

THE LIVING SUBSURFACE: MICROBIAL OVERPRINTING OF SUBSURFACE GEOLOGICAL PROCESSES AND IMPLICATIONS FOR NATURAL RESOURCE EXPLORATION

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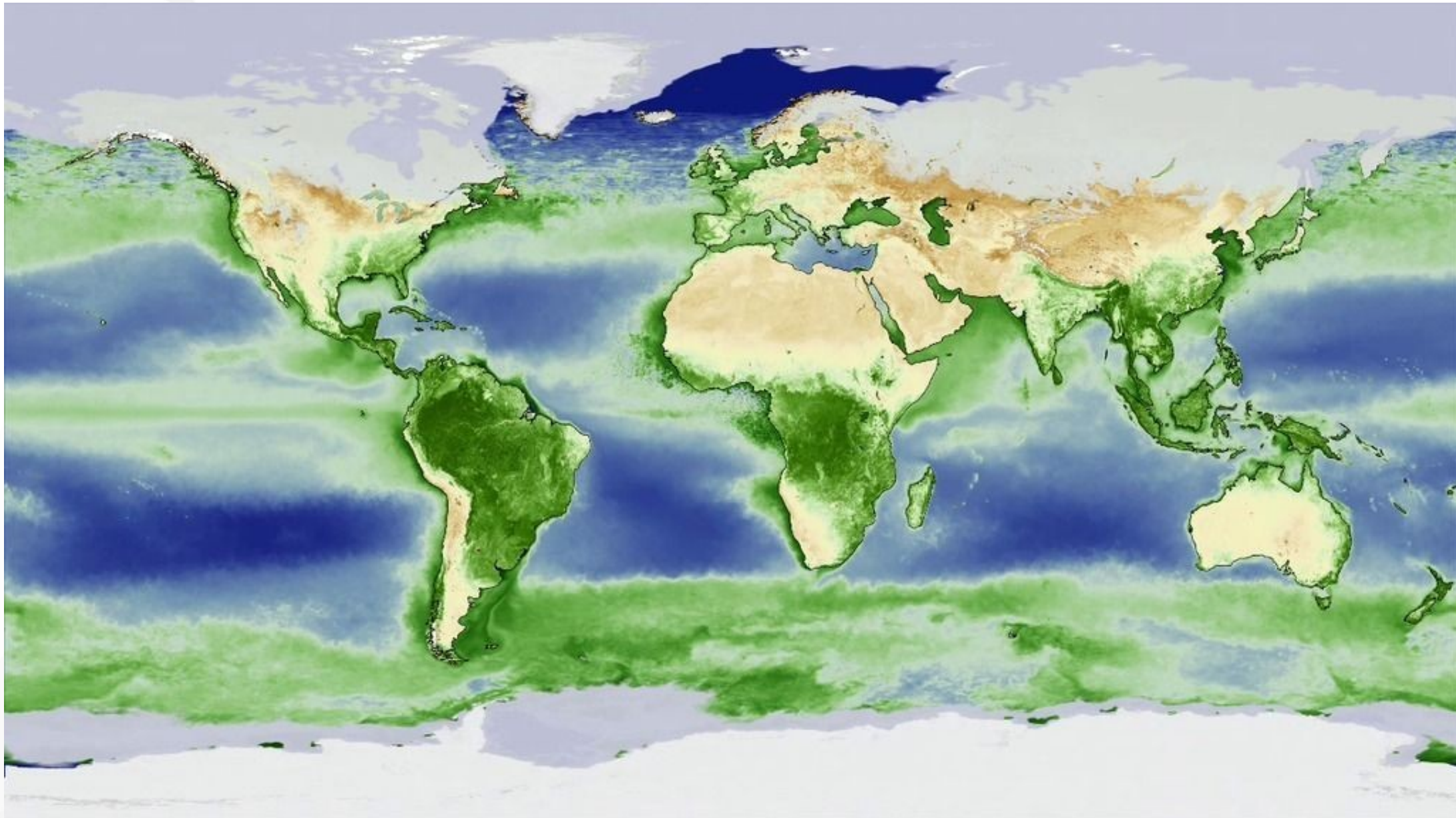
**CNR
IRBIM**
ISTITUTO PER LE
RISORSE BIOLOGICHE
E LE BIOTECNOLOGIE
MARINE



RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

ELSI
EARTH - LIFE SCIENCE INSTITUTE

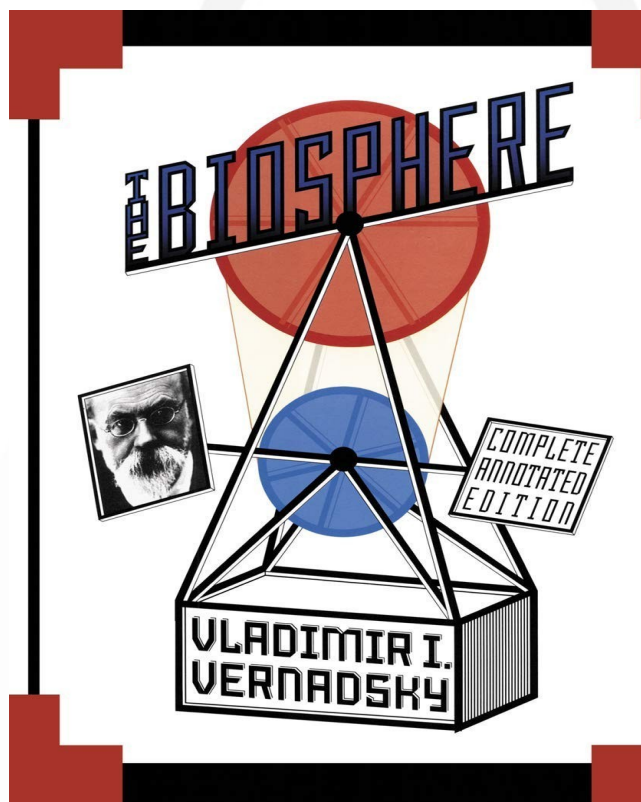






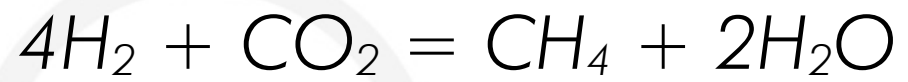


LIFE IS A
GEOLOGICAL FORCE
THAT SHAPES THE
EARTH

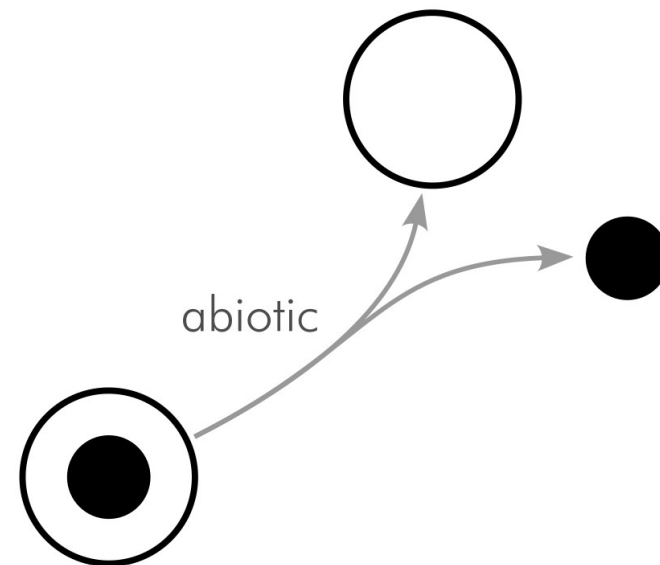


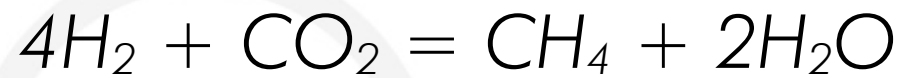
LIFE IS A GEOLOGICAL FORCE THAT SHAPES THE EARTH

Vladimir I. Vernadsky
The Biosphere, 1926



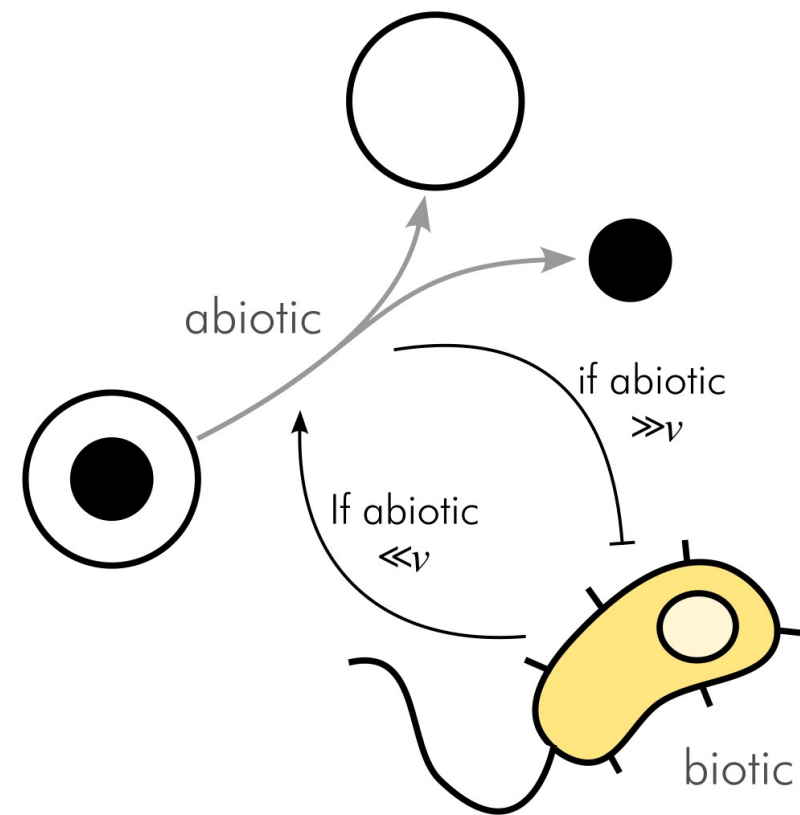
$\Delta G^\circ -48 \text{ kJ/mol}$

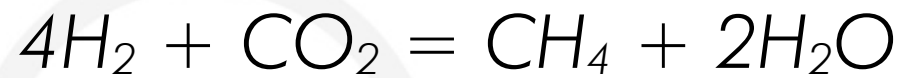




$$\Delta G^\circ -48 \text{ kJ/mol}$$

For biology to use a redox reaction for energy conservation it needs:





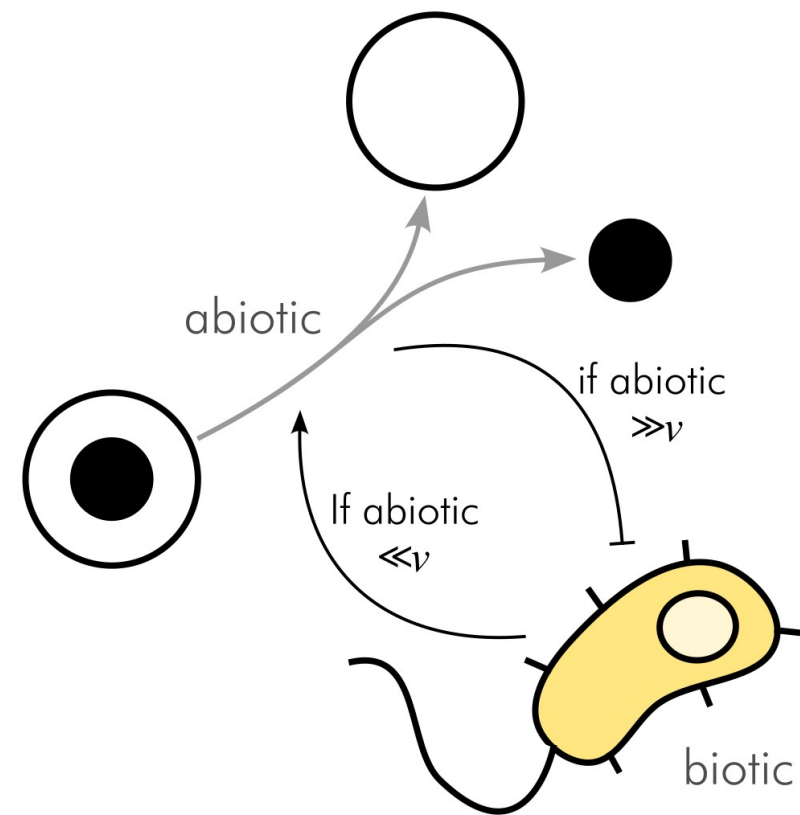
$$\Delta G^\circ -48 \text{ kJ/mol}$$

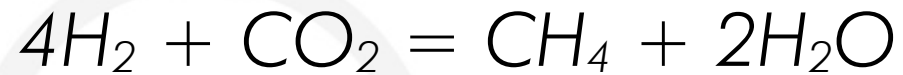
For biology to use a redox reaction for energy conservation it needs:

1. The reaction to be **exergonic**

(have a negative ΔG_r)

AND





$$\Delta G^\circ -48 \text{ kJ/mol}$$

For biology to use a redox reaction for energy conservation it needs:

1. The reaction to be **exergonic**

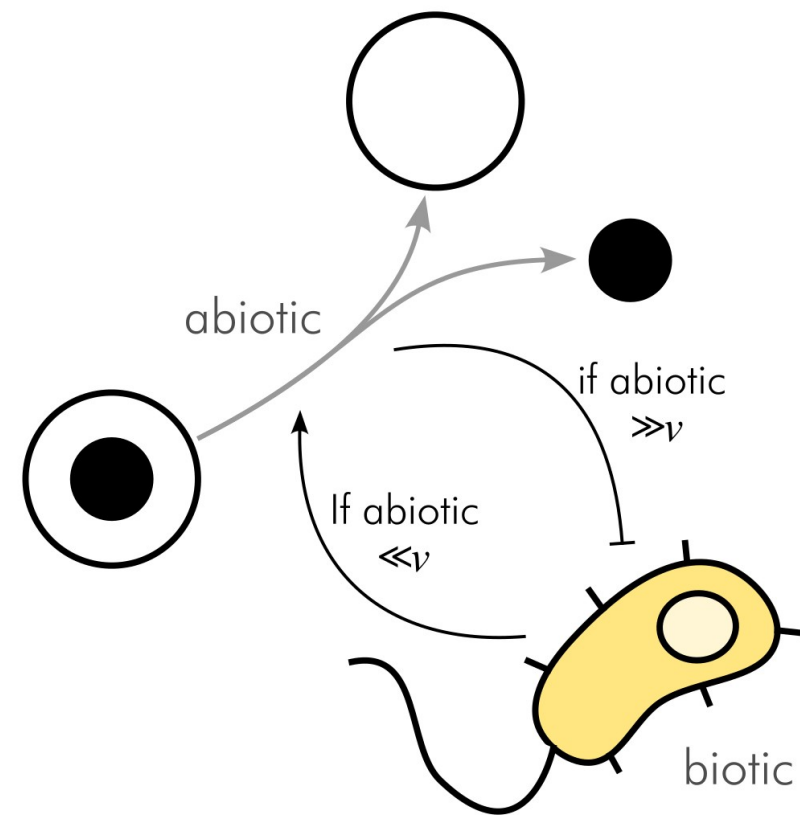
(have a negative ΔG_r)

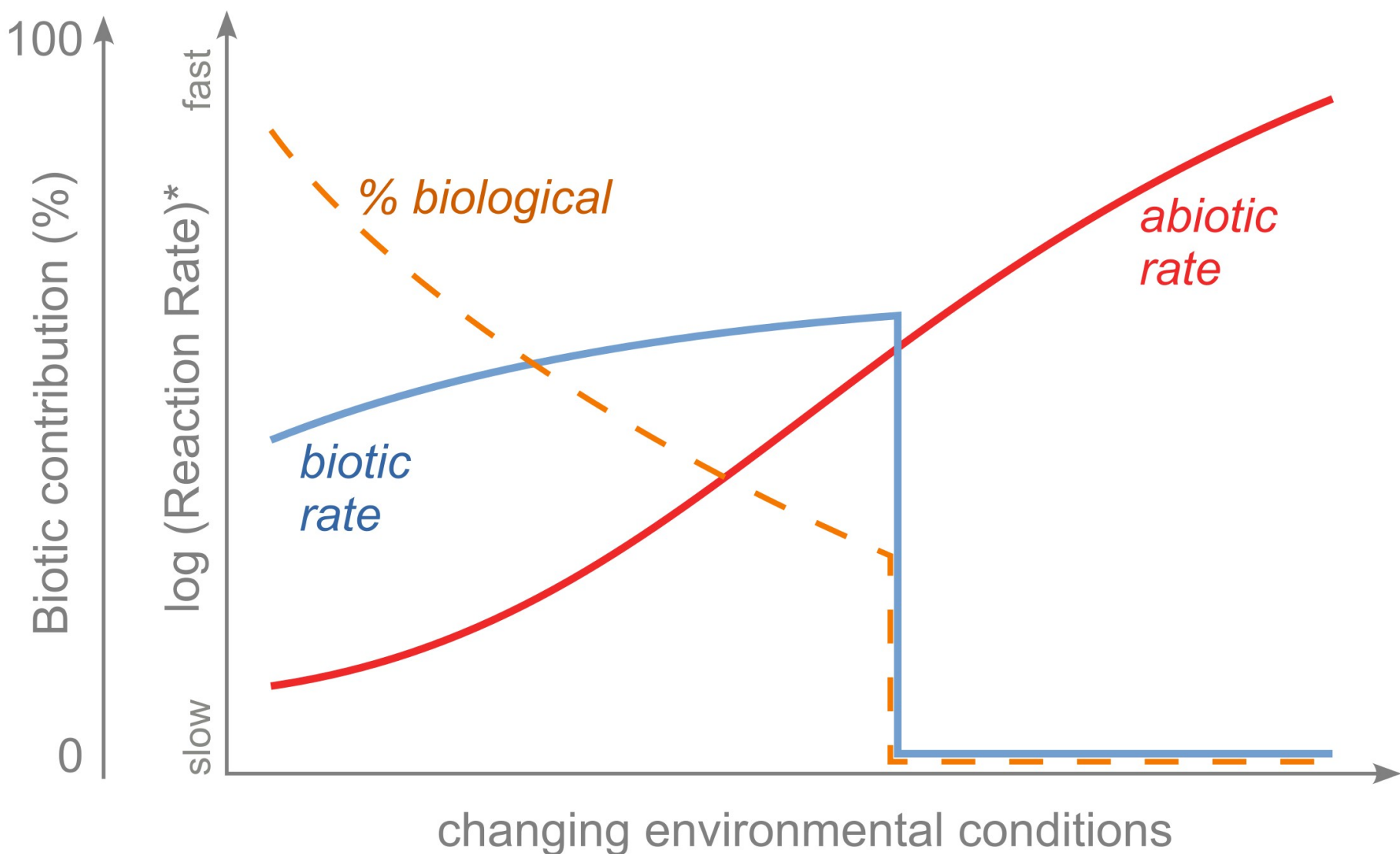
AND

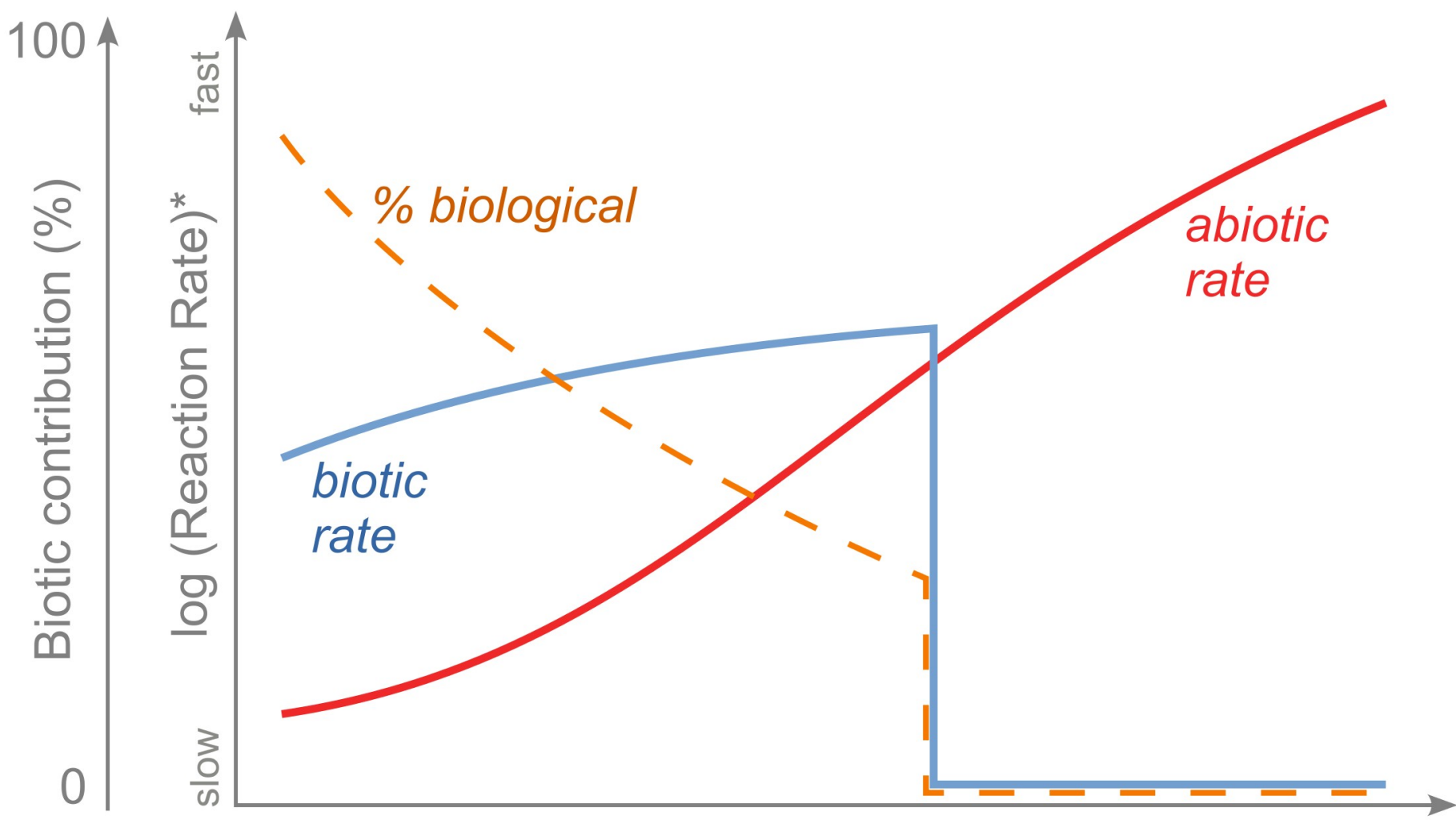
2. The **abiotic** reaction needs to be slow

