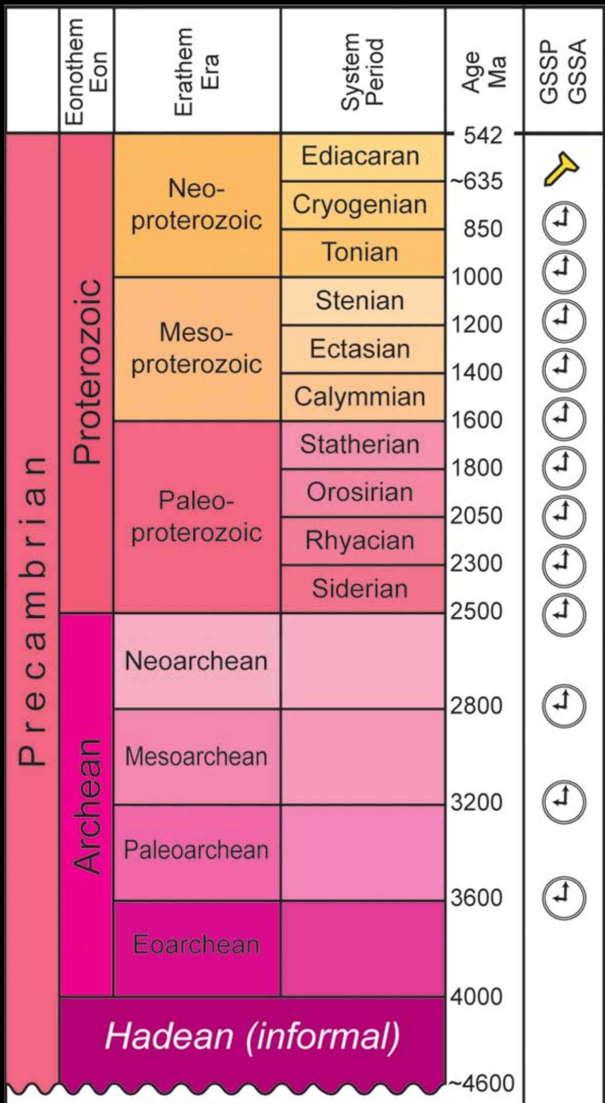
Fertilisation azotée de l'océan primitif par des microorganismes continentaux à l'Archéen ?

Thomazo C, Couradeau E, Garcia-Pichel F

INTRODUCTION



- Ocean formation

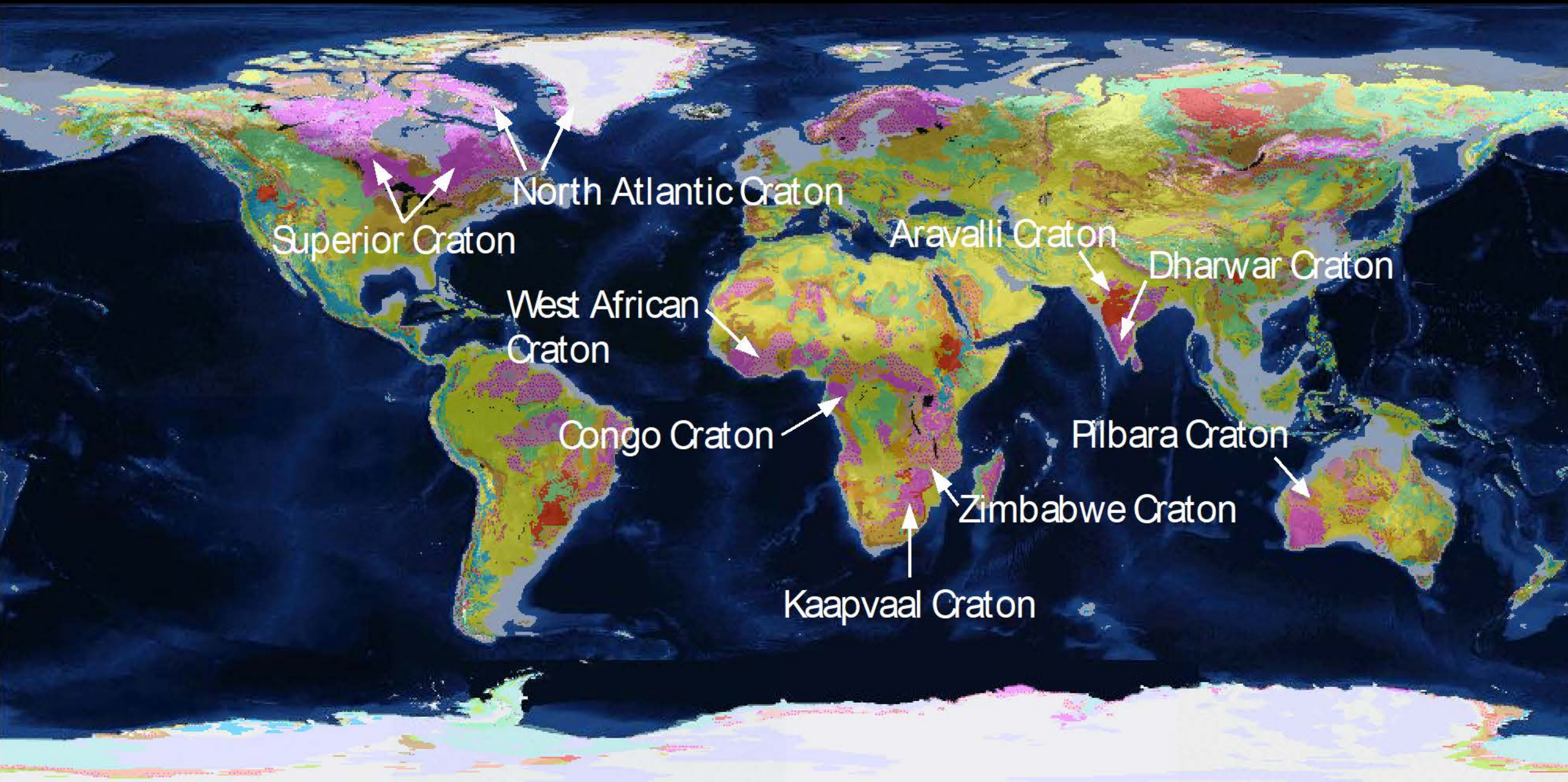
- **Oxidation of the environment**
Ocean and Atmosphere

- Continental crustal growth

- **Development of life**

~ Half of the geological record

INTRODUCTION



… BUT Poorly archived, few sediments most of them deposited after 3.5 Ga, **metamorphism to at least 200°C**

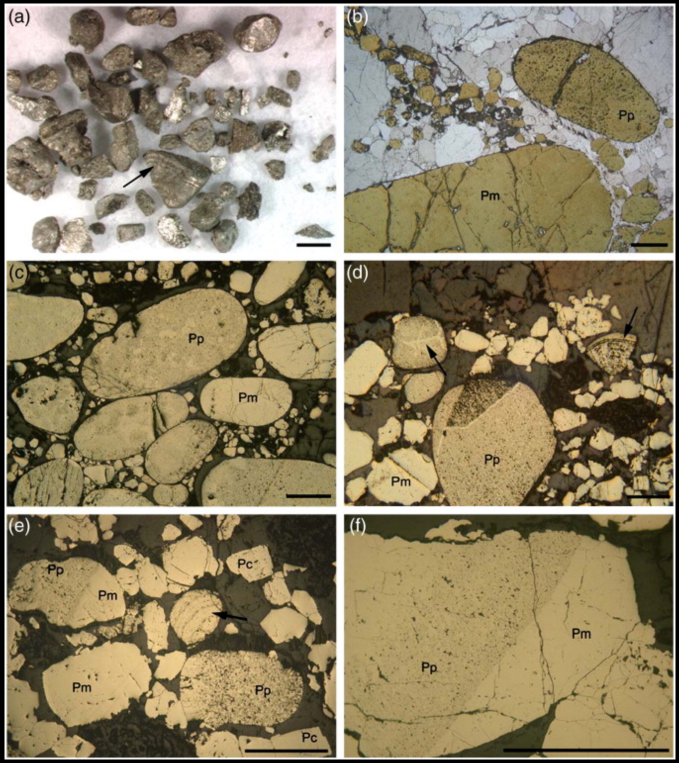
INTRODUCTION

The records of Earth oxygenation

1/ Looks for the chemistry of sedimentary deposits (ox or red)

Banded Iron Formation

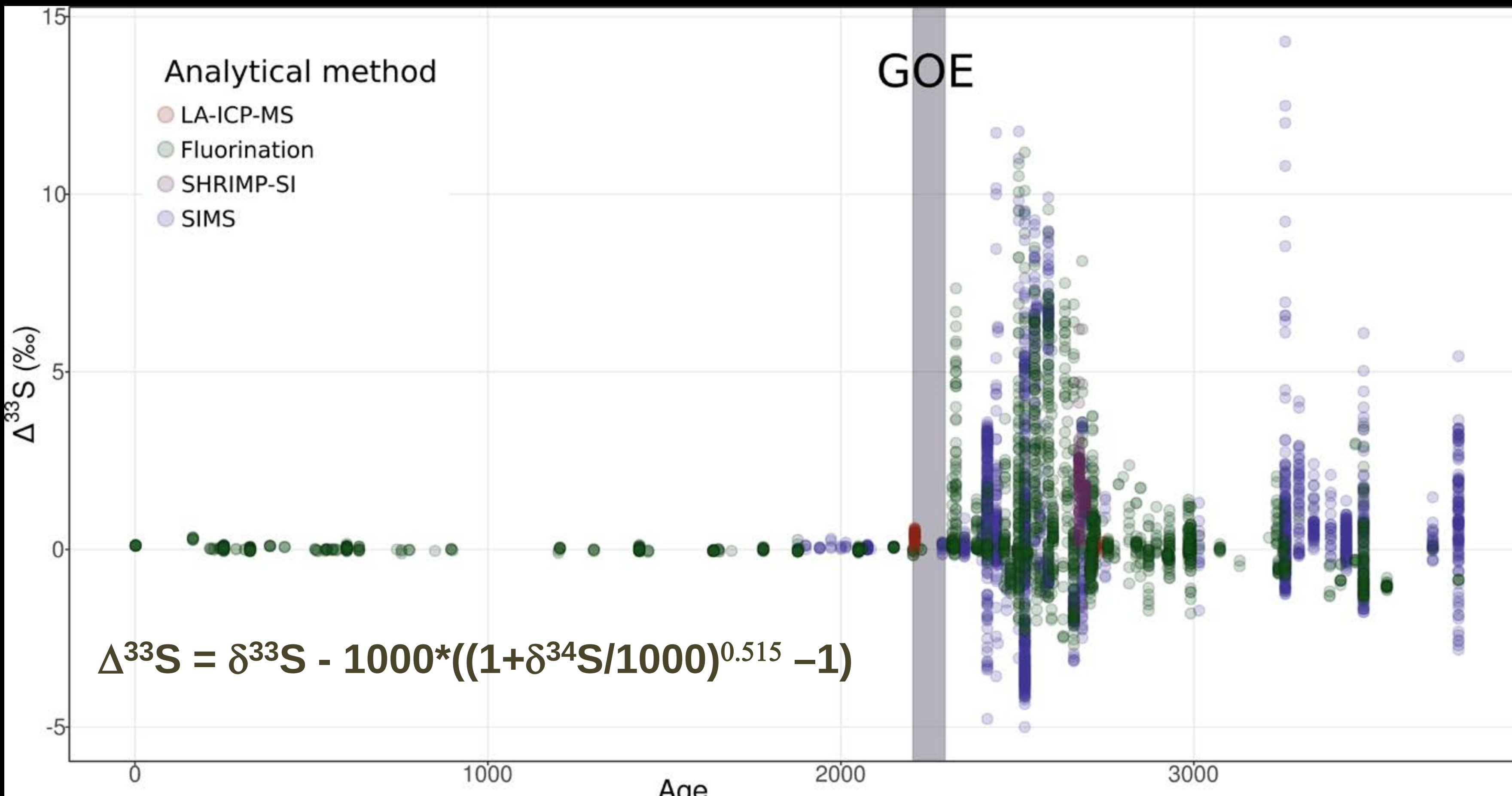
Detritial pyrites



Hofmanna et al., 2009

The records of Earth oxygenation

1/ Looks for the type of sedimentary deposist (ox or red)
2/ Looks for chemical signature of oxygen in the ocean / atmosphere

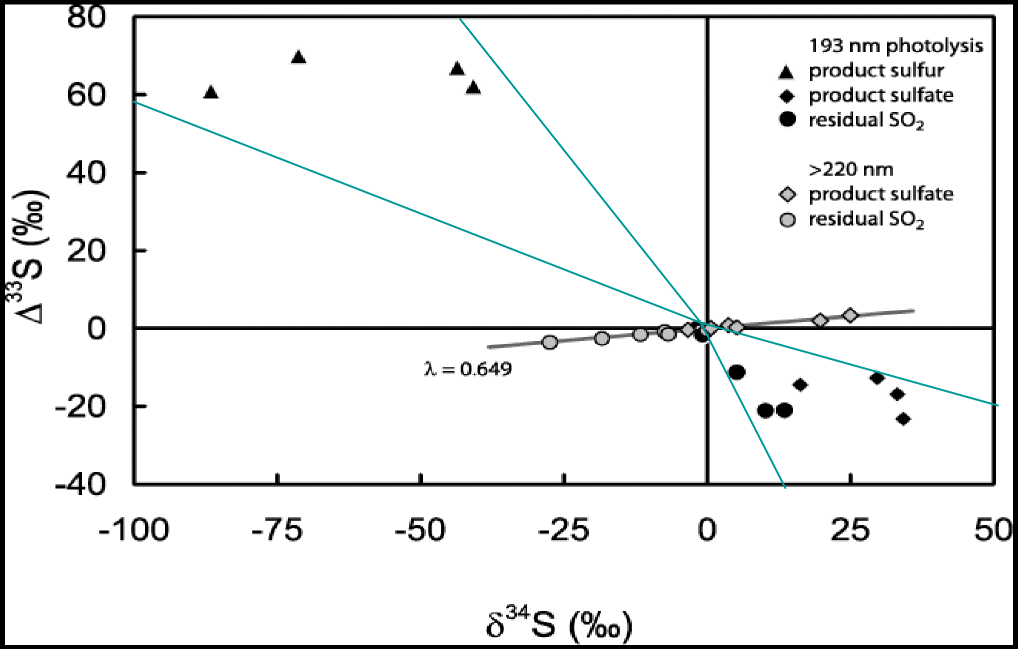


$$\Delta^{33}S = \delta^{33}S - 1000*((1+\delta^{34}S/1000)^{0.515} - 1)$$

INTRODUCTION

The records of Earth oxygenation

- MIF-S are produced in lab experiment during UV photolysis of SO_2



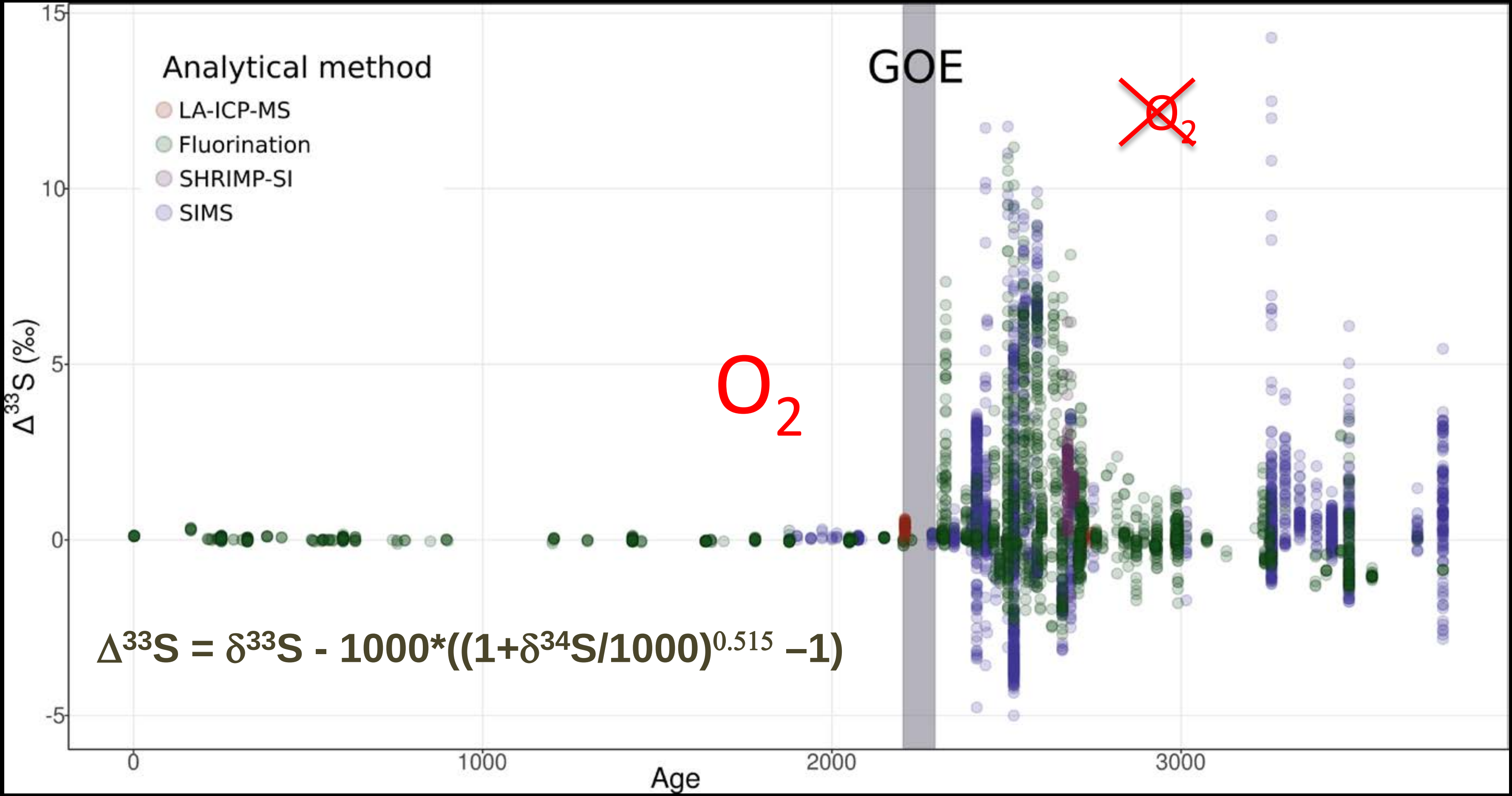
Farquhar et al., 2000

Photolytic reaction of S in anoxic atmosphere

Without O_2 (O_3)

The records of Earth oxygenation

1/ Looks for the type of sedimentary deposist (ox or red)
2/ Looks for chemical signature of oxygen in the ocean / atmosphere



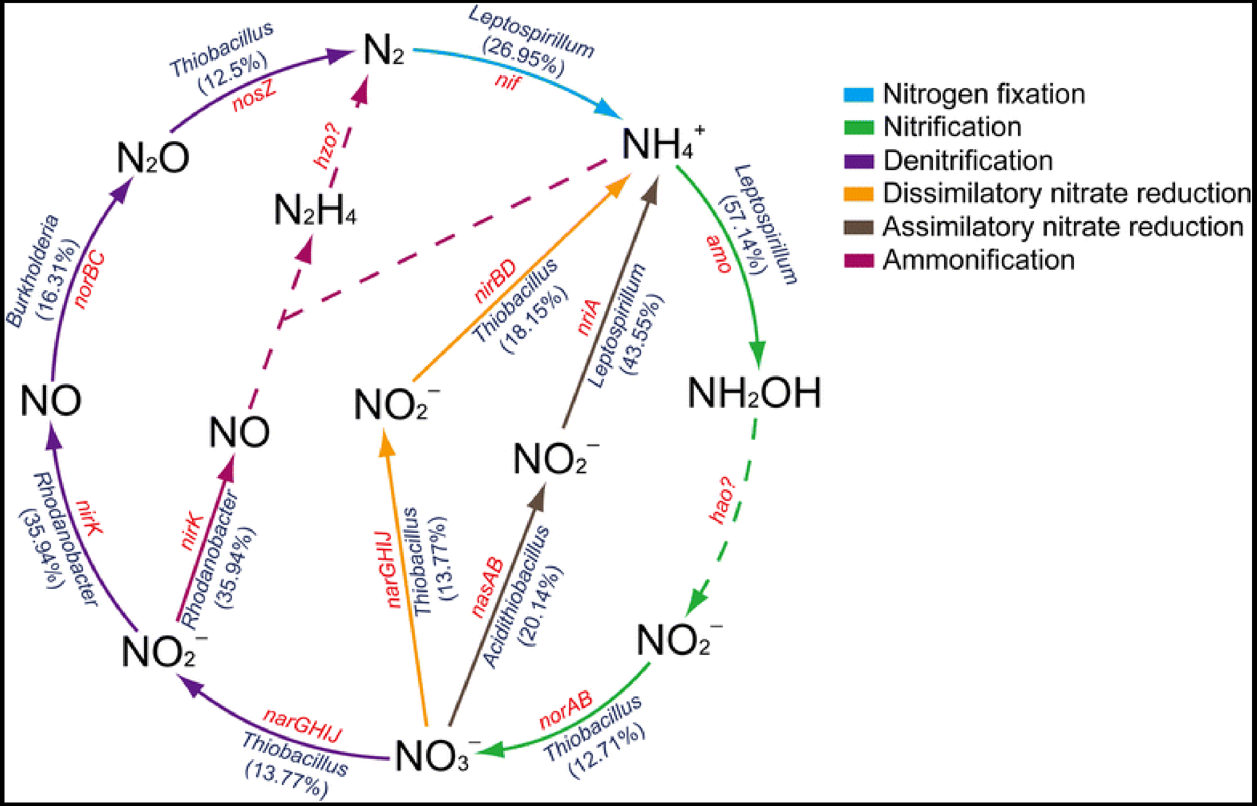
$$\Delta^{33}S = \delta^{33}S - 1000*((1+\delta^{34}S/1000)^{0.515} - 1)$$

