MICROBIOLOGY OF EXTREME ENVIRONMENTS

Extreme environments 2

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BIOLOGY OF EXTREME ENVIRONMENTS

DIPARTIMENTO DI BIOLOGIA

SURFACE MARINE SEDIMENTS

Deep sea surface sediments

Deep sea surface sediments represent a large reservoir of microbial diversity. For a very long time they have been considered a biological desert

Despite this available information represent a small subset of global distribution of sediments

Different definitions of deep sea surface sediments are available. The first concerns the definition of "deep sea" the second of "surface sediments"

The **deep sea** is defined either as the portion of the Ocean deeper than 200 m (the nominal depth of the photic zone), the depth of the actual photic zone, the portion of the ocean deeper than 1,000 m or the depths of the oceans after the continental shelf break

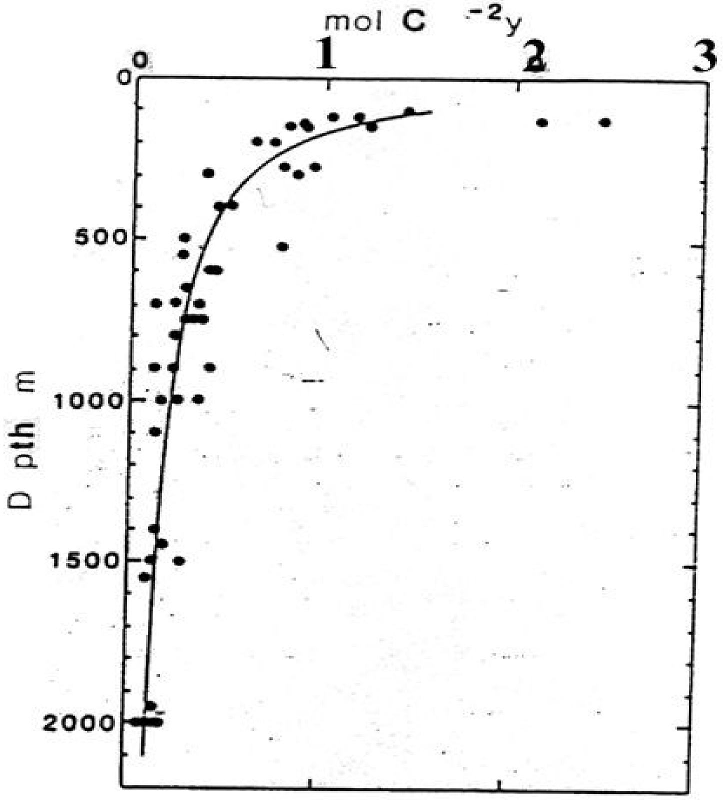
Surface sediments are defined as going from the benthic boundary layer (the interface between sediments and water) and either a depth of 30 cm or 1 meter

Biology is sustained by exports from the photic zone, lateral input of organic matter or in situ production by chemolithoautotrophy

Reduction in Vertical Flux over Depth

The Martin Curve

50% losses by 300 m
75% losses by 500 m
90% losses by 1500 m



Martin and Knauer 1981

Deep Sea Exploration

"From the time of Pliny until the late nineteenth century...humans believed there was no life in the deep. It took a historic expedition in the ship Challenger between 1872 and 1876 to prove Pliny wrong; its deep-sea dredges and trawls brought up living things from all depths that could be reached. Yet even in the twentieth century scientists continued to imagine that life at great depth was insubstantial, or somehow inconsequential. The eternal dark, the almost inconceivable pressure, and the extreme cold that exist below one thousand meters were, they thought, so forbidding as to have all but extinguished life. The reverse is in fact true....(below 200 meters) lies the largest habitat on Earth."

Tim Flannery, ***Where Wonders Await Us****, New York Review of Books*
December 2007

(very) Brief history of Deep-Sea exploration

1843 *- British naturalist Edward Forbes states that life cannot exist below 500 m, the azoic zone.*

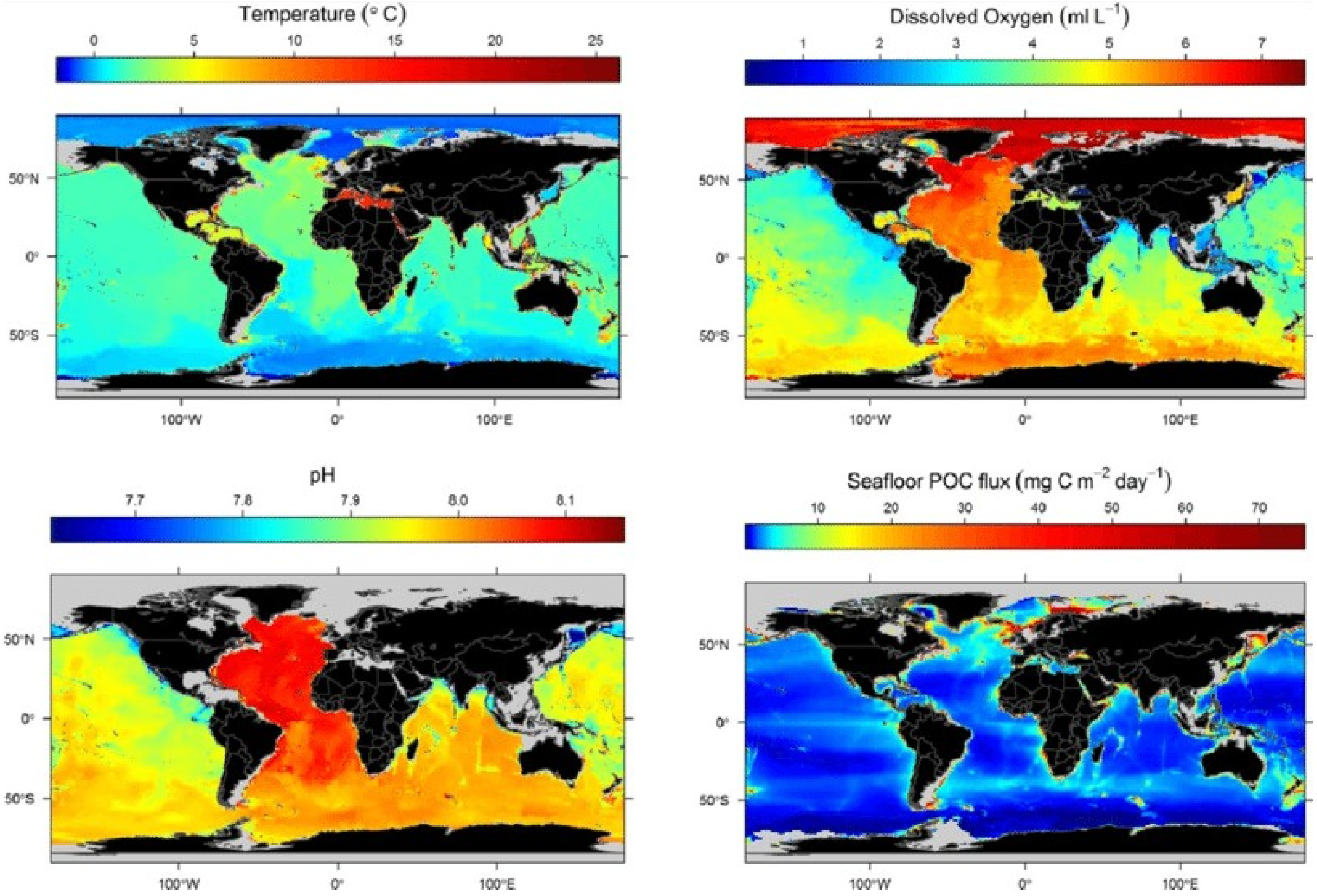
1867 *- American naturalist Louis F. de Pourtales conducts dredging operations finding prolific life extending below 500 m.*

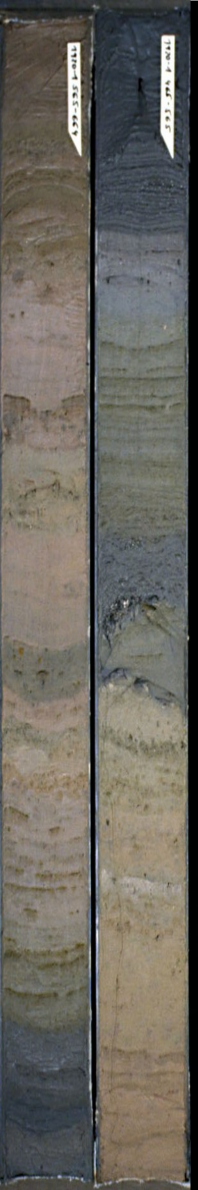
1872 *- Voyage of the H.M.S. Challenger. Four year cruise around the world testing the salinity, temperature and density of the seawater and life. This research forms the basis of modern oceanography.*

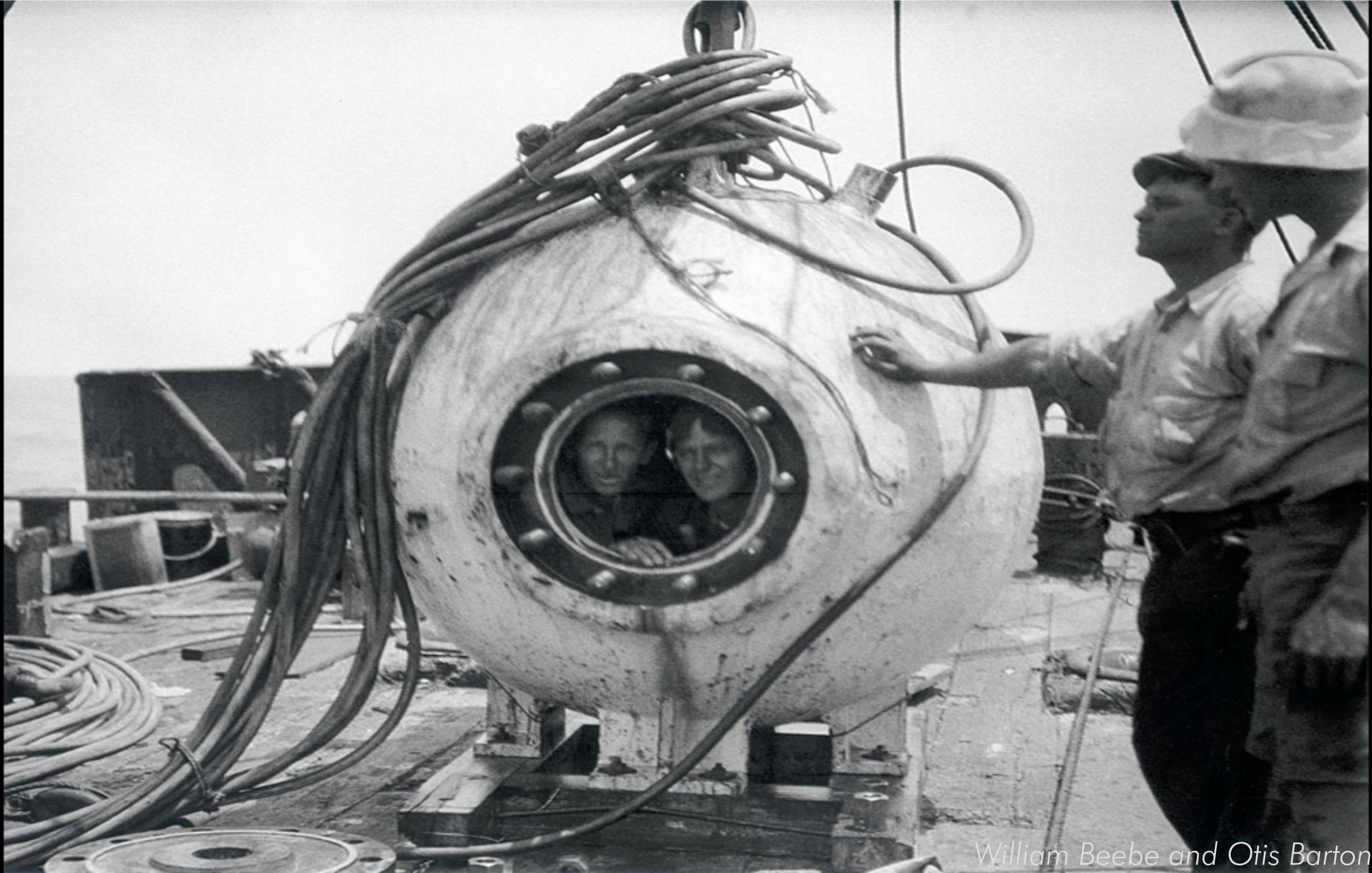
1951 *- The British ship Challenger II bounces sound waves off the ocean bottom and locates what appears to be the sea's deepest point. The Challenger Deep located off the coast of the Marianas Islands in the Pacific Ocean.*

January 23, ***1960*** *- Deepest Ocean Dive. Jacques Piccard and Dan Walsh descend into the Challenger deep with the bathyscaphe Trieste. The divers discover fish and other amazing deep-sea life at these tremendous depths.*

