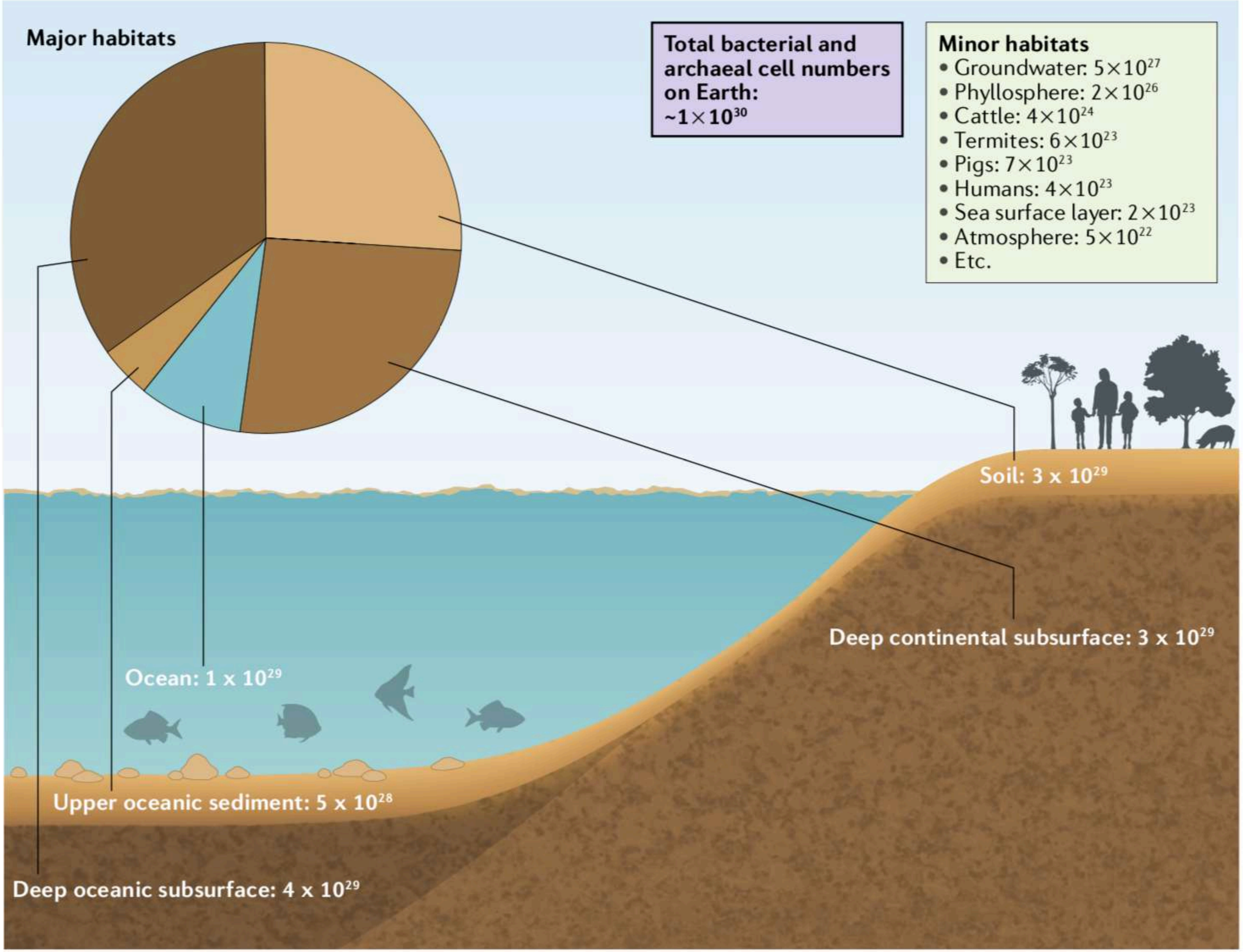
L07c

Microbial Ecology

- Study of the **interactions** of microorganisms with their **environment (including organic matter)**, **each other**, and plant and animal species (**other organisms**) —> <u>symbioses, biogeochemical cycles, climate change</u>
- **Marine sediment ecosystem**
- **Ocean ecosystem**
- **Freshwater ecosystem**

Microbial abundance



Total bacterial and archaeal cell numbers on Earth:
~1×10^{30}

Minor habitats
- Groundwater: 5×10^{27}
- Phyllosphere: 2×10^{26}
- Cattle: 4×10^{24}
- Termites: 6×10^{23}
- Pigs: 7×10^{23}
- Humans: 4×10^{23}
- Sea surface layer: 2×10^{23}
- Atmosphere: 5×10^{22}
- Etc.

Atmo

Bio

Aqua

Geo

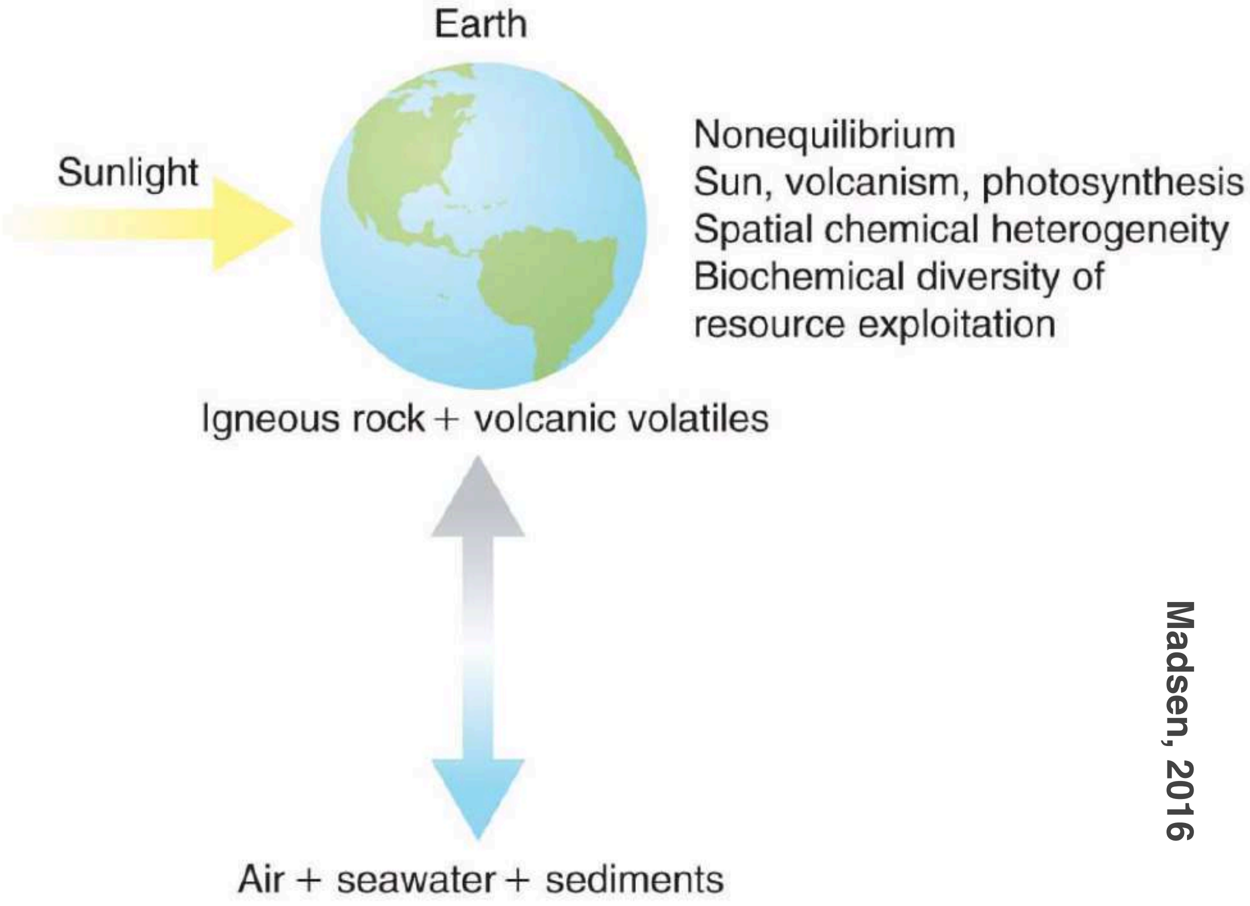
Spheres

Flemming & Wuertz, 2019

MARINE SEDIMENTS
OCEAN FLOOR

Marine sediments as a microbial ecosystem

- Global view of Earth: a heterogeneous mixture of rocks, water, gases, organisms is maintained in a non equilibrium state by sunlight and volcanism
- Hydrothermal vents, cold seeps are oasis of primary production and microbial and biochemical diversity


Earth

Sunlight

Nonequilibrium
Sun, volcanism, photosynthesis
Spatial chemical heterogeneity
Biochemical diversity of
resource exploitation

Igneous rock + volcanic volatiles

Air + seawater + sediments

Madsen, 2016

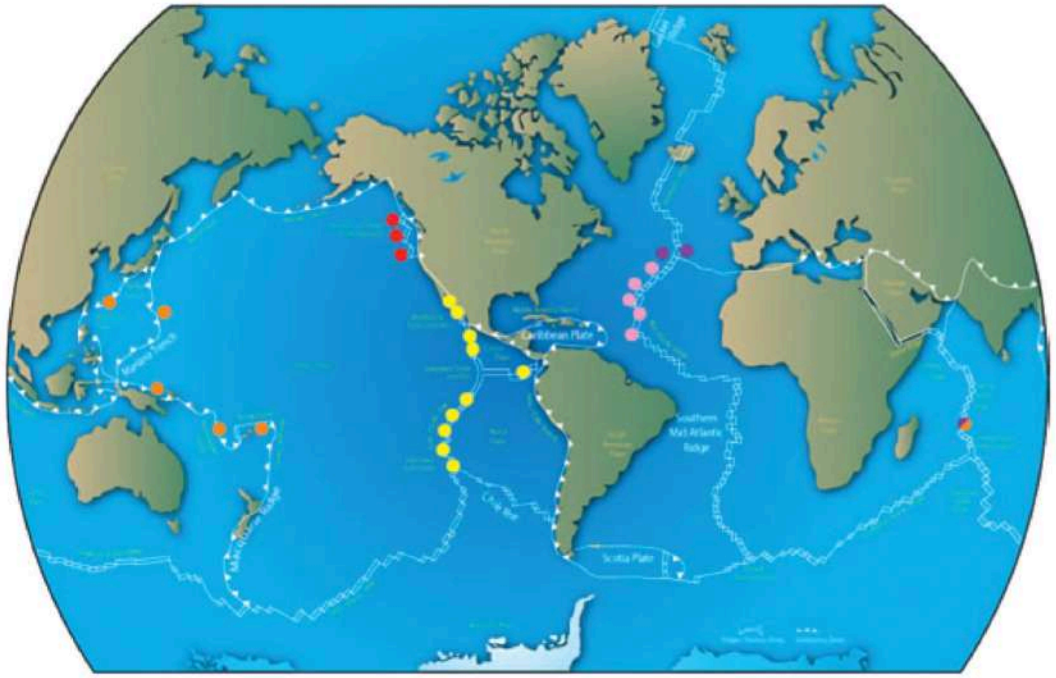


Figure 4.10 Plate tectonic map of the globe showing major plate boundaries, mid-ocean ridges, and distribution of hydrothermal vent sites. Colored circles show vents with similar animal communities. (Courtesy of E. Paul Oberlander, with permission from Woods Hole Oceanographic Institute.)

Madigan et al. 2018

- Approximately 1x10^{9} microbes in 1 g of upper sediment
- Biofilm

Microbial metabolic pathways shaping Earth ecosystem

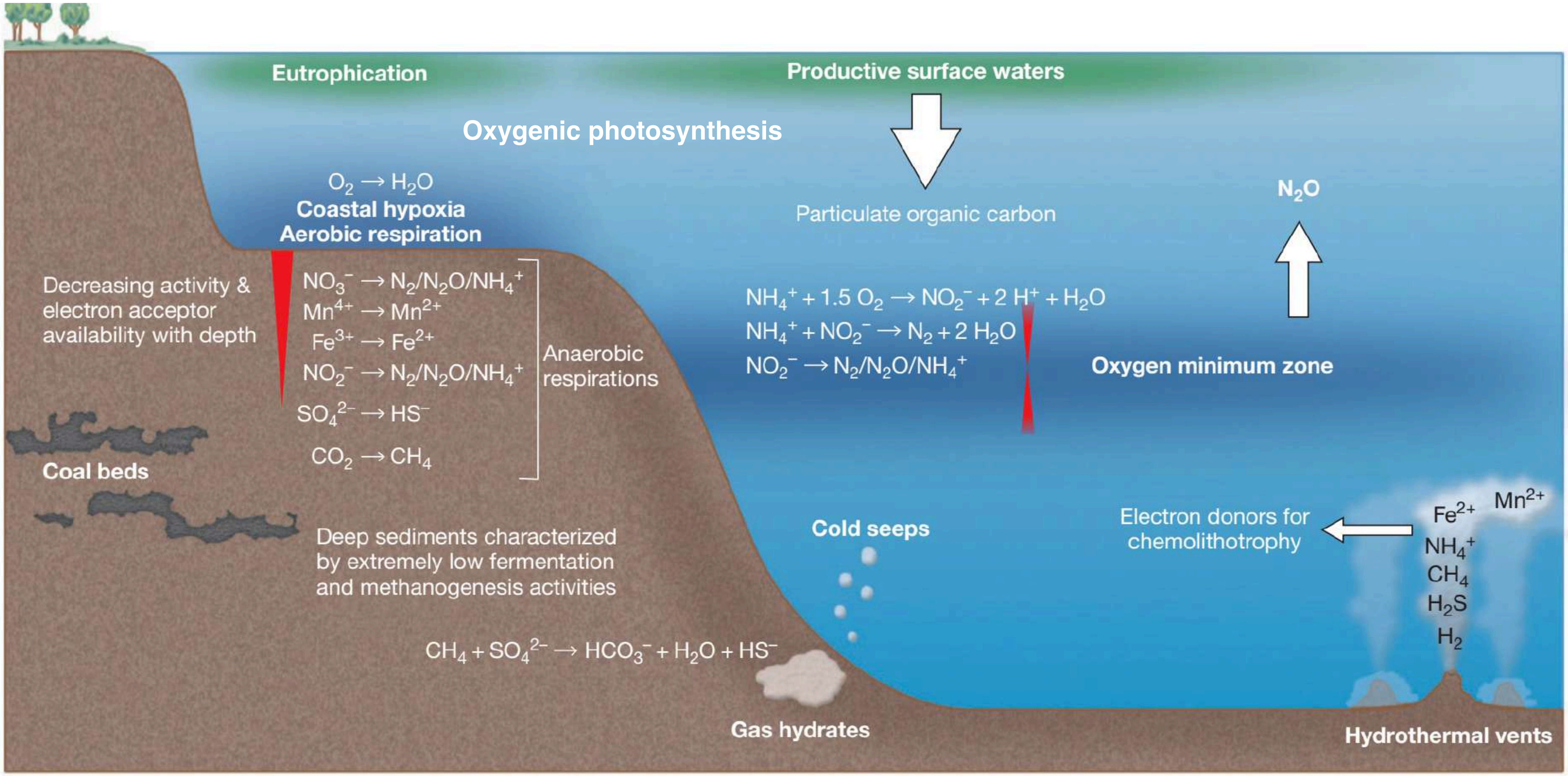


Figure 20.20 Diversity of marine systems and associated microbial metabolic processes. Decreasing electron acceptor availability with depth into the sediment or with increasing distance into an oxygen minimum zone is indicated by red wedges. Sulfate becomes limiting only at greater depths in marine sediments. The indicated metabolic diversity is covered in Chapter 14.

Madigan et al. 2018

Terrestrial *vs* marine fingerprint

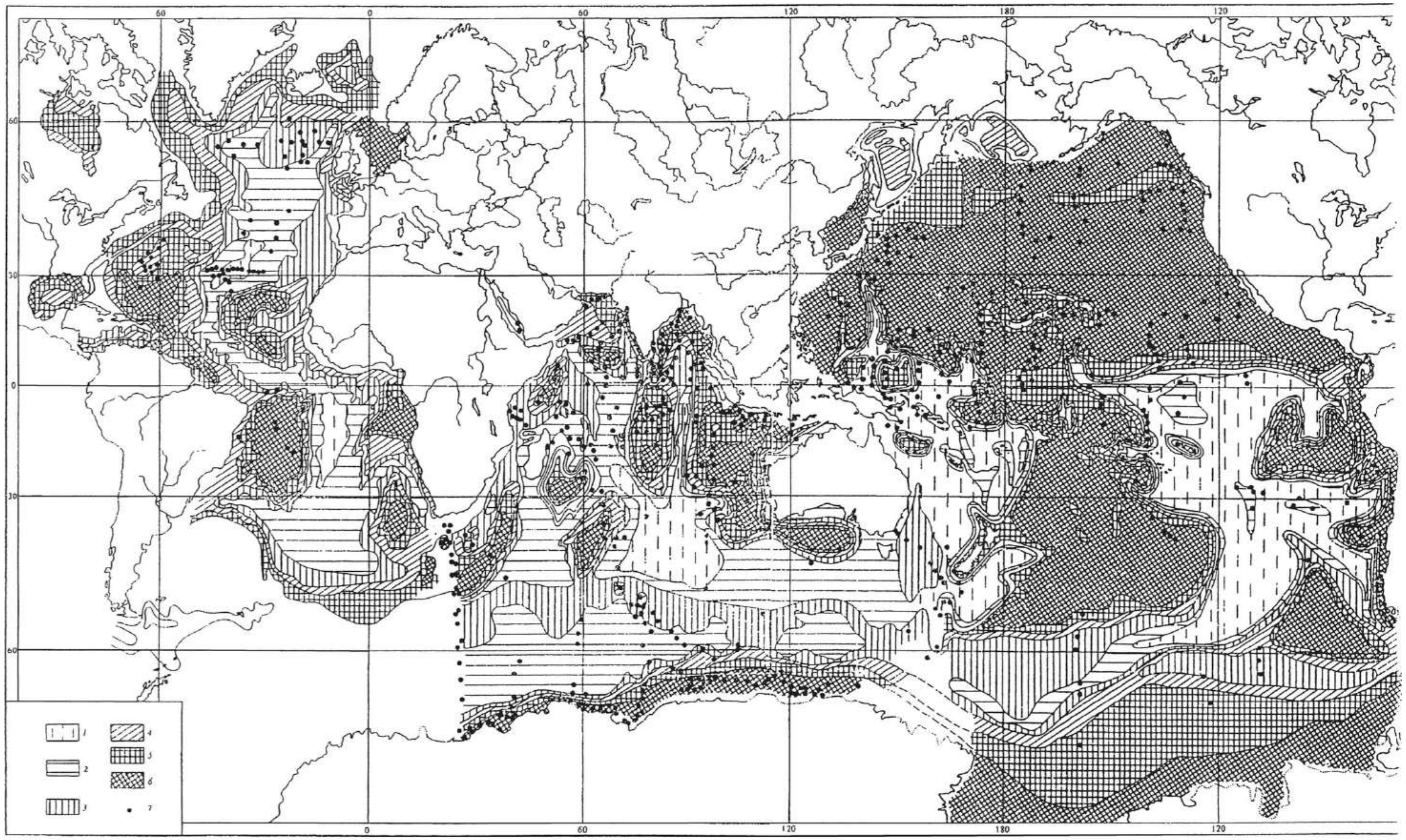
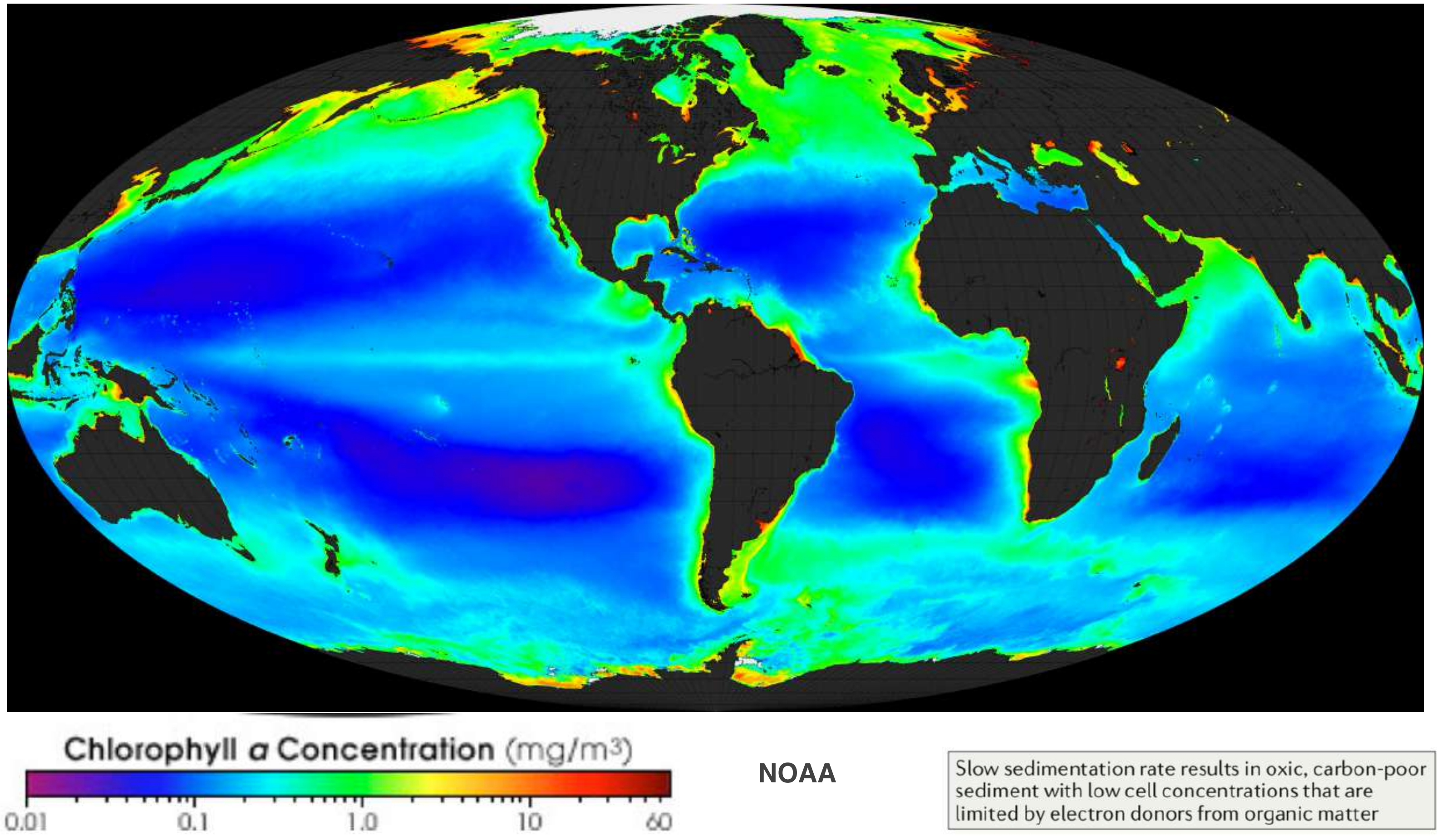


Figure 4.11 Composition of ocean sediments: percent derived from continents (terrigenous) versus autochothonous biotic sources. The six boxes in the key (numbered 1–6) show values from <10% (1, lightest shading) to >90% (6, darkest shading) terrigenous sediment. (From Lisitzin, A.P. 1996. *Oceanic Sedimentation*, pp. 28–29. American Geophysical Union, Washington, DC. Copyright 1996, American Geophysical Union. Reproduced by permission of American Geophysical Union.)