The records of Earth oxygenation

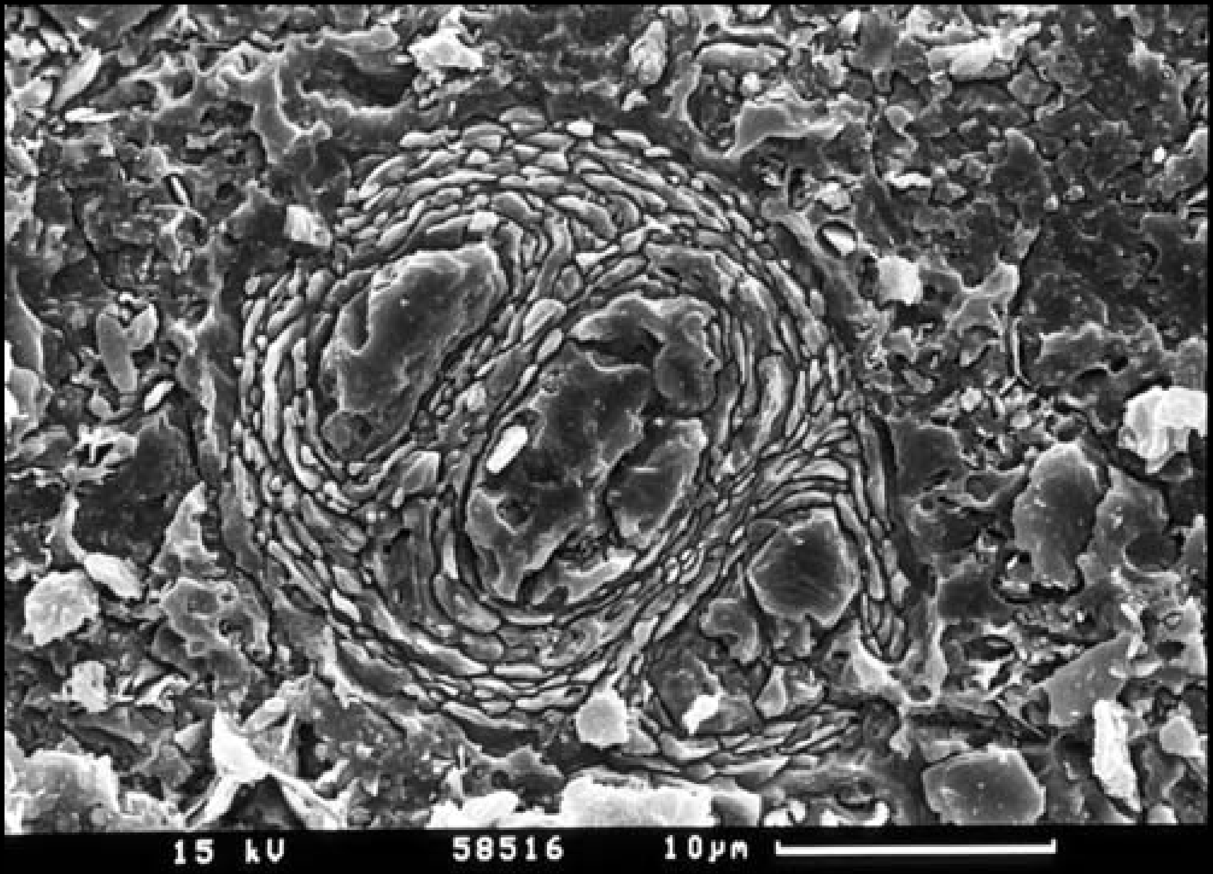
1/ Looks for the type of sedimentary deposist (ox or red)
2/ Looks for chemical signature of oxygen in the ocean / atmosphere
3/ Looks for biological record of metabolisms performing respiration (O_2 but also sulfate, nitrate, iron oxydes etc.)

Type	Lifestyle	Electron acceptor	Products	E_o' [V]	Example organisms
Aerobic respiration	Obligate and facultative aerobes	O_2	$H_2O + CO_2$	+0.82	eukaryotes and aerobic prokaryotes
Nitrate reduction	Facultative aerobes	nitrate (NO_3^-)	nitrite (NO_2^-)	+0.40	*E.coli*
Fumarate respiration	Facultative aerobes	fumarate	succinate	+0.03	*E.coli*
Sulfate respiration	Obligate anaerobes	sulfate (SO_4^{2-})	sulfide (HS^-)	-0.22	*Desulfobacter latus*
Sulfur respiration	Facultative aerobes and obligate anaerobes	sulfur (S^0)	sulfide (HS^-)	-0.27	*Desulfuromonadal es*

Early Earth Nitrogen metabolisms ?



INTRODUCTION



Unknown Paleozoic microfossil probably related to *O. duoportius* (SEM image, etched rock surface) - *credit Axel Munnecke*

… most of the time organic remain are difficult to recognize and classify … though chemical reaction is unknown

INTRODUCTION

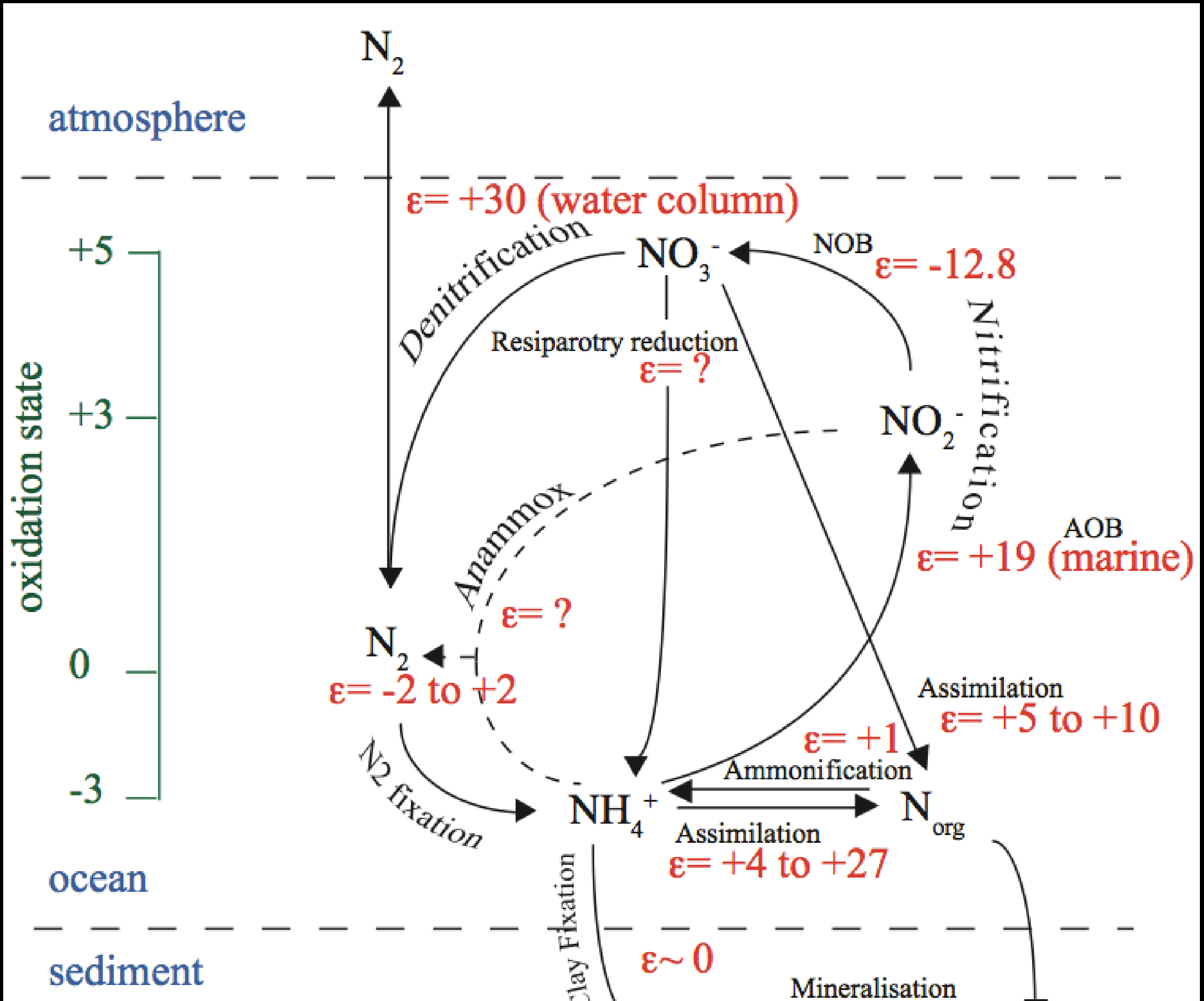
Stable isotopes are used to trace:

The origin of organic remains (because life tend to exert strong fractionation compare to abiotic reaction).

Different metabolic activities = different fractionations and byproducts precipitating as bio-minerals.

Moreover, Secondary alterations can be tested in most cases (*Rayleigh distillation model*).

Lessons from the modern N cycle



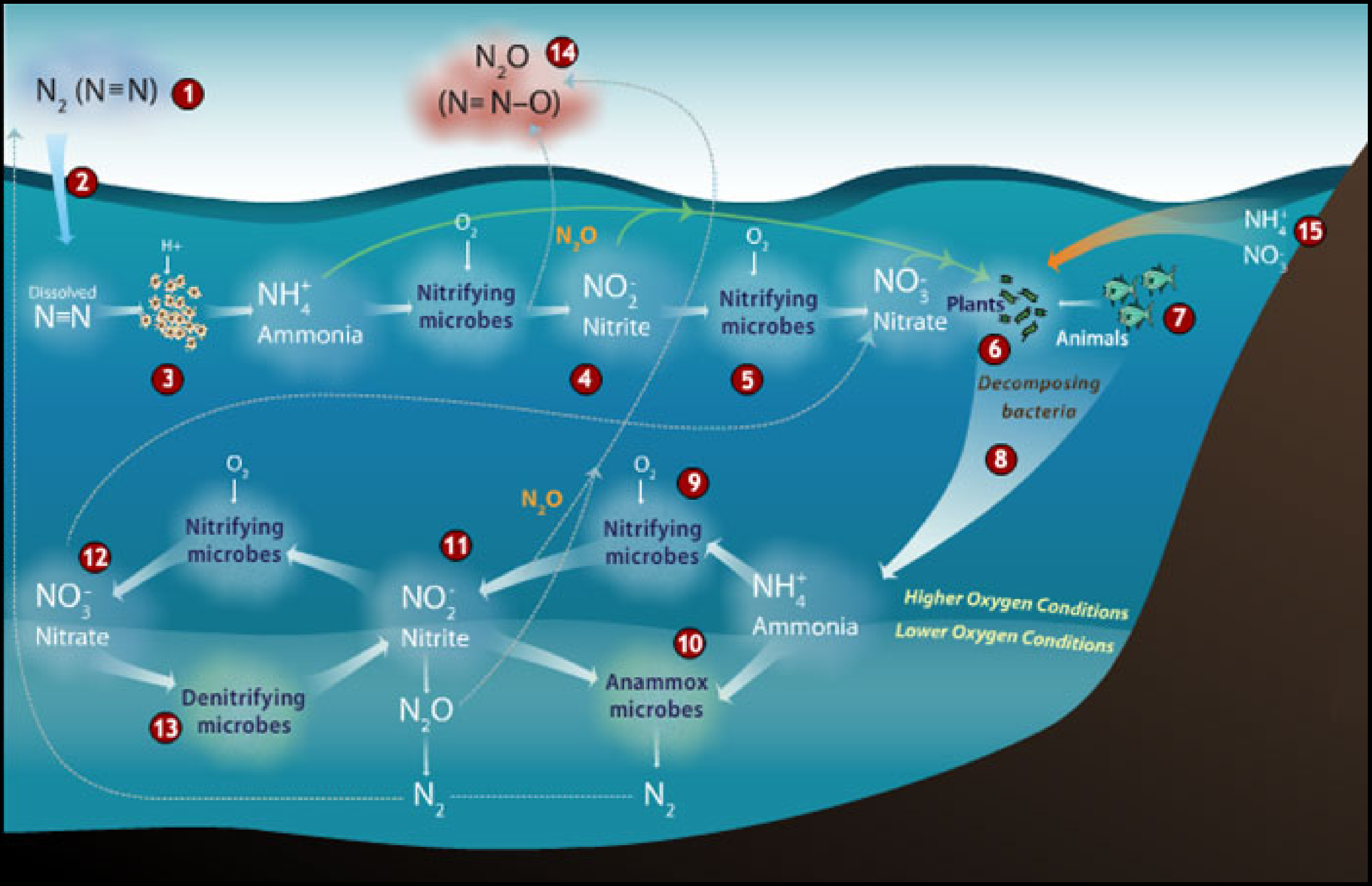
After Godfrey & Falkowski, 2009; Thomazo et al., 2011; Stüeken, 2013

N is one of the major nutrients

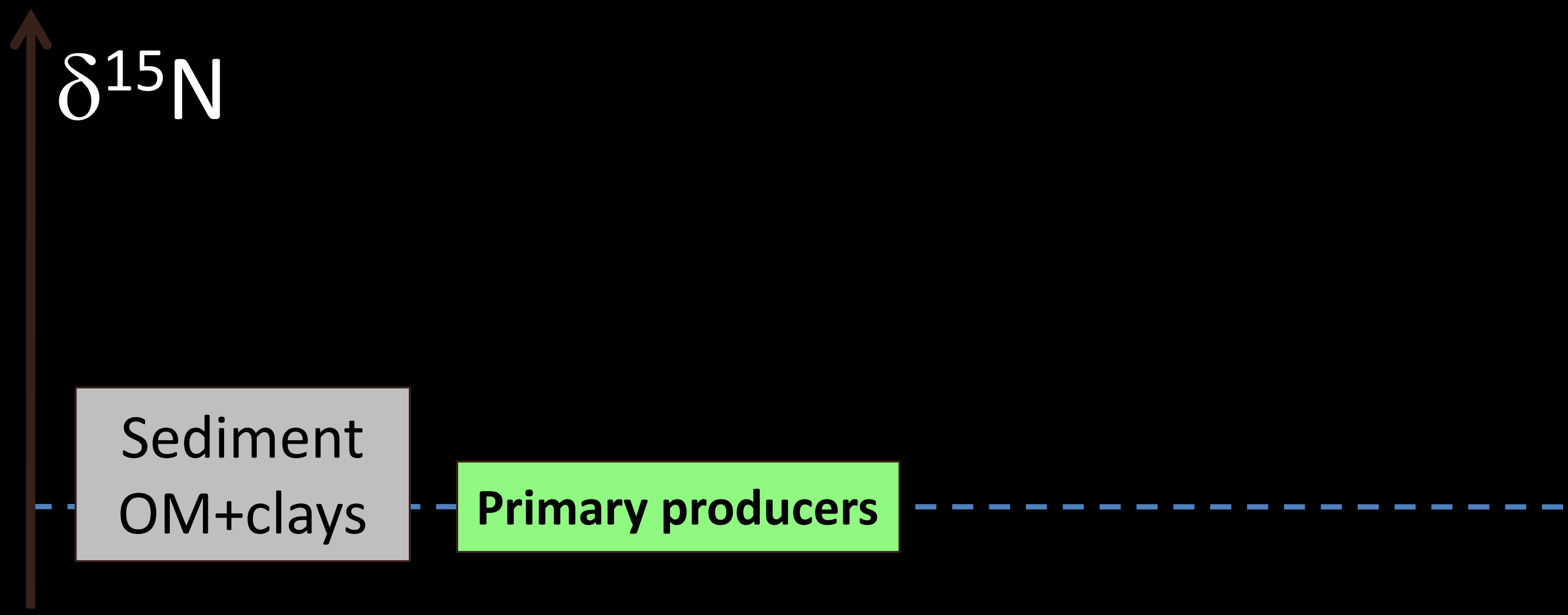
=> The N cycle interacts strongly with primary productivity

The N cycle is mediated by redox reactions

Lessons from the modern N cycle

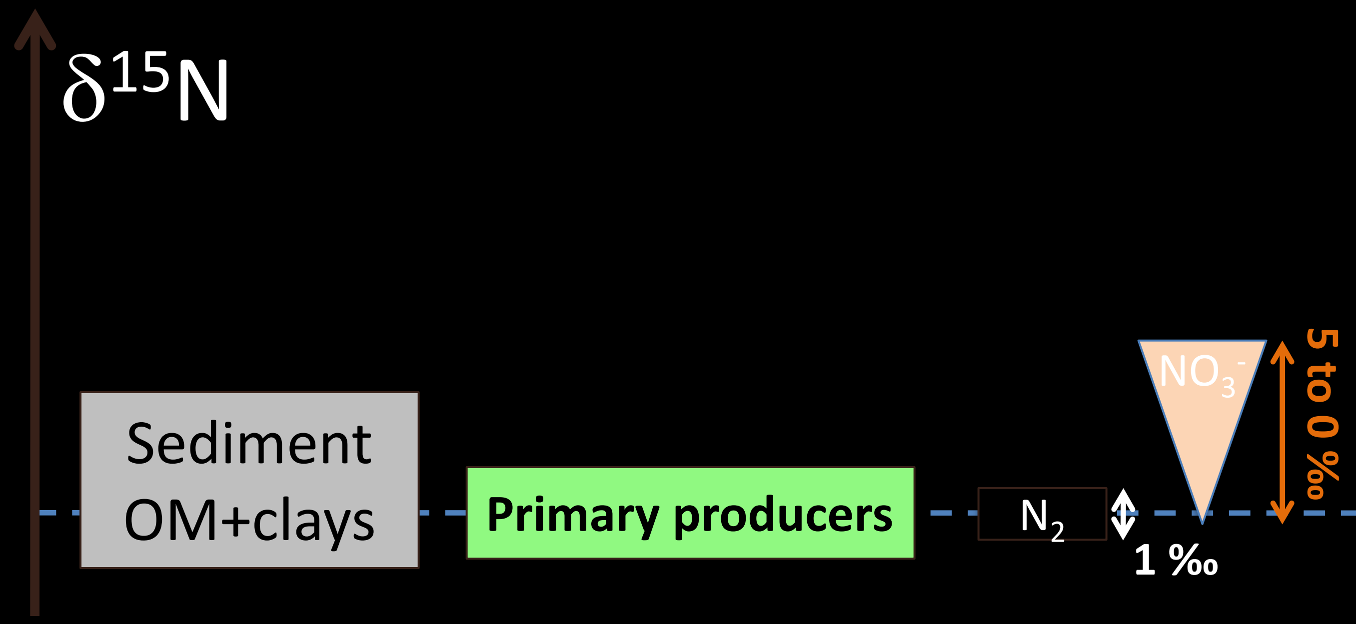


Lessons from the modern N cycle



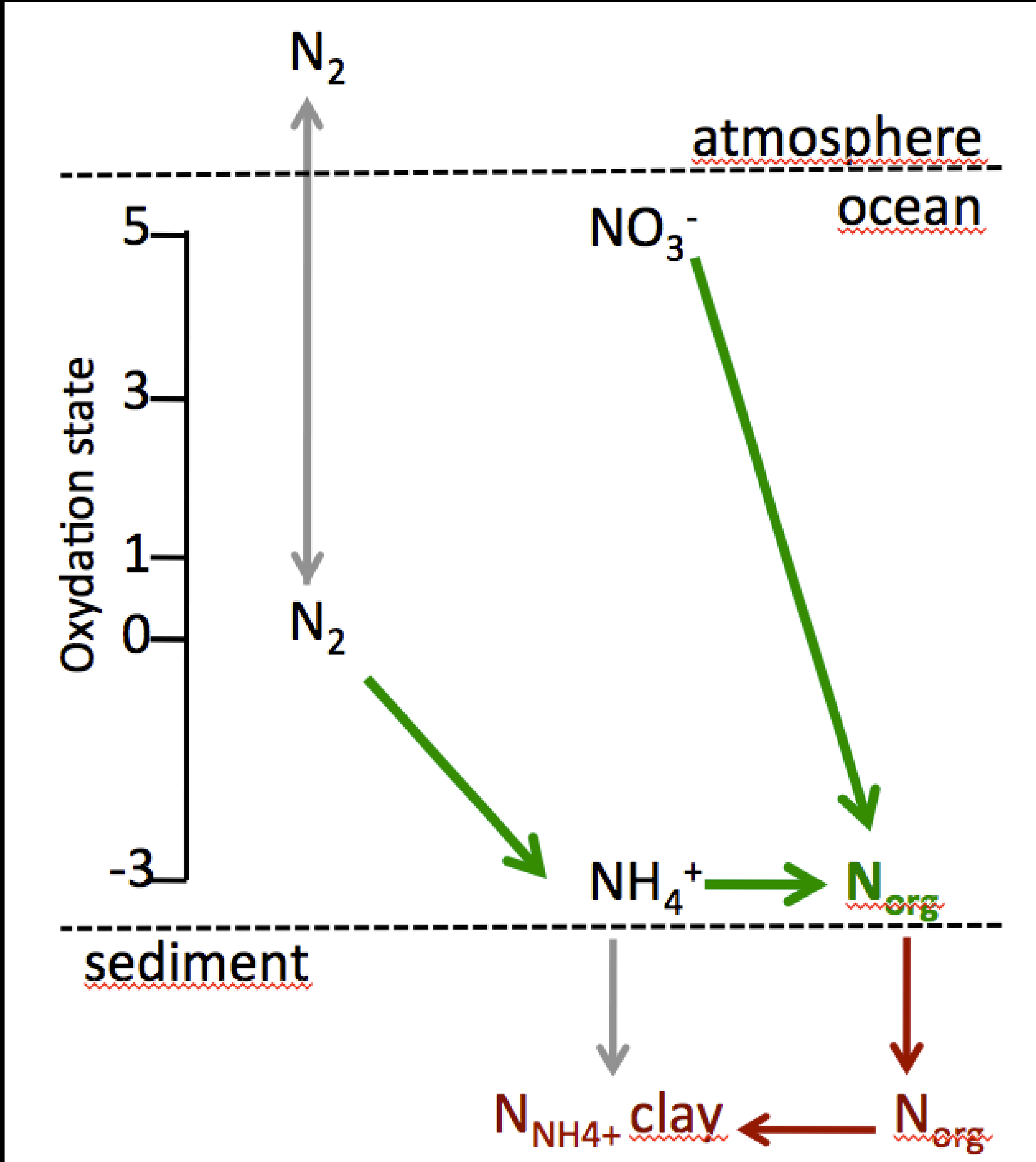
$\delta^{15}N_{sed}$ records $\delta^{15}N_{primary\ producers}$