OR

needs to have an activation barrier







changing environmental conditions



ENERGY AND REDOX COUPLES ON EXTANT EARTH

Oxygen as an electron acceptor			
1	$2\text{H}_2(\text{aq}) + \text{O}_2(\text{aq}) \rightleftharpoons 2\text{H}_2\text{O}$	4	
2	$2\text{NH}_4^+ + 3/2\text{CO}_2(\text{aq}) + \text{N}_2(\text{aq}) + 2\text{H}^+ + 3\text{H}_2\text{O}$		
3	$2\text{NH}_4^+ + 2\text{O}_2 + \text{N}_2\text{O}(\text{aq}) + 2\text{H}^+ + 3\text{H}_2\text{O}$	44	$\text{CO}(\text{aq}) + 1/2\text{O}_2(\text{aq}) + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{H}^+$
Nitrate as an electron acceptor			
4	$2\text{NH}_4^+ + 5/2\text{CO}_2(\text{aq}) + 2\text{NO}(\text{aq}) + 2\text{H}^+ + \text{H}_2\text{O}$	45	$\text{H}_2(\text{aq}) + \text{NO}_3^- \rightleftharpoons \text{H}_2\text{O} + \text{NO}_2^- + \text{H}^+$
5	$\text{NH}_4^+ + 3/2\text{O}_2(\text{aq}) + 2\text{H}^+ + \text{H}_2\text{O}$	46	$2\text{H}_2\text{S}(\text{aq}) + \text{NO}_3^- \rightleftharpoons \text{pyrite} + \text{NO}_2^- + 2\text{H}^+$
6	$\text{NH}_4^+ + 2\text{O}_2(\text{aq}) + 2\text{H}^+ + \text{H}_2\text{O}$	47	$\text{H}_2\text{S}(\text{aq}) + \text{NO}_3^- \rightleftharpoons \text{NO}_2^- + \text{H}_2\text{O} + \text{H}^+$
7	$\text{N}_2(\text{aq}) + 1/2\text{CO}_2(\text{aq}) + \text{N}_2\text{O}(\text{aq})$	48	$2\text{H}_2\text{S}(\text{aq}) + 4\text{NO}_3^- \rightleftharpoons \text{pyrite} + 4\text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}$
8	$\text{N}_2(\text{aq}) + \text{O}_2(\text{aq}) \rightleftharpoons 2\text{H}^+ + \text{H}_2\text{O}$	49	$\text{H}_2\text{S}(\text{aq}) + 4\text{NO}_3^- \rightleftharpoons 4\text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}$
9	$\text{N}_2(\text{aq}) + 3/2\text{O}_2(\text{aq}) \rightleftharpoons 2\text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}$	50	$\text{pyrite} + \text{NO}_3^- \rightleftharpoons 2\text{sulfur} + \text{Fe}^{+2} + \text{N}_2\text{O}(\text{aq}) + \text{H}_2\text{O}$
10	$\text{N}_2(\text{aq}) + 5/2\text{O}_2(\text{aq}) \rightleftharpoons 2\text{NO}_3^- + 2\text{H}^+ + \text{H}_2\text{O}$	51	$\text{pyrite} + 3\text{NO}_3^- \rightleftharpoons 3\text{NO}_2^- + \text{Fe}^{+2} + \text{H}_2\text{O}$
11	$\text{N}_2\text{O}(\text{aq}) + 1/2\text{CO}_2(\text{aq}) + \text{N}_2(\text{aq}) + \text{H}_2\text{O}$	52	$\text{pyrite} + 7\text{NO}_3^- \rightleftharpoons \text{Fe}^{+2} + 2\text{SO}_4^{-2} + 7\text{H}_2\text{O} + \text{N}_2\text{O}(\text{aq}) + \text{H}_2\text{O}$
		53	$2\text{sulfur} + 2\text{NO}_3^- \rightleftharpoons \text{S}_2\text{O}_3^{-2} + 2\text{NO}_2^- + 2\text{H}^+ + \text{H}_2\text{O}$
		74	$\text{NH}_4^+ + 3\text{NO}_3^- \rightleftharpoons 2\text{H}^+ + 4\text{NO}_2^- + \text{H}_2\text{O}$
		75	$\text{N}_2(\text{aq}) + 3\text{NO}_3^- + \text{H}_2\text{O} \rightleftharpoons 5\text{NO}_2^- + 2\text{H}^+$
		76	$\text{N}_2\text{O}(\text{aq}) + 2\text{NO}_3^- + \text{H}_2\text{O} \rightleftharpoons 4\text{NO}_2^- + 2\text{H}^+$
		77	$2\text{NO}(\text{aq}) + \text{NO}_3^- + \text{H}_2\text{O} \rightleftharpoons 3\text{NO}_2^- + 2\text{H}^+$
		78	$\text{NO}_3^- \rightleftharpoons \text{NO}_2^- + 1/2\text{O}_2(\text{aq}) + \text{H}^+$
		79	$3\text{H}_2(\text{aq}) + 2\text{H}^+ + 2\text{NO}_3^- \rightleftharpoons 2\text{NO}(\text{aq}) + 4\text{H}_2\text{O}$
		80	$6\text{H}_2\text{S}(\text{aq}) + 3\text{Fe}^{+2} + 2\text{NO}_3^- \rightleftharpoons 3\text{pyrite} + 2\text{NO}(\text{aq}) + 4\text{H}_2\text{O}$
		81	$3\text{H}_2\text{S}(\text{aq}) + 2\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons 3\text{sulfur} + 2\text{NO}(\text{aq}) + 4\text{H}_2\text{O}$
		82	$6\text{H}_2\text{S}(\text{aq}) + 8\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons 3\text{S}_2\text{O}_3^{-2} + 8\text{NO}(\text{aq}) + 7\text{H}_2\text{O}$
		83	$3\text{H}_2\text{S}(\text{aq}) + 8\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons 8\text{NO}(\text{aq}) + 3\text{SO}_4^{-2} + 4\text{H}_2\text{O}$
			$3\text{pyrite} + 2\text{NO}_3^- + 8\text{H}^+ \rightleftharpoons 3\text{H}_2\text{S}(\text{aq}) + 2\text{NO}(\text{aq}) + 4\text{H}_2\text{O}$

Using only CHNOS and Fe
 Everett Shock group wrote **1,460**
 thermodynamic valid redox reactions
 potentially used by microbes!

139	$\text{HCO}_3^- + \text{N}_2\text{O}(\text{aq}) + 2\text{H}_2\text{O} \rightleftharpoons 4\text{CO}(\text{aq}) + 2\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons 4\text{CO}_2(\text{aq}) + \text{N}_2\text{O}(\text{aq}) + \text{H}_2\text{O}$	762	$4\text{N}_2(\text{aq}) + \text{S}_2\text{O}_3^{-2} + \text{H}_2\text{O} + 2\text{H}^+ \rightleftharpoons 2\text{H}_2\text{S}(\text{aq}) + 4\text{N}_2\text{O}(\text{aq})$	8
140	$4\text{CO}(\text{aq}) + 2\text{NO}_3^- + 3\text{H}_2\text{O} \rightleftharpoons 4\text{HCO}_3^- + \text{N}_2\text{O}(\text{aq}) + 2\text{H}^+$	763	$2\text{N}_2(\text{aq}) + \text{S}_2\text{O}_3^{-2} + \text{H}_2\text{O} + 2\text{H}^+ \rightleftharpoons 2\text{H}_2\text{S}(\text{aq}) + 4\text{NO}(\text{aq})$	8
141	$\text{NH}_4^+ + \text{NO}_3^- \rightleftharpoons \text{N}_2\text{O}(\text{aq}) + 2\text{H}_2\text{O}$	764	$4\text{N}_2(\text{aq}) + 3\text{S}_2\text{O}_3^{-2} + 7\text{H}_2\text{O} \rightleftharpoons 6\text{H}_2\text{S}(\text{aq}) + 8\text{NO}_2^- + 2\text{H}^+$	24
142	$4\text{N}_2(\text{aq}) + 2\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons 5\text{N}_2\text{O}(\text{aq}) + \text{H}_2\text{O}$	765	$4\text{N}_2(\text{aq}) + 5\text{S}_2\text{O}_3^{-2} + 2\text{H}^+ + 9\text{H}_2\text{O} \rightleftharpoons 10\text{H}_2\text{S}(\text{aq}) + 8\text{NO}_3^-$	40
143	$2\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons \text{N}_2\text{O}(\text{aq}) + 2\text{O}_2(\text{aq}) + \text{H}_2\text{O}$	766	$4\text{N}_2\text{O}(\text{aq}) + \text{S}_2\text{O}_3^{-2} + 2\text{H}^+ + \text{H}_2\text{O} \rightleftharpoons 2\text{H}_2\text{S}(\text{aq}) + 8\text{NO}(\text{aq})$	8
144	$5\text{H}_2(\text{aq}) + 2\text{NO}_3^- + 2\text{H}^+ \rightleftharpoons \text{N}_2(\text{aq}) + 6\text{H}_2\text{O}$	767	$2\text{N}_2\text{O}(\text{aq}) + \text{S}_2\text{O}_3^{-2} + 3\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2\text{S}(\text{aq}) + 4\text{NO}_2^- + 2\text{H}^+$	8
145	$10\text{H}_2\text{S}(\text{aq}) + 2\text{NO}_3^- + 5\text{Fe}^{+2} \rightleftharpoons 5\text{pyrite} + \text{N}_2(\text{aq}) + 8\text{H}^+ + \text{H}_2\text{O}$	768	$\text{N}_2\text{O}(\text{aq}) + \text{S}_2\text{O}_3^{-2} + 2\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2\text{S}(\text{aq}) + 2\text{NO}_3^-$	8
		769	$8\text{NO}(\text{aq}) + \text{S}_2\text{O}_3^{-2} + 5\text{H}_2\text{O} \rightleftharpoons 2\text{H}_2\text{S}(\text{aq}) + 8\text{NO}_2^- + 6\text{H}^+$	8

ENERGY AND REDOX COUPLES ON EXTANT EARTH

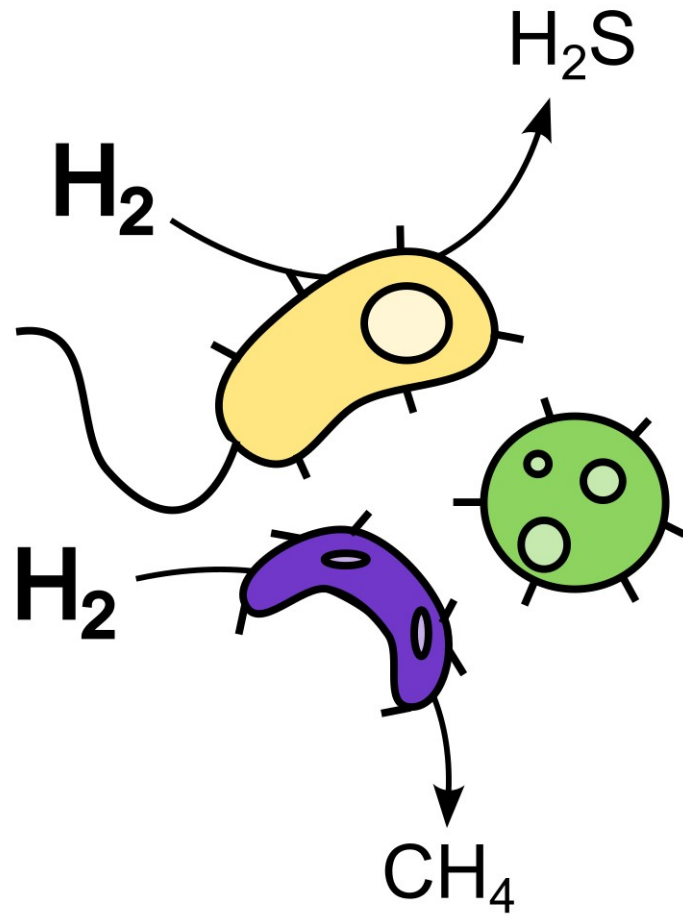
	Oxygen as an electron acceptor	
1	$2\text{H}_2(\text{aq}) + \text{O}_2(\text{aq}) \rightleftharpoons 2\text{H}_2\text{O}$	4
2	$2\text{NH}_4^+ + 3/2\text{O}_2(\text{aq}) \rightleftharpoons \text{CO}_2(\text{aq}) + 2\text{H}^+ + 3\text{H}_2\text{O}$	
3	$2\text{NH}_4^+ + \text{N}_2\text{O}(\text{aq}) \rightleftharpoons 2\text{H}_2\text{O} + 2\text{NO}(\text{aq})$	
4	$2\text{NH}_4^+ + 2\text{NO}(\text{aq}) \rightleftharpoons 2\text{H}_2\text{O} + 2\text{N}_2(\text{aq})$	
5	$\text{NH}_4^+ + 2\text{H}^+ + \text{I}_2 \rightleftharpoons \text{N}_2(\text{aq}) + \text{N}_2\text{O}(\text{aq}) + 2\text{H}_2\text{O}$	
6	$\text{NH}_4^+ + 2\text{H}^+ + \text{I}_2 \rightleftharpoons \text{N}_2(\text{aq}) + \text{N}_2\text{O}(\text{aq}) + 2\text{H}_2\text{O}$	
7	$\text{N}_2(\text{aq}) + \text{N}_2\text{O}(\text{aq}) \rightleftharpoons 2\text{N}_2(\text{aq})$	
8	$\text{N}_2(\text{aq}) \rightleftharpoons 2\text{N}_2(\text{aq})$	
9	$\text{N}_2(\text{aq}) \rightleftharpoons 2\text{N}_2(\text{aq})$	
10	$\text{N}_2(\text{aq}) \rightleftharpoons 2\text{N}_2(\text{aq})$	
11	$\text{N}_2\text{O}(\text{aq}) + 1/2\text{O}_2(\text{aq}) \rightleftharpoons 3\text{NO}_2^- + 2\text{Fe}^{+2}$	

Using only CHNOS and Fe

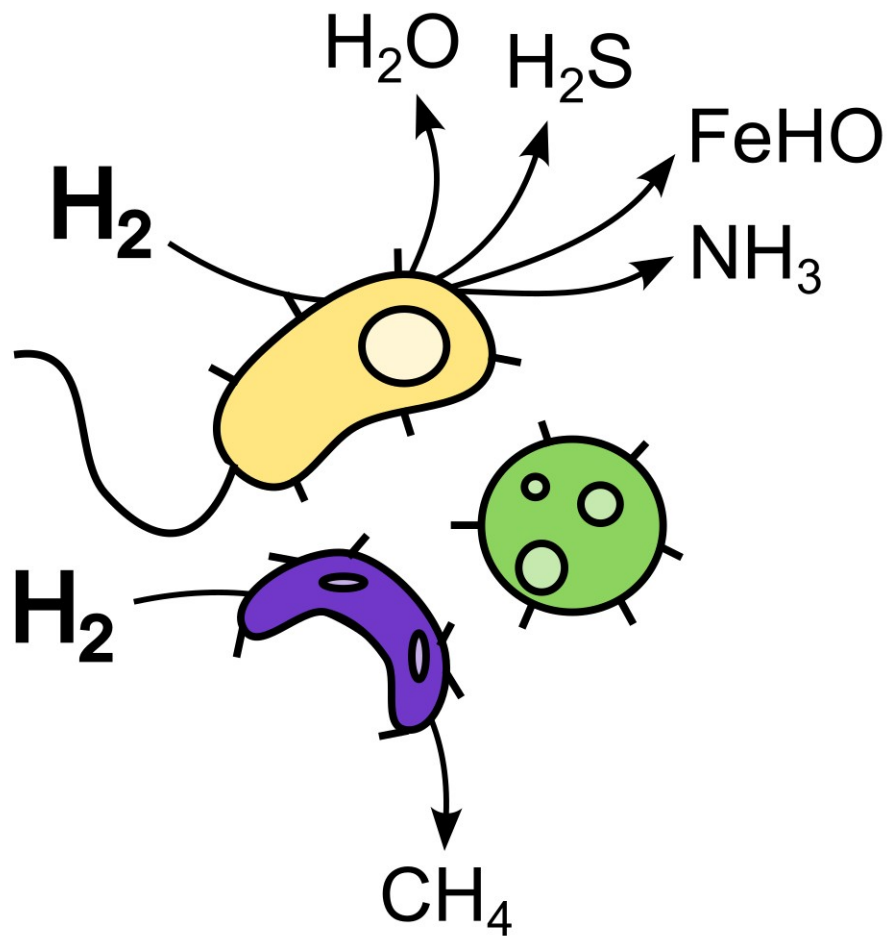
We do not know how many of these reactions are actually used by Life (if at all!) and how do they map to the Tree of Life!