Madsen, 2016

- Marine sediments are influenced by terrestrial ecosystem and water column ecosystem
- Marine sediments: clay-silt-sand
- Marine sediments are very dynamic

Ocean surface photosynthesis dictates sedimentation



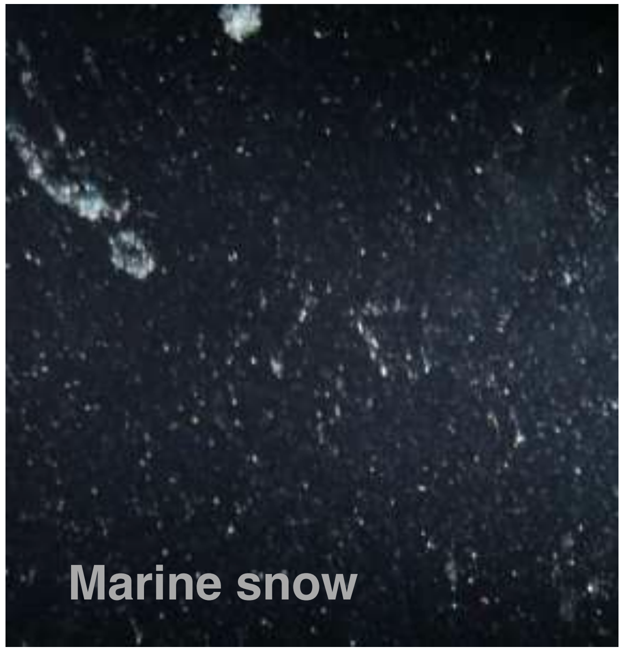
NOAA

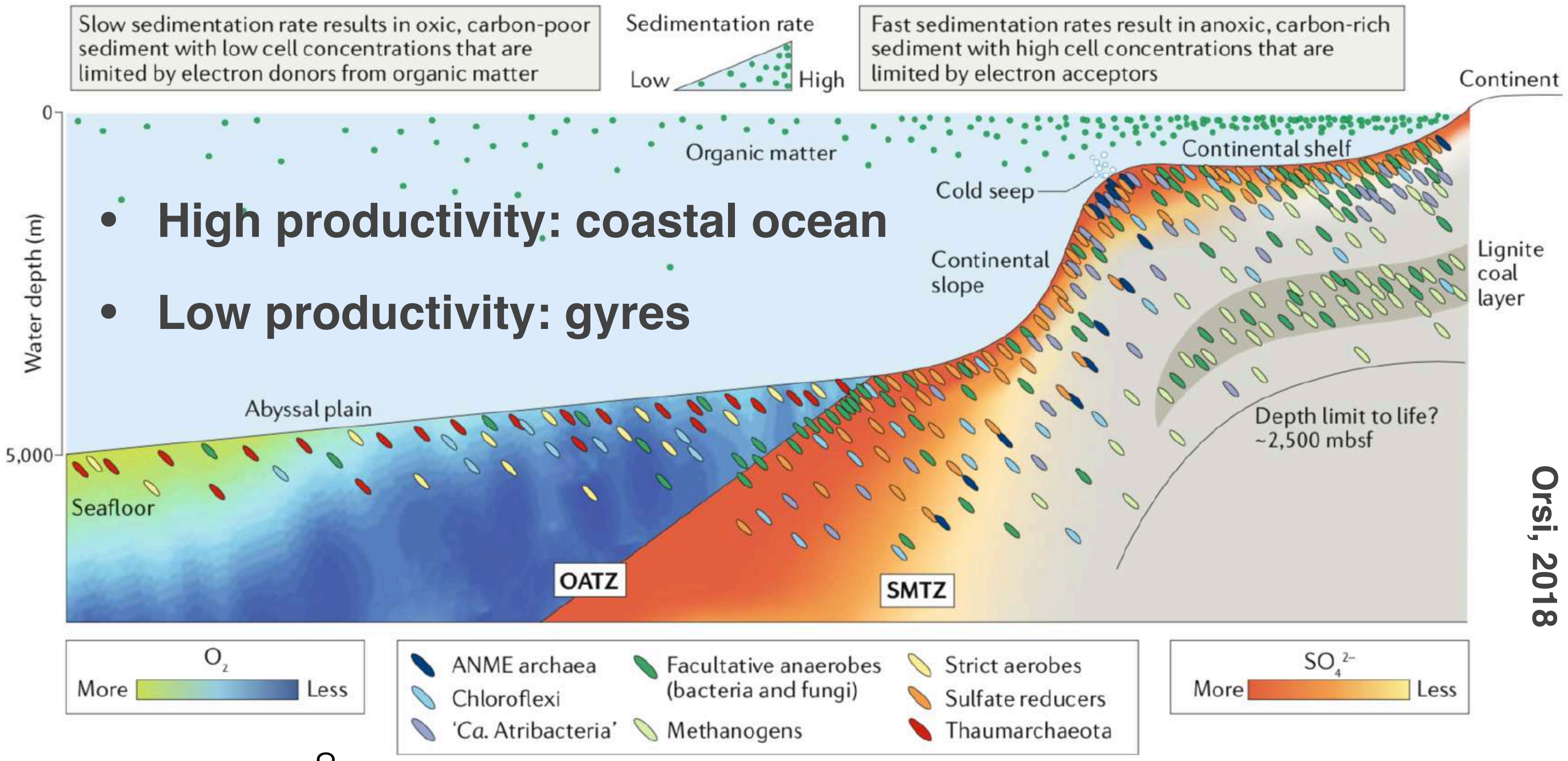
- Chlorophyll data from satellite to inform on photosynthesis —> organic matter production by microscopic algae (phytoplankton) and cyanobacteria

- Life and death in the upper ocean create a down-ward flux of organic matter and associated minerals

Dead organisms

Fecal pellets



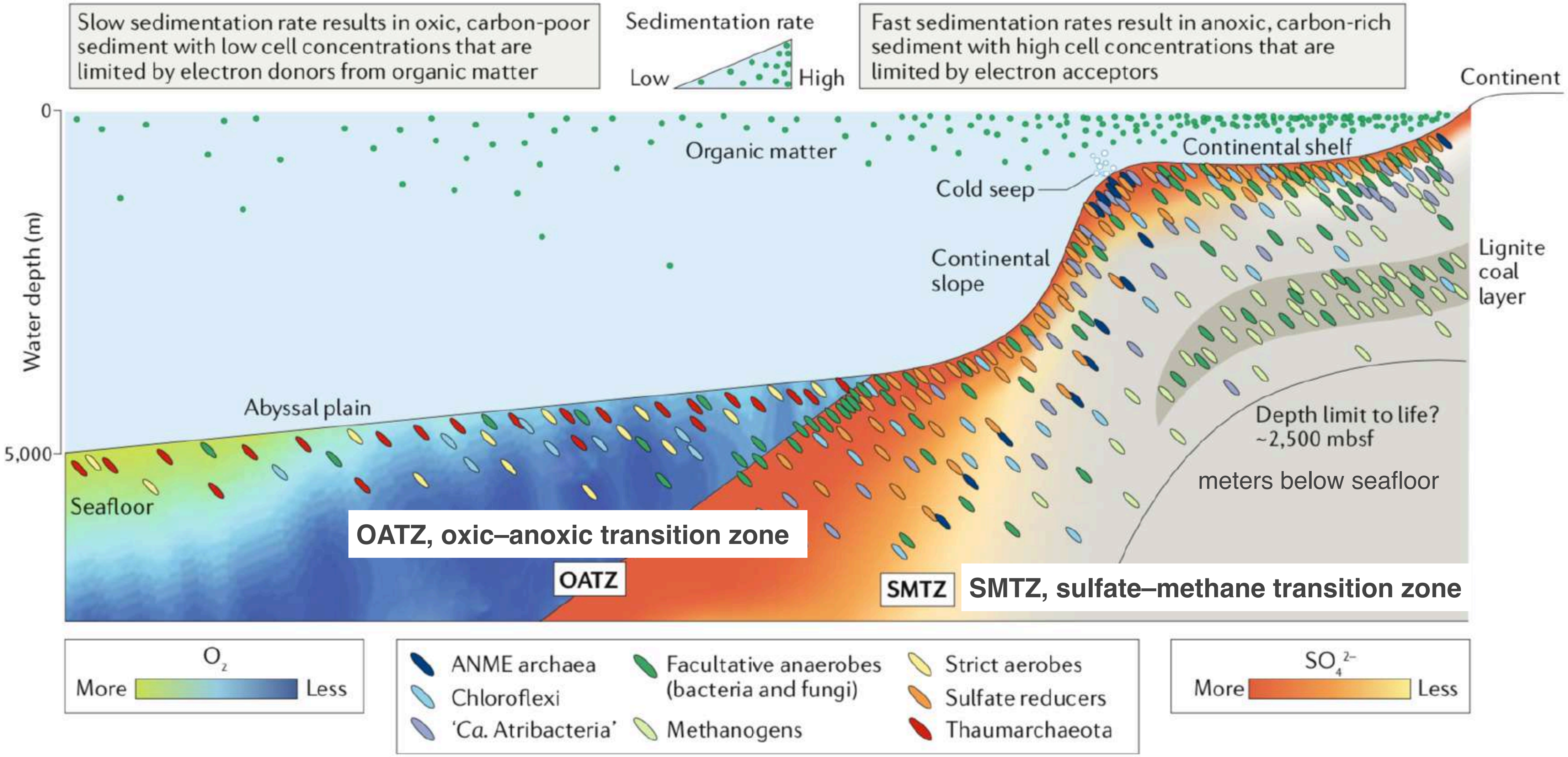


- **High productivity: coastal ocean**
- **Low productivity: gyres**

Orsi, 2018

Sedimentation rate

- Redox conditions in seafloor and subseafloor ecosystems are linked to sedimentation rate and distance from shore
- Ultra-low rates of organic matter sedimentation under oligotrophic gyres lead to deep O_2 penetration (left), and consequently, the survival of microbial communities is limited by availability of electron donors from organic matter
- Faster sedimentation rates closer to shore cause anoxic conditions shortly below the seafloor owing to the rapid consumption of oxygen for organic matter oxidation at the sediment surface (right), terminal electron acceptors—> sulfate



meters below seafloor

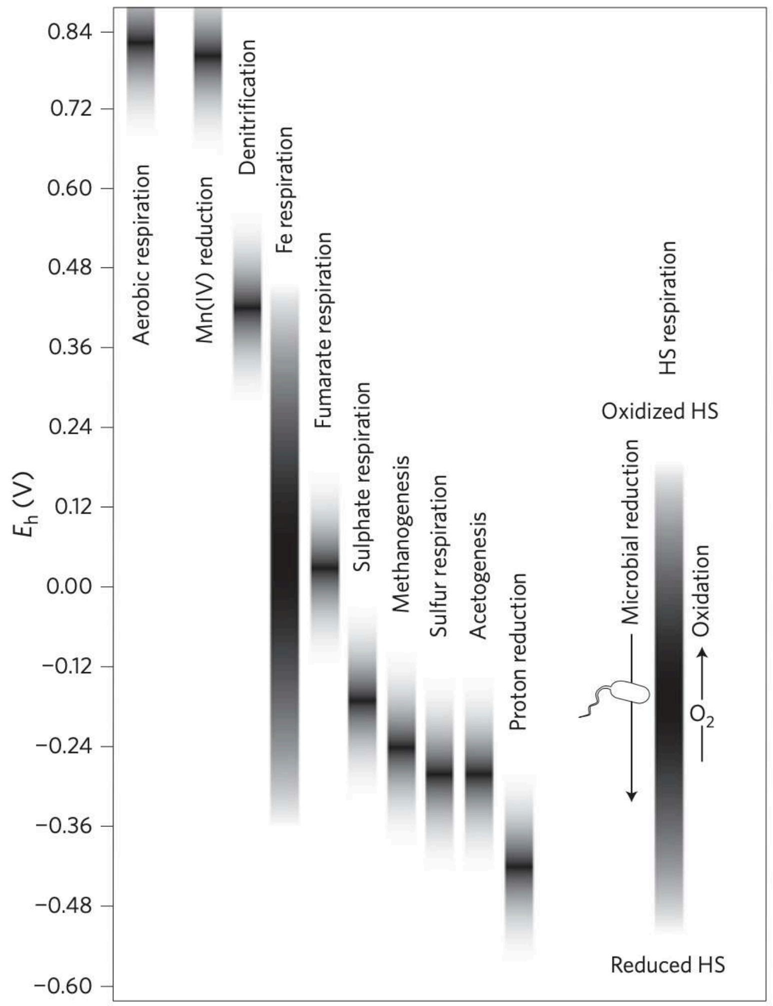
OATZ, oxic–anoxic transition zone

SMTZ, sulfate–methane transition zone

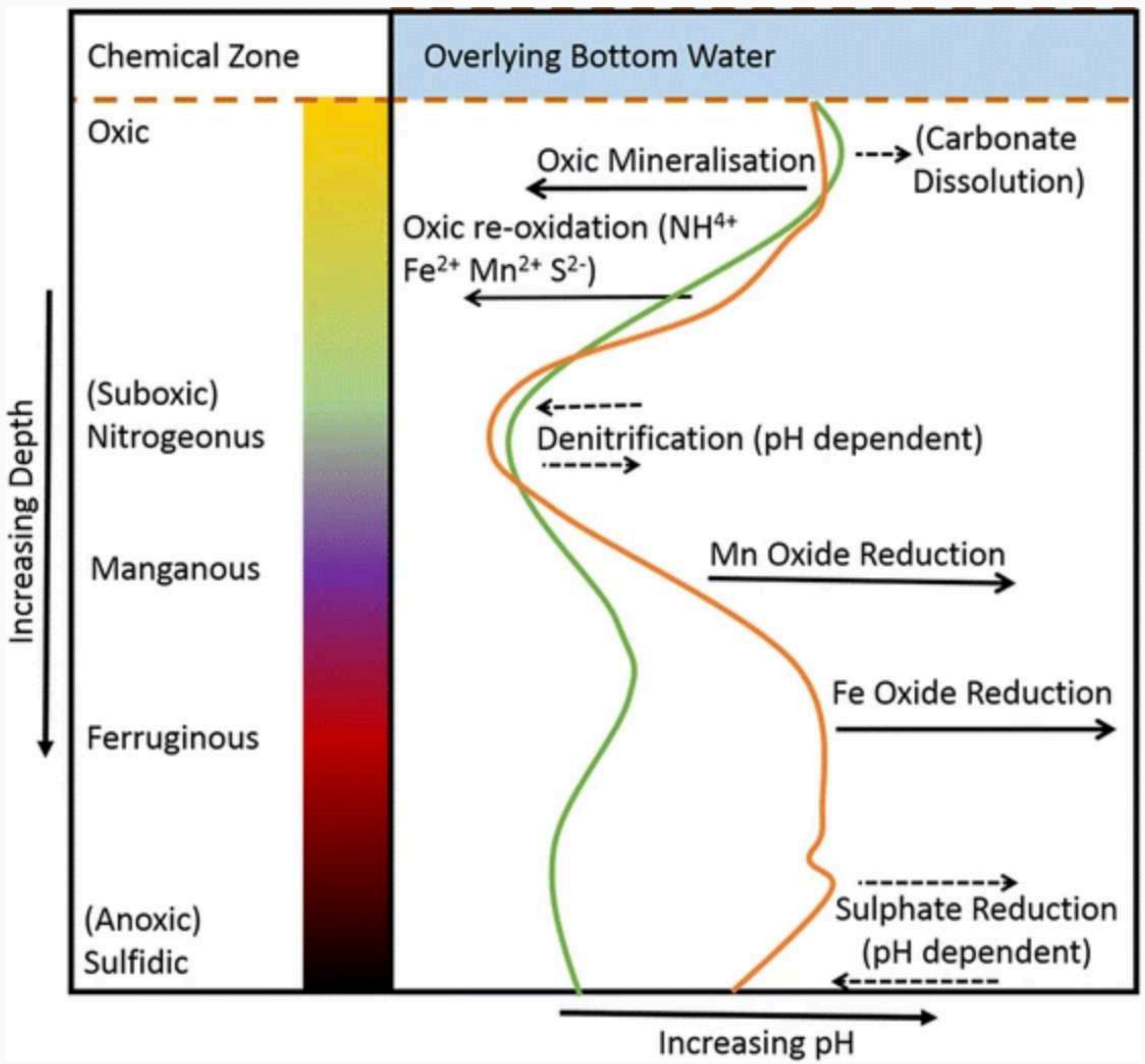
Orsi, 2018

Sediment: Organic matter decomposition/respiration —> nutrient recycling

- **Microbes able to respire in multiple ways will always choose available acceptors with the biggest potential difference to the donor**



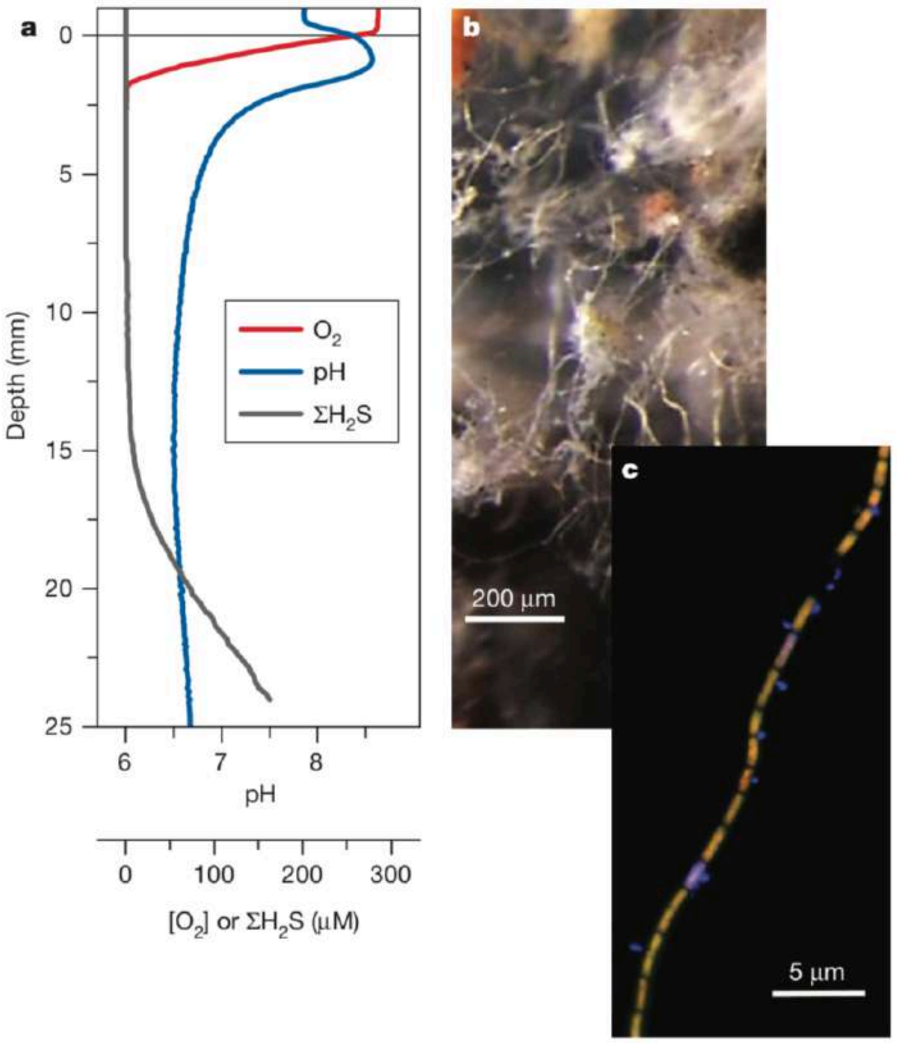
Klüpfel et al., 2014



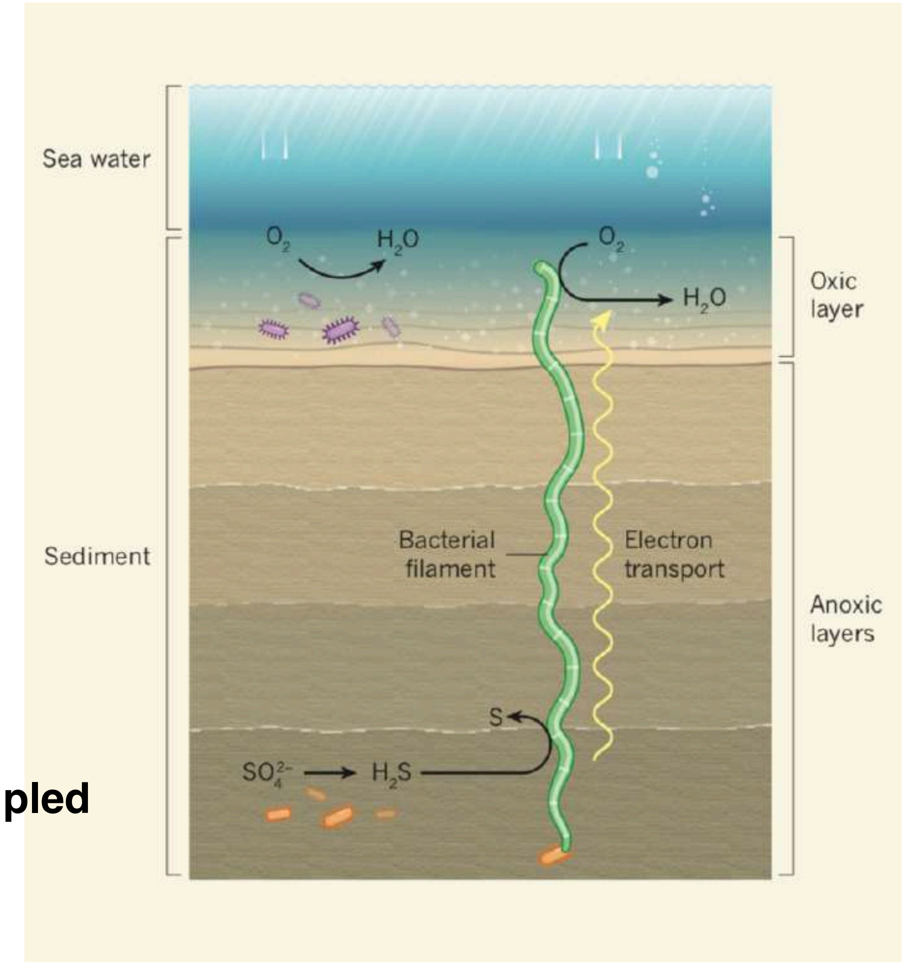
Silburn et al., 2017

Sharing the burden in the sediment

Pfeffer et al., 2012



Reguera, 2012



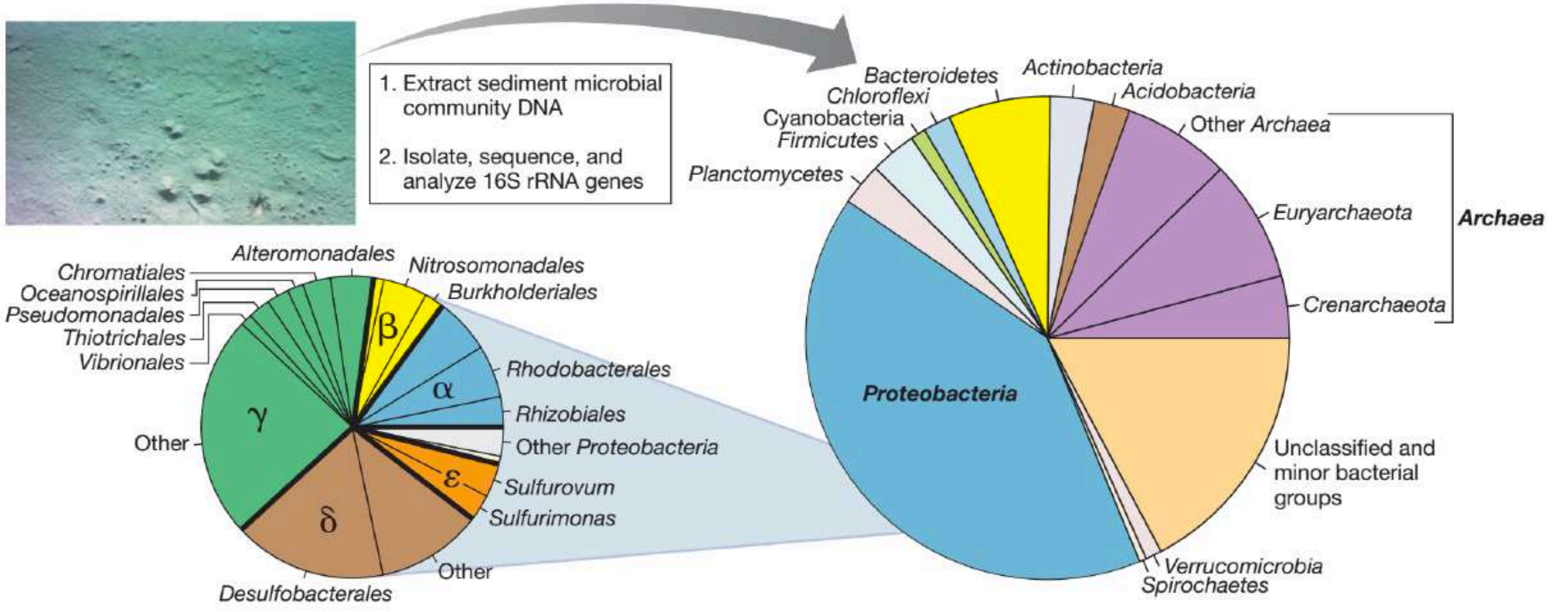
Spatially coupled

Spatially segregated

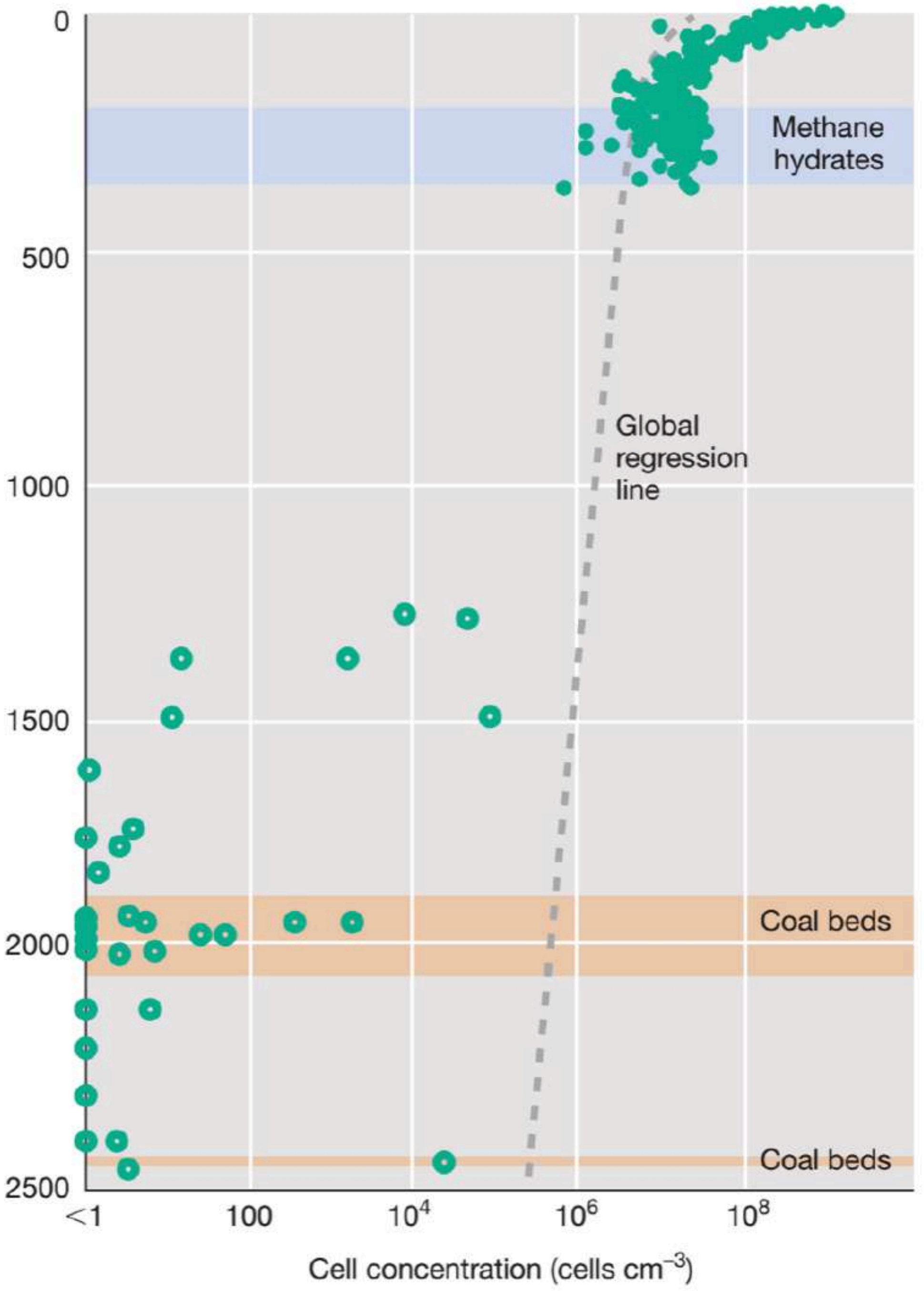
- Microorganisms (purple) in the upper layers of marine sediments use oxygen (O_2) that diffuses from sea water as an acceptor of electrons, which they produce in energy-generating metabolic reactions. **As a result, other microbes (orange) in deeper, anoxic layers (where oxygen is scarce or absent) have to use other electron acceptors such as sulphate (SO_4^{2-}) for growth**. Transfer of electrons to oxygen results in the formation of water, whereas electron transfer to sulphate produces hydrogen sulphide (H_2S), which is poisonous to many organisms
- Long bacterial filaments could transport electrons generated when hydrogen **sulphide is converted into sulphur (S)** at the bottom of the sediments and use them to consume oxygen in the upper layers
- During classical sulfur (S) oxidation, bacteria consume both O_2 and H_2S, and, as a result, both half-reactions of the overall redox reaction occur in the same location
- During electrogenic sulfur oxidation, **long-distance electron transport (LDET)** allows multicellular cable bacteria to harvest H_2S in deeper horizons of the seafloor, while still keeping access to O_2, which is available only in the top millimetres of the sediment. **By separating the two half-reactions in space, cable bacteria can outcompete classical sulfide oxidizing bacteria**