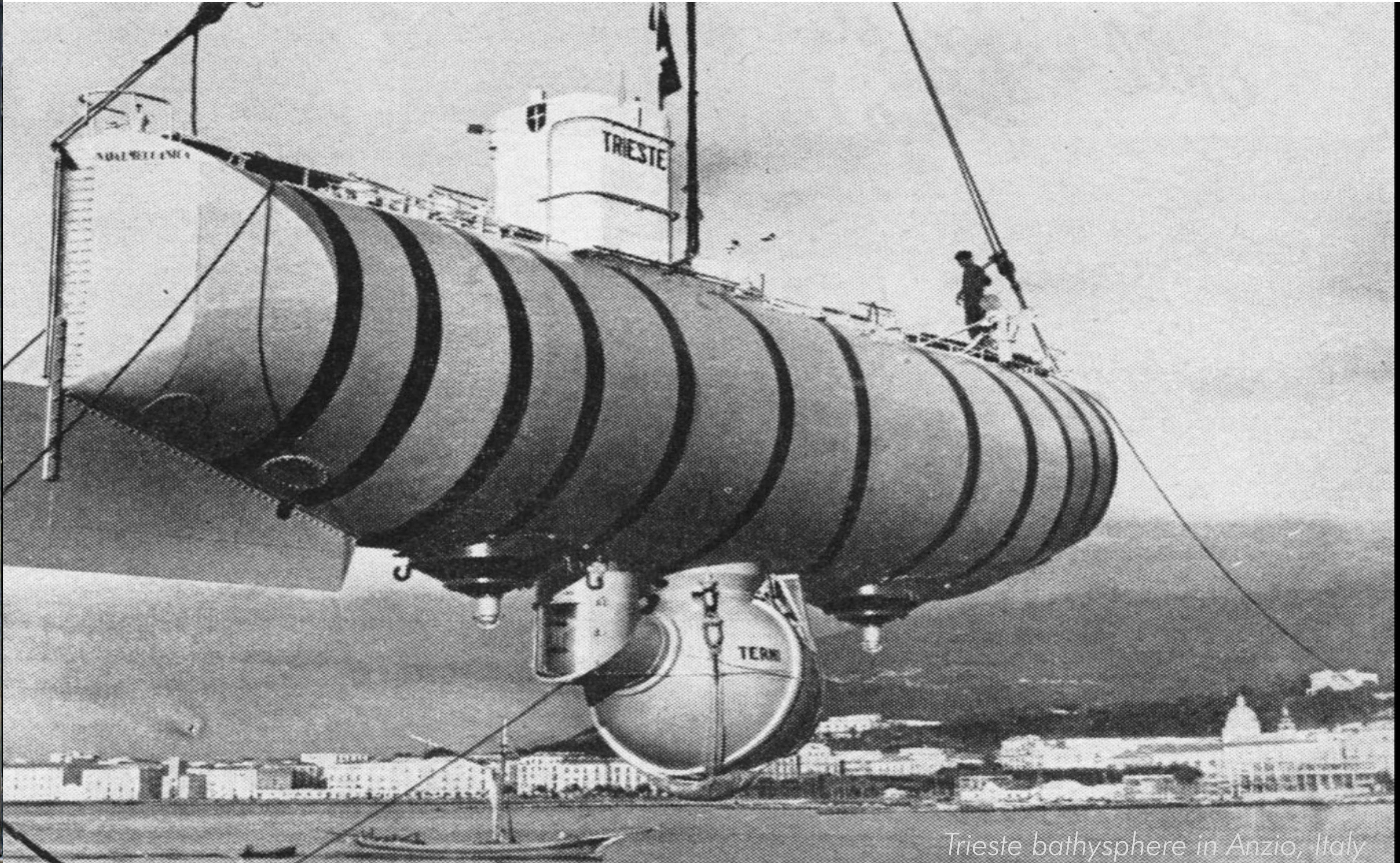
February 17, ***1977*** *- Hydrothermal Vents Discovered. Scientists aboard the deep sea submersible, Alvin, discover and document incredible deep sea hydrothermal vents in the eastern Pacific ocean. This discovery rocks the scientific community because, for the first time, an ecosystem has been found that thrives without the energy of the Sun.*


Temperature (° C)
0 5 10 15 20 25
Dissolved Oxygen (ml L−1)
1 2 3 4 5 6 7
pH
7.7 7.8 7.9 8.0 8.1
Seafloor POC flux (mg C m−2 day−1)
10 20 30 40 50 60 70
50°N
0°
50°S
100°W
0°
100°E





