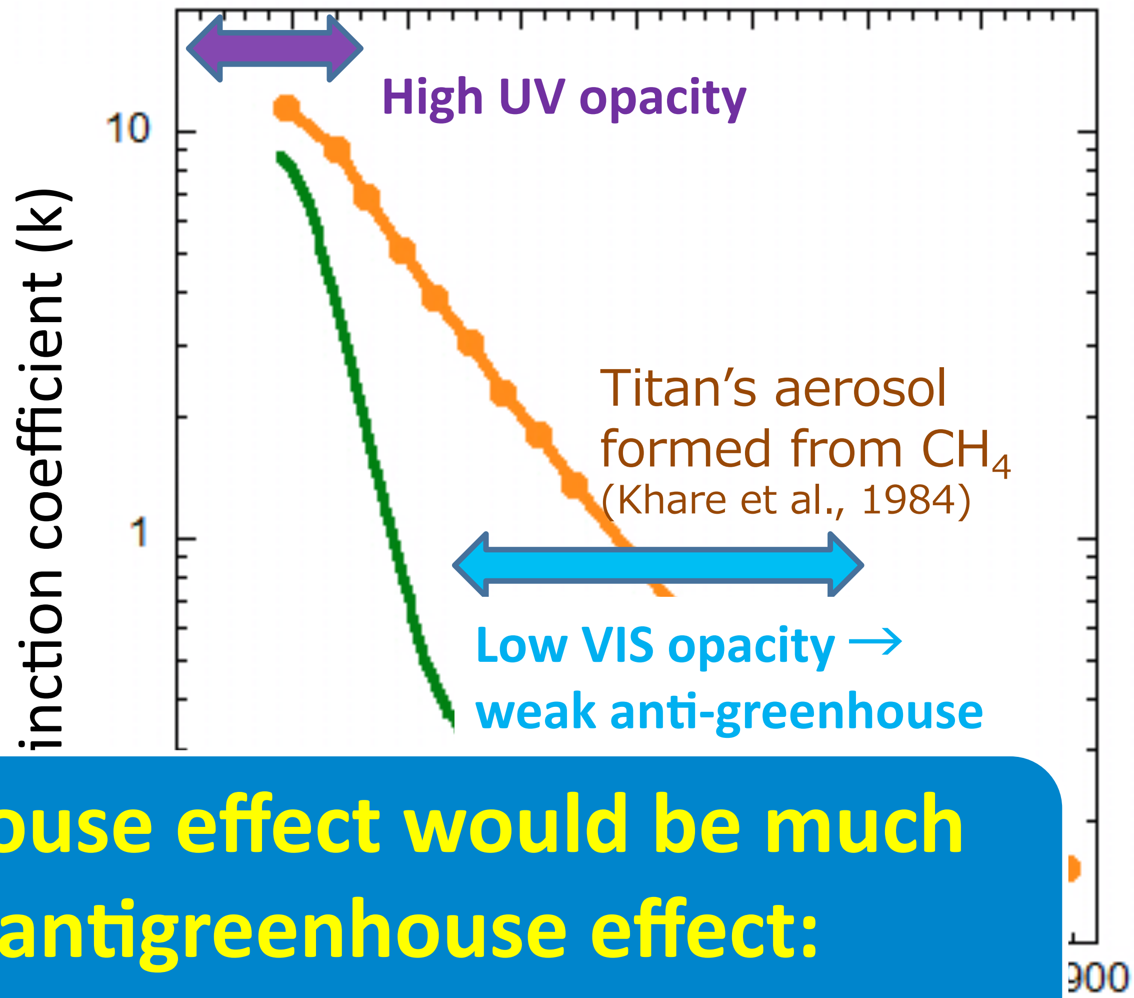
Titan-like haze would cause effective UV shield not causing antigreenhouse effect

Experiments: Optical constants of aerosols

(Sekine et al., 2008a, in prep.)



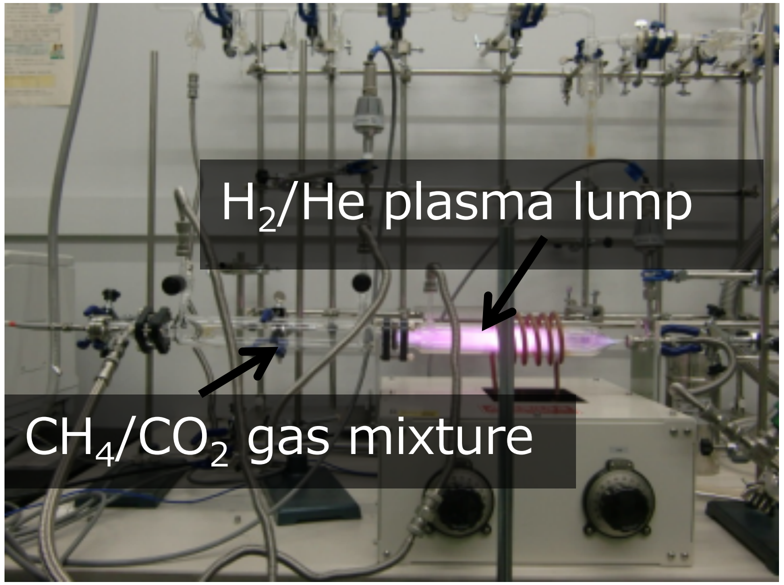


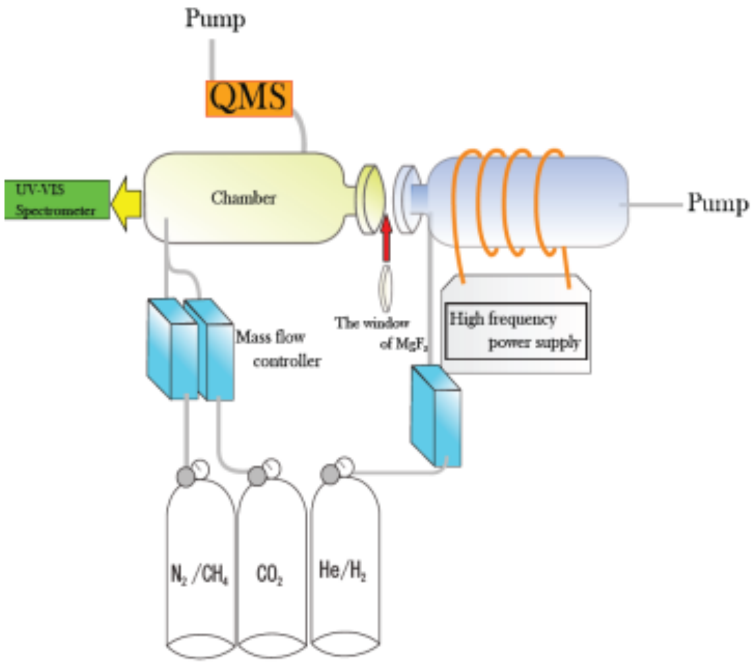


- **Indirect greenhouse effect would be much stronger than antigreenhouse effect:**

If haze formed, Earth would become warm

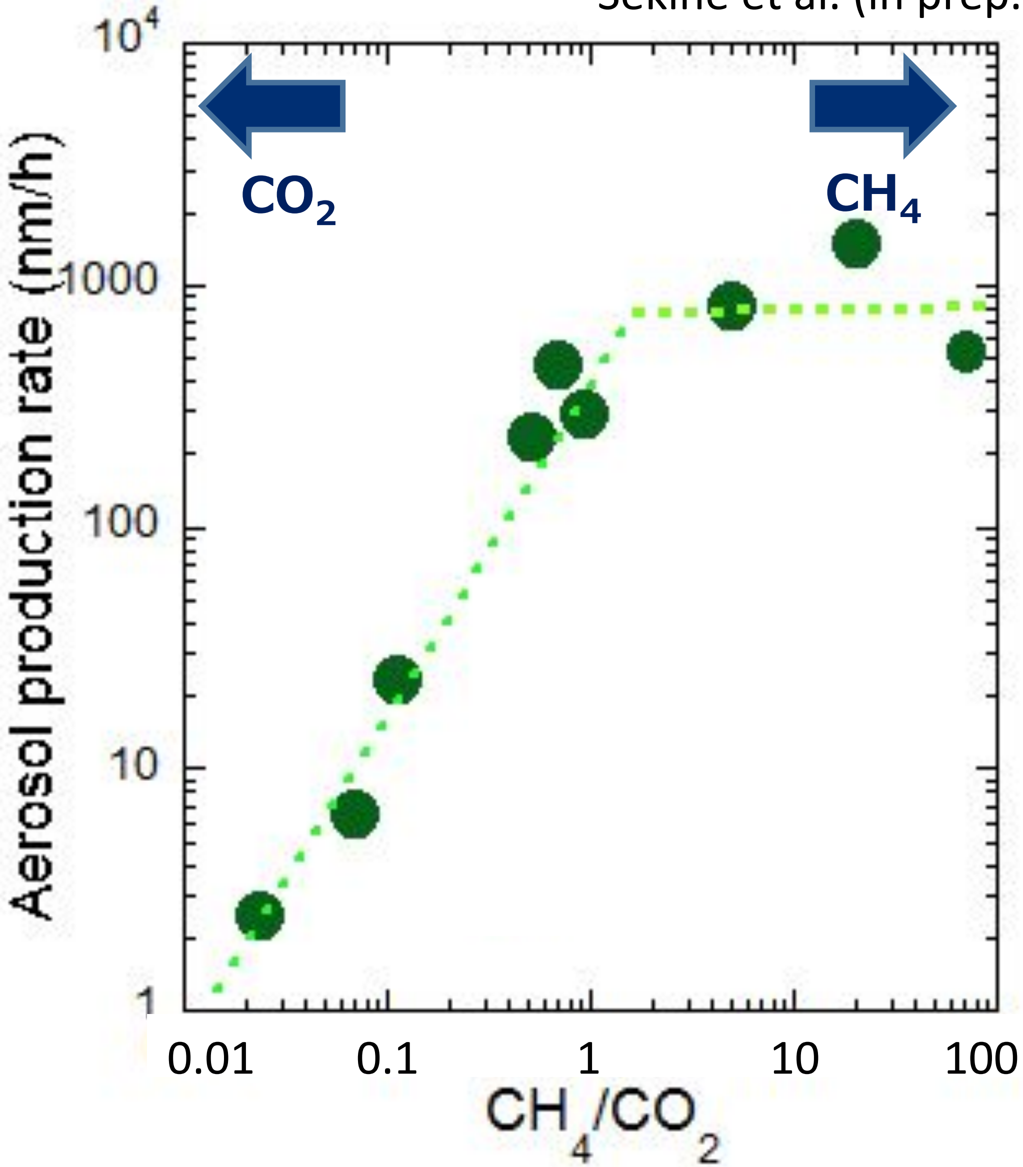
Laboratory experiments on Earth's haze





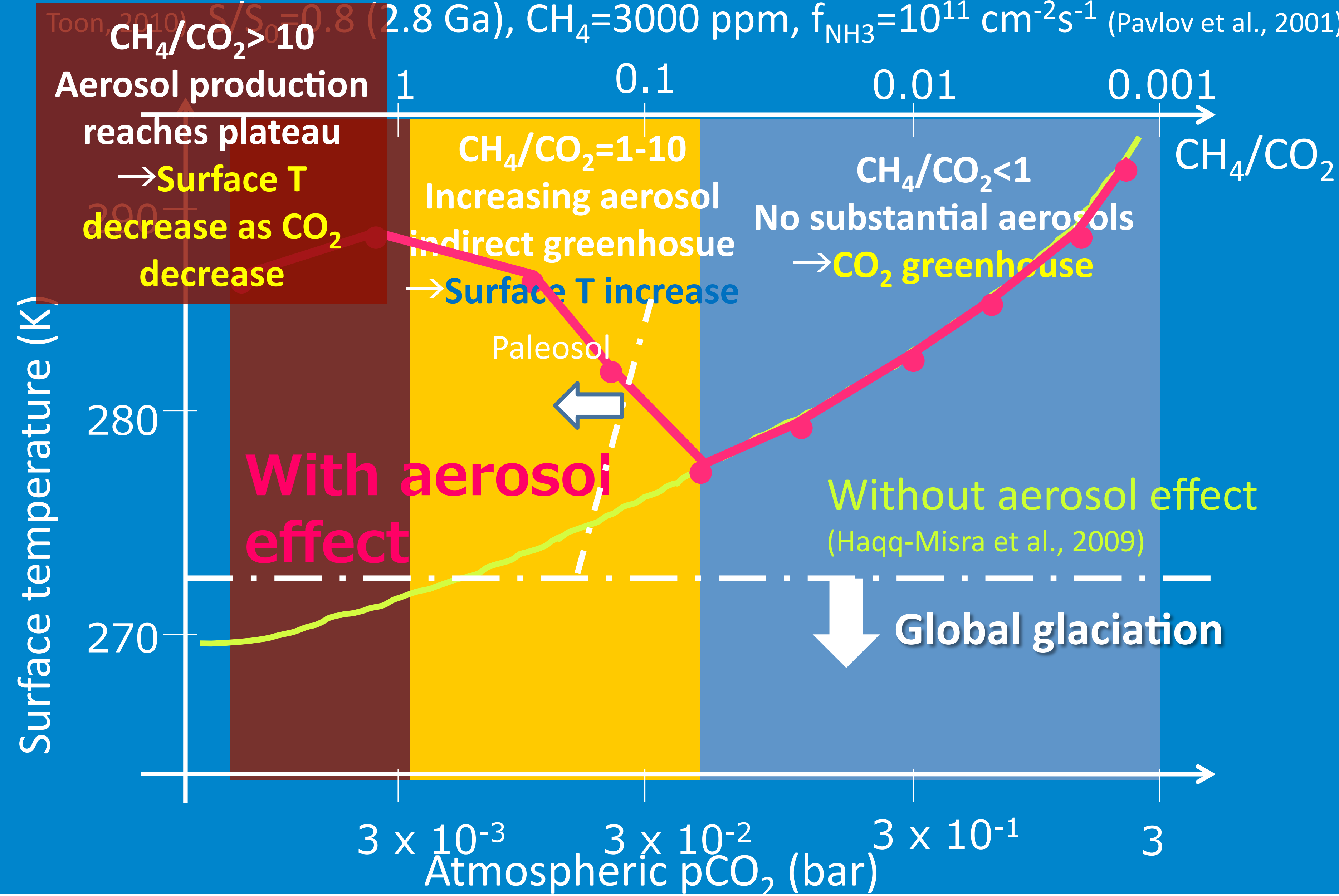
Aerosol production rate for CH_4/CO_2

Sekine et al. (in prep.)

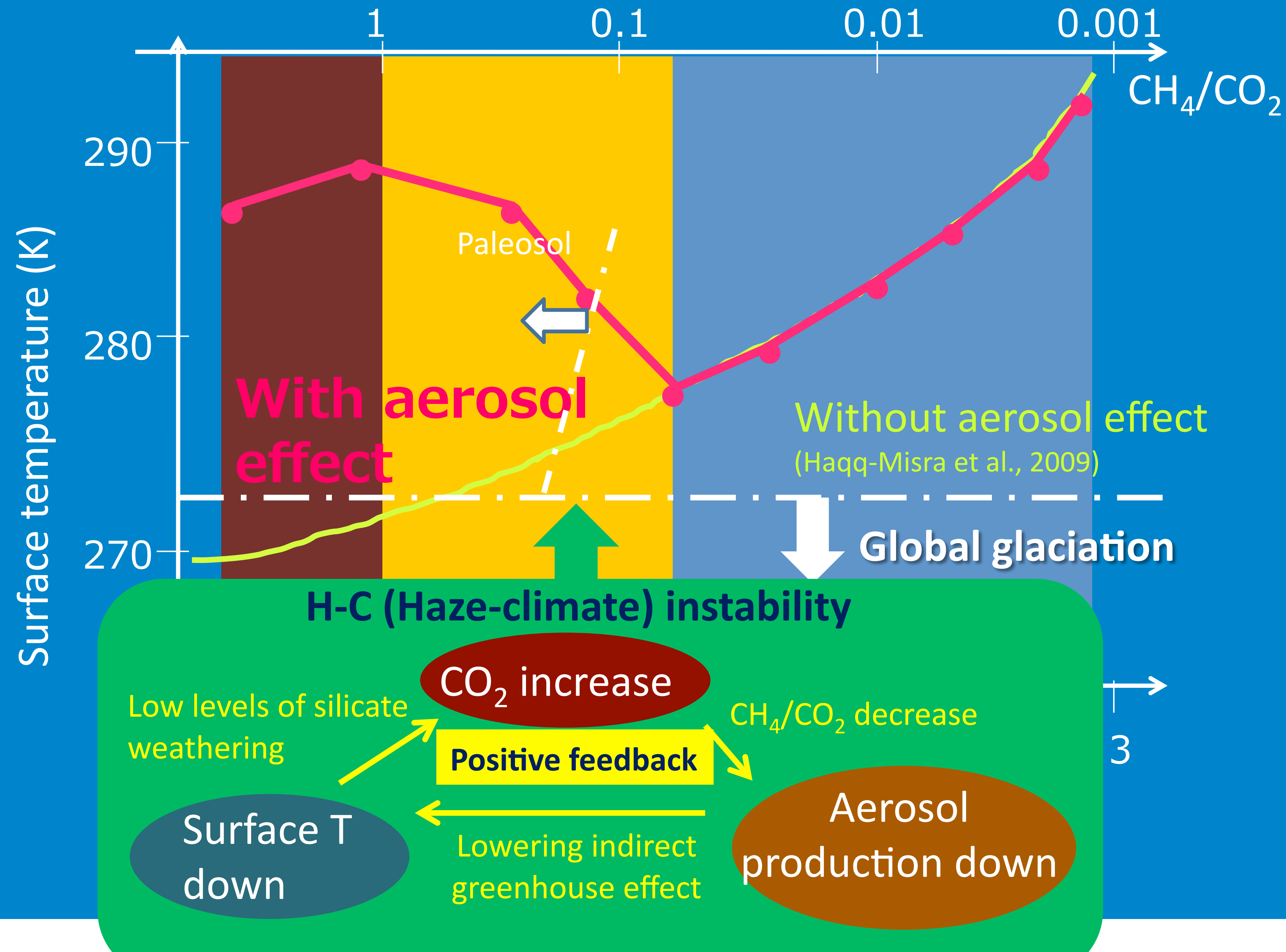


Haze, CH_4 & surface temperature

We introduced our experimental results into microphysical model (Wolf & Toon, 2010) S/S_0=0.8 (2.8 Ga), CH_4=3000 ppm, $f_{NH3}=10^{11}$ $cm^{-2}s^{-1}$ (Pavlov et al., 2001)

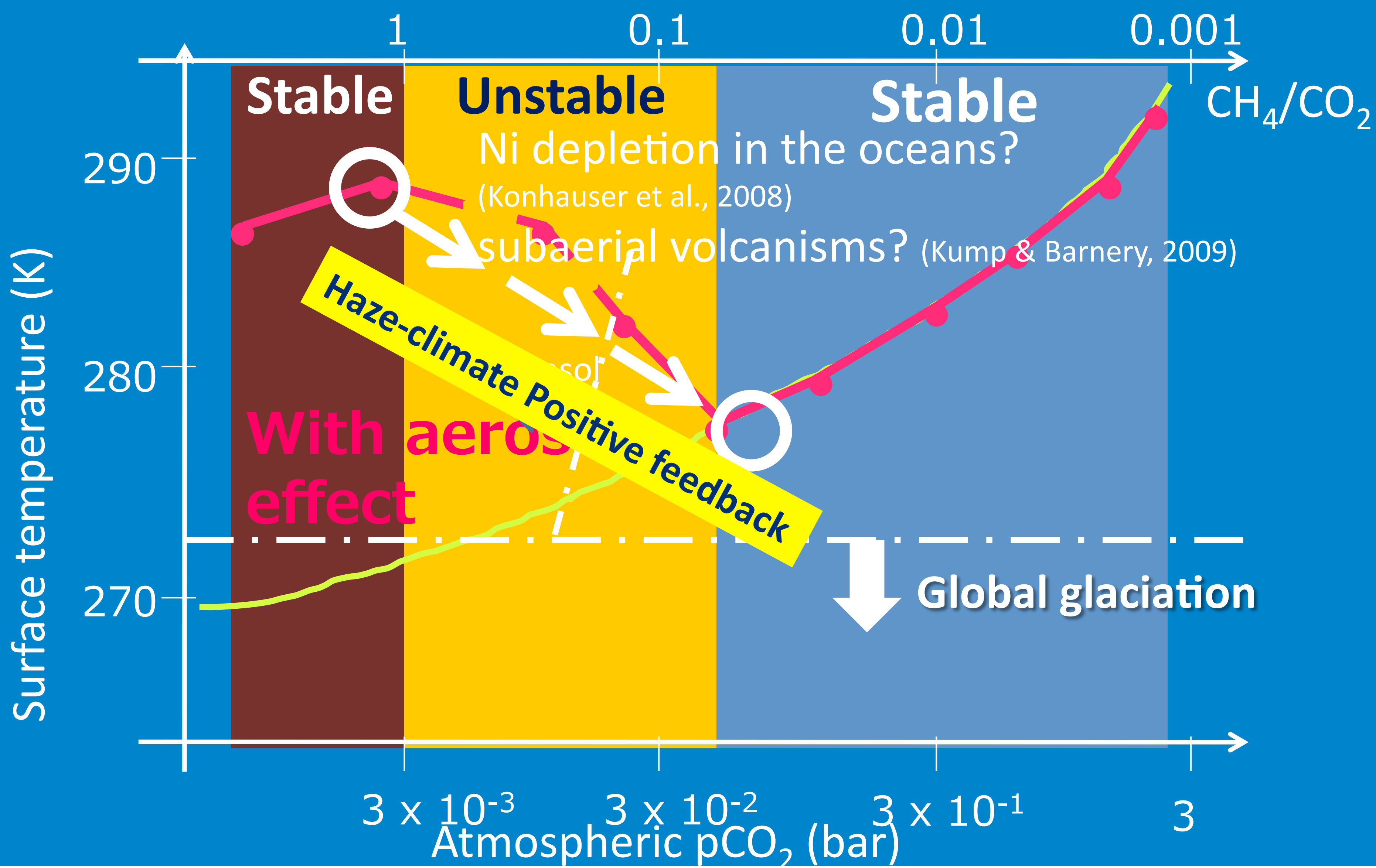


Haze, CH_4 & surface temperature

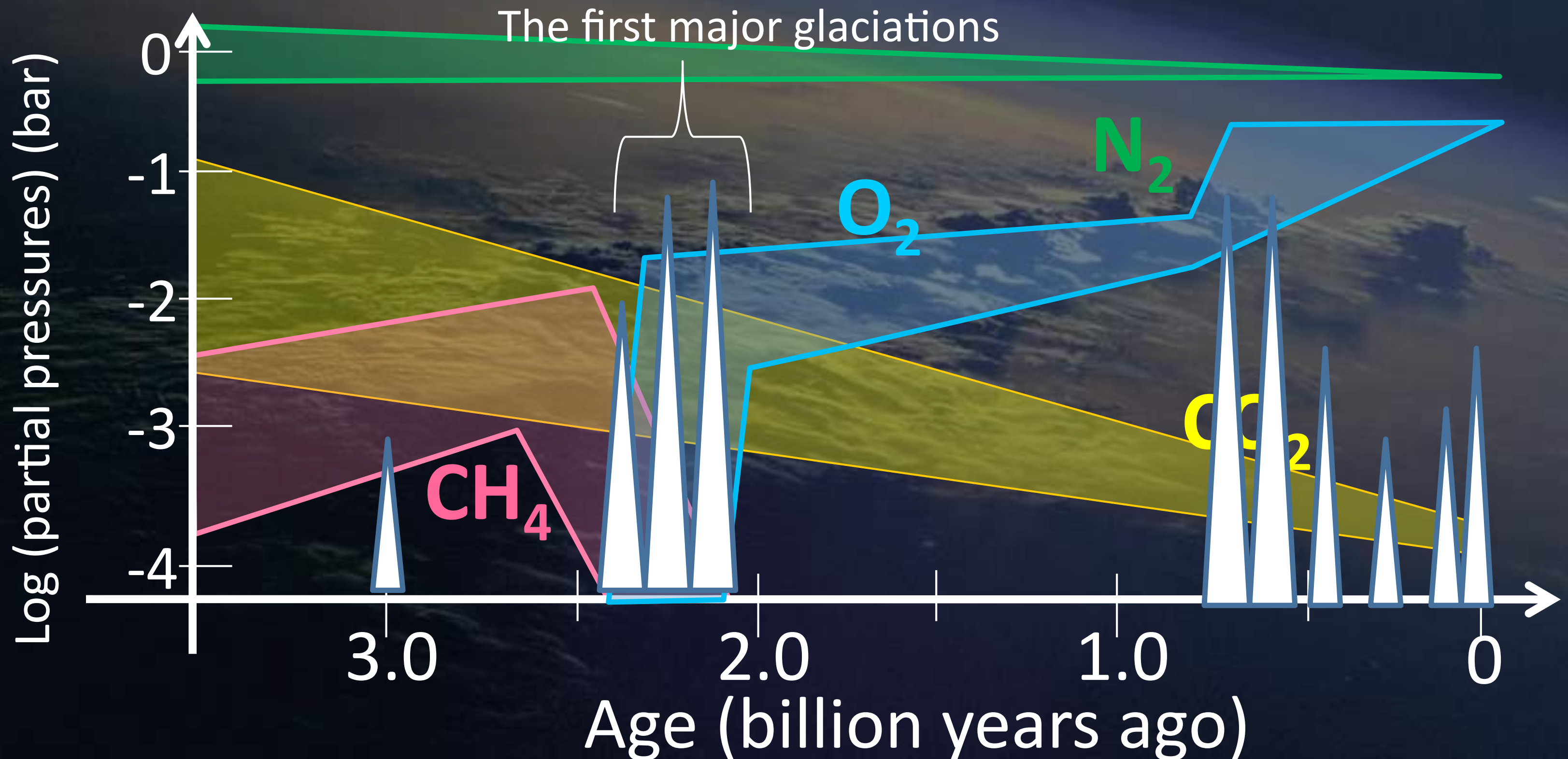


Haze, CH_4 & surface temperature

Because the yellow region is unstable, Earth might have been in the red region in the diagram in Archean given paleosol constraints