Microbial abundance and diversity in the sediment

- Structured 3D environment at high pressure at low temperature
- Hydrothermal vents, cold seeps, brines, carcasses as oasis of metabolic diversity (e.g. symbiosis, temperature, relatively fresh organic matter)



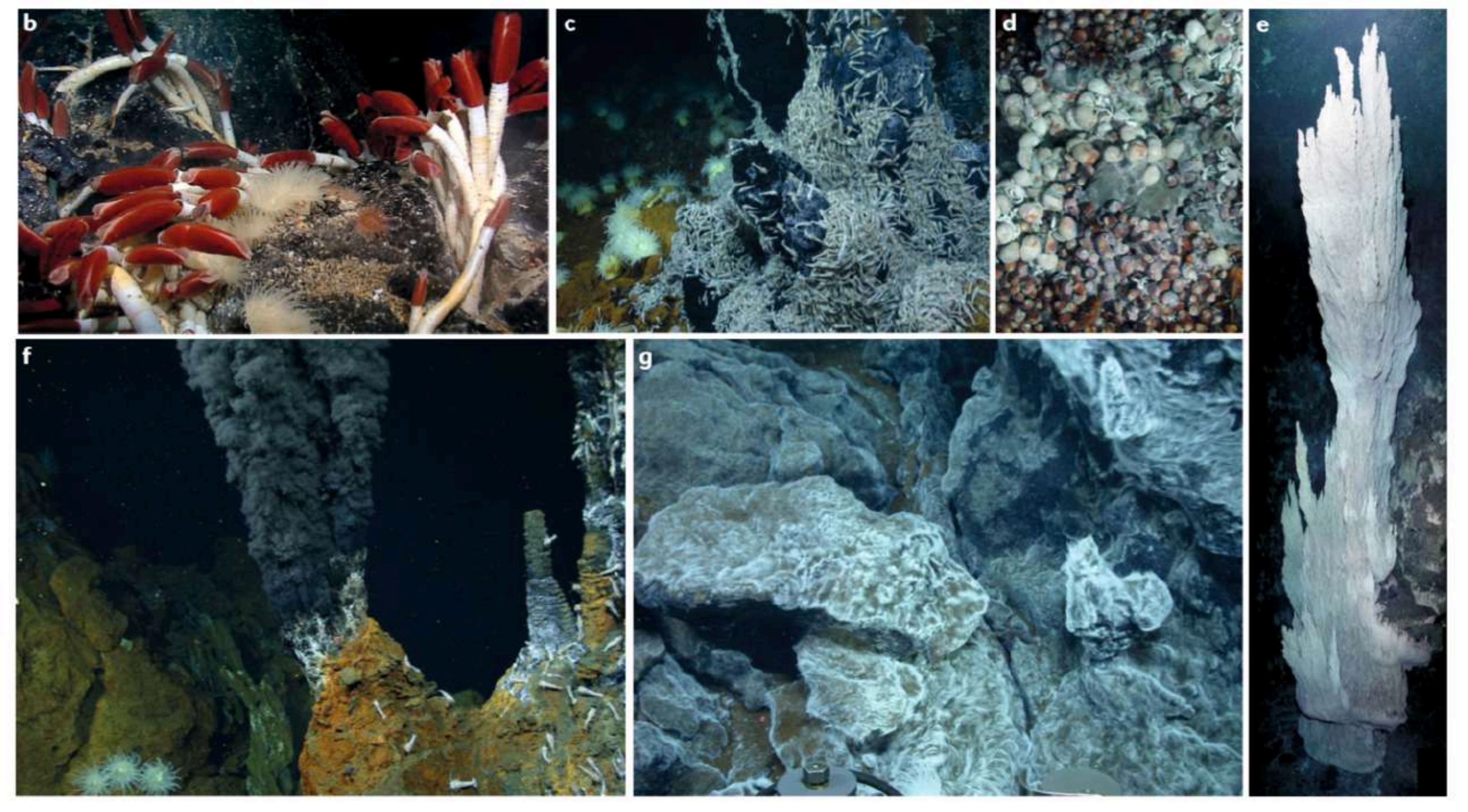
- 16SrRNA gene based diversity

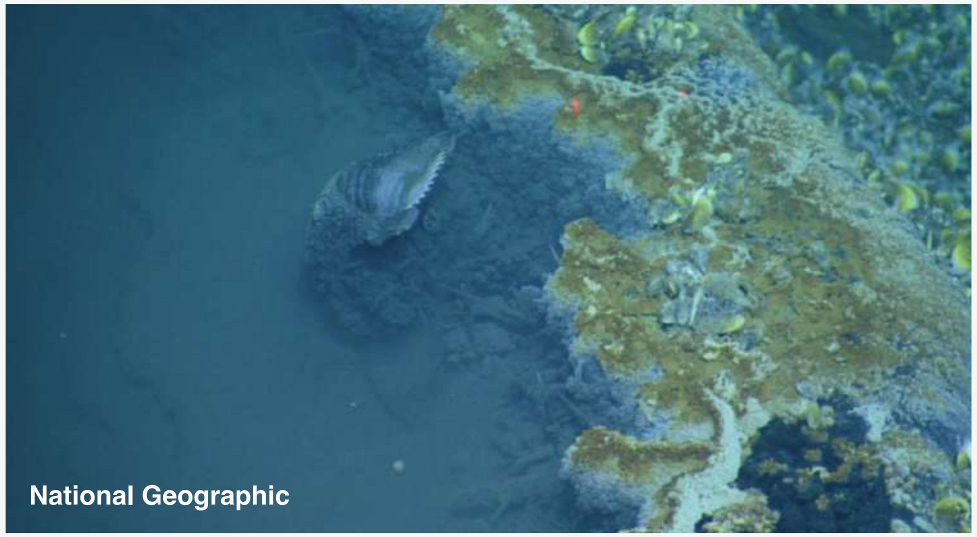


Madigan et al. 2018

Oasis in the deep ocean

Dick, 2019




National Geographic


[STAGES OF A WHALE-FALL COMMUNITY]

A dead whale that sinks to the seafloor brings a sudden bonanza of food to the dark, desertlike expanse. The community of organisms that springs up undergoes three ecological stages. Each stage is characterized by different species and different food webs—although at many such sites, the stages can overlap.

SCAVENGER STAGE

Hagfish—primordial relatives of vertebrates that are virtually blind and live on the muddy seafloor—eat much of the blubber and muscle tissue, helped by other scavengers, including sleeper sharks and some crabs.

DURATION: UP TO 2 YEARS

OPPORTUNIST STAGE

Animals feed on leftover scraps of meat and blubber and on whale oil that has soaked the surrounding sediment. This second wave of scavengers includes snails, bristle worms and hooded shrimp. Meanwhile "zombie worms" [*see illustration on page 84*] begin to spread their roots into the bones and feed on their lipid content.

DURATION: UP TO 2 YEARS

SULFOPHILIC STAGE

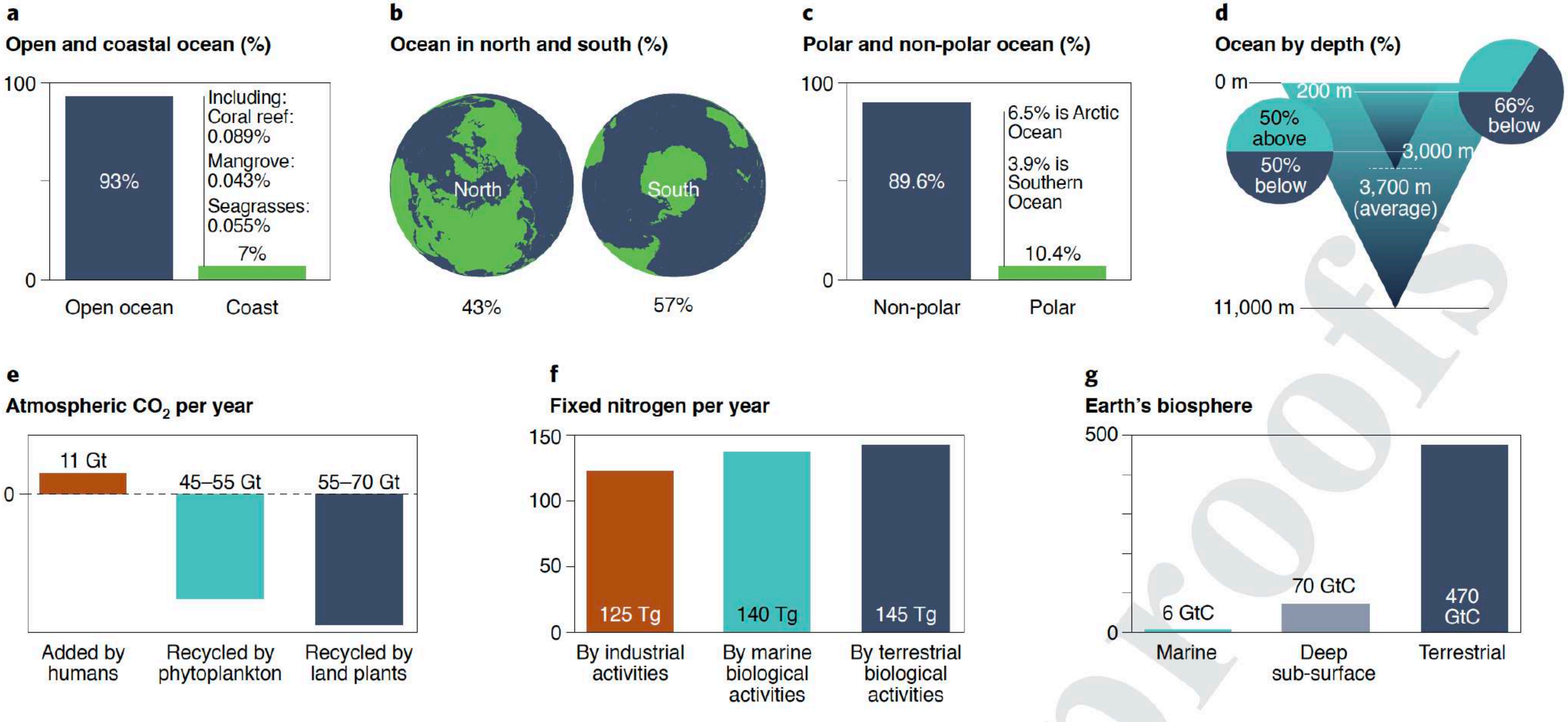
Anaerobic bacteria produce hydrogen sulfide, which other, "sulfophilic," bacteria use for energy. The sulfophilic bacteria, in turn, support all other organisms (*inset at bottom*). Mussels, tube worms and clams derive energy from sulfophilic bacteria that live symbiotically within them. Bristle worms and limpets feed on mats of such microbes. Crustaceans such as squat lobsters prey on other animals.

DURATION: UP TO 50 YEARS

National Geographic

SEAWATER: COASTAL And OPEN OCEAN

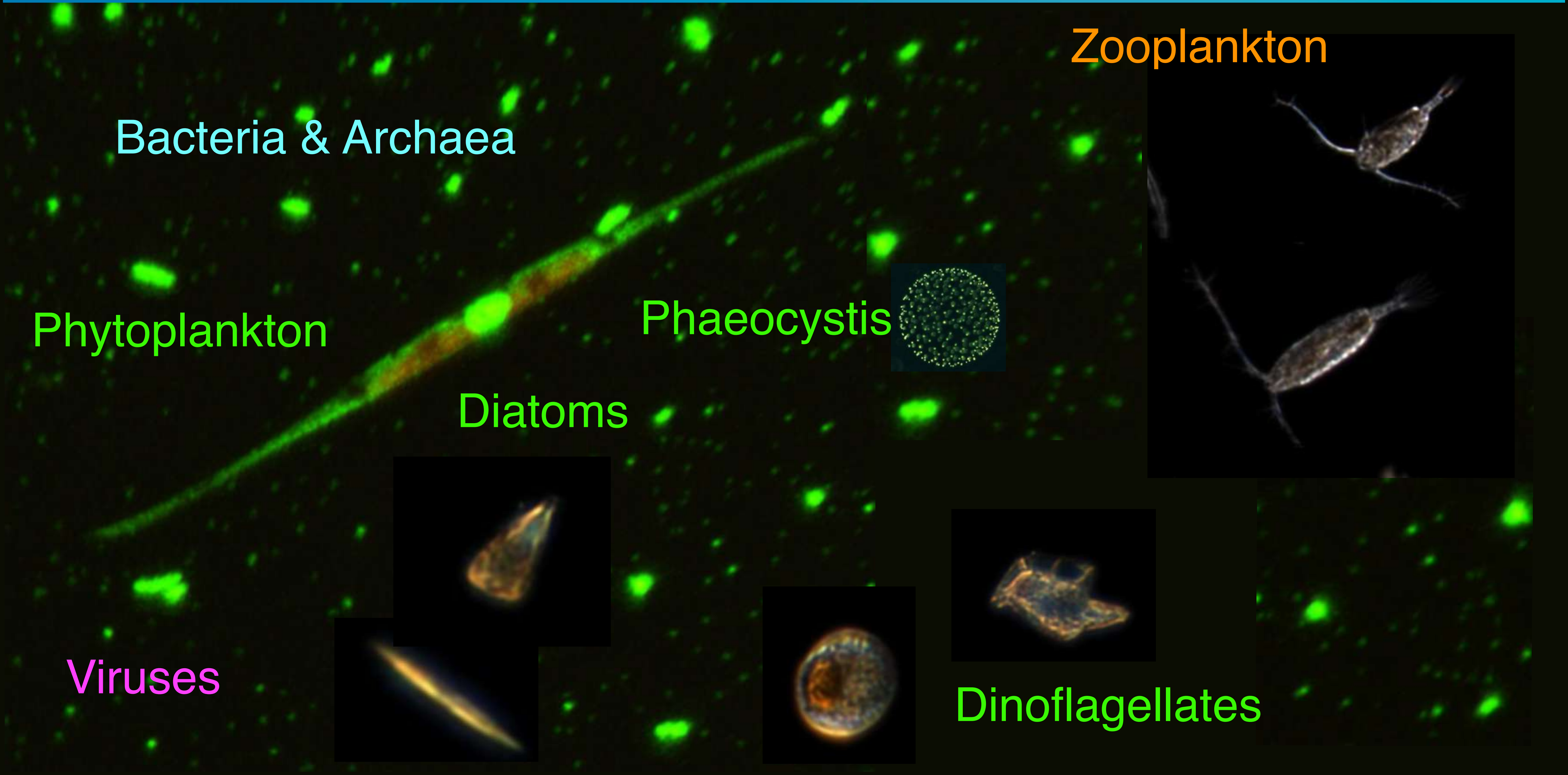
Key features related to the ocean microbiome



Tara Ocean Foundation et al., 2023

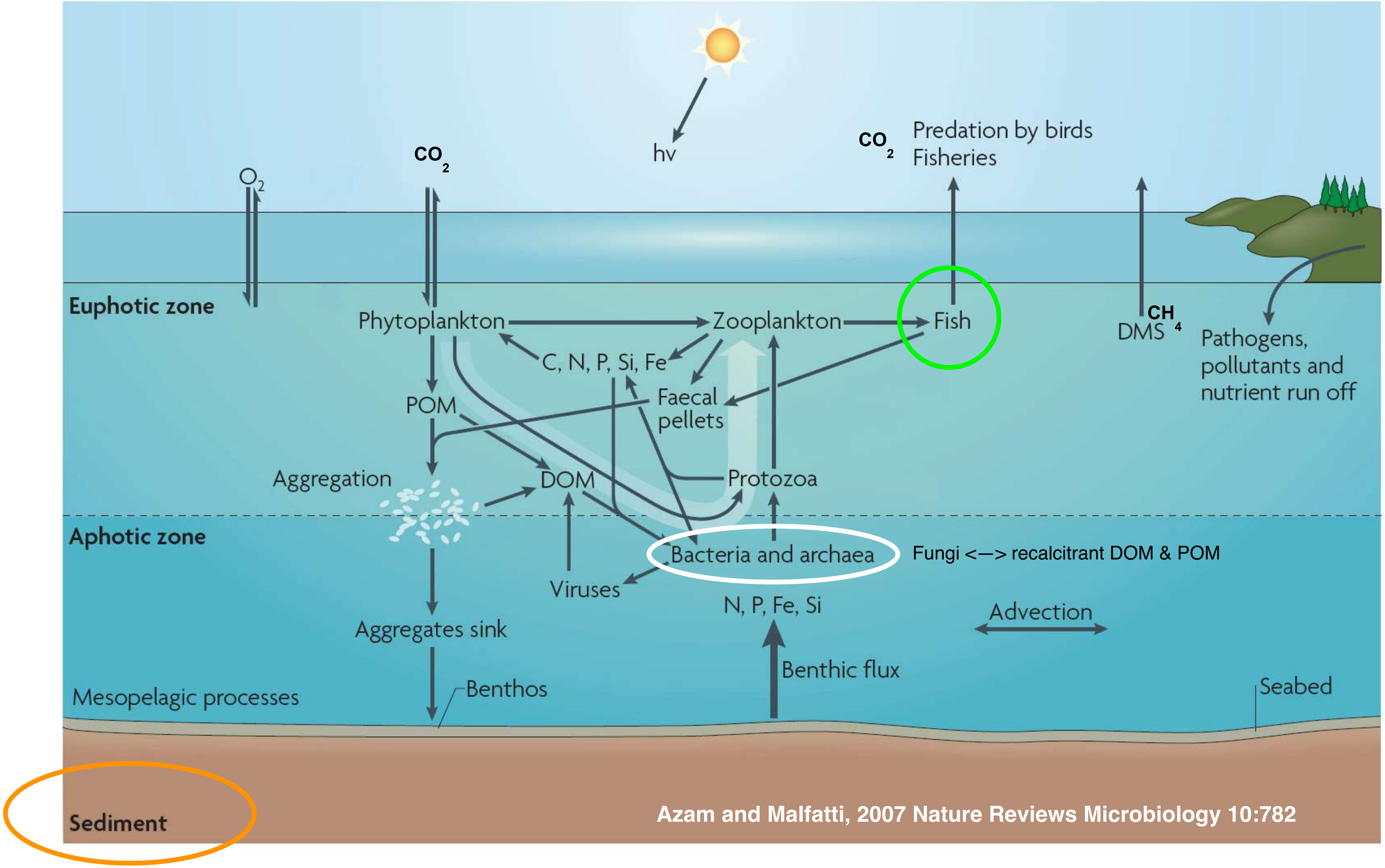
Upper ocean water column

SeaSCAPES microbial dynamics



Malfatti, Jaffe, Countway

Fate of fixed carbon in ocean ecosystem

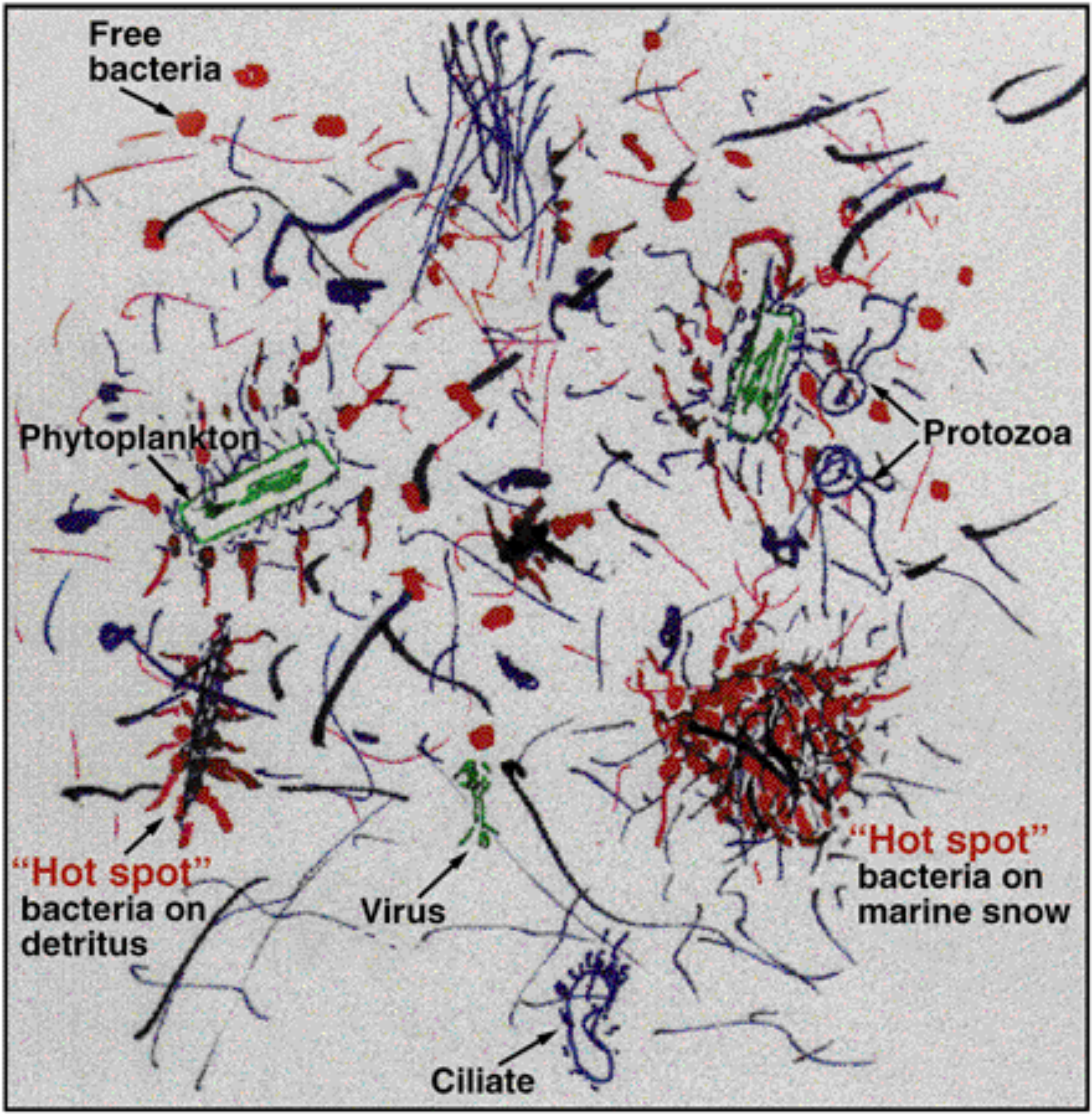


Fungi <—> recalcitrant DOM & POM

Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

Seasonality —> high and low production

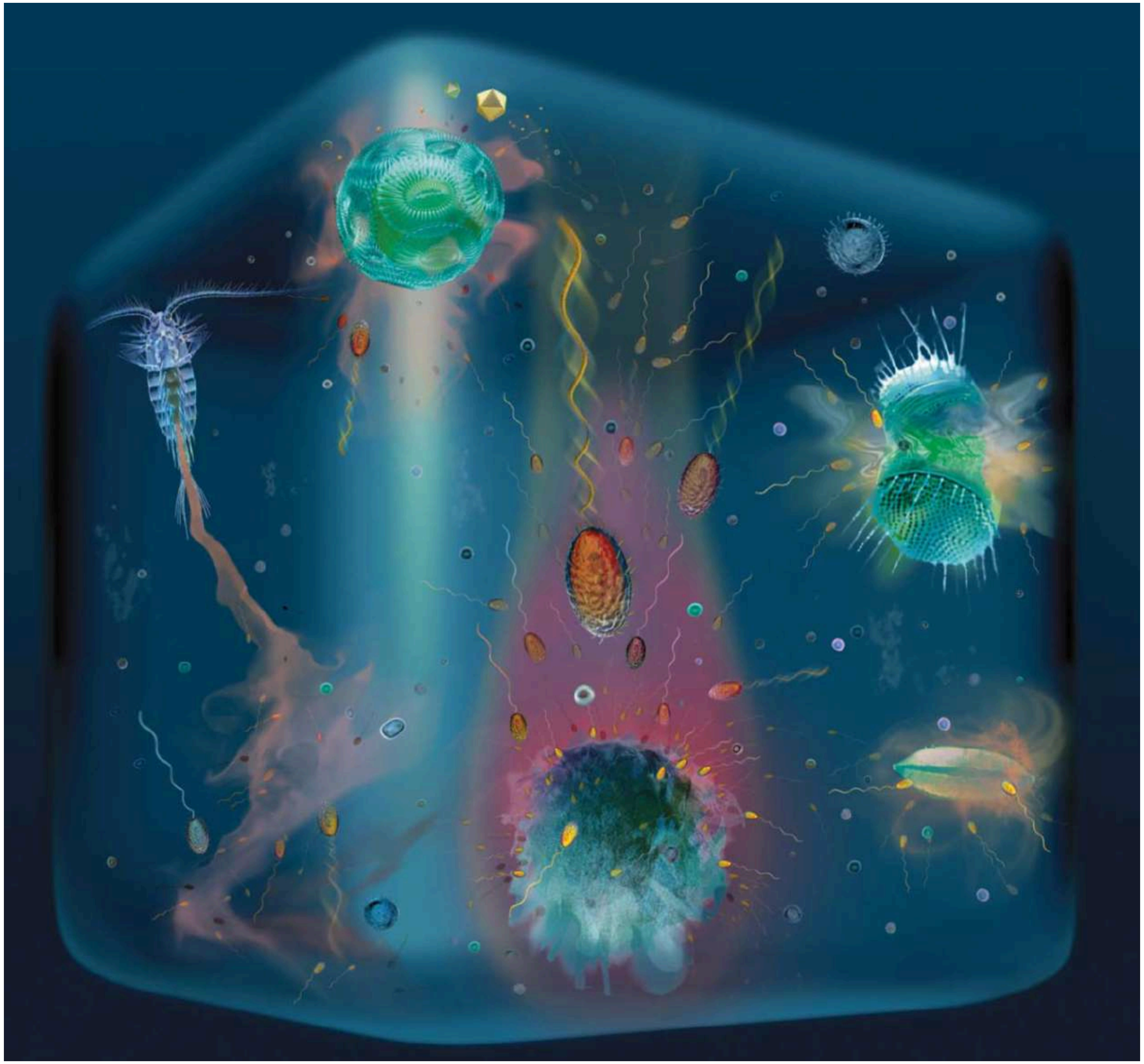
Marine microbial environment: impressionistic painting