Lessons from the modern N cycle



$\delta^{15}N_{primary\ producers}$ records nitrogen sources $\delta^{15}N$

Lessons from the modern N cycle

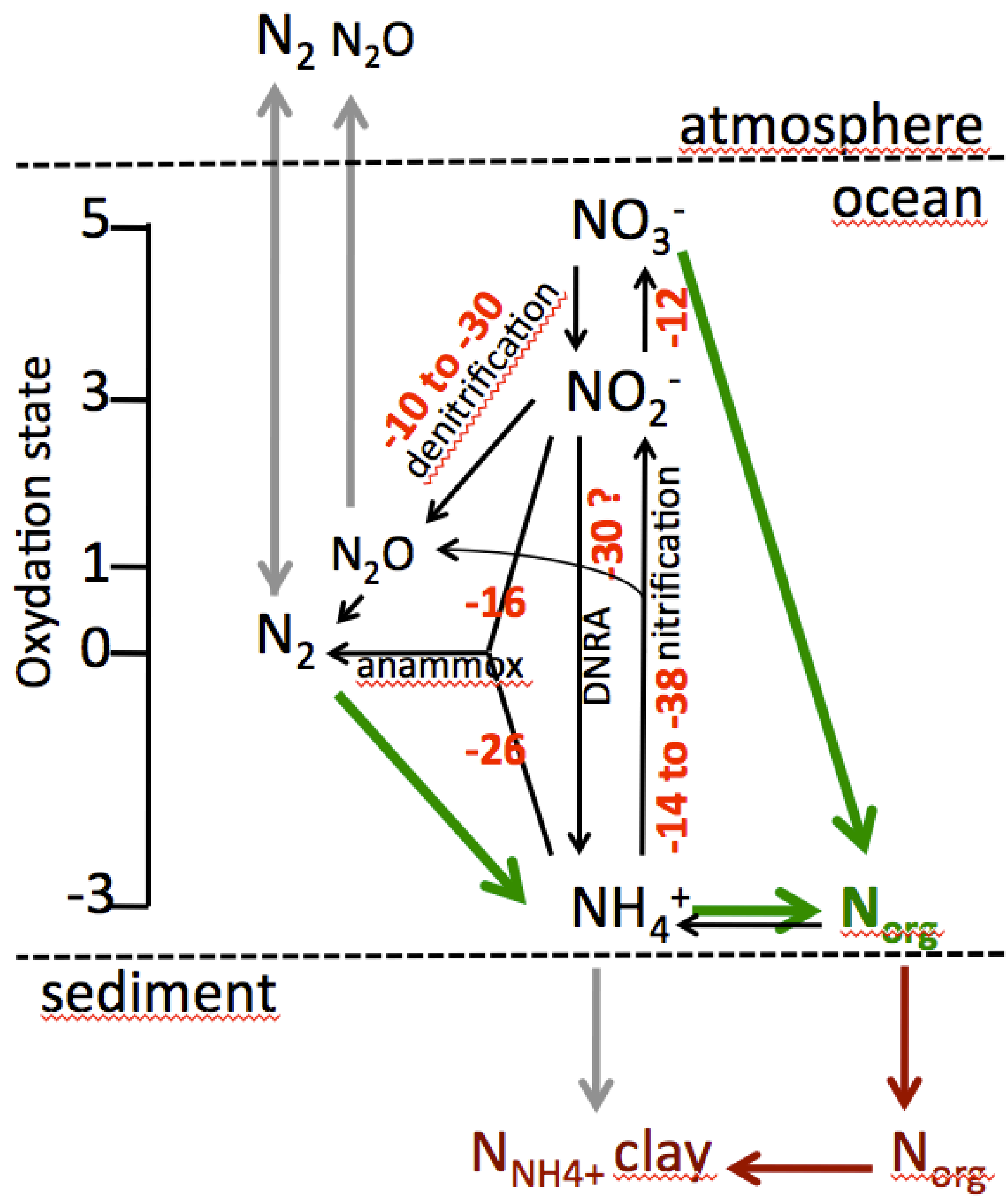


Lessons from the modern N cycle

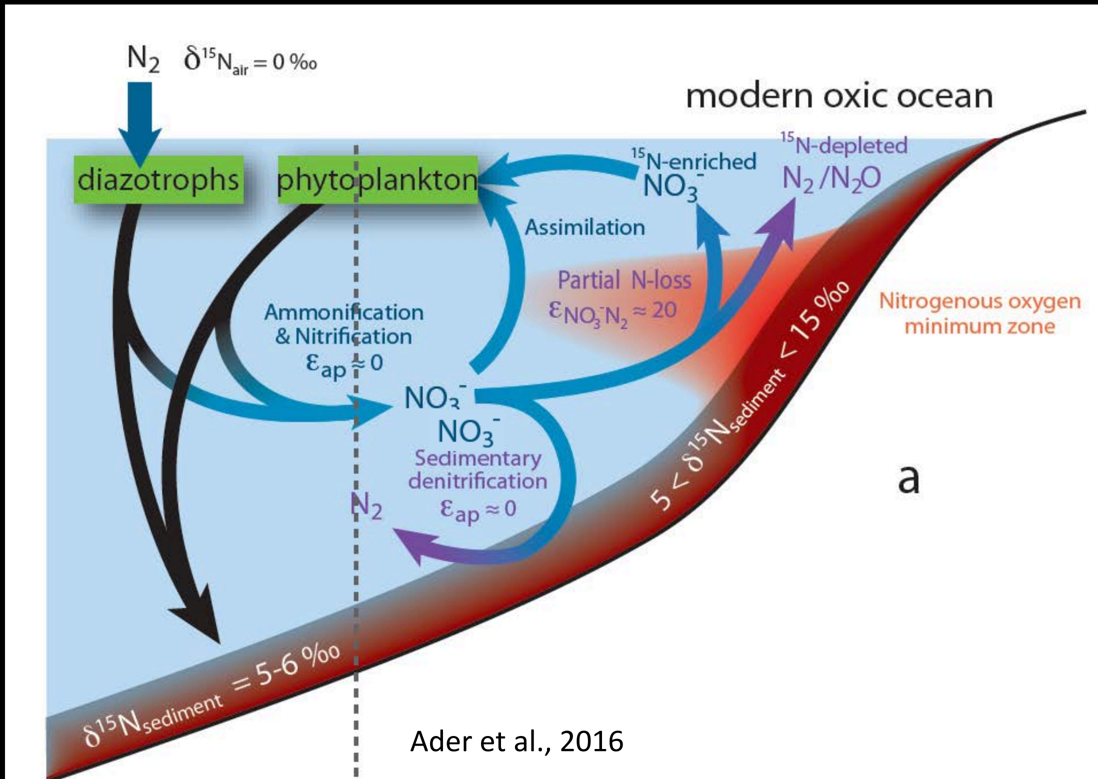
$\varepsilon = \delta^{15}N_{product} - \delta^{15}N_{reactant}$

! Can be expressed only when the reaction is not quantitative !

The $\delta^{15}N$ of nitrogen sources depend on how the nitrogen cycle operates

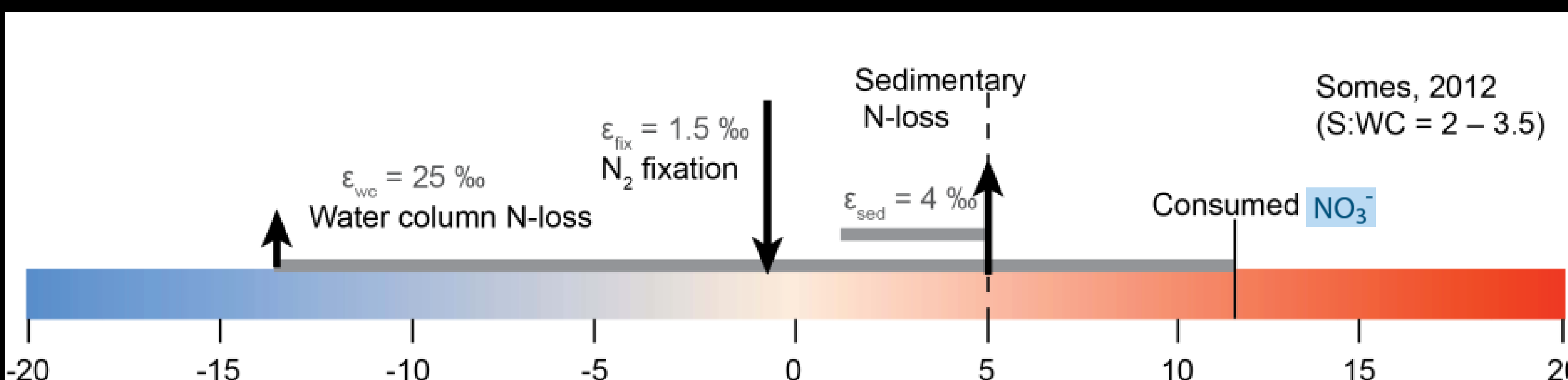


Lessons from the modern N cycle

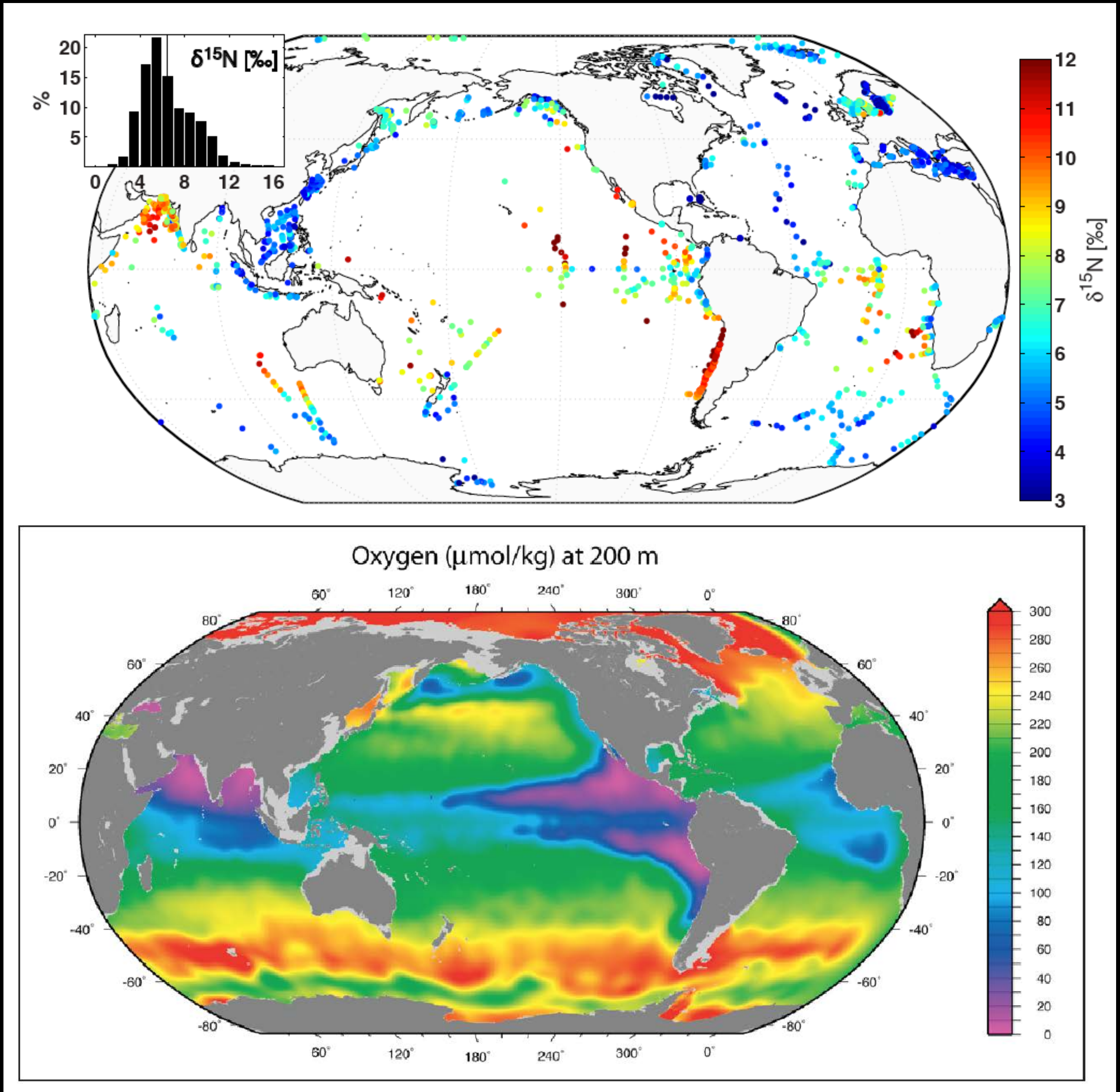


$\delta^{15}N$ is controlled by the balance of nitrogen fixation and denitrification

All the Phaneroizoic record can be interpreted like this (e.g. Algeo et al. 2014)