52	pyrite + 7NO ₃ ⁻ + H ₂ O	4H ₂ O + 4H ⁺	4N ₂ (aq) + 2NO ₃ ⁻ + 2H ⁺ ⇌ 5N ₂ O(aq) + H ₂ O	786	9H ₂ O ⇌ 10H ₂ S(aq) + 8NO ₃ ⁻	40
53	Fe ⁺² + 2SO ₄ ⁻² + 7NO ₂ ⁻ + 8H ⁺	3sulfur + 2NO(aq) + 4H ₂ O	2NO ₃ ⁻ + 2H ⁺ ⇌ N ₂ O(aq) + 2O ₂ (aq) + H ₂ O	787	4N ₂ O(aq) + S ₂ O ₃ ⁻² + 2H ⁺ + H ₂ O ⇌ 2H ₂ S(aq) + 8NO(aq)	8
83	3S ₂ O ₃ ⁻² + 8NO(aq) + 7H ₂ O	6H ₂ S(aq) + 8NO ₃ ⁻ + 2H ⁺	5H ₂ (aq) + 2NO ₃ ⁻ + 2H ⁺ ⇌ N ₂ (aq) + 6H ₂ O	788	2N ₂ O(aq) + S ₂ O ₃ ⁻² + 3H ₂ O ⇌ 2H ₂ S(aq) + 4NO ₂ ⁻ + 2H ⁺	8
	3H ₂ S(aq) + 8NO ₃ ⁻ + 2H ⁺	8NO(aq) + 3SO ₄ ⁻² + 4H ₂ O	10H ₂ S(aq) + 2NO ₃ ⁻ + 5Fe ⁺²	769	N ₂ O(aq) + S ₂ O ₃ ⁻² + 2H ₂ O ⇌ 2H ₂ S(aq) + 2NO ₃ ⁻	8
	3pyrite + 2NO ₃ ⁻ + 8H ⁺		⇌ 5pyrite + N ₂ (aq) + 8H ⁺	10	8NO(aq) + S ₂ O ₃ ⁻² + 5H ₂ O ⇌ 2H ₂ S(aq) + 8NO ₂ ⁻ + 6H ⁺	8

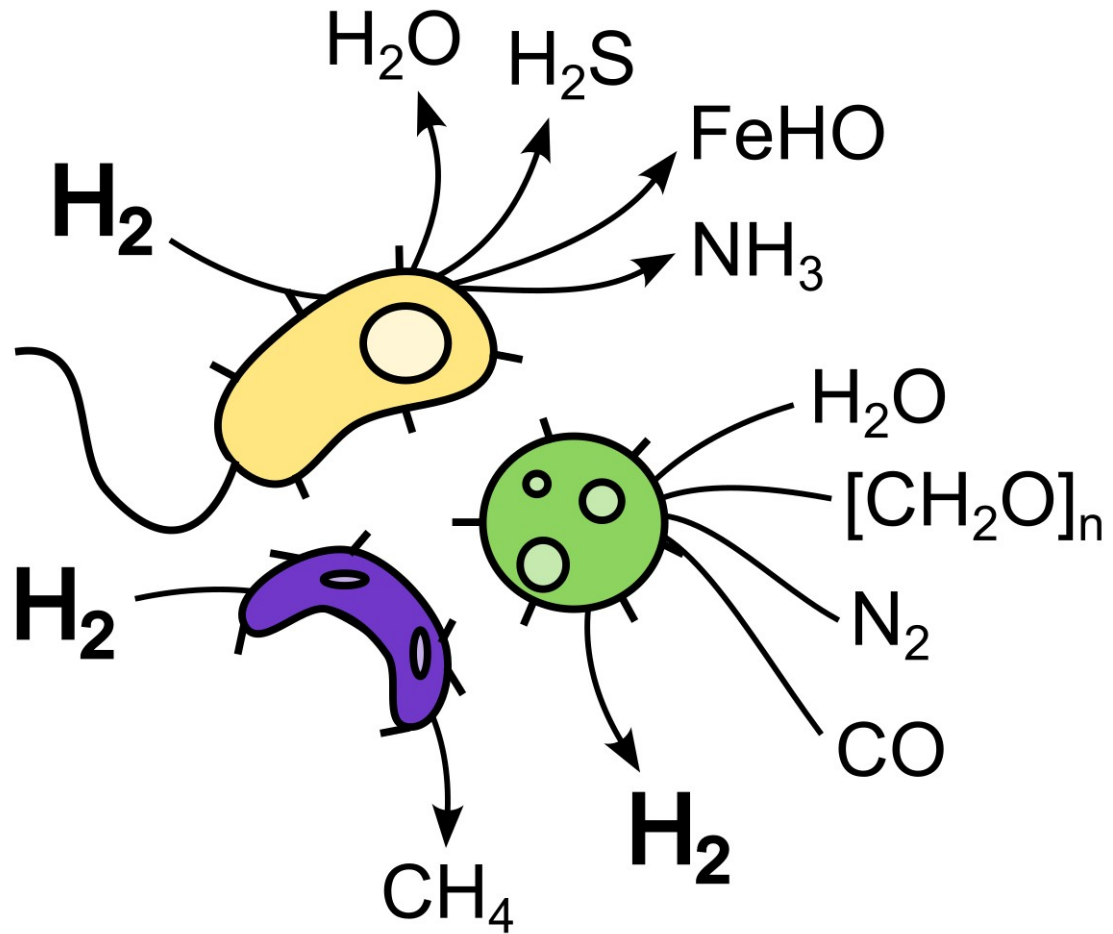
Who's there? What are they doing?



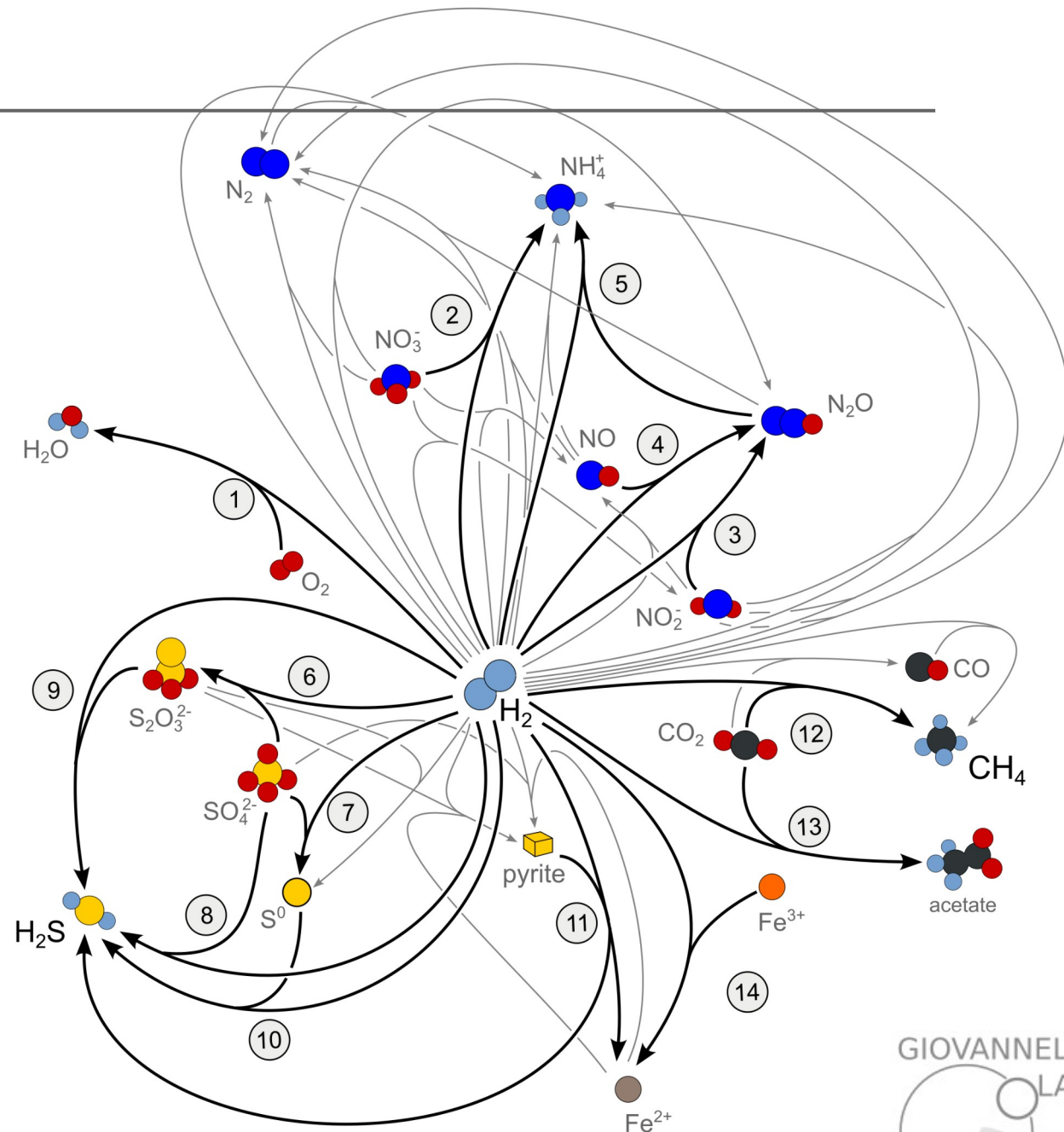
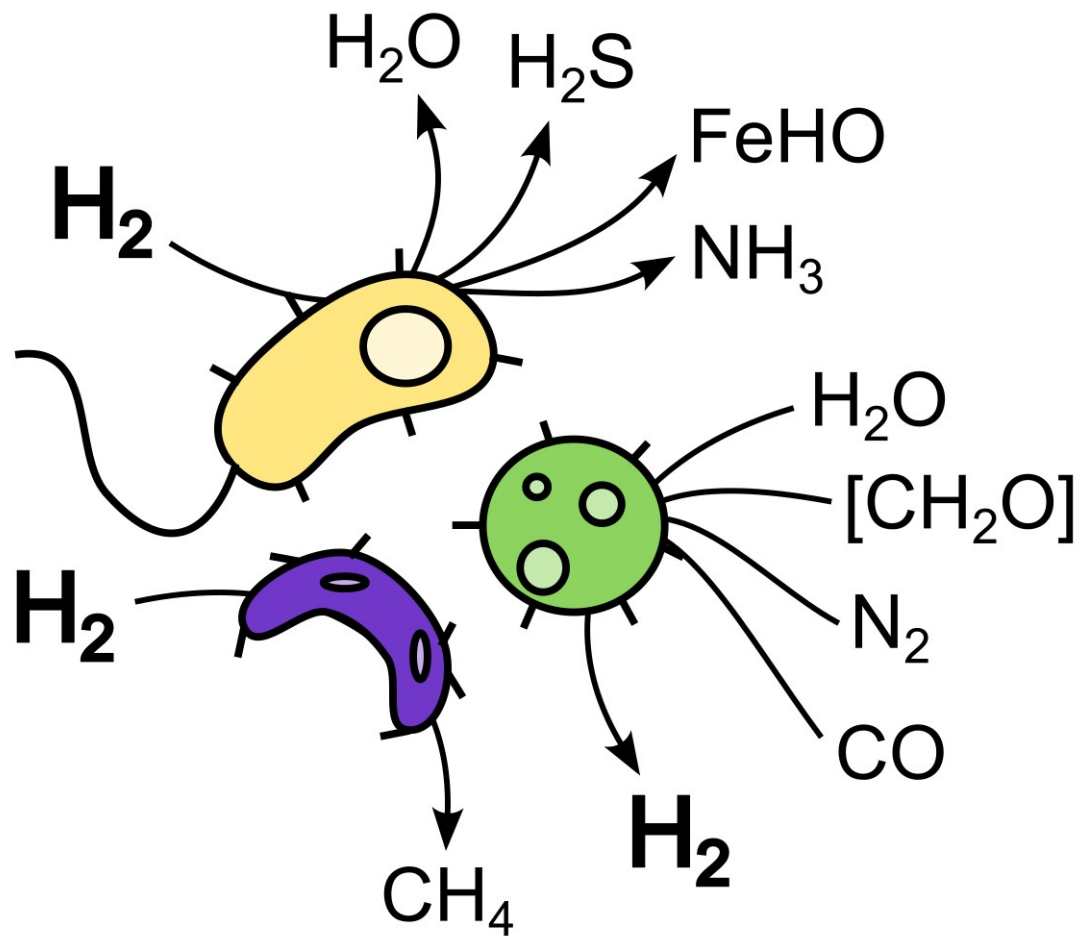
Who's there? What are they doing?



Who's there? What are they doing?



Who's there? What are they doing?



Cascone et al, 2025 EarthArXiv

Proc. Natl. Acad. Sci. USA
Vol. 89, pp. 6045–6049, July 1992
Microbiology

The deep, hot biosphere

(geochemistry/planetology)

THOMAS GOLD

Cornell University, Ithaca, NY 14853

Contributed by Thomas Gold, March 13, 1992

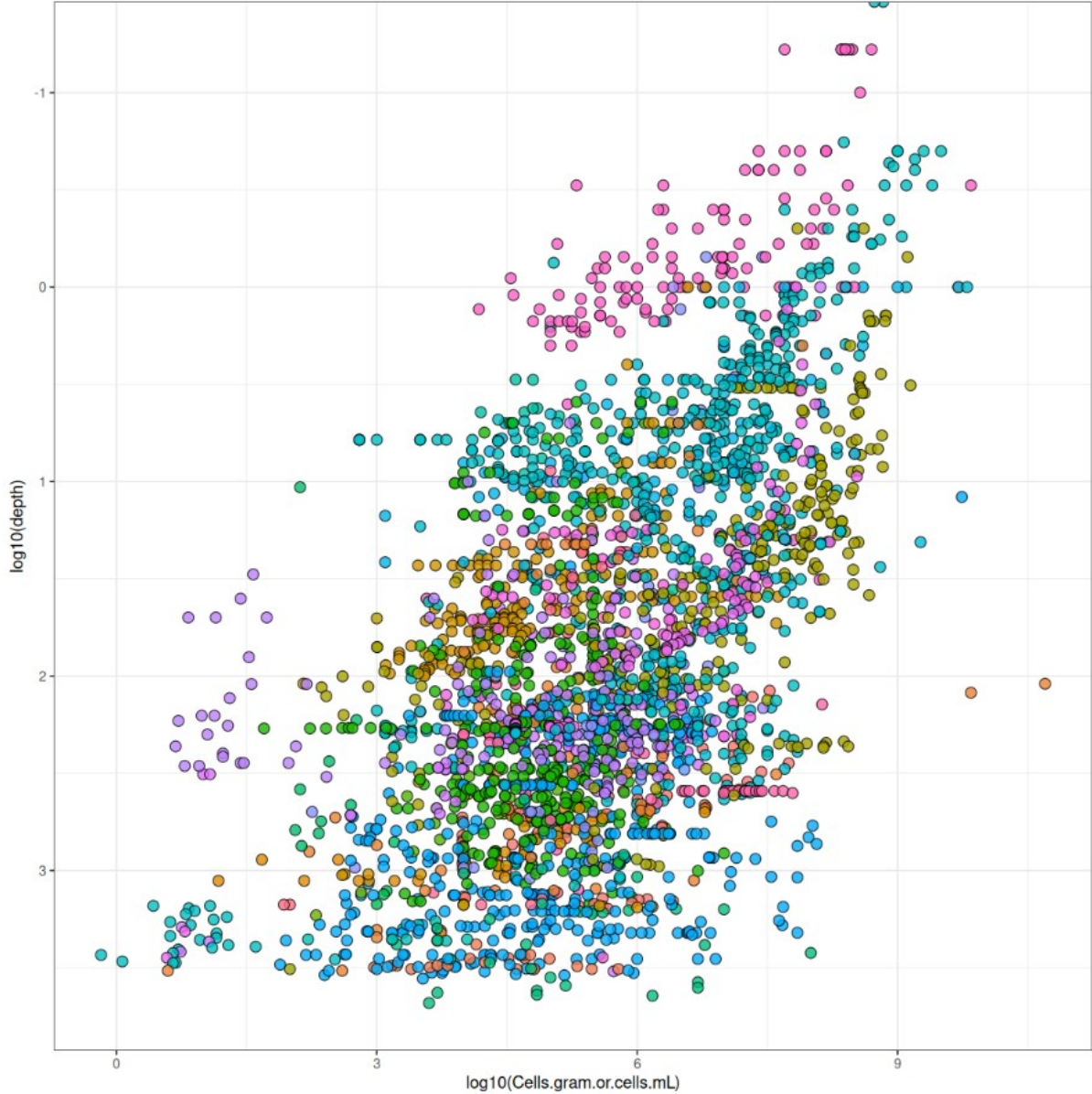
ABSTRACT There are strong indications that microbial life is widespread at depth in the crust of the Earth, just as such life has been identified in numerous ocean vents. This life is not dependent on solar energy and photosynthesis for its primary energy supply, and it is essentially independent of the surface circumstances. Its energy supply comes from chemical sources, due to fluids that migrate upward from deeper levels in the Earth. In mass and volume it may be comparable with all surface life. Such microbial life may account for the presence of biological molecules in all carbonaceous materials in the outer crust, and the inference that these materials must have derived from biological deposits accumulated at the surface is therefore not necessarily valid. Subsurface life may be widespread among the planetary bodies of our solar system, since many of them have equally suitable conditions below, while having totally inhospitable surfaces. One may even speculate that such life may be widely disseminated in the universe, since planetary type bodies with similar subsurface conditions may be common as solitary objects in space, as well as in other solar-type systems.

We are familiar with two domains of life on the Earth: the surface of the land and the body of the oceans. Both domains

gasification. As liquids, gases, and solids make new contacts, chemical processes can take place that represent, in general, an approach to a lower chemical energy condition. Some of the energy so liberated will increase the heating of the locality, and this in turn will liberate more fluids there and so accelerate the processes that release more heat. Hot regions will become hotter, and chemical activity will be further stimulated there. This may contribute to, or account for, the active and hot regions in the Earth's crust that are so sharply defined.

Where such liquids or gases stream up to higher levels into different chemical surroundings, they will continue to represent a chemical disequilibrium and therefore a potential energy source. There will often be circumstances where chemical reactions with surrounding materials might be possible and would release energy, but where the temperature is too low for the activation of the reactions. This is just the circumstance where biology can successfully draw on chemical energy. The life in the ocean vents is one example of this. There it is bacterial life that provides the first stage in the process of drawing on this form of chemical energy; for example, methane and hydrogen are oxidized to CO₂ and water, with oxygen available from local sulfates and metal