By Farooq Azam

Azam, F. 1998 Science 280:694-696

Marine microbial microenvironment

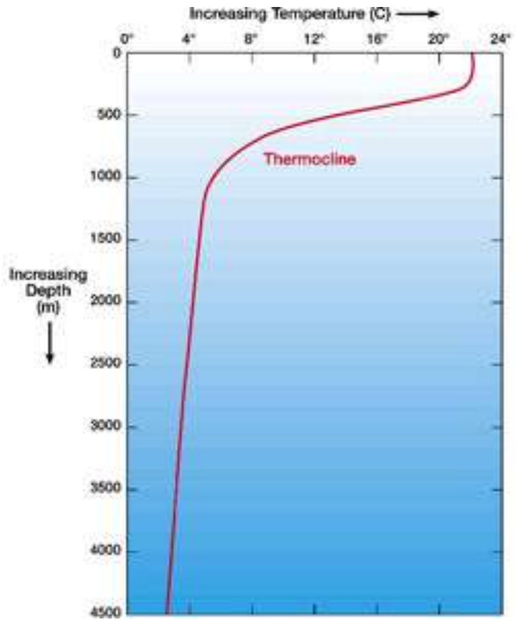


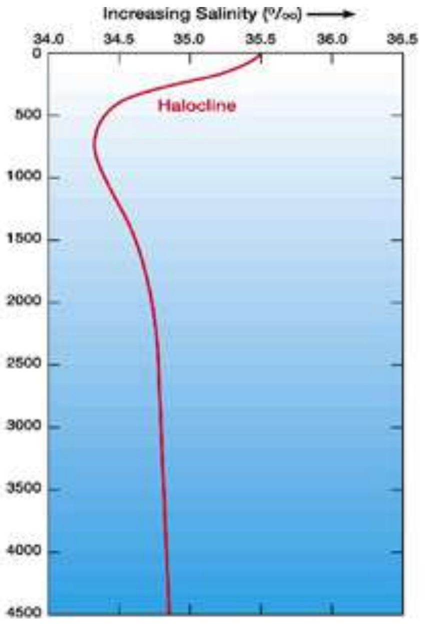
Stocker, 2012

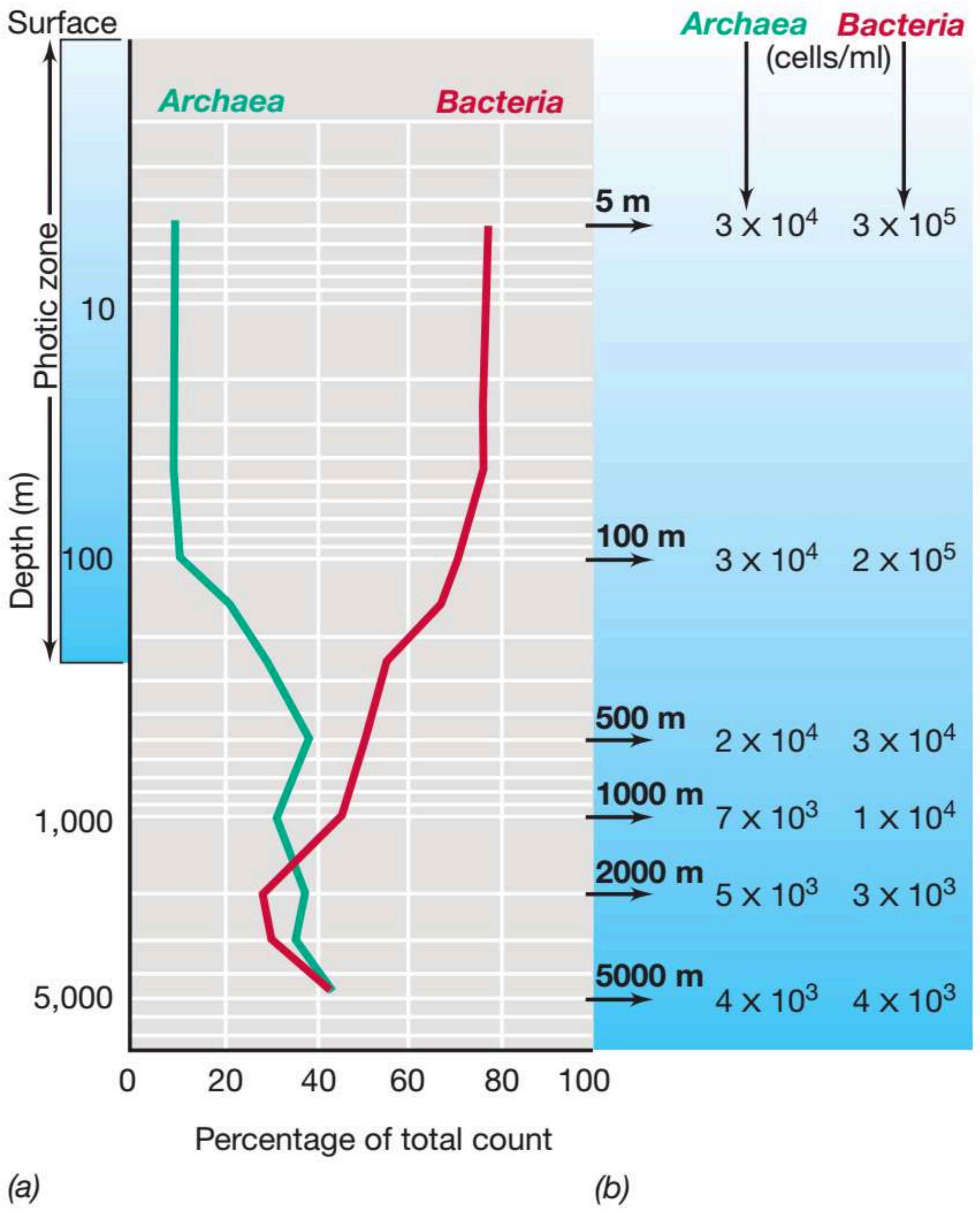
- Disparate processes contribute to make the ocean a sea of gradients, from the vantage point of microorganisms

Microbial abundance in ocean

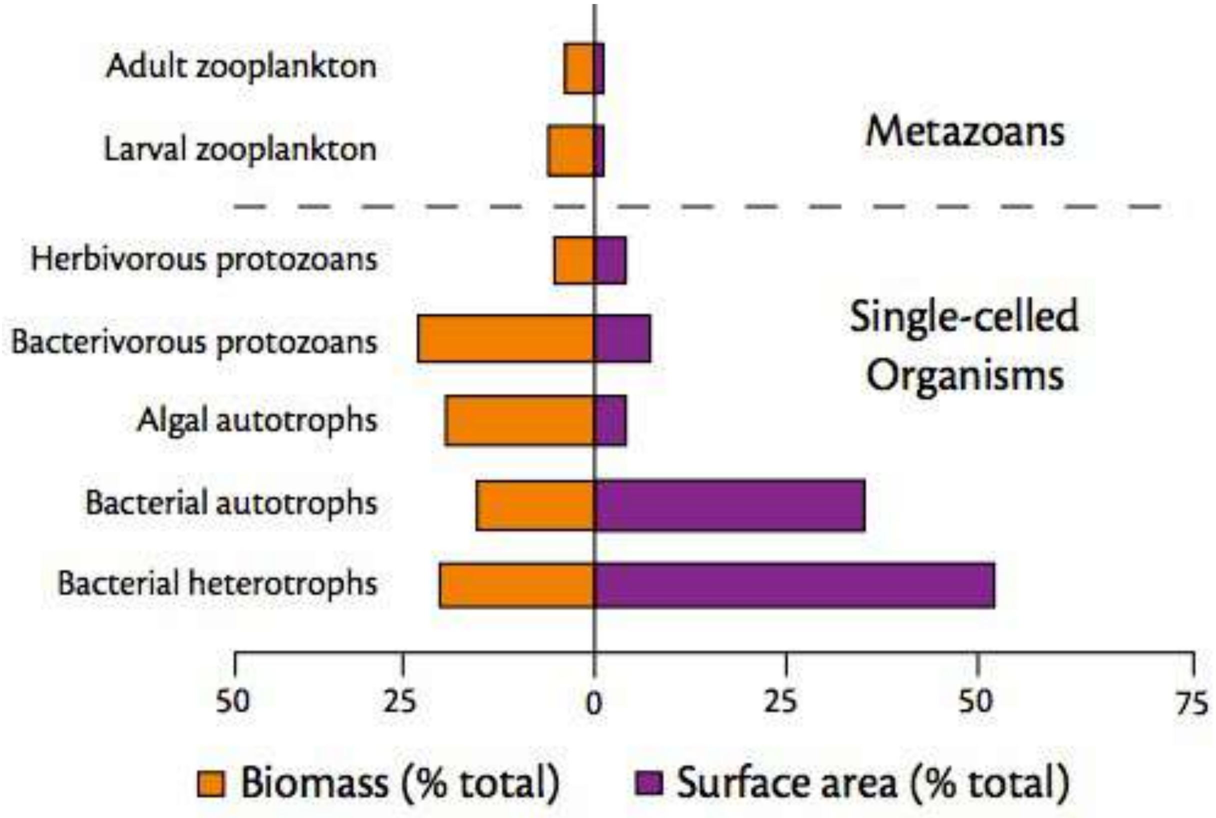
- Photic zone 0-200 m
- More than 96% of ocean is dark and with a constant temperature (~ 4^0C)
- Microbes in coastal ocean $1X10^6$ cells/mL
- Archaea dominate at depth
- Primary production sustain ocean interior—> organic matter degradation and sediment too!





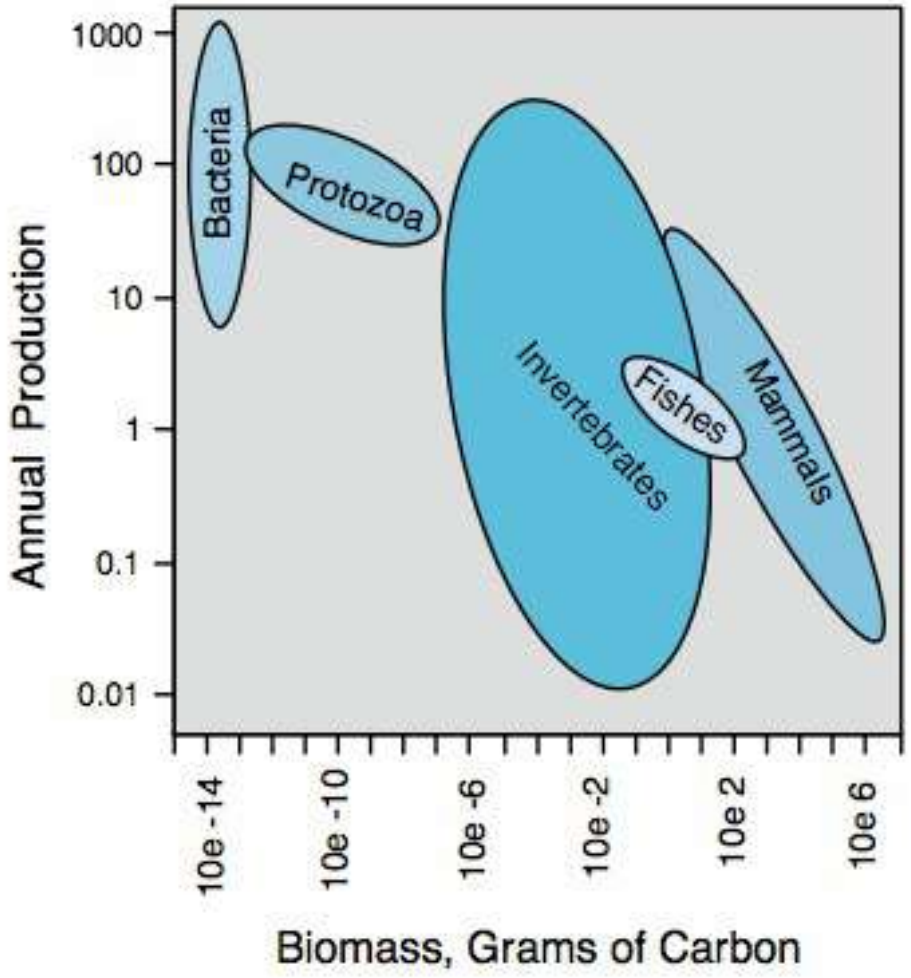


Madigan et al. 2018



Bacteria/Archaea represent 90% the total biomass in the ocean

Bacteria/Archaea are the most productive organisms in the ocean and contribute up to 90% to biota respiration



Pomeroy et al. 2015

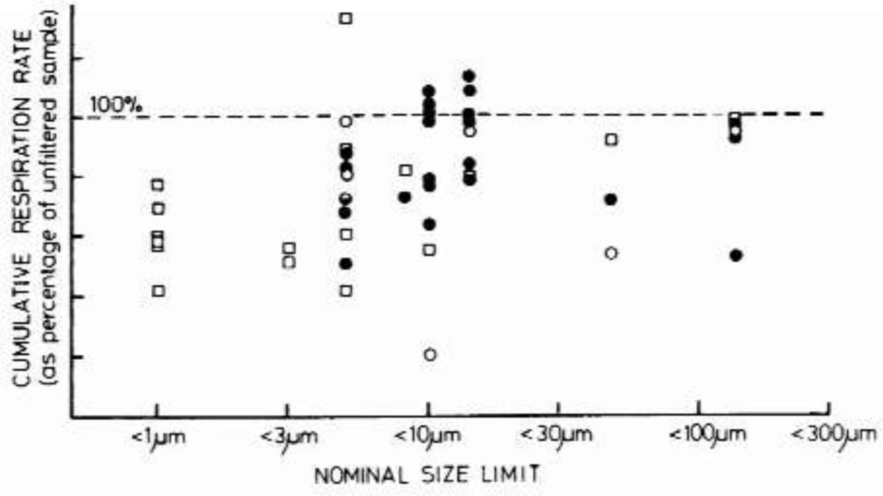
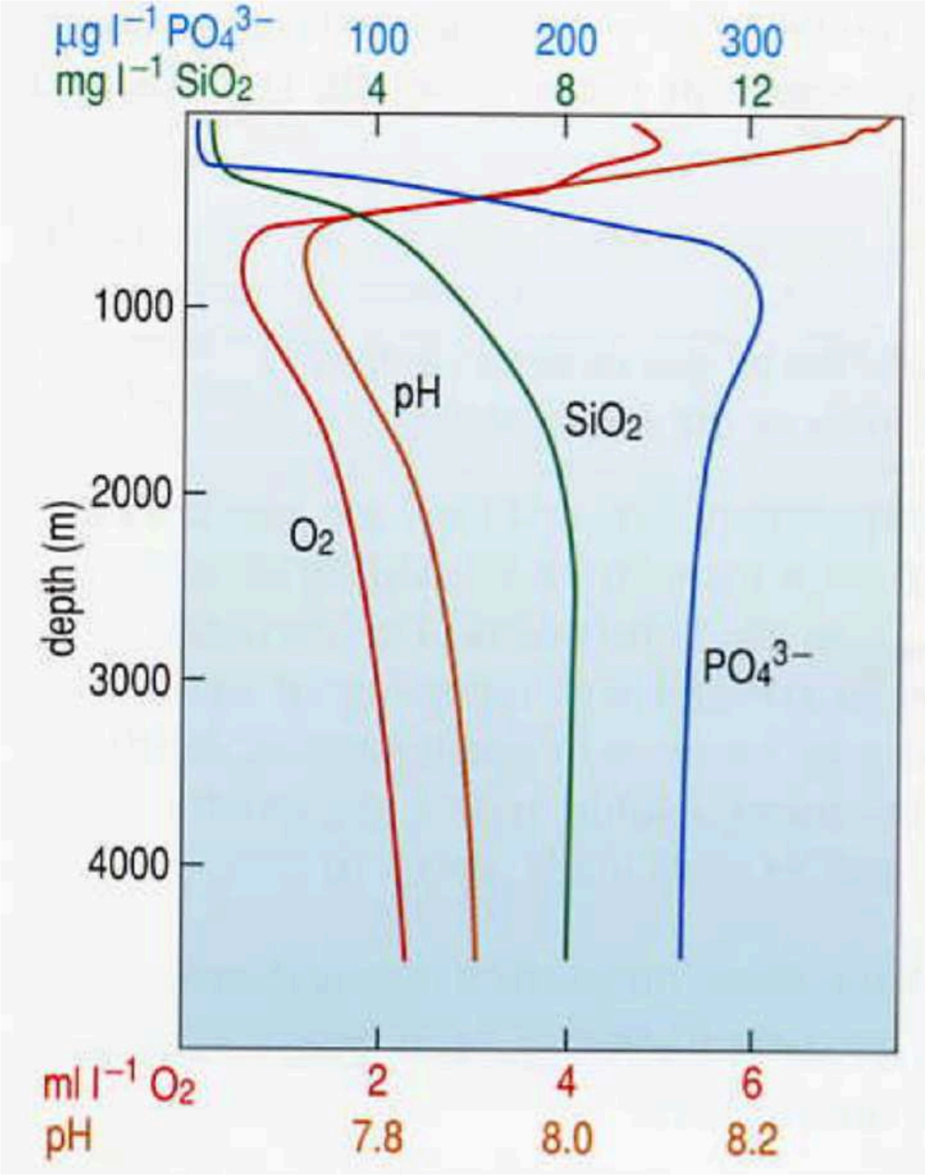


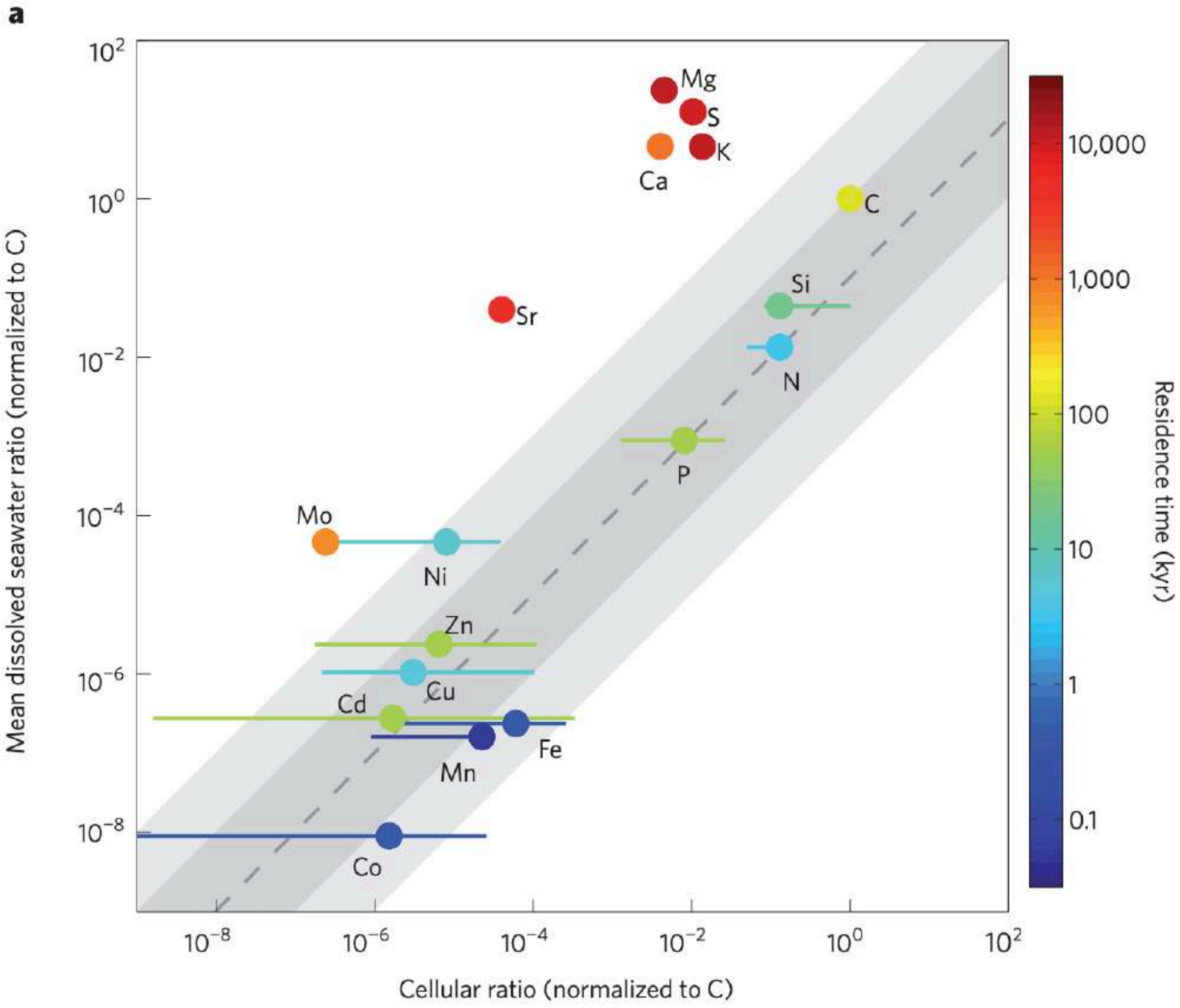
Figure 6. Distribution of respiratory activity with size. (□) CEPEX, samples from bag; (○) Loch Ewe, samples from bag; (●) Loch Ewe samples from outside bag. Data are expressed as cumulative respiration up to various size limits, normalized against the rate in the unfiltered sample. All the data points are for a single size horizon and are not replicates.