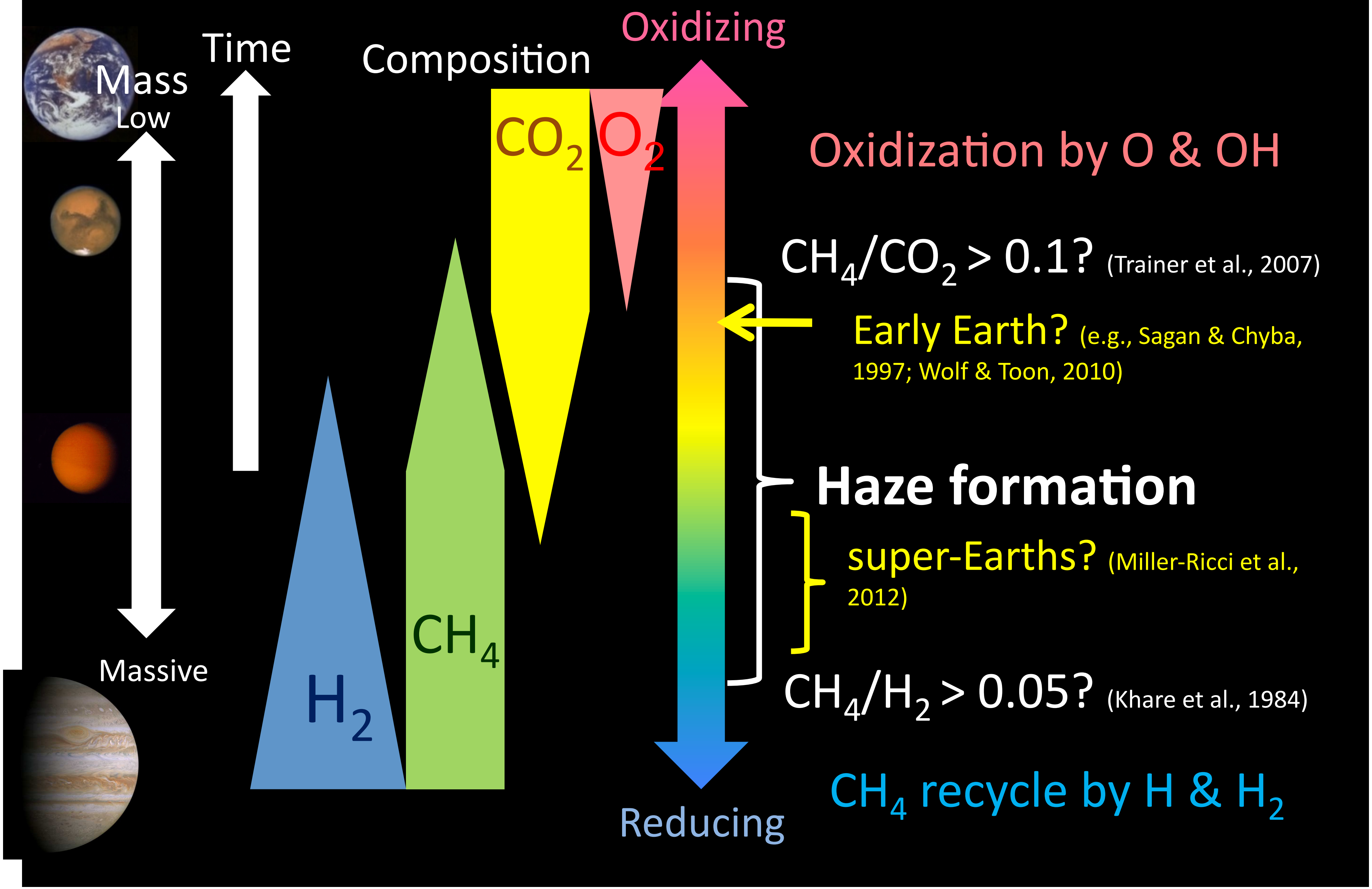


The repeated severe glaciations from 2.5 to 2.2 Ga at the transition from reducing to oxidizing atmosphere



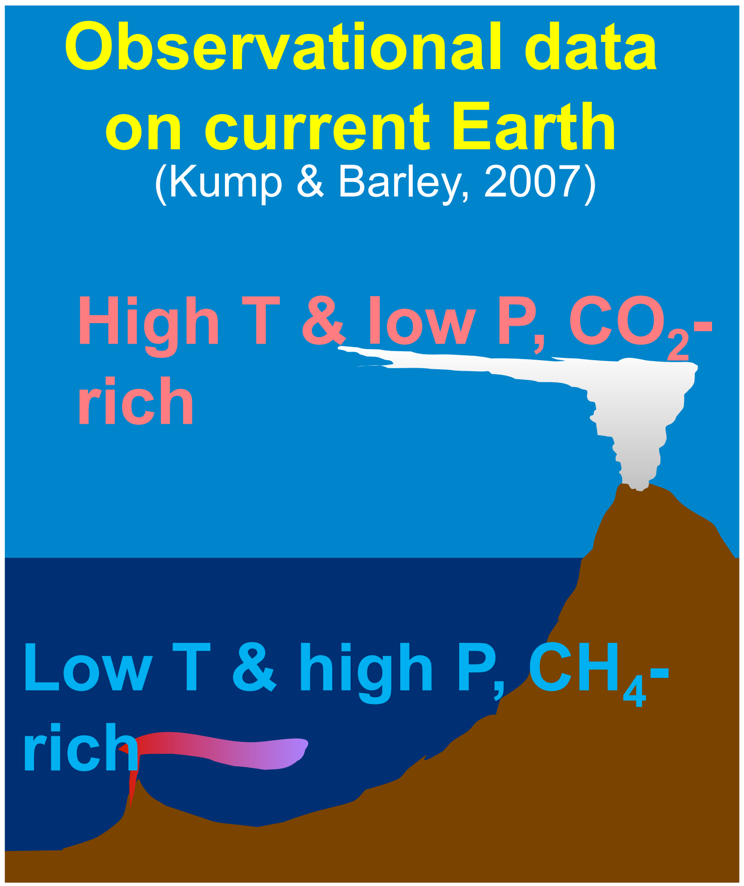
(Holland, 1984; Tajika & Matsui, 1992; Kasting, 1993; Rye & Holland, 1998; Farquhar et al., 2000; Pavlov & Kasting, 2002; Canfield, 2005; Hoffman & Schrag, 2002; Kump, 2008; Holland, 2006)

Implications for exoplanets

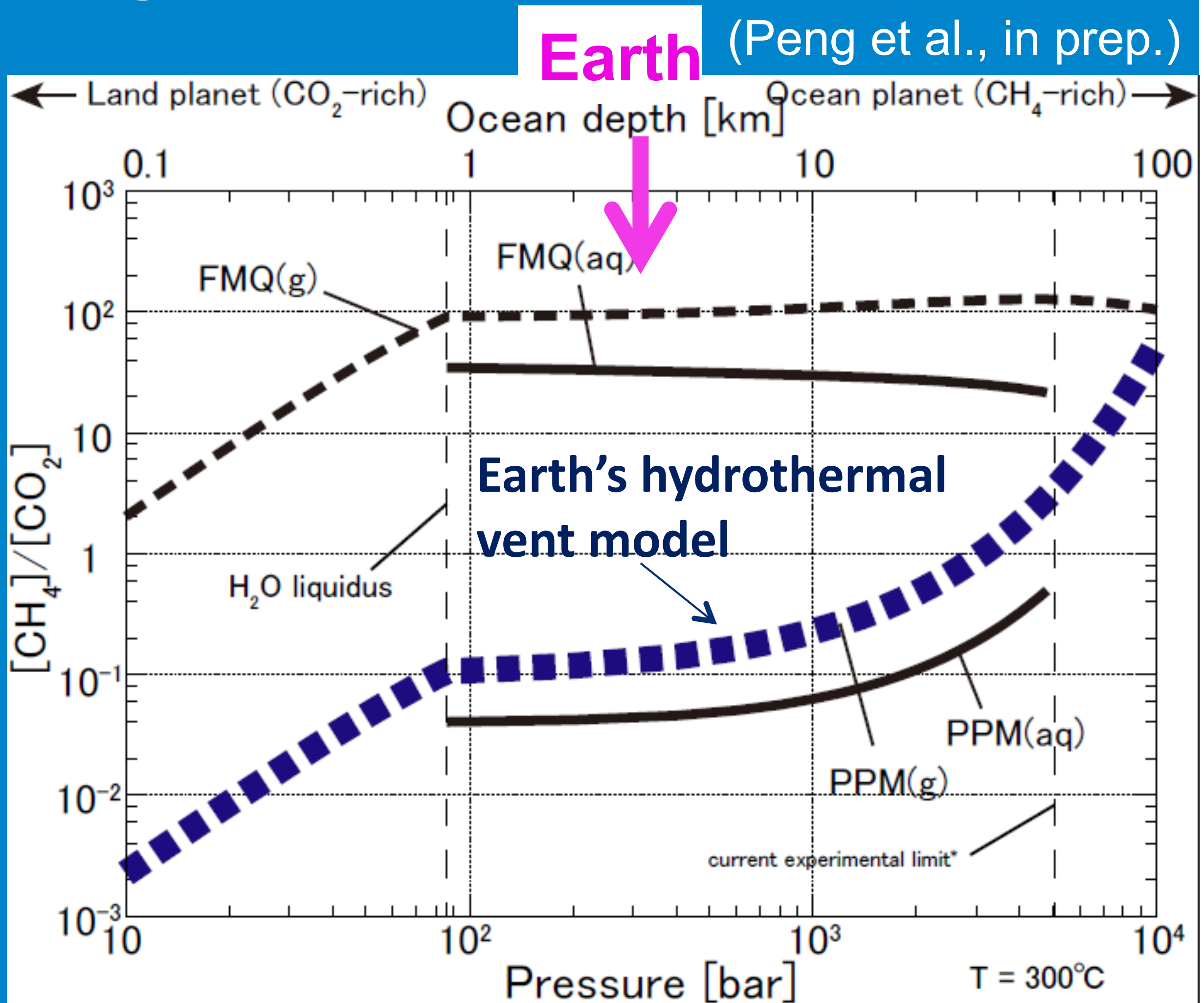


Organic haze on terrestrial exoplanets?

What is an important parameter to determine the redox conditions of atmosphere? → Earth-mass planets can have oceans with a wide range of water mass: **Ocean mass?**

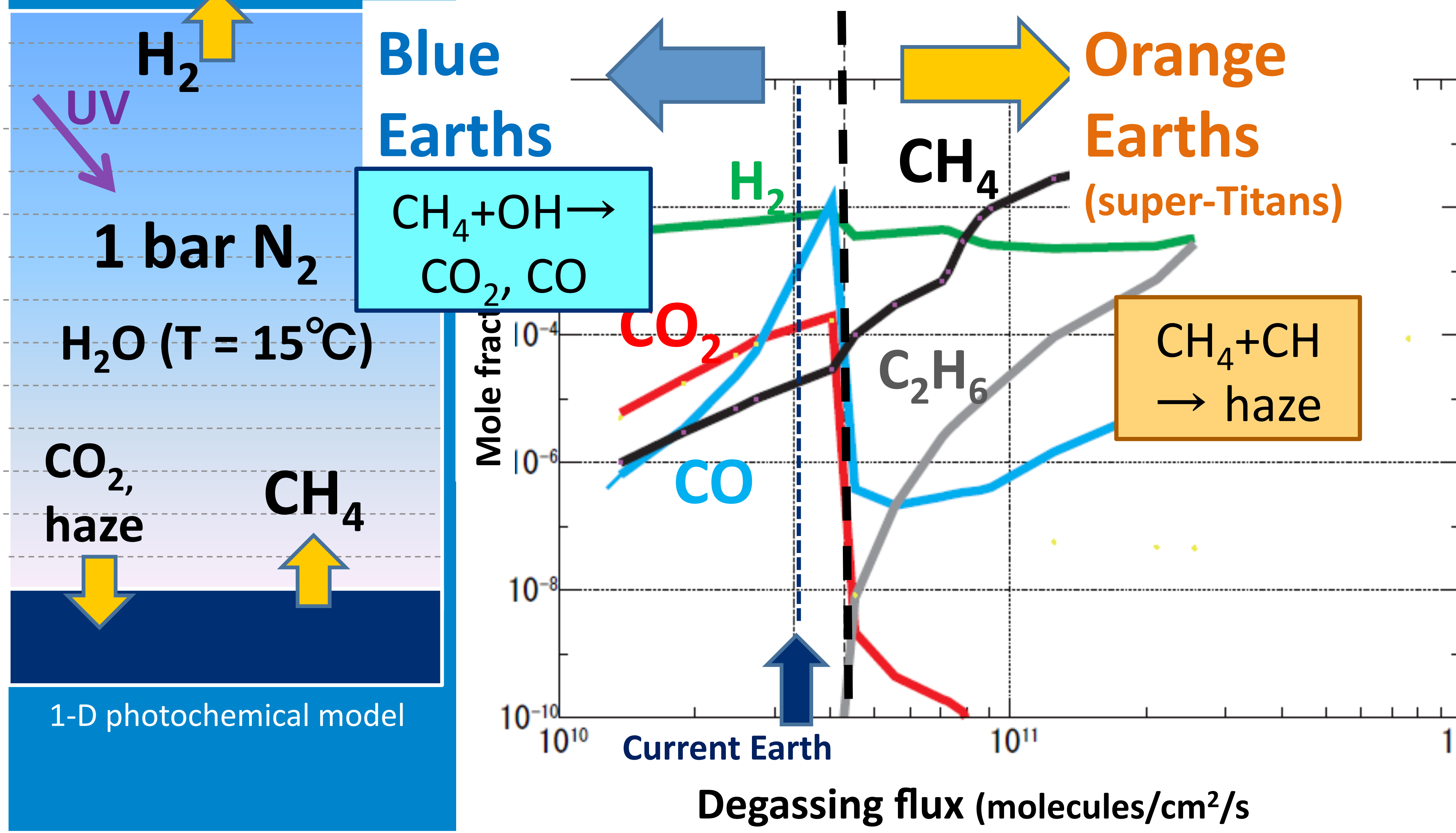


(Peng et al., in prep.)



Organic haze on terrestrial exoplanets?

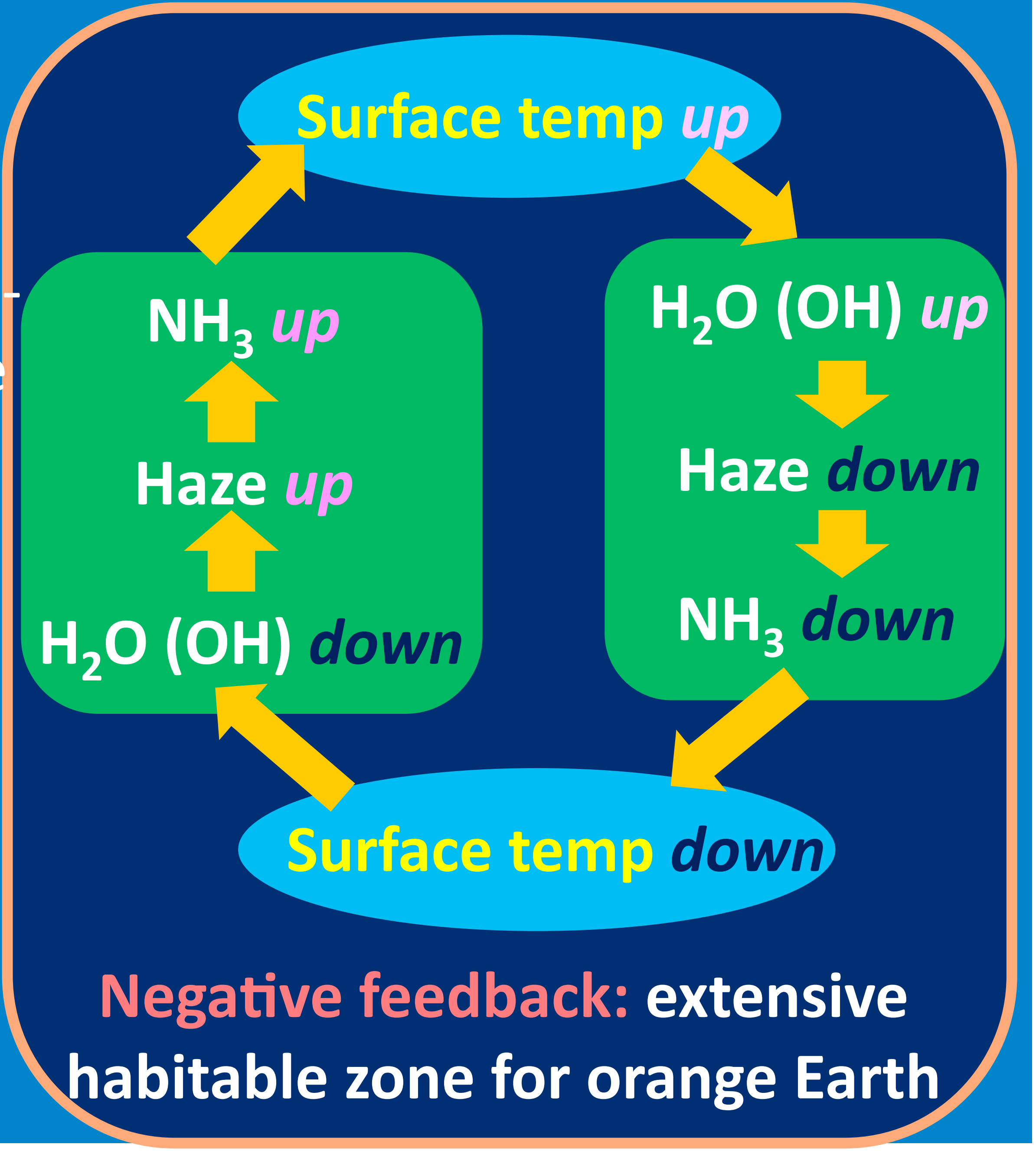
- Atmospheric composition of planets with ocean depth 100 km



Habitability of ocean planets

Habitable zone for deep ocean planets
→ very narrow because of the absence of carbon-silicate cycle and positive feedback of water

Abe et al. (2011)



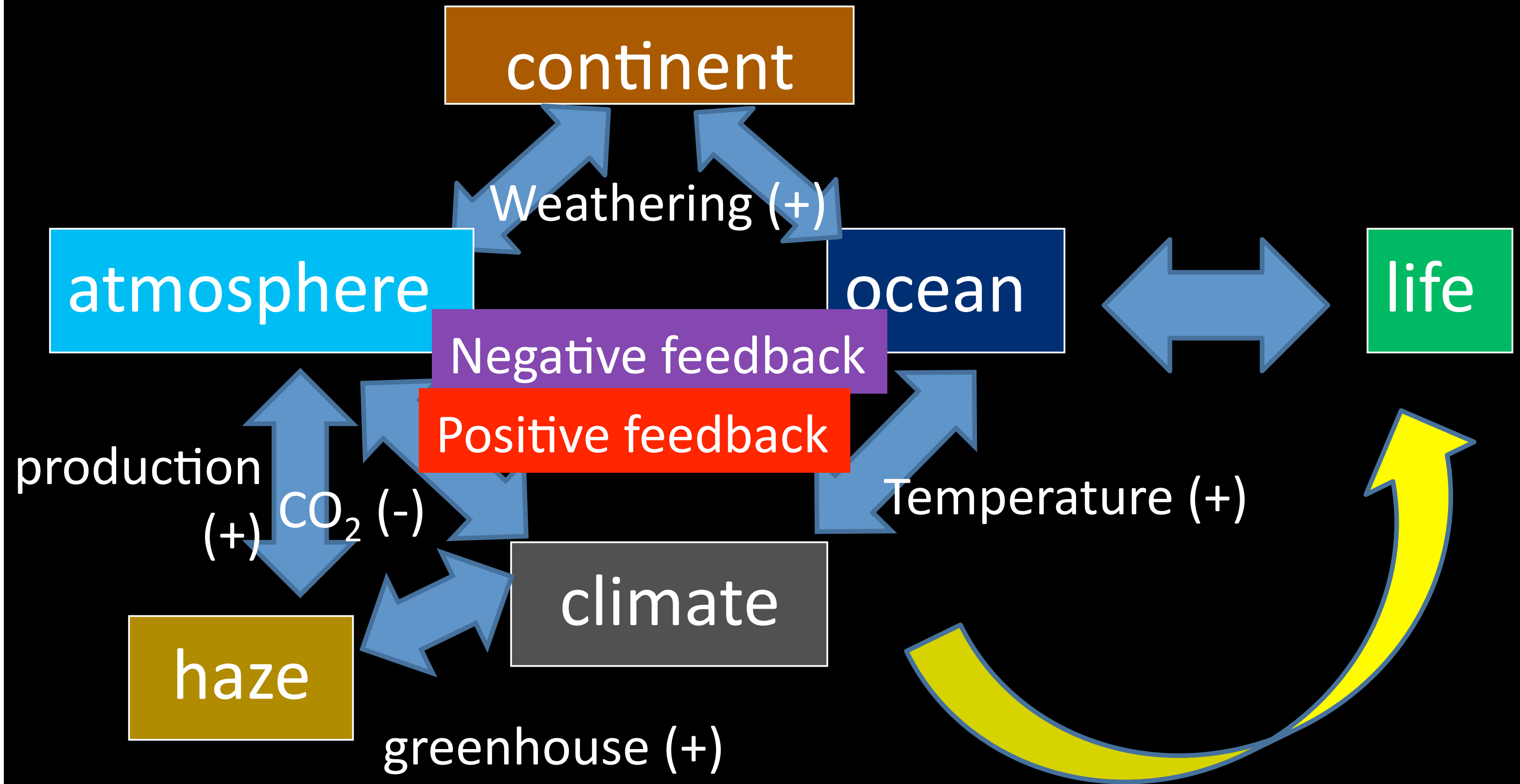
Summary: Archean Earth

- Hot mantle and/or submarine volcanisms on early Earth
  → Reducing, CH_4-rich atmosphere
  → ***Evolution of the interior affect the chemical conditions of the atmosphere and ocean***

- Organic haze may have kept early Earth habitable:
  A hidden instability between climate & haze
  CH_4 ↓ → haze ↓ → low T & CO_2 ↑ → haze ↓ ･･･
  → ***Any decrease in CH_4 triggered severe glaciations***