A Subsurface Biosphere



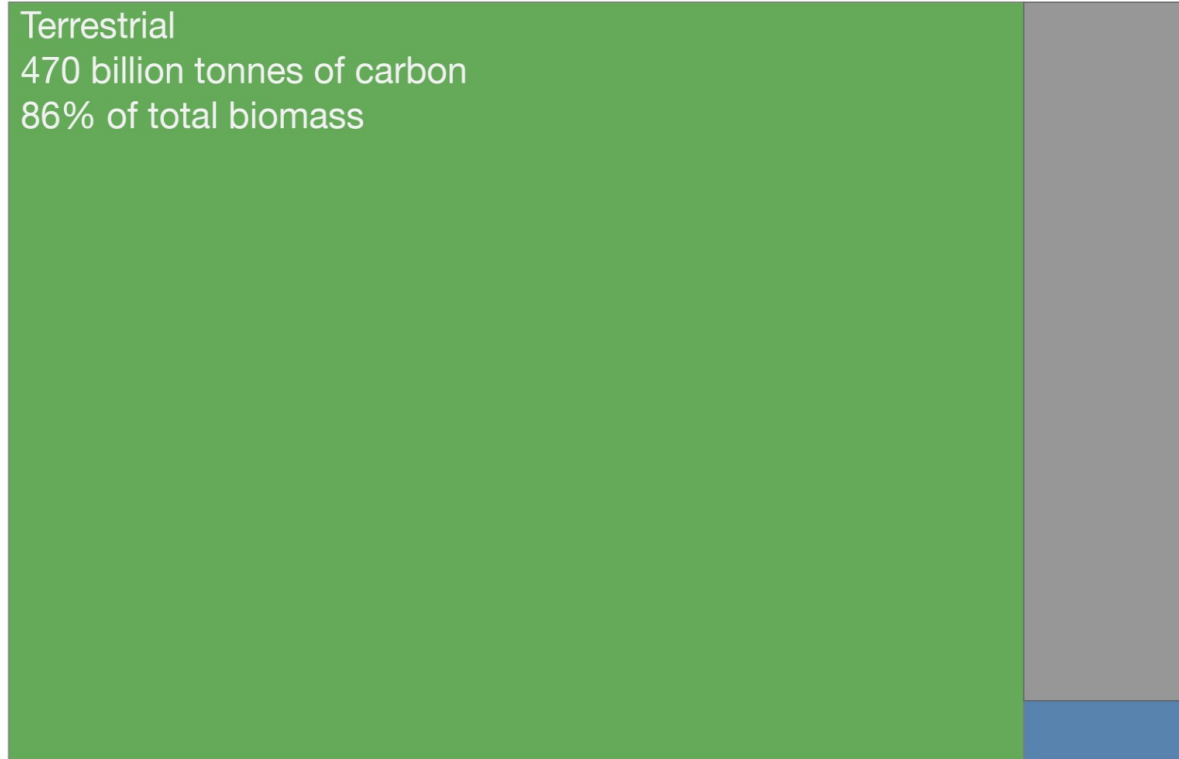
A Subsurface Biosphere

Global biomass: 546 billion tonnes of carbon

Terrestrial
470 billion tonnes of carbon
86% of total biomass

Deep subsurface
70 billion tonnes of carbon
13% of total biomass

Marine
6 billion tonnes of carbon
1% of total biomass



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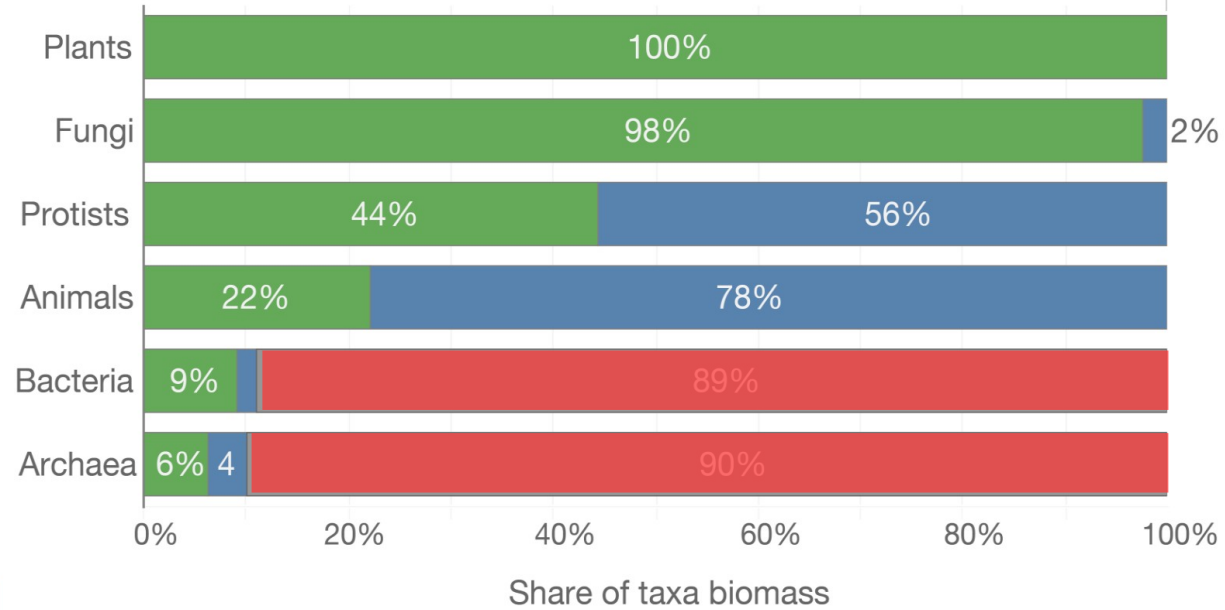
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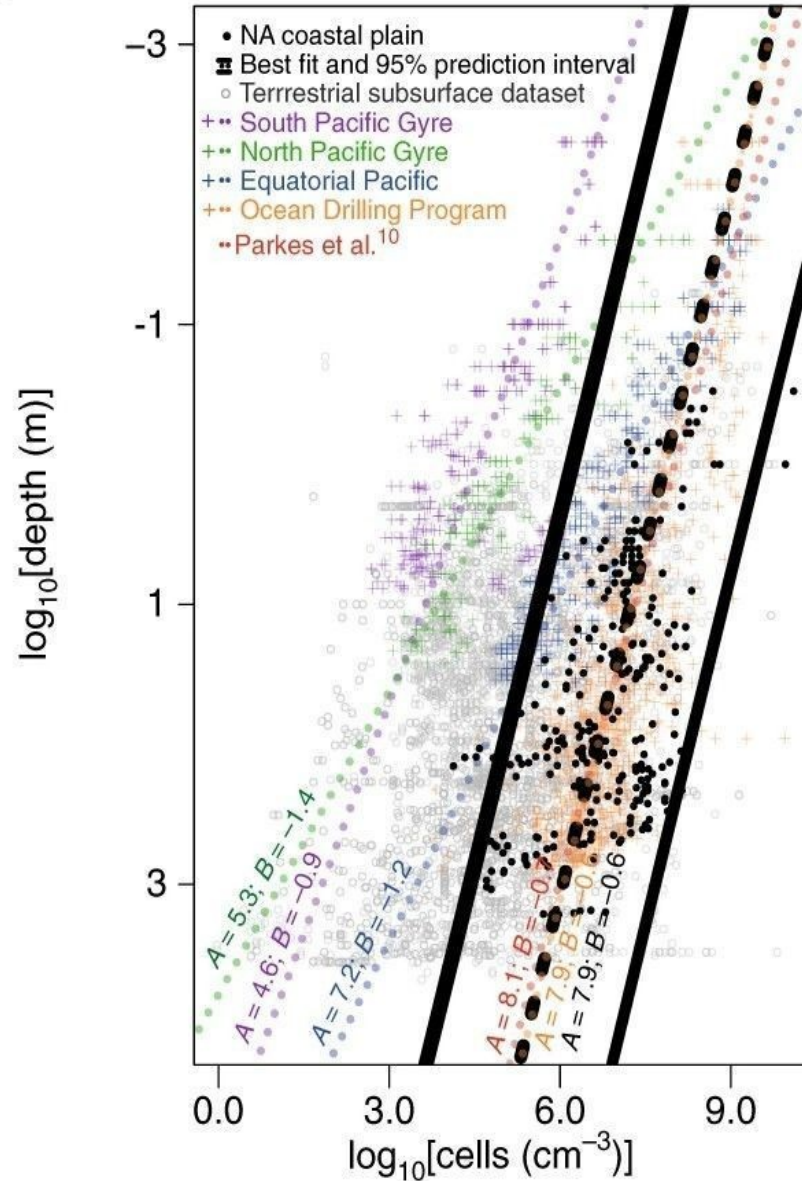
In which environment do taxa live?

<0.2% plant biomass
from marine environments



A Subsurface Biosphere

b



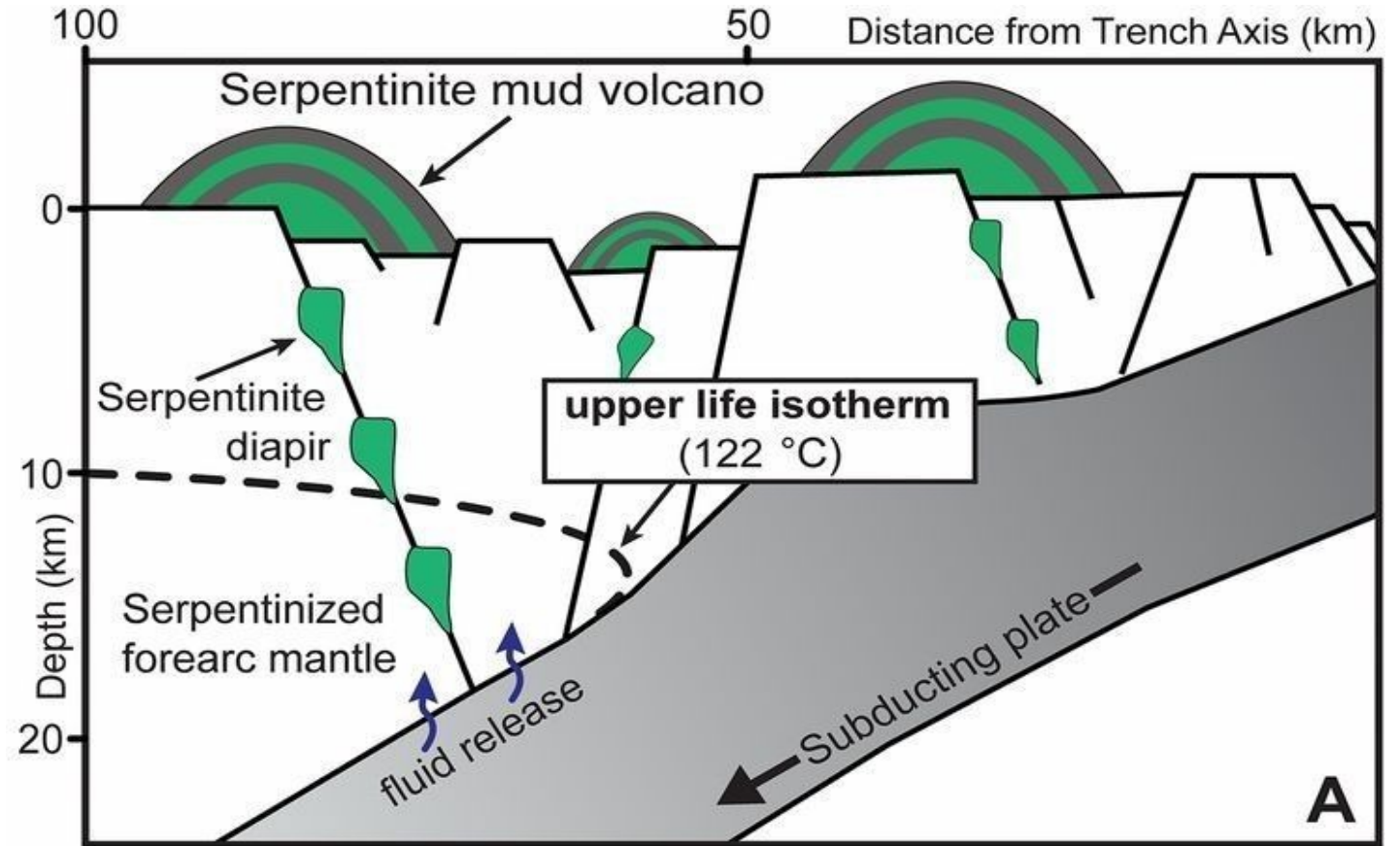
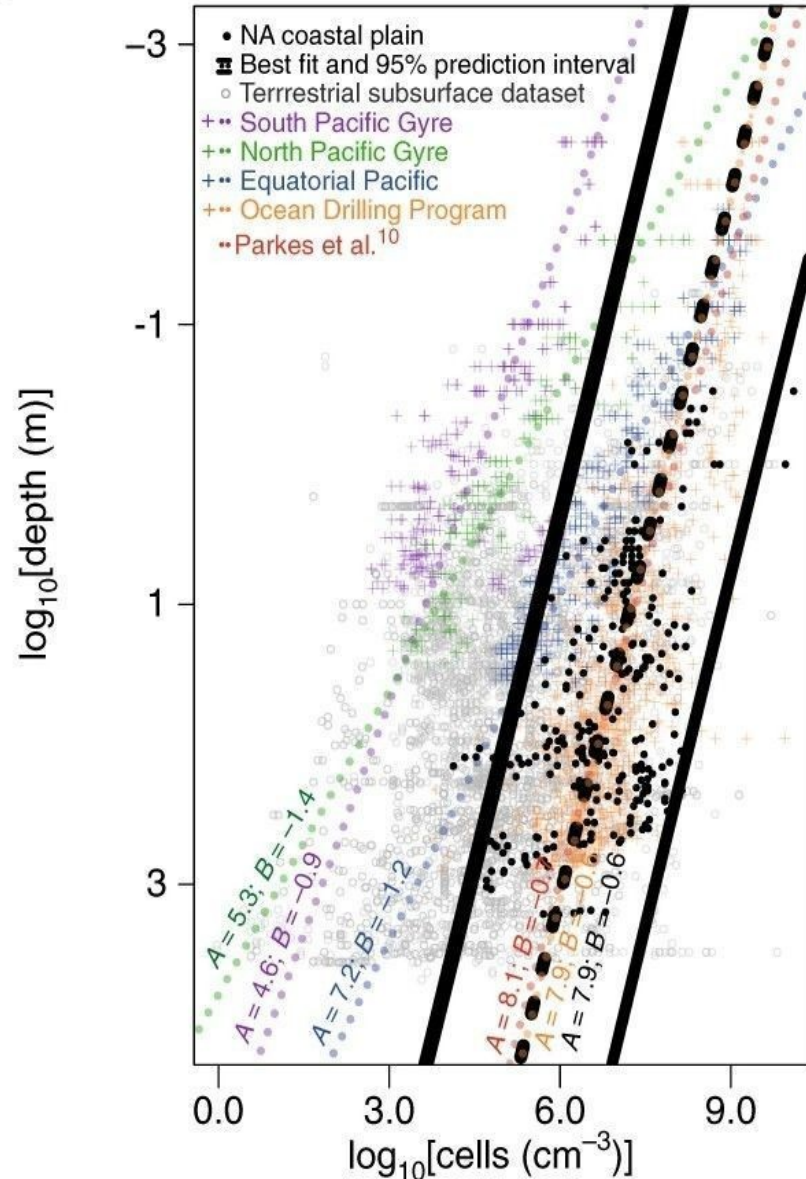
Current depths:

Continental ~ 5 km

Marine ~ 2.5 km

A Subsurface Biosphere

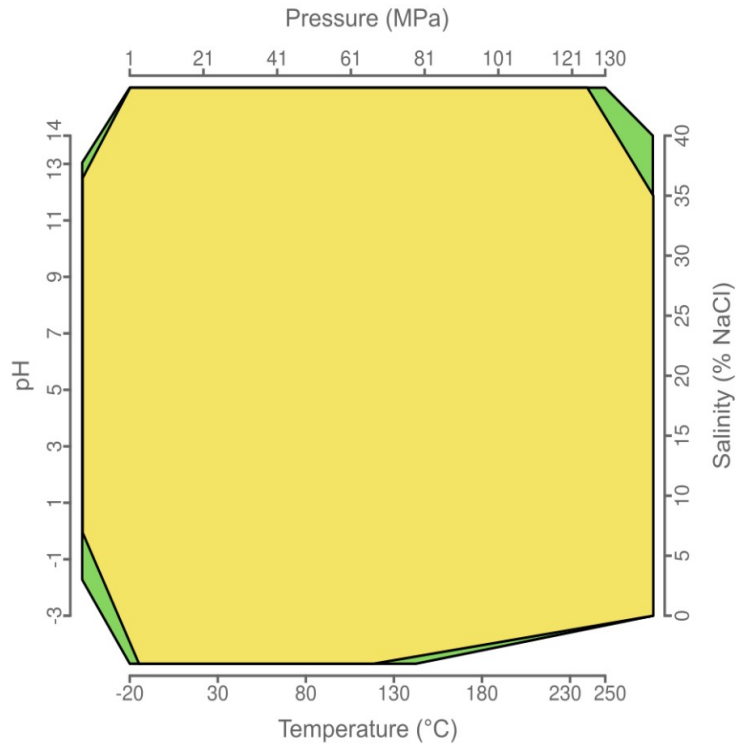
b



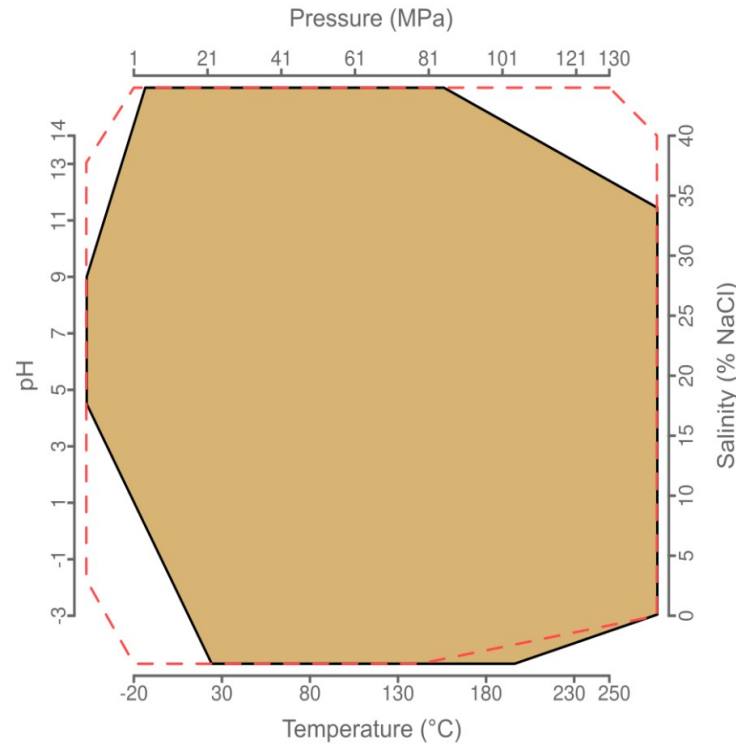
Magnabosco et al 2018 Nature Geoscience; Plumper et al 2017 PNAS

A Subsurface Biosphere

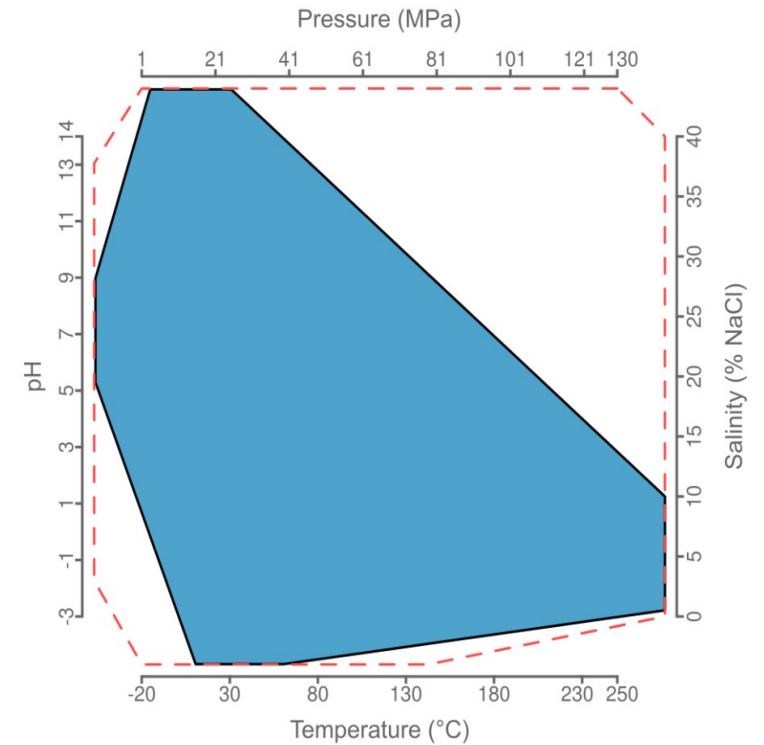
Limits of life on Earth



Porous reservoirs

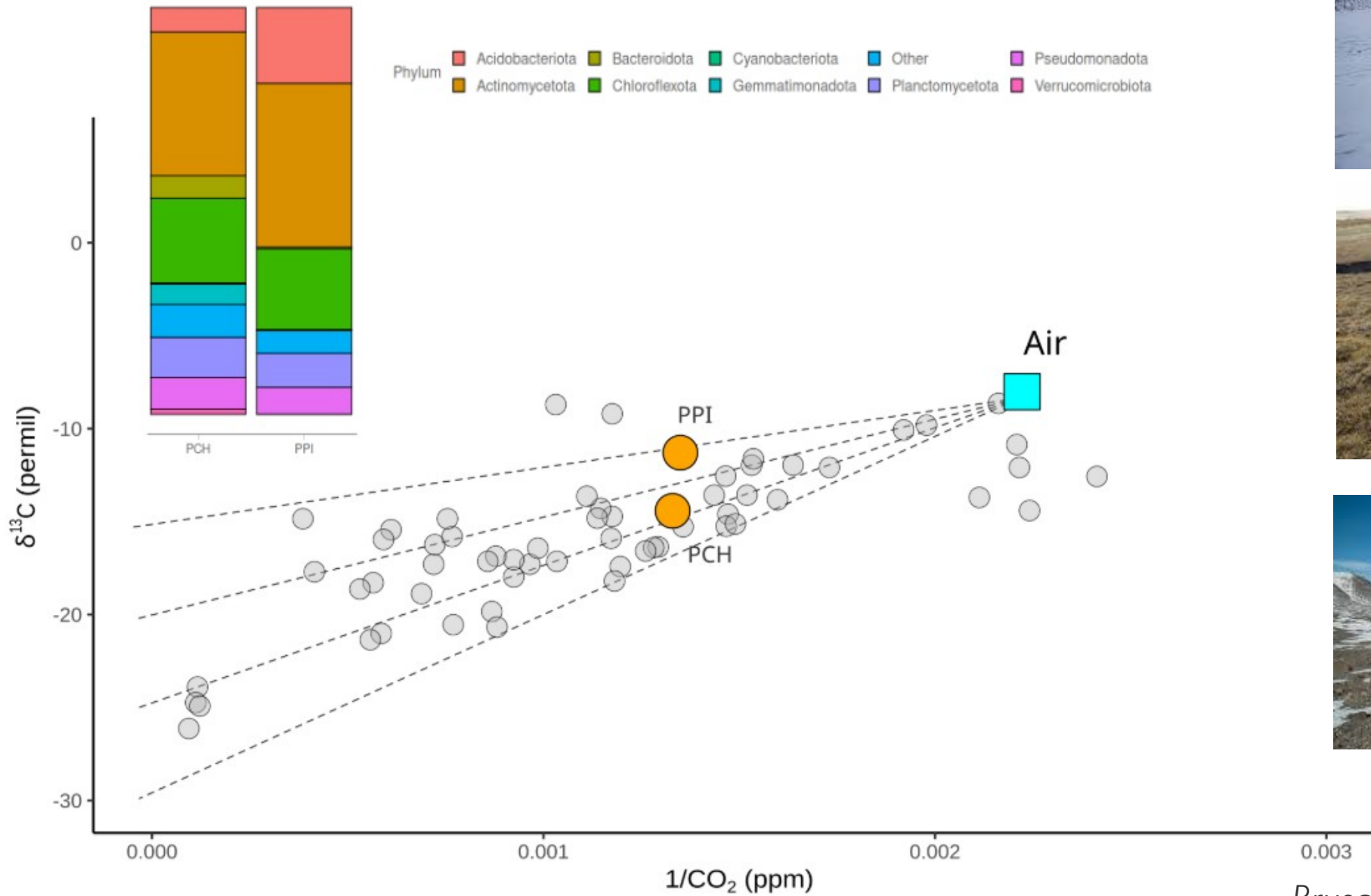


Deep aquifers



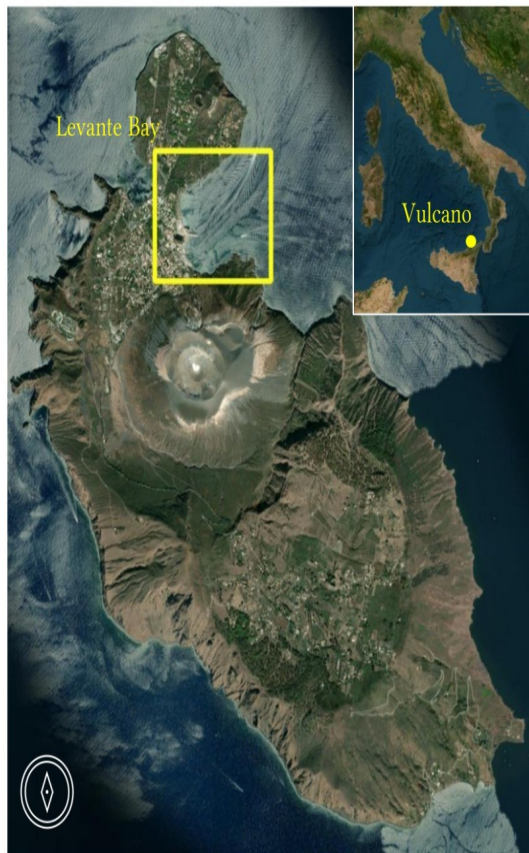
Limits of life on Earth overlap with most reservoir and traps