Williams (1984)

Ocean: Organic matter decomposition/respiration —> nutrient recycling

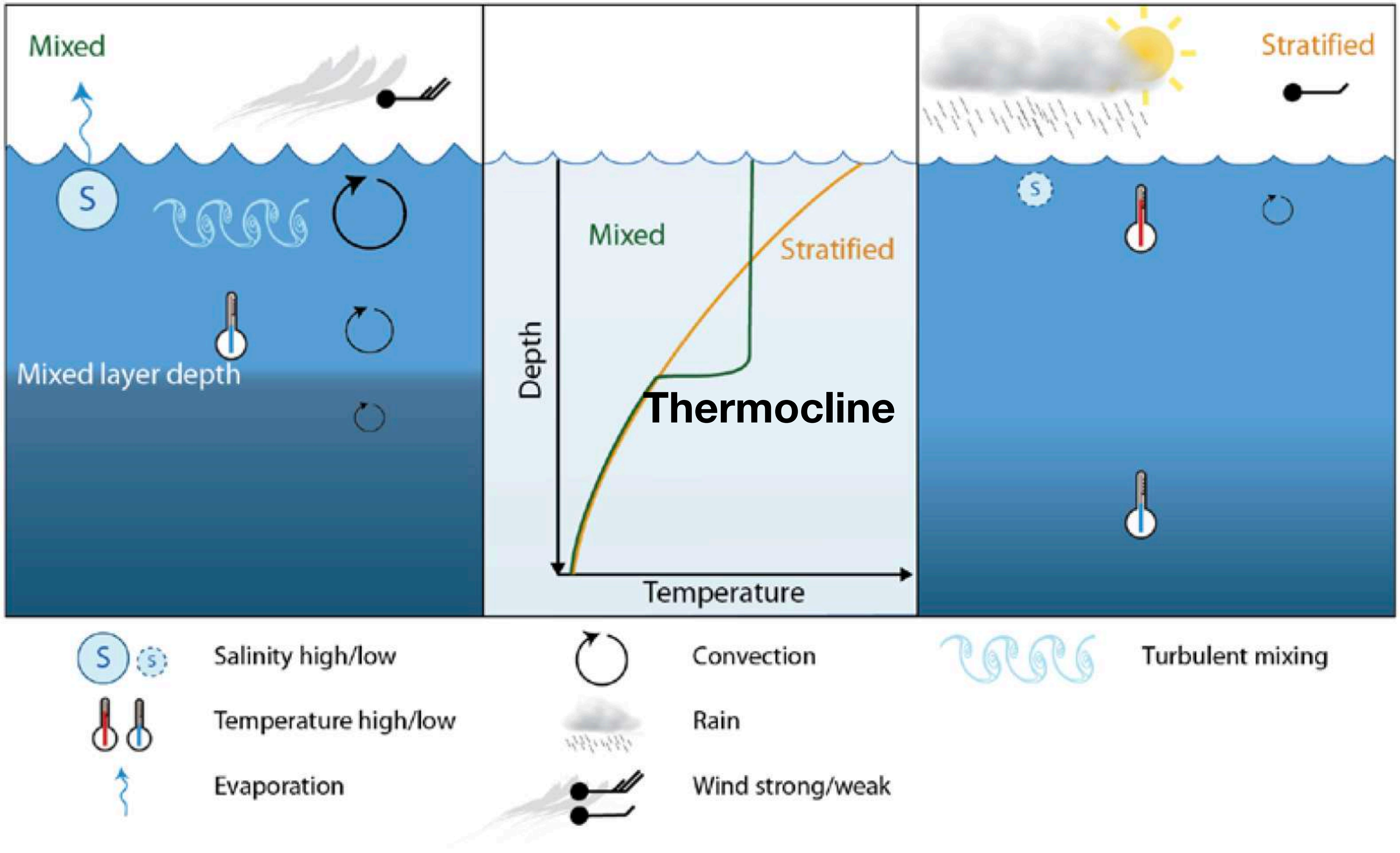
- **Microbial degradation of organic matter in the water column generate nutrient fluxes available for primary producers (limiting nutrients based on cell demands)**
- **Microbial action with organic matter at the microscope structure ocean-basin scale**





Moore et al., 2013

Seasonality in the ocean: factors affecting the mixed layer depth and C fixation in the food web and C biogeochemical cycle

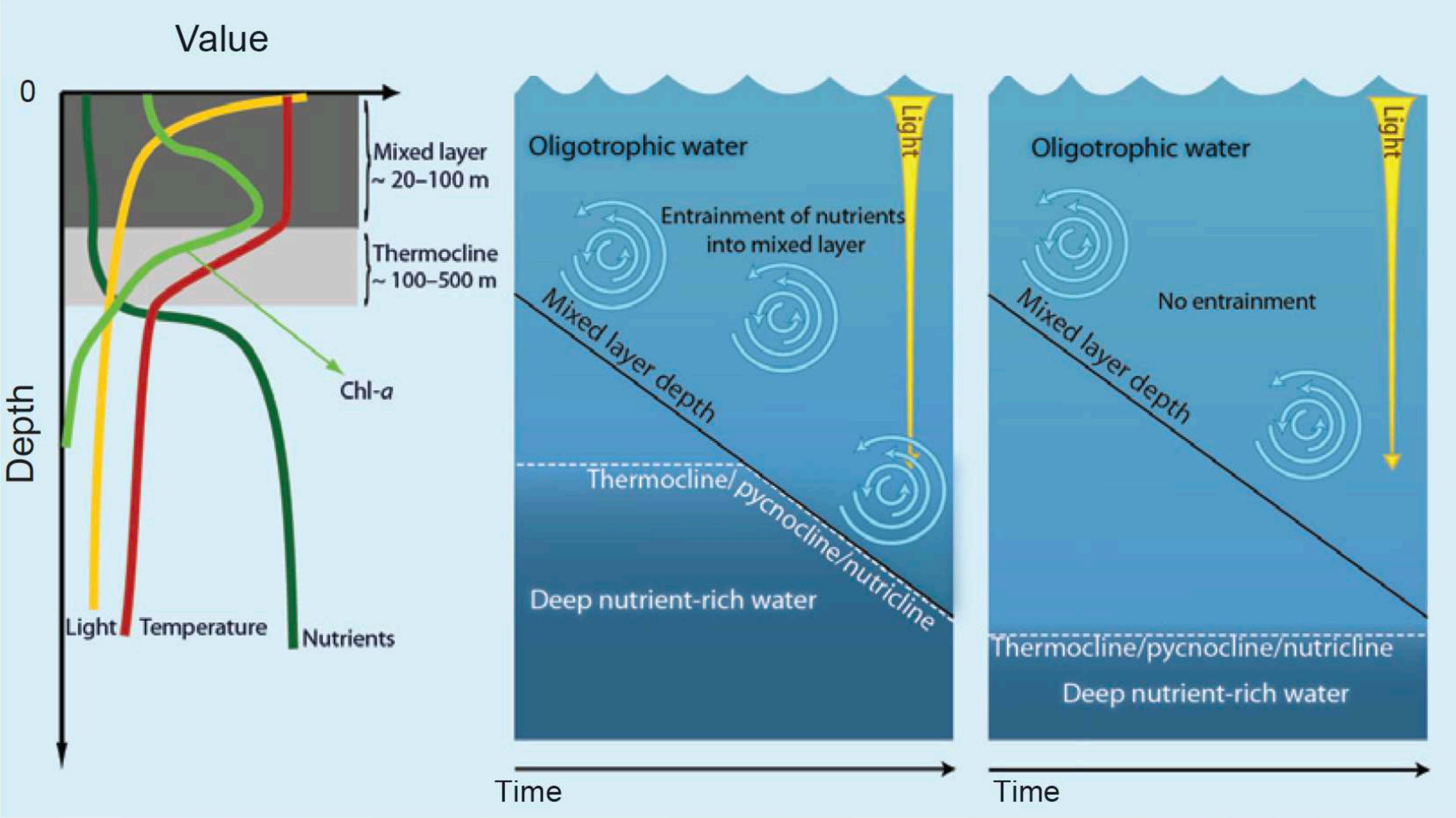


cooling, evaporation and strong winds

heating, precipitation and slight winds

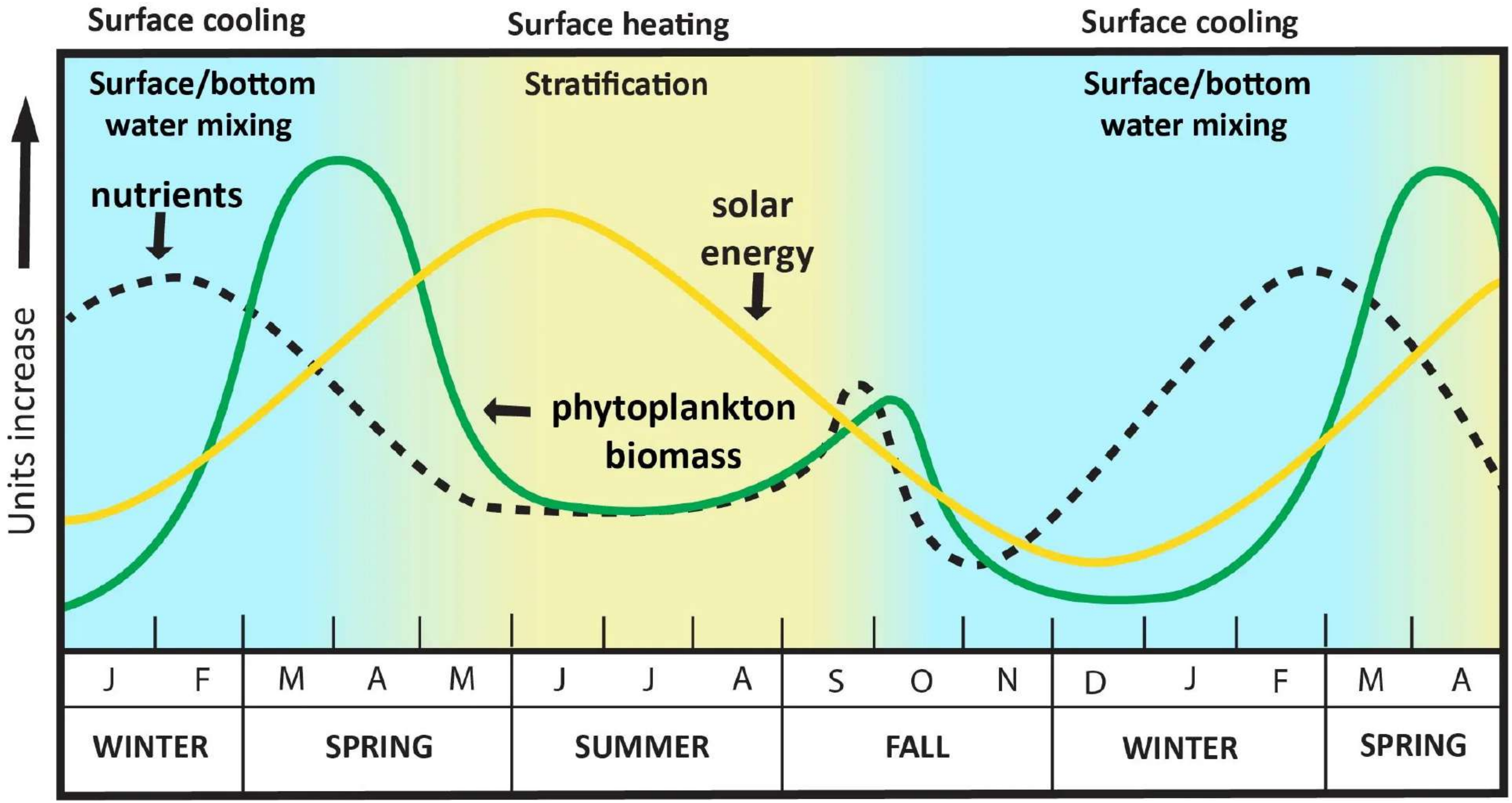
Ganachaud et al., 2011

Influence of the thermocline and mixed layer depth on transfer of nutrients to surface waters for C fixation into organic matter by photoauthotrophs



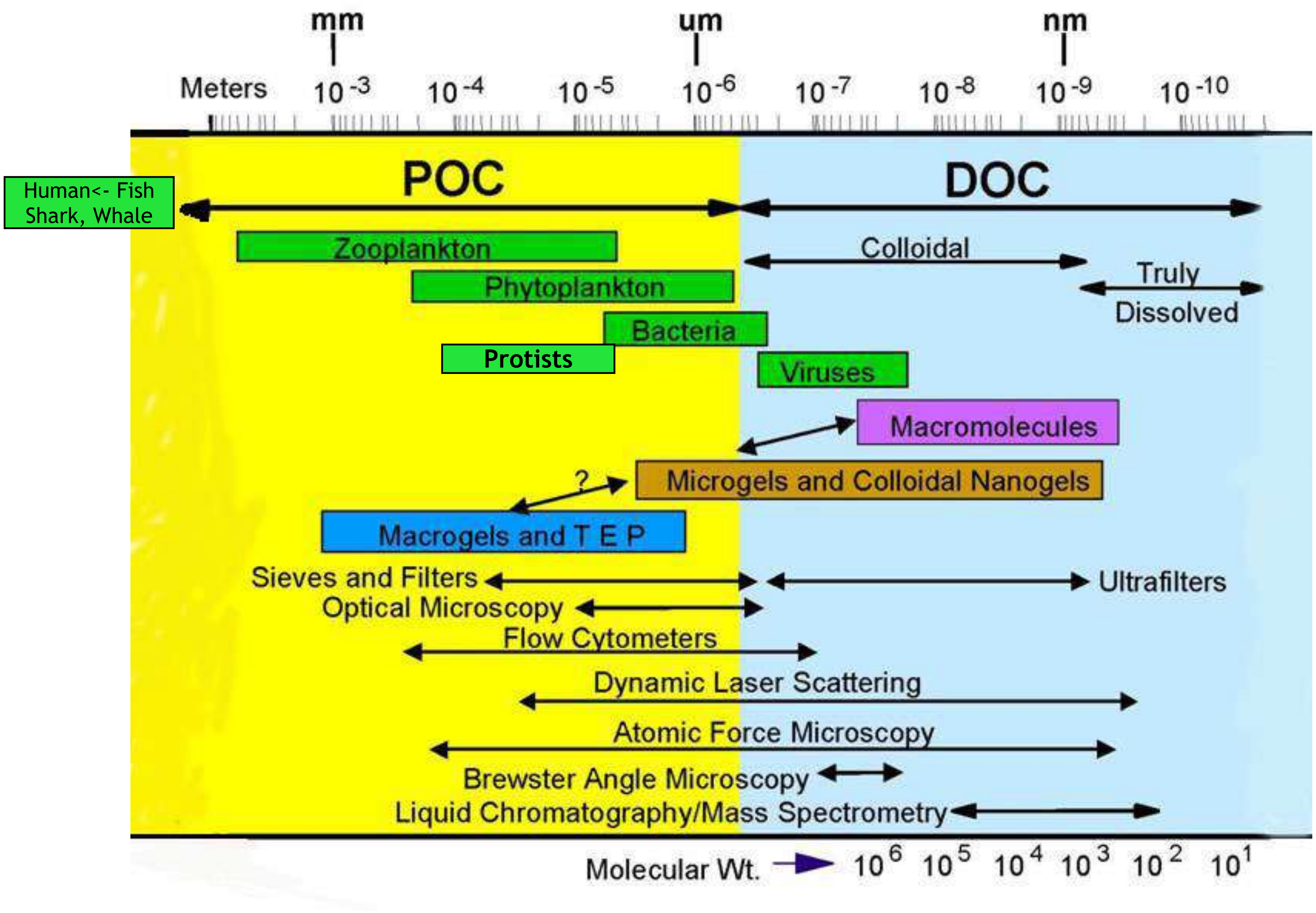
Ganachaud et al., 2011

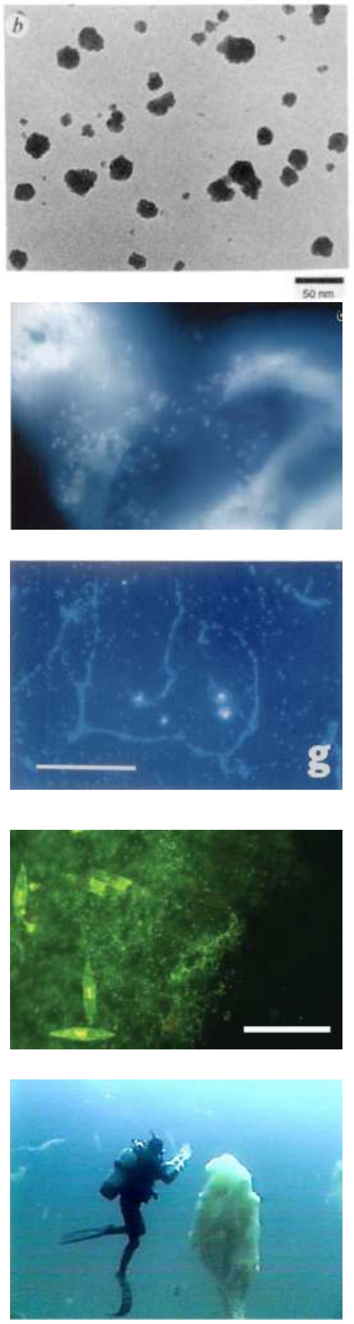
Seasonality in C fixation



https://datalab.marine.rutgers.edu/ooi-lab-exercises/lab-7-identify-factors-that-control-primary-production-in-the-western-temperate-atlantic-ocean/lab-7-instructor-guide/

Organic matter continuum: a unifying concept to understand how bacteria perceive and interact with organic matter

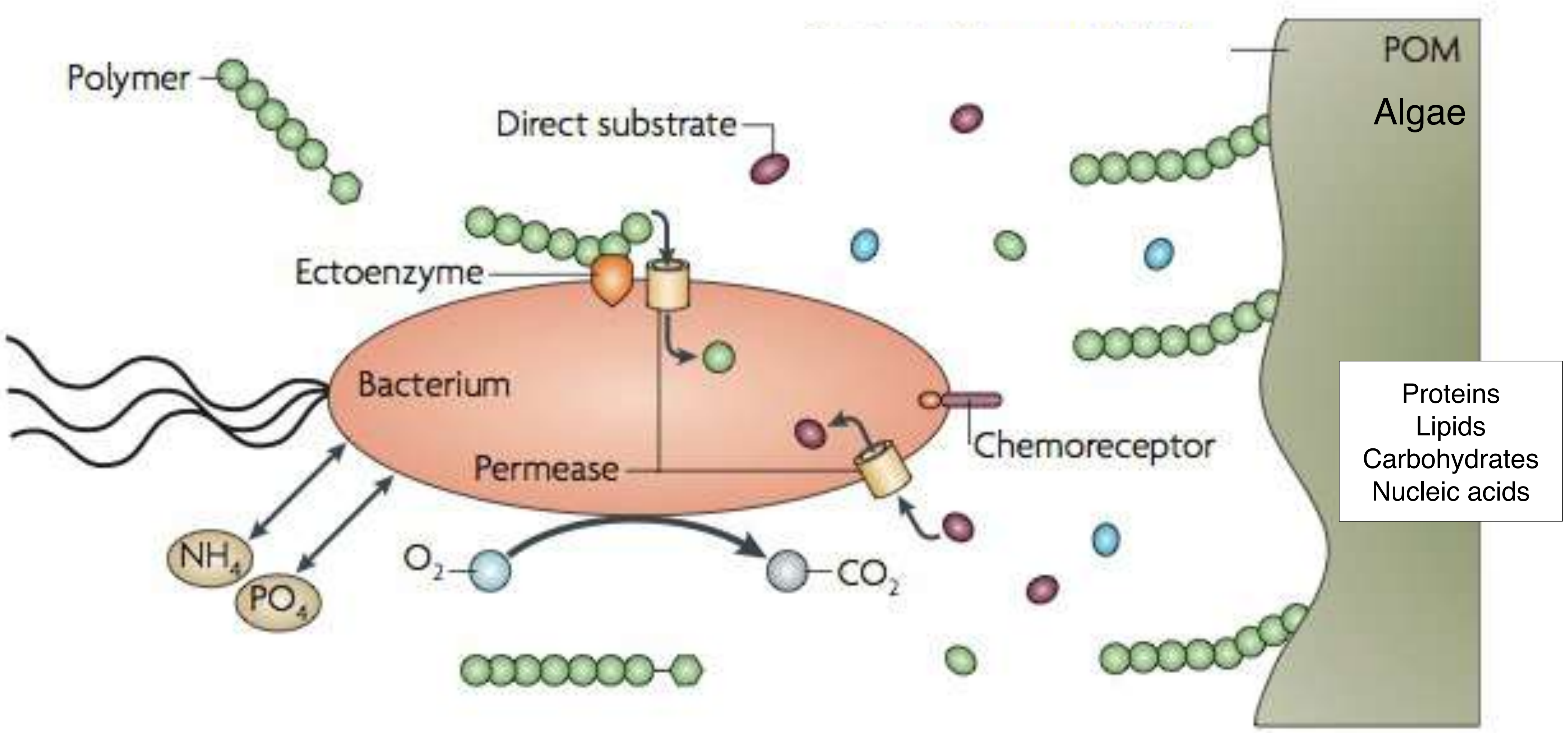




By Farooq Azam

- Ocean is replete with transparent gel particles (~ million/liter) creating a gel-like milieu
- Primary production is the source of the great chemical and structural complexity

Microbial adaptive strategies for growth at small scale

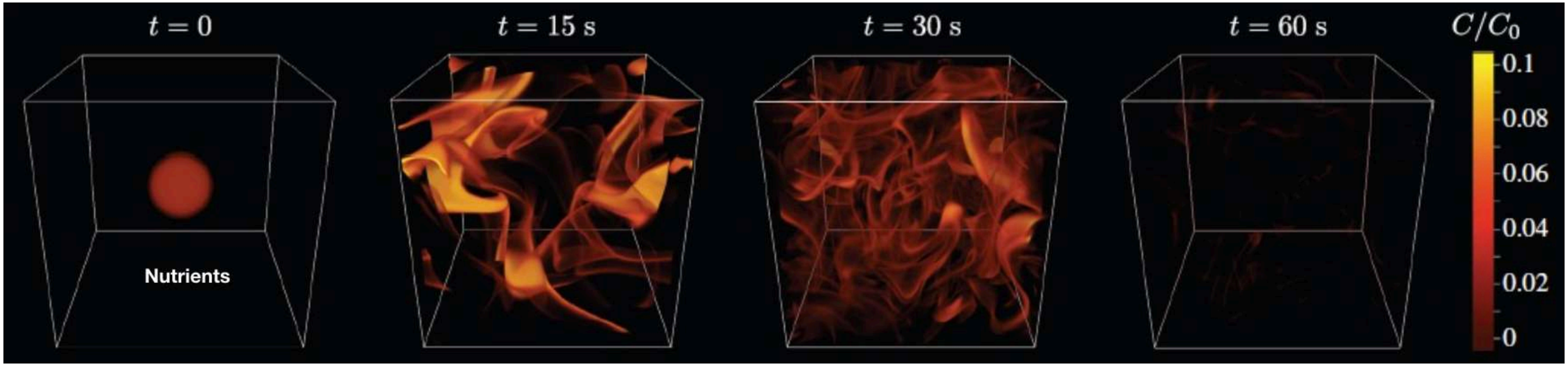


Azam and Malfatti, 2007 Nature Reviews Microbiology 10:782

By Farooq Azam

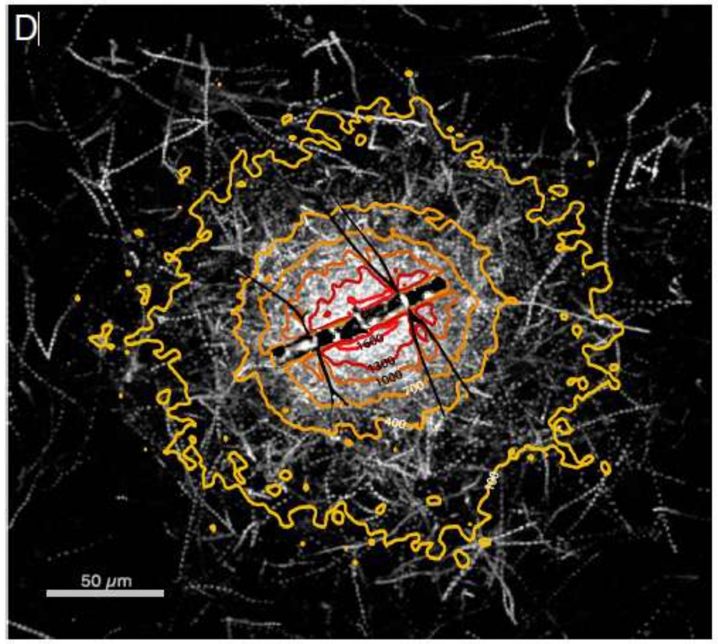
- **Motility, environmental sensing (interacting with molecules)- MCPs**
- **Significance of spatial coupling hydrolysis-uptake (permease) on the cell**
- **Cell surface hydrolases; 10^2-10^4 x variability in cell-specific activity**
- **Coordinated behavior and biochemistry in space and time**

Nutrient patch evolution and sources

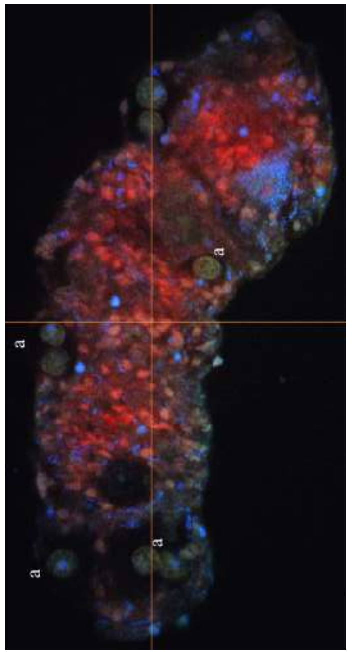


Taylor 2012, Science

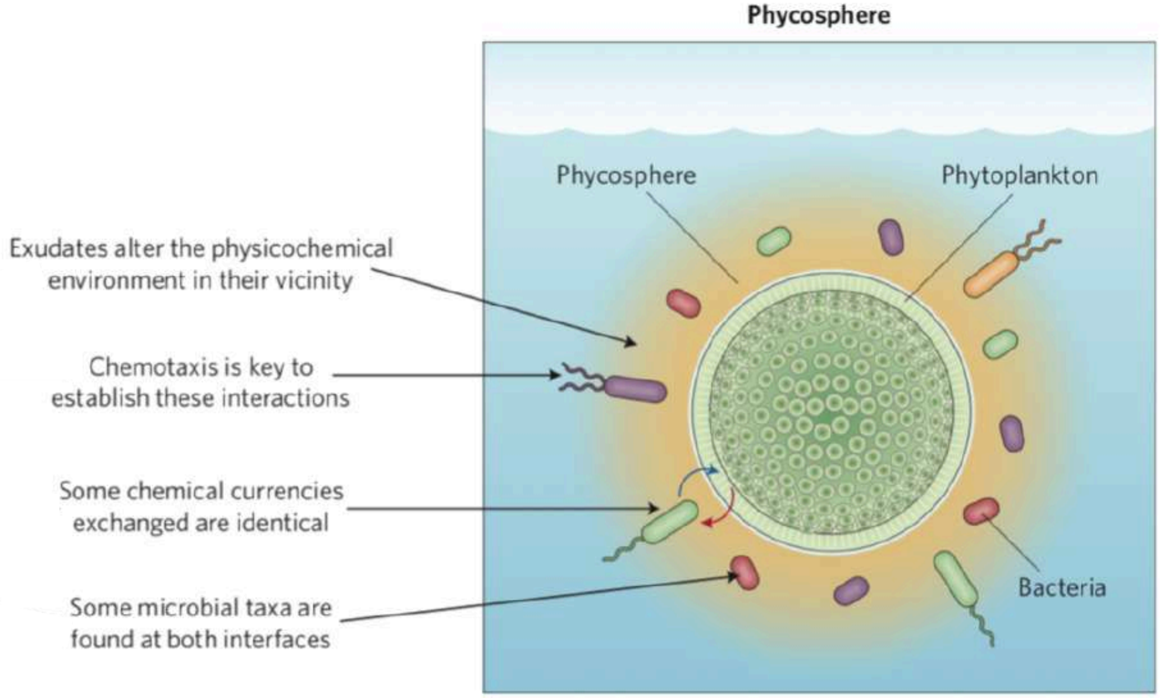
- Low Reynolds number —> high viscosity
- Modelling in time and space in a turbulent flow (L= 5.65 cm)
- Nutrient sources: living phytoplankton, dying phytoplankton, dying copepods, marine snow plume, fecal pellets



Smriga et al. 2016



Malfatti unpub.