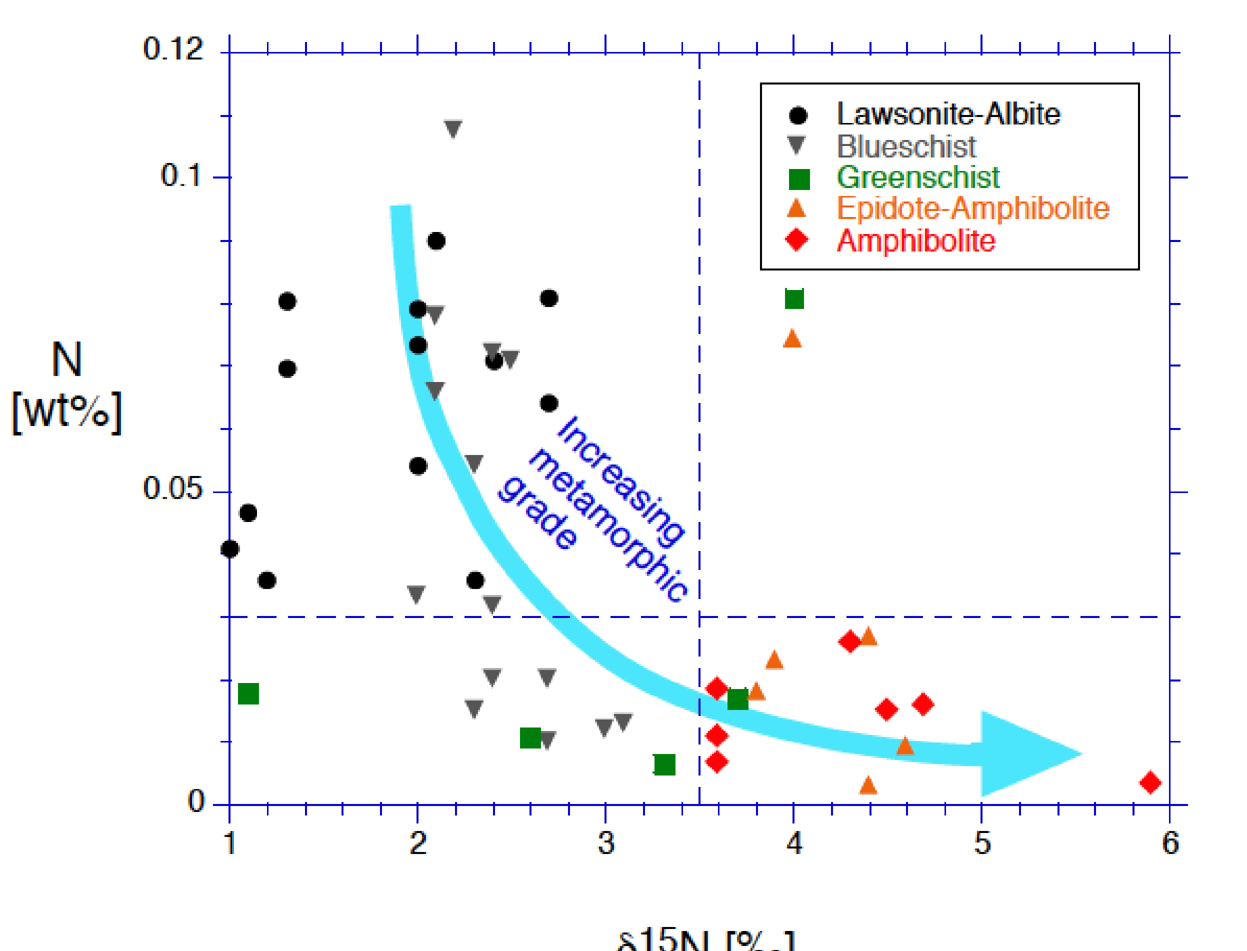


Lessons from the modern N cycle



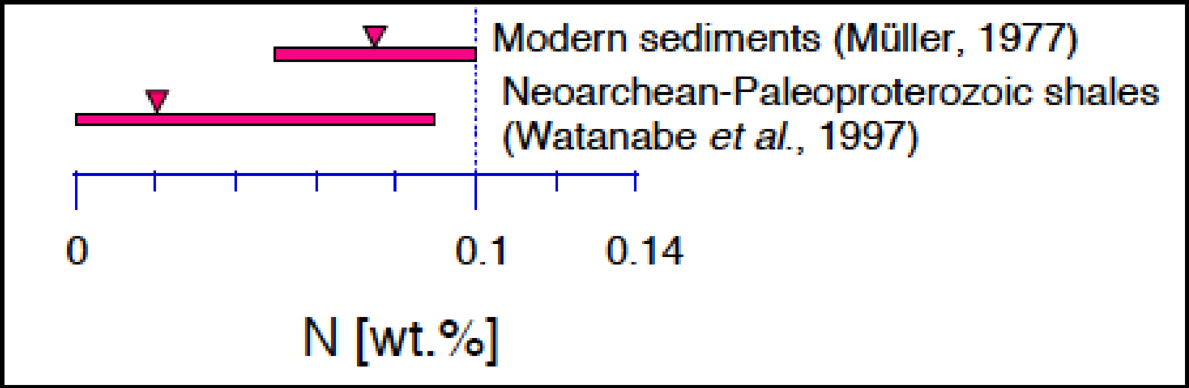
Early Earth complications

* Sedimentary N content and $\delta^{15}N$ evolve with metamorphism

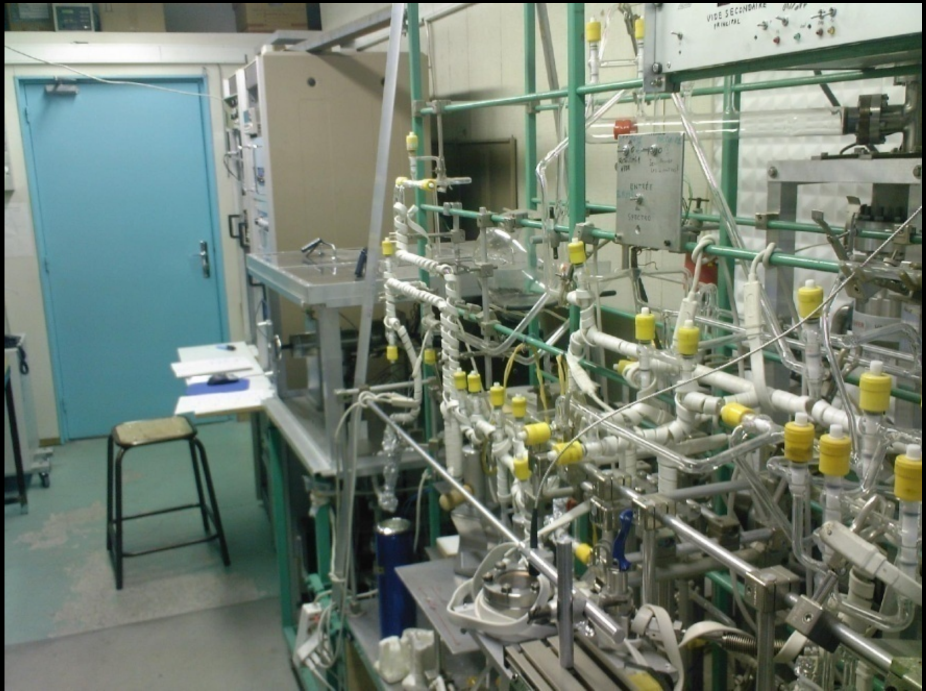


Modified from bebout & fogel, 1994

Early Earth complications



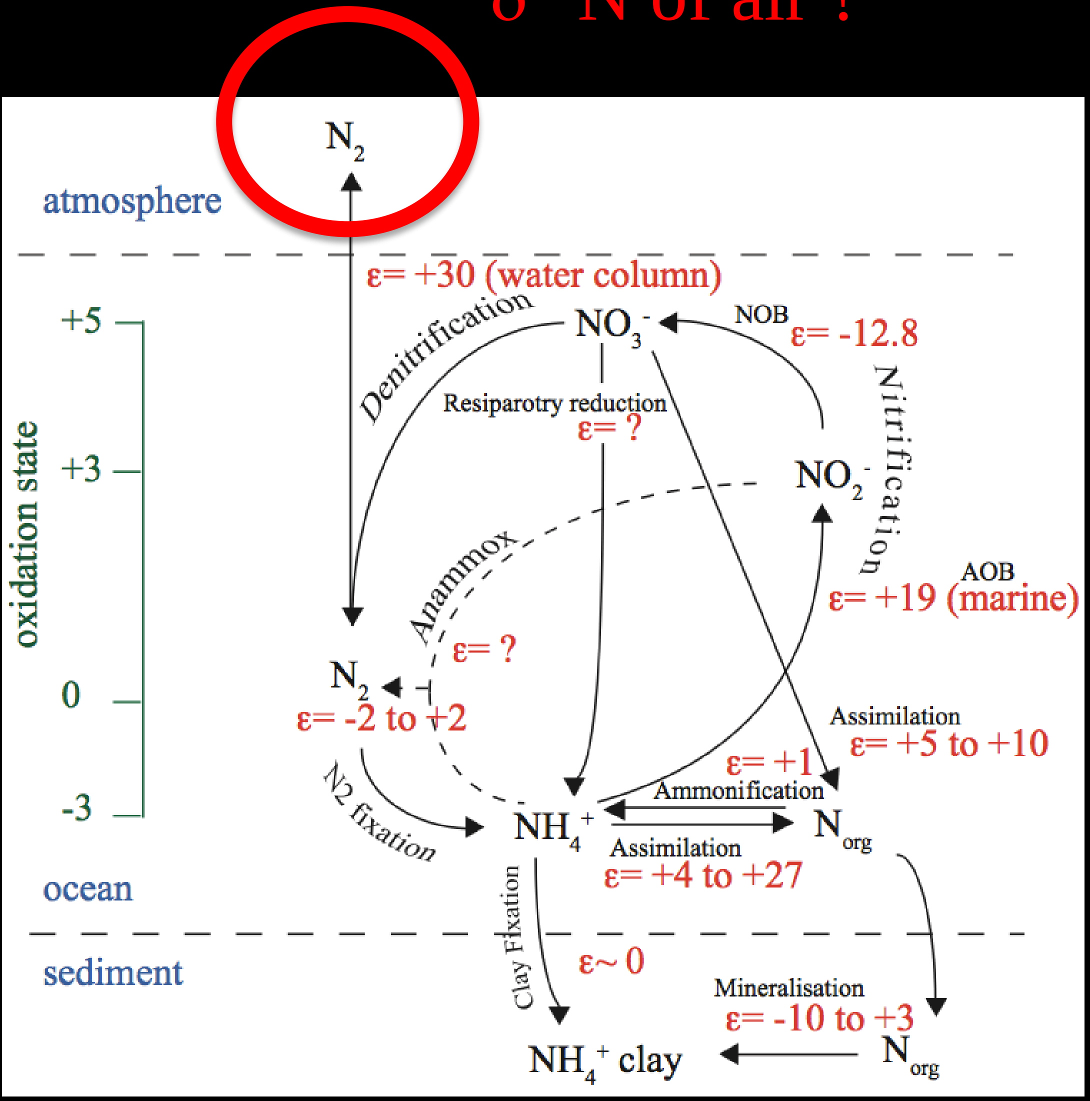
Static mass spectrometer instrument (IPGP)



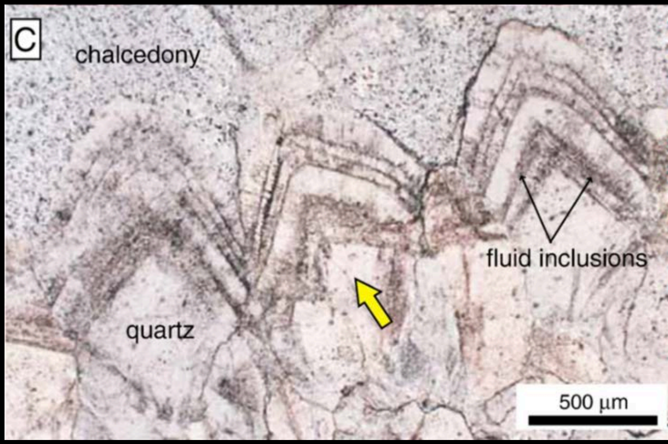
➢ Allow $\delta^{15}N$ determination with a precision of ±0.5‰ (2σ) on ~30 nmol of Nitrogen

Early Earth complications

$\delta^{15}N$ of air ?

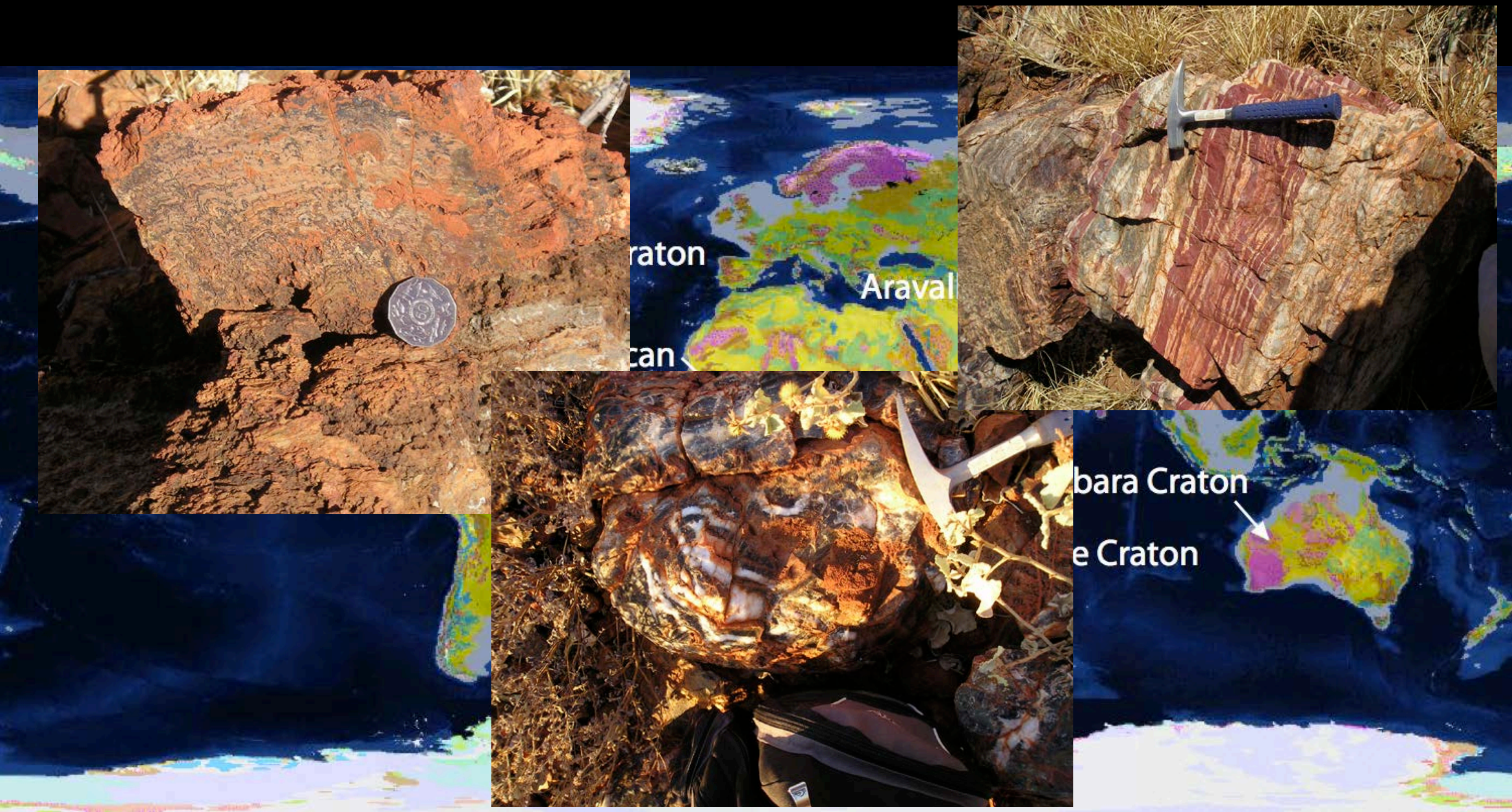


- ➢ $\delta^{15}N$ N_2-bearing fluid inclusion at 3.5 Ga close to 0‰ *(Nishizawa, 2007)*
- ➢ N_2 *reservoir does not evolve significantly ? (Marty, 2015)*

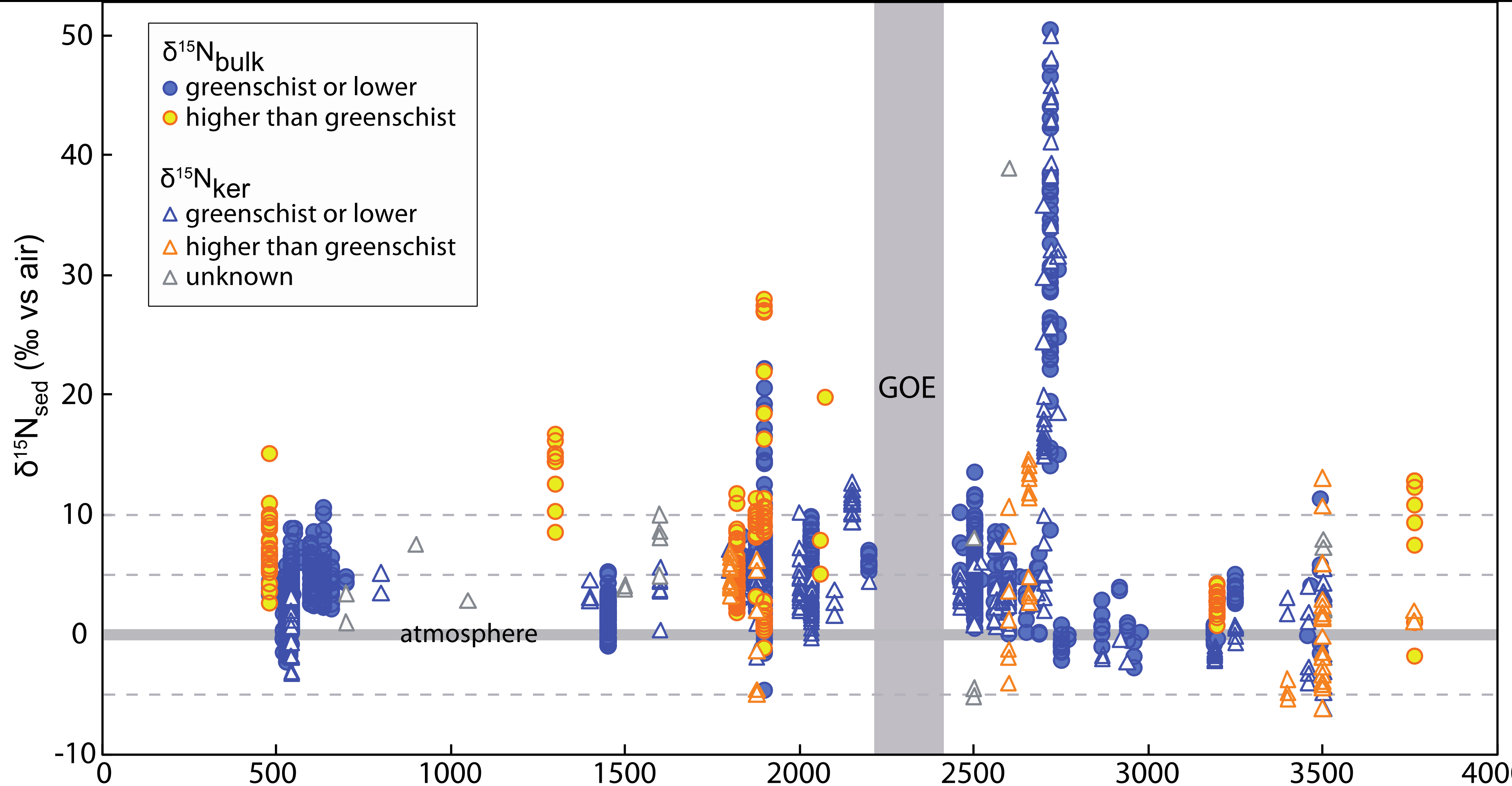


Precambrian sedimentary nitrogen isotopes

➢ Compilation of **874 published $\delta^{15}N$** between 3.8 Ga and 500 Ma. Measured on various Precambrian sedimentary lithologies and phases (Kerogen, Phyllosilicates, shales and carbonates, cherts and BIFs and N_2-bearing fluid inclusion).



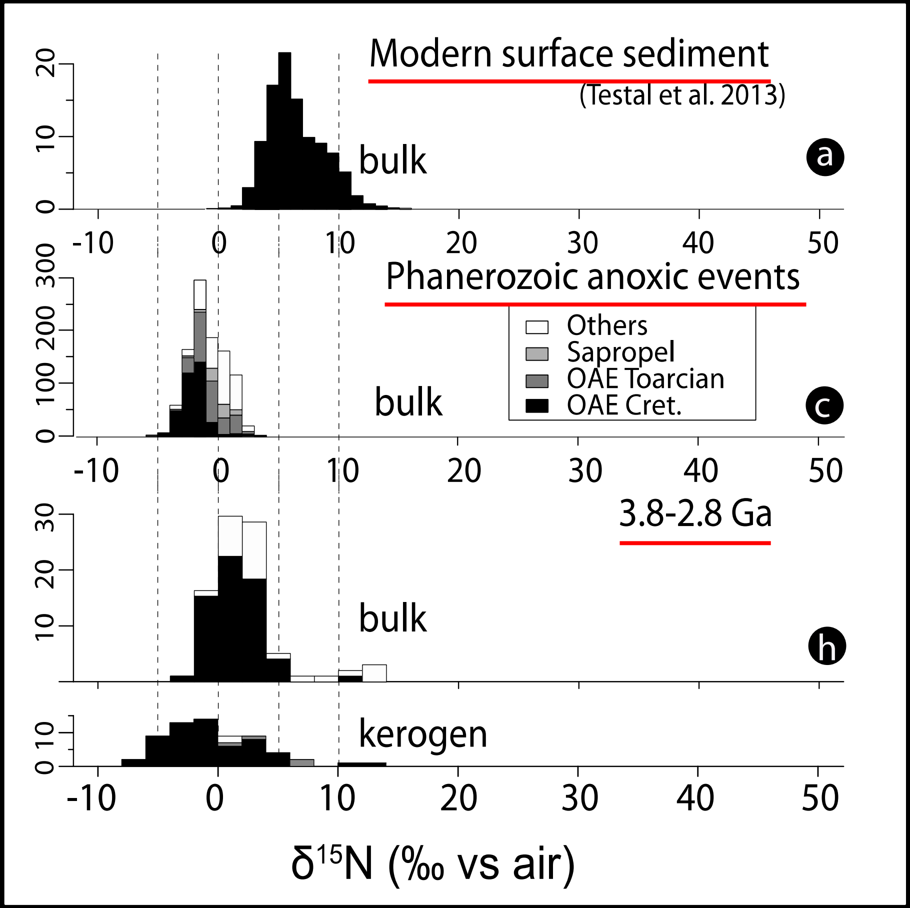
Precambrian sedimentary nitrogen isotopes

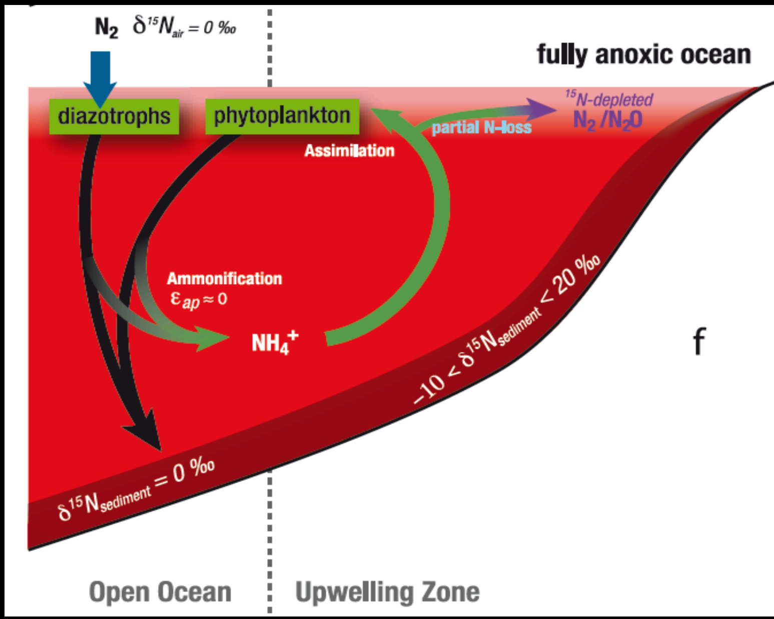


Ader et al., 2016

3.8 – 2.8 Ga

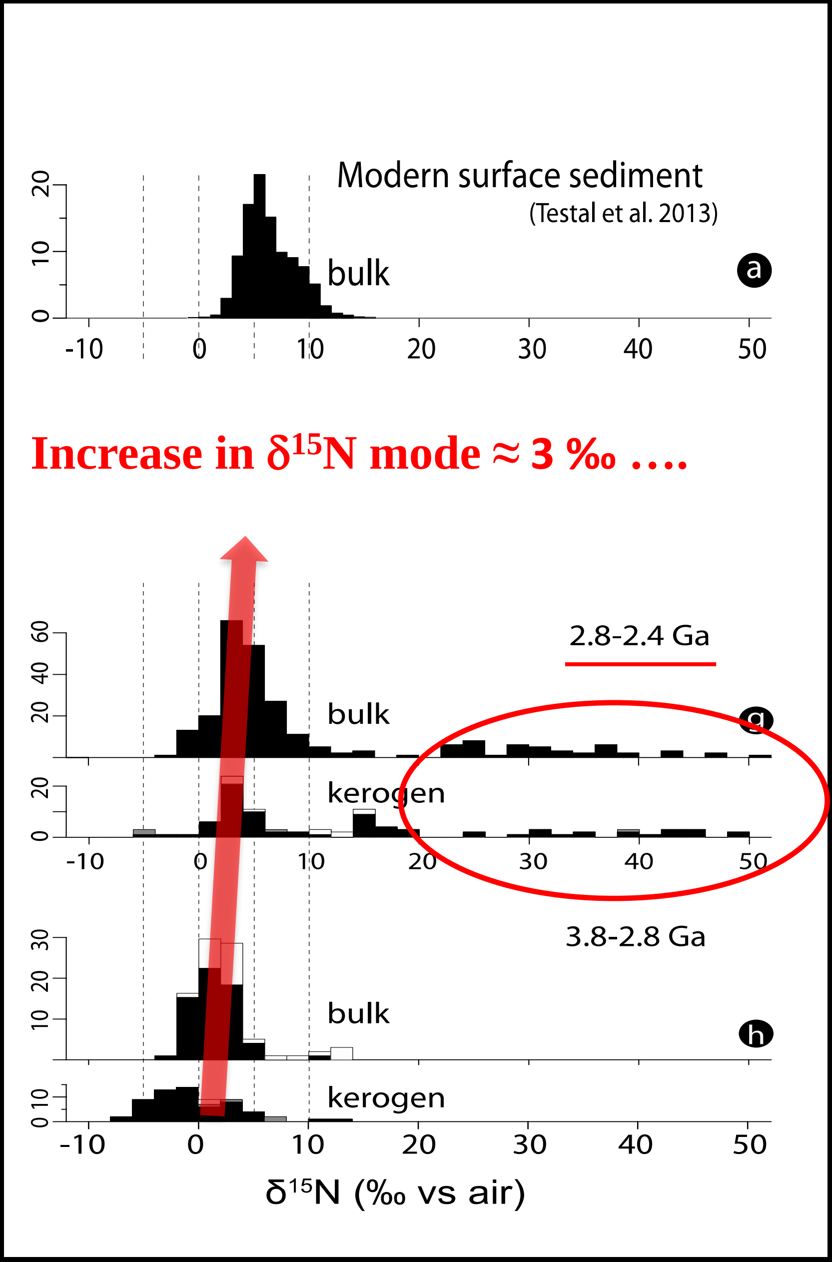
δ^{15}N mode ≈ 1 ‰
⇒ minor fractionation consistent with fully anoxic oceans