Microbial greenhouse gas release



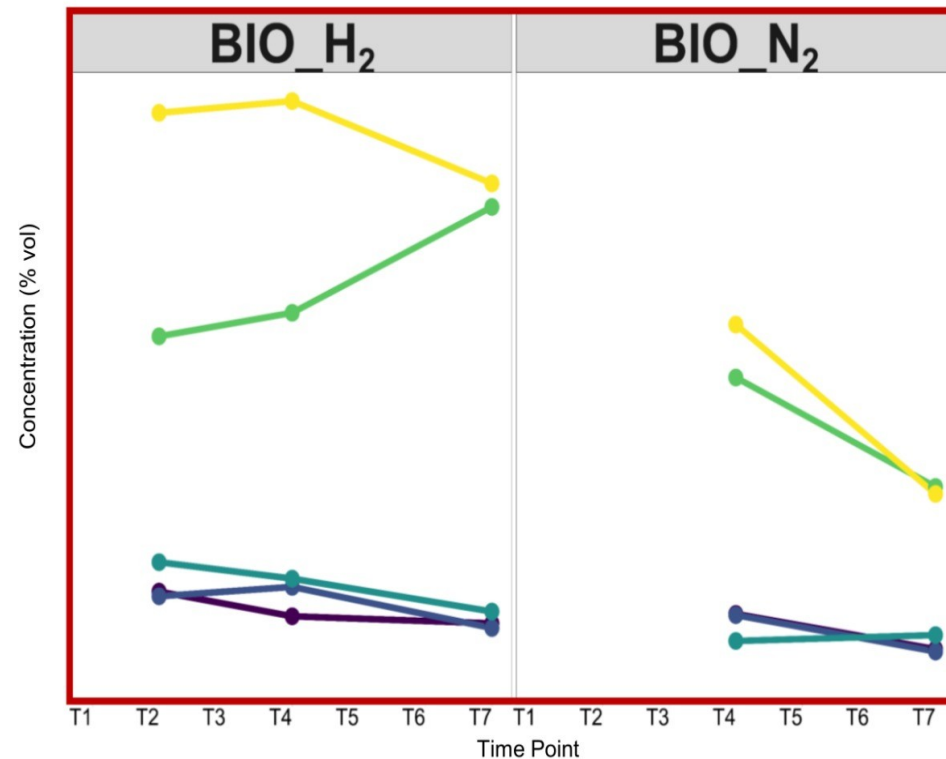
Microbial consumption of hydrothermal H₂

offers a great opportunity to study Biosphere

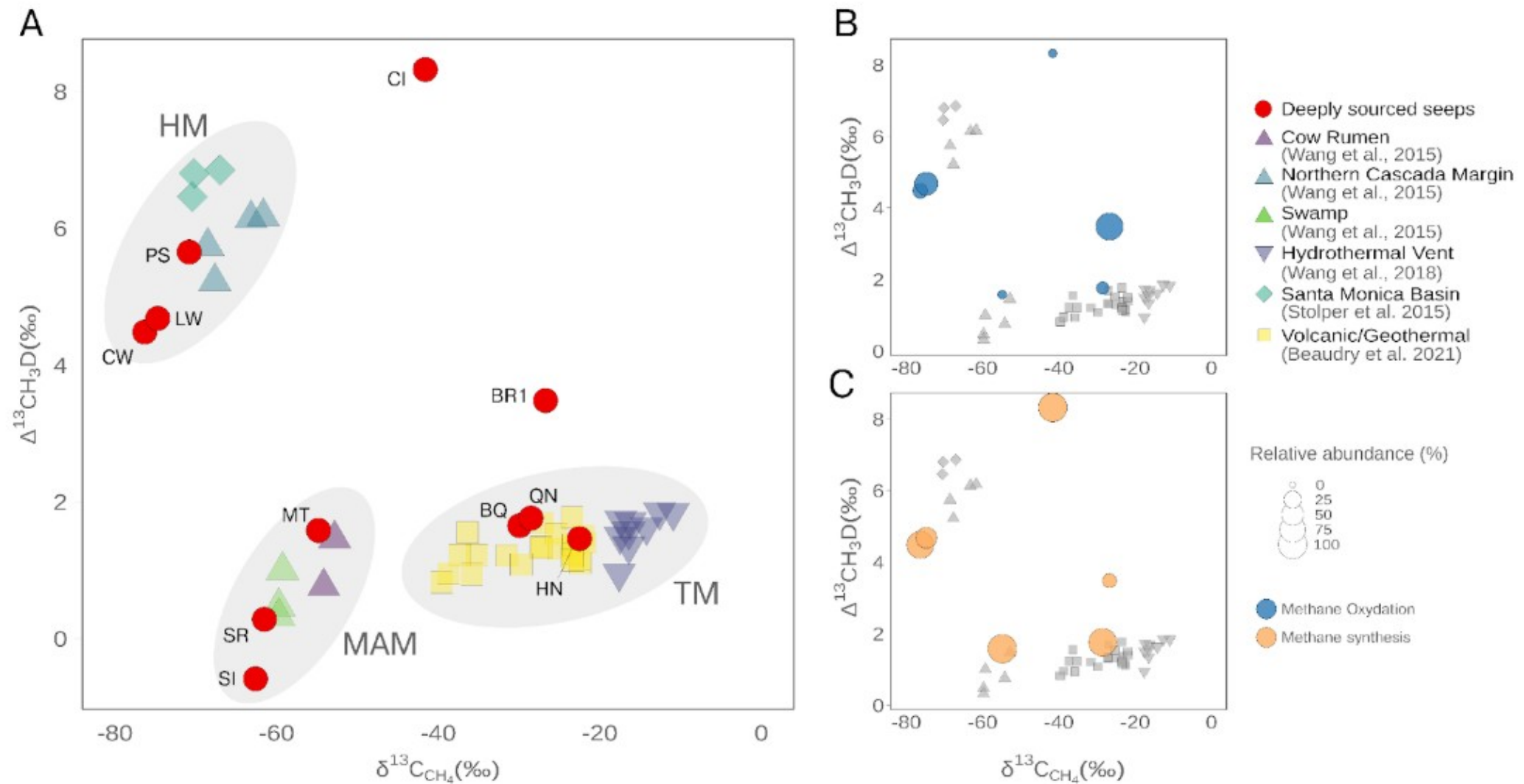


More than 30
have provided
volcanic activity

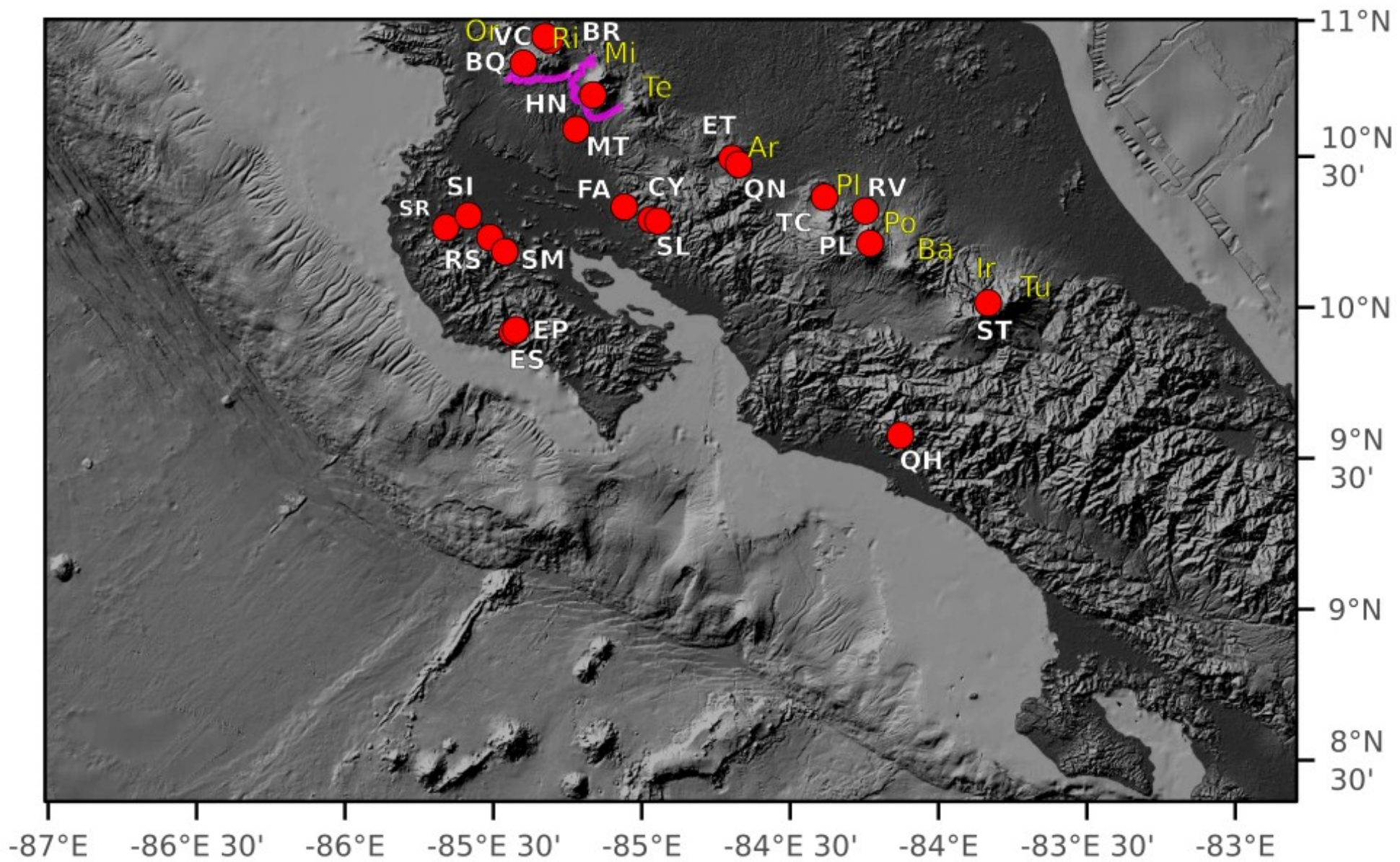
However, several
are not yet
understood, especially
on the geoclimatic
Bay.



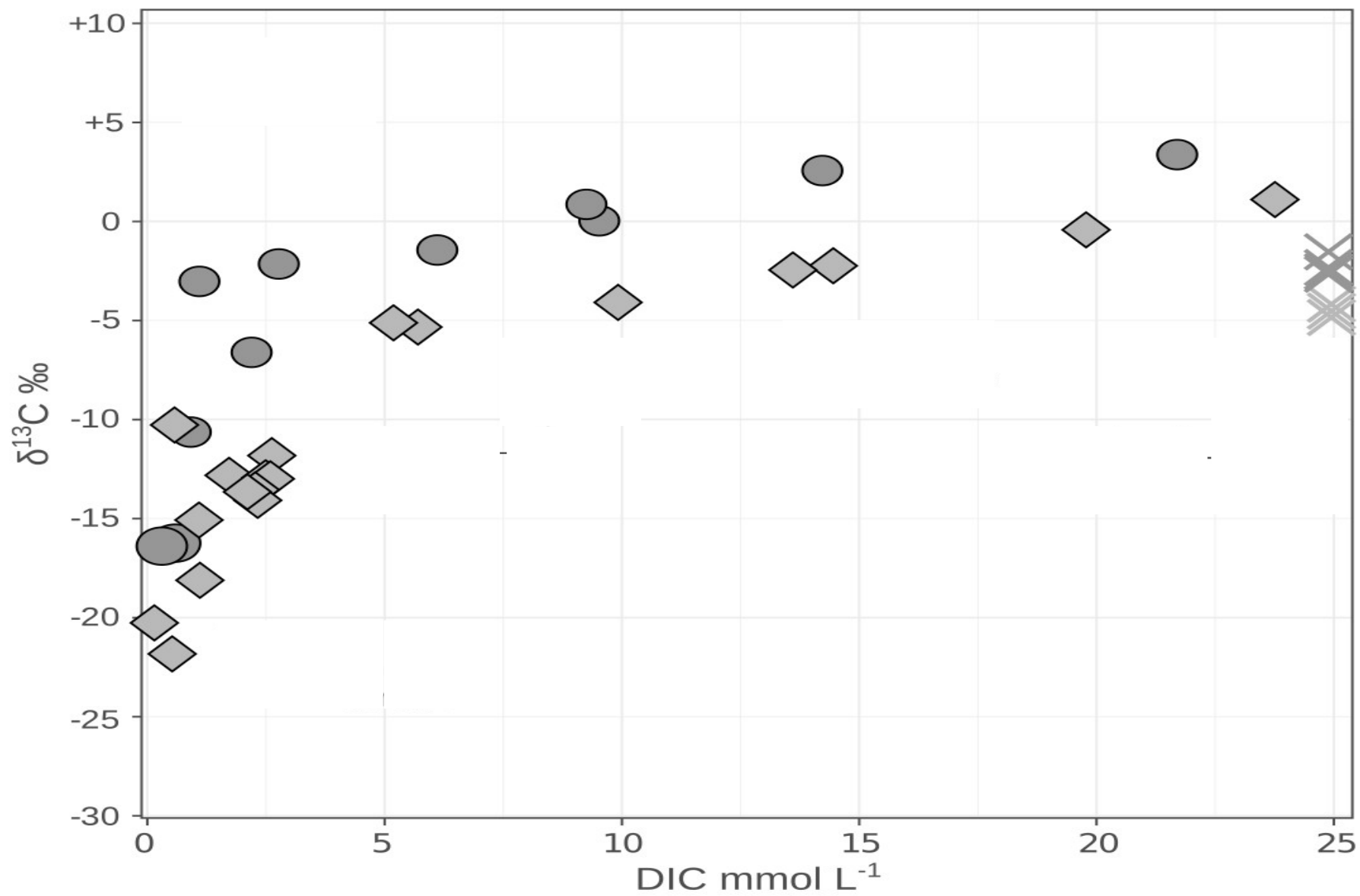
Microbial overprint of methane in convergent margins