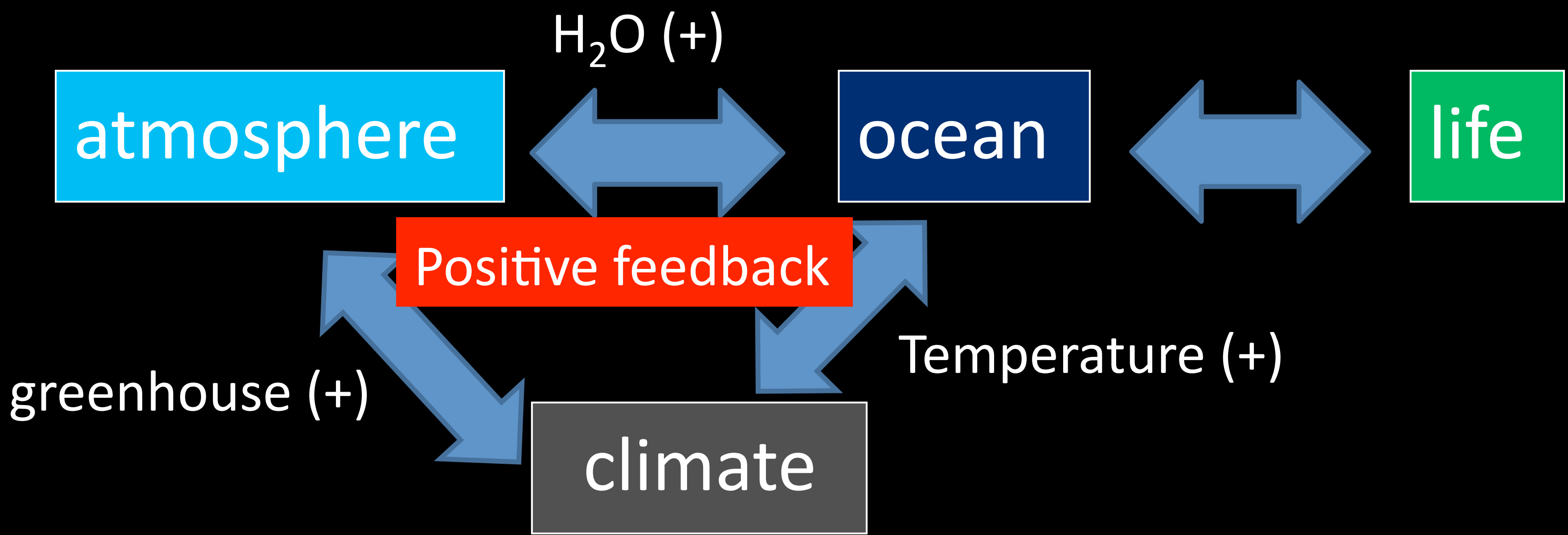
Summary: system diagrams

Current
Early Earth



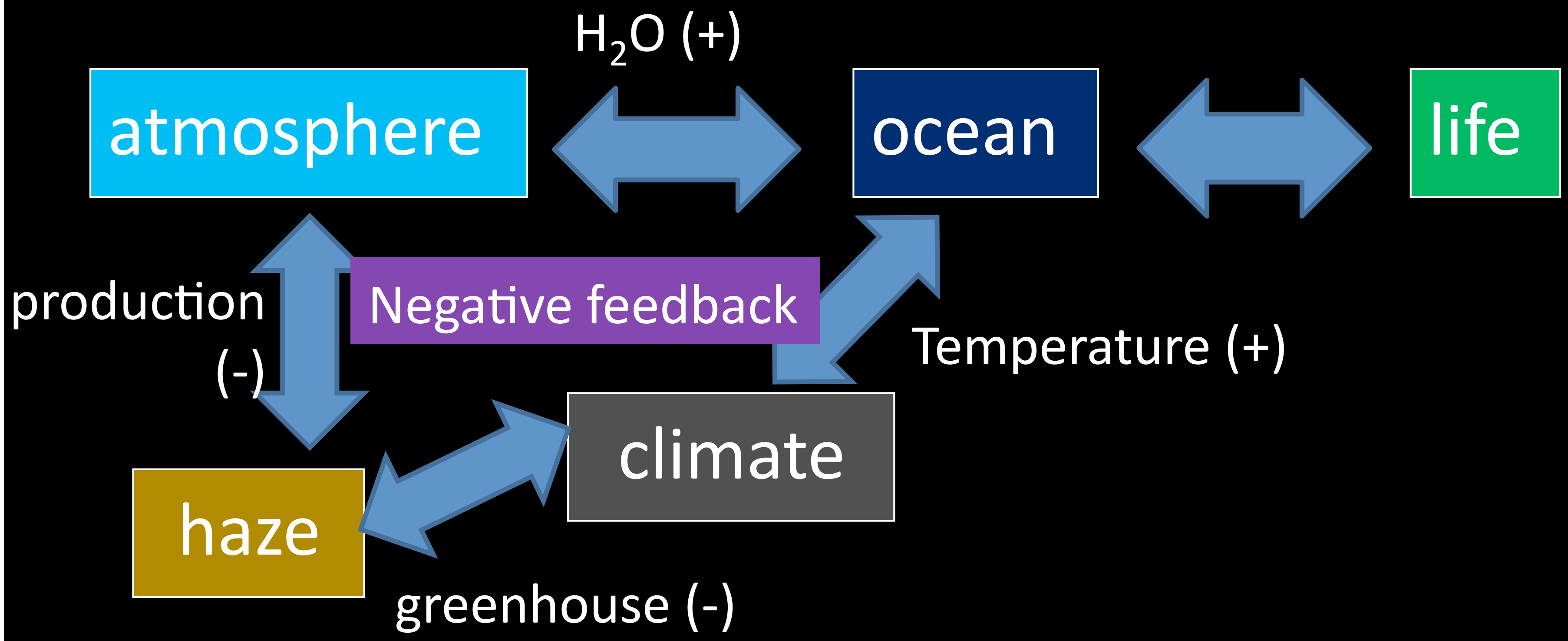
Summary: system diagrams

Deep ocean "blue" Earths



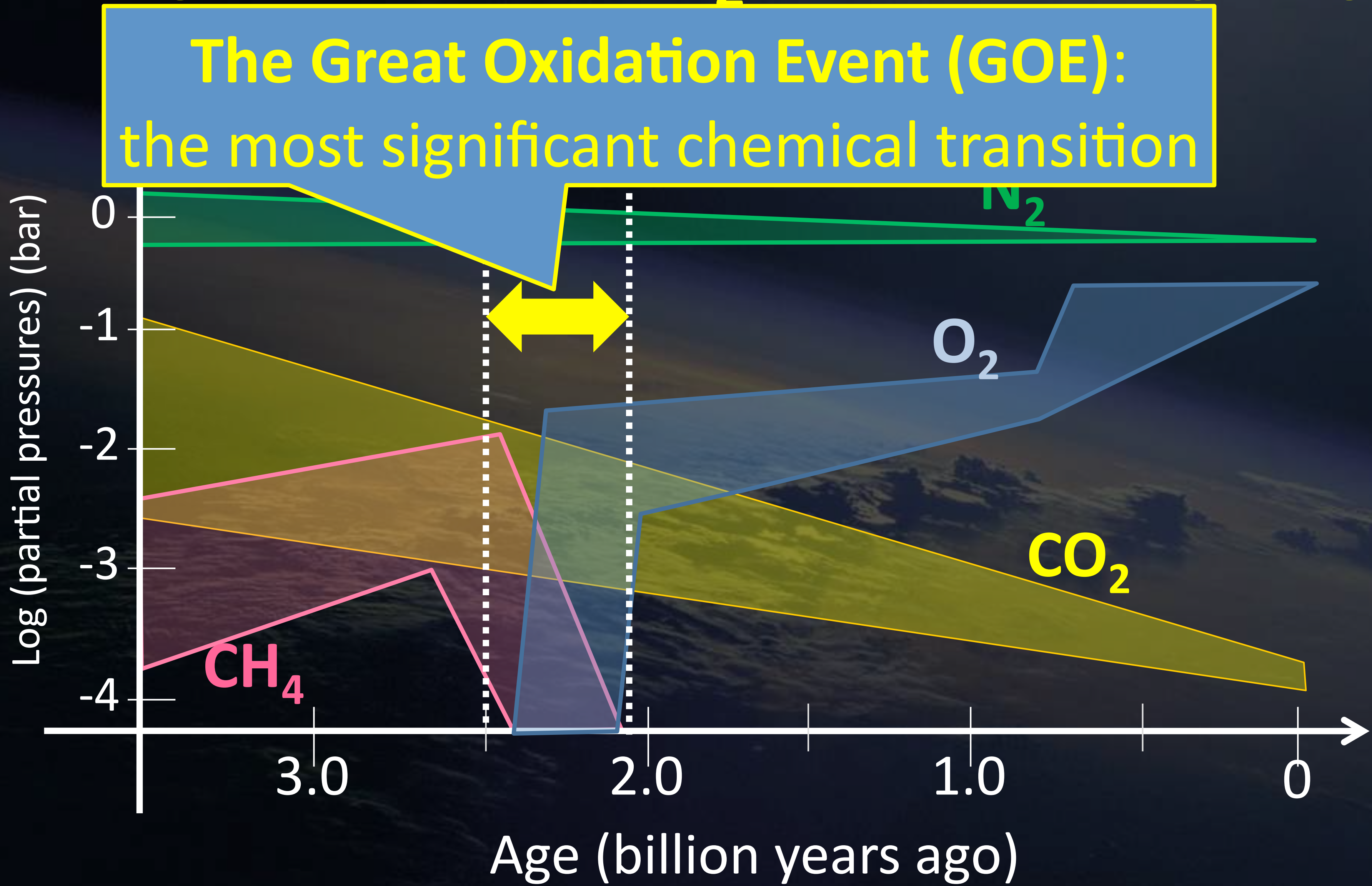
Summary: system diagrams

Deep ocean “orange” Earths



2. How and why did atmospheric O_2 levels rise?

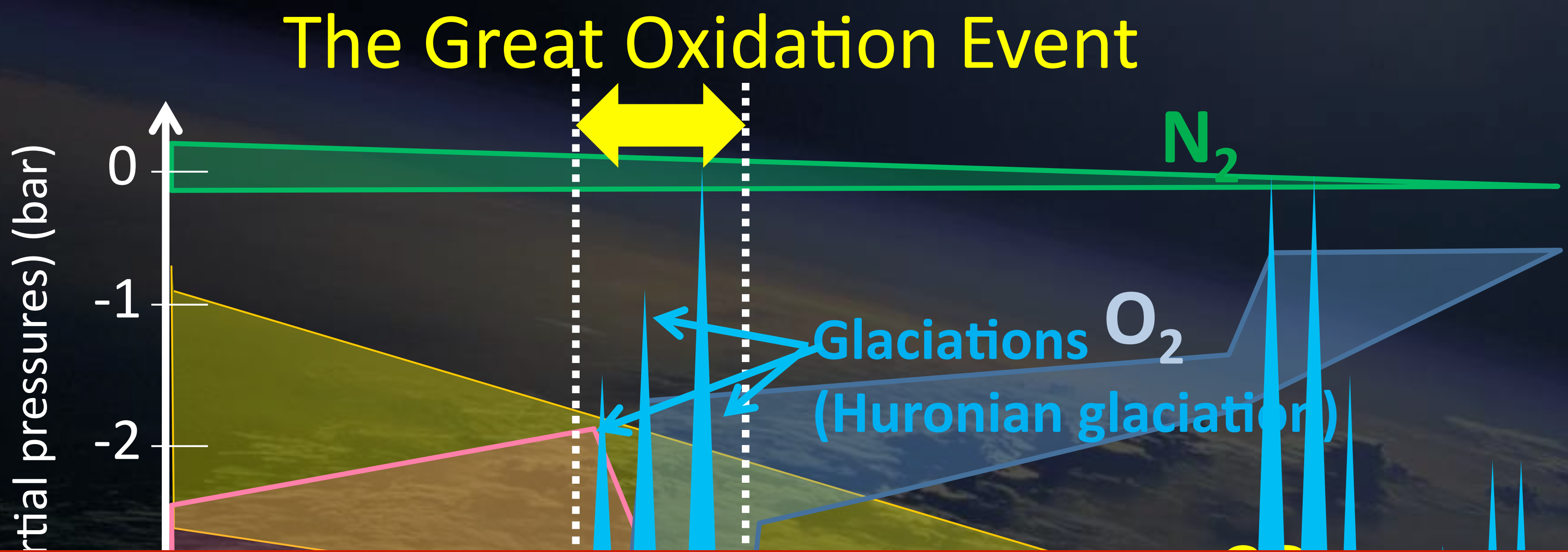
Why & how did O_2 increase rapidly?



(Holland, 1984; Tajika & Matsui, 1992; Kasting, 1993;
Rye & Holland, 1998; Farquhar et al., 2000; Pavlov et al., 2001; Hoffman & Schrag, 2000; Zahnle et al., 2006)

Why did O_2 increase so rapidly?

Key: Climate change (decline in CH_4 ⇒ severe glaciation)



Relationship between climate change & rise in O_2

increase O_2 → decrease in CH_4, trigger a glaciation

climate change → shift in balance of oxidant & reductant

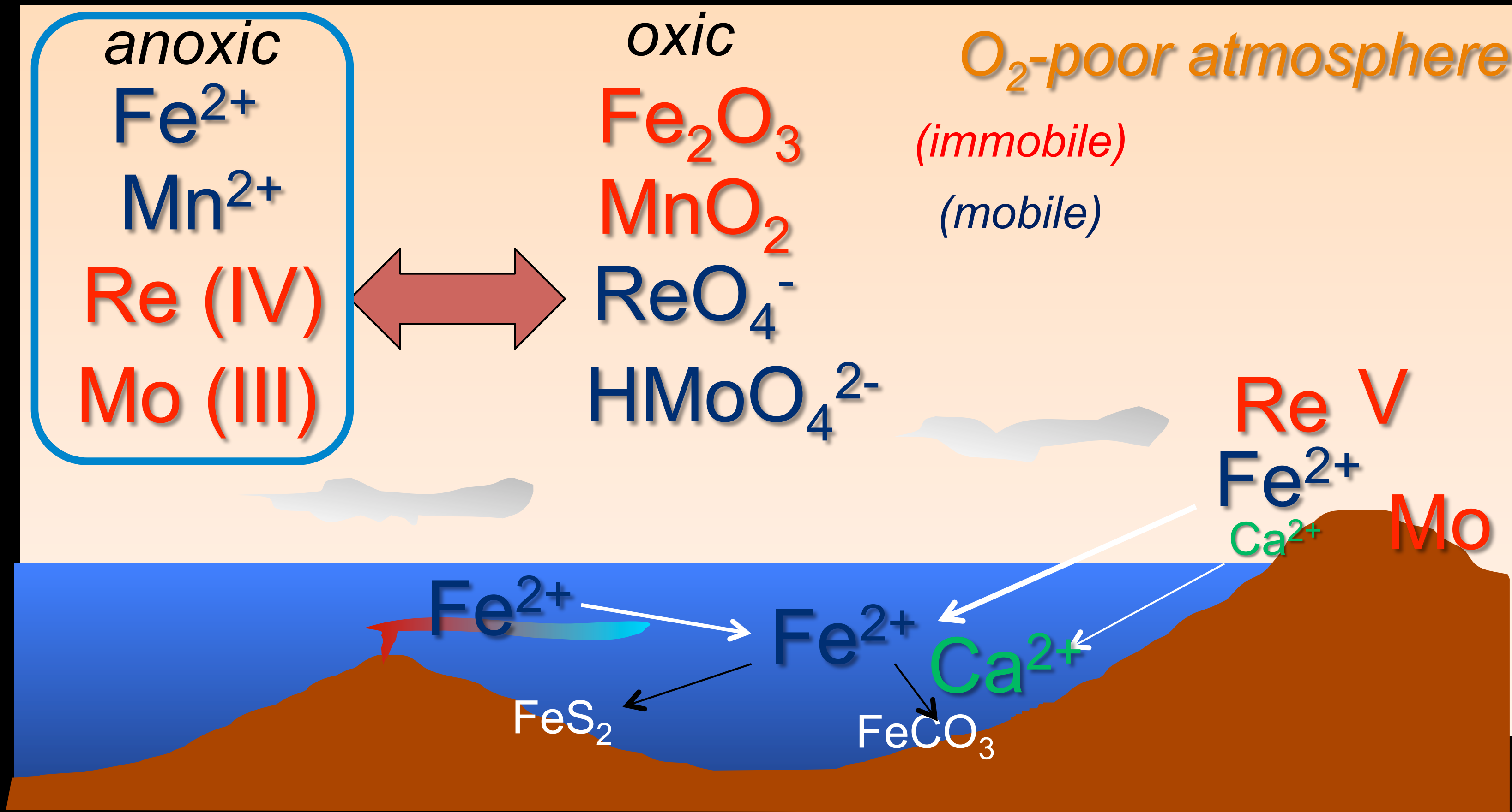
⇒ detailed change in O_2 in response to glaciation

Problems

We need new proxy for investigating continuous records of O_2 in response to glaciation

Proxy for reconstructing O_2 levels

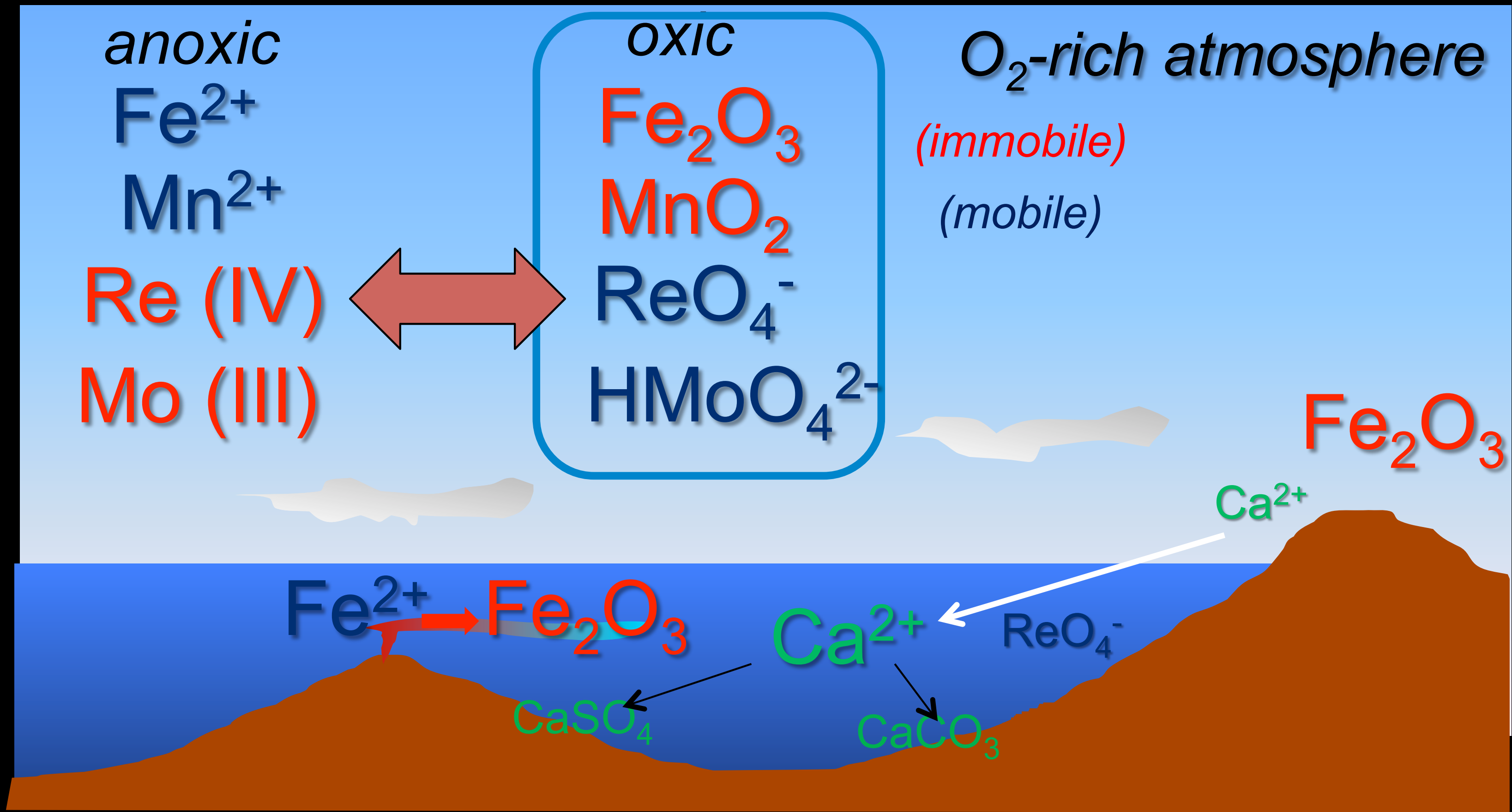
Redox sensitive elements (Fe, Mn, Mo, Re, V) show variations in solubility as a function of redox states



(e.g., Tribovillard et al., 2000)

Proxy for reconstructing O_2 levels

Redox sensitive elements (Fe, Mn, Mo, Re, V) show variations in solubility as a function of redox states

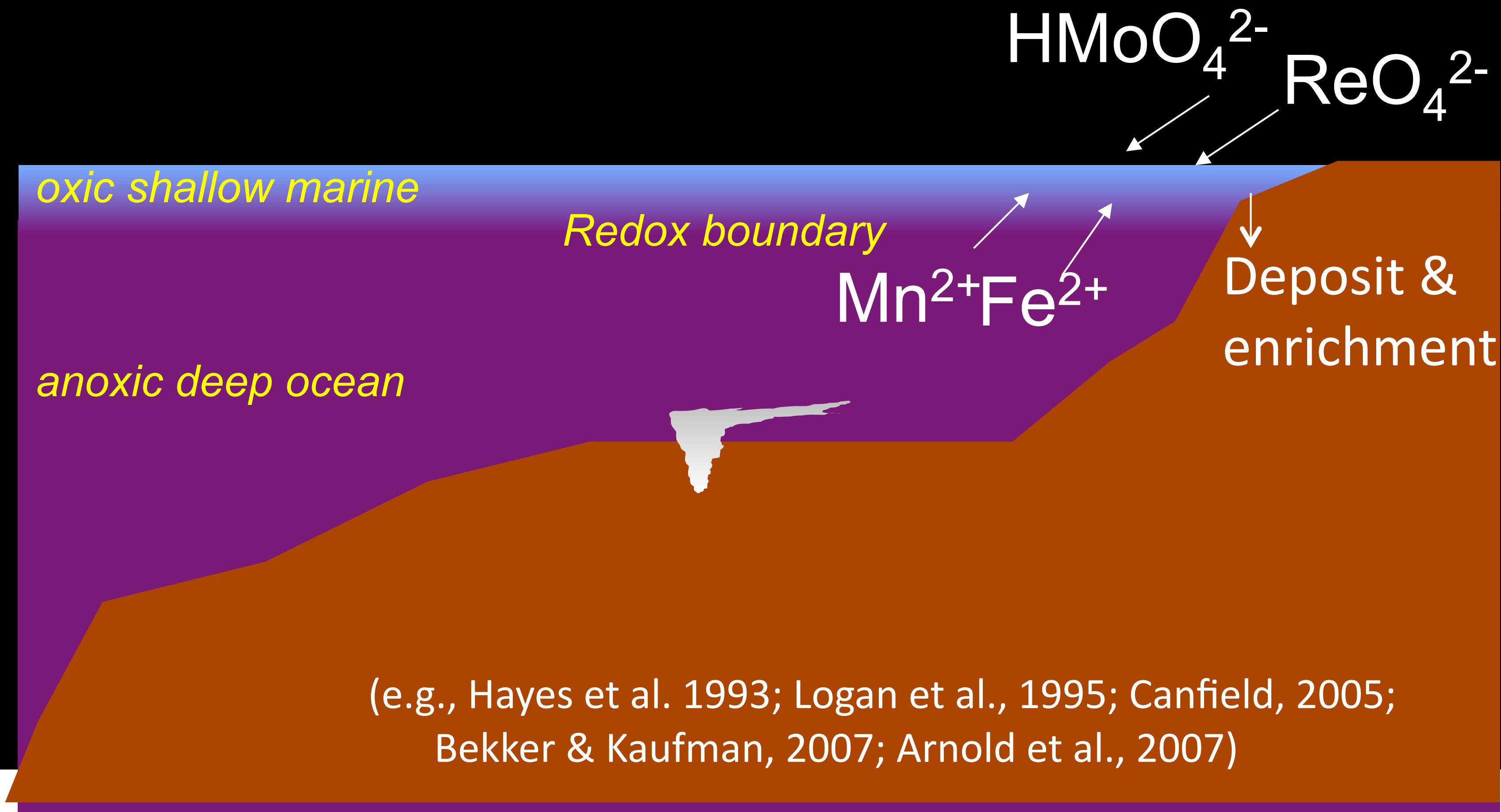


(e.g., Tribovillard et al., 2000)