Exudates alter the physicochemical environment in their vicinity

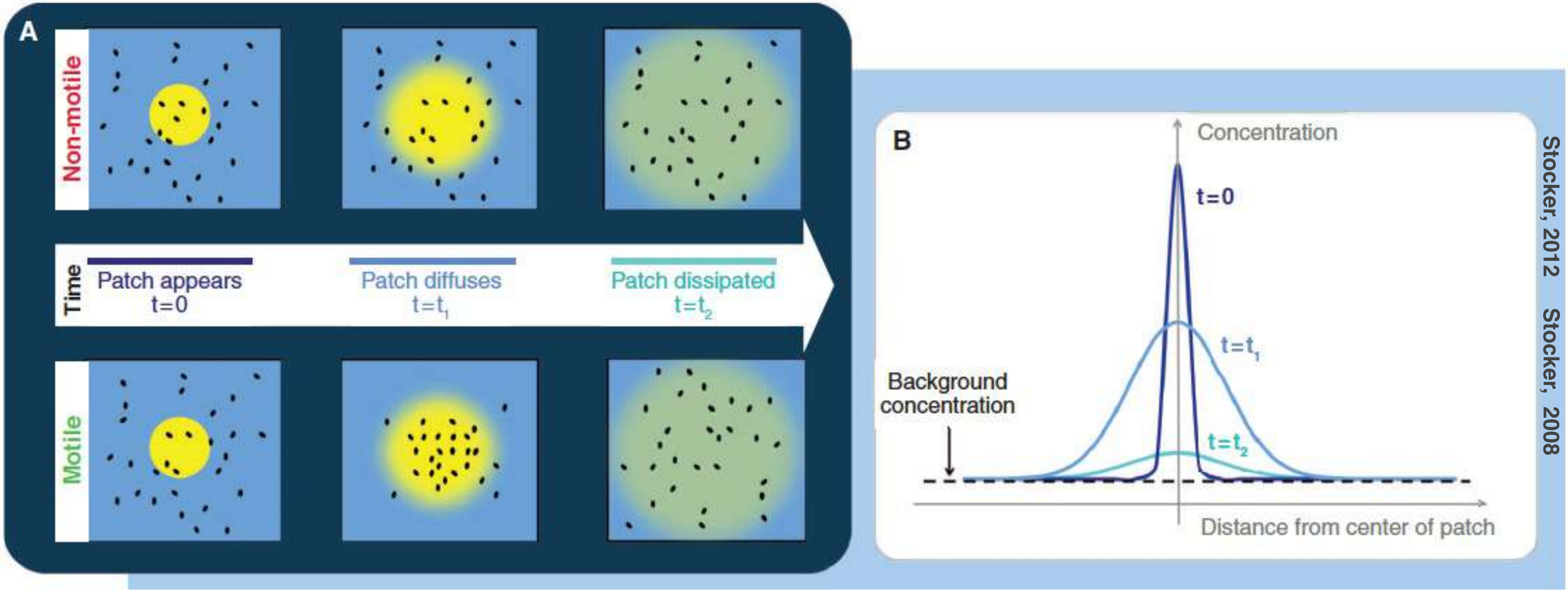
Chemotaxis is key to establish these interactions

Some chemical currencies exchanged are identical

Some microbial taxa are found at both interfaces

Seymour et al. 2017

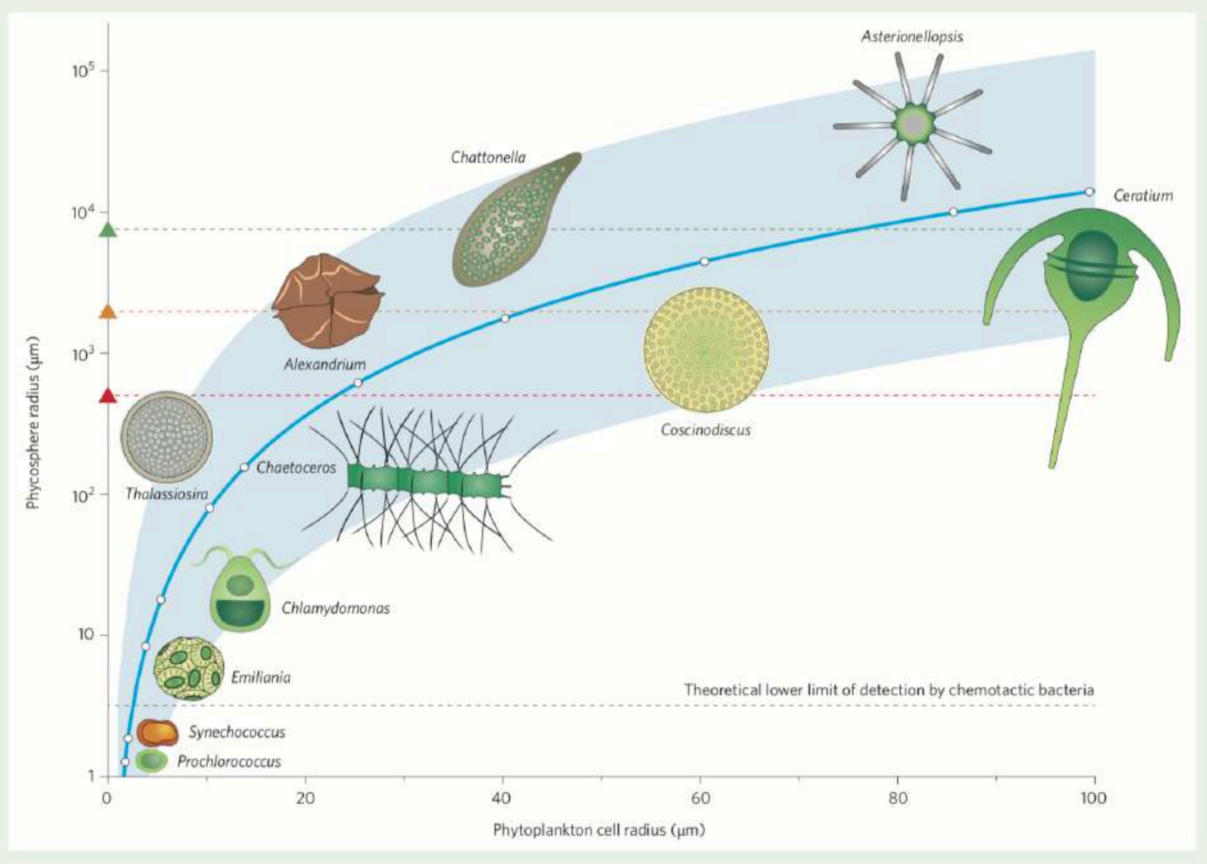
Marine bacteria can exploit ephemeral nutrient patches



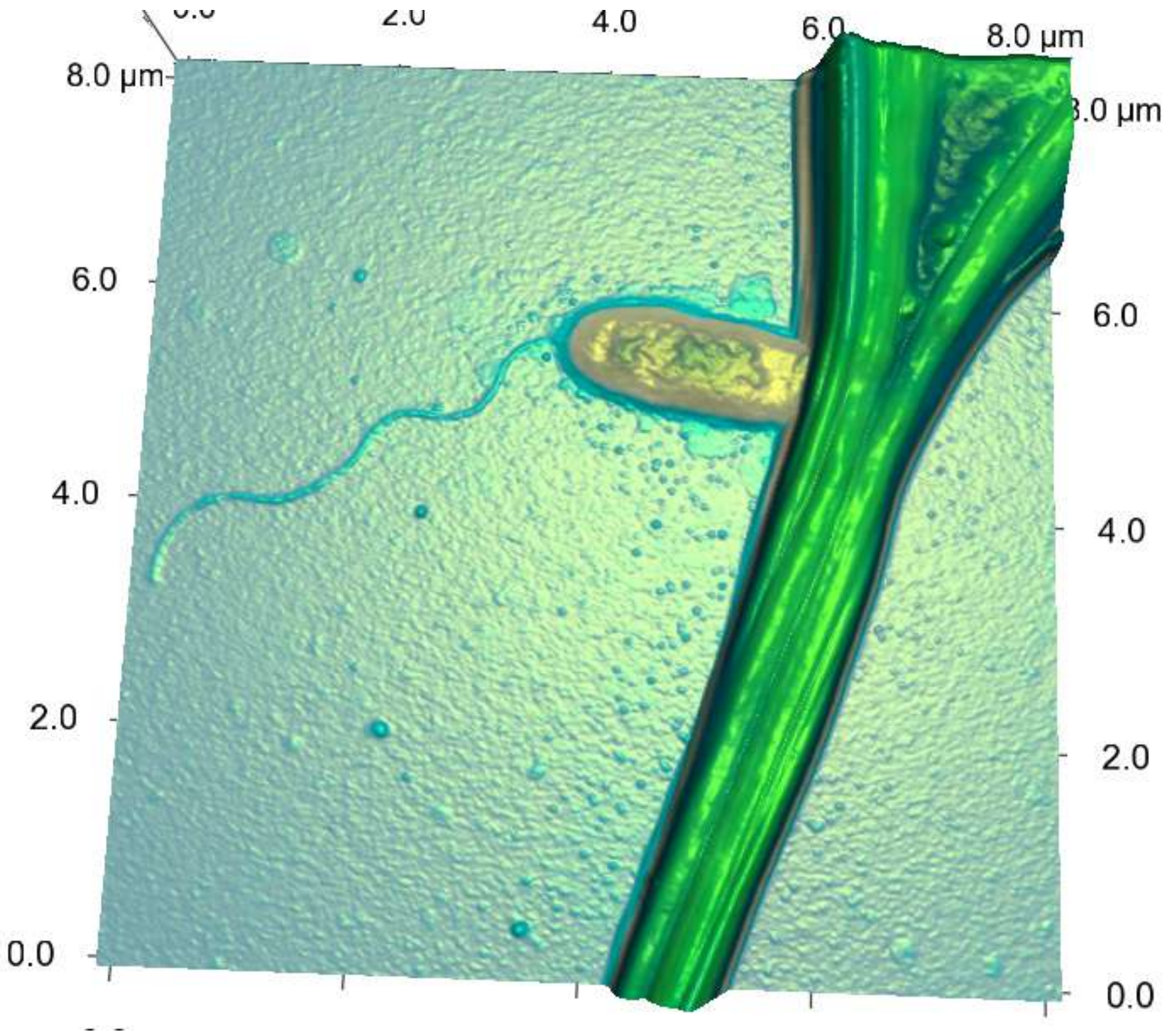
Stocker, 2012 Stocker, 2008

- Motility as an adaptive strategy to respond to nutrient patches
- Exploration: non motile 0.45 pL (Brownian motion) vs motile 0.5 μL every (motility 50 μm/s) 10 min
- Daily exploration: non motile ~ 430 μm cube vs motile ~ 1 cm cube chemotactic
- Copiotrophic populations outcompete nonmotile, oligotrophic populations during diatom blooms and bloom collapse conditions (more motile cells)

Bacteria-phytoplankton interactions



Seymour et al. 2017

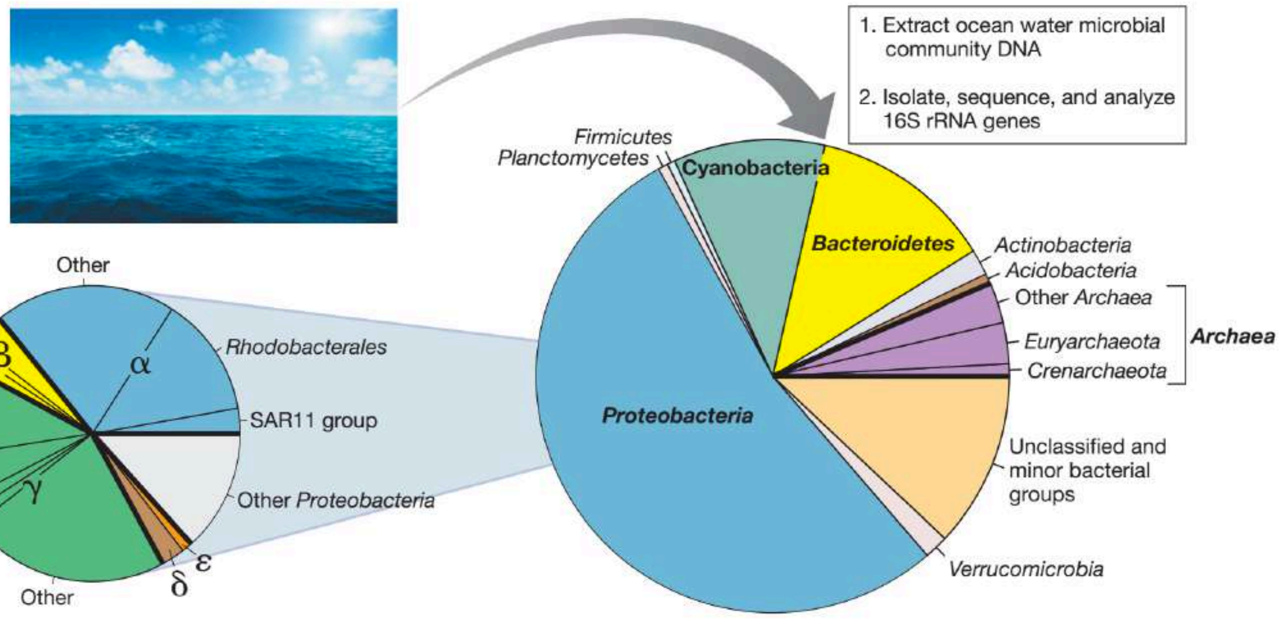


Malfatti unpub.

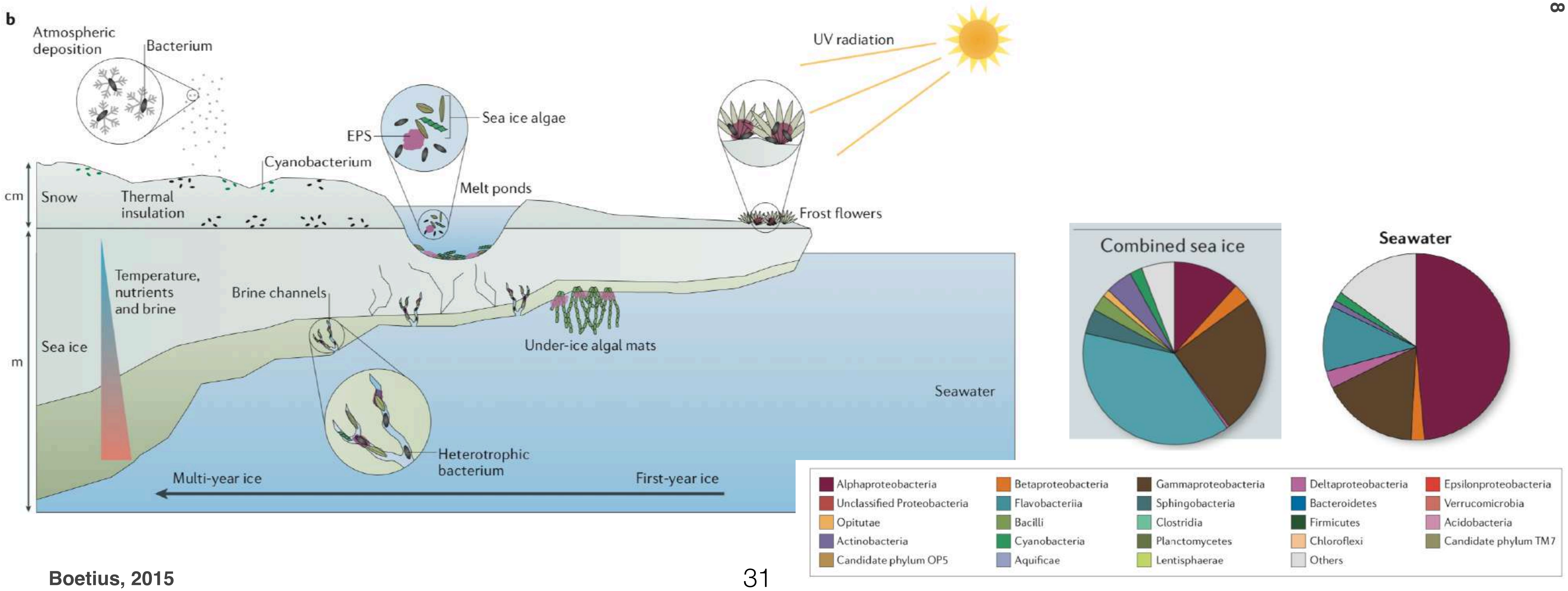
- The phycosphere, defined as the region surrounding a phytoplankton cell that is enriched in organic substrates exuded by the cell, is an important microenvironment for planktonic aquatic bacteria
- The phycosphere is defined as the region where the concentration is >50% above background

Ocean & sea ice diversity

- Seasonality in the ocean
- Extreme seasonality in sea ice ecosystem

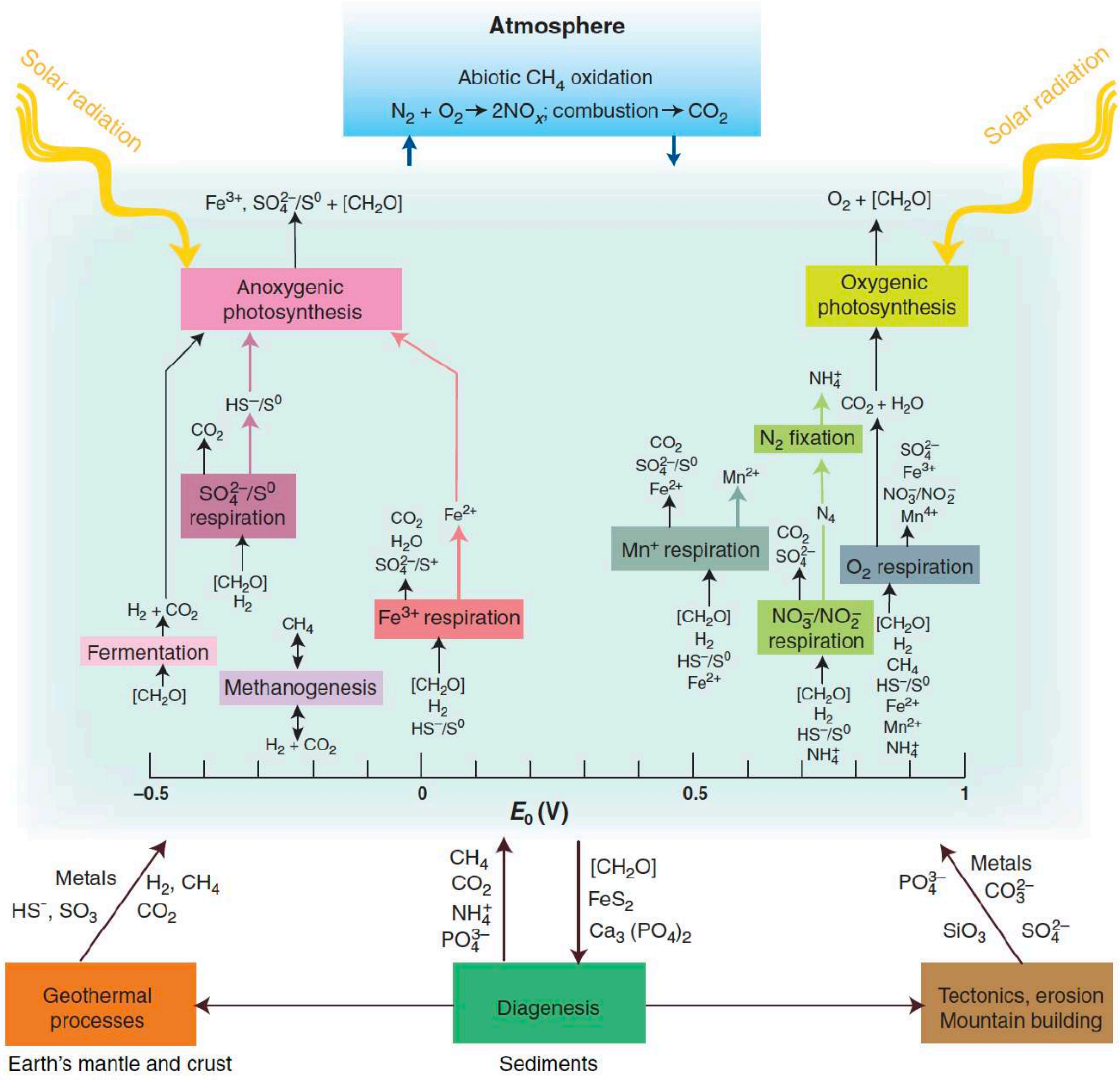


Madigan et al. 2018



Boetius, 2015

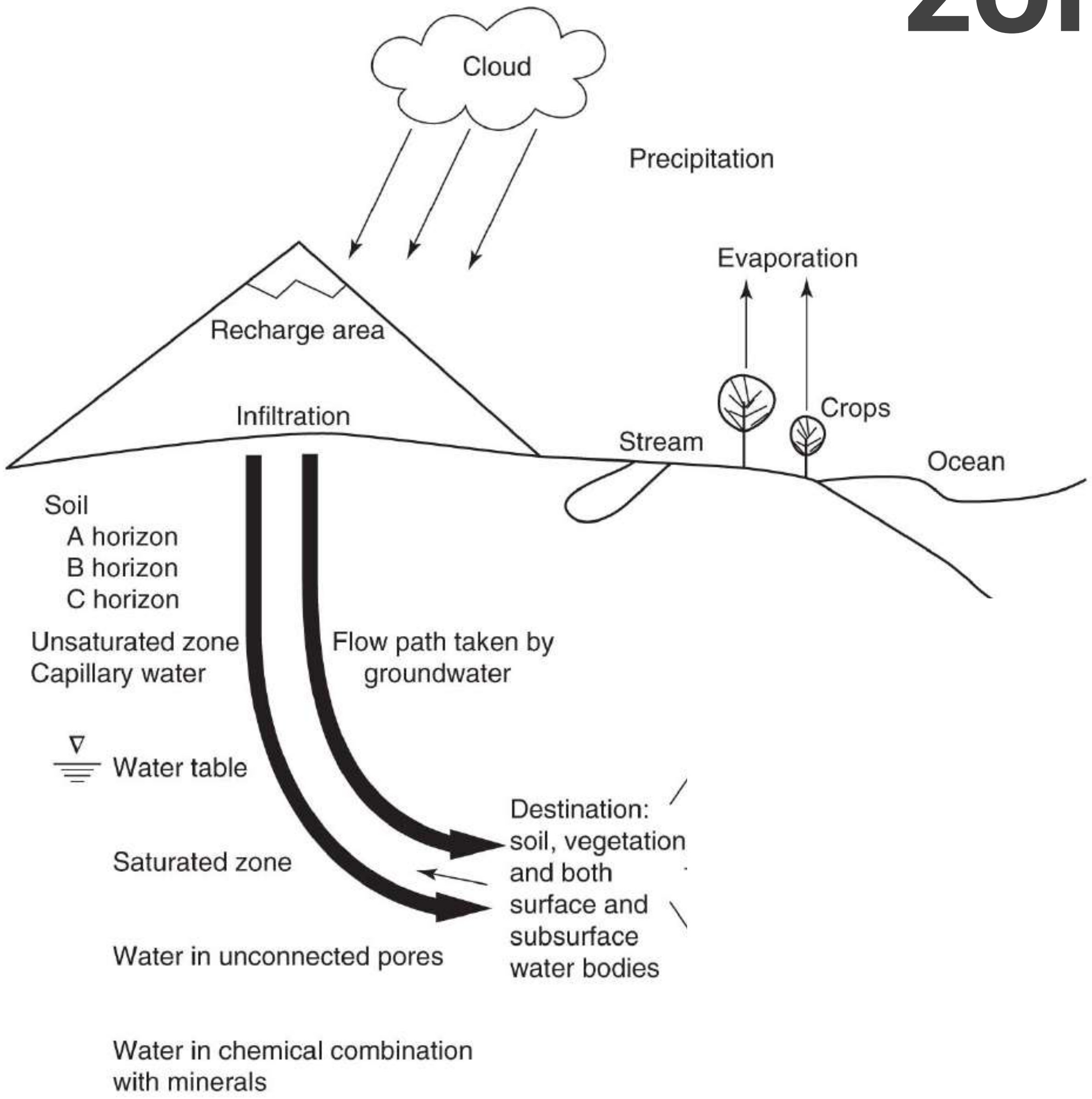
Biosphere model



Falkowski et al., 2008

FRESHWATER:
LAKE
RIVER

Hydrological cycle-soil-subsurface zone



Madsen, 2016

Figure 4.12 Conceptual flow system for understanding the role of soil and subsurface habitats in the hydrologic cycle. (Reprinted from Madsen, E.L. 1995. Impacts of agricultural practices on subsurface microbial ecology. *Adv. Agron.* **54**:1–67. Copyright 1995, with permission from Elsevier.)