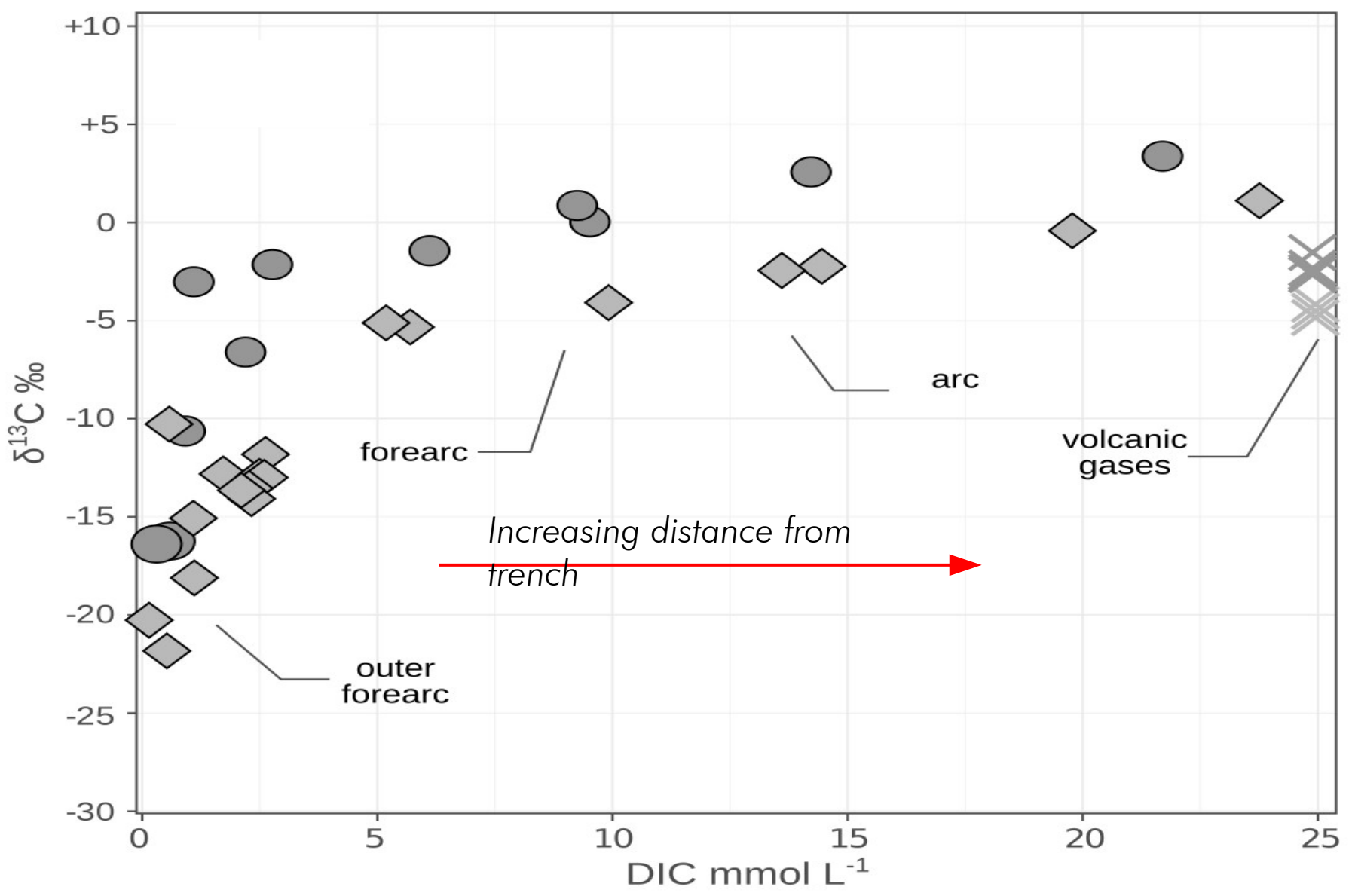
THE CENTRAL AMERICAN VOLCANIC ARC



Barry et al 2019 Nature; Fullerton et al. 2021 Nat Geosci



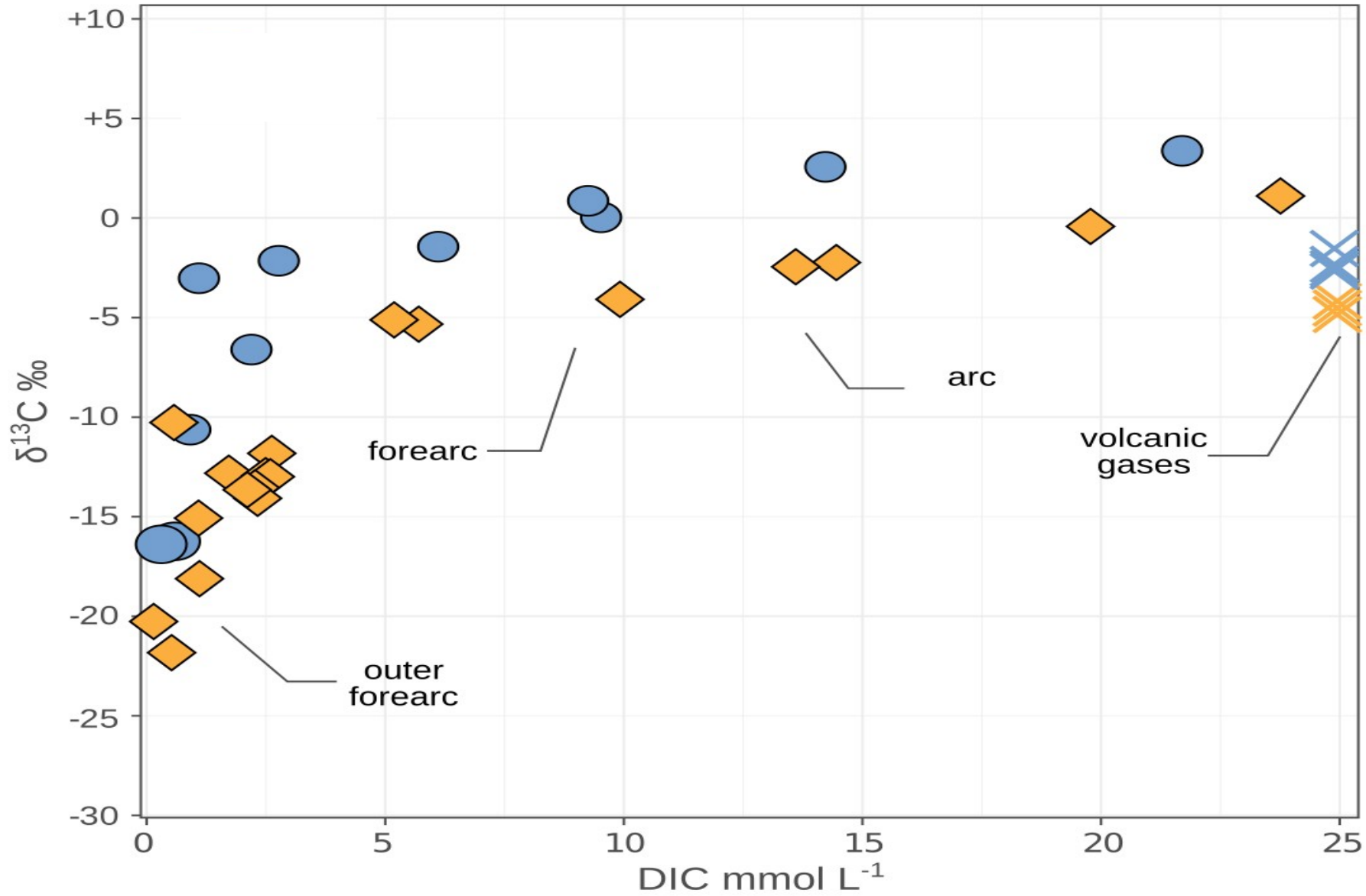
Barry et al, 2019 Nature



Barry et al, 2019 Nature

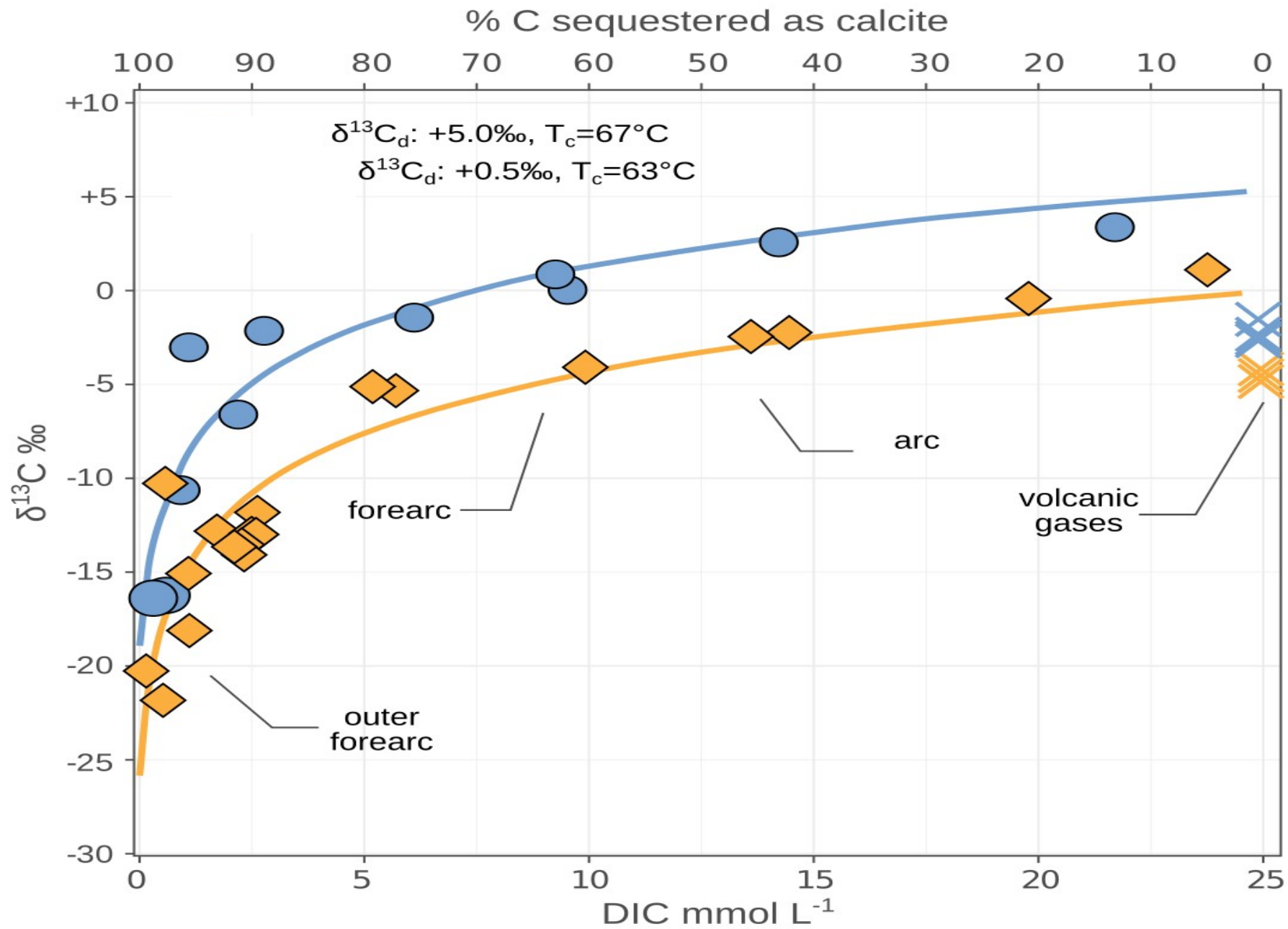


Rayleigh isotopic fractionation

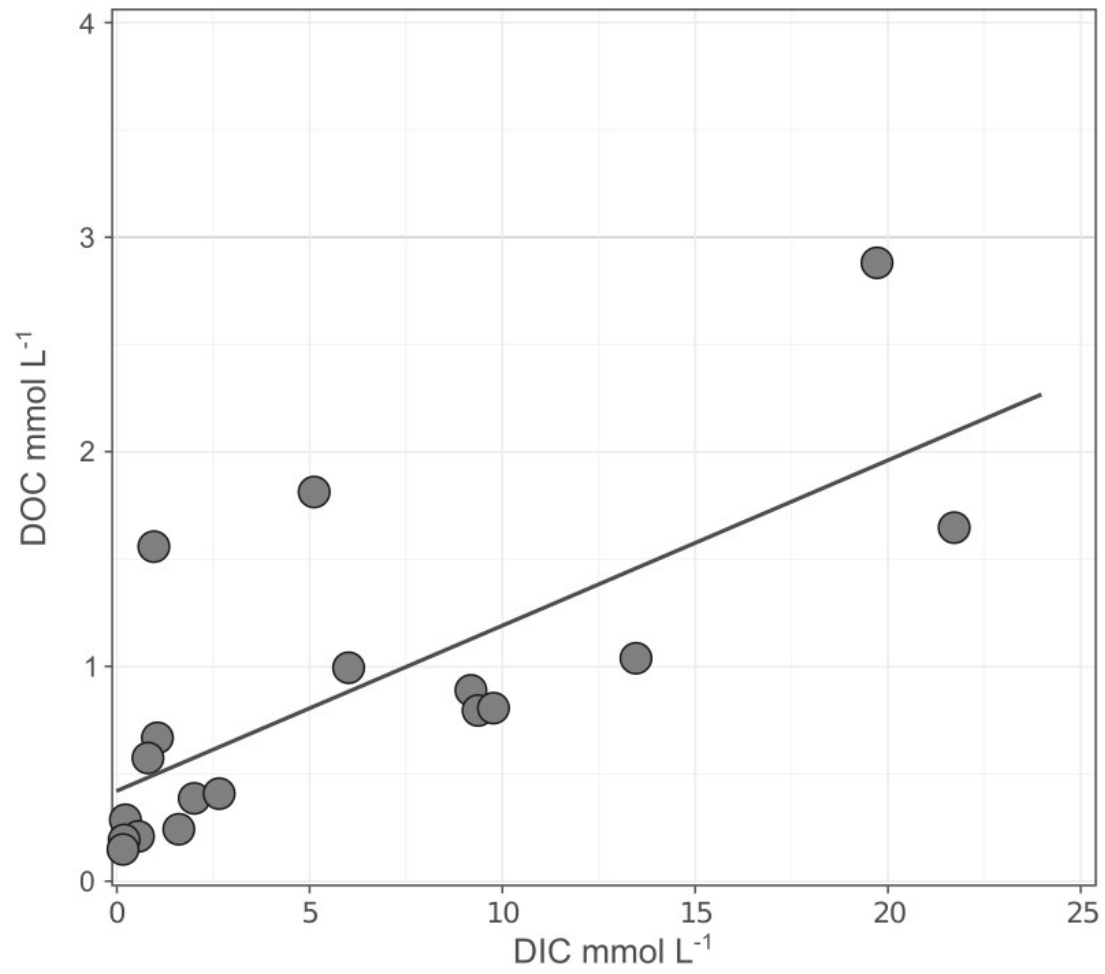


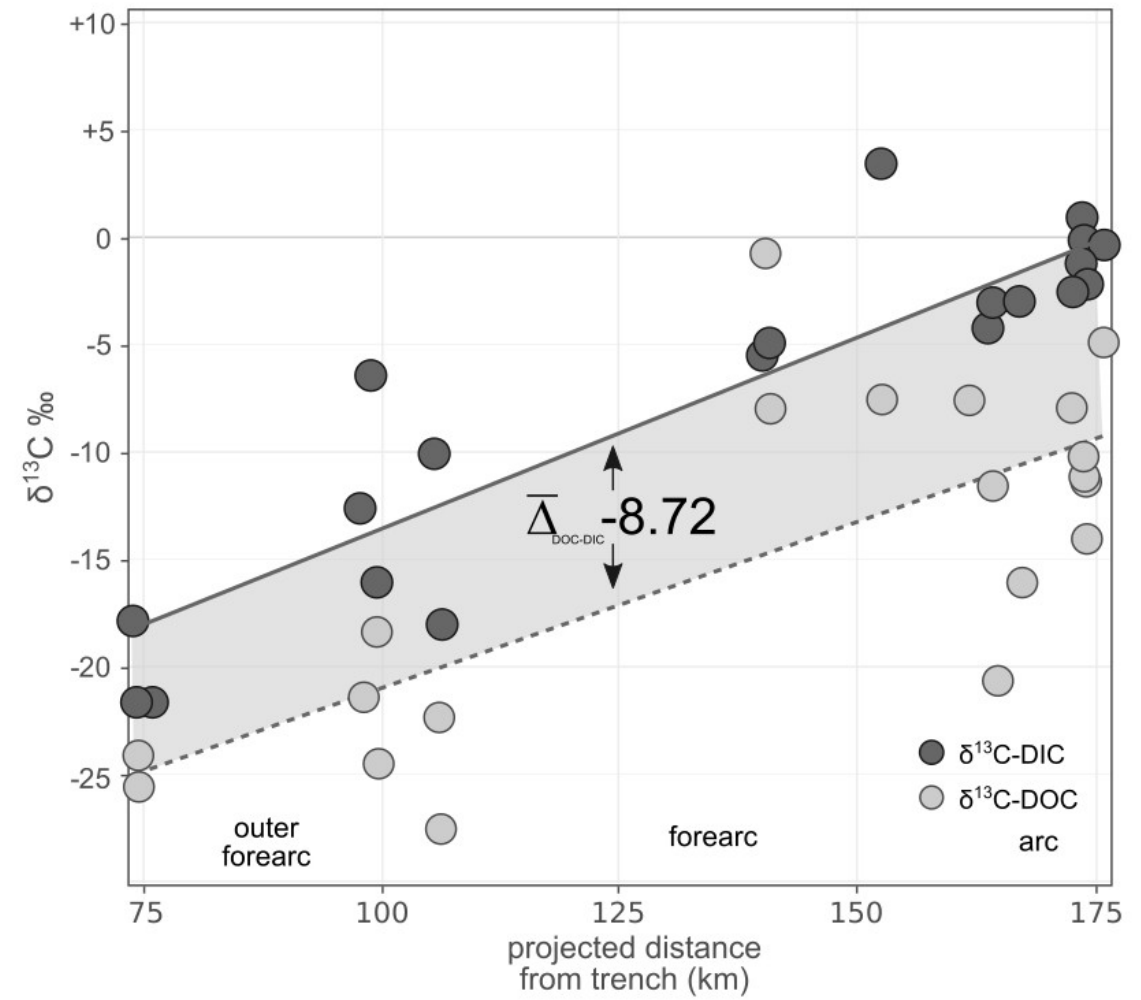
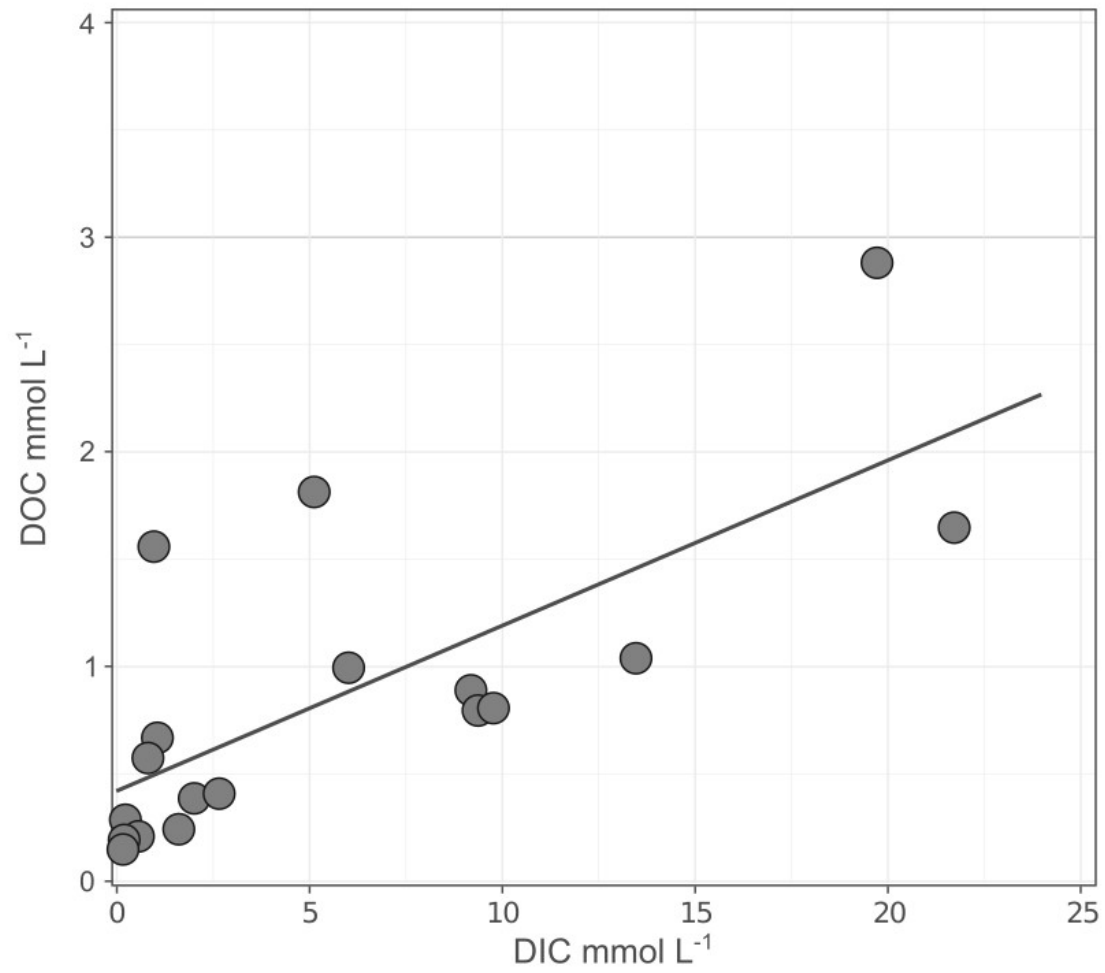
Barry et al, 2019 Nature