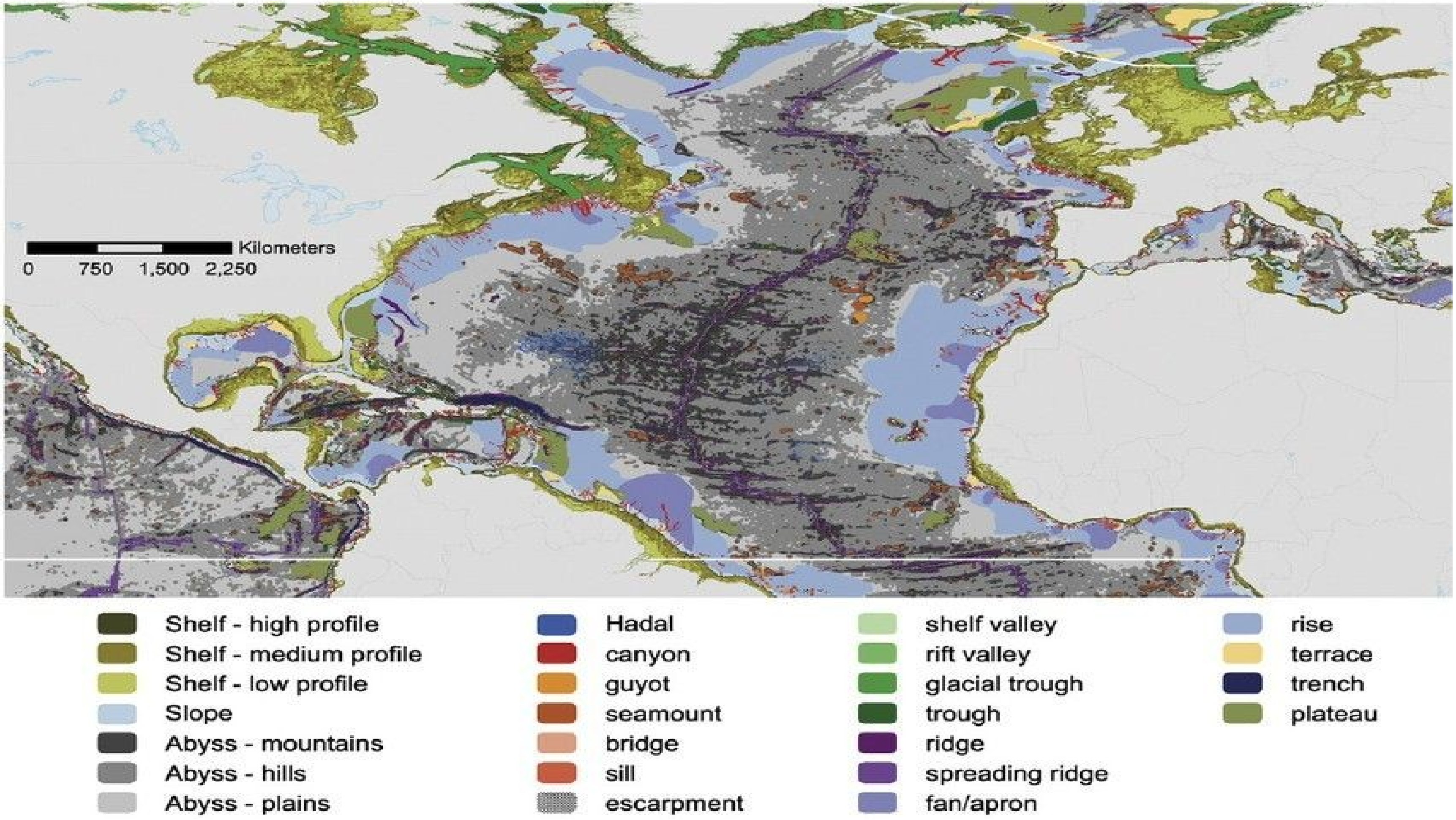
William Beebe and Otis Barton



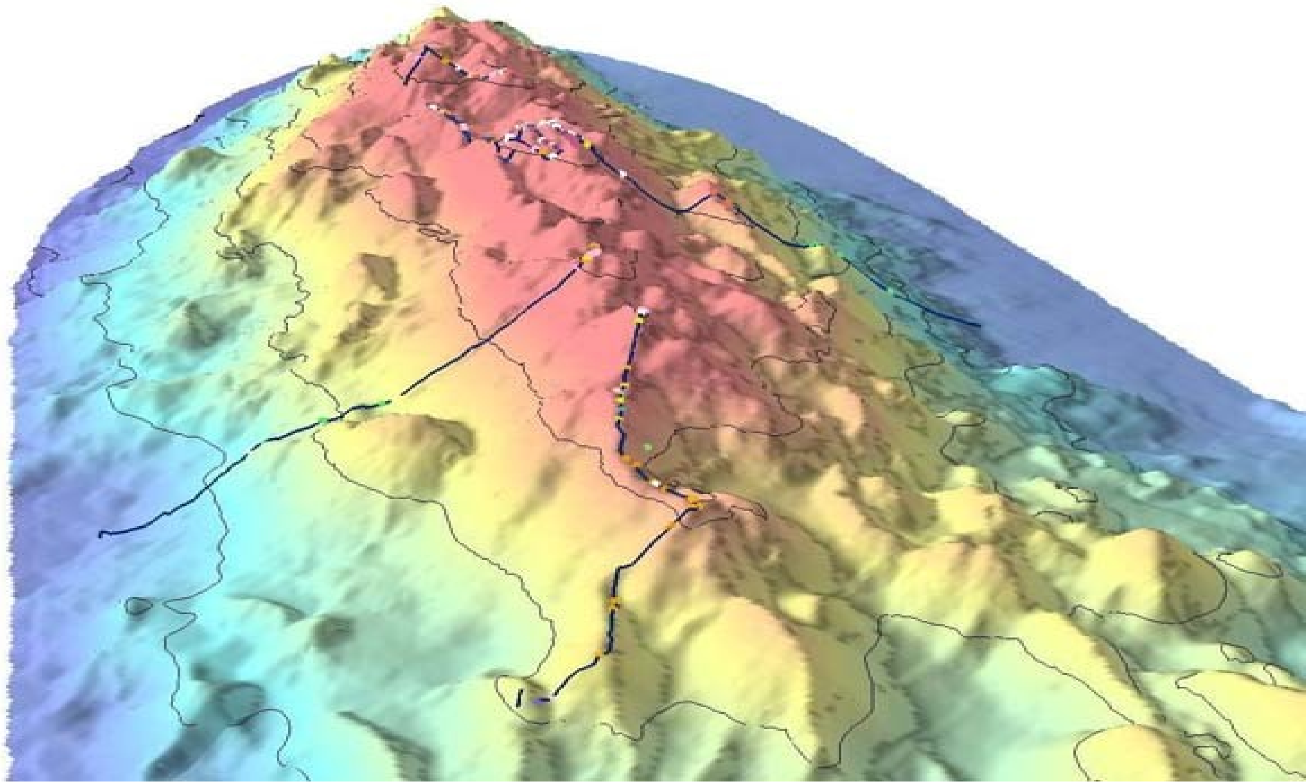
Trieste bathysphere in Anzio, Italy

Jacques Piccard and Dan Walsh inside the Trieste

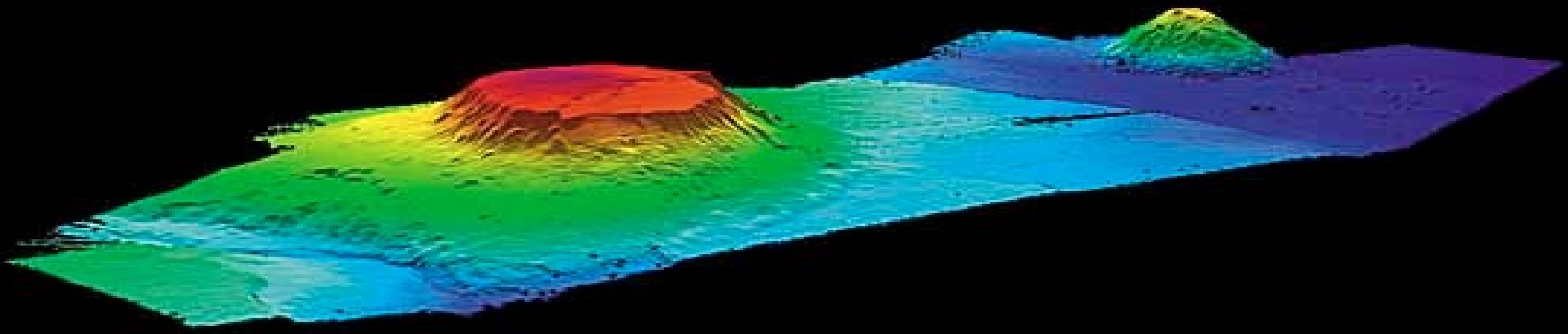
Seafloor geomorphology



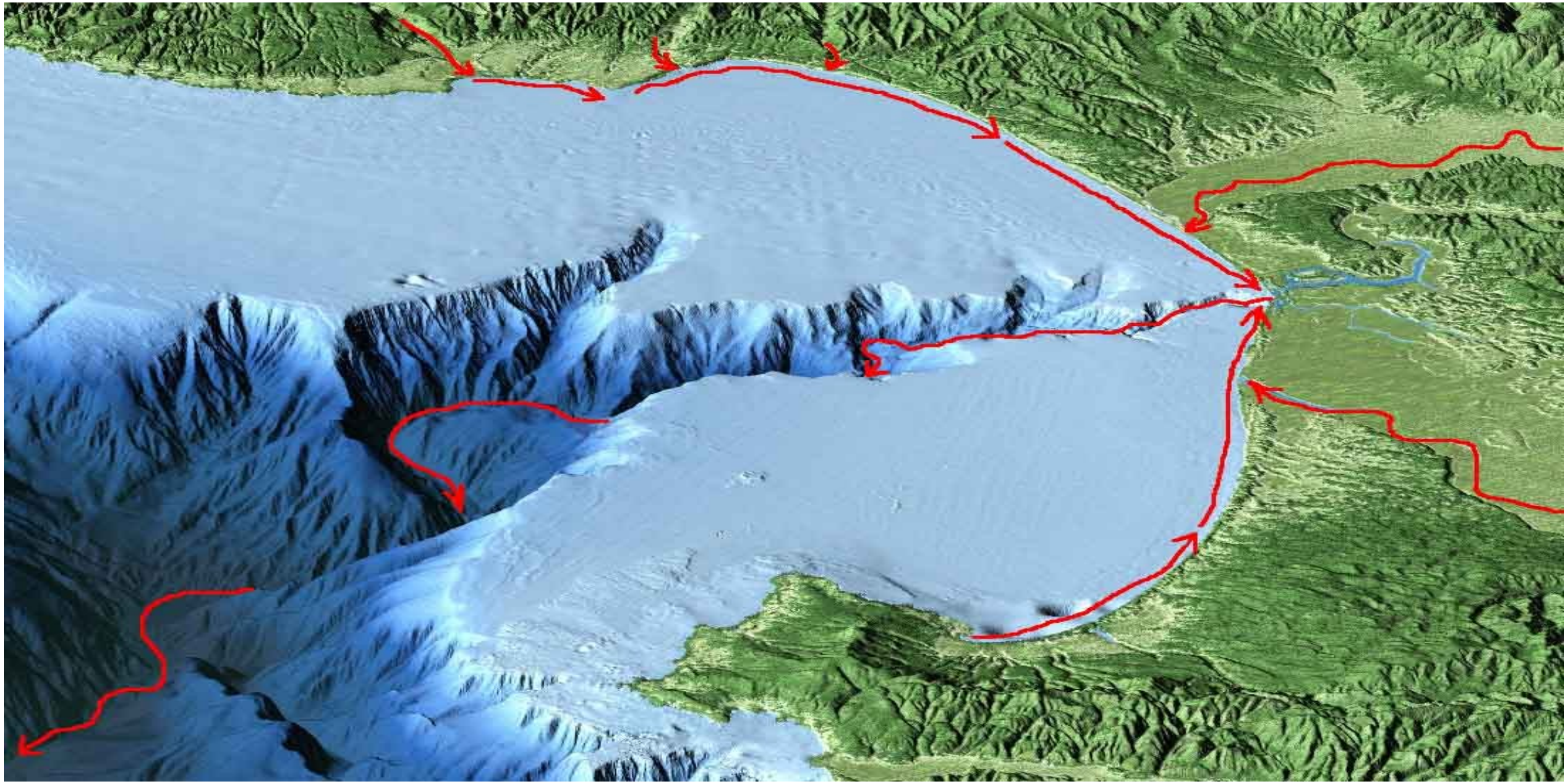
Seamounts



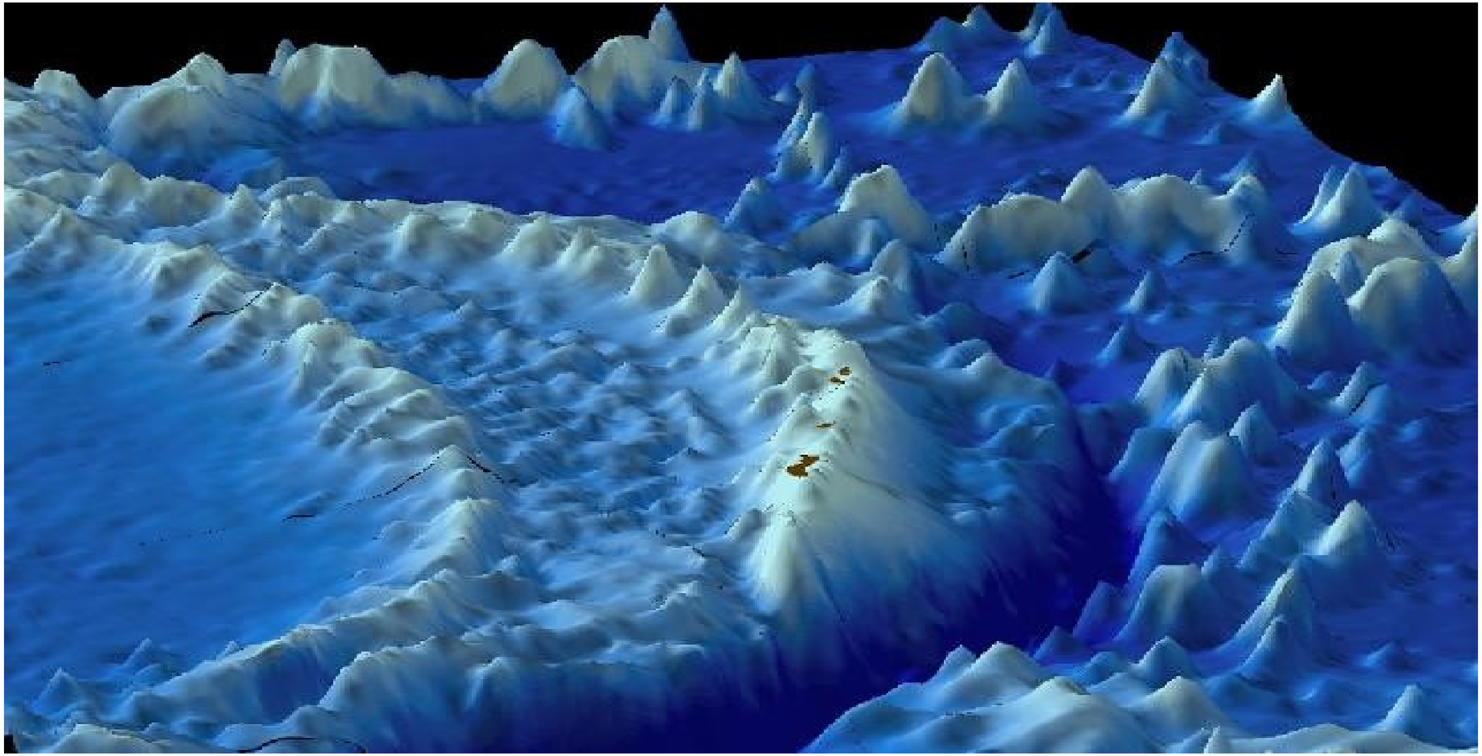
Guyont



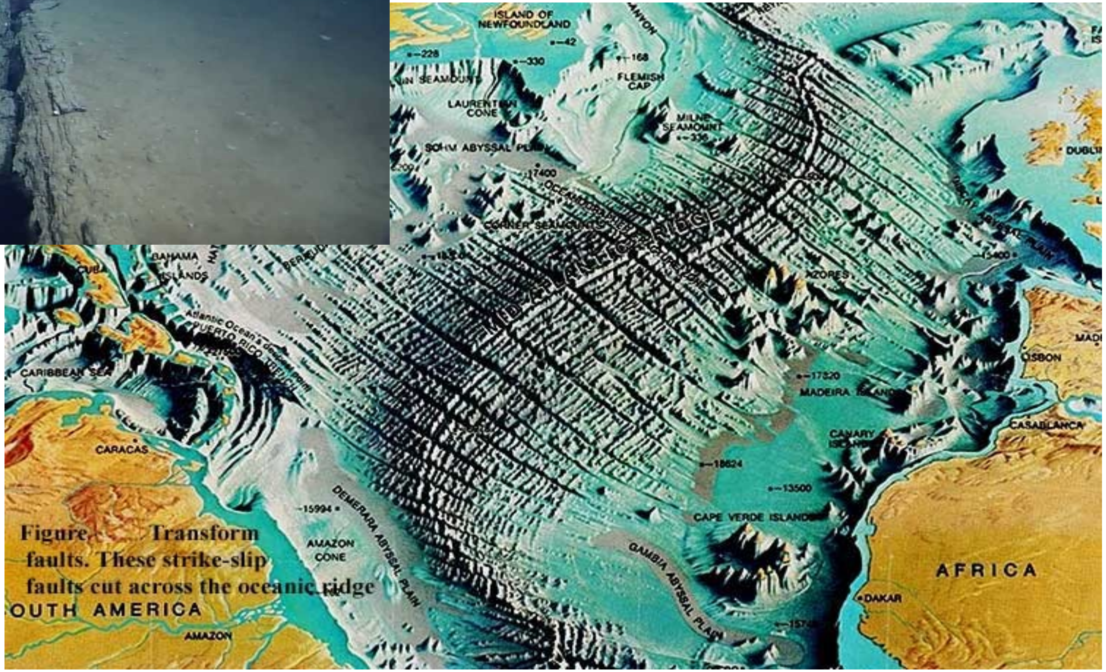
Canyons



Trenches

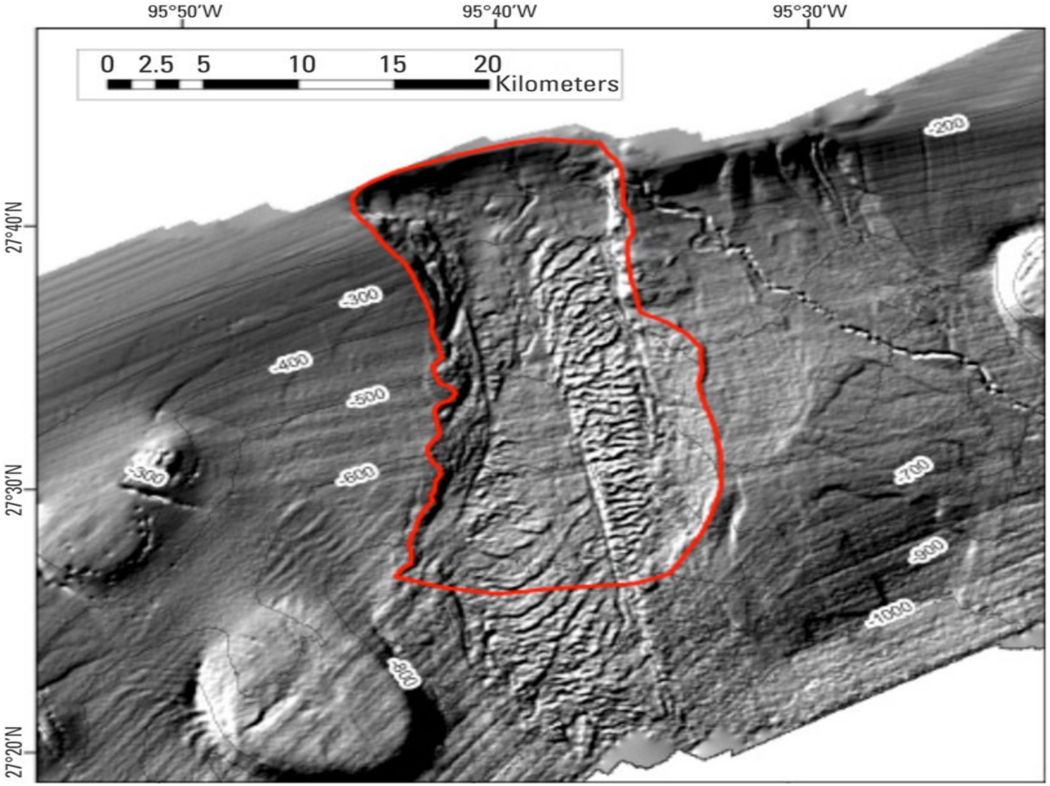


Ridges

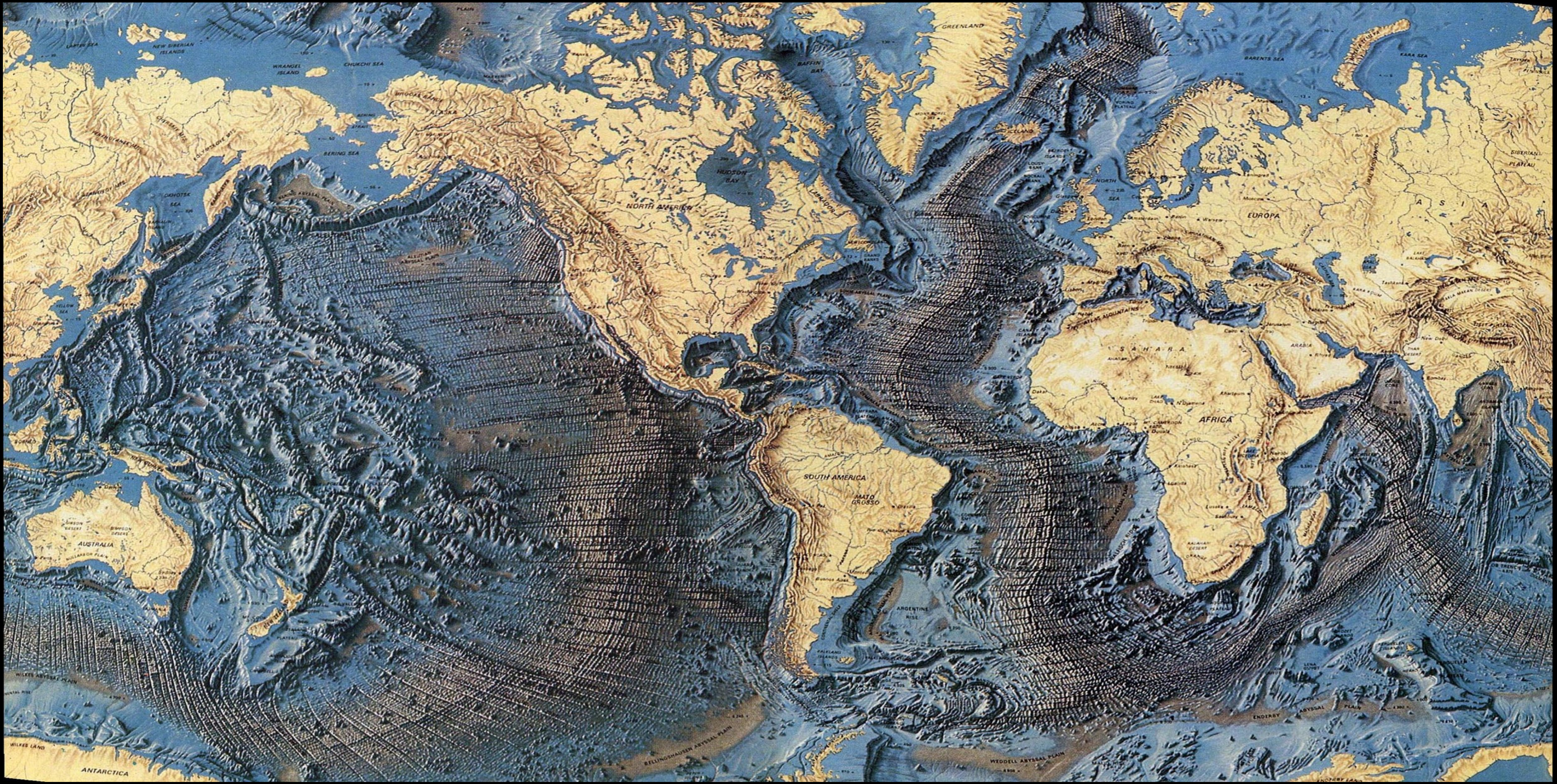


ISLAND OF NEWFOUNDLAND
FLEMISH CAP
LAURENTIAN CONE
MILNE SEAMOUNT
SOHM ABYSSAL PLAIN
BAHAMA ISLANDS
CUBA
PUERTO RICO TRENCH
CARIBBEAN SEA
CARACAS
AZORES
LISBON
MADEIRA ISLANDS
CASABLANCA
CANARY ISLANDS
CAPE VERDE ISLANDS
GAMBIA ABYSSAL PLAIN
DEMERARA ABYSSAL PLAIN
AMAZON CONE
AFRICA
DAKAR
DUBLIN
AMAZON
Figure Transform faults. These strike-slip faults cut across the oceanic ridge
OUTH AMERICA