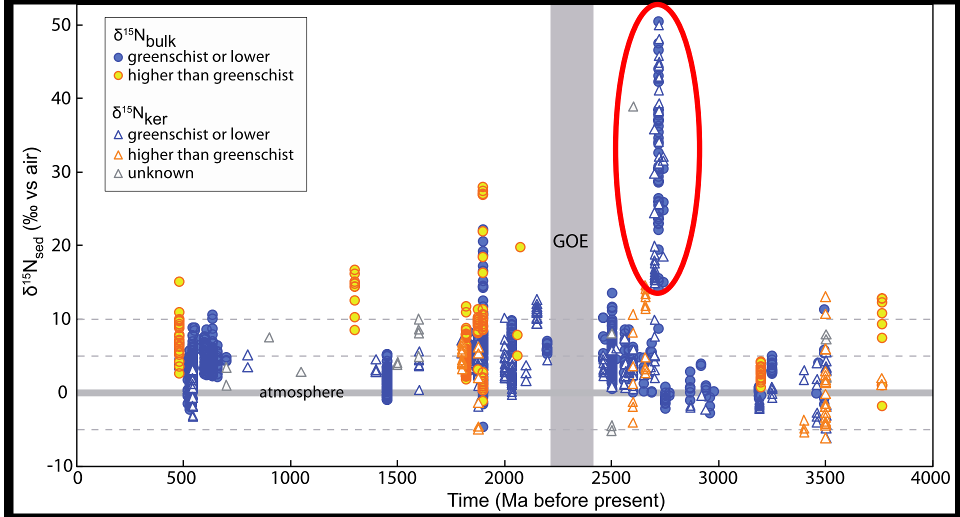


- Ammonium is the main bioavailable fixed N species

2.8 – GOE

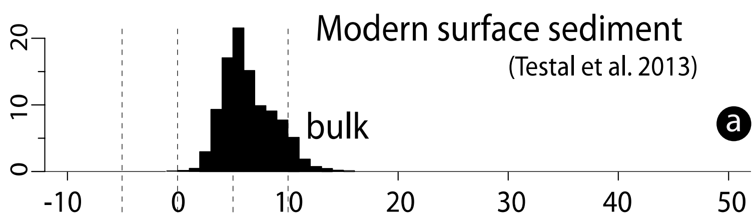


Increase in δ^{15}N mode ≈ 3 ‰ ….



… values up to 55‰ !

2.8 – GOE



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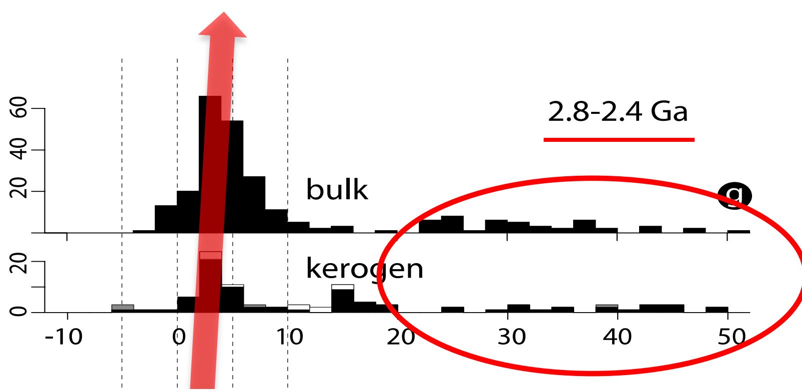

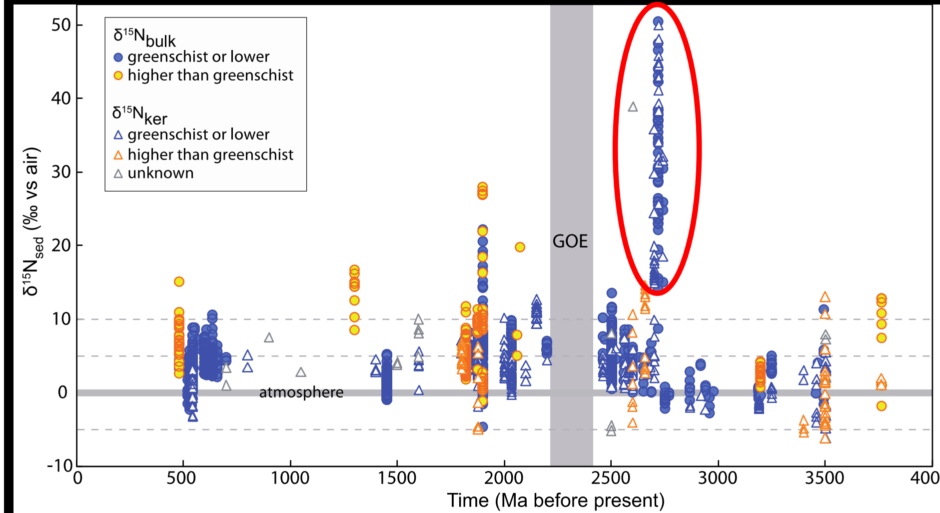

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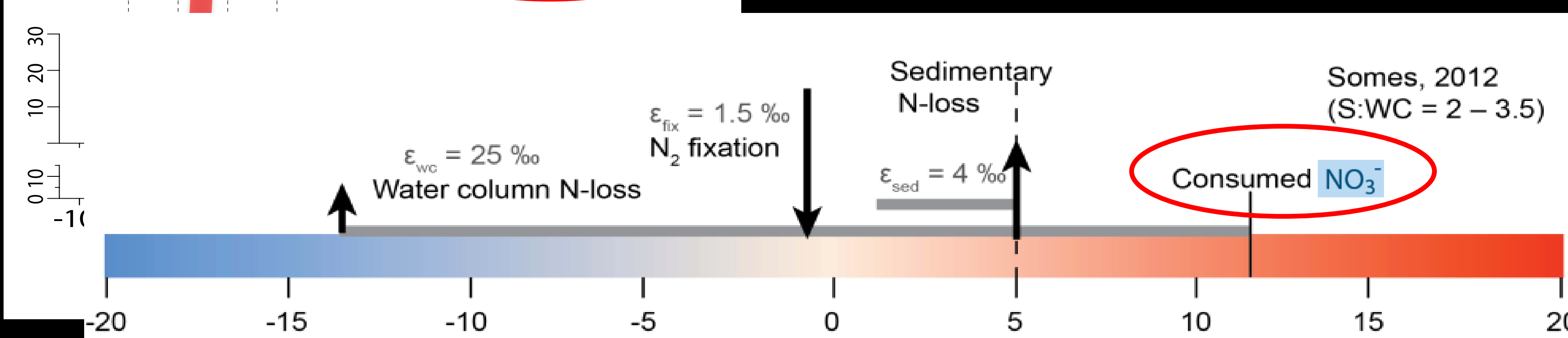
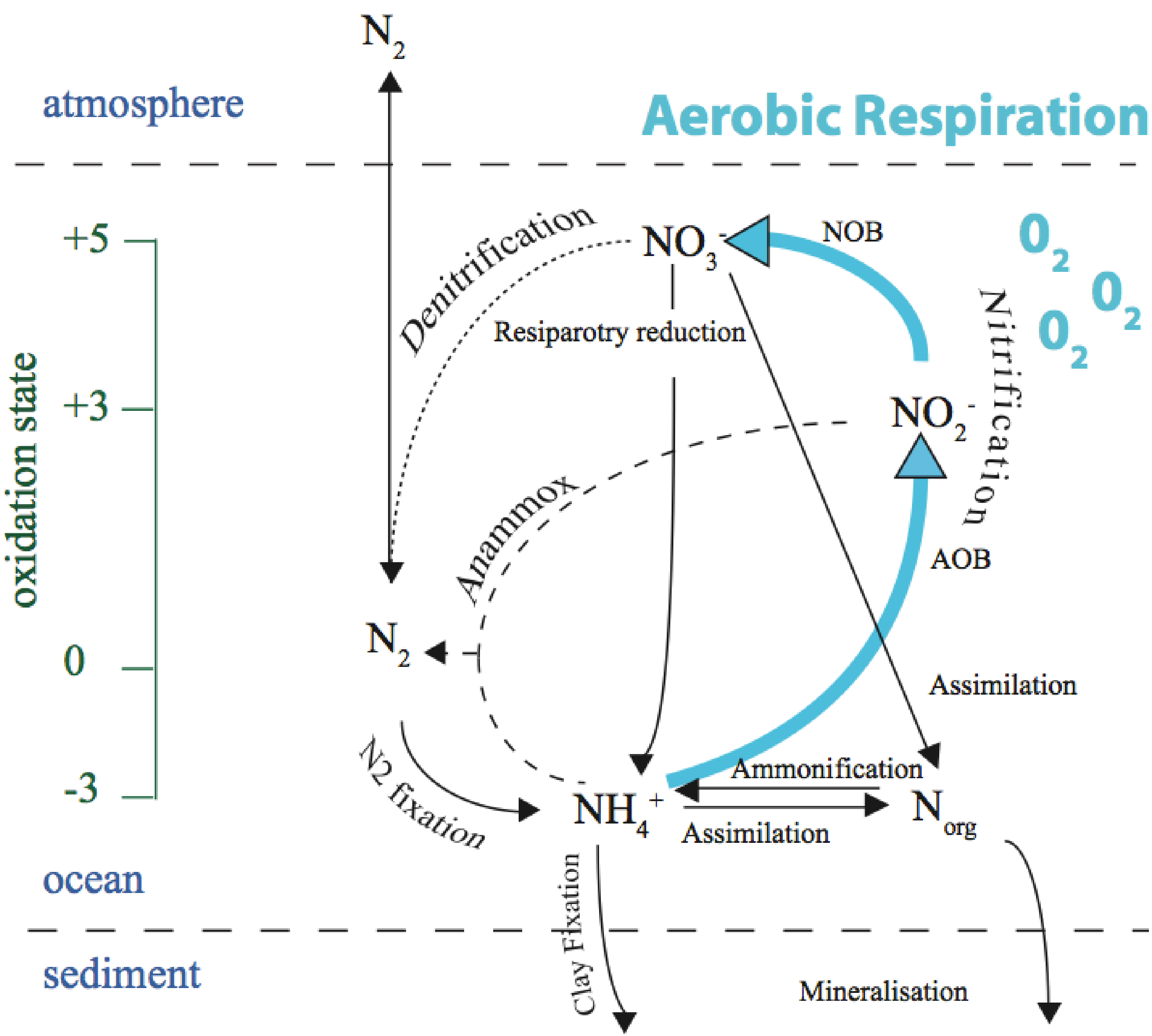


2.8 – GOE

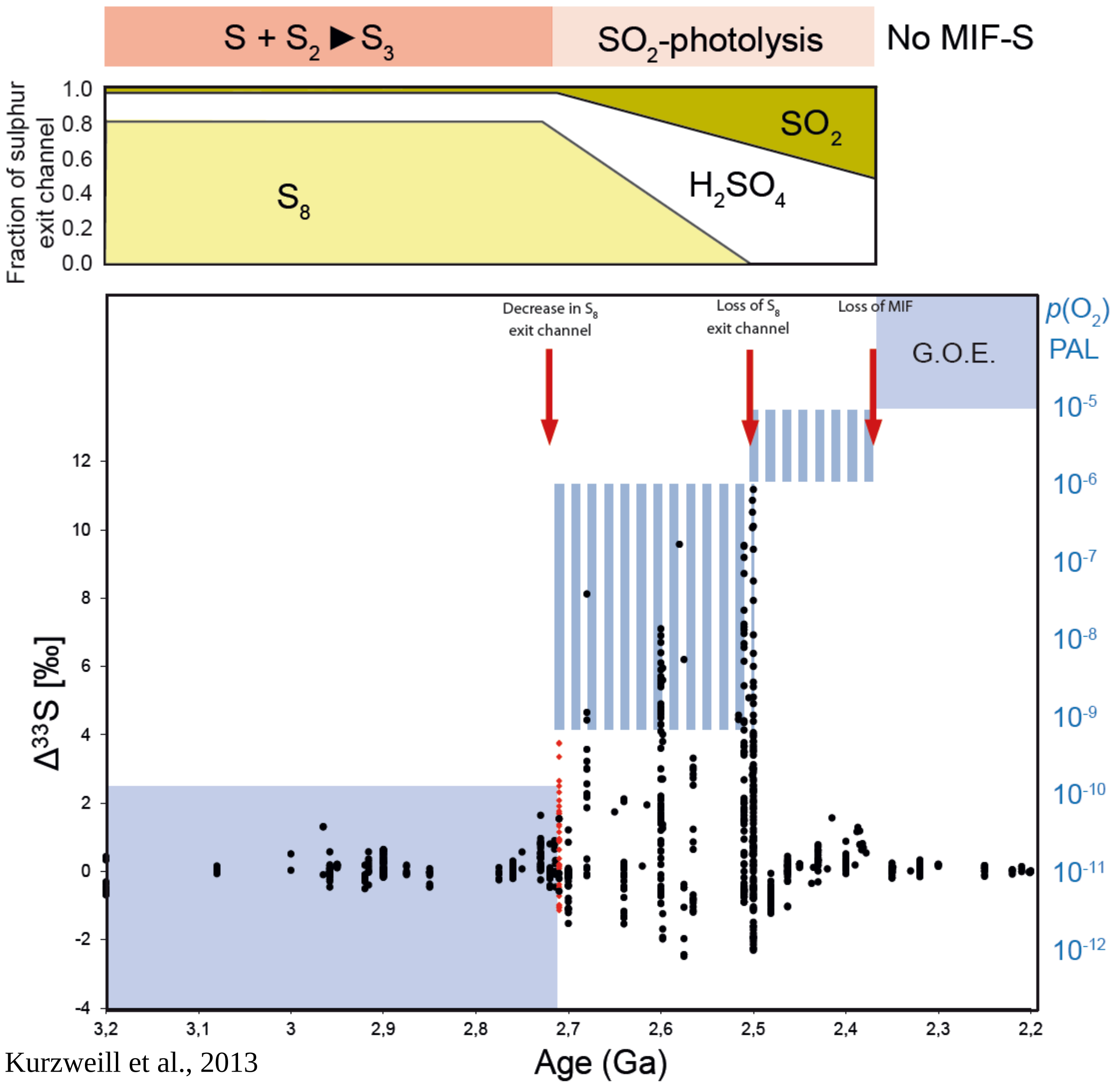
- **occurrence of O_2 (possibly cryptic) in Archean oceans**

- ***Must have help to slowly growth a stable nitrate reservoir (nitrification)*** **…..**



Thomazo et al., 2011

2.8 – GOE

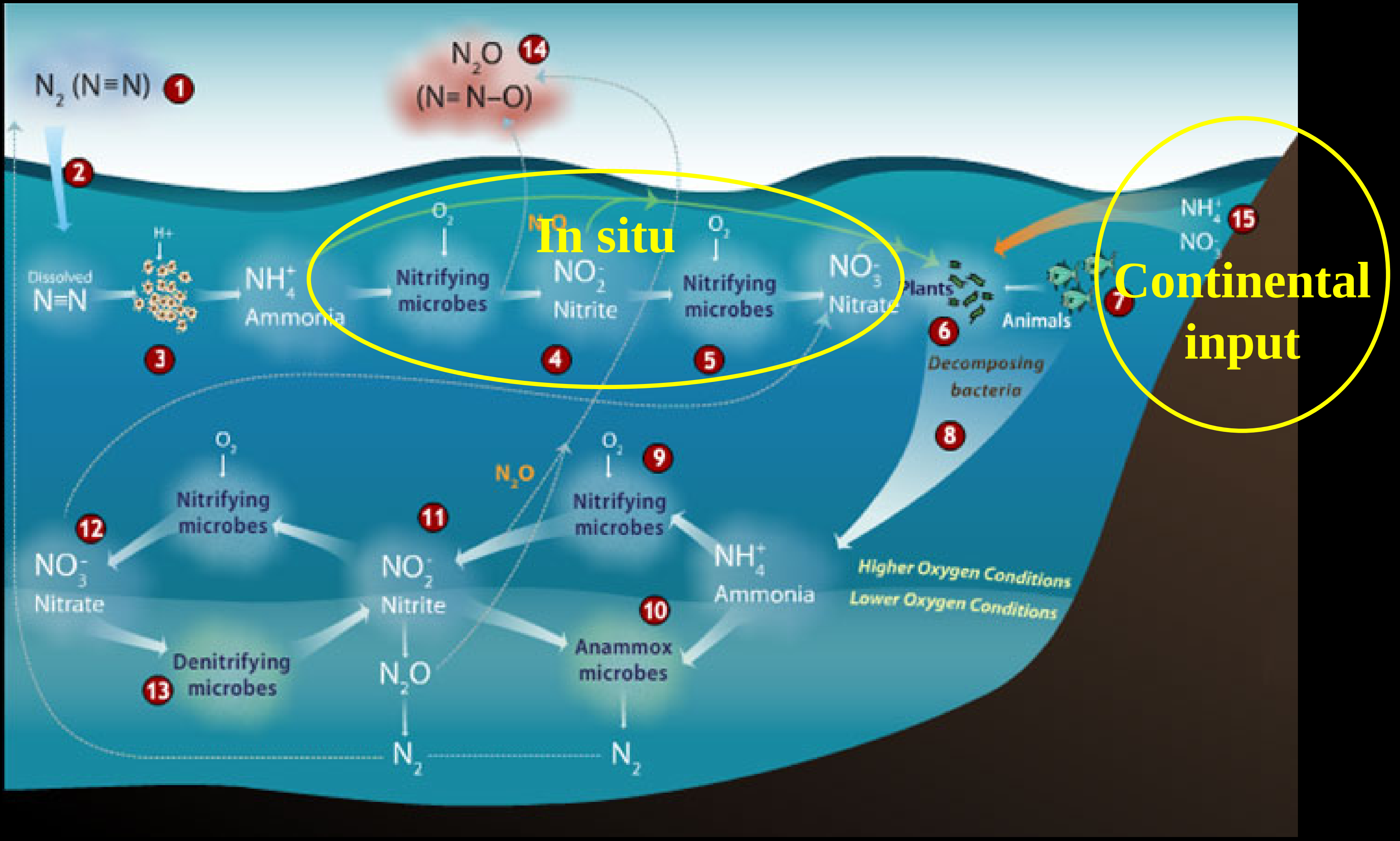


Kurzweill et al., 2013

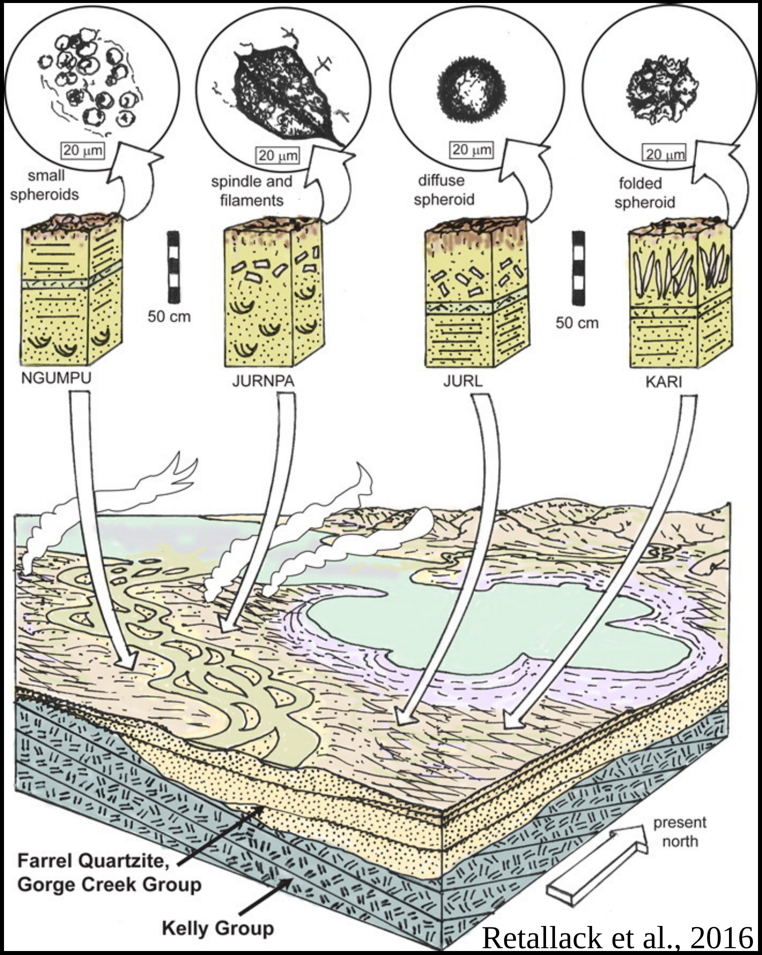
- Consistent with MIFs record (increase in oxygen!)