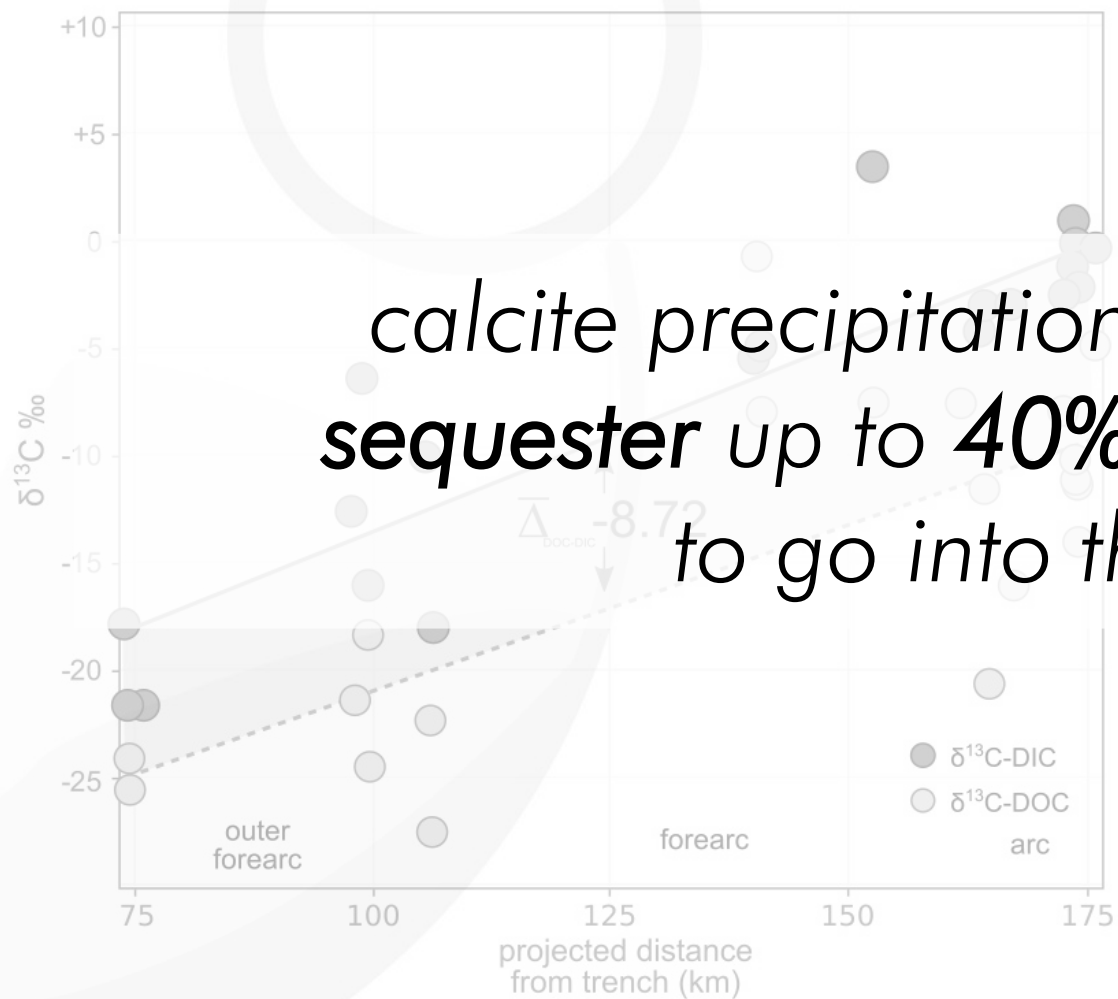




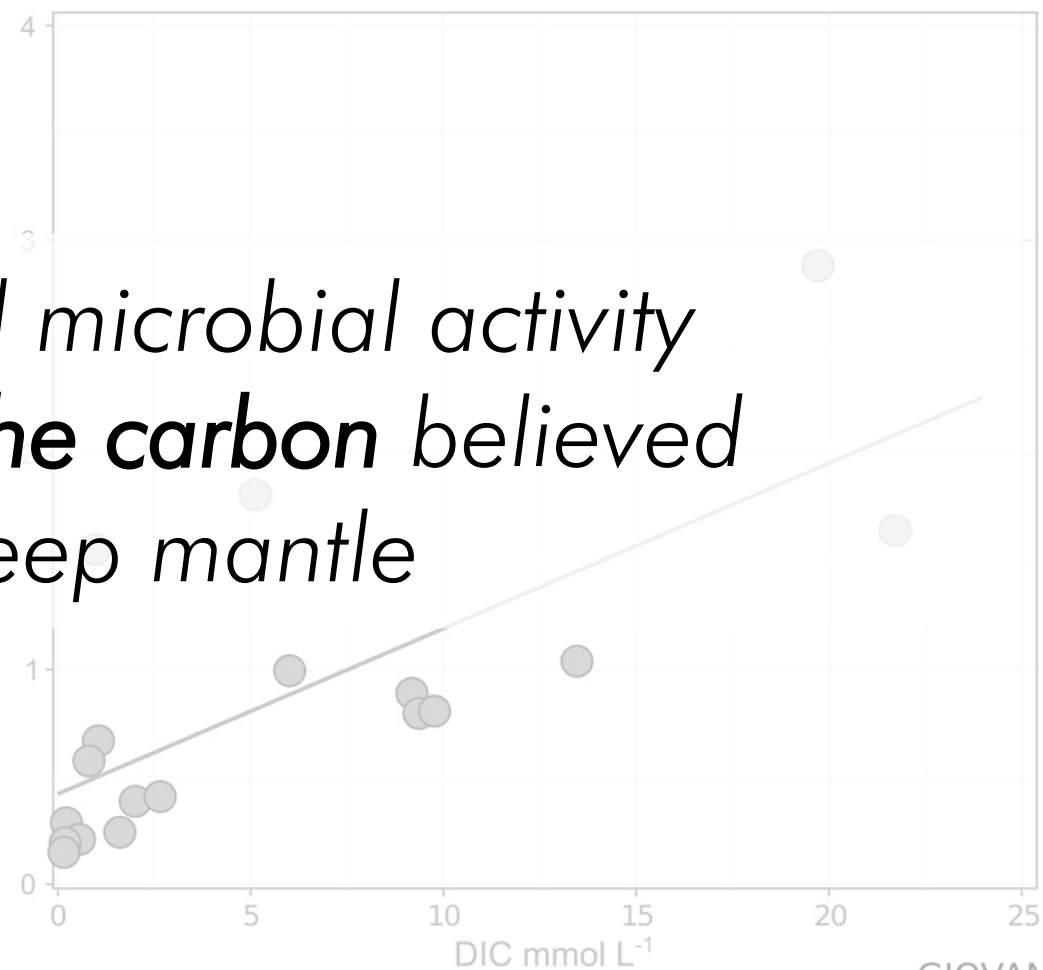
Barry et al, 2019 Nature

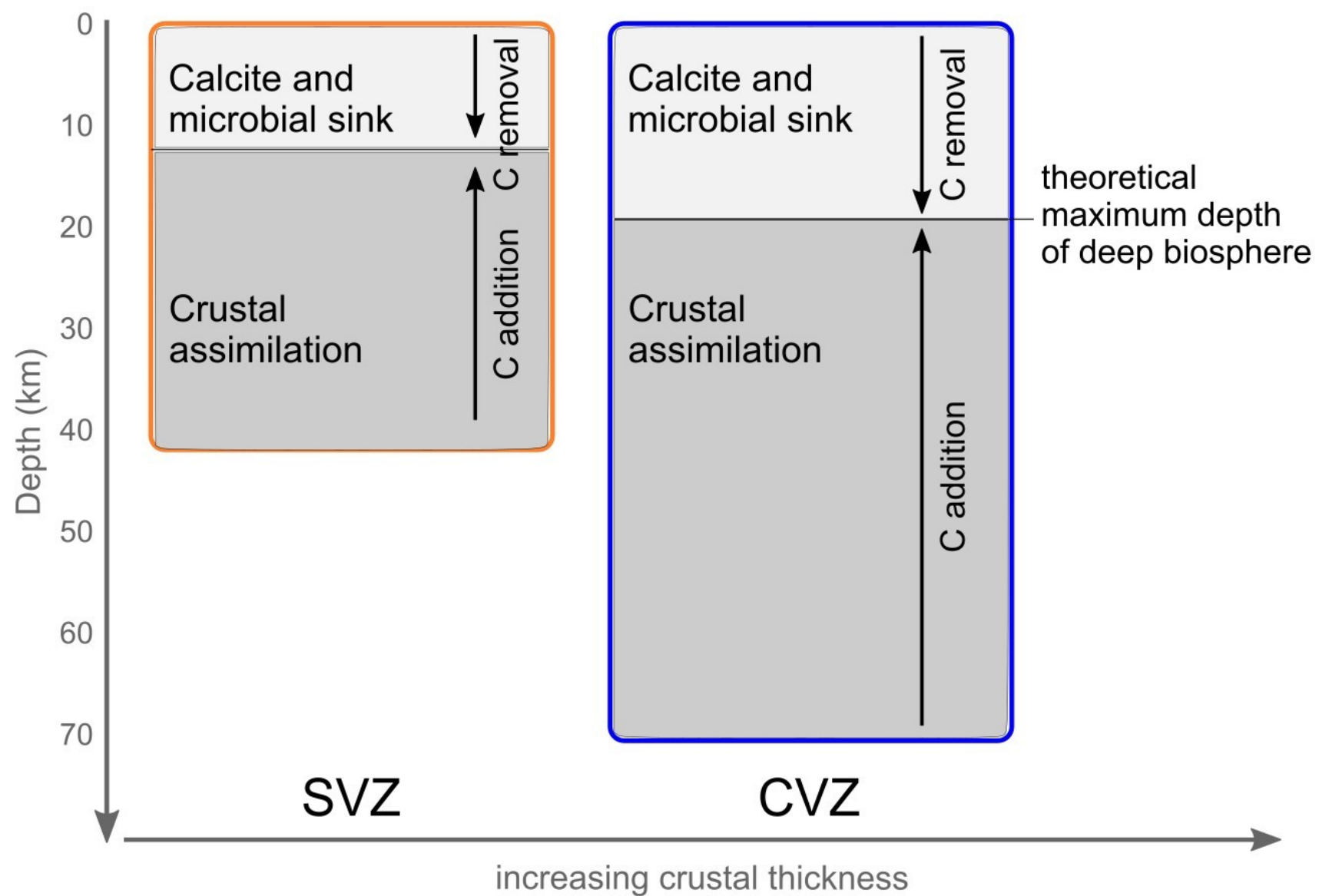




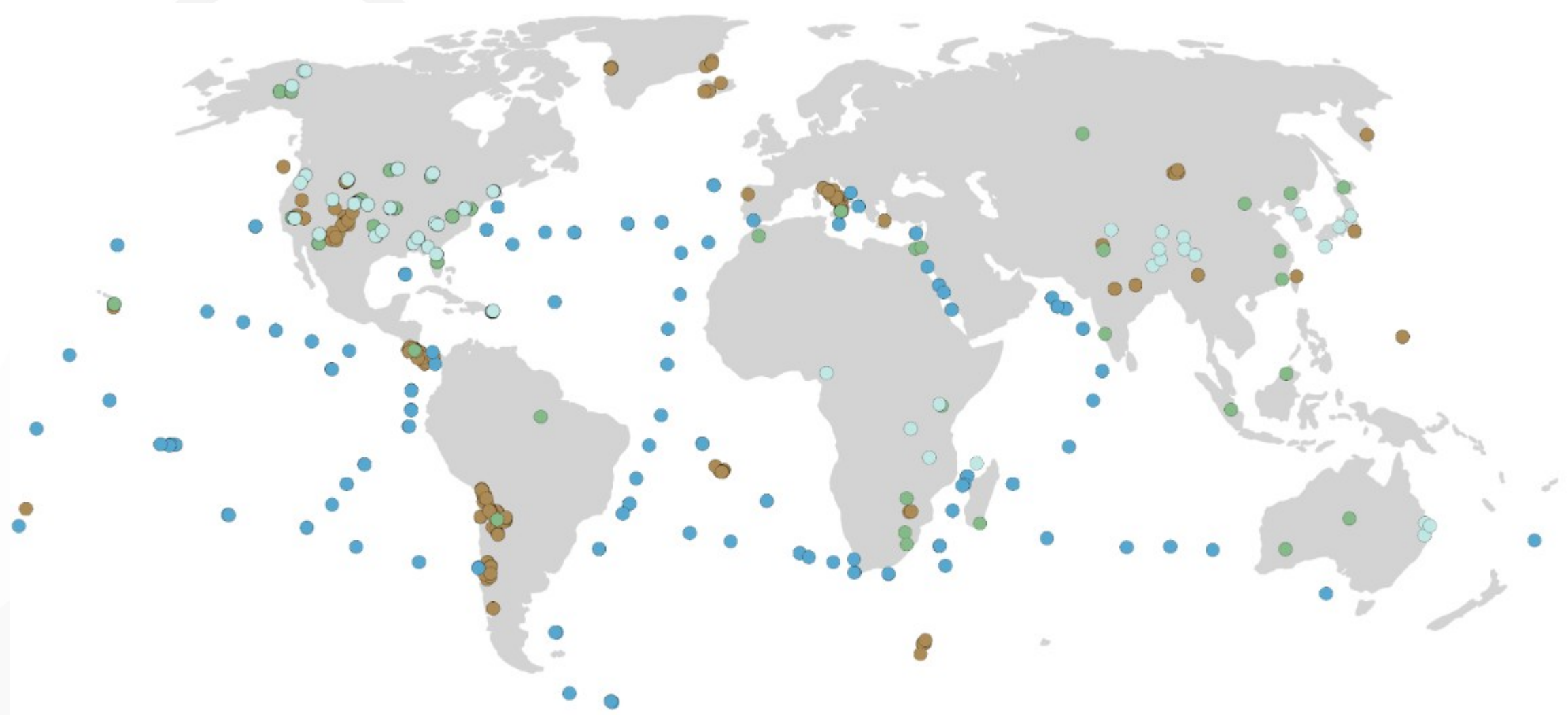


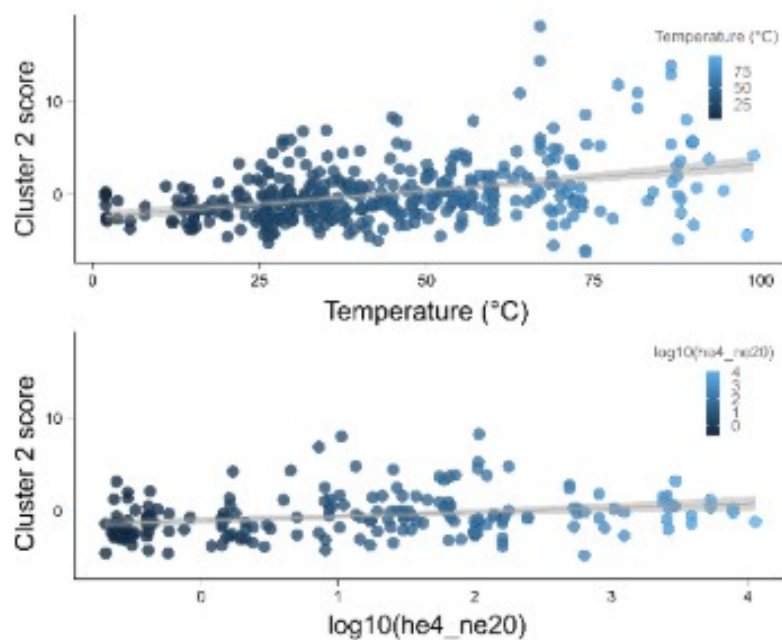
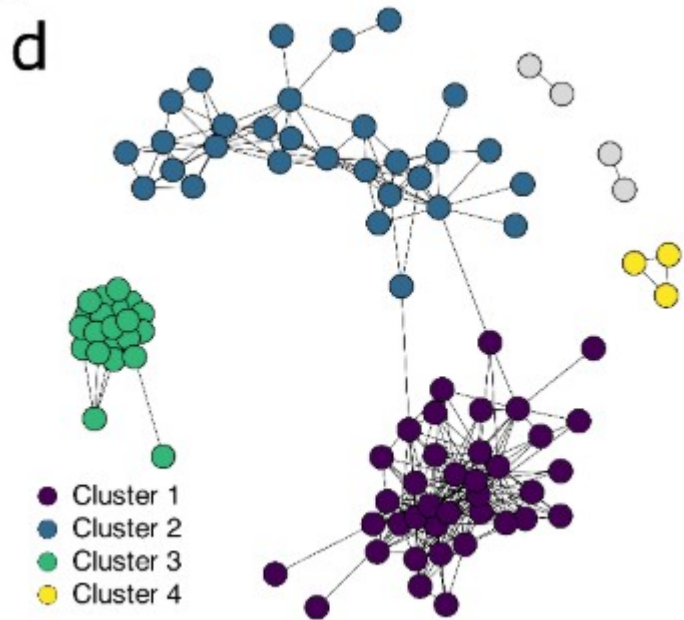
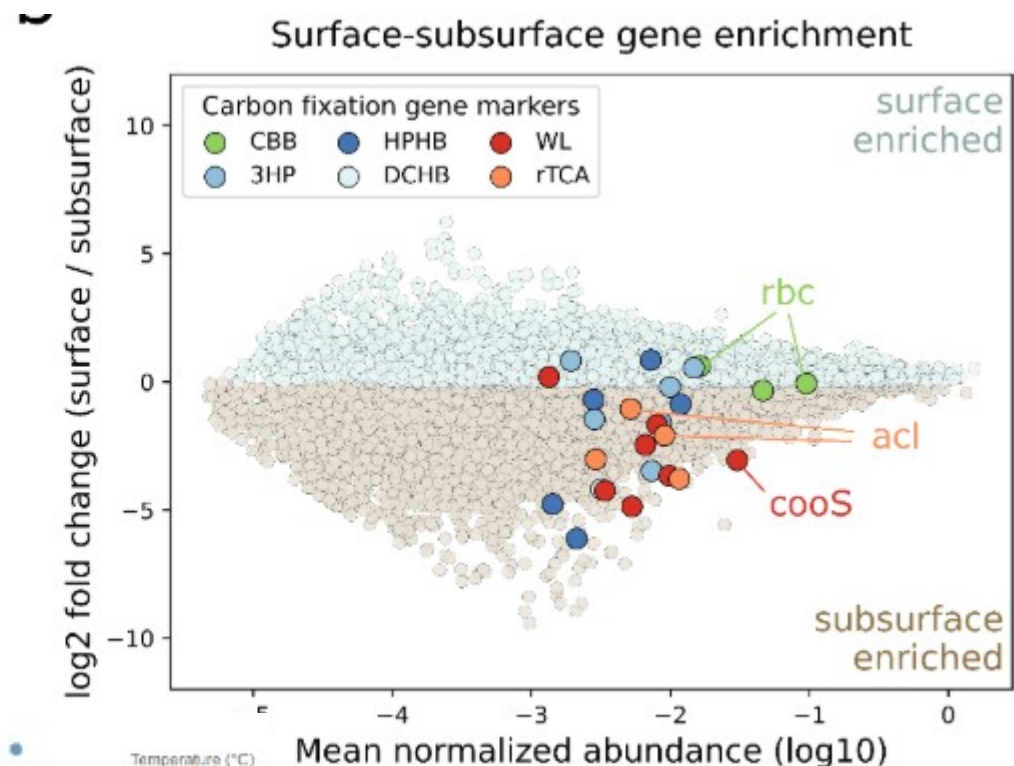
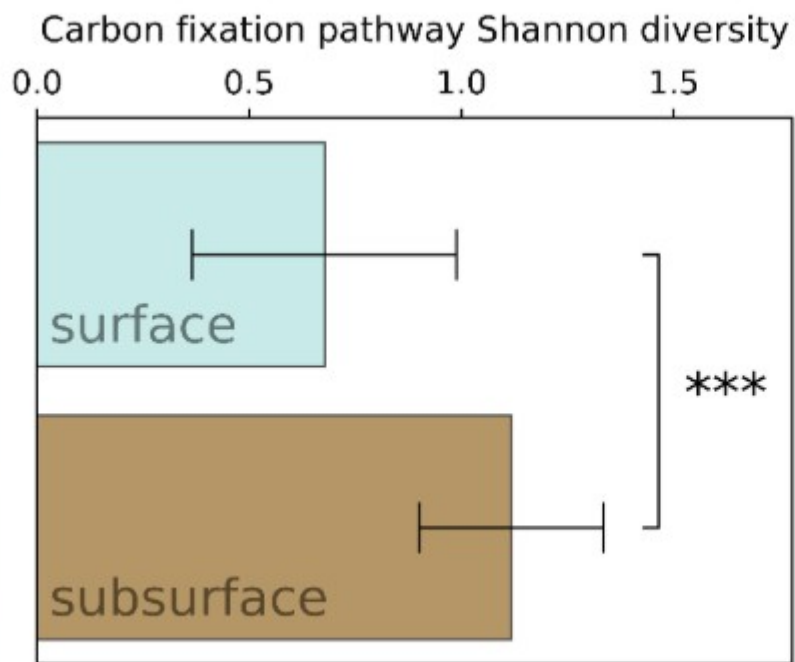
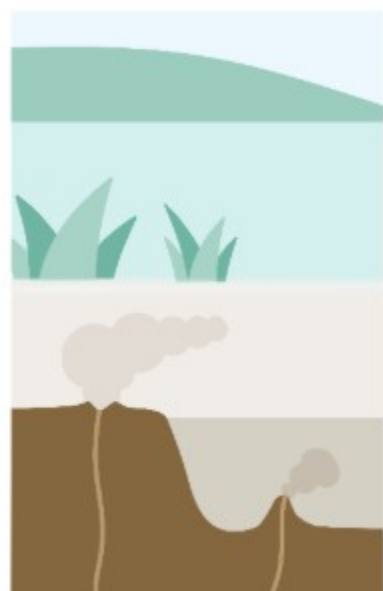
*calcite precipitation and microbial activity
 sequester up to 40% of the carbon believed
 to go into the deep mantle*

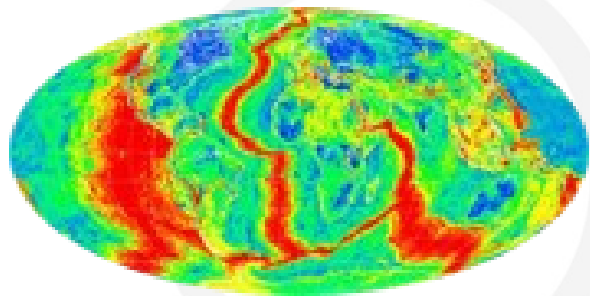




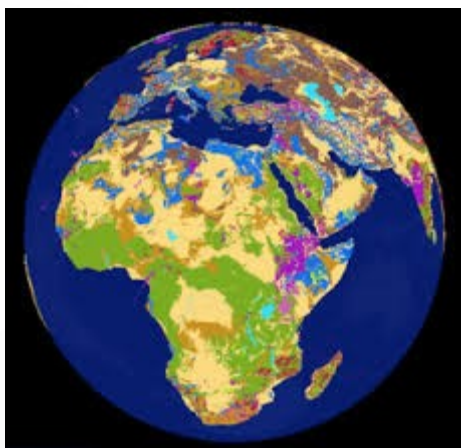
GLOBAL SUBSURFACE CARBON FIXATION



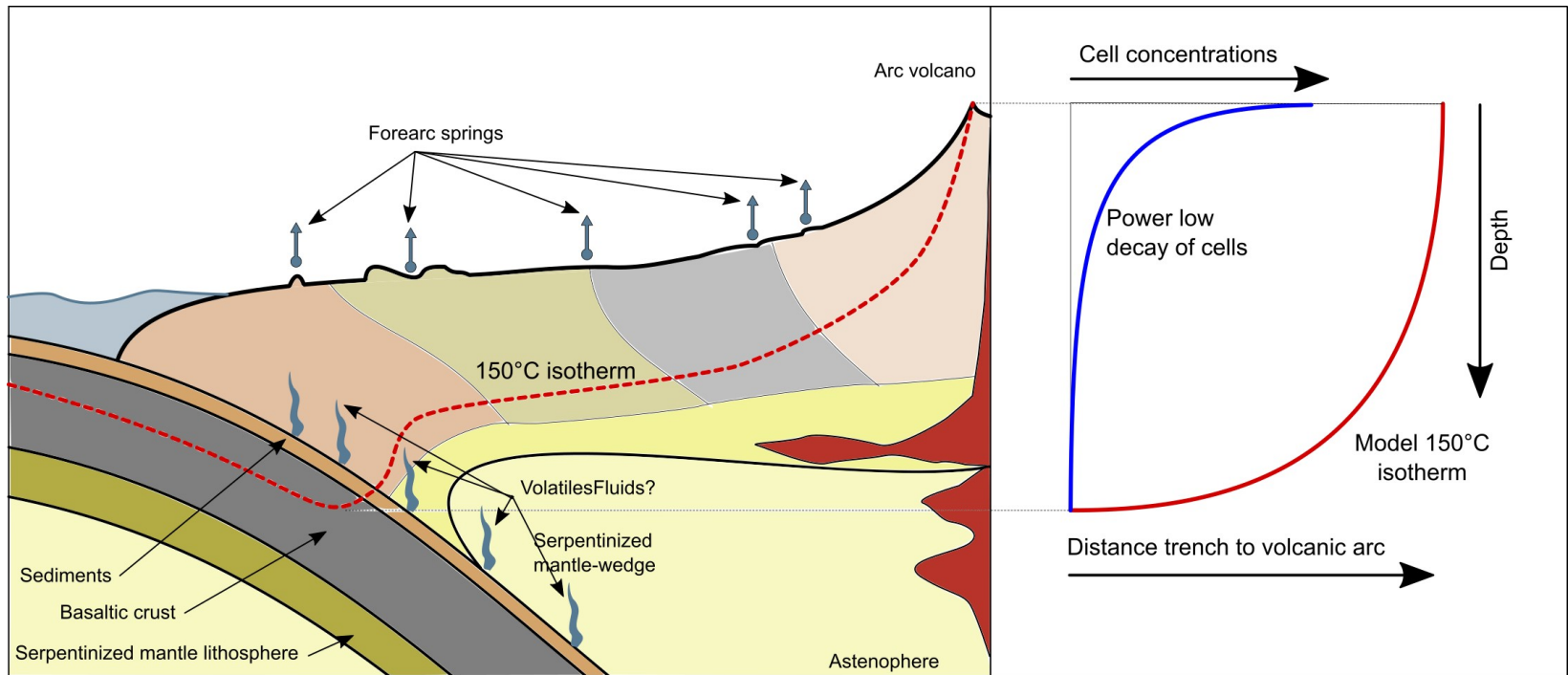




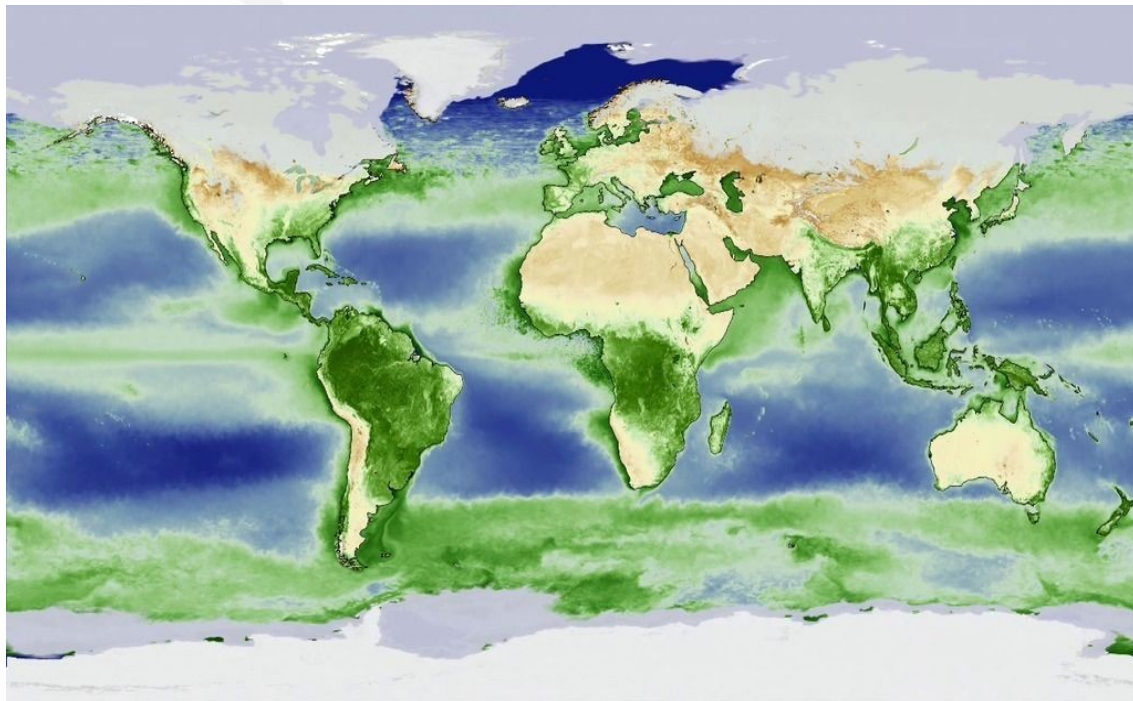
Lucazeau (2019)