Landslides



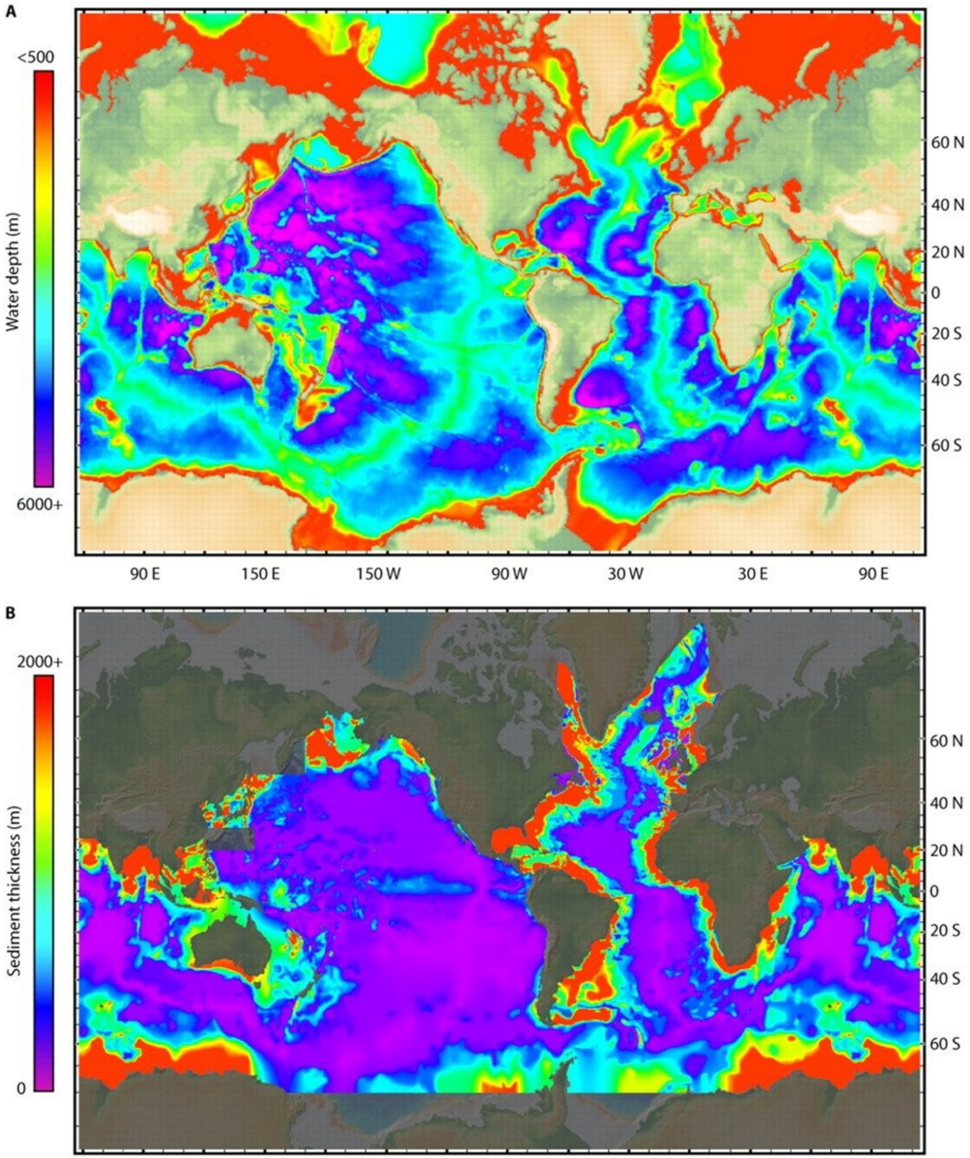
95°50'W
95°40'W
95°30'W
0 2.5 5 10 15 20
Kilometers
27°40'N
27°30'N
27°20'N
-200
-300
-400
-500
-600
-300
-700
-900
-1000
-800

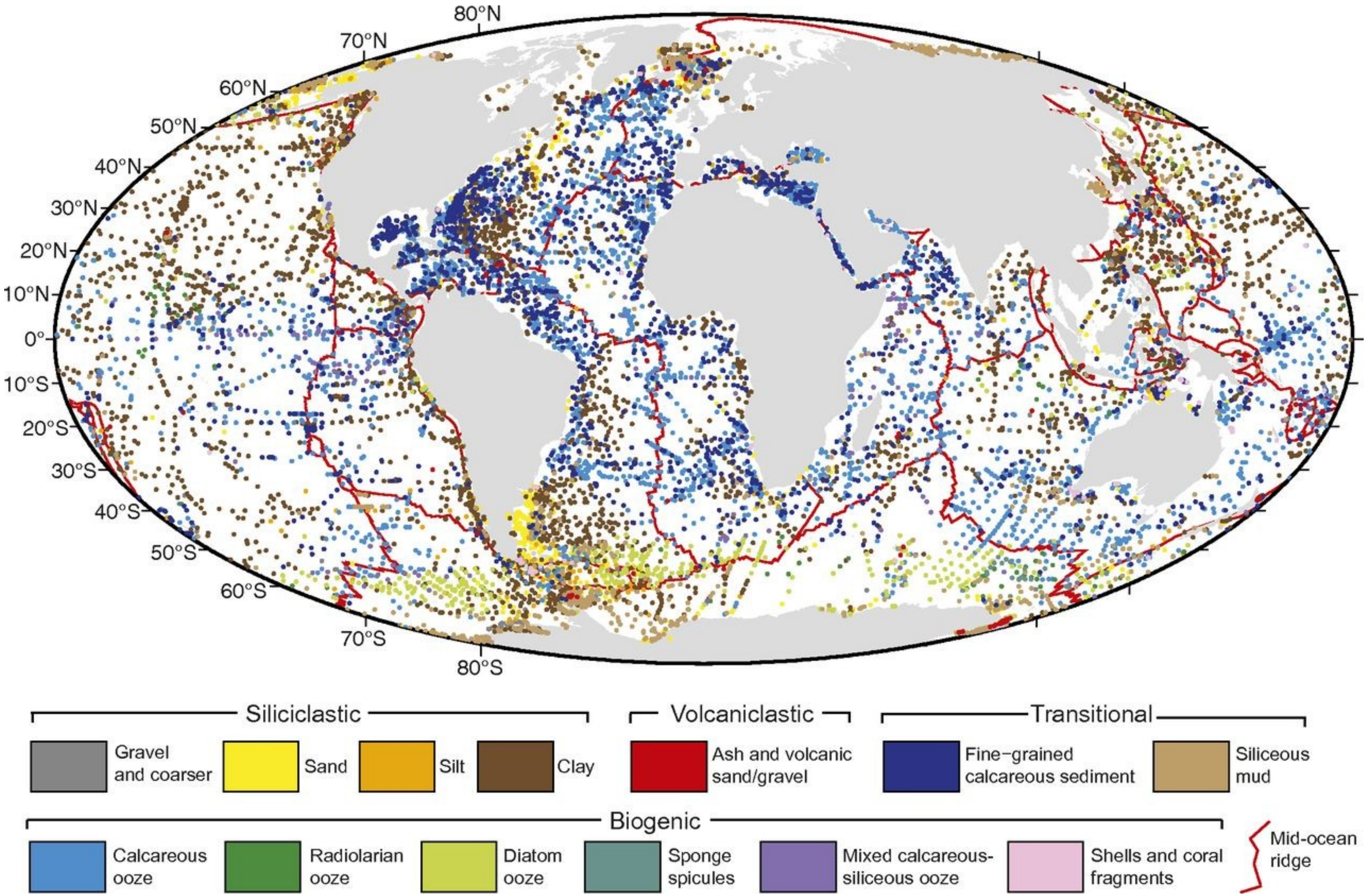


Heezen and Tharp, 1977

Water depth (m)

Sediment thickness (m)




80°N
70°N
60°N
50°N
40°N
30°N
20°N
10°N
0°
10°S
20°S
30°S
40°S
50°S
60°S
70°S
80°S
Siliciclastic
Gravel and coarser
Sand
Silt
Clay
Volcaniclastic
Ash and volcanic sand/gravel
Transitional
Fine−grained calcareous sediment
Siliceous mud
Biogenic
Calcareous ooze
Radiolarian ooze
Diatom ooze
Sponge spicules
Mixed calcareous-siliceous ooze
Shells and coral fragments
Mid-ocean ridge

Age of Oceanic Lithosphere (m.y.)

Data source:

Muller, R.D., M. Sdrolias, C. Gaina, and W.R. Roest 2008. Age, spreading rates and spreading symmetry of the world's ocean crust,Geochem. Geophys. Geosyst., 9, Q04006, doi:10.1029/2007GC001743.