- Water connects upper microbiomes (soil) with subsurface microbiome
- Lower microbiome at ~ 4 km at 125^0C
- Underneath there are saturated and unsaturated subsurface zone
- Subsurface zone associated microbiome is important in dictating chemical composition of the water flowing in it (beside the influence of the soil and geological strata)

About **30%** of all freshwater is **terrestrial ground water,** whereas the world's l**otic (streams and rivers)** and **lentic (lakes)** systems contribute only **0.3%**

Groundwater flow is governed largely by **recharge and discharge rates** and the **hydraulic properties of the saturated rocks**

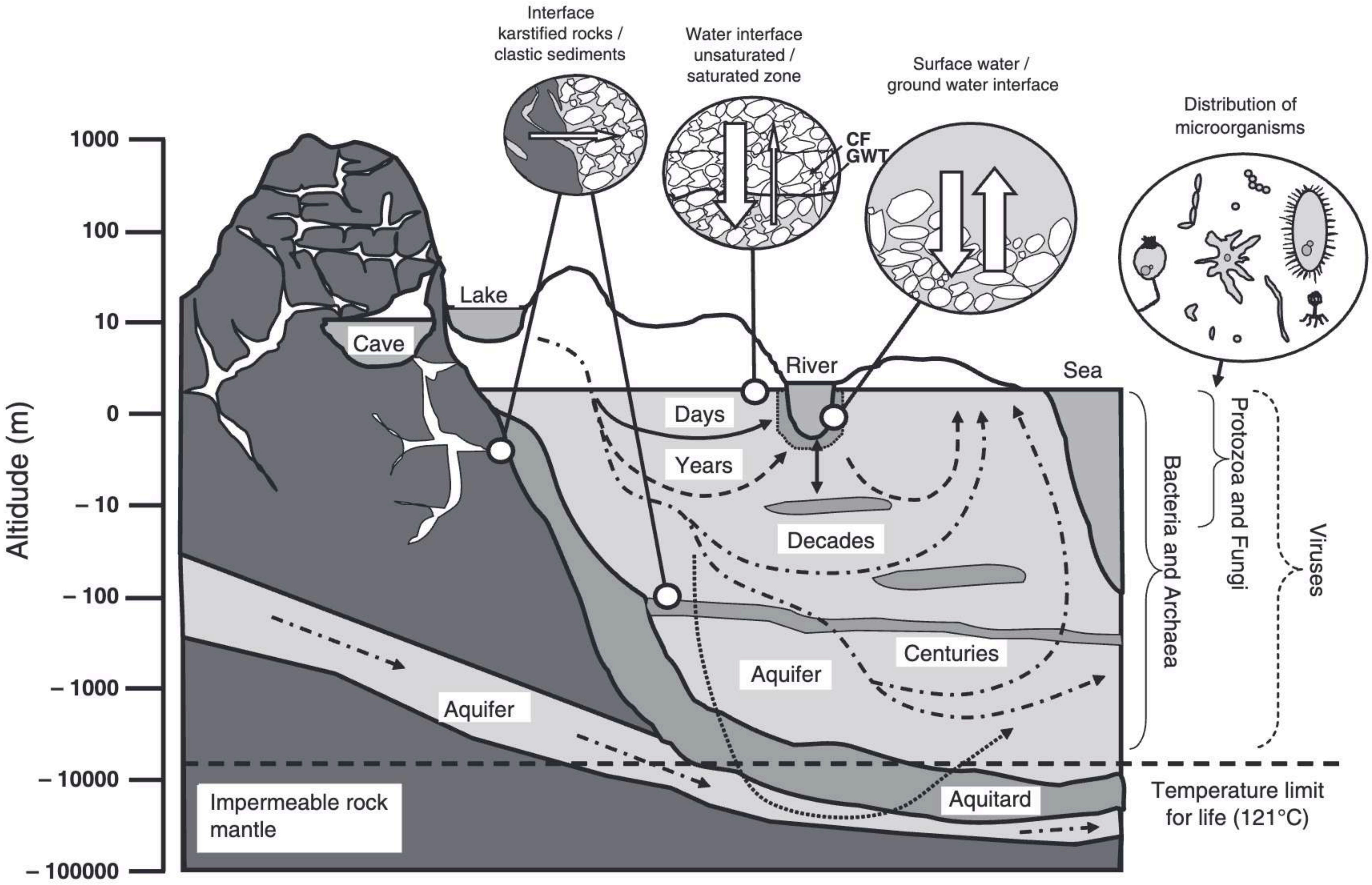
Groundwater-flow paths are derived from hydraulic gradients between areas of recharge (e.g., precipitation in high topographic regions) and discharge (e.g., springs in low topographic regions)

Groundwater environment are characterised by **continuous darkness and limited nutrients —> slow growing microbes**

Groundwater ecosystems deliver services that are of immense societal and economic value, such as:

1) purification of water and its storage in good quality for decades and centuries,
2) active biodegradation of anthropogenic contaminants and inactivation and elimination of pathogens,
3) nutrient recycling, and
4) mitigation of floods and droughts

Aquatic surface and subsurface microbial ecosystems



GRIEBLER AND LUEDERS, 2009

Arrows depict the flow of water carrying energy and matter through the subsurface, with boxes next to arrows indicating typical groundwater residence times.
Circles highlight transition zones between habitat types. Curly braces indicate the distribution of different microbial groups in the subsurface. CF, capillary fringe;GWT, groundwater table

Low microbial abundance in low C system

GRIEBLER AND LUEDERS, 2009

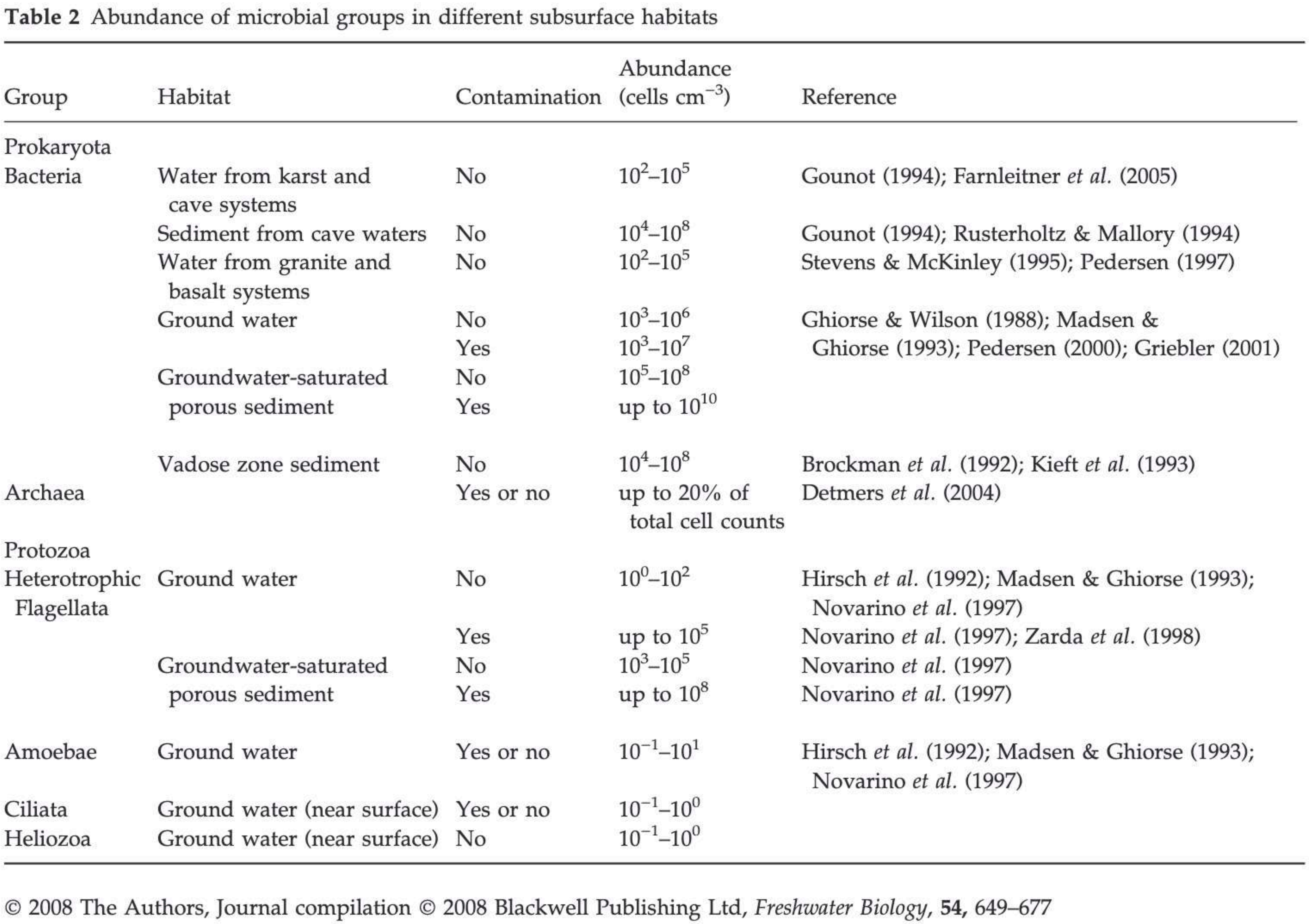
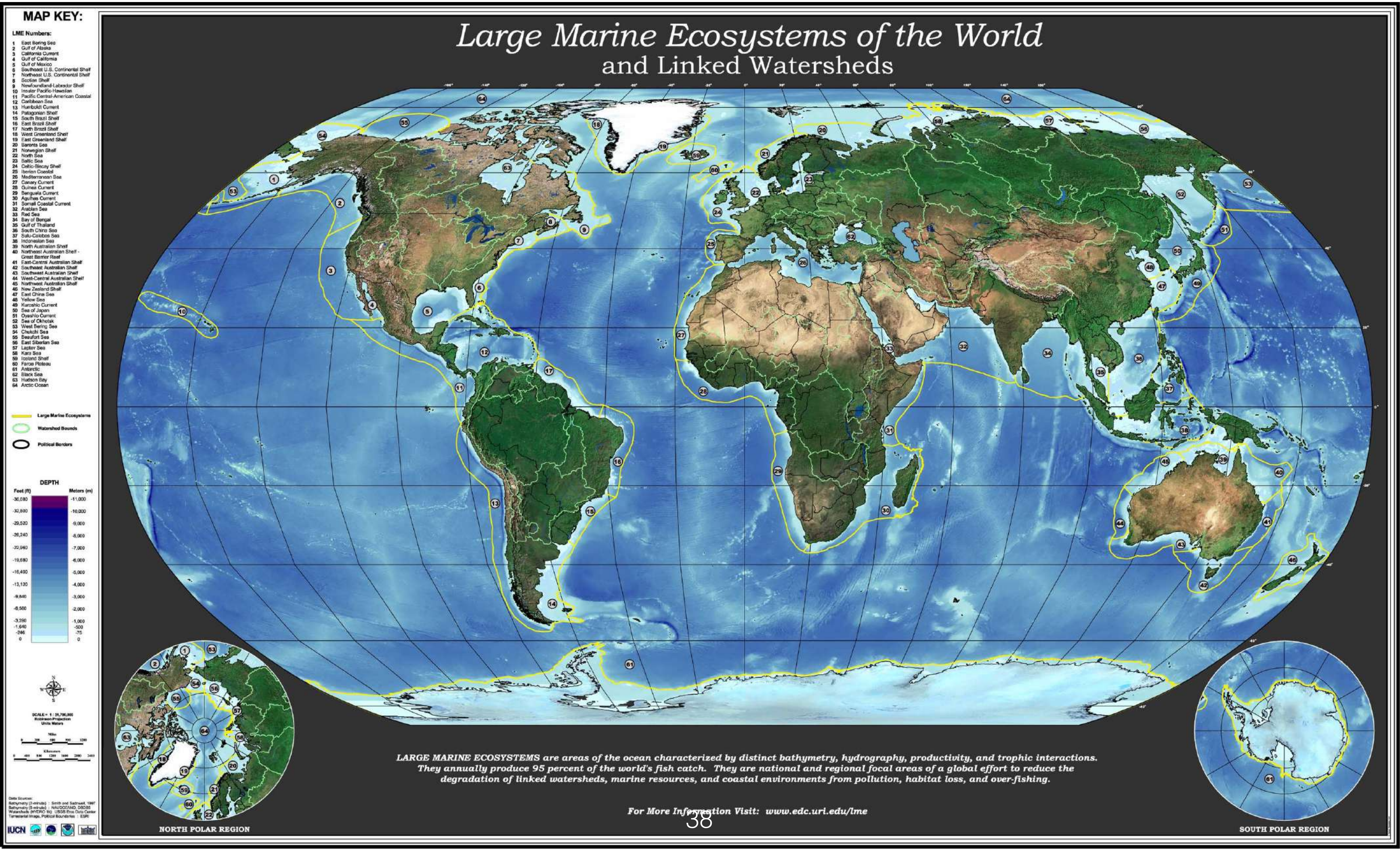


Table 2 Abundance of microbial groups in different subsurface habitats

Group	Habitat	Contamination	Abundance (cells cm^{-3})	Reference
Prokaryota				
Bacteria	Water from karst and cave systems	No	10^{2}–10^{5}	Gounot (1994); Farnleitner *et al.* (2005)
	Sediment from cave waters	No	10^{4}–10^{8}	Gounot (1994); Rusterholtz & Mallory (1994)
	Water from granite and basalt systems	No	10^{2}–10^{5}	Stevens & McKinley (1995); Pedersen (1997)
	Ground water	No	10^{3}–10^{6}	Ghiorse & Wilson (1988); Madsen & Ghiorse (1993); Pedersen (2000); Griebler (2001)
		Yes	10^{3}–10^{7}	
	Groundwater-saturated porous sediment	No	10^{5}–10^{8}	
		Yes	up to 10^{10}	
	Vadose zone sediment	No	10^{4}–10^{8}	Brockman *et al.* (1992); Kieft *et al.* (1993)
Archaea		Yes or no	up to 20% of total cell counts	Detmers *et al.* (2004)
Protozoa				
Heterotrophic Flagellata	Ground water	No	10^{0}–10^{2}	Hirsch *et al.* (1992); Madsen & Ghiorse (1993); Novarino *et al.* (1997)
		Yes	up to 10^{5}	Novarino *et al.* (1997); Zarda *et al.* (1998)
	Groundwater-saturated porous sediment	No	10^{3}–10^{5}	Novarino *et al.* (1997)
		Yes	up to 10^{8}	Novarino *et al.* (1997)
Amoebae	Ground water	Yes or no	10^{-1}–10^{1}	Hirsch *et al.* (1992); Madsen & Ghiorse (1993); Novarino *et al.* (1997)
Ciliata	Ground water (near surface)	Yes or no	10^{-1}–10^{0}	
Heliozoa	Ground water (near surface)	No	10^{-1}–10^{0}	

Large marine ecosystems and watersheds

- On land watersheds don’t comunicate with other watersheds
- Characteristic chemical and biological fingerprint of each watershed



Large Marine Ecosystems of the World
and Linked Watersheds

LARGE MARINE ECOSYSTEMS are areas of the ocean characterized by distinct bathymetry, hydrography, productivity, and trophic interactions. They annually produce 95 percent of the world's fish catch. They are national and regional focal areas of a global effort to reduce the degradation of linked watersheds, marine resources, and coastal environments from pollution, habitat loss, and over-fishing.

For More Information Visit: www.edc.uri.edu/lme

Data Sources:
Bathymetry (2-minute) : Smith and Sandwell, 1997
Bathymetry (5-minute) : NAVOCEANO, DBDB5
Watersheds (HYDRO 1k): USGS Eros Data Center
Terrestrial Image, Political Boundaries : ESRI

Lake as a complex microbial ecosystem

Madsen, 2016

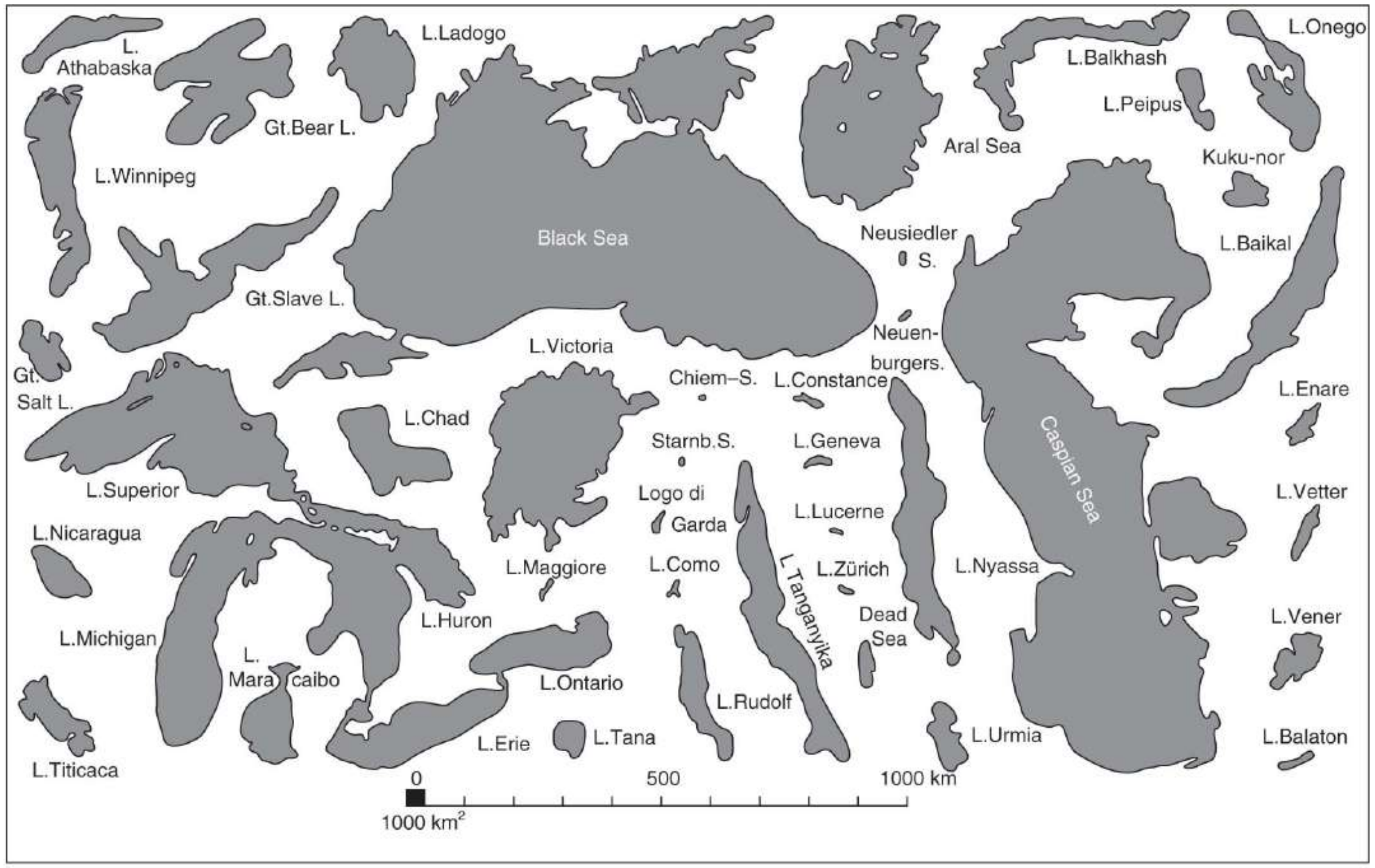
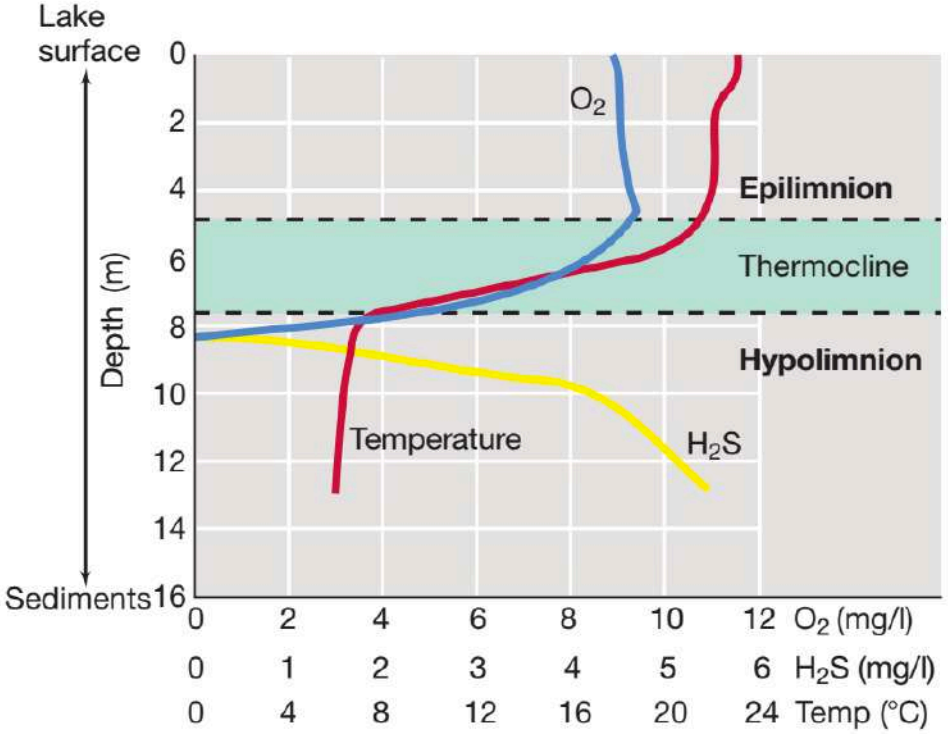


Figure 4.5 Major lakes of the world showing an approximate comparison of the surface areas of many of the larger inland waters, all drawn to the same scale. The Aral Sea has experienced catastrophic reductions in area (more than half of that depicted here) because of diversion of water for agriculture. (Reprinted from Wetzel, R.G. 2001. *Limnology: Lake and River Ecosystems*, 3rd edn. Academic Press, San Diego, CA. Copyright 2001, with permission from Elsevier.)

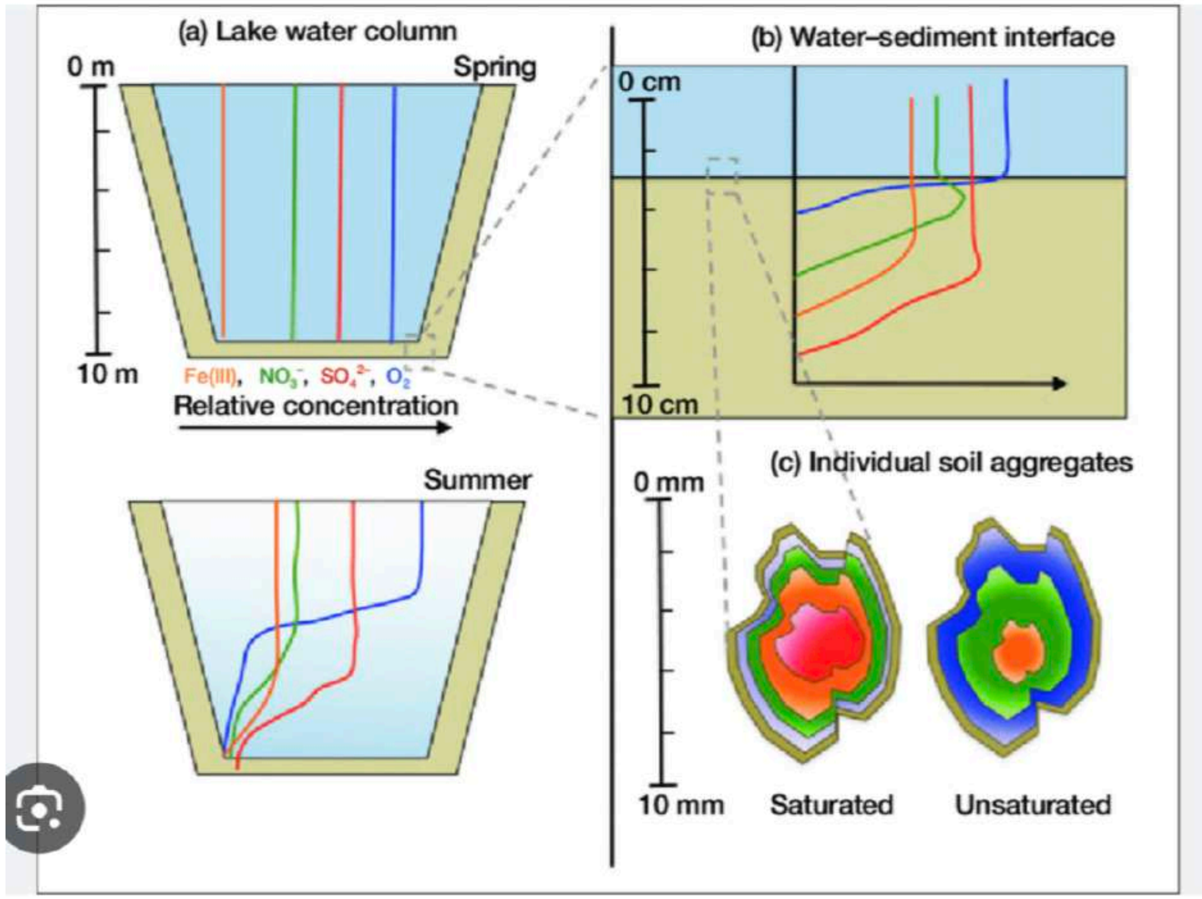
- Seasonality in the water column

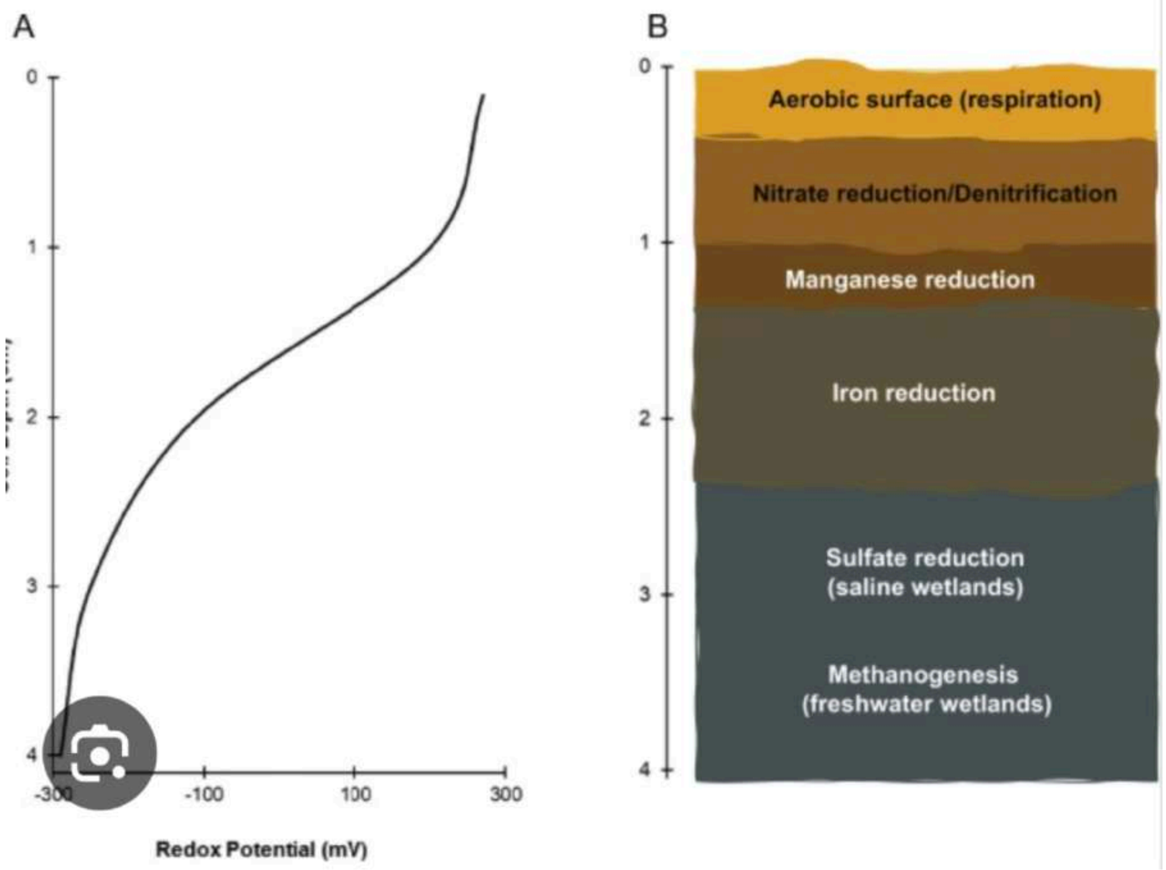


Madigan et al. 2018

- Nutrient inputs from terrestrial vegetation and human activities drive microbial activities in production and decomposition of organic matter
- Microalgal bloom (thus including Cyanobacteria)
- Organic matter decomposition can create anoxia (lack of O_2)