Lessons from the modern N cycle

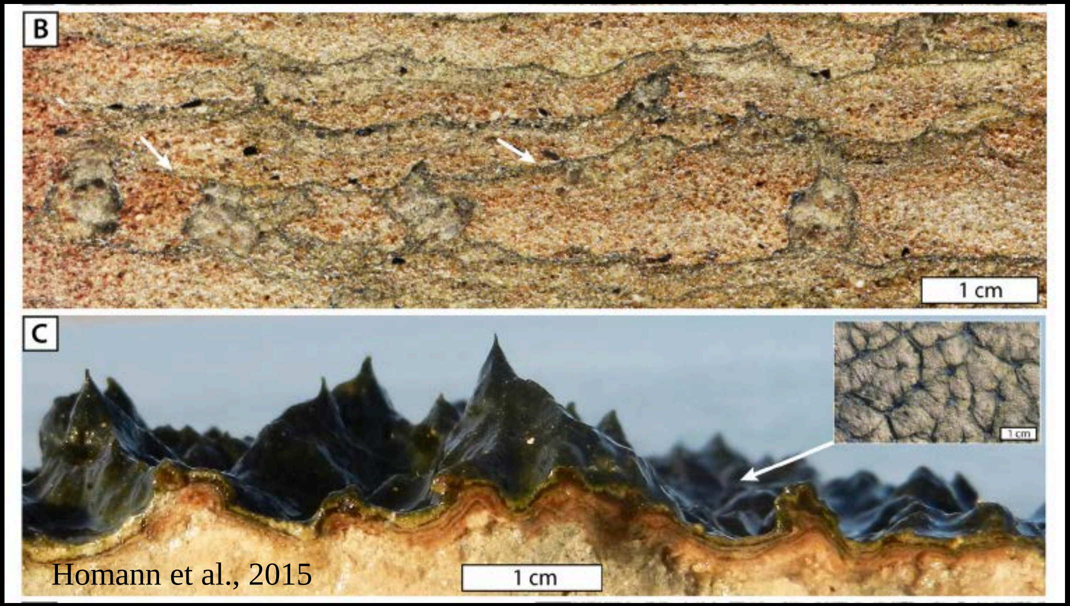
Origin of the nitrate signal preserved in the $\delta^{15}N$ sedimentary record?



An Archean continental biomass ?

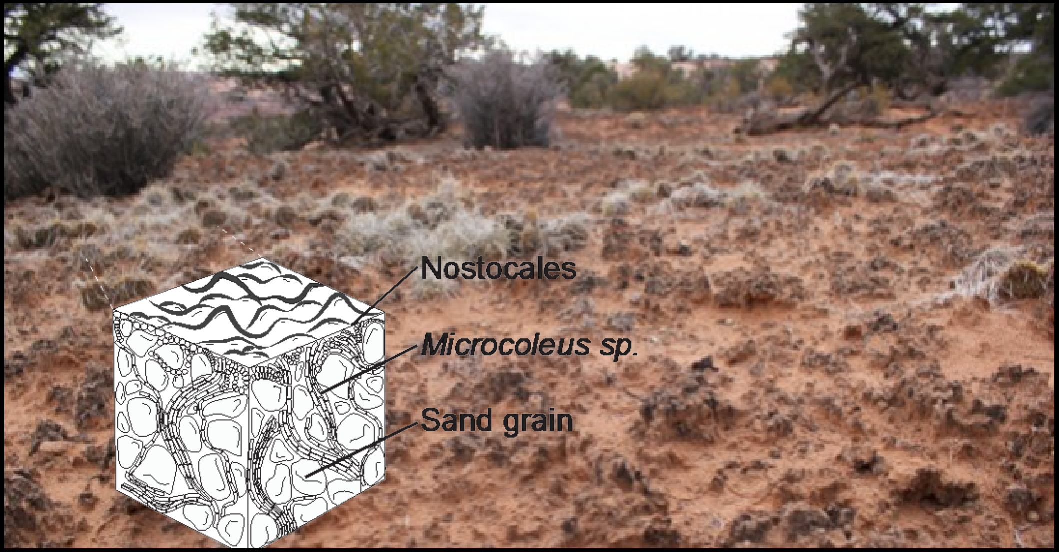


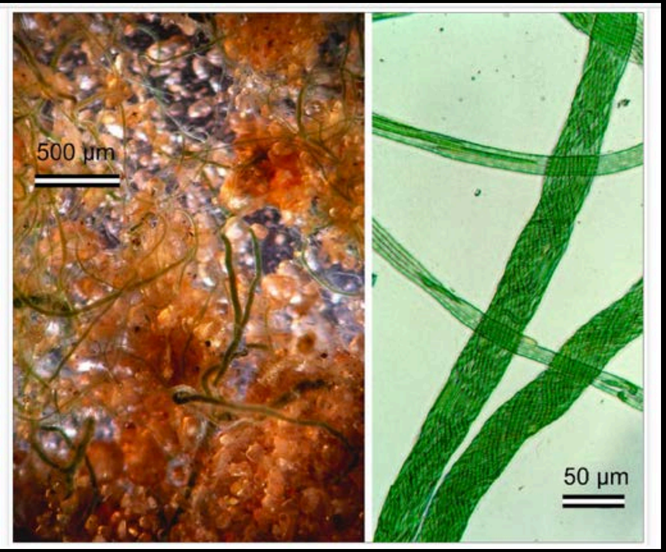
Coastal-plain paleosols - 3.0 Ga Farrel Quartzite (Western Australia)

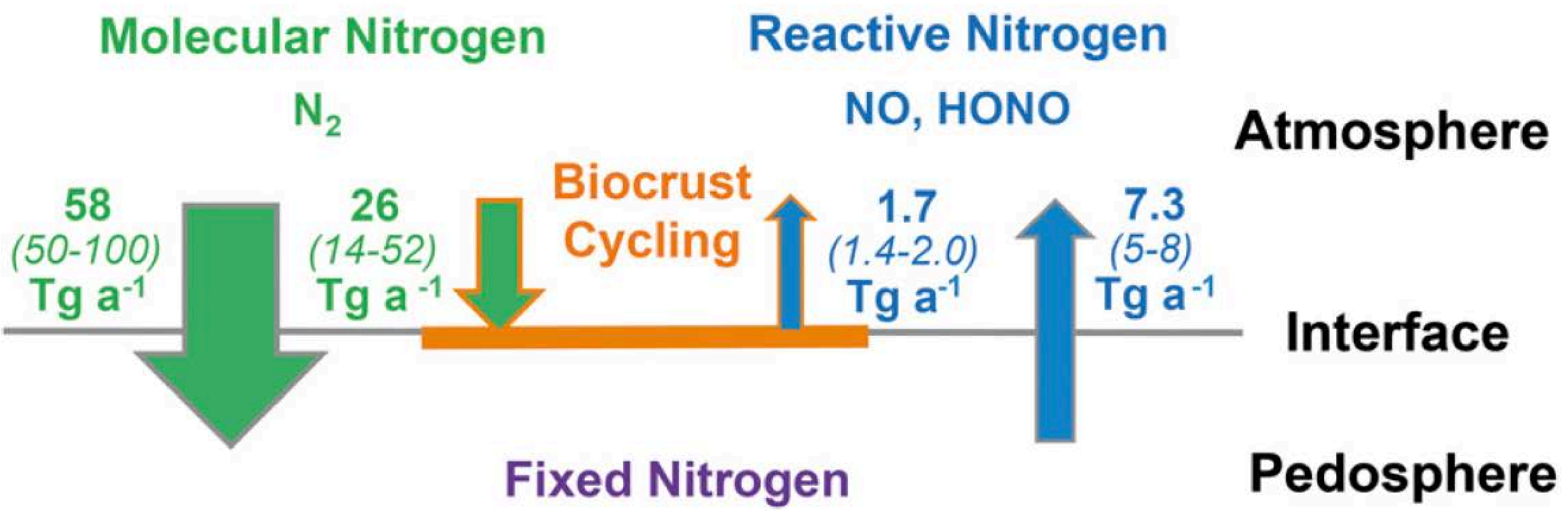


Wavy-crinkly microbial mats - 3.2 Ga Moodies Group sandstone (South Africa)

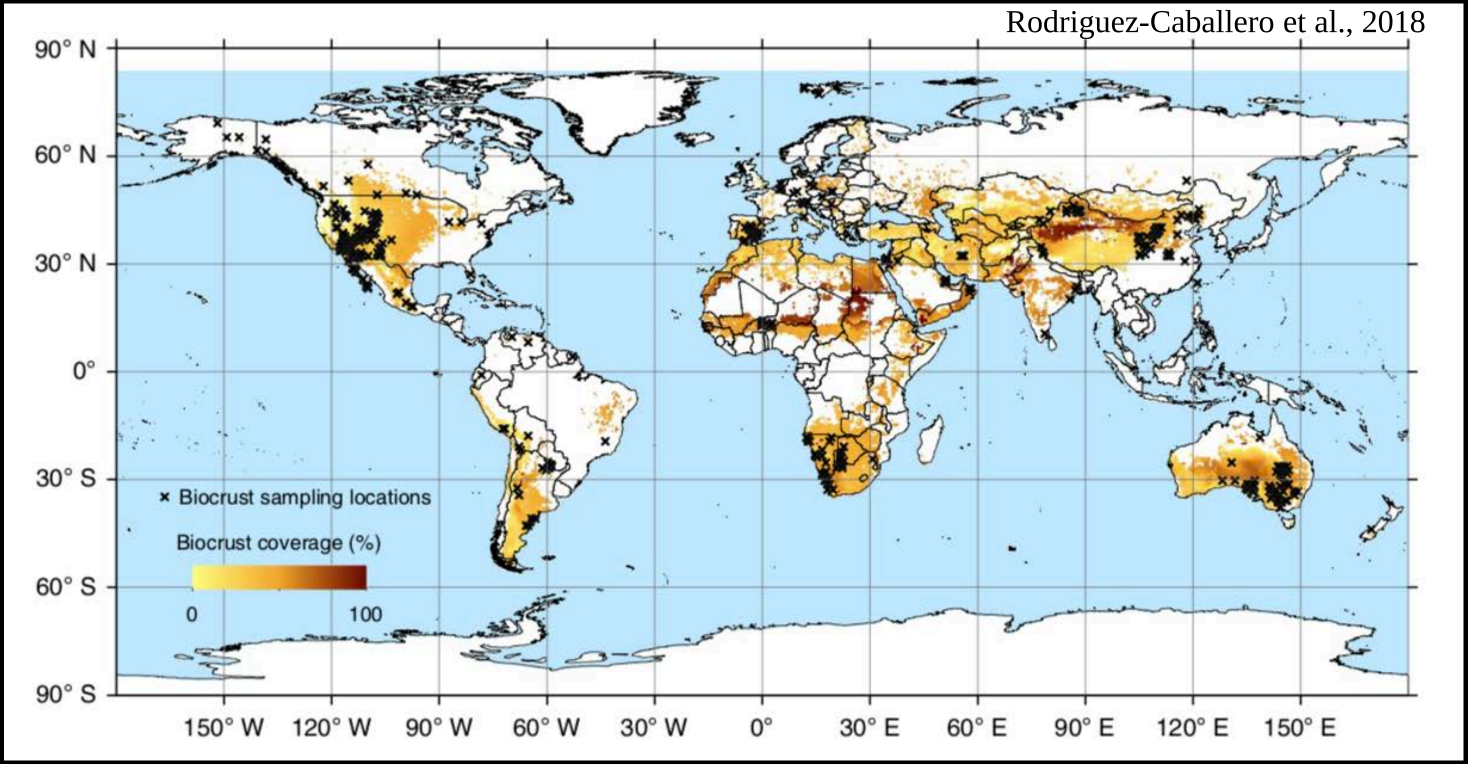
Modern Biocrusts







Modern Biocrusts



- Modern BSCs are arguably the most extensive biofilm on the planet covering up to 12% of Earth's continental area

- They are primarily built by cyanobacteria performing oxygenic photosynthesis

Modern Biocrusts

Modern Biocrusts

	Location	Net N outputs from crusts to subsurface soil (m^{-2} yr^{-1})
Johnson et al.[43]	Colorado Plateau	2.080–8.820[a]
Thiet et al.[46]	Lake Michigan	0.020–0.800[a]
Rychert & Skujins[49]; West & Skujins[50]	Cold desert	0.19–1.9
Rychert et al.[51]	Australia	0.025
Evans & Johansen[52]	Sonoran Desert	0.133–0.342
Evans & Lange[53]; Belnap[54, 55]; Russow et al.[56]; Stewart et al.[57,58,59]; Caputa et al.[60]	Global	0.0133–1.9
Elbert et al.[42]	Global	0.144[b]

Direct estimate

extrapolated from the nitrogen import fluxes

= N input times 19% of export

Modern Biocrusts

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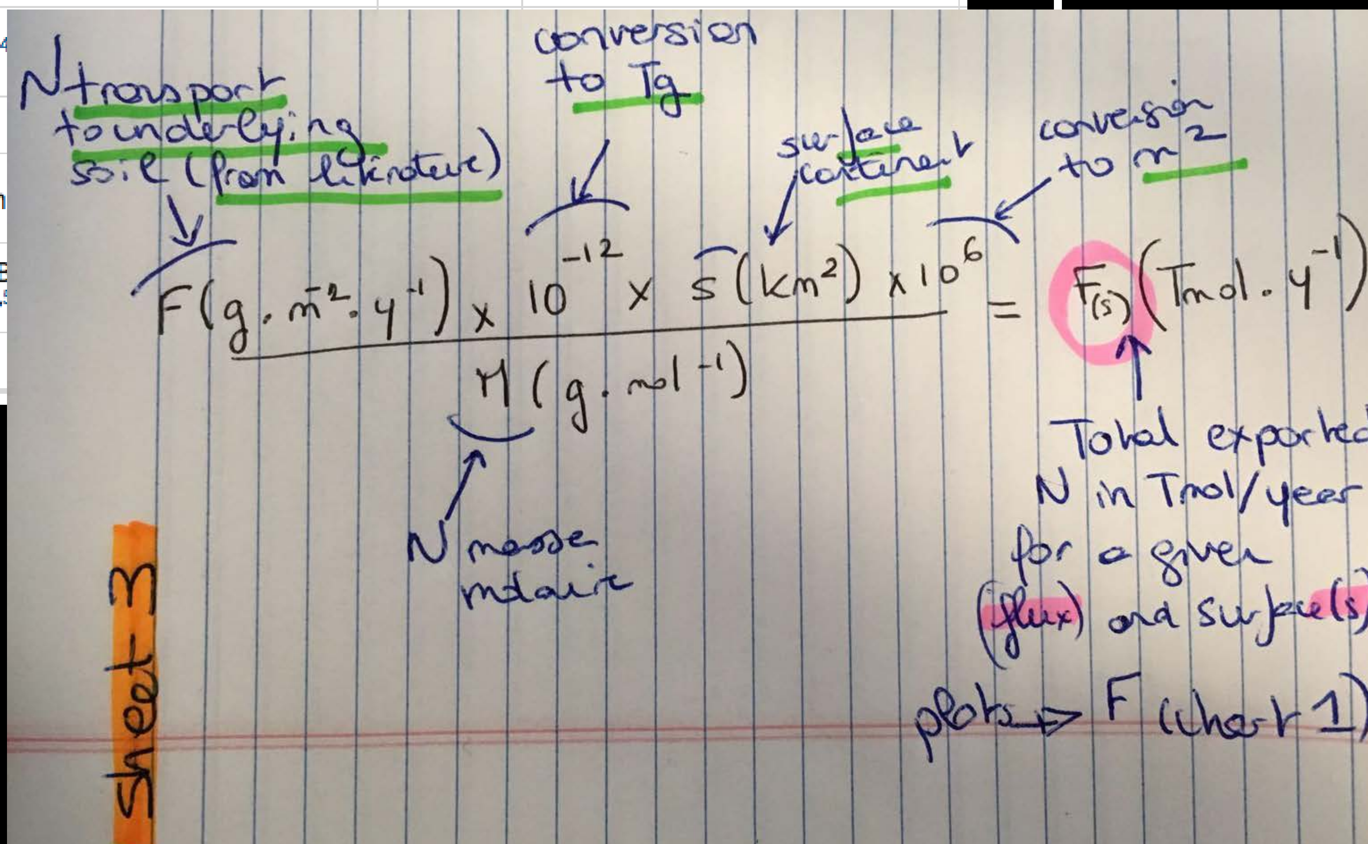
Elbert et al.[42]		