Transition from reducing to oxidizing conditions

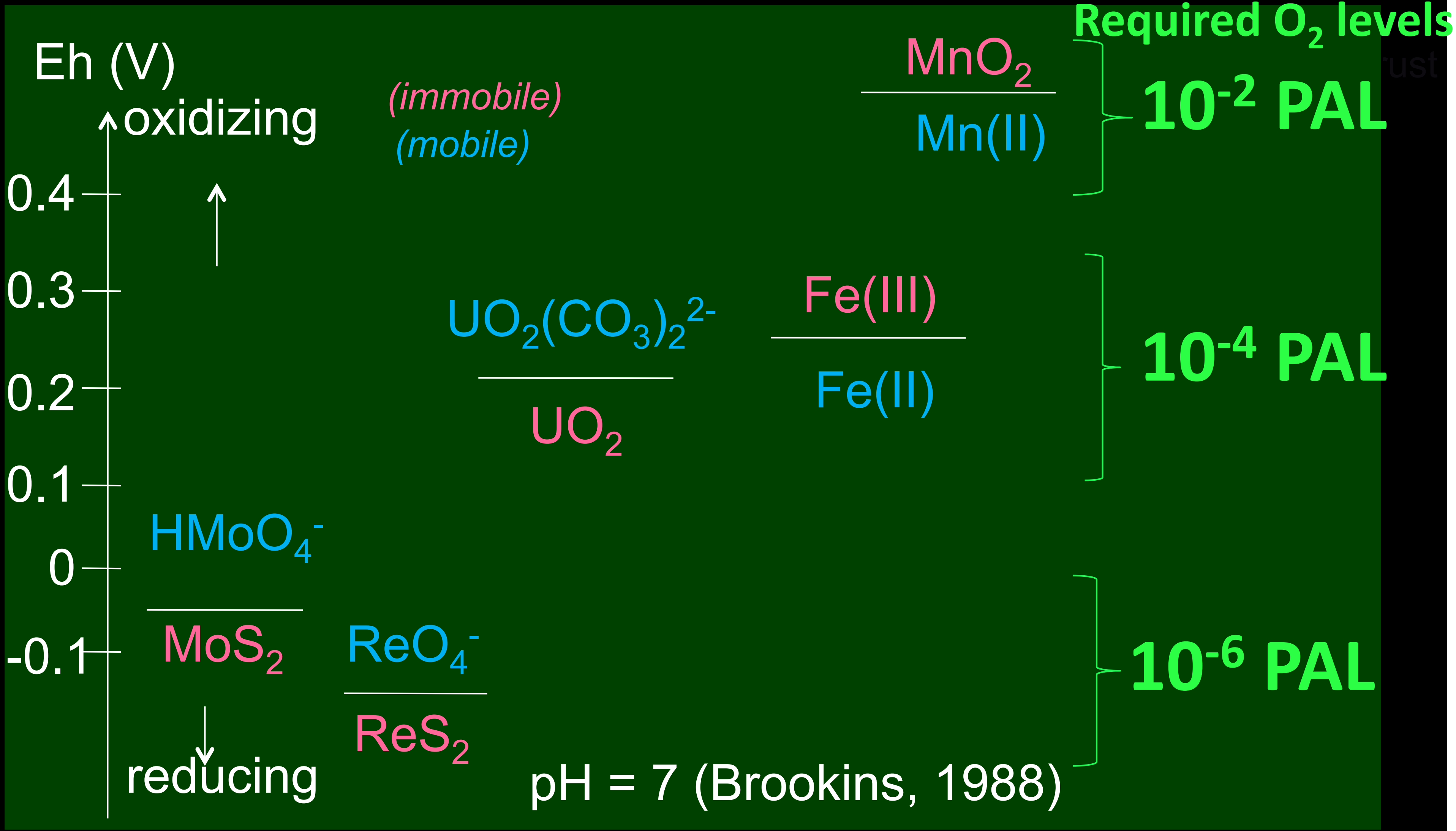
- Reduction of oxidative Mo & Re, oxidation of Fe & Mn might have occurred around the redox boundary in shallow marine

→ Enrichments of redox sensitive elements



(e.g., Hayes et al. 1993; Logan et al., 1995; Canfield, 2005; Bekker & Kaufman, 2007; Arnold et al., 2007)

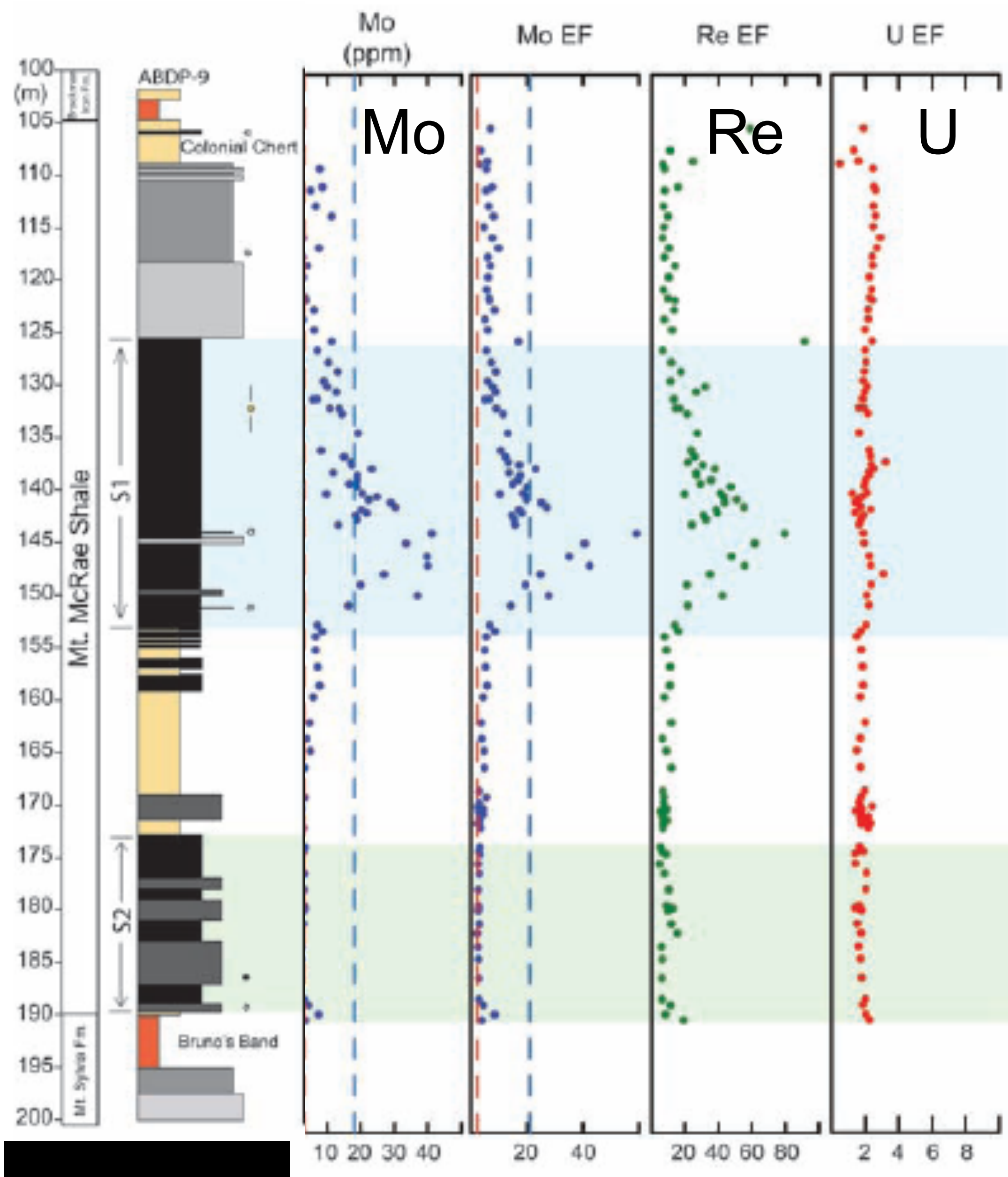
Potentials for oxidization



Comparison of enrichments and/or depletion would aid in the reconstruction of O_2 levels

A Whiff of O_2 at 2.5 Ga?

(before the Great Oxidation Event) (Anbar et al., 2007)



Marine sediments at 2.6 – 2.5 Ga: temporal, weak increase in O_2
(Anbar et al., 2007; Kaufmann et al., 2007: Kendall et al., 2010)

Enrichments of Mo & Re
→ $pO_2 > 10^{-6}$ PAL

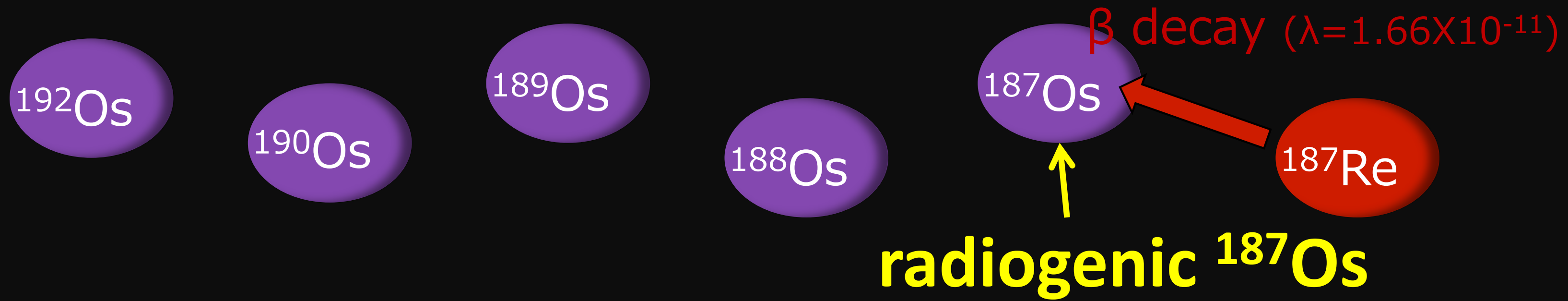
No enrichments of U & Fe
→ $pO_2 < 10^{-4}$ PAL

MIF-S → $pO_2 < 10^{-5}$ PAL

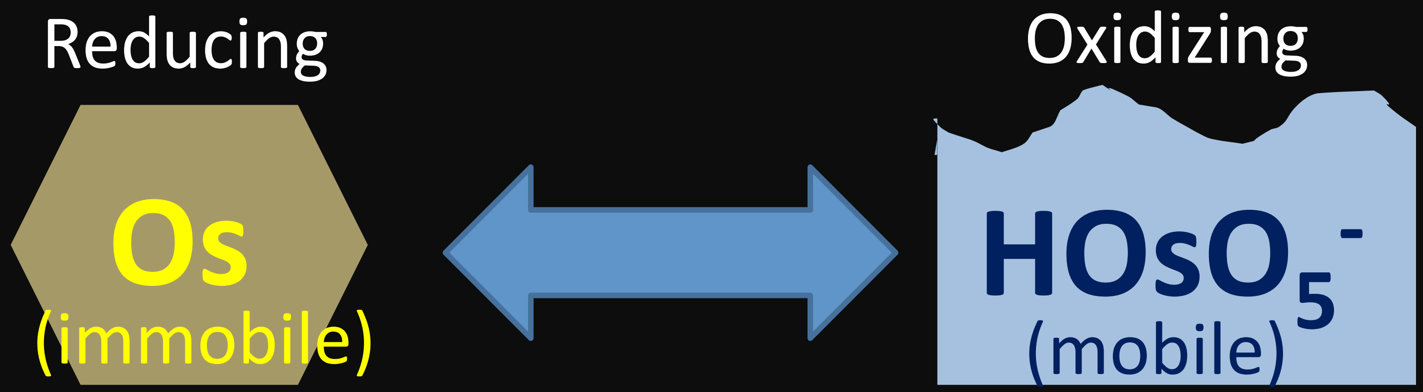
10^{-6}– 10^{-5} PAL

Osmium (Os) isotopic compositions in oceans (Sekine et al., 2011 Nature Comms.)

- **Point 1**: Continental crusts have high concentrations of radiogenic ^{187}Os decayed from ^{187}Re in continents.



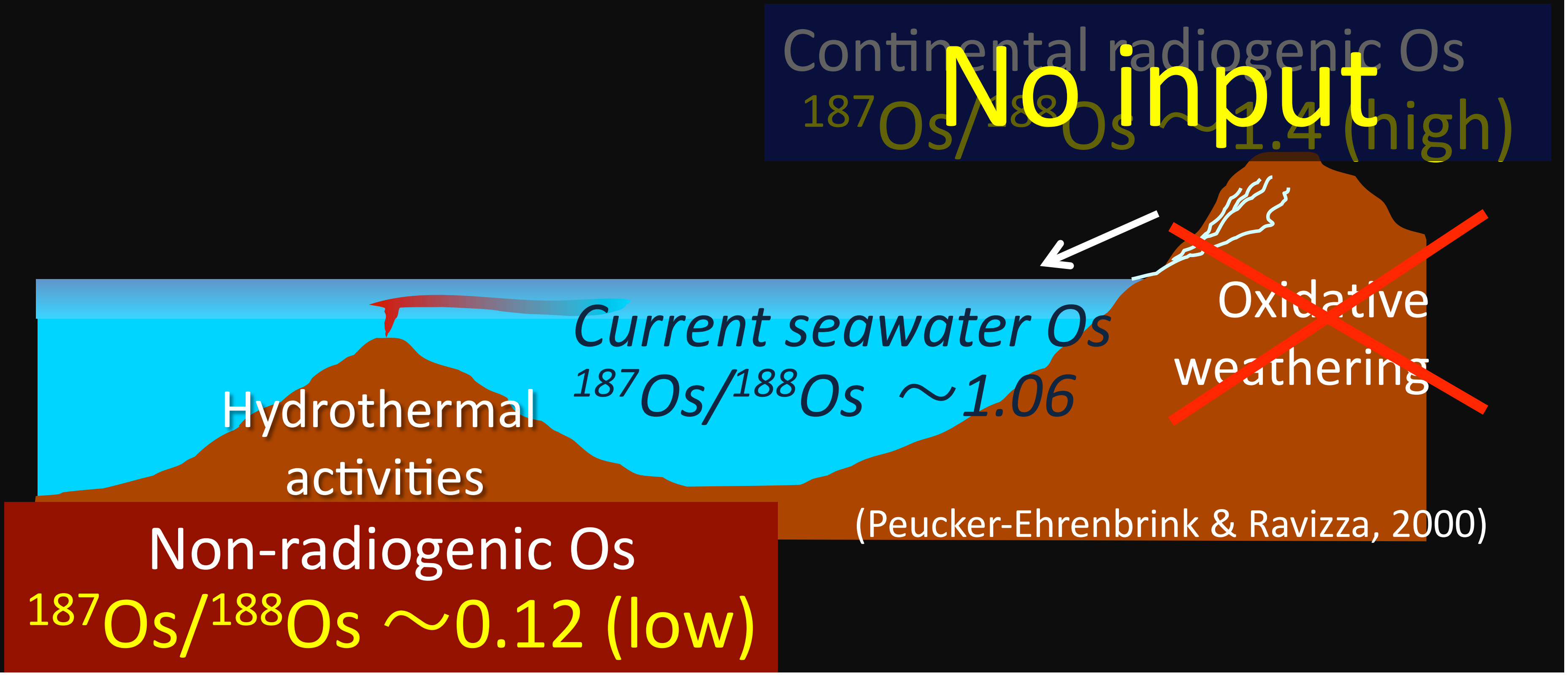
- **Point 2**: Os is a redox-sensitive element: under oxidizing conditions (> 10^{-4} PAL), mobile in water as oxidized ion



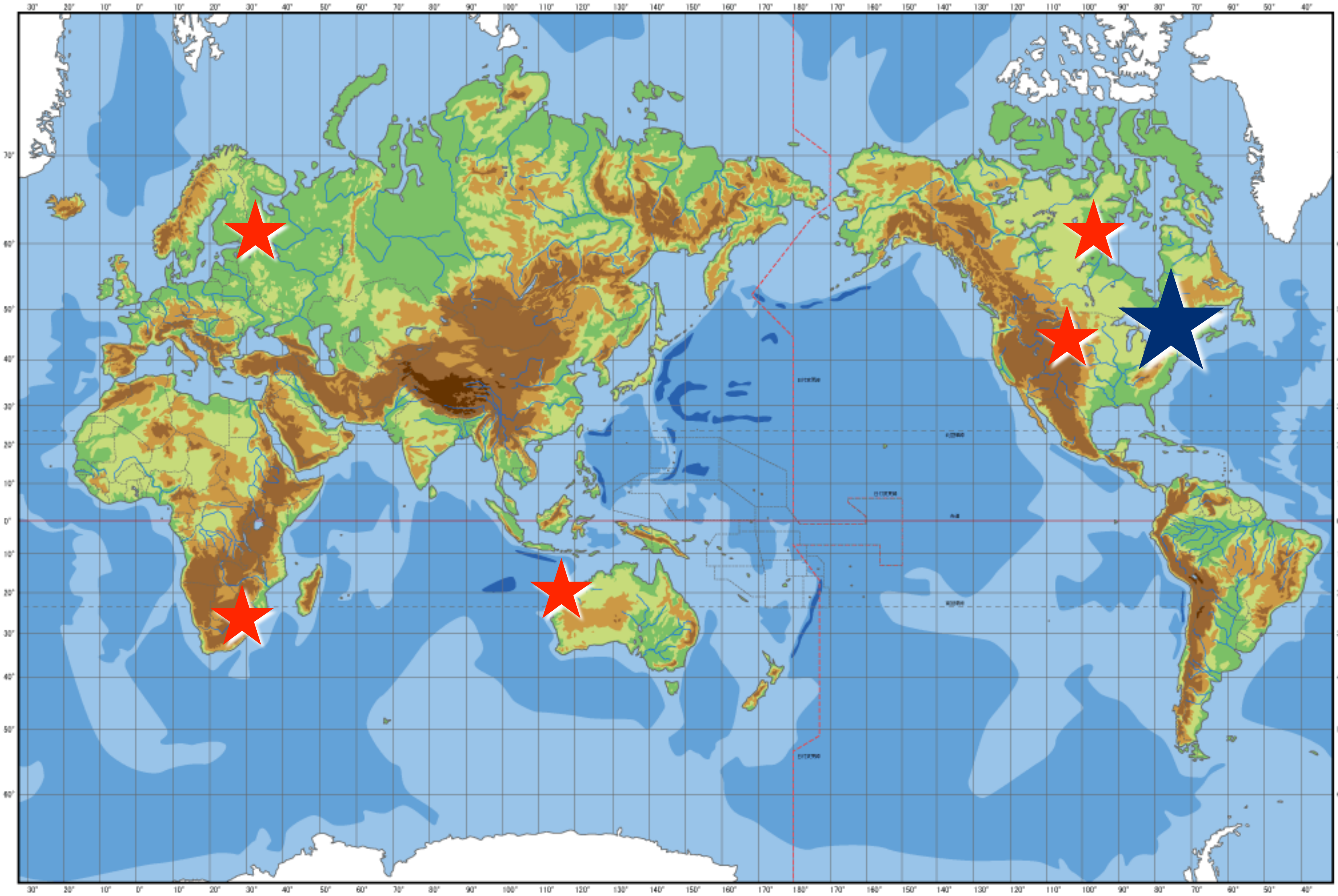
Osmium (Os) isotopic compositions in oceans (Sekine et al., 2011 Nature Comms.)