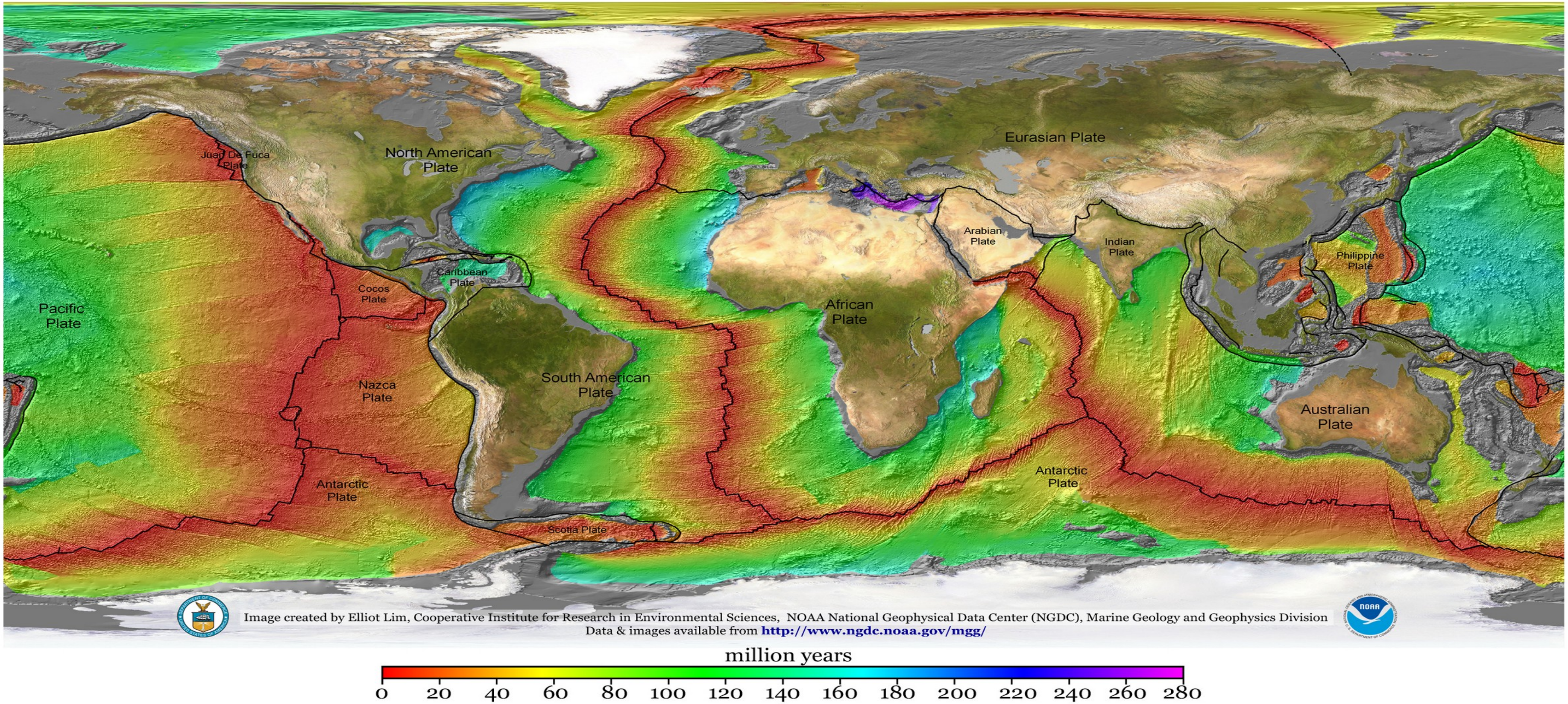


Plate Tectonic and the Seafloor

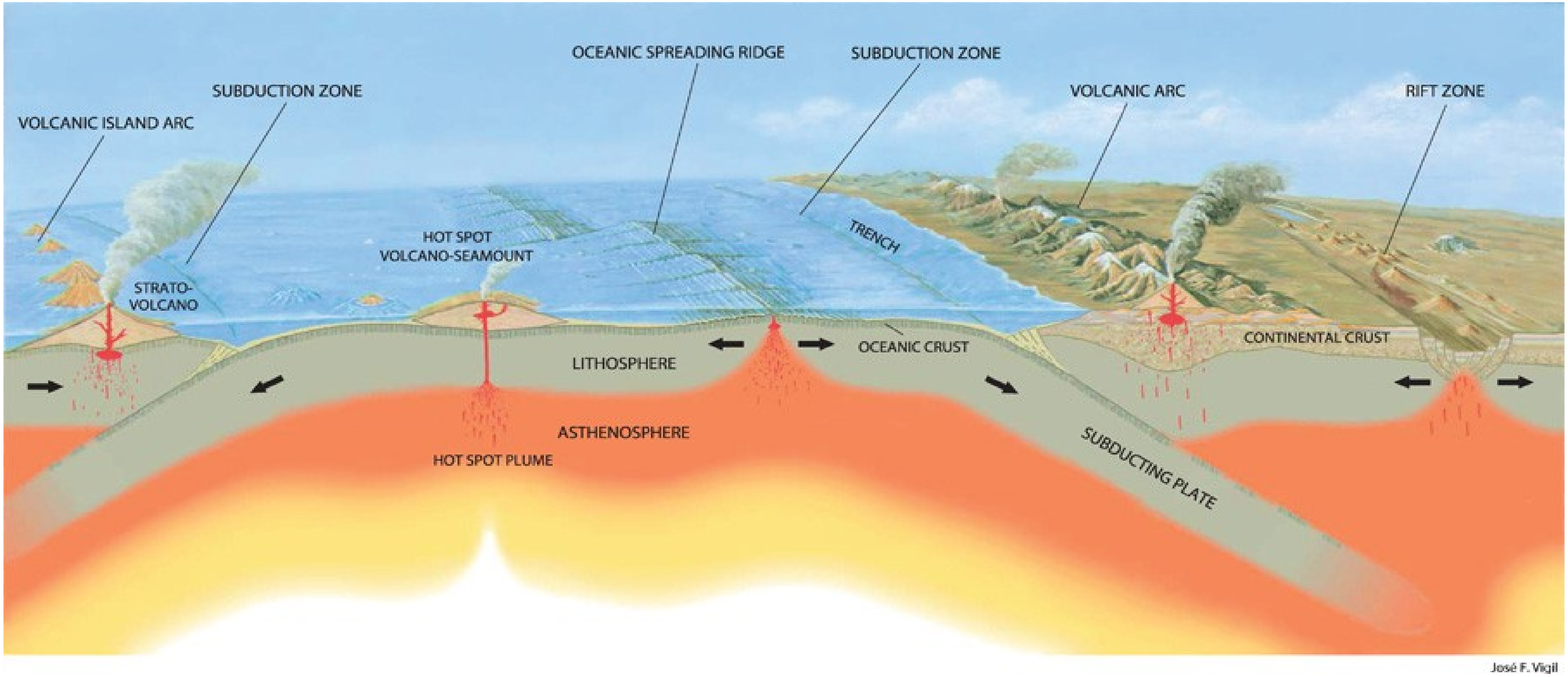
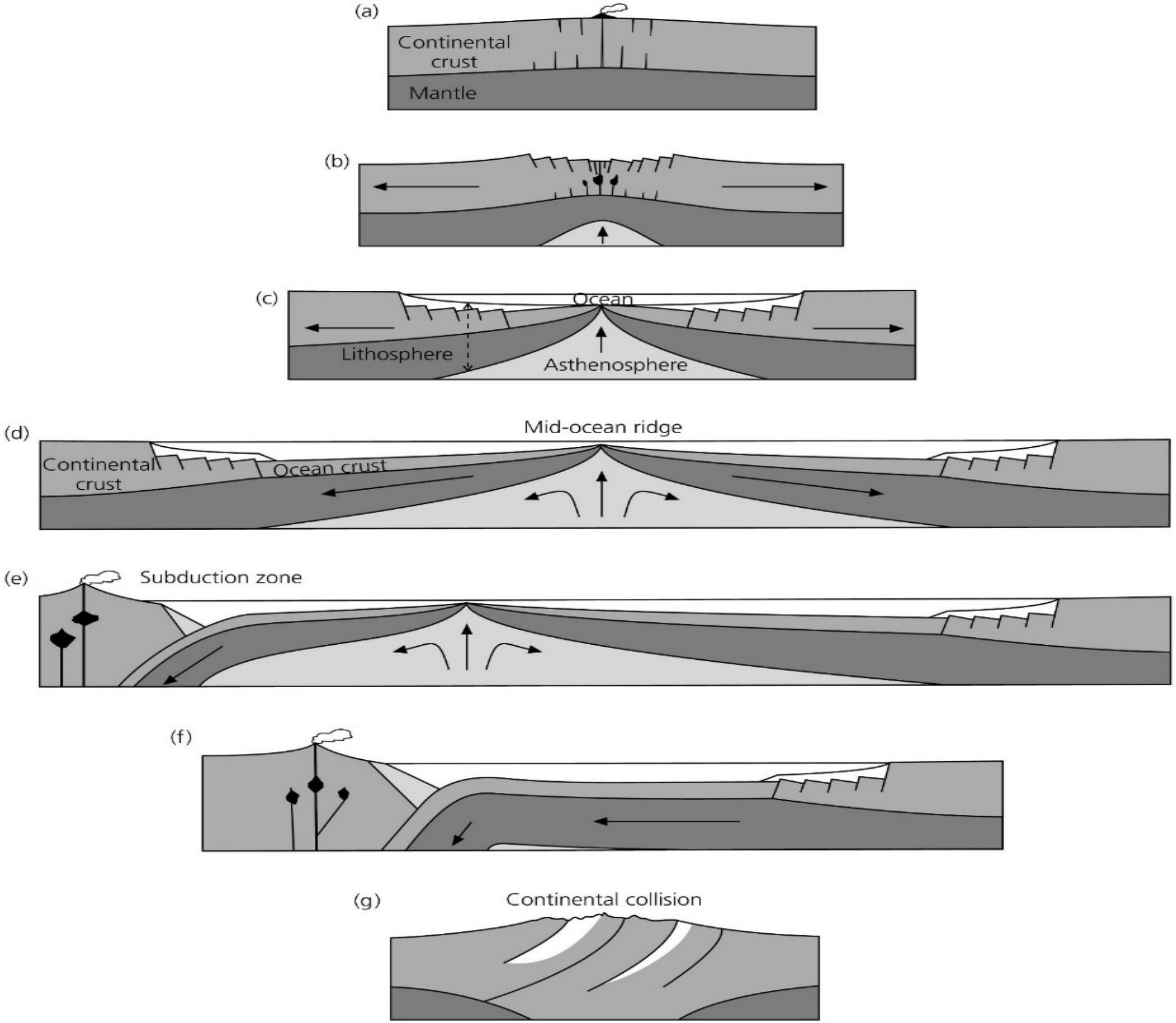
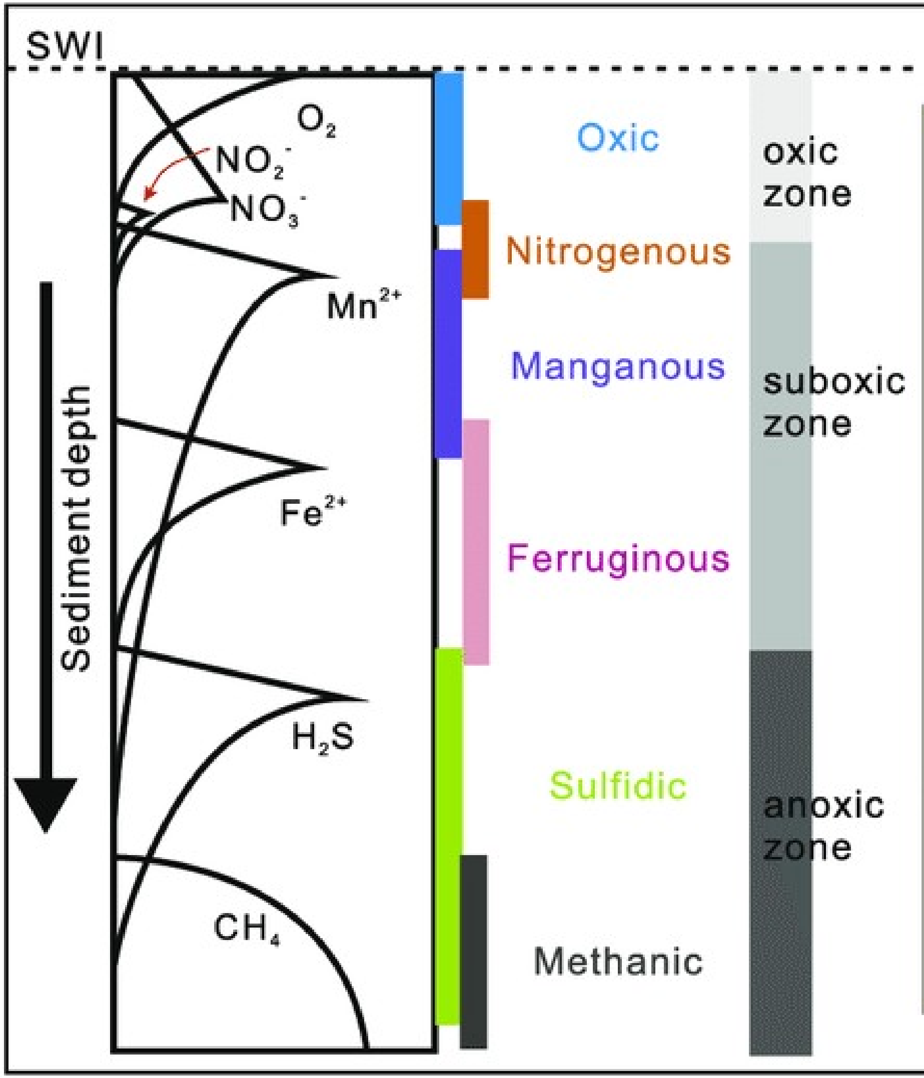


Figure 5.6-1: Schematic diagram of the Wilson cycle.





Respiration reactions in marine sediment pore-waters at 25°C and pH = 7:

Oxic respiration:

$$2O_2 + C_2H_3O_2^- \rightarrow 2HCO_3^- + H^+$$

Denitrification:

$$8NO_3^- + 3H^+ + 5C_2H_3O_2^- \rightarrow 4N_2 + 10HCO_3^- + 4H_2O$$

Mn reduction:

$$7H^+ + 4MnO_2 + C_2H_3O_2^- \rightarrow 4Mn^{2+} + 2HCO_3^- + 4H_2O$$

Fe reduction:

$$15H^+ + 8FeOOH + C_2H_3O_2^- \rightarrow 8Fe^{2+} + 2HCO_3^- + 12H_2O$$

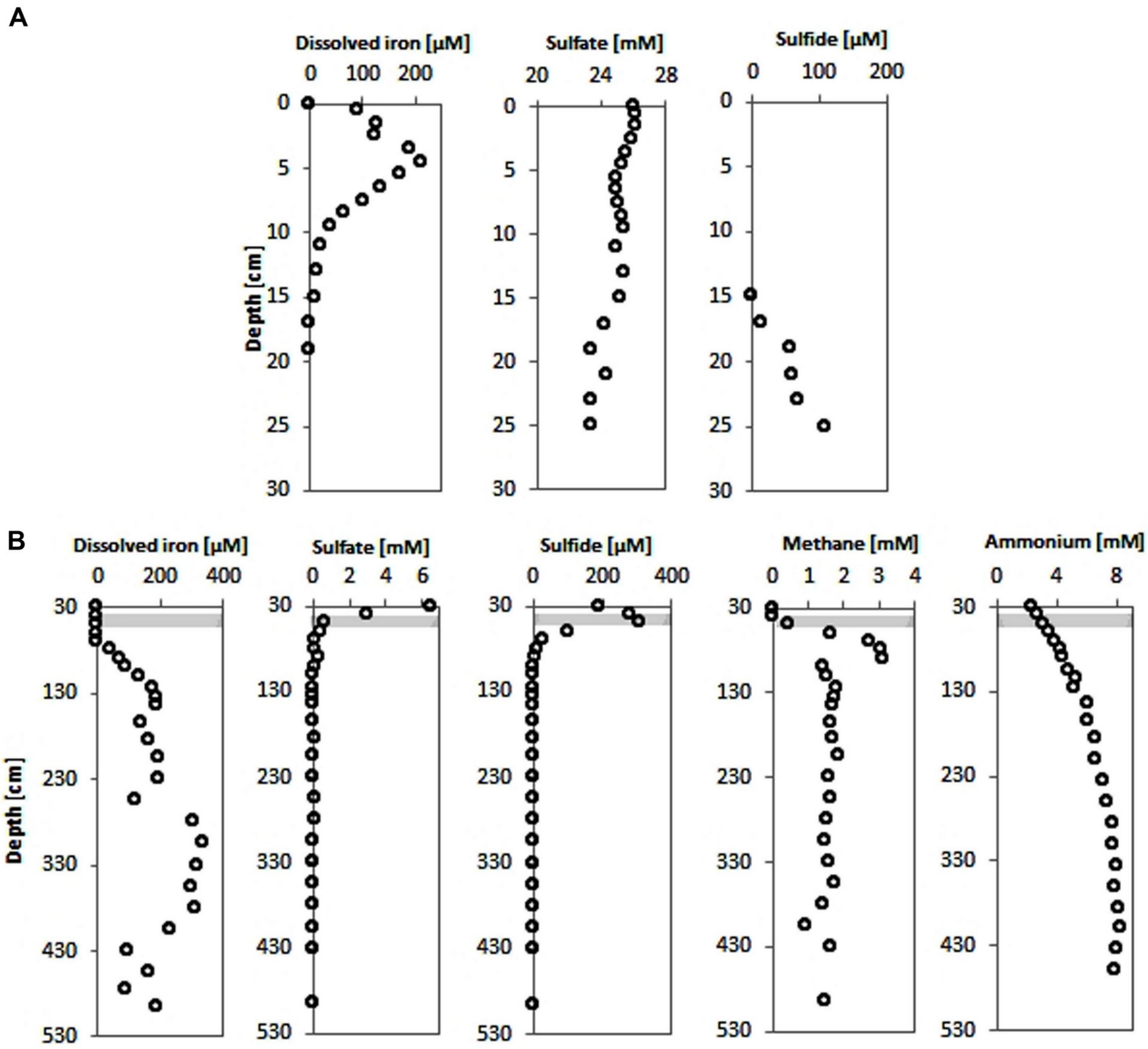
Sulfate reduction:

$$H^+ + SO_4^{2-} + C_2H_3O_2^- \rightarrow H_2S + 2HCO_3^-$$

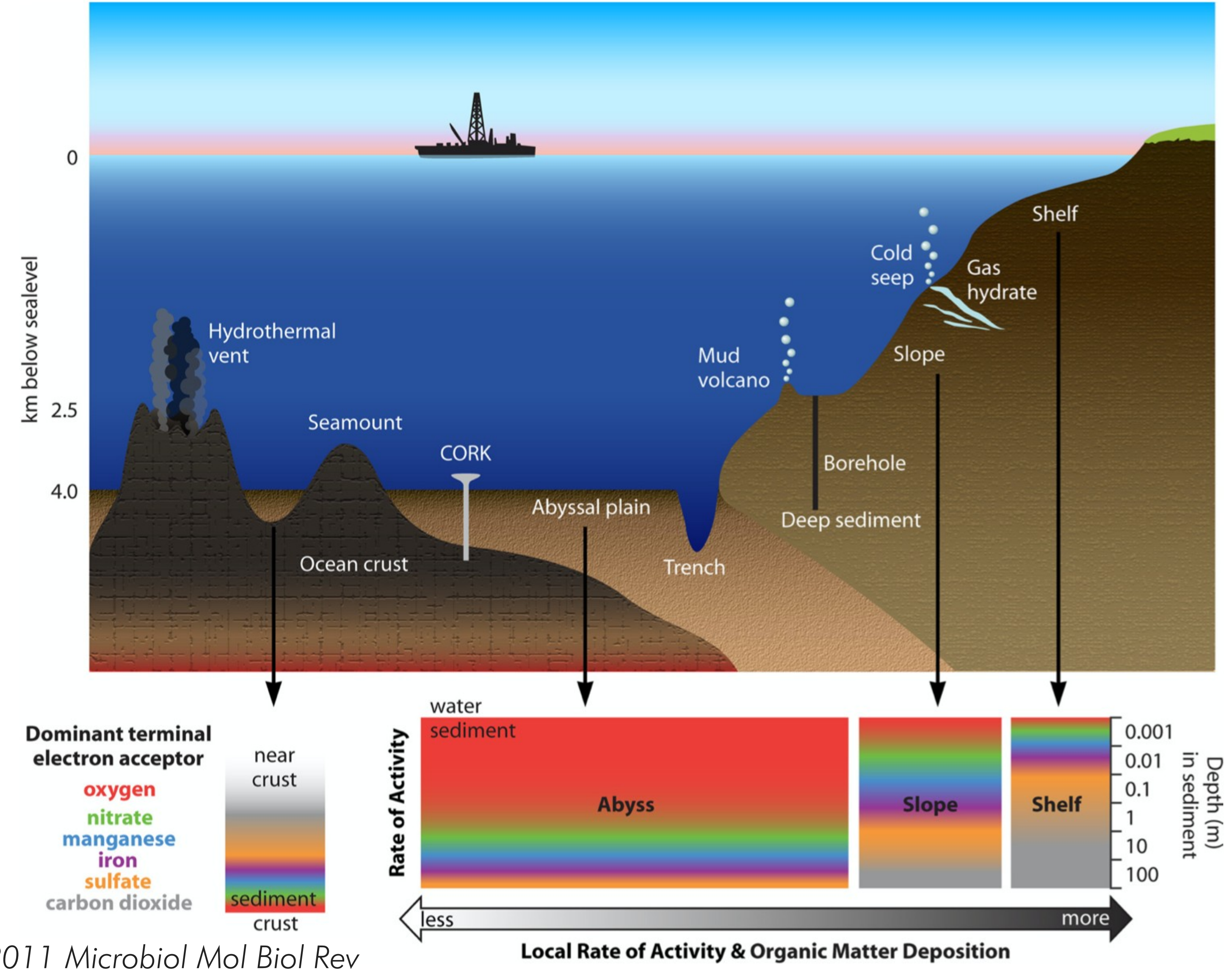
Methanogenesis:

$$H_2O + C_2H_3O_2^- \rightarrow CH_4 + HCO_3^-$$

Algeo et al. 2015 PNAS

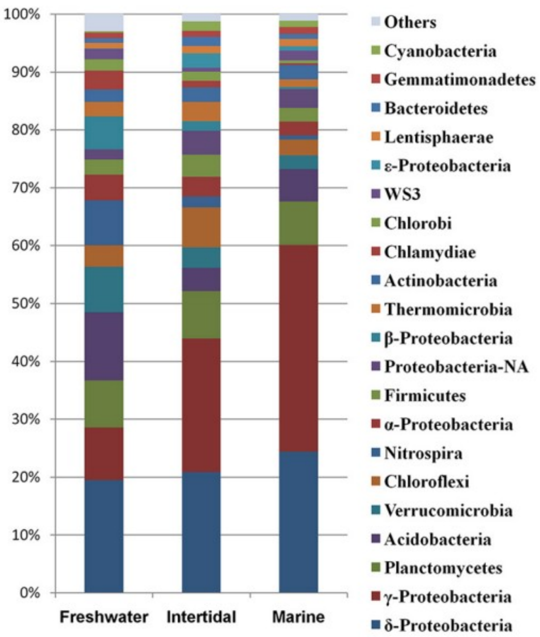


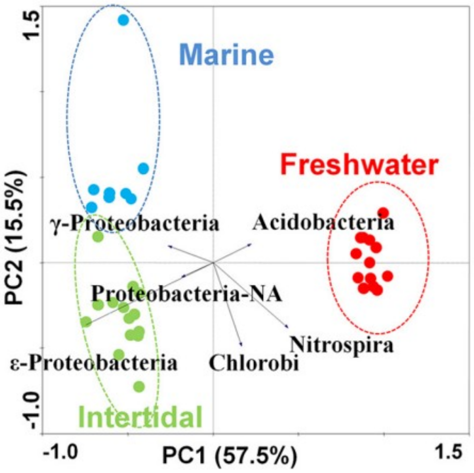
A
Dissolved iron [µM]
0 100 200
Sulfate [mM]
20 24 28
Sulfide [µM]
0 100 200
Depth [cm]
0 5 10 15 20 25 30
B
Dissolved iron [µM]
0 200 400
Sulfate [mM]
0 2 4 6
Sulfide [µM]
0 200 400
Methane [mM]
0 1 2 3 4
Ammonium [mM]
0 4 8
Depth [cm]
30 130 230 330 430 530