Steep microbial gradients in lake and sediment shape microbial community and metabolism





Mobilian and Craft, 2022

The redox potential is used to describe a system's overall reducing or oxidizing capacity

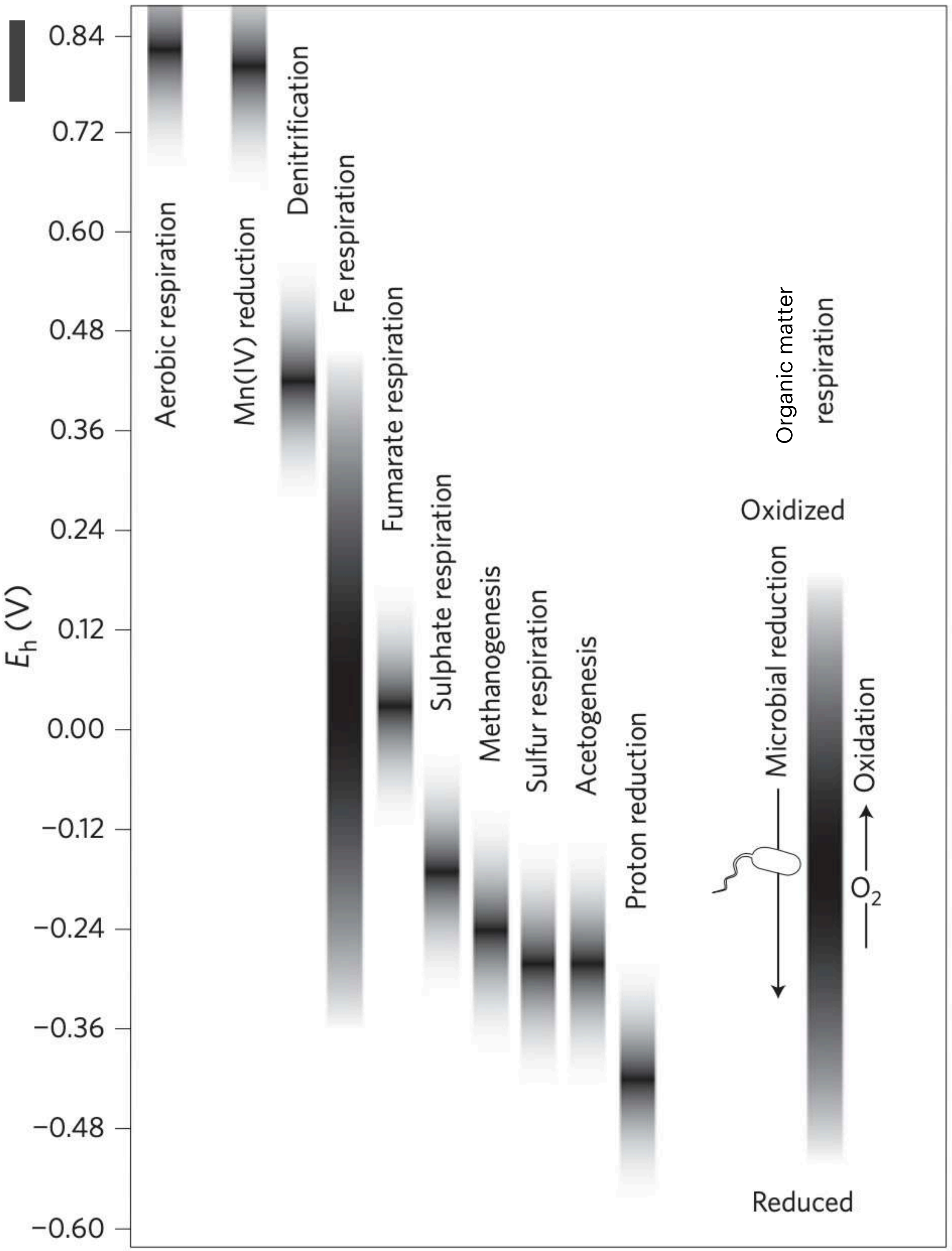
The redox potential is measured in millivolts (mV) relative to a standard hydrogen electrode and is commonly measured using a platinum electrode with a saturated calomel electrode as reference

In well-oxidized water, with oxygen concentrations $> \sim 1$ mg O_2 L^{-1}, the redox potential will be **> 300–500 mV**

In reduced environments, such as in the deep water of stratified lakes or the sediment of eutrophic lakes, the redox potential will be **< 100 mV or even negative**

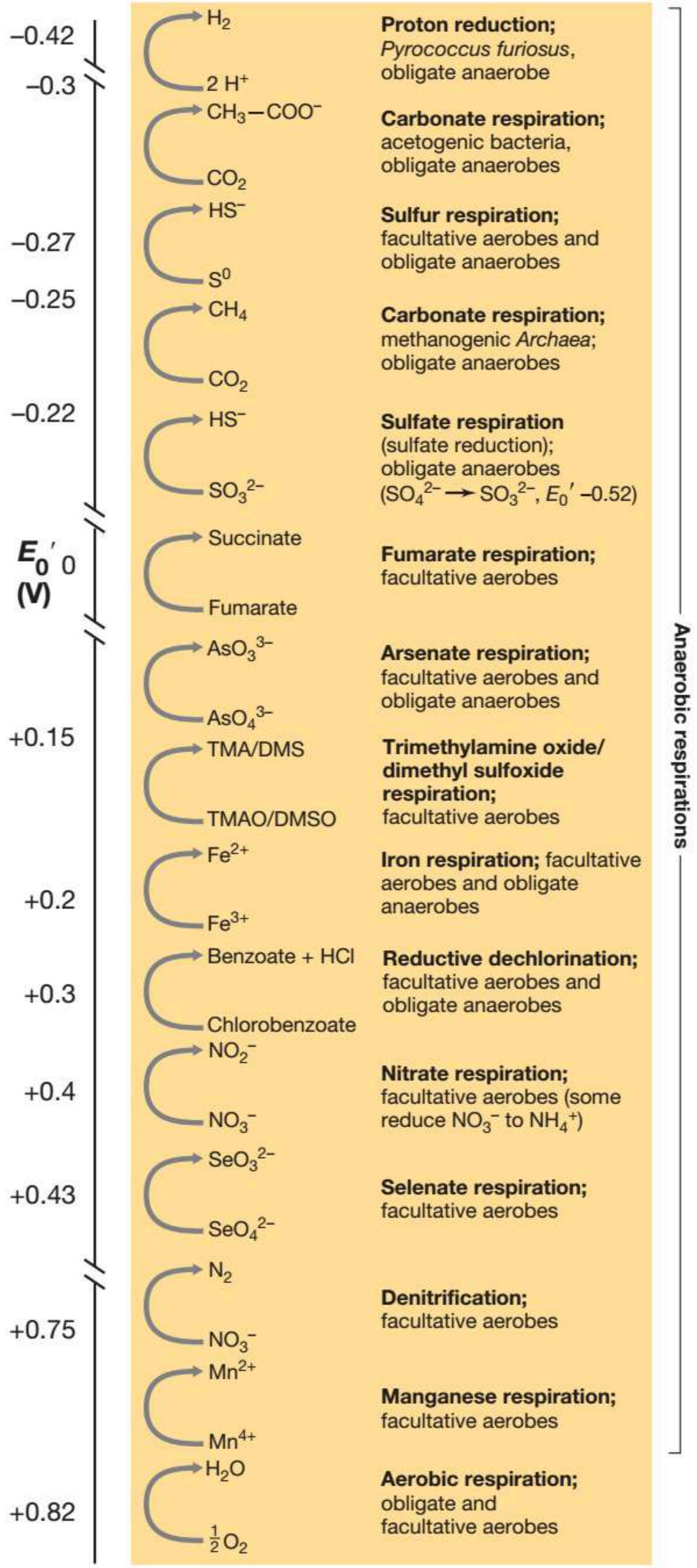
Reduction potential ranges of microbial respiration

- The achievable energy yield of ETC depends on the difference in electrical potential between electron donor and acceptor
- Microbes able to respire in multiple ways will always choose available acceptors with the **biggest potential difference** to the donor (e.g., *E. coli* O2 > NO3-> fumarate)

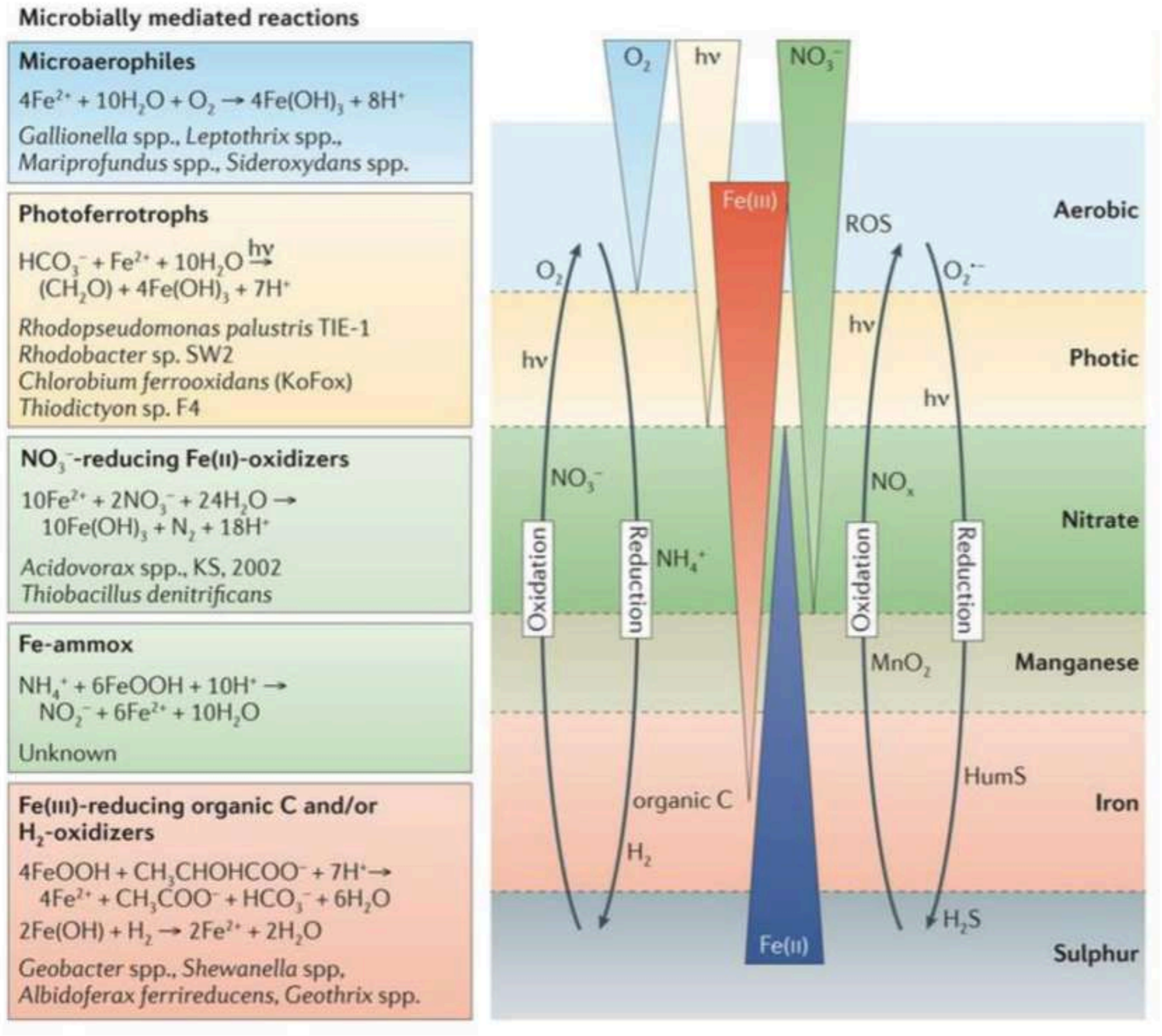


Klüpfel et al., 2014

Anaerobic respiration



Couple	Respiration
H_2 / $2H^+$	**Proton reduction;** *Pyrococcus furiosus*, obligate anaerobe
$CH_3{-}COO^-$ / CO_2	**Carbonate respiration;** acetogenic bacteria, obligate anaerobes
HS^- / S^0	**Sulfur respiration;** facultative aerobes and obligate anaerobes
CH_4 / CO_2	**Carbonate respiration;** methanogenic *Archaea*; obligate anaerobes
HS^- / SO_3^{2-}	**Sulfate respiration** (sulfate reduction); obligate anaerobes ($SO_4^{2-} \rightarrow SO_3^{2-}$, E_0' −0.52)
Succinate / Fumarate	**Fumarate respiration;** facultative aerobes
AsO_3^{3-} / AsO_4^{3-}	**Arsenate respiration;** facultative aerobes and obligate anaerobes
TMA/DMS / TMAO/DMSO	**Trimethylamine oxide/ dimethyl sulfoxide respiration;** facultative aerobes
Fe^{2+} / Fe^{3+}	**Iron respiration;** facultative aerobes and obligate anaerobes
Benzoate + HCl / Chlorobenzoate	**Reductive dechlorination;** facultative aerobes and obligate anaerobes
NO_2^- / NO_3^-	**Nitrate respiration;** facultative aerobes (some reduce NO_3^- to NH_4^+)
SeO_3^{2-} / SeO_4^{2-}	**Selenate respiration;** facultative aerobes
N_2 / NO_3^-	**Denitrification;** facultative aerobes
Mn^{2+} / Mn^{4+}	**Manganese respiration;** facultative aerobes
H_2O / $\frac{1}{2}O_2$	**Aerobic respiration;** obligate and facultative aerobes



Microbially mediated reactions

Microaerophiles

$4Fe^{2+} + 10H_2O + O_2 \rightarrow 4Fe(OH)_3 + 8H^+$

Gallionella spp., *Leptothrix* spp., *Mariprofundus* spp., *Sideroxydans* spp.

Photoferrotrophs

$HCO_3^- + Fe^{2+} + 10H_2O \xrightarrow{h\nu} (CH_2O) + 4Fe(OH)_3 + 7H^+$

Rhodopseudomonas palustris TIE-1
Rhodobacter sp. SW2
Chlorobium ferrooxidans (KoFox)
Thiodictyon sp. F4

NO_3^--reducing Fe(II)-oxidizers

$10Fe^{2+} + 2NO_3^- + 24H_2O \rightarrow 10Fe(OH)_3 + N_2 + 18H^+$

Acidovorax spp., KS, 2002
Thiobacillus denitrificans

Fe-ammox

$NH_4^+ + 6FeOOH + 10H^+ \rightarrow NO_2^- + 6Fe^{2+} + 10H_2O$

Unknown

Fe(III)-reducing organic C and/or H_2-oxidizers

$4FeOOH + CH_3CHOHCOO^- + 7H^+ \rightarrow 4Fe^{2+} + CH_3COO^- + HCO_3^- + 6H_2O$

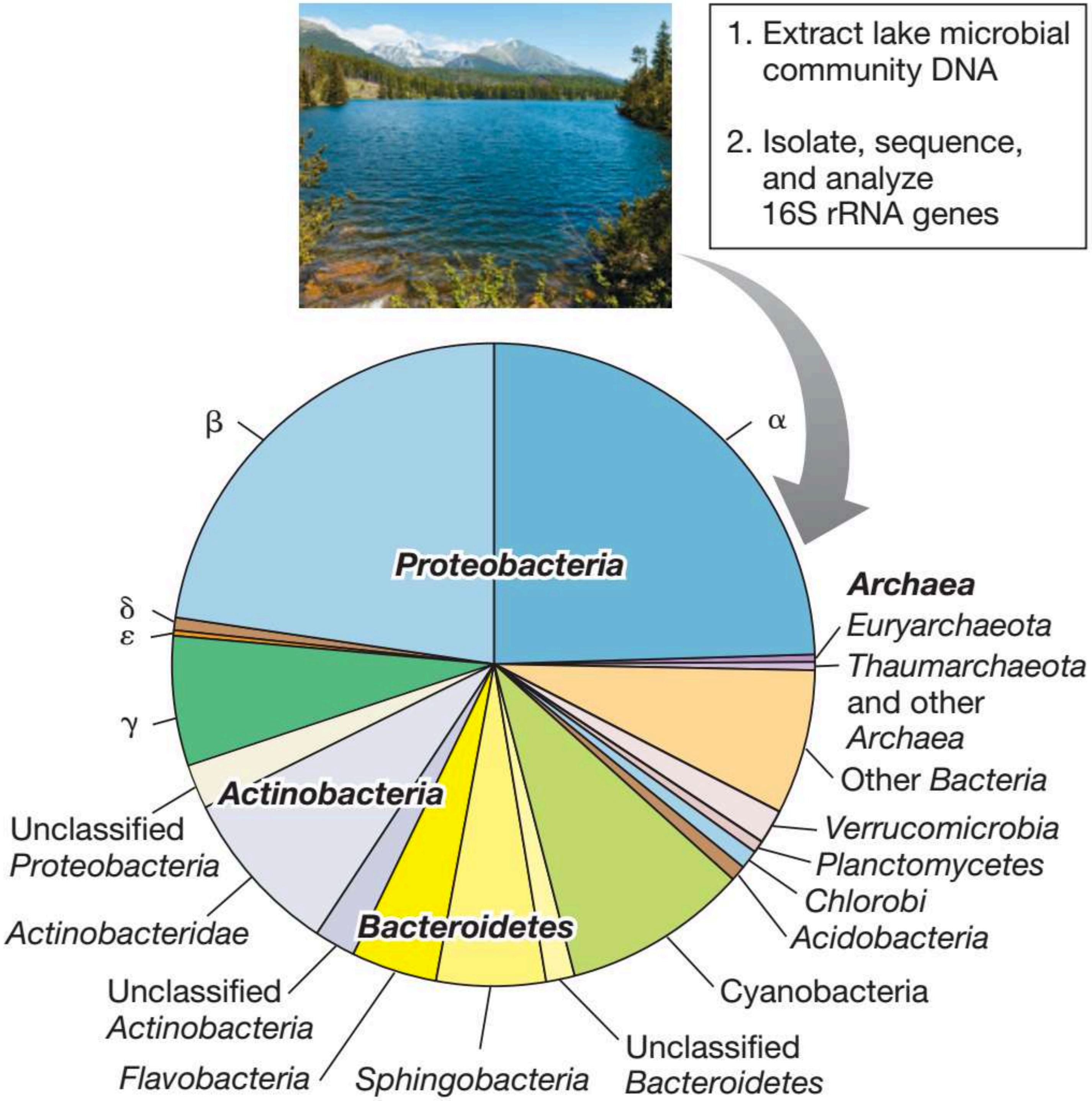
$2Fe(OH) + H_2 \rightarrow 2Fe^{2+} + 2H_2O$

Geobacter spp., *Shewanella* spp., *Albidoferax ferrireducens*, *Geothrix* spp.

Madigan et al. 2018

Melton et al., 2014

Freshwater microbial diversity



1. Extract lake microbial community DNA
2. Isolate, sequence, and analyze 16S rRNA genes

Madigan et al. 2020

- 16S rRNA gene based diversity

Biogeochemical processes

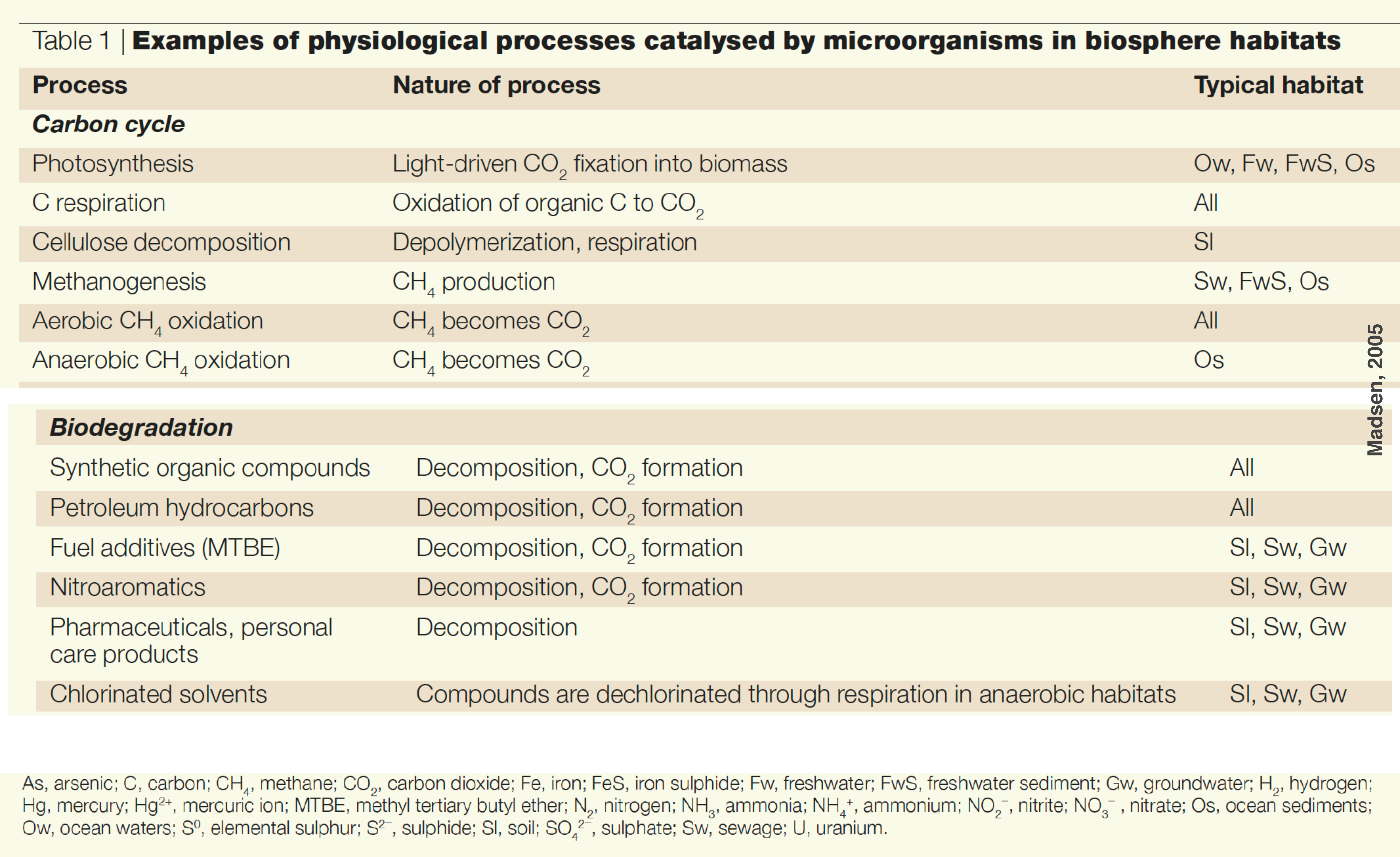


Table 1 | **Examples of physiological processes catalysed by microorganisms in biosphere habitats**

Process	Nature of process	Typical habitat
Carbon cycle		
Photosynthesis	Light-driven CO_2 fixation into biomass	Ow, Fw, FwS, Os
C respiration	Oxidation of organic C to CO_2	All
Cellulose decomposition	Depolymerization, respiration	Sl
Methanogenesis	CH_4 production	Sw, FwS, Os
Aerobic CH_4 oxidation	CH_4 becomes CO_2	All
Anaerobic CH_4 oxidation	CH_4 becomes CO_2	Os
Biodegradation		
Synthetic organic compounds	Decomposition, CO_2 formation	All
Petroleum hydrocarbons	Decomposition, CO_2 formation	All
Fuel additives (MTBE)	Decomposition, CO_2 formation	Sl, Sw, Gw
Nitroaromatics	Decomposition, CO_2 formation	Sl, Sw, Gw
Pharmaceuticals, personal care products	Decomposition	Sl, Sw, Gw
Chlorinated solvents	Compounds are dechlorinated through respiration in anaerobic habitats	Sl, Sw, Gw

As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^- , nitrate; Os, ocean sediments; Ow, ocean waters; S^0, elemental sulphur; S^{2-}, sulphide; Sl, soil; SO_4^{2-}, sulphate; Sw, sewage; U, uranium.

Madsen, 2005

Nitrogen cycle		
N_2 fixation	N_2 gas becomes NH_3	Sl, Ow
NH_4^+ oxidation	NH_3 becomes NO_2^-, NO_3^-	Sl, Sw
Anaerobic NH_4^+ oxidation	NO_2^- and NH_3 become N_2 gas	Sw, Os
Denitrification	NO_3^- is used as an electron acceptor and converted to N_2 gas	Sl, Sw
Sulphur cycle		
S_2 oxidation	S^{2-} and S^0 become SO_4^{2-}	Os, FwS
SO_4^{2-} reduction	SO_4^{2-} is used as an electron acceptor and converted to S^0 and S^{2-}	Os, Sw, Gw
Other elements		
H_2 oxidation	H_2 is oxidized to H^+, electrons reduce other substances	Sw, Sl, Os, FwS
Hg methylation and reduction	Organic Hg is formed and Hg^{2+} is converted to Hg	FwS, Os
(per)chlorate reduction	Oxidants in rocket fuel and other sources are converted to chloride	Gw
U reduction	U oxyanion is used as an electron acceptor; therefore immobilized	Gw
As reduction	As oxyanion is used as an electron acceptor; therefore toxicity is diminished	FwS, Gw
Fe oxidation, acid mine drainage	FeS ores are oxidized, strong acidity is generated	FwS, Gw

Madsen, 2005

As, arsenic; C, carbon; CH_4, methane; CO_2, carbon dioxide; Fe, iron; FeS, iron sulphide; Fw, freshwater; FwS, freshwater sediment; Gw, groundwater; H_2, hydrogen; Hg, mercury; Hg^{2+}, mercuric ion; MTBE, methyl tertiary butyl ether; N_2, nitrogen; NH_3, ammonia; NH_4^+, ammonium; NO_2^-, nitrite; NO_3^- , nitrate; Os, ocean sediments; Ow, ocean waters; S^0, elemental sulphur; S^{2-}, sulphide; Sl, soil; SO_4^{2-}, sulphate; Sw, sewage; U, uranium.