Oxidizing atmospheres ⇒ radiogenic Os delivered to ocean

Reducing atmospheres ⇒ non-radiogenic Os

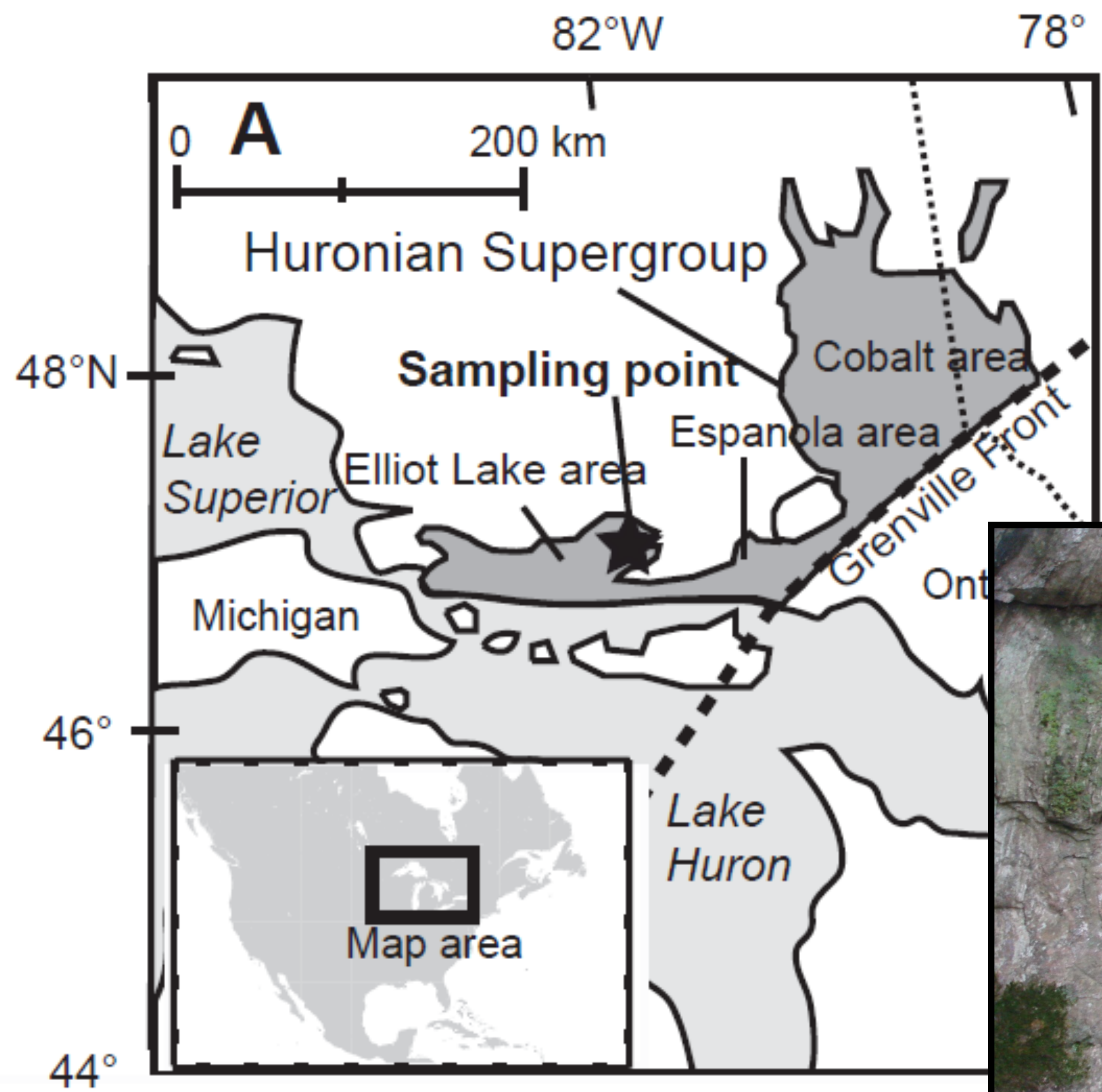


Sedimentary sequences in Paleoproterozoic
2.5 – 2.0 Ga

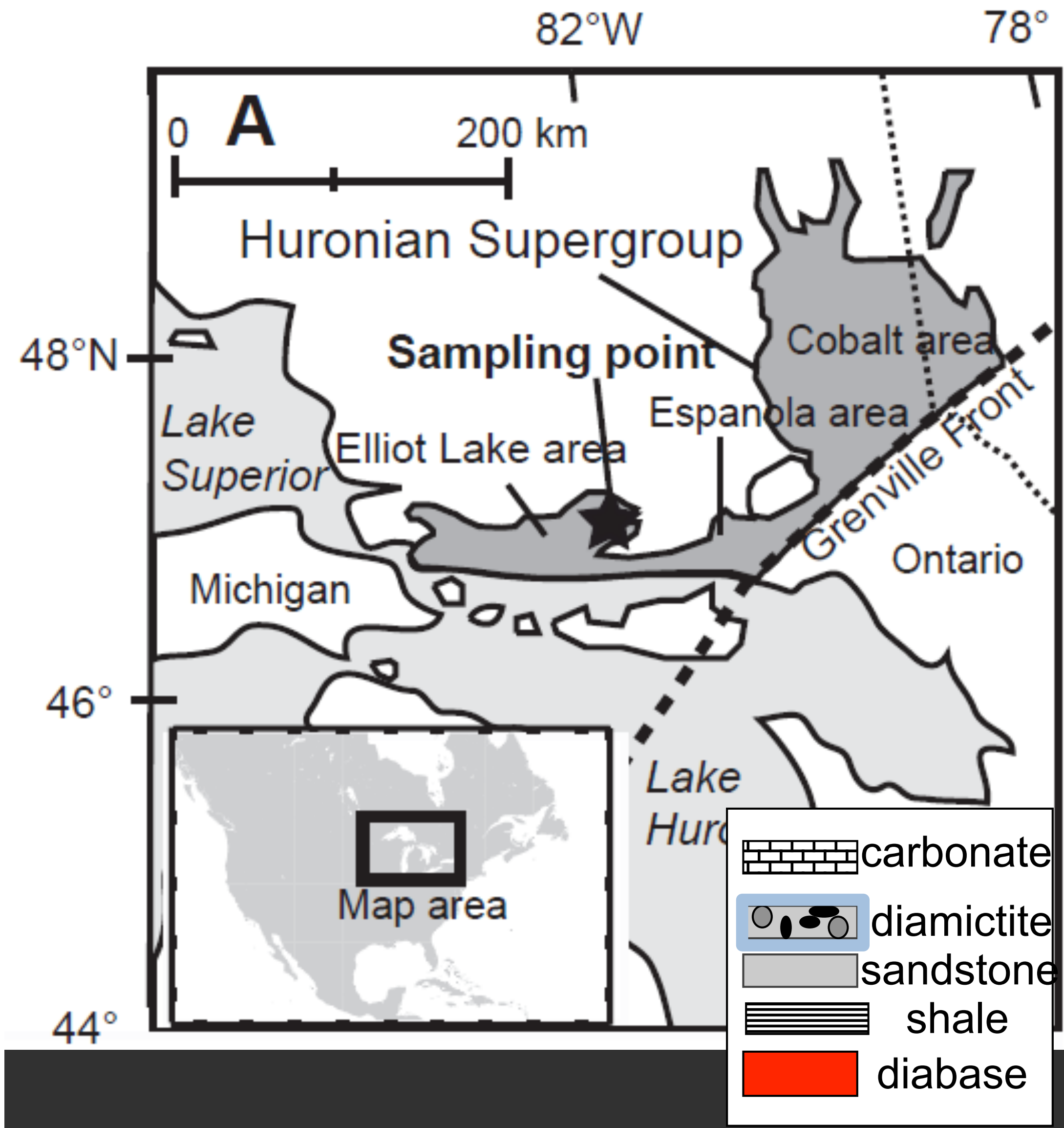


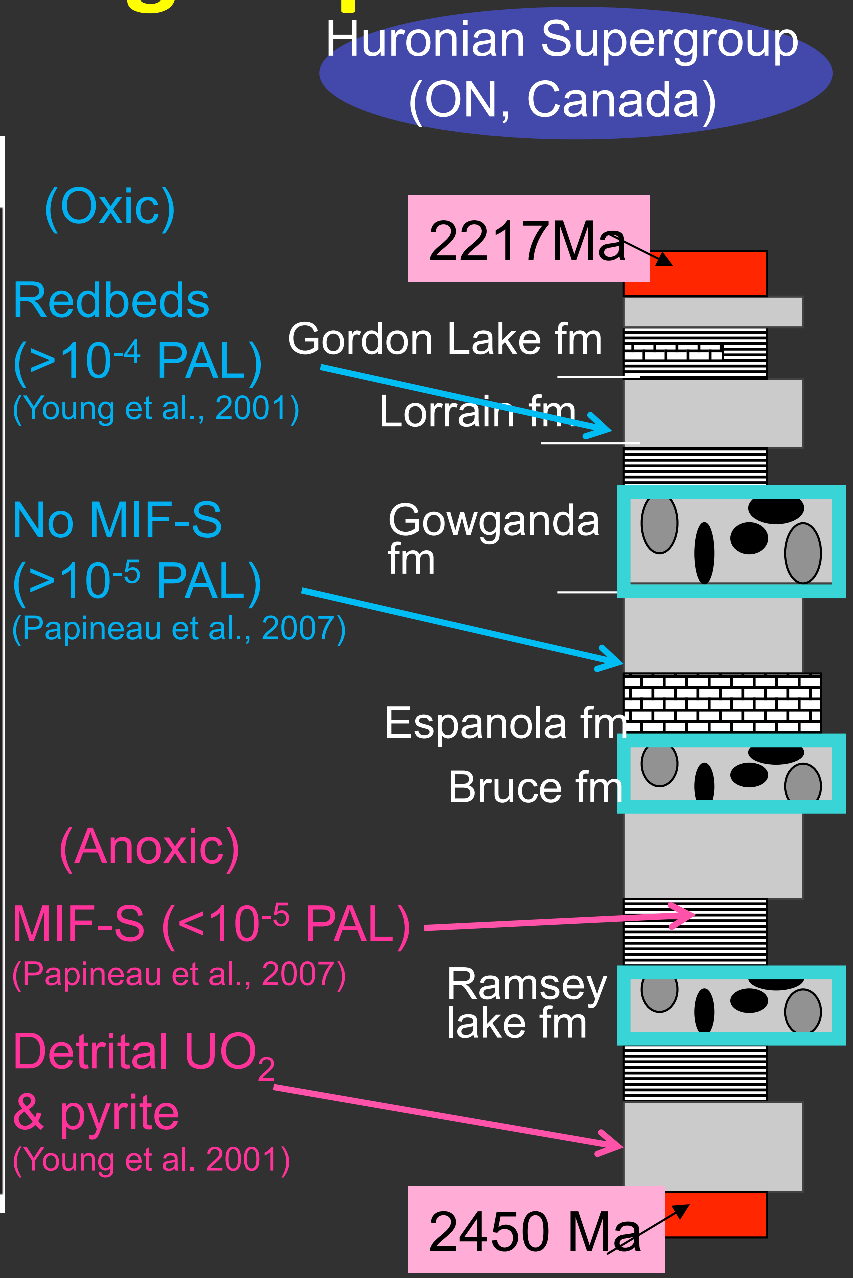
Huronian Supergroup

Most continuous sedimentary sequence of GOE.



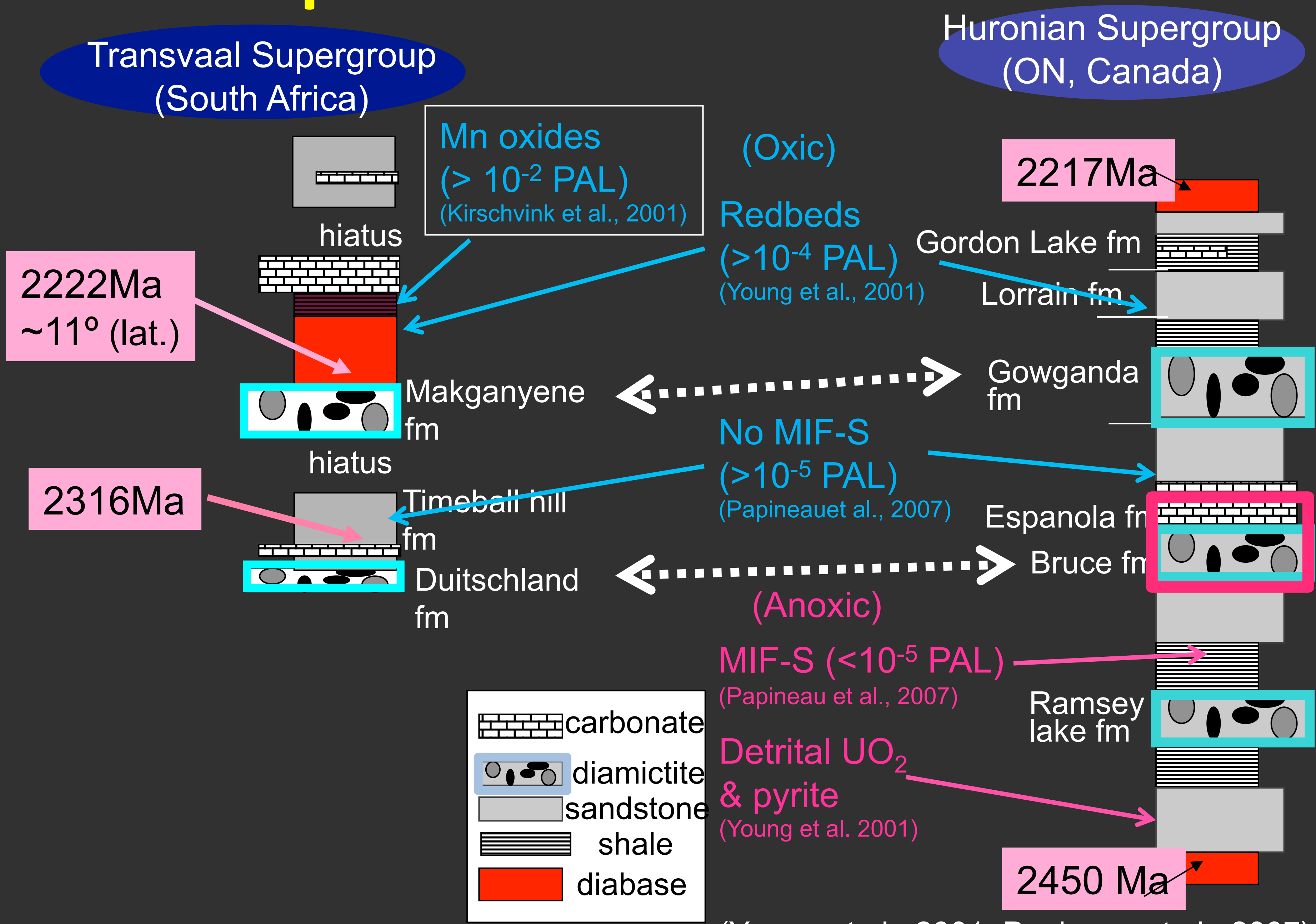
Huronian Supergroup





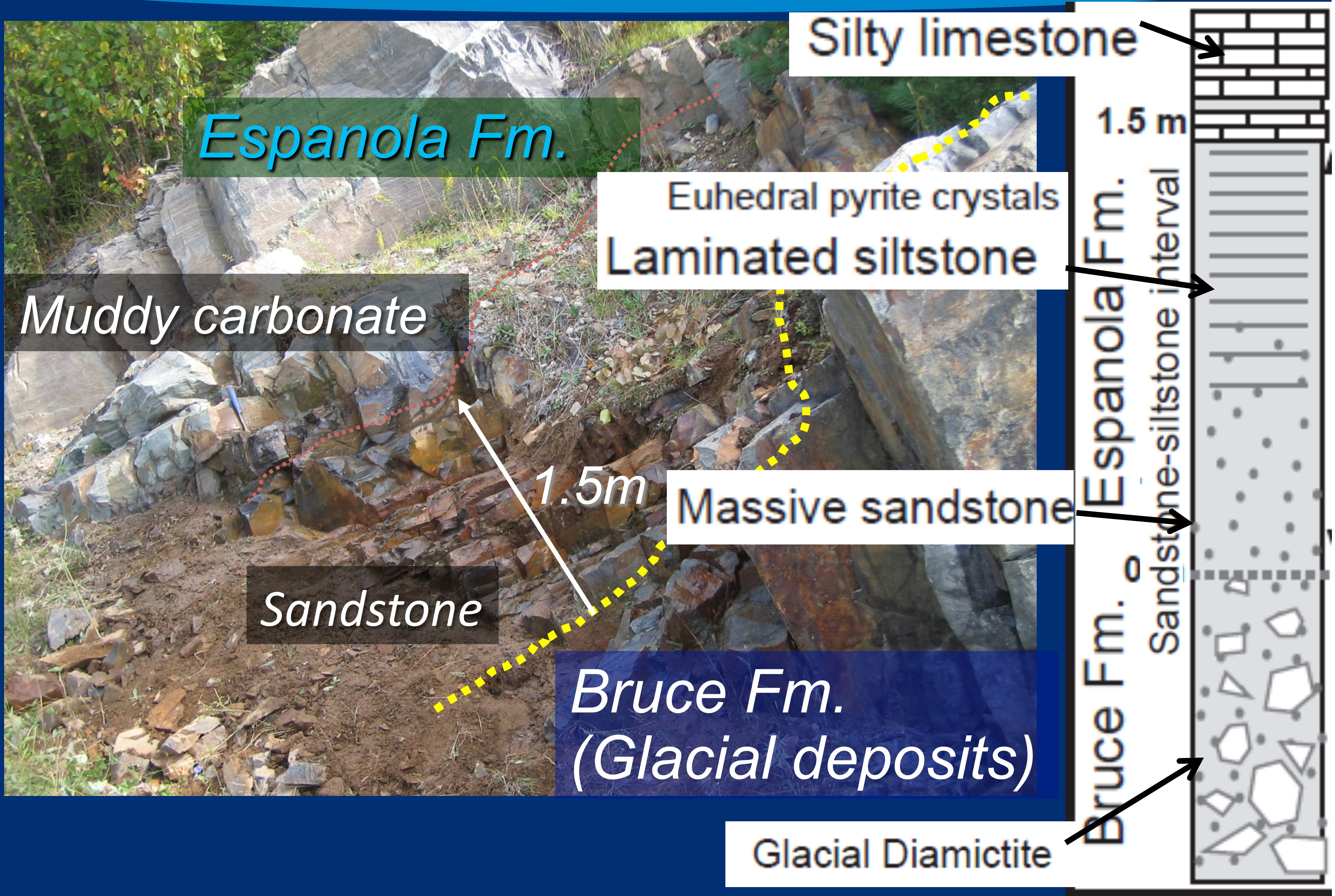
(Young et al., 2001; Papineau et al., 2007)

Comparison with South Africa



(Young et al., 2001; Papineau et al., 2007)

Boundary between Bruce & Espanola fms



Analysis

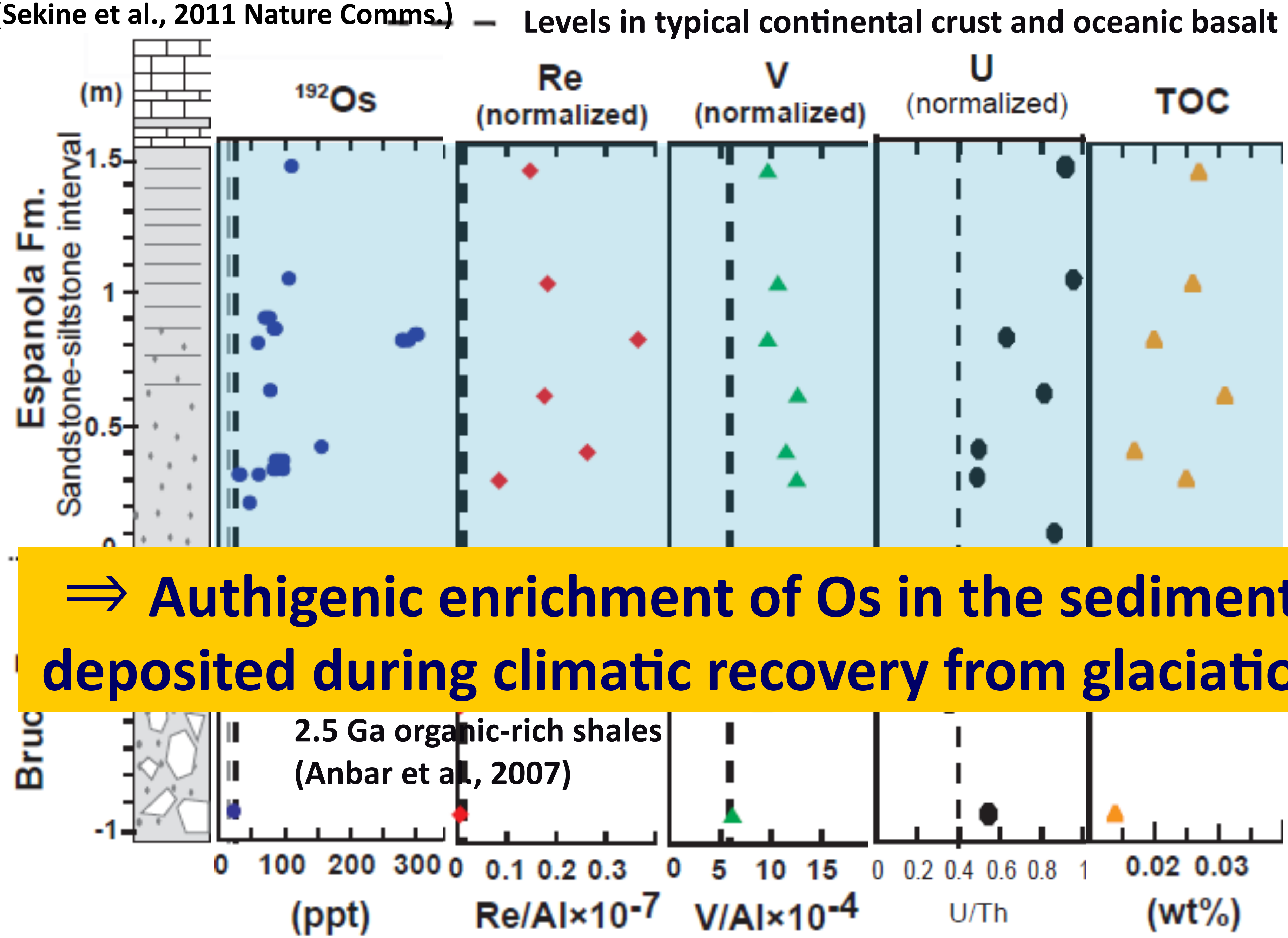
- Measurements of the concentrations and isotope compositions of both Re and Os with a TIMS (JAMSTEC)

  (e.g., Suzuki & Tatsumi, 2001; Kato et al. 2005)

(at JAMSTEC)

Abundances of Os & redox-sensitive metals

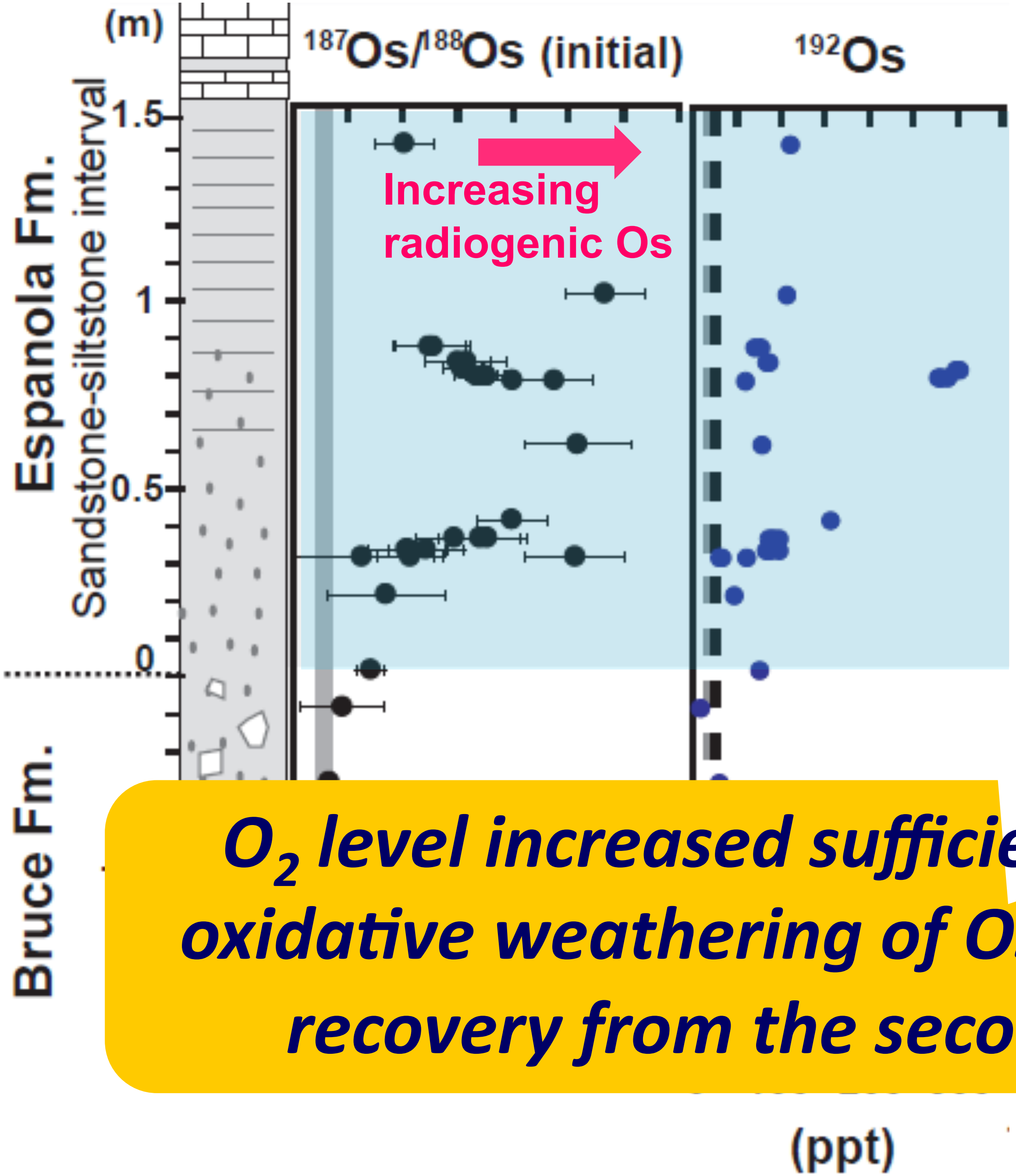
(Sekine et al., 2011 Nature Comms.)



⇒ Authigenic enrichment of Os in the sediments deposited during climatic recovery from glaciation.

Variation in initial $^{187}Os/^{188}Os$ (age =2.3±0.2 Ga)

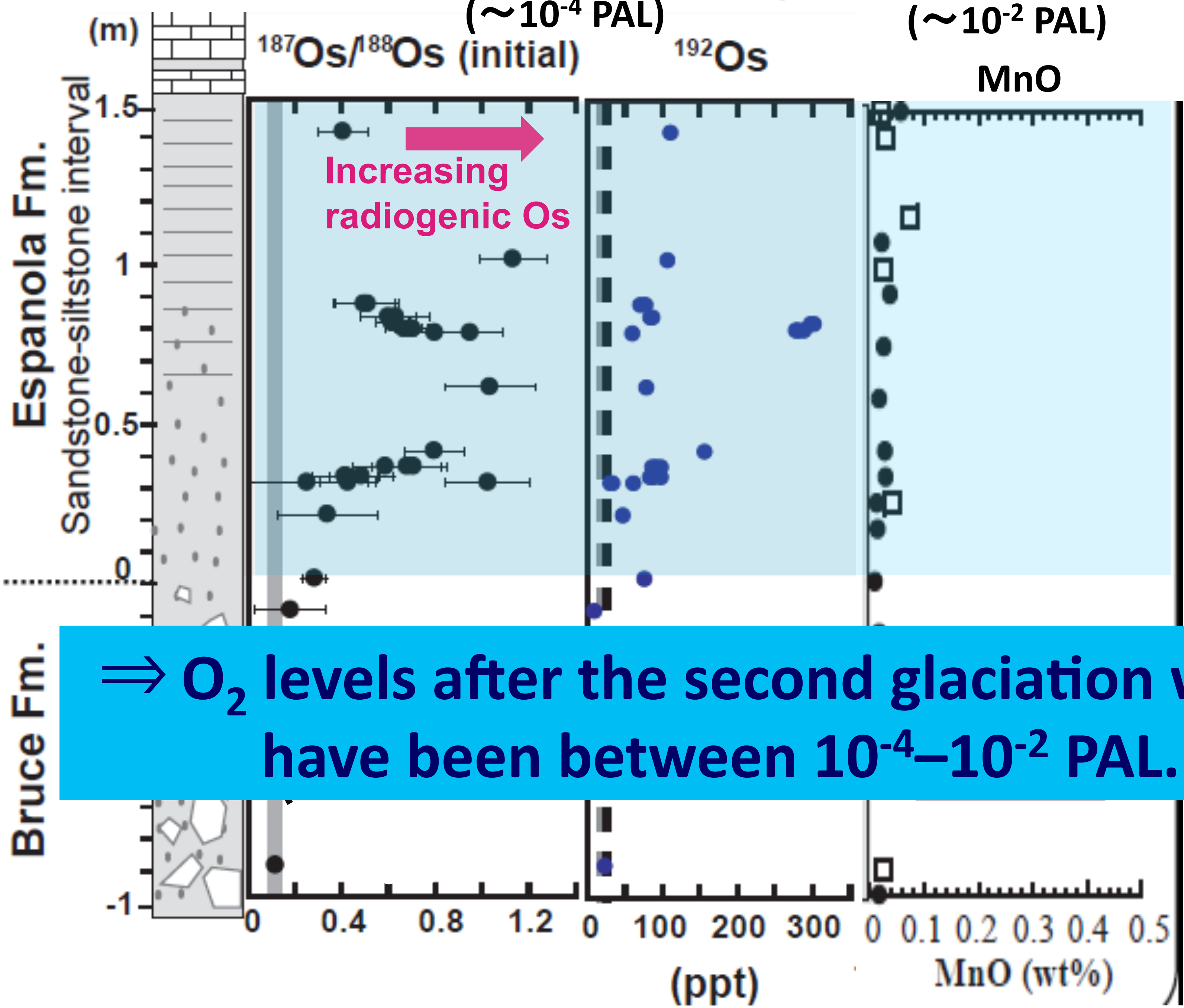
(Sekine et al., 2011 Nature Comms.)