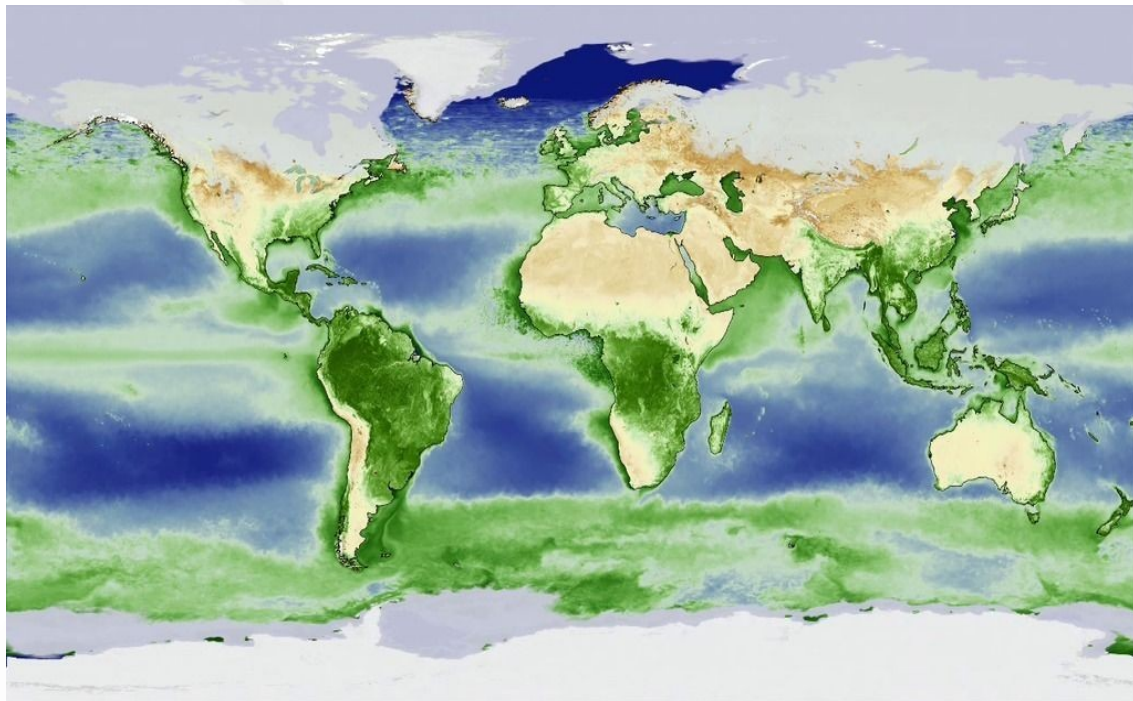
GLiM



Global continental rates of Carbon fixation
 $2.65 \text{ Pg C yr}^{-1} (0.31-2.99)$



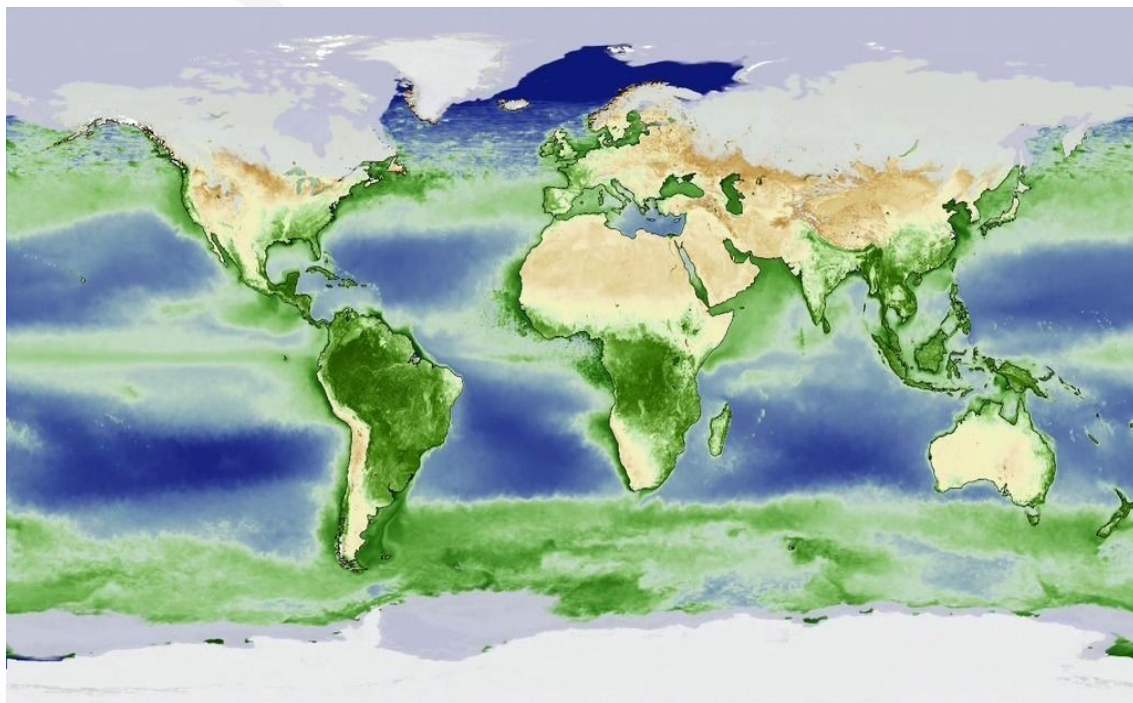
~2-3% of surface primary productivity



~2-3% of surface primary productivity



10x volcanic flux to the surface



~2-3% of surface primary productivity

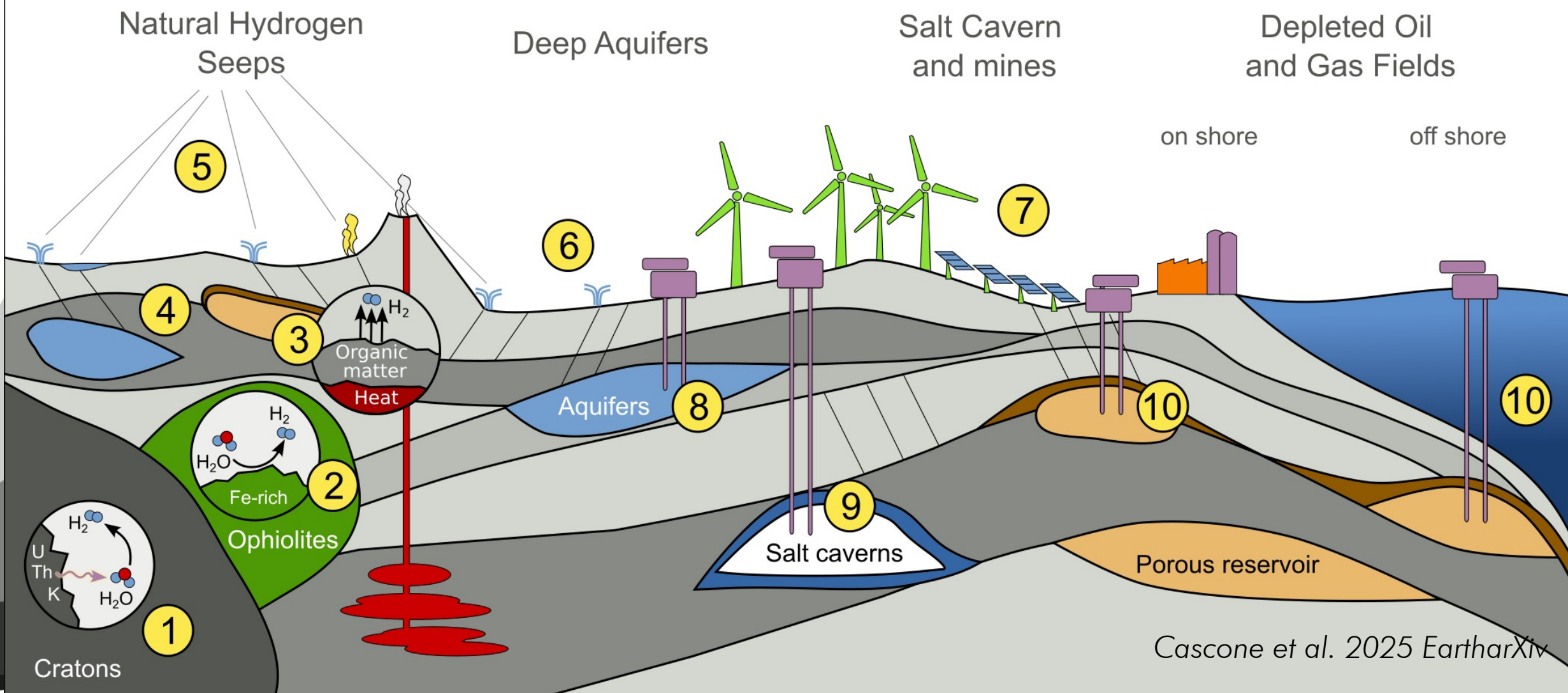


10x volcanic flux to the surface

This suggest that a **large fraction** of the inorganic carbon used by life in the subsurface is of **geological origin**

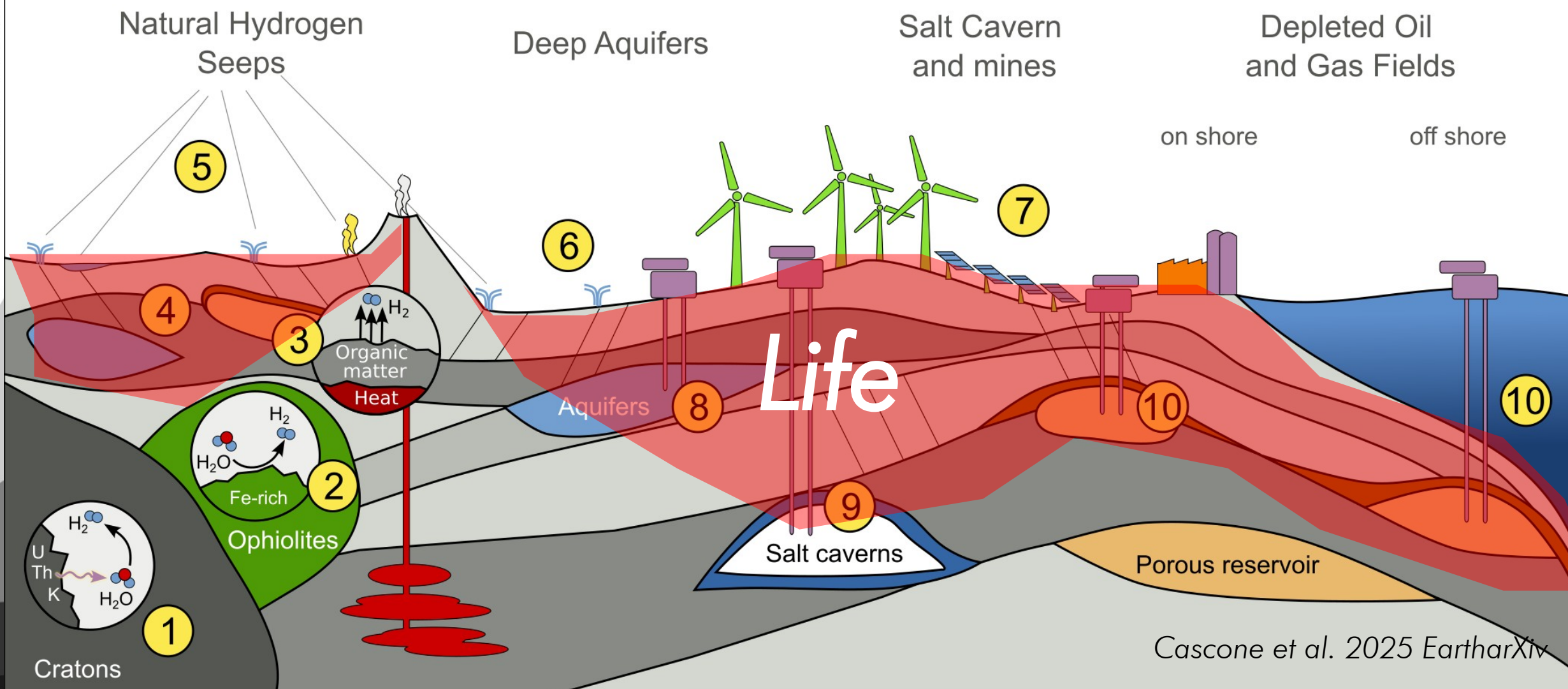
Natural Hydrogen

Underground Hydrogen Storage



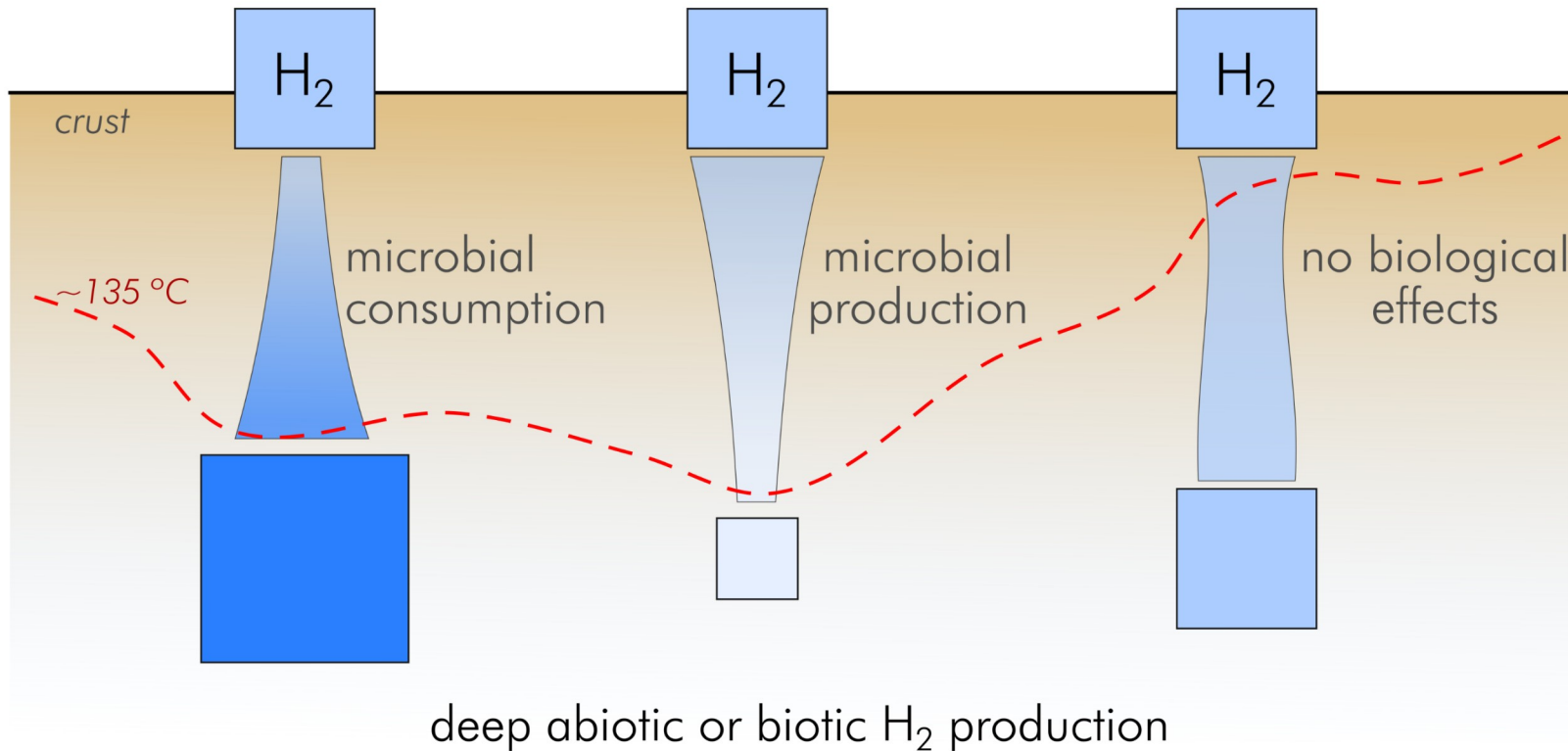
Natural Hydrogen

Underground Hydrogen Storage



Assessing the microbial problem

H₂ prospecting or UHS operations



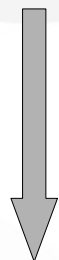
- Impact the H₂ production in the kitchen
- Impact the H₂ during migration
- Impact the H₂ during storage in the traps

Is my process, part of my process or
the path of my proxy in the **boundary
domain of life?**

(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35
% salinity, 0-2 Gpa)

Is my process, part of my process or
the path of my proxy in the **boundary
domain of life?**

(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35
% salinity, 0-2 Gpa)



NO

Geology Rocks!
You're good to go!

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**

(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES

How much time/space has life to interact with it?

NO

Geology Rocks!
You're good to go!

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**
(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES →

How much time/space has life to interact with it?

Little →

Geology Rocks!
You're good to go!

NO ↓

Geology Rocks!
You're good to go!

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**
(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES →

How much time/space has life to interact with it?

Little →

Geology Rocks!
You're good to go!

NO ↓

Geology Rocks!
You're good to go!

A lot ↓

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**
(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES →

How much time/space has life to interact with it?

Little →

Geology Rocks!
You're good to go!

NO ↓

Geology Rocks!
You're good to go!

A lot ↓

What's the relative biotic/abiotic contribution?

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**
(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES →

How much time/space has life to interact with it?

Little →

Geology Rocks!
You're good to go!

NO ↓

Geology Rocks!
You're good to go!

A lot ↓

What's the relative biotic/abiotic contribution?

Known ↓

Great, you can calculate. You're good to go!

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**
(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES →

How much time/space has life to interact with it?

Little →

Geology Rocks!
You're good to go!

NO ↓

Geology Rocks!
You're good to go!

A lot ↓

What's the relative biotic/abiotic contribution?

Known ↓

Great, you can calculate. You're good to go!

Unknown ↓

Is my process, part of my process or the path of my proxy in the **boundary domain of life?**
(that is -18–135 °C, 0–12.8 pH, below boiling, 0–35 % salinity, 0-2 Gpa)

YES →

How much time/space has life to interact with it?

Little →

Geology Rocks!
You're good to go!

NO ↓

Geology Rocks!
You're good to go!

A lot ↓

What's the relative biotic/abiotic contribution?

Known ↓

Great, you can calculate. You're good to go!

Unknown ↓

Squishy things are messing your work.
Call a Microbiologist!



FUNDING



icdp



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