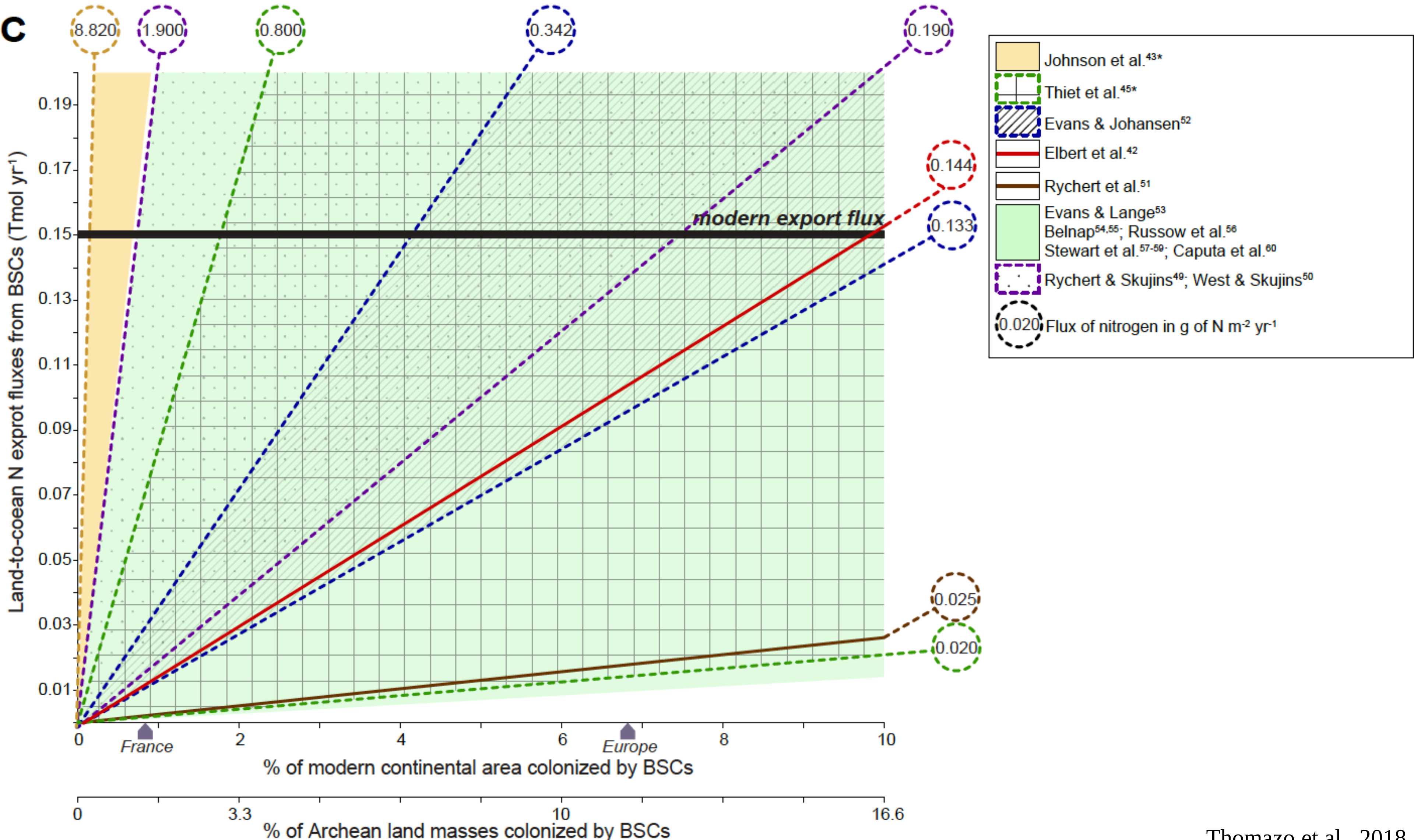
Direct estimate

d from

n import



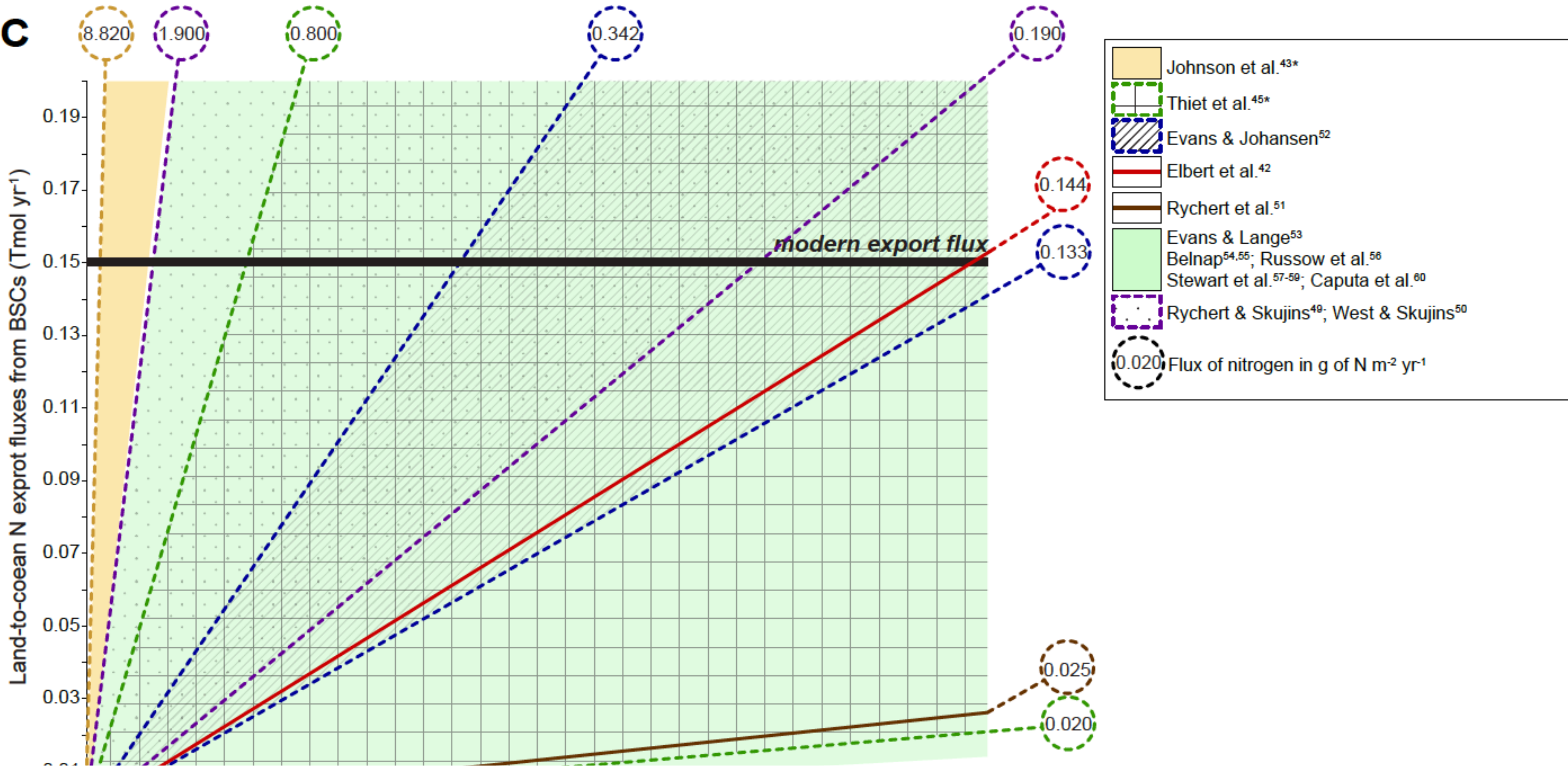
Modern Biocrusts



Thomazo et al., 2018

assuming a total emerged surface of about 90 Mkm2 at around 2.45 Ga, i.e., 60% of the present day value

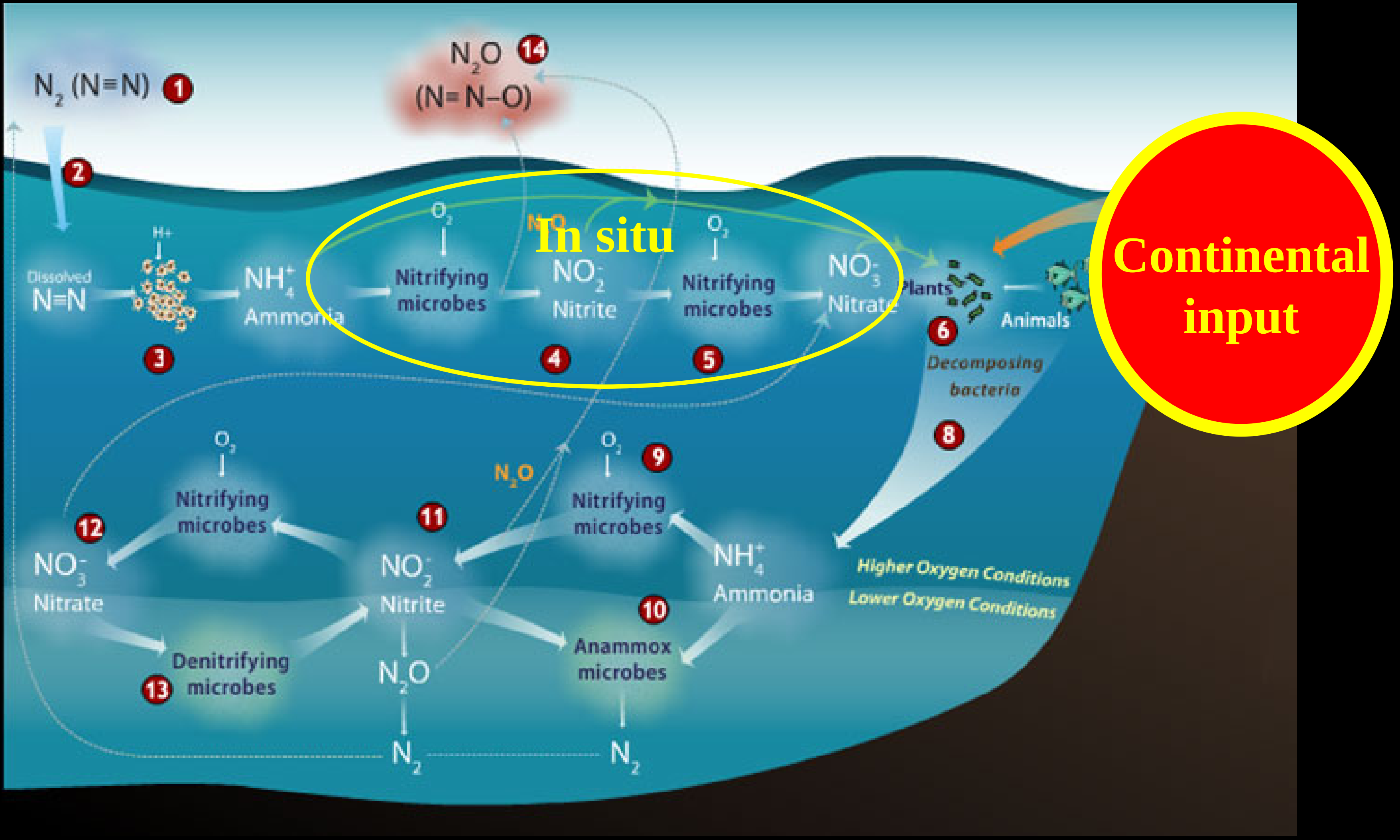
Modern Biocrusts



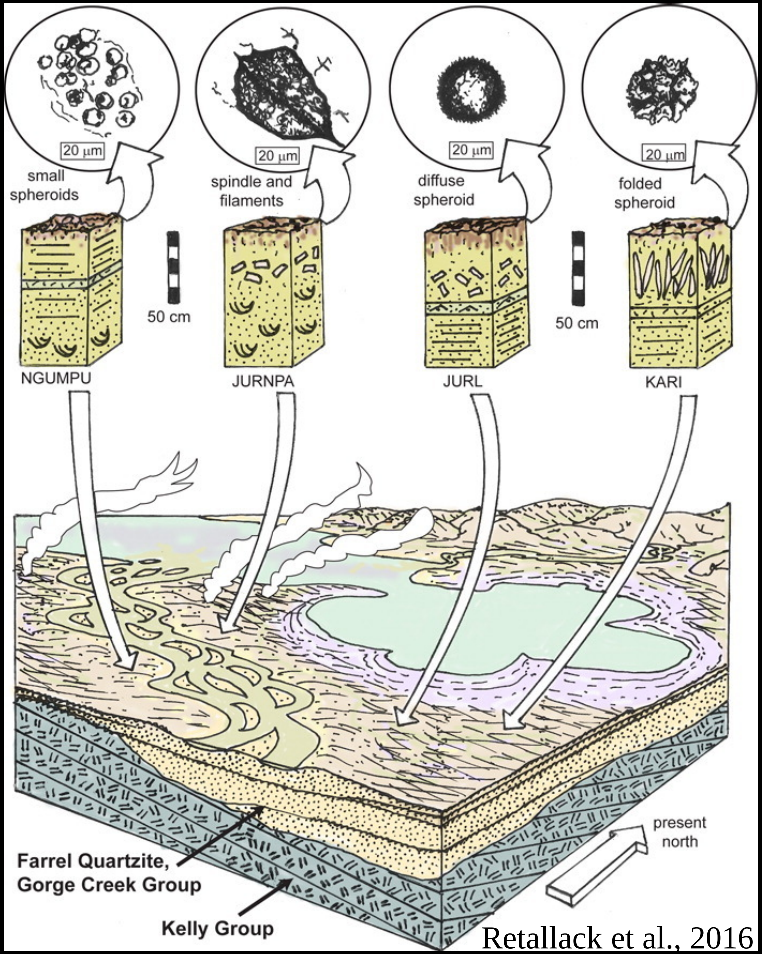
Large range of fluxes but averages direct and indirect estimates suggest that between 16% of colonization of Archean continents with terrestrial « cyanobacteria » would be enough to recapitulate the modern N export from land to ocean!

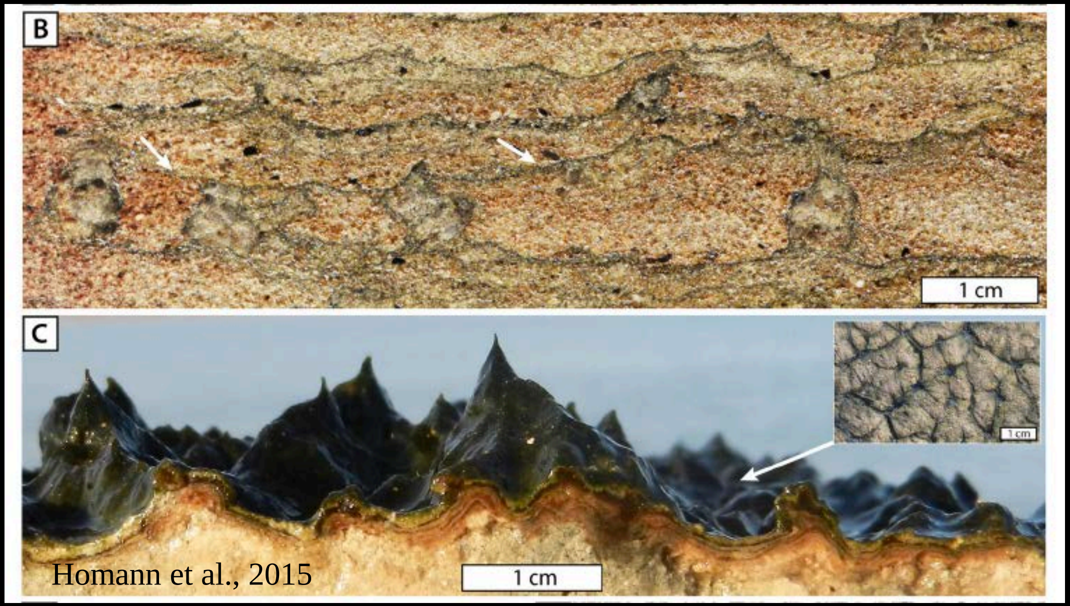
Lessons from the modern N cycle

Origin of the nitrate signal preserved in the $\delta^{15}N$ sedimentary record?



Archean record of Biocrusts?





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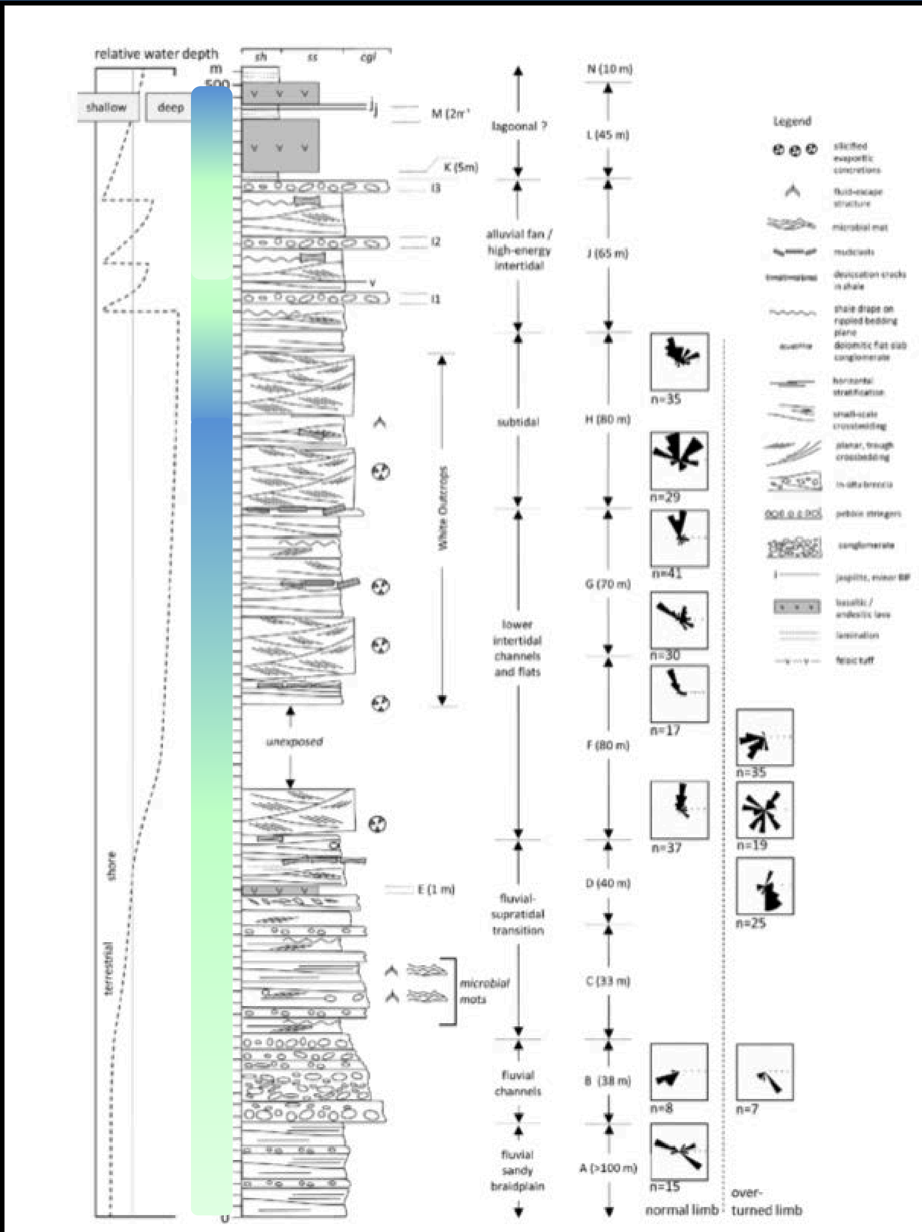
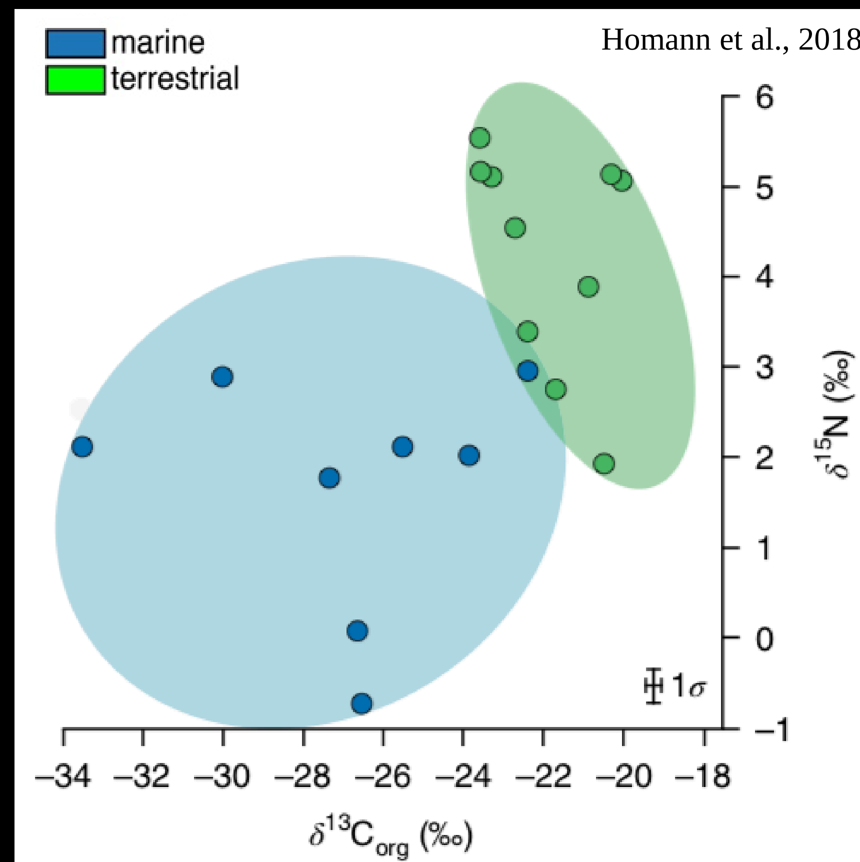


Figure 5. Stratigraphic column of Moodies strata in the western Dycedale Syncline, measured along the normal limb.