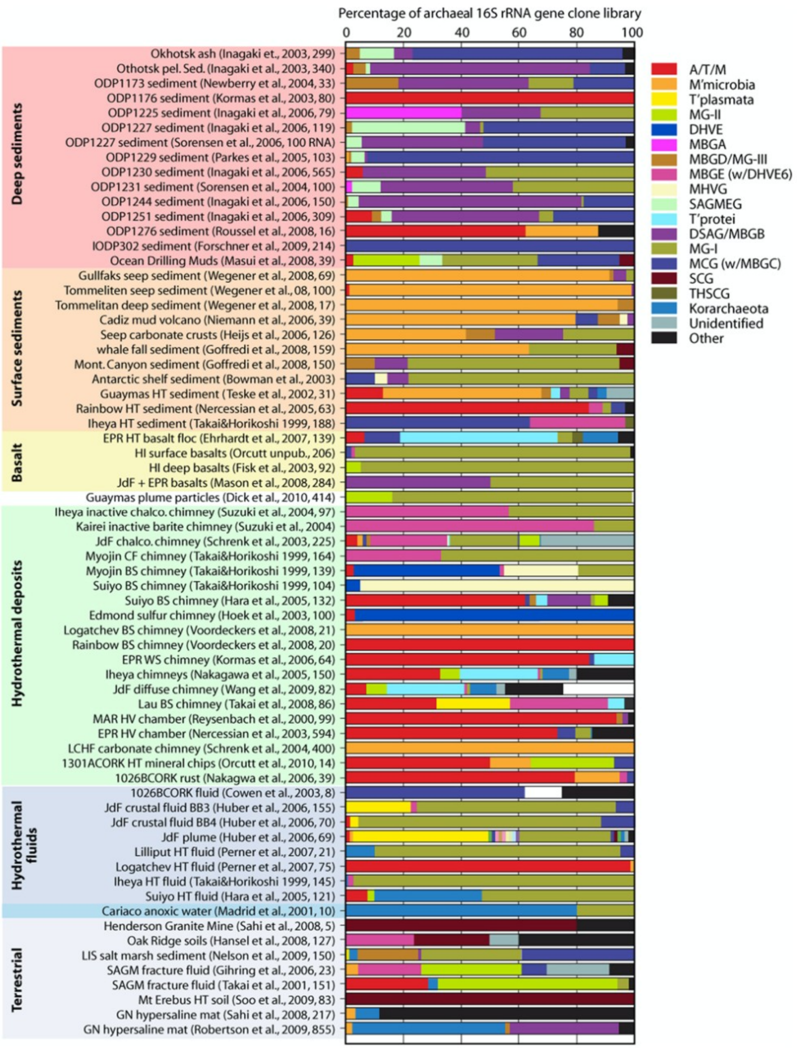


Orcutt et al 2011 Microbiol Mol Biol Rev

Marine Sediments Diversity

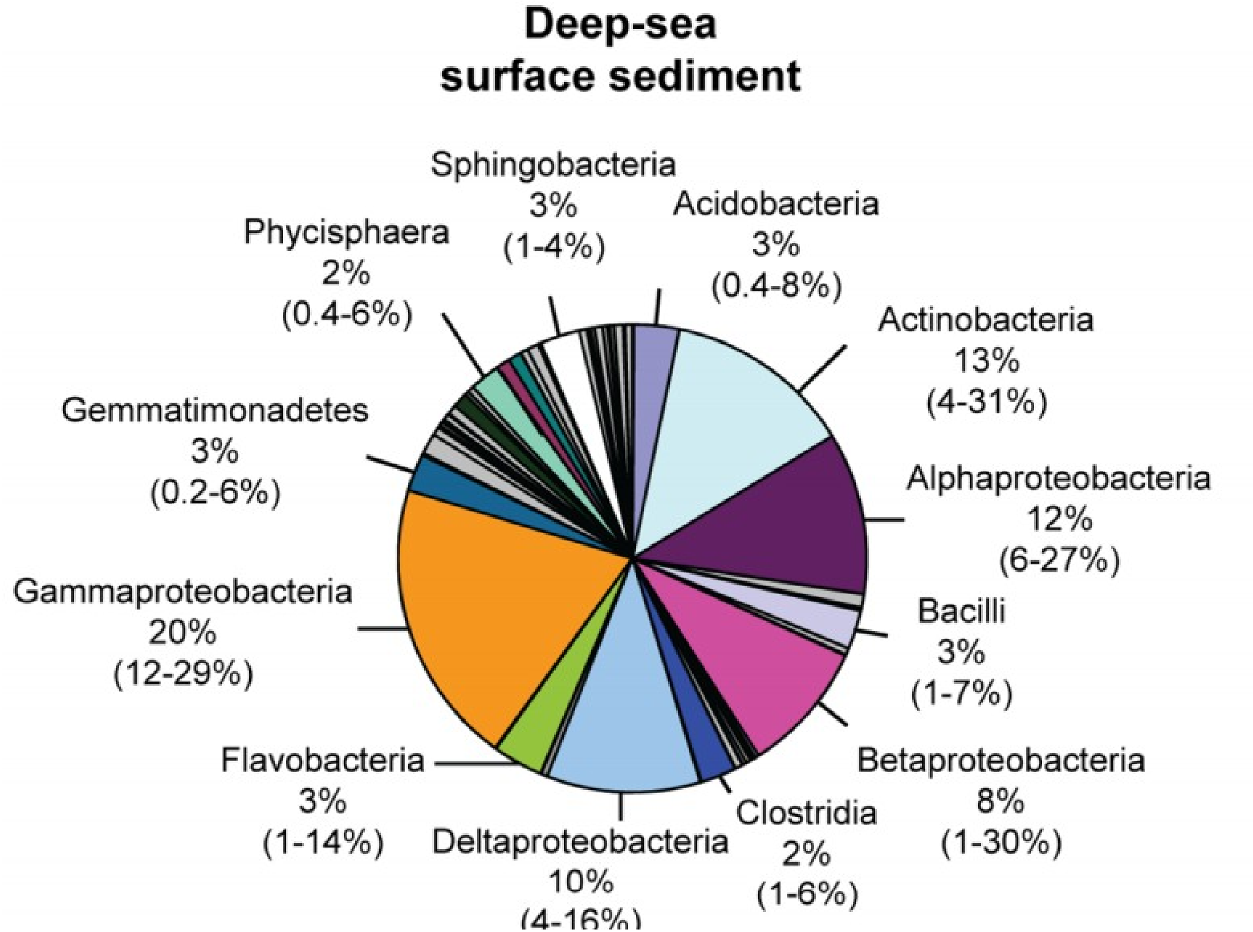




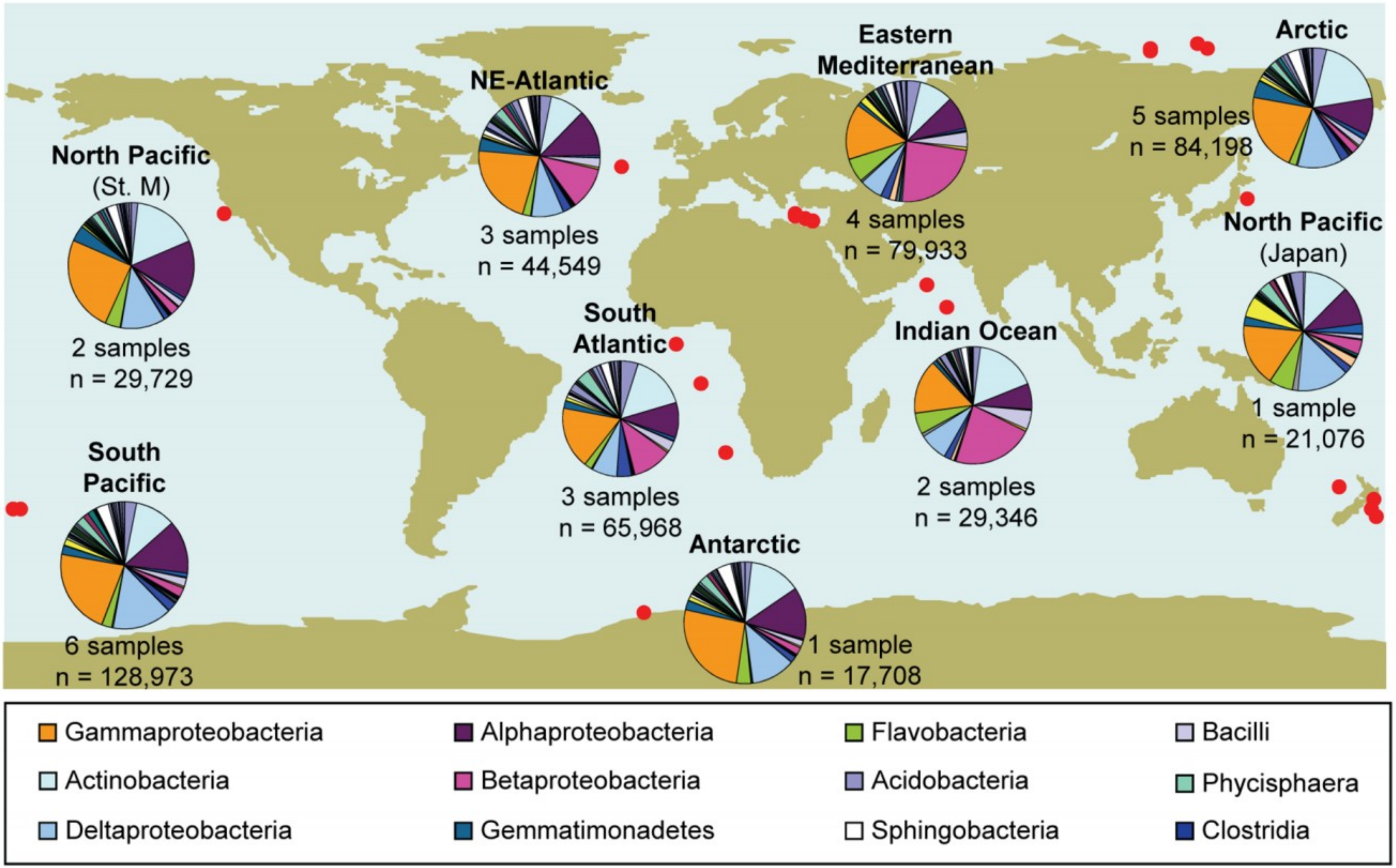


Wang et al. 2012 Appl Env Microbiol

Orcutt et al. 2011 Microbiol Mol Biol Rev



Bienhold et al. 2016 Plos ONE



Bacterial community composition in deep-sea sediments at water depths >1000 m

Bienhold et al. 2016 Plos ONE

Case study: the Mediterranean Sea

The Mediterranean Sea

Average depth of 1,500 m

Deepest recorded point is 5,267 m

Covers an approximate area of 2.5 million km^2

Divided in three sector, Western, Central and Eastern Med

The Strait of Gibraltar (connection with Atlantic) is only 14 km wide

Evaporation greatly exceeds precipitation and river runoff

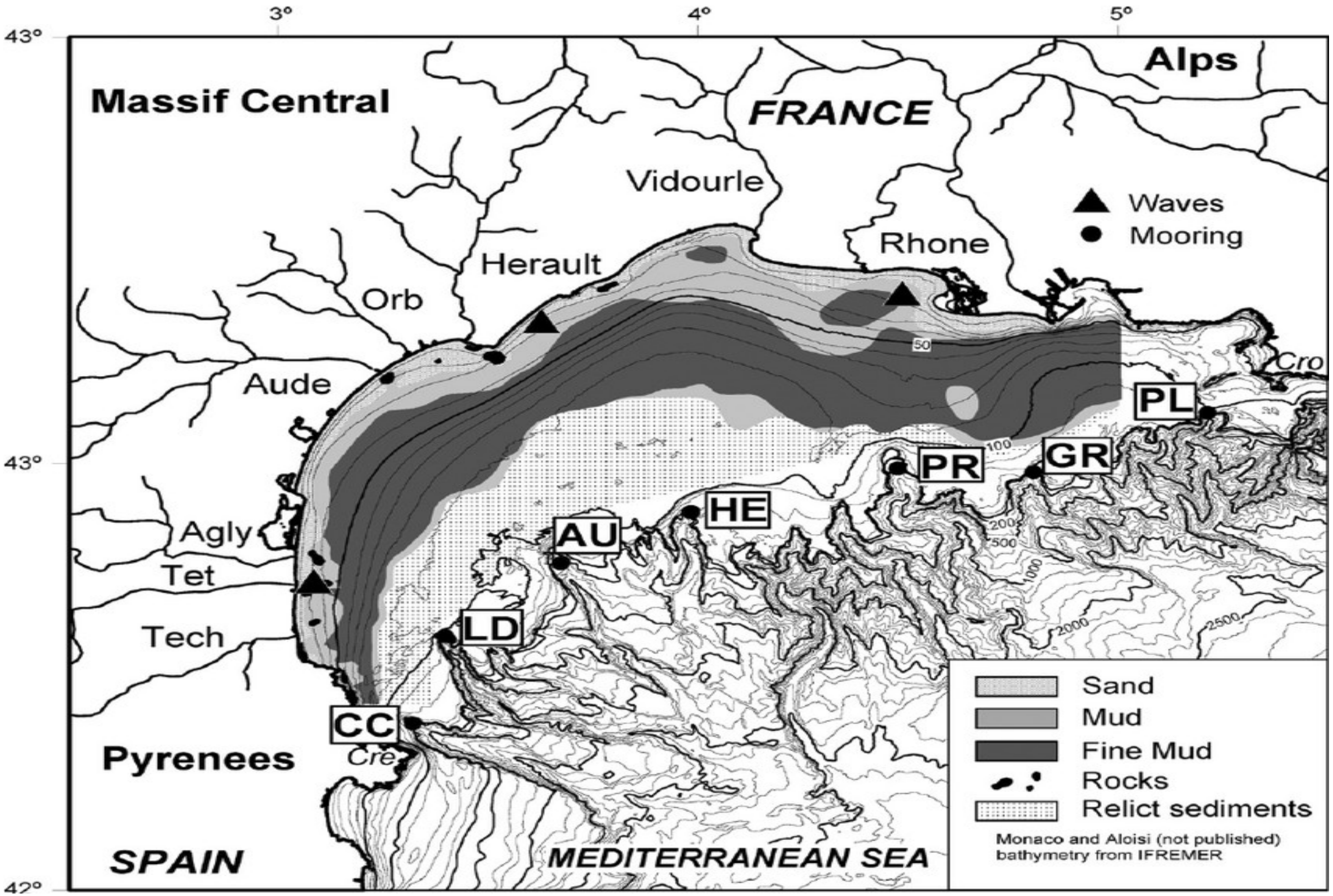
Evaporation is especially high in its eastern half, causing the water level to decrease and salinity to increase eastward

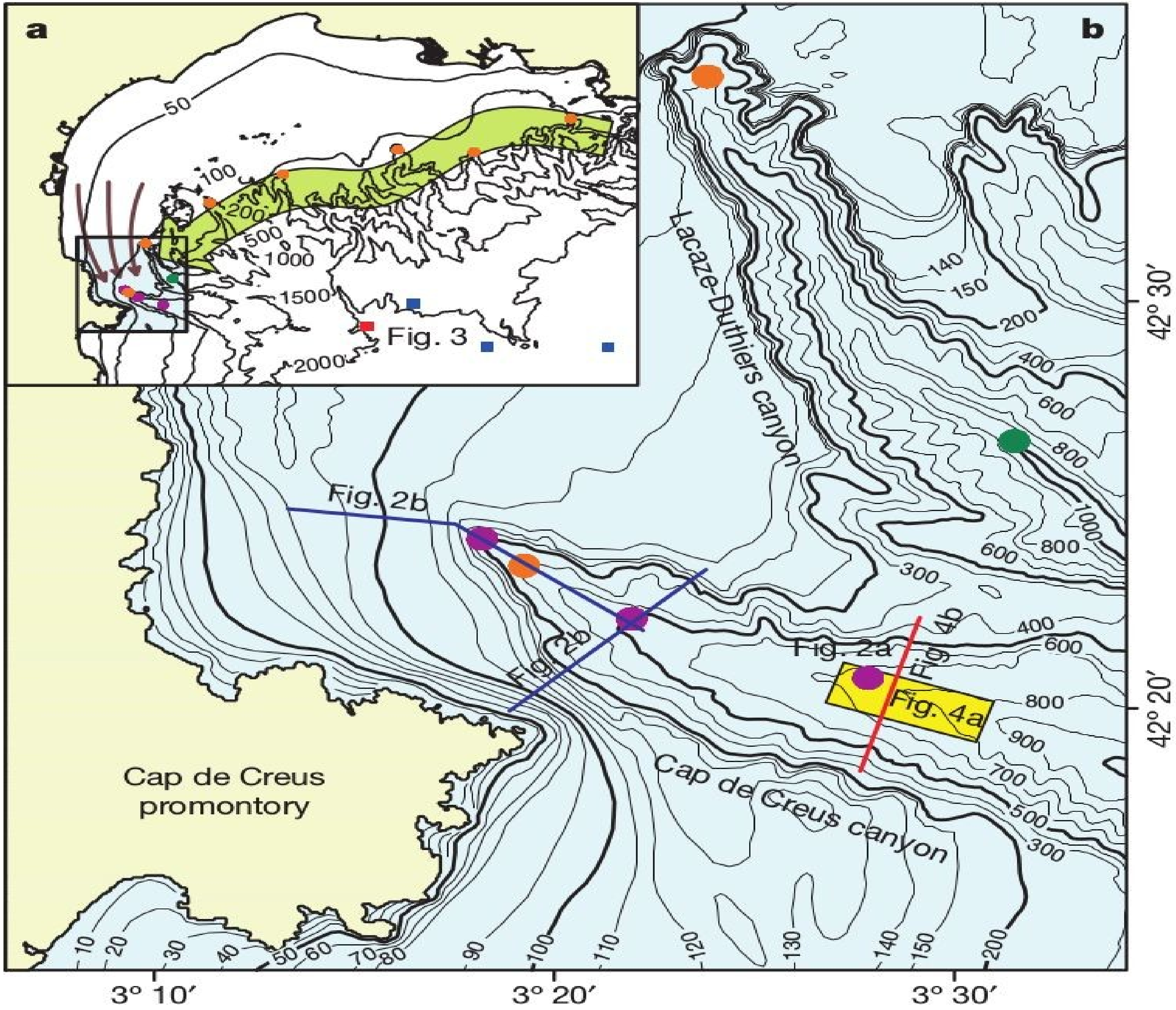
The salinity at 5 m depth is 3.8%

Deep-sea temperature are constant at 13.8°C

Heavily populated since ancient times

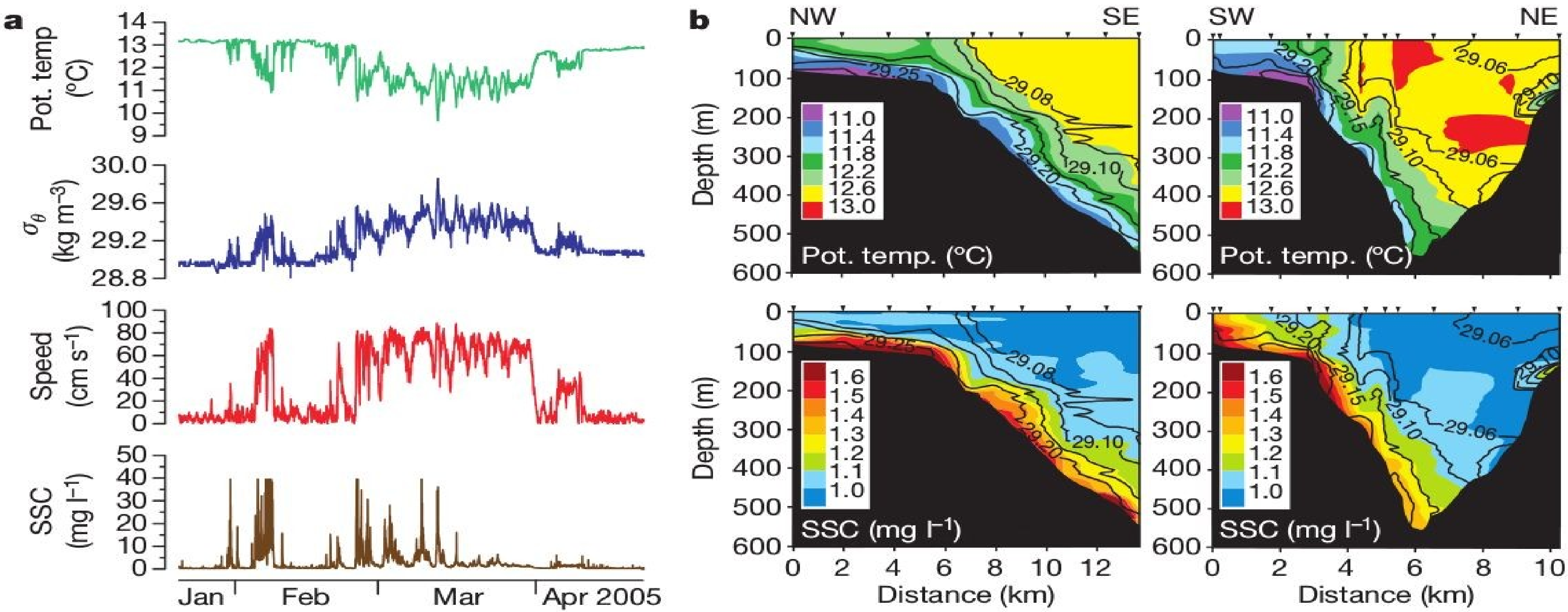
Mediterranean Canyons and lateral inputs of OM





a
b
50
100
200
500
1000
1500
2000
Fig. 3
Lacaze-Duthiers canyon
140
150
200
400
600
800
1000
600
800
300
400
600
Fig. 2b
Fig. 2b
Fig. 2a
Fig. 4b
Fig. 4a
800
900
700
500
300
Cap de Creus canyon
Cap de Creus promontory
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
200
42° 30′
42° 20′
3° 10′
3° 20′
3° 30′

Dense Waters Cascading Events



SUBSURFACE ENVIRONMENTS

Subsurface Environments

The **subsurface biosphere** is loosely defined as the habitable region beneath the top layer of soils and sediments where the limits of habitability are typically defined by some physical process (like temperature, pore space, water activity, et...)

Current estimates of the habitable volume of the subsurface range from ~2.0 to 2.3 10^9 km^3 , or roughly twice the volume of our oceans, but might be more

This large biosphere is estimated to hold ~70% of all bacterial and archaeal cells and potentially over 80% all bacterial and archaeal species

Average estimates for subsurface biosphere are 2.9 x 10^{29} cells (10^{22}-10^{24} stars in the universe by comparison)

Current investigations spans the marine and terrestrial subsurface, often involving drilling or access through existing caves and mines

The marine subsurface environments appear to be less diverse in term of habitat diversity compared to the terrestrial subsurface, and it is mainly divide in sedimentary habitats and crustal environments

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.

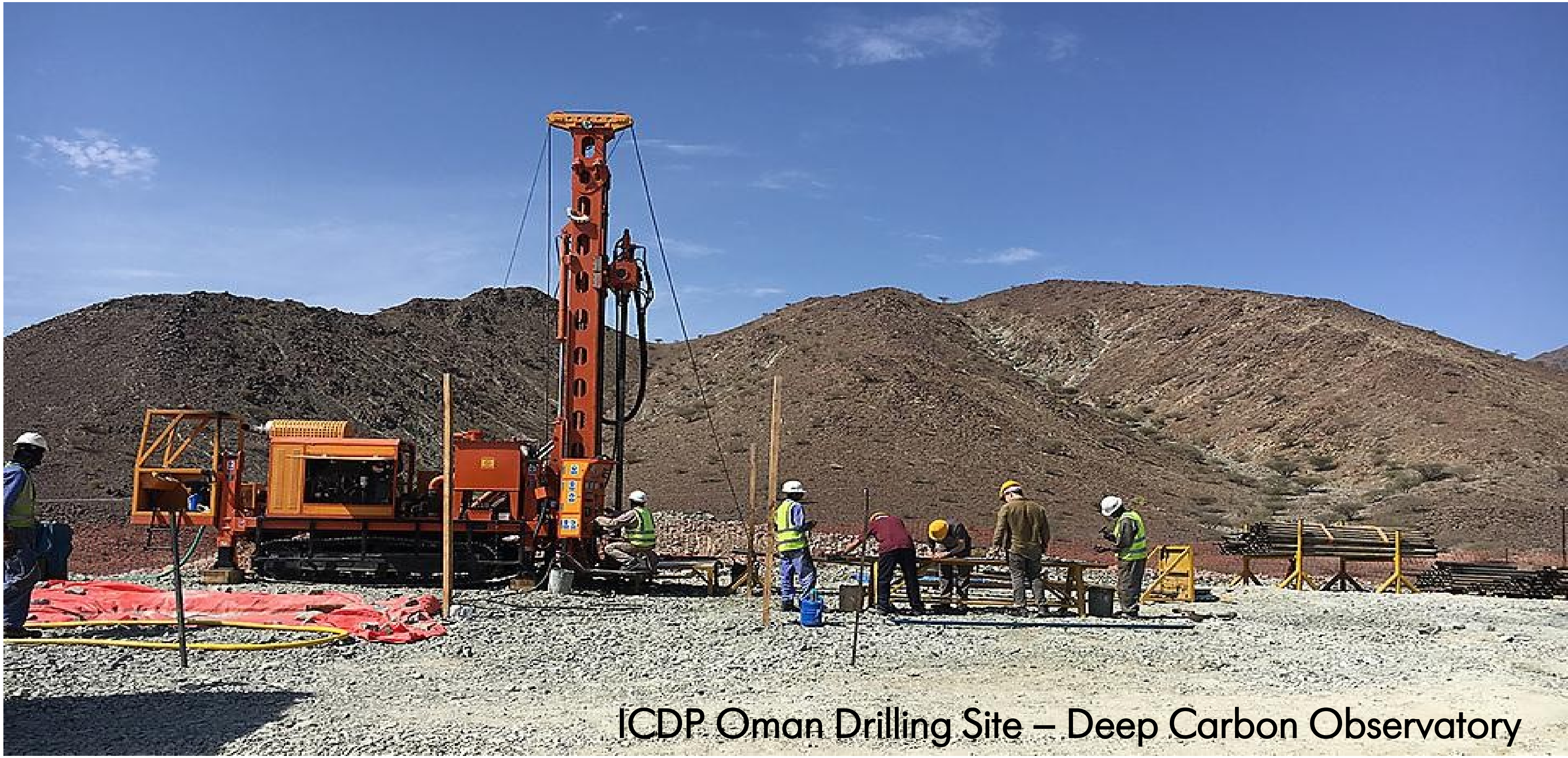
We are familiar with two domains of life on the Earth: the surface of the land and the body of the oceans. Both domains