⇒ A marked increase in the input of radiogenic Os

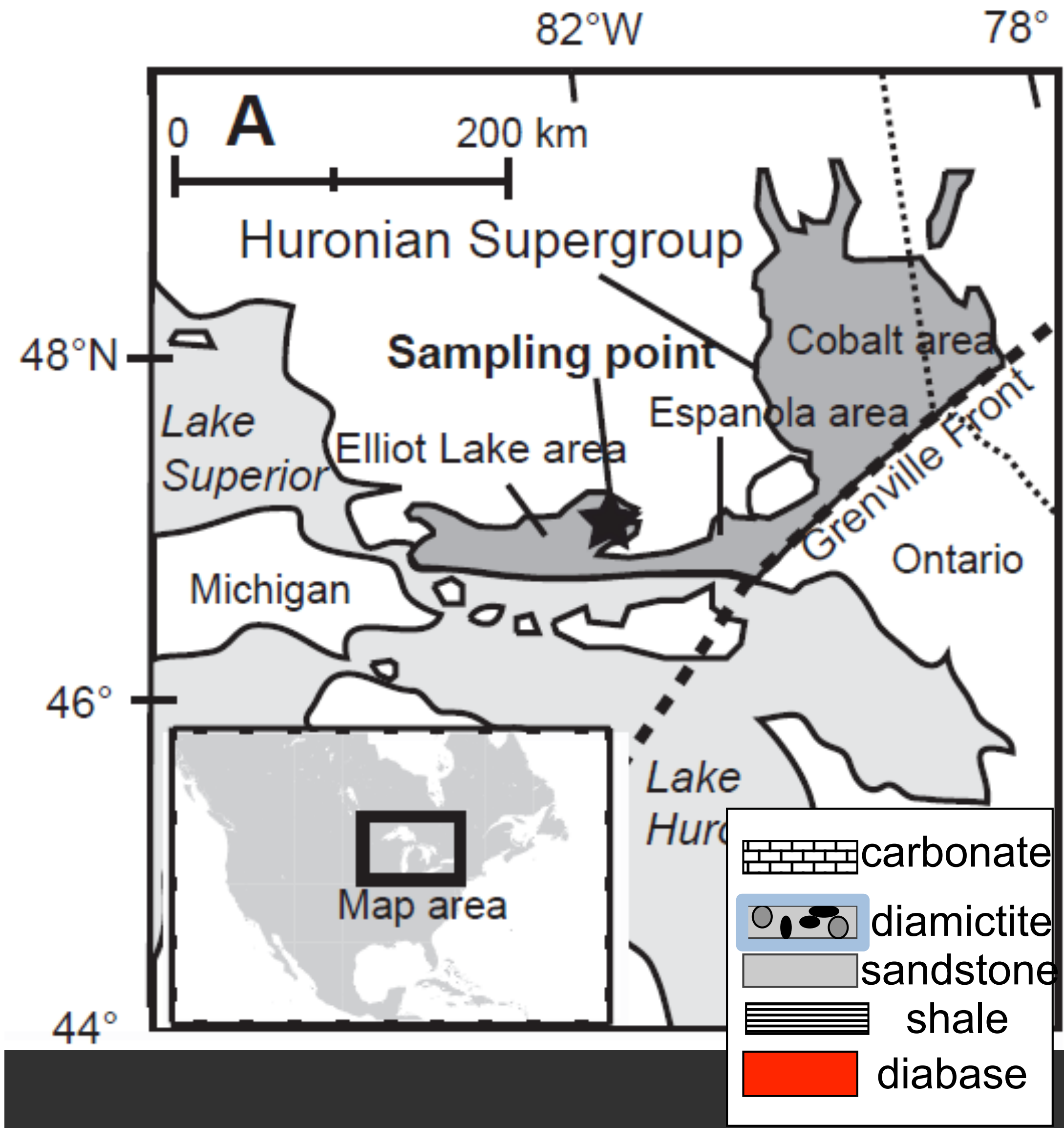
O_2 level increased sufficient to occur the oxidative weathering of Os during climatic recovery from the second glaciation

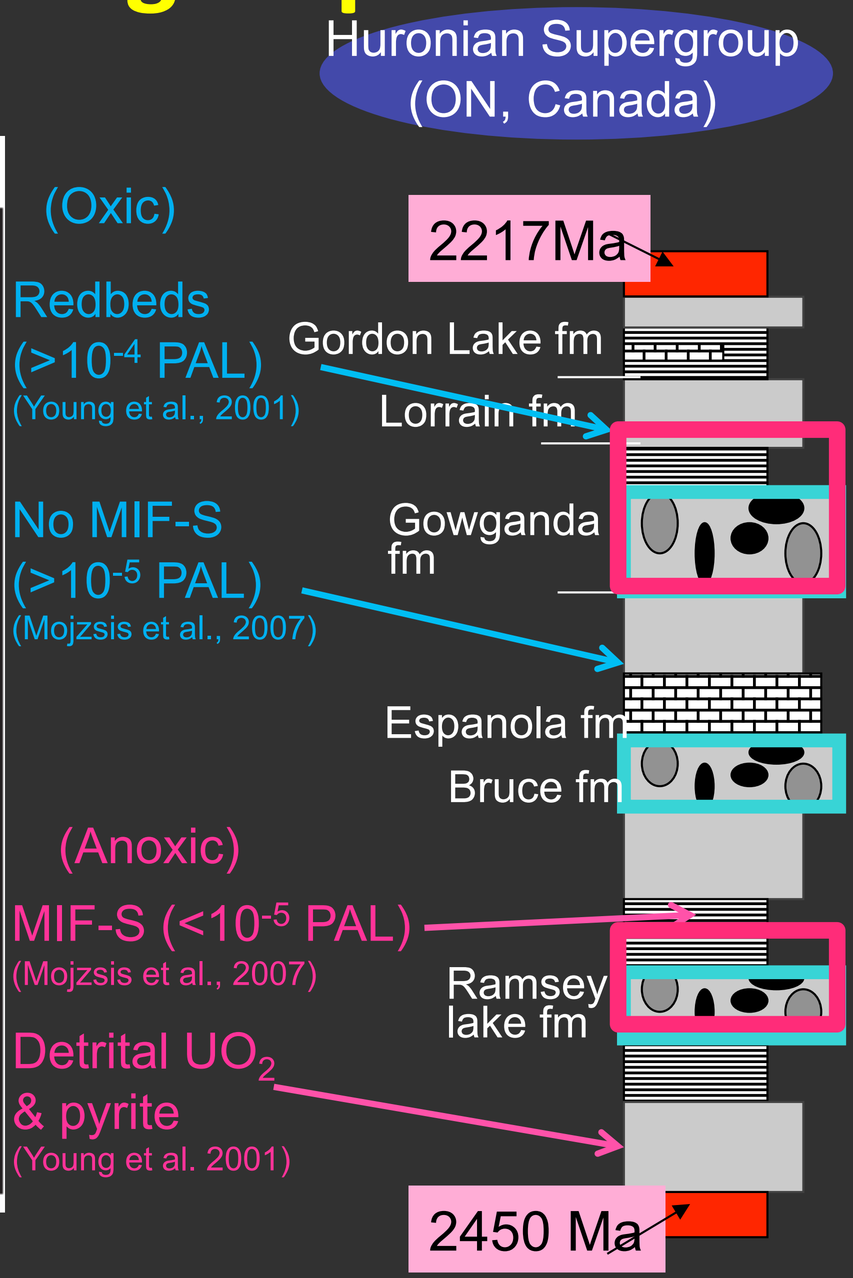
Variation in initial $^{187}Os/^{188}Os$ (age =2.3±0.2 Ga)



⇒ O_2 levels after the second glaciation would have been between 10^{-4}–10^{-2} PAL.

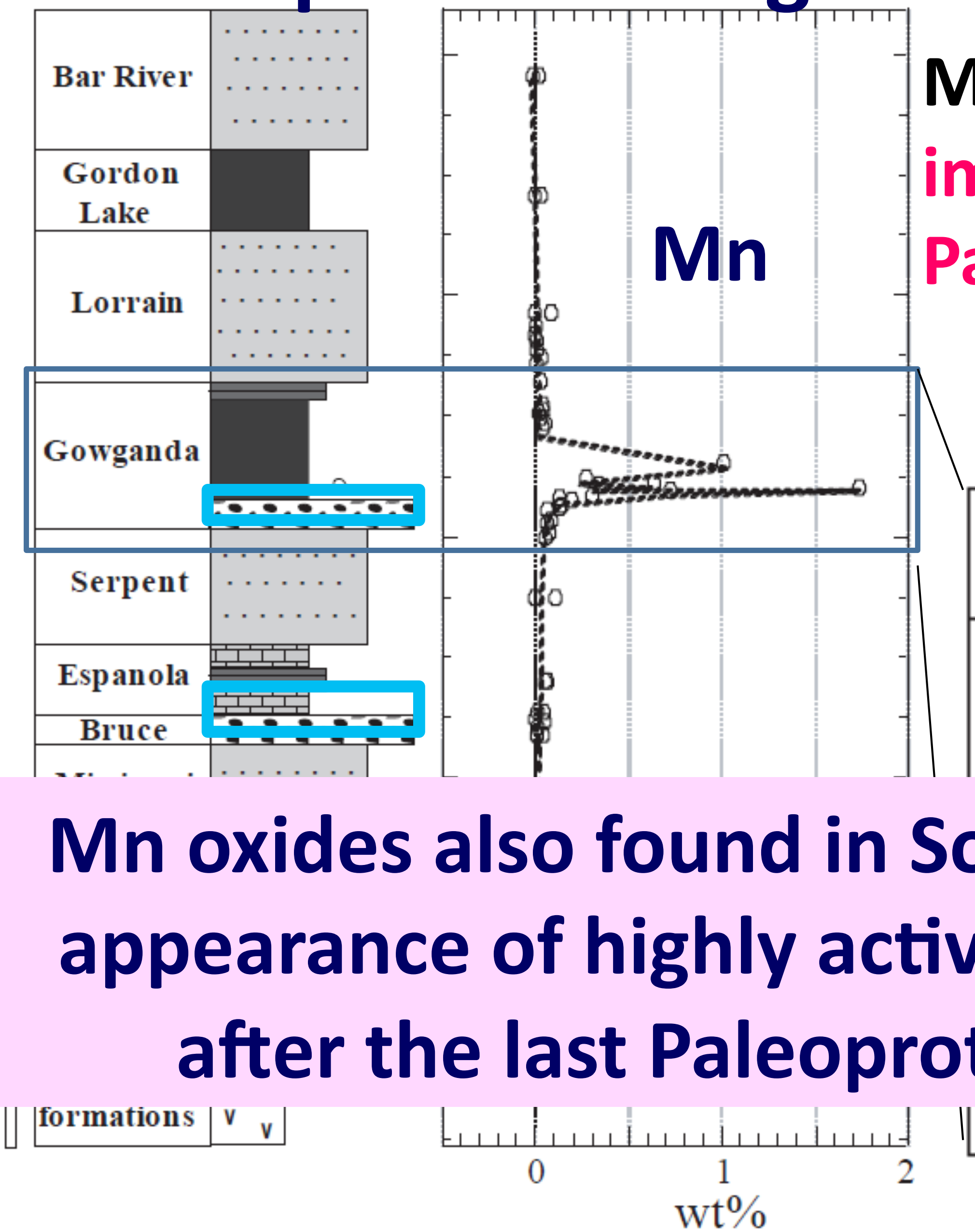
Huronian Supergroup





(Young et al., 2001; Papineau et al., 2007)

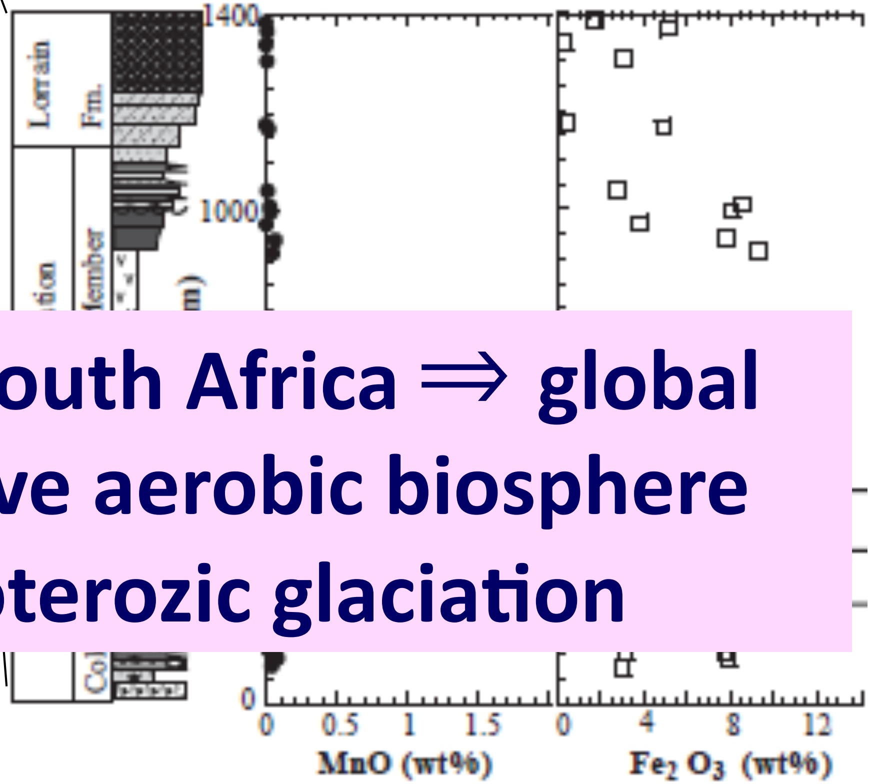
Mn concentration throughout the Paleoproterozoic glaciations (Sekine et al., 2011, EPSL)



Mn enrichments:

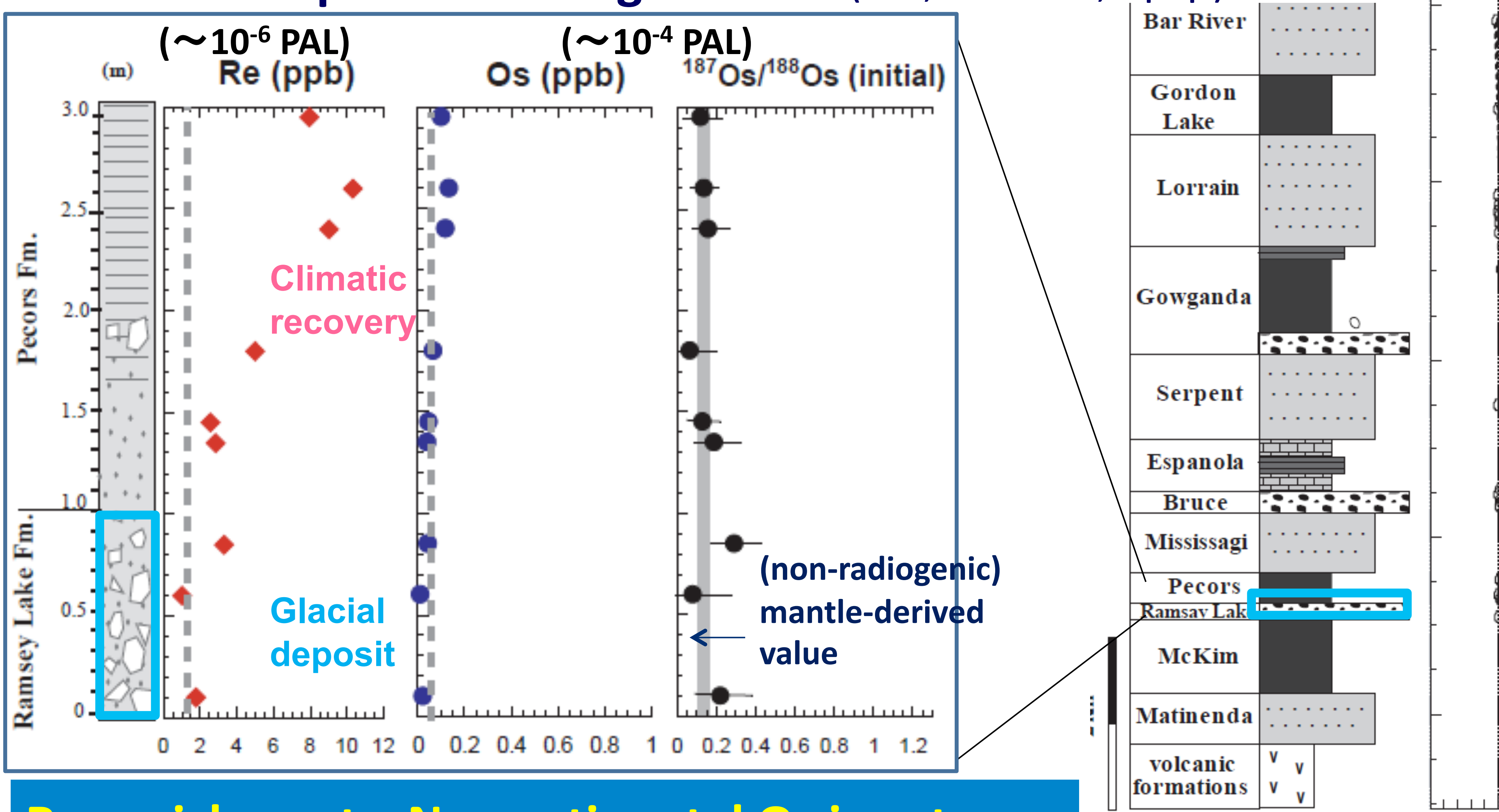
immediately after the last Paleoproterozoic glaciation

$pO_2 > 10^{-2}$ PAL



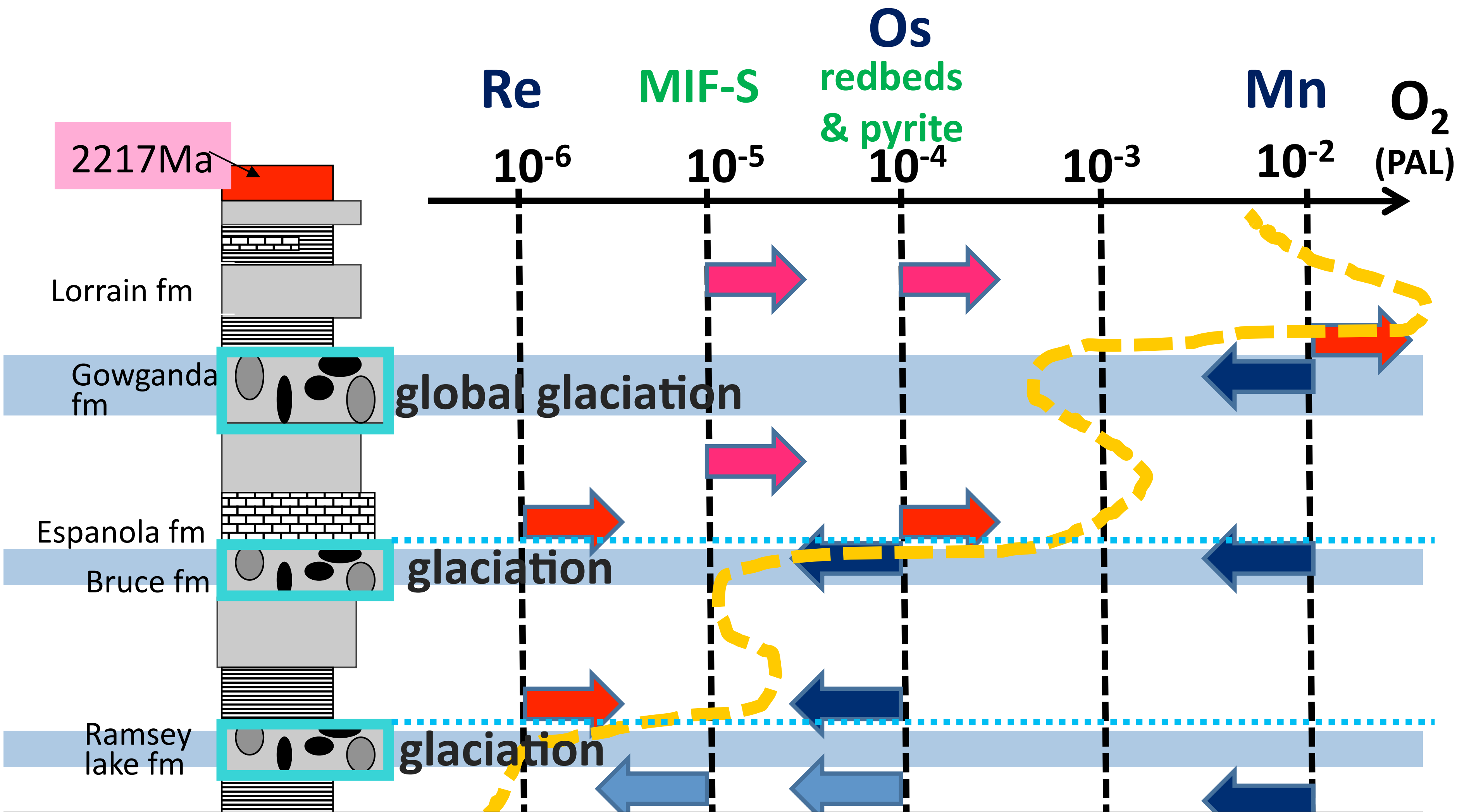
Mn oxides also found in South Africa ⇒ global appearance of highly active aerobic biosphere after the last Paleoproterozic glaciation

Variations in Os & Re in the aftermath of the first Paleoproterozoic glaciation (Goto, Sekine et al., in prep.)