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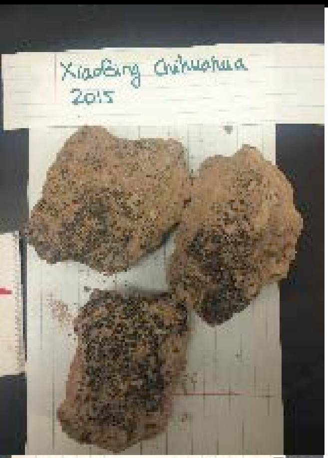
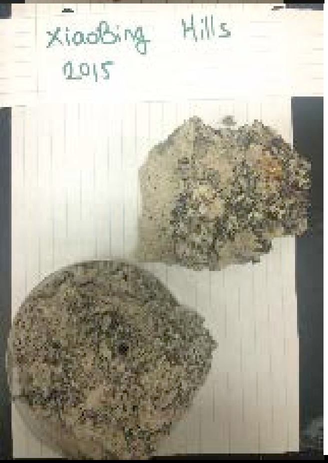
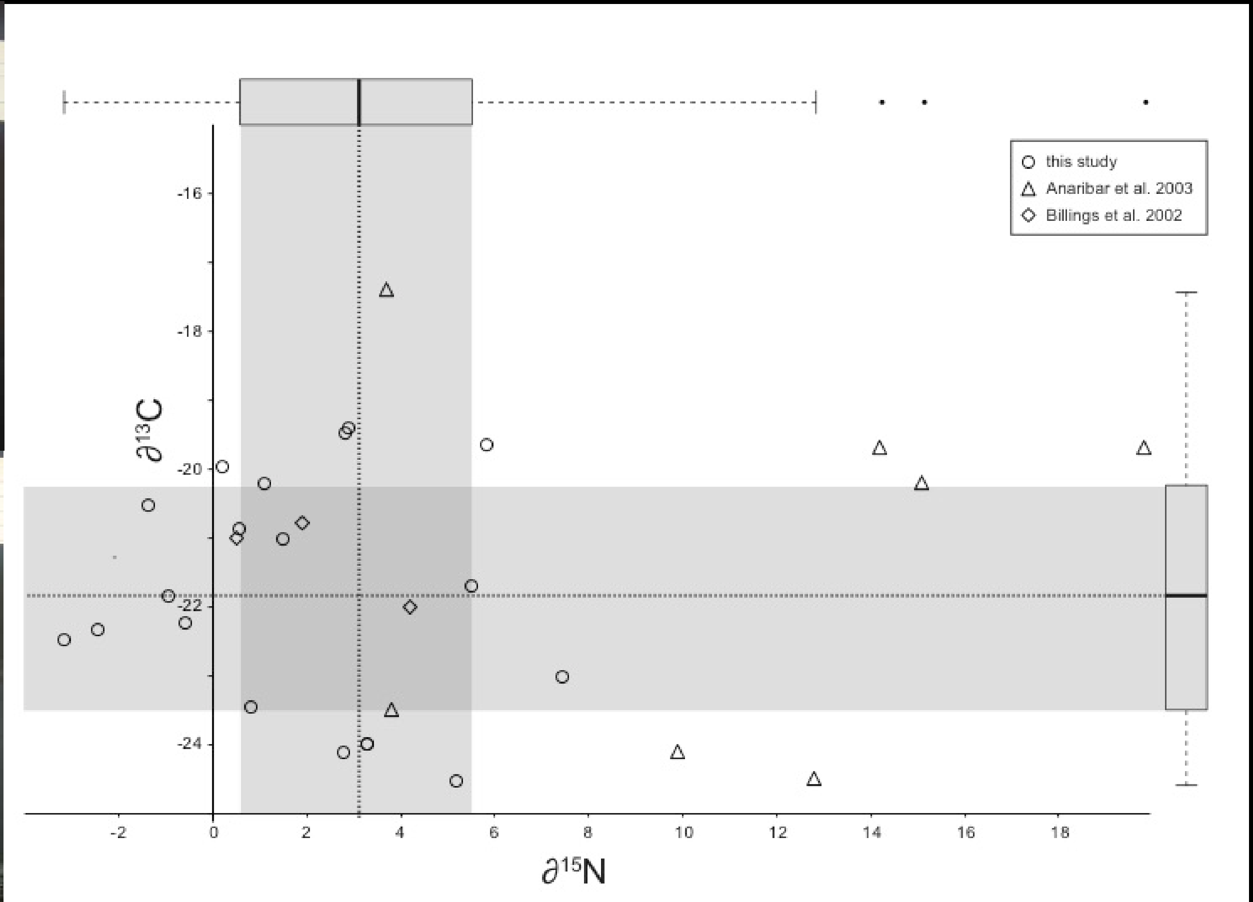
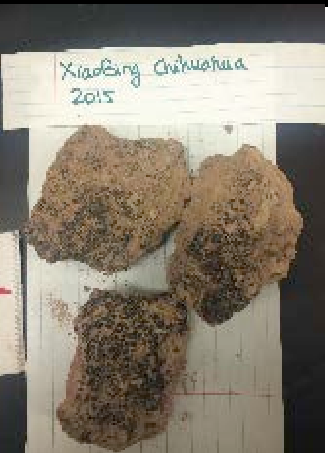
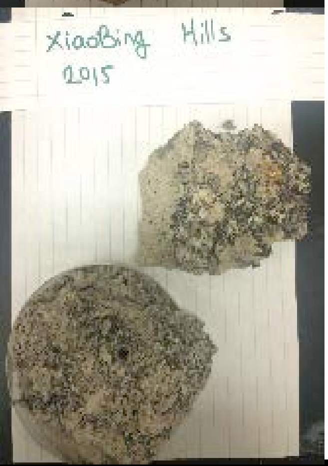


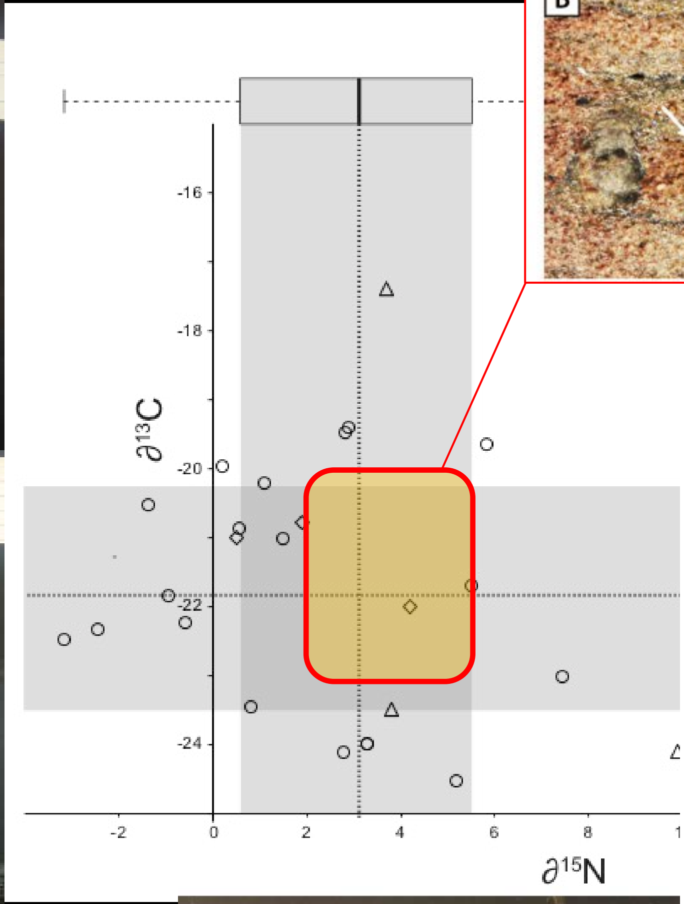


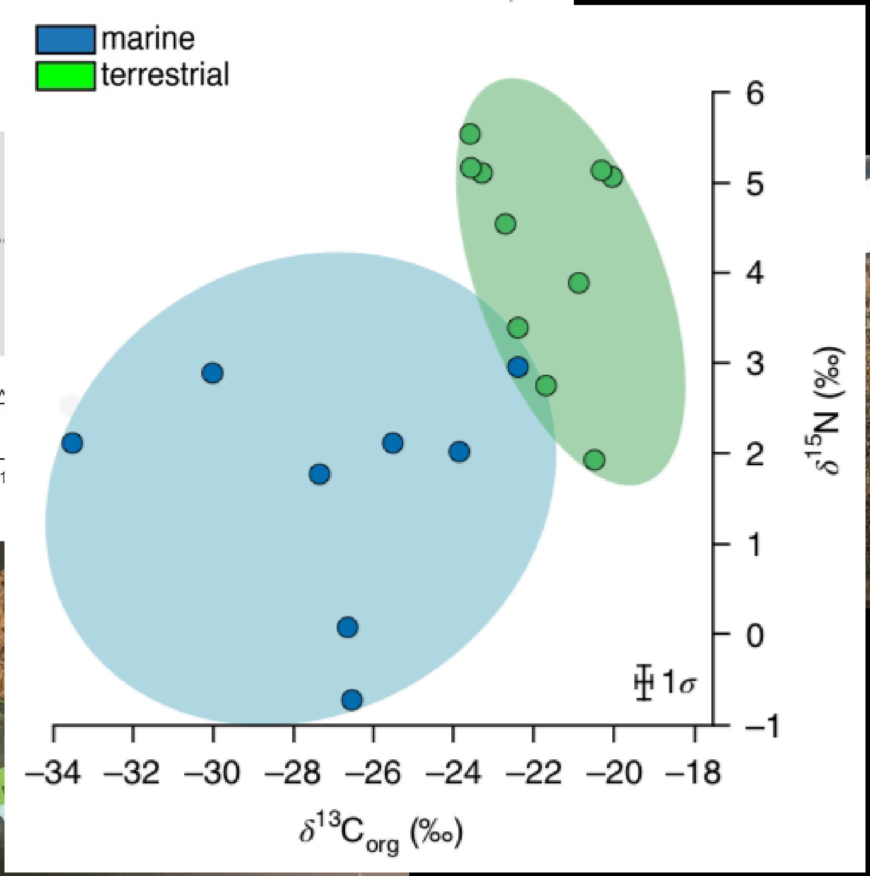


Archean record of Biocrusts?

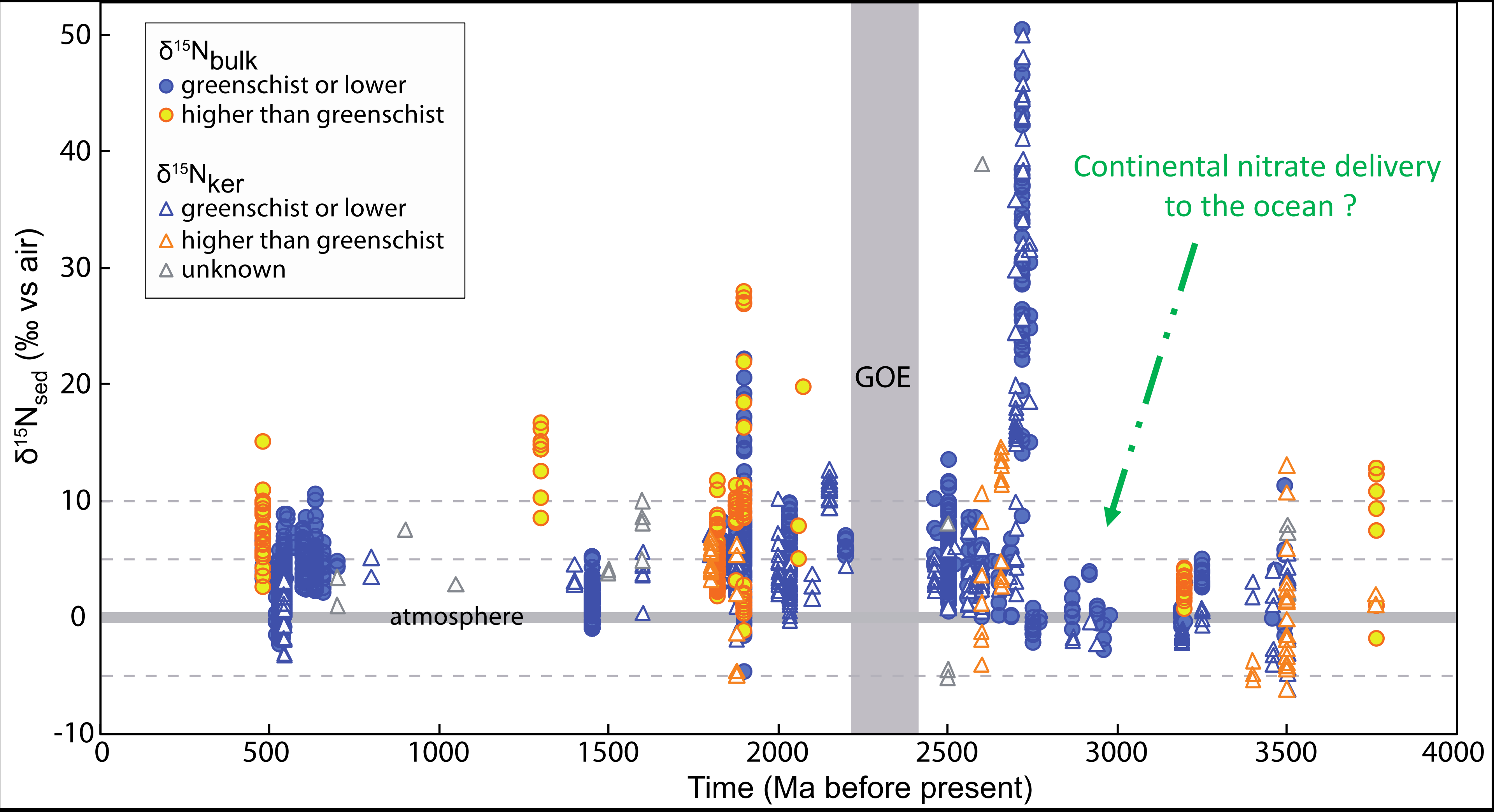






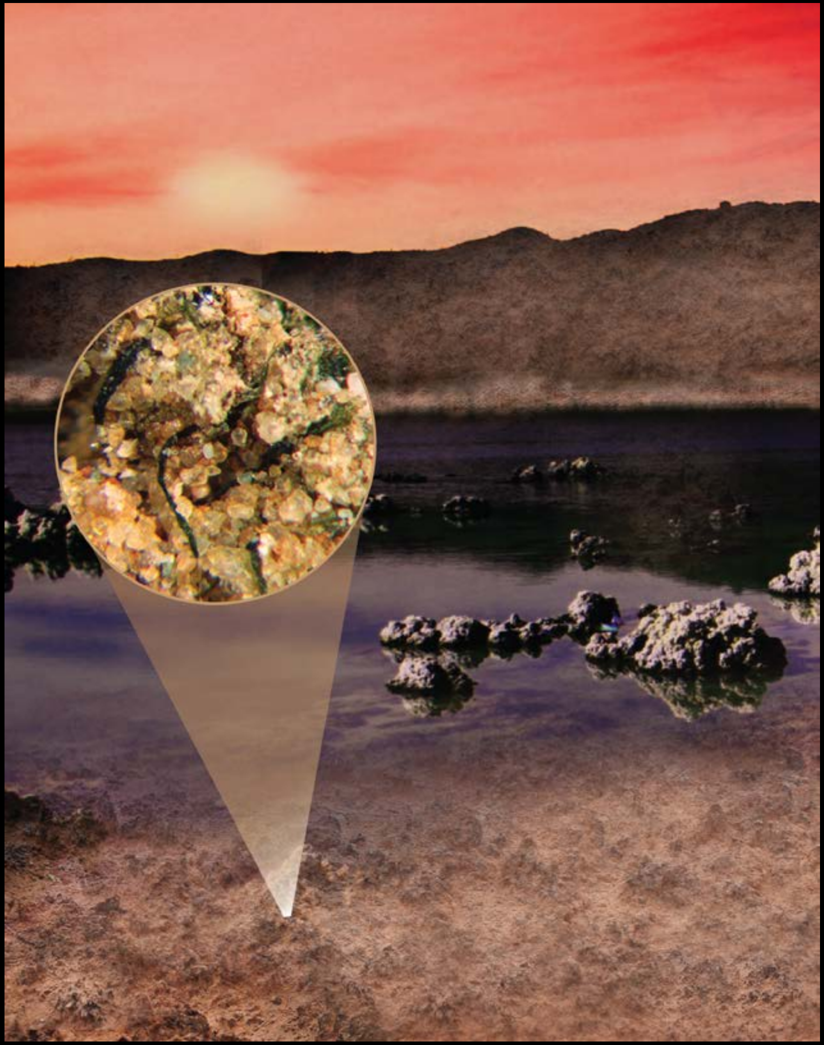


Precambrian sedimentary nitrogen isotopes



Conclusions

- Part of **the evolution of the early biogeochemical cycle of nitrogen** underline the **increasing oxygen concentration before the GOE**.



- **Nitrate** – the oxidized form of nitrogen – **is cycled by organisms since at least 2.7 Ga (δ^{15}N record)**

- **Part of this nitrate may come from a continental biocrusts-like Archean biosphere** (3.2 Ga – earlier?)

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Possible nitrogen fertilization of the early Earth Ocean by microbial continental ecosystems

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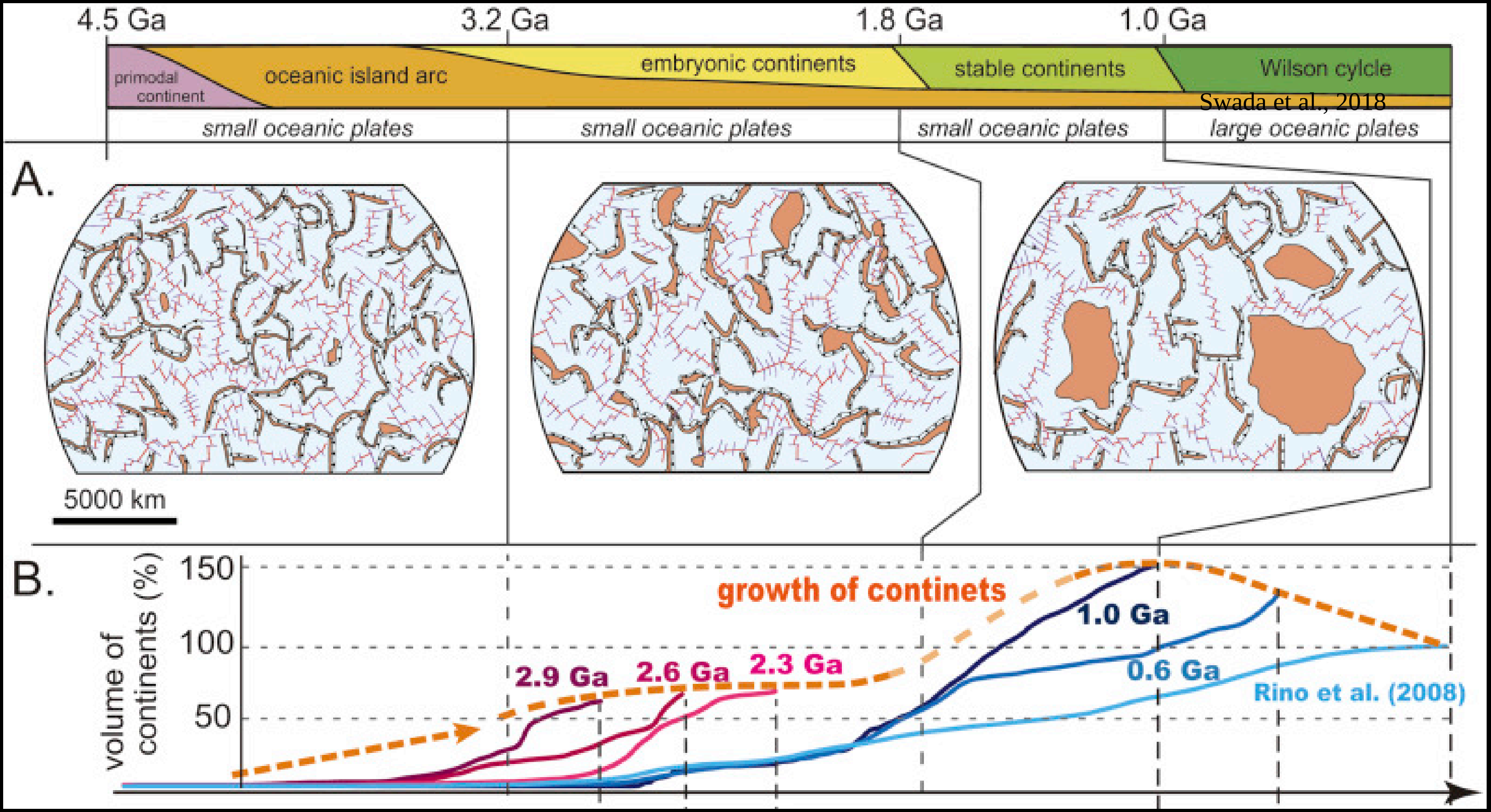
erc European Research Council Established by the European Commission



4.5 Ga
3.2 Ga
1.8 Ga
1.0 Ga
primodal continent
oceanic island arc
embryonic continents
stable continents
Wilson cylcle
Swada et al., 2018
small oceanic plates
small oceanic plates
small oceanic plates
large oceanic plates
A.
5000 km
B.
volume of continents (%)
150
100
50
growth of continets
2.9 Ga
2.6 Ga
2.3 Ga
1.0 Ga
0.6 Ga
Rino et al. (2008)