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 CO_2 and water, with oxygen available from local sulfates and metal

Gold, 1992 PNAS

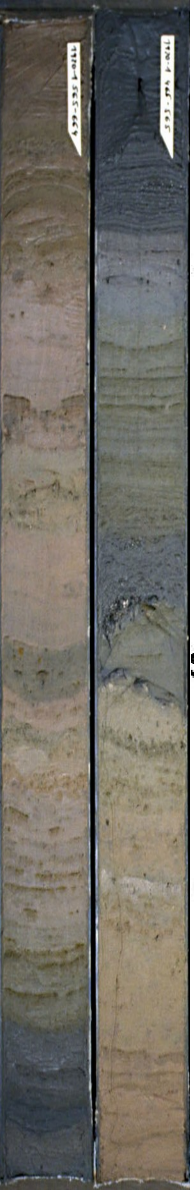

NSF International Ocean Discovery Program
Joides Resolution
NSF International Ocean Discovery Program

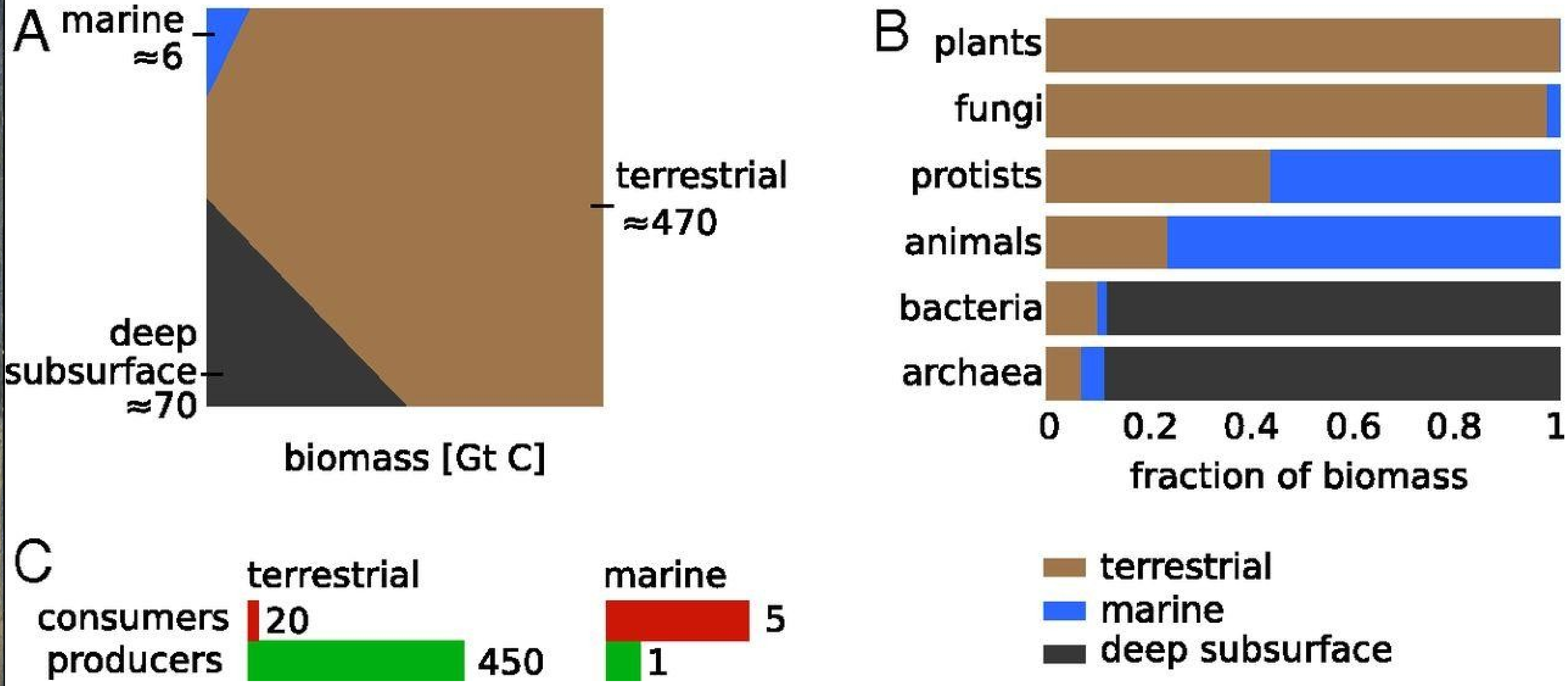


ICDP Oman Drilling Site – Deep Carbon Observatory

2.4 km Deep Canadian Mine – Deep Carbon Observatory

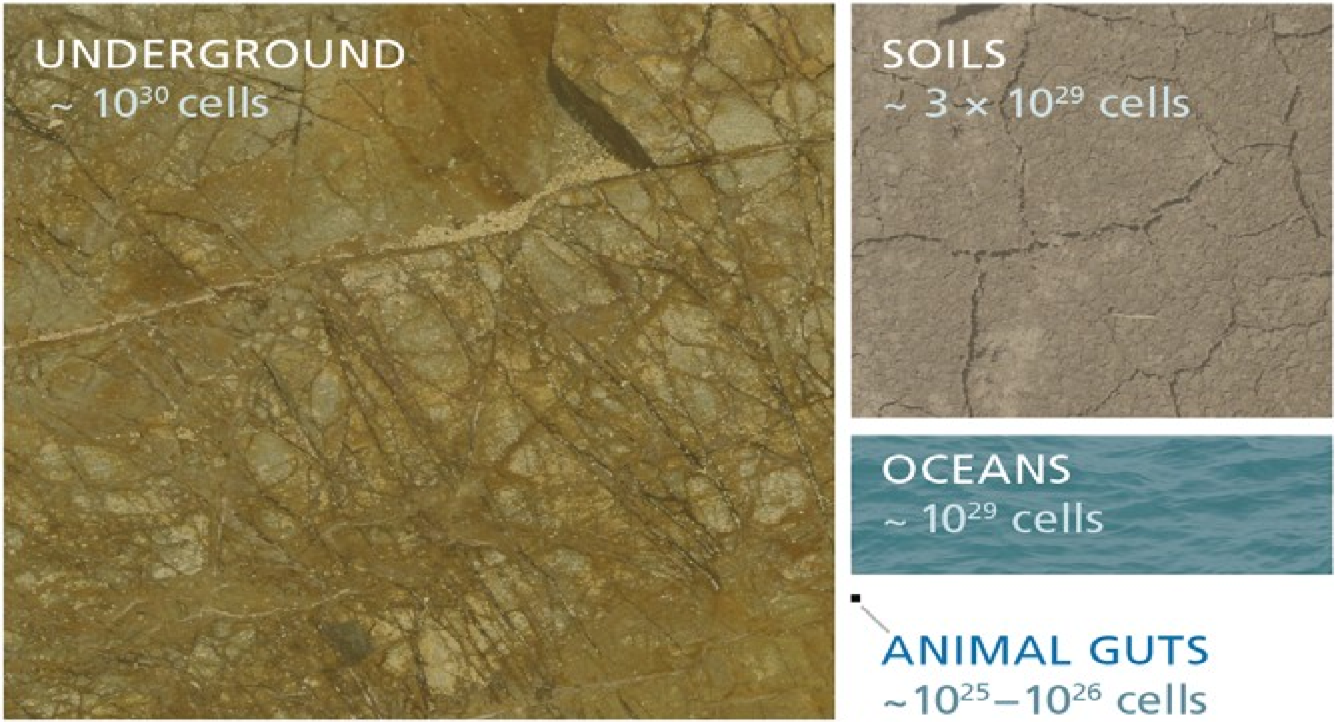
Deep Subsurface Environments



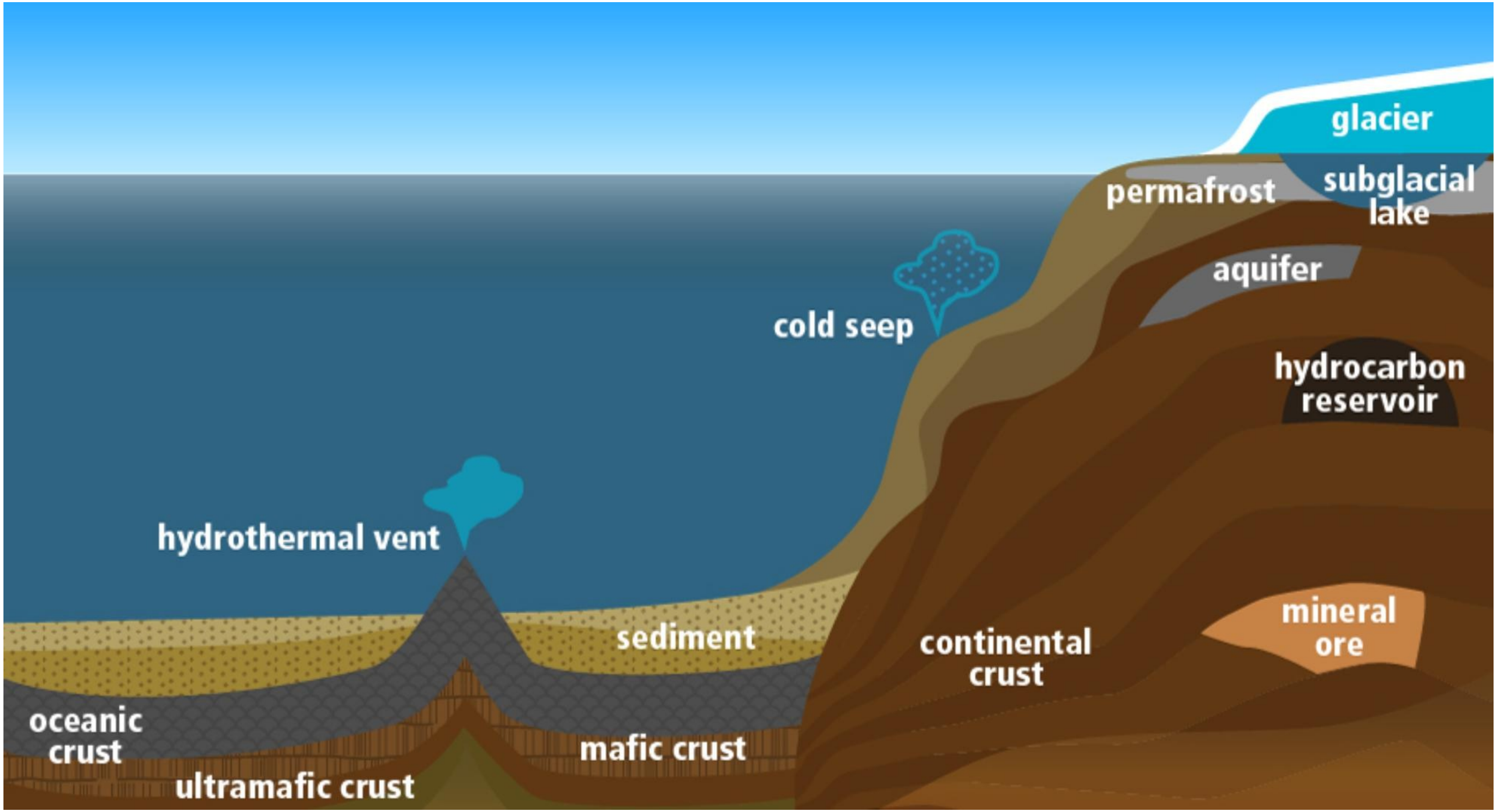


Bar-On et al 2018 PNAS

Number of Prokaryotes

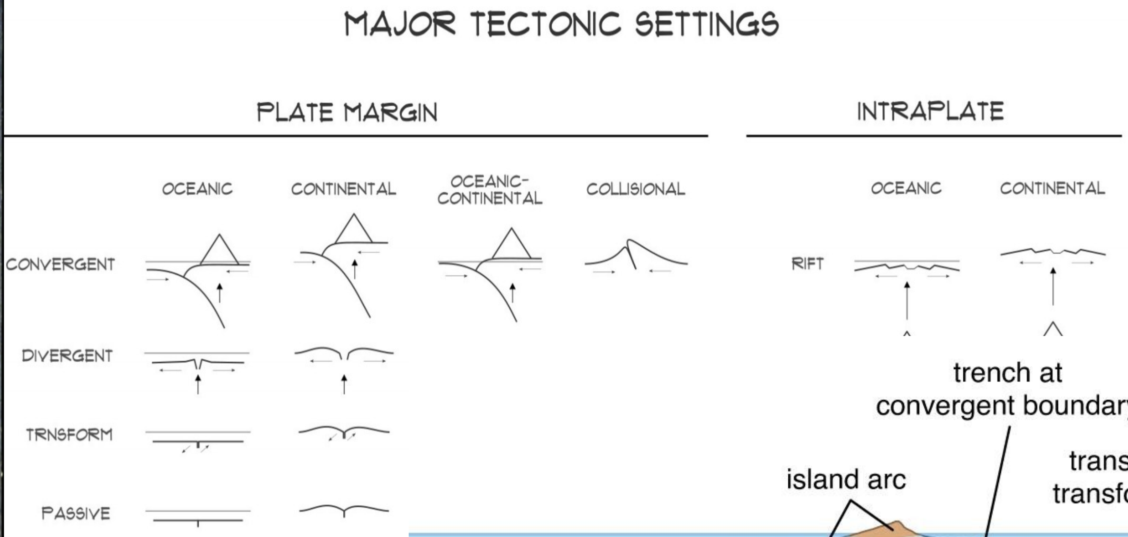