Re enrichments, No continental Os inputs ⇒ pO_2 ~ 10^{-6}–10^{-4} PAL

Evolution of O_2 levels during the GOE



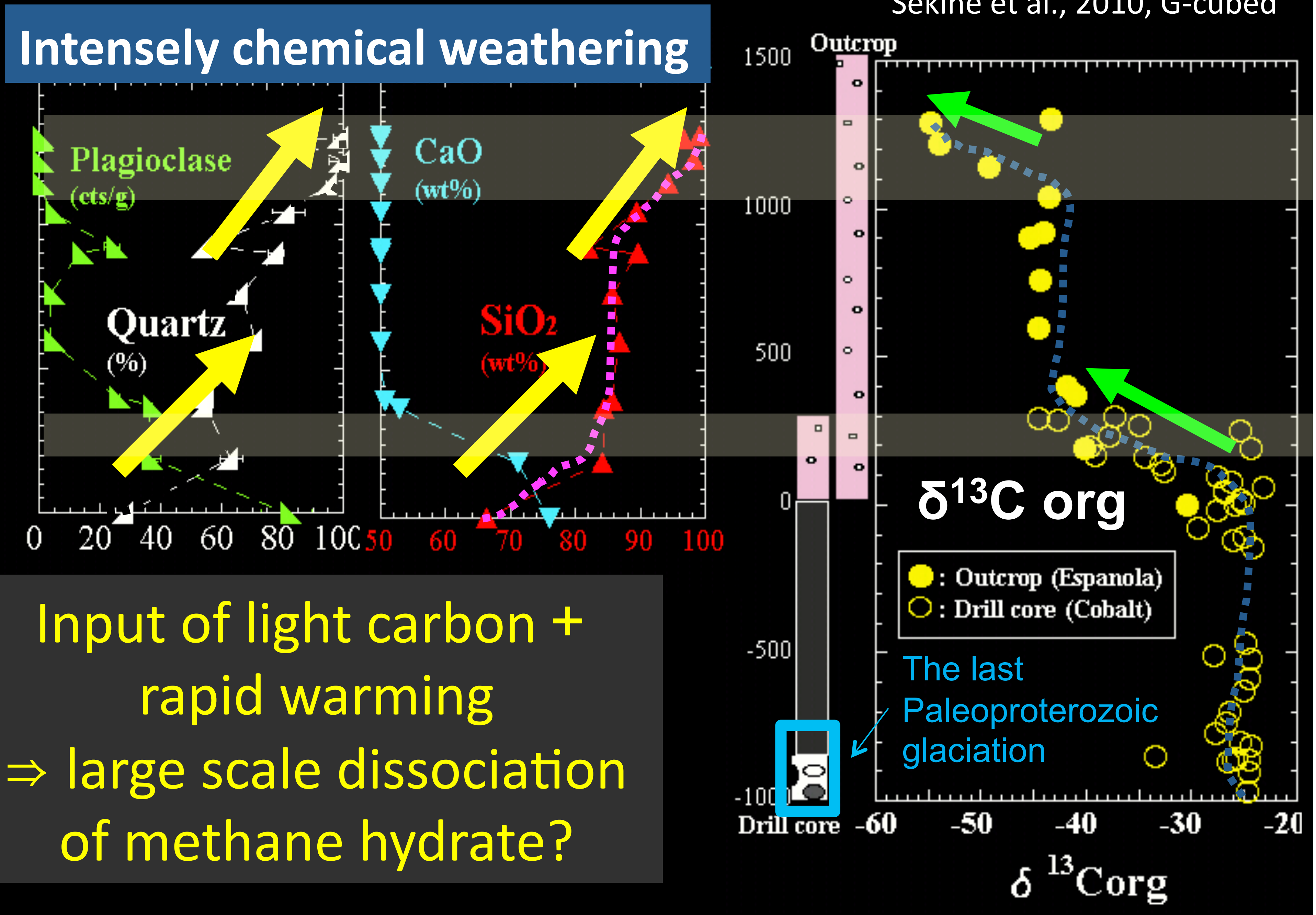
Step-like increases in O_2 in response to glaciations

→ ***Why did climatic recovery accelerate oxygenation?***

(Young et al., 2001; Papineau et al., 2007; Sekine et al., 2010; 2011a b; Goto et al., in prep)

Evidence for a hot & humid condition

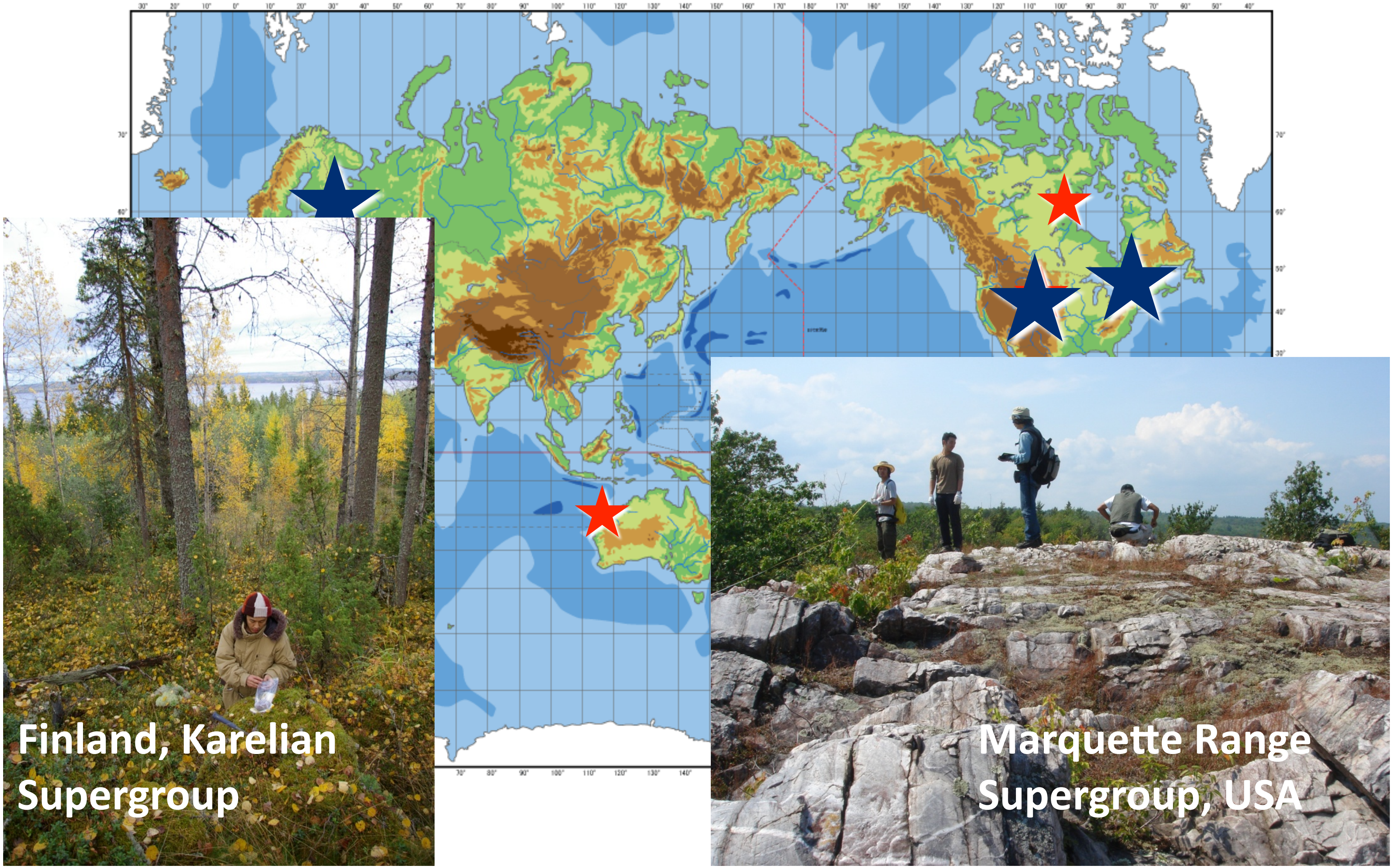
Sekine et al., 2010, G-cubed



Input of light carbon + rapid warming

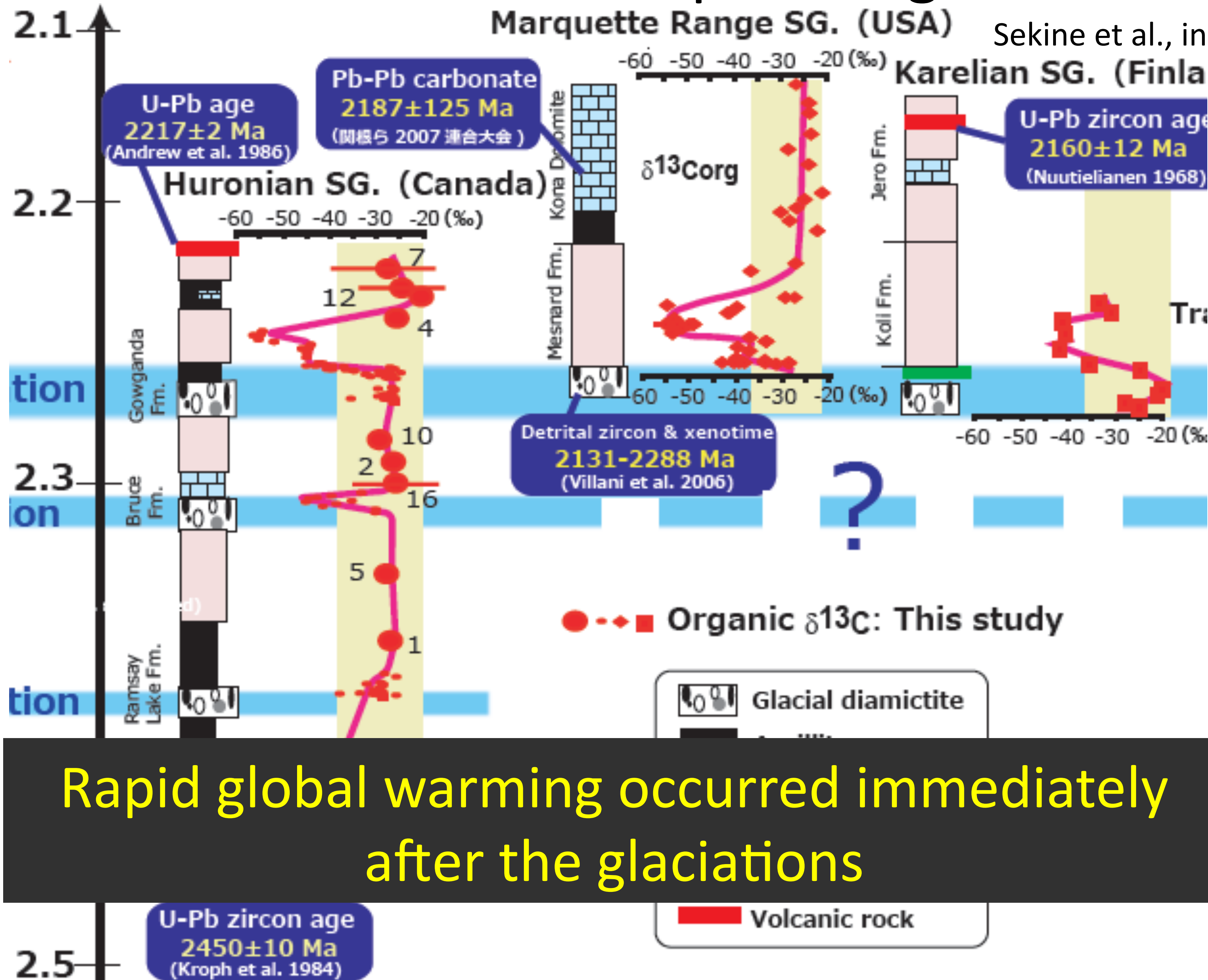
⇒ large scale dissociation of methane hydrate?

Sedimentary sequences in Paleoproterozoic 2.5 – 2.0 Ga



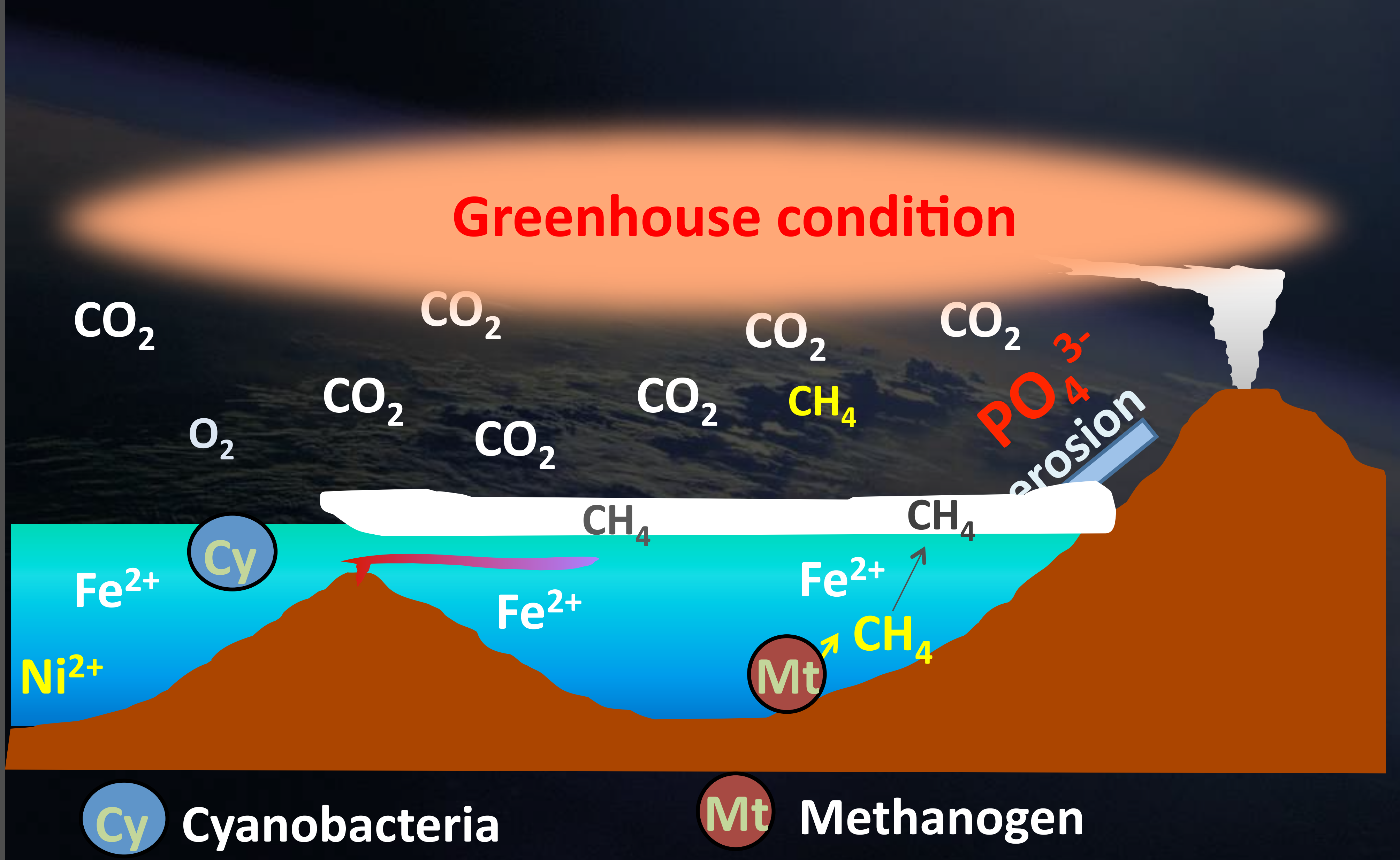
Variations of carbon isotope in organic matter

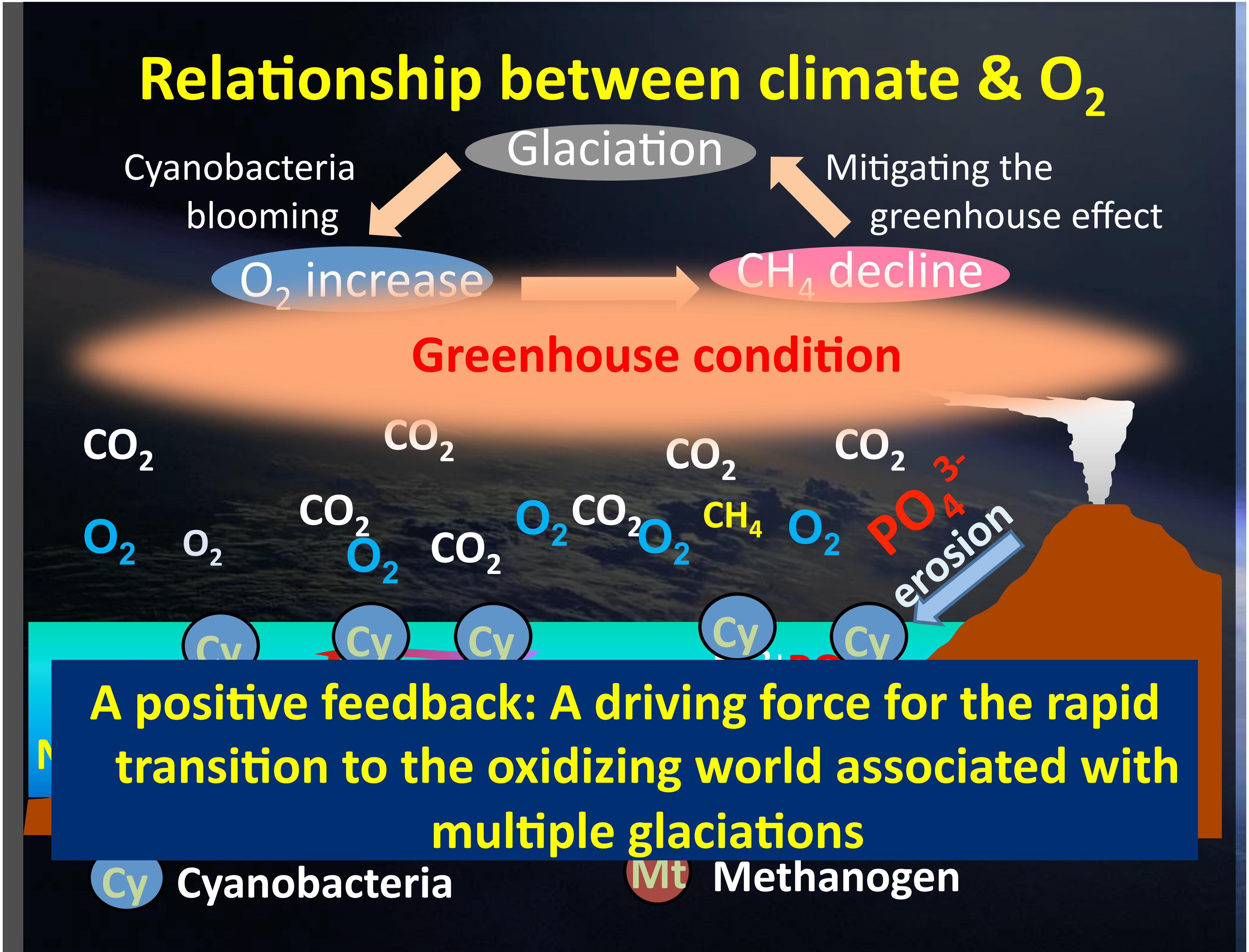
Sekine et al., in prep.



Rapid global warming occurred immediately after the glaciations

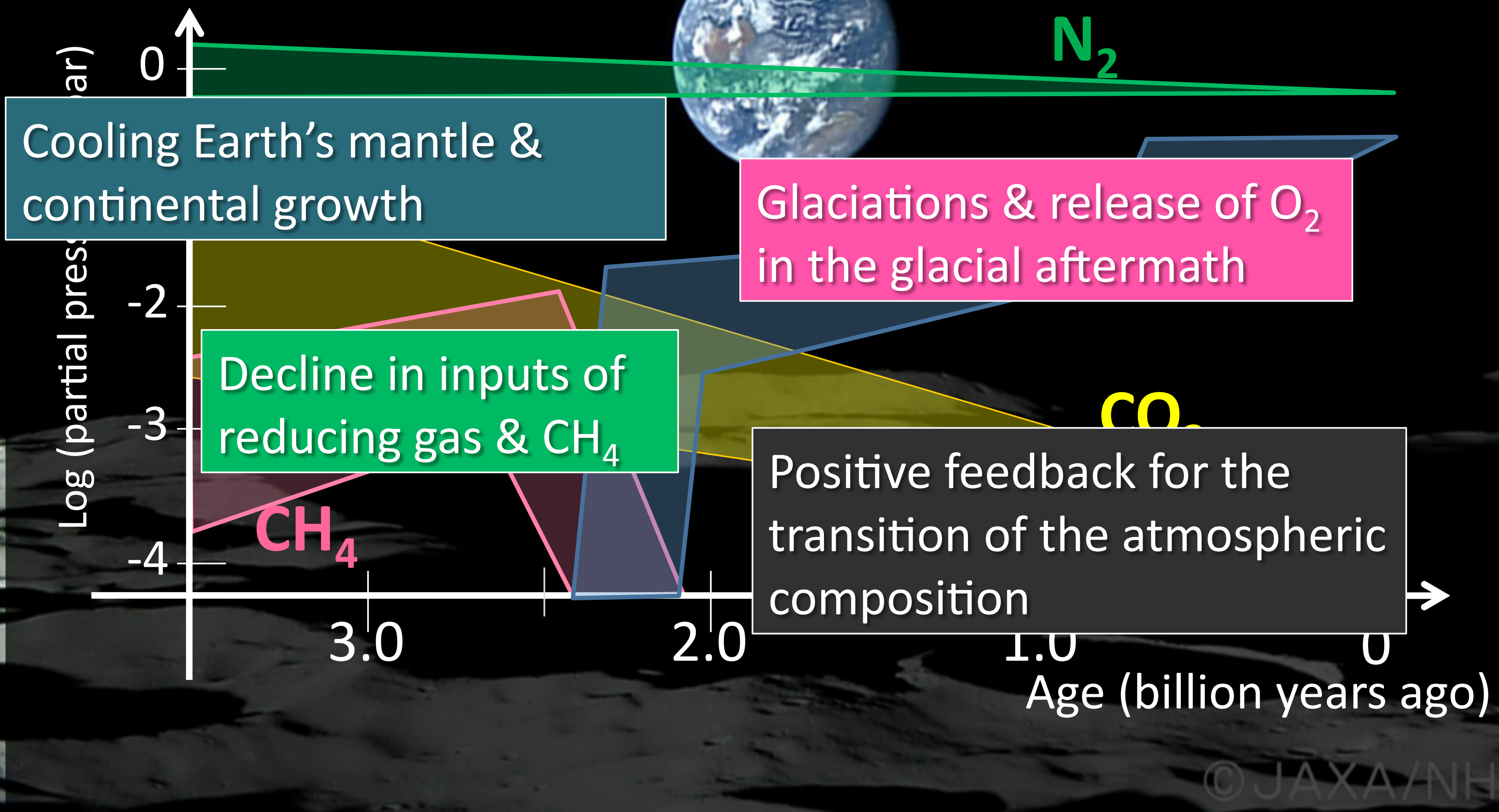
Relationship between climate & O_2




Relationship between climate & O_2
Glaciation
Cyanobacteria blooming
Mitigating the greenhouse effect
O_2 increase
CH_4 decline
Greenhouse condition
CO_2
CO_2
CO_2
CO_2
CO_2
CO_2
CO_2
O_2
O_2
O_2
O_2
O_2
O_2
CH_4
PO_4^{3-}
erosion
Cy
A positive feedback: A driving force for the rapid transition to the oxidizing world associated with multiple glaciations
Cy Cyanobacteria
Mt Methanogen

Summary

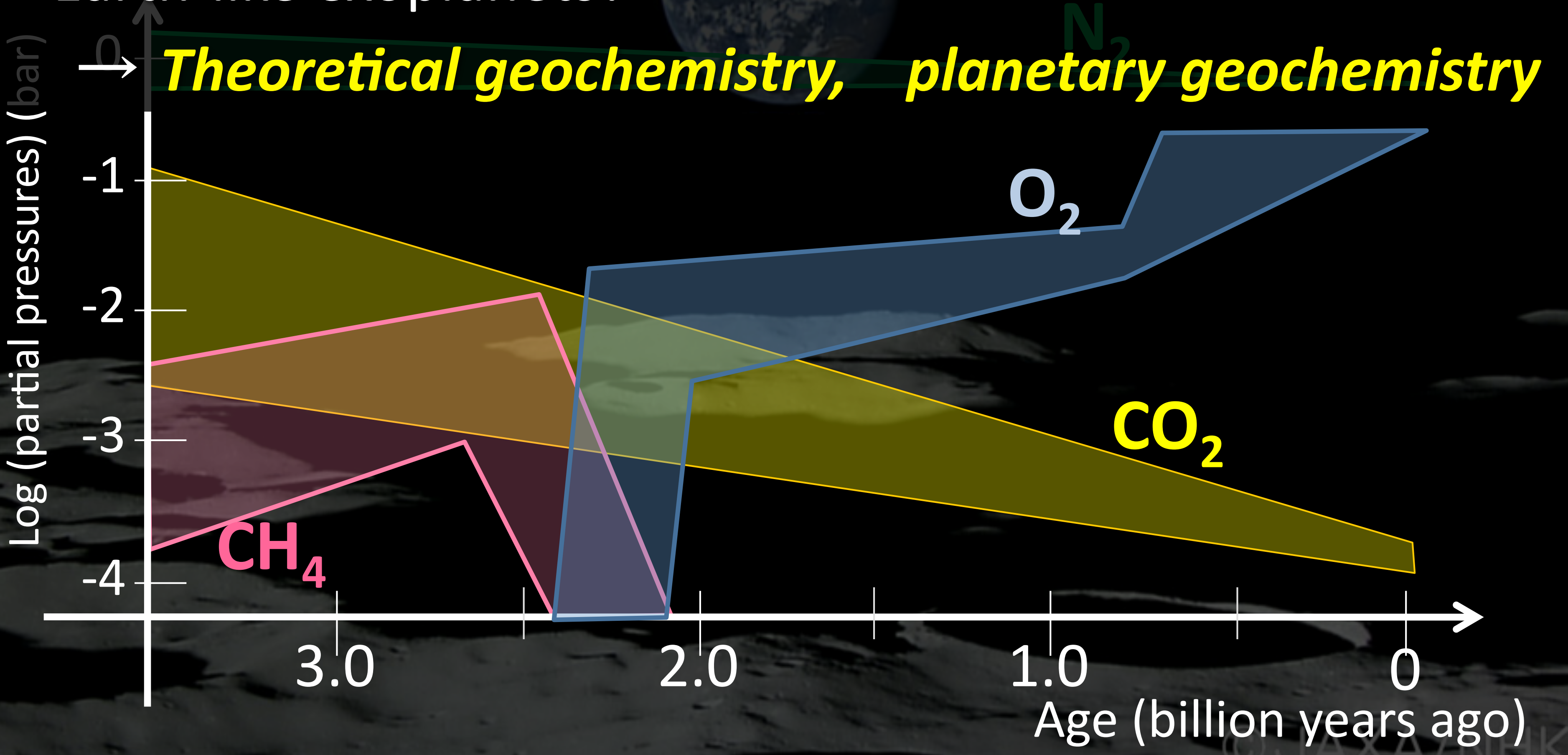
- In Earth's history, the evolutions of the atmosphere, ocean, and climate have been closely related with that of life.



Remaining questions

- What determines O_2 levels of the steady states?
- How can we generalize the evolution of Earth to apply to Earth-like exoplanets?

→ ***Theoretical geochemistry, planetary geochemistry***



What determines the steady states?

Redox (reducing-oxidizing) states of atmosphere:

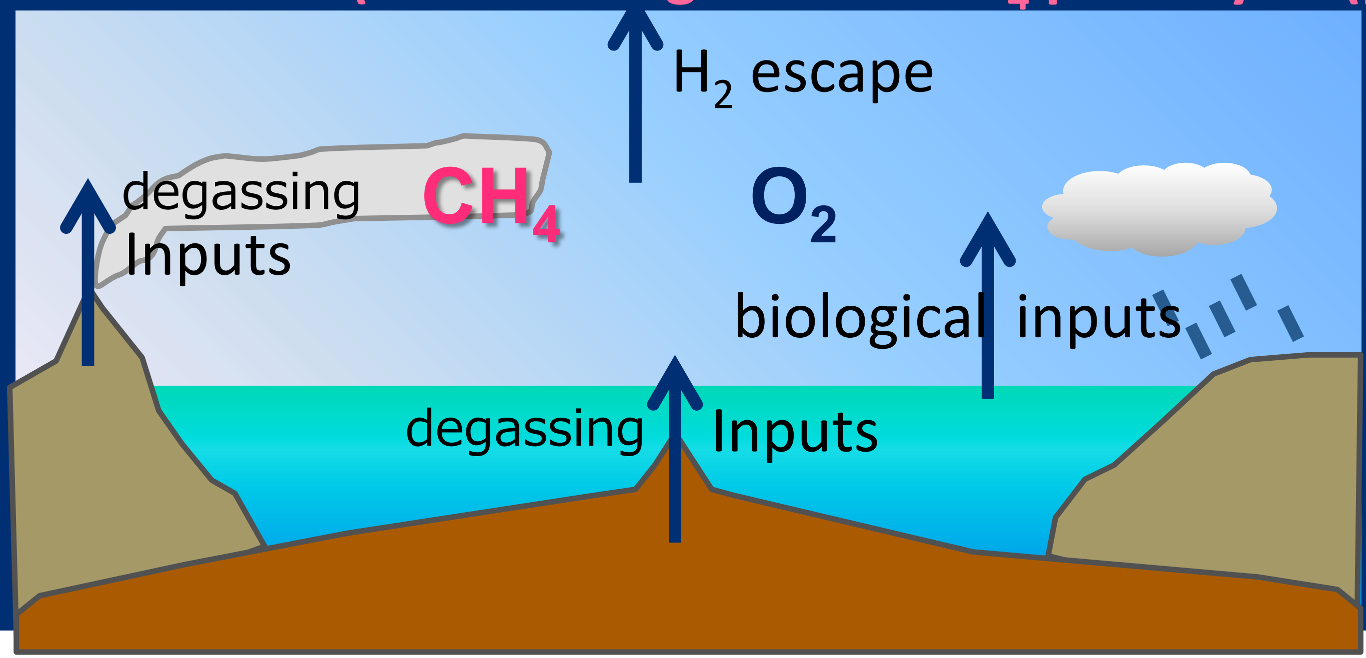
- flux of oxidants (O_2, SO_2, etc)
- flux of reductants (CH_4, H_2S, H_2, Fe^{2+}, etc)

Simplified C-H-O system: steady state (Goldblatt et al., 2006)

flux of oxidants (= photosynthesis + H_2 escape – weathering (pO_2))

||

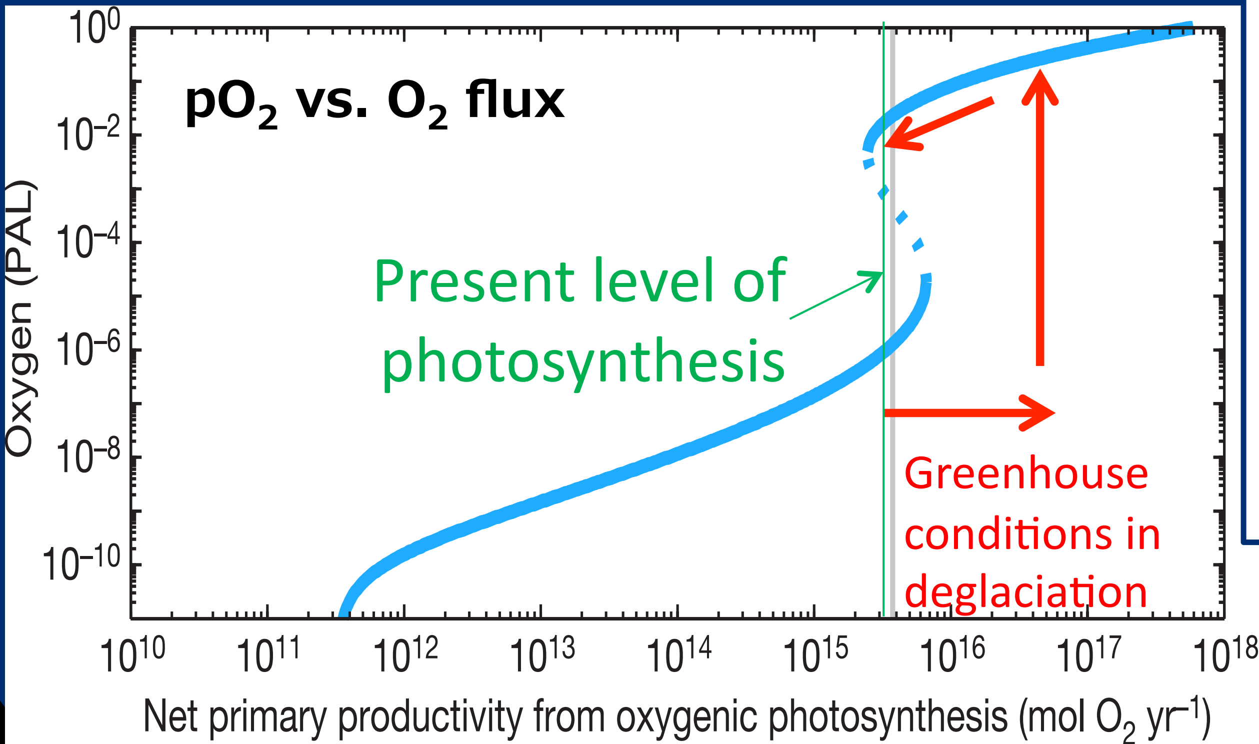
flux of reductants (= methanogenesis – CH_4 photolysis (pO_2))

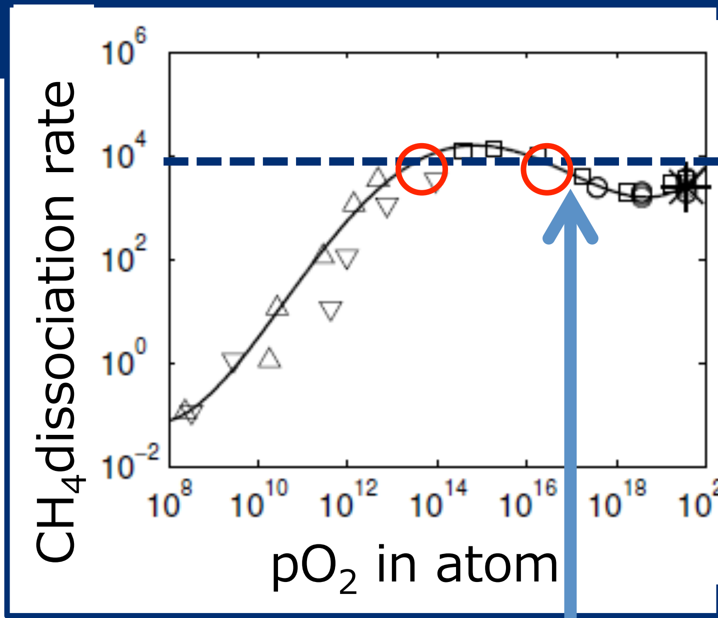


What determines the steady state?

Redox (reducing-oxidizing) states of the atmosphere

Multiple steady states (Goldblatt et al., 2006)





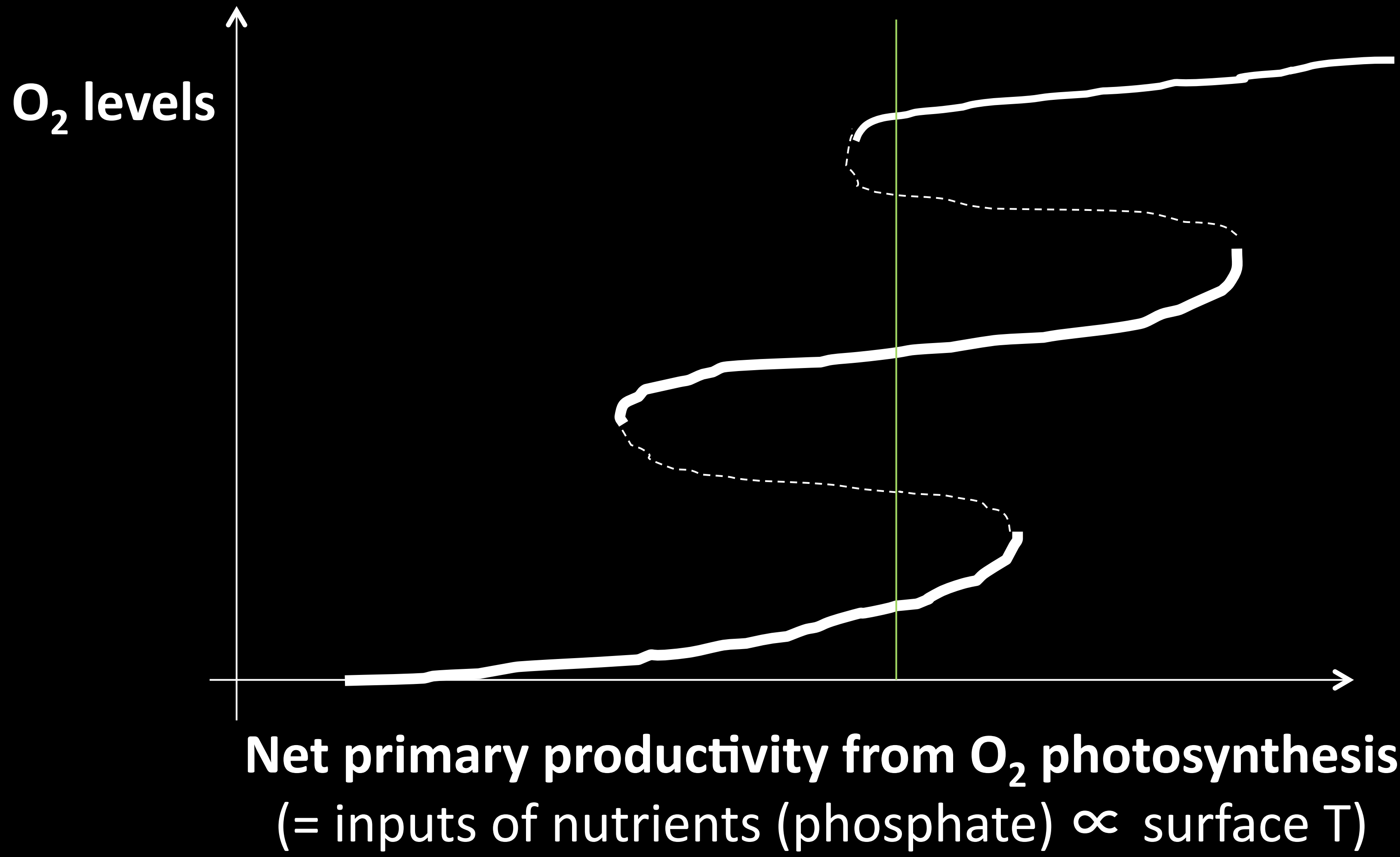
UV shielding by O_3

Climatic perturbations in the Paleoproterozoic → triggering a jump to another steady state of the redox states of the atmosphere

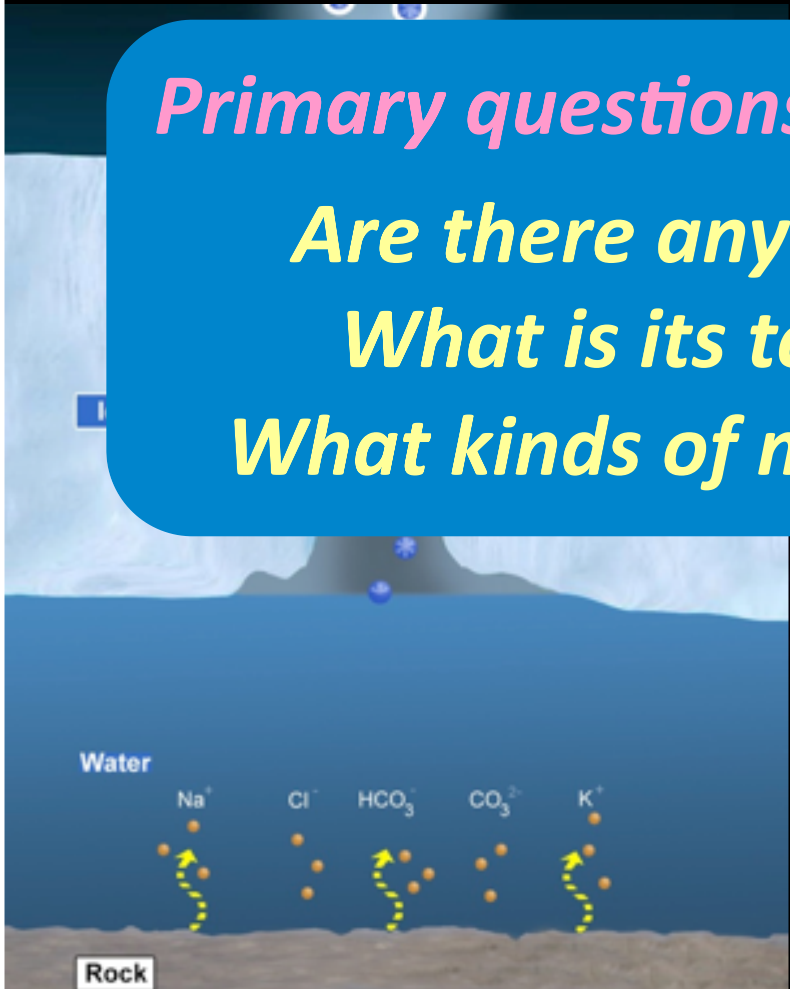
What determines the steady states?

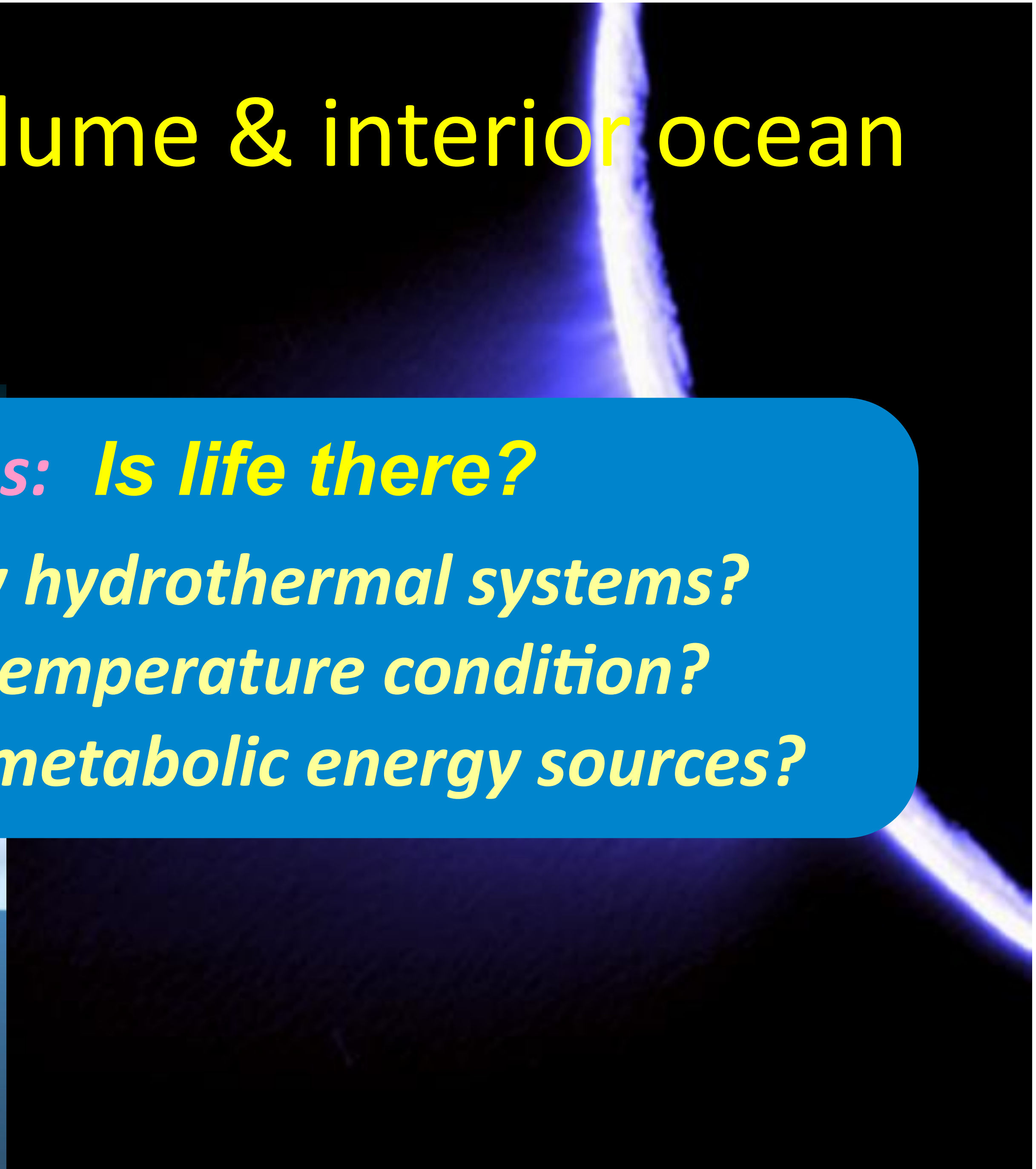
Redox (reducing-oxidizing) states of the atmosphere

- Inputs of oxidants (O_2, SO_2, etc)
- Inputs of reductants (CH_4, H_2S, H_2, Fe^{2+}, etc)



Enceladus' plume & interior ocean





Primary questions: ***Is life there?***

Are there any hydrothermal systems?
What is its temperature condition?
What kinds of metabolic energy sources?

(Schumidt et al., 2007; Postberg et al., 2011)

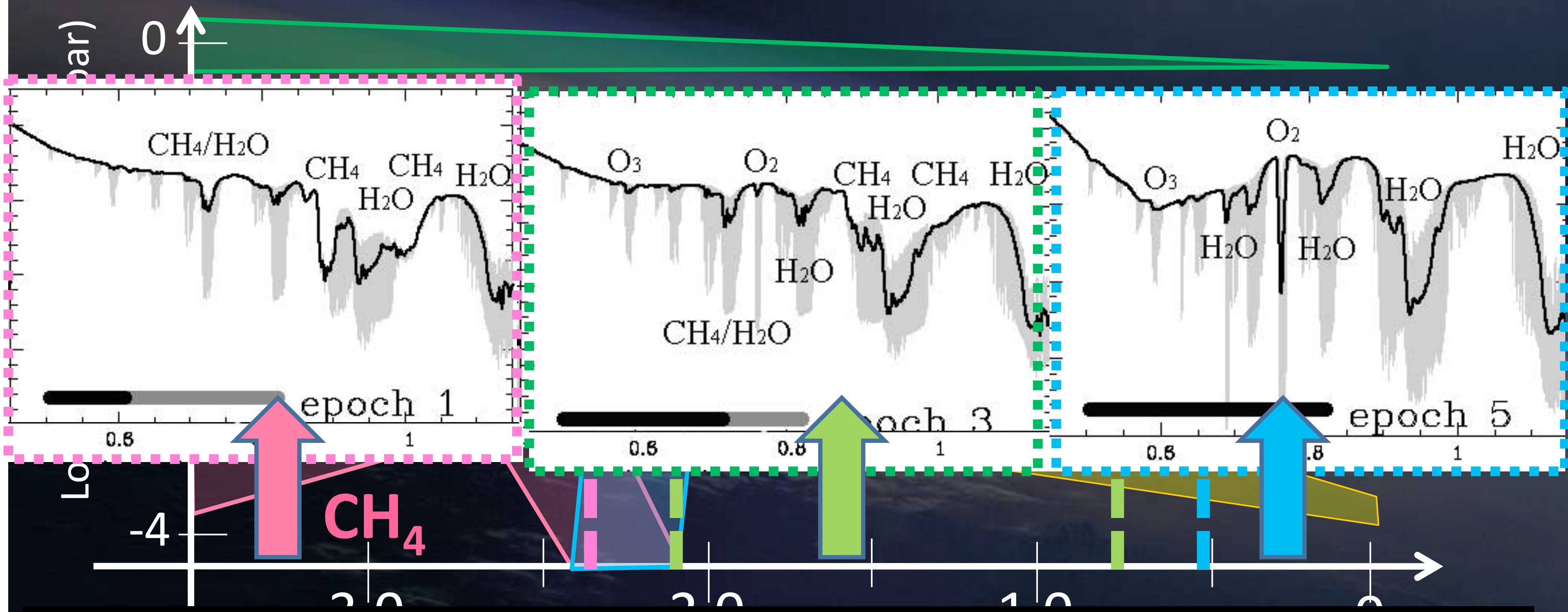
Mars geochemistry

2004-: Mars Rovers
Eagle crater (Opp)
Gusev crater (Spt)

1996-2006: Mars Global Surveyor
(TES: 6 km/pix)
2003-: Mars Express
(OMEGA: 0.3-2 km/pix)
2008-: Mars Reconnaissance Orbiter
(CRISM, HiRISE: 18 m/pix, 0.3 m/pix)

How can Earth's evolution be seen from space?

Characterization of evolution of Earth's atmosphere → Modeling spectra from Earth-like exoplanets with TPF & Darwin (e.g., Kaltenegger et al., 2007)



How many Earths have oxidizing or reducing atmospheres?

(Holland, 1984; Tajika & Matsui, 1992; Kasting, 1993; Rye & Holland, 1998; Farquhar et al., 2000; Pavlov & Kasting, 2002; Canfield, 2005; Hoffman & Schrag, 2002; Kump, 2008; Holland, 2006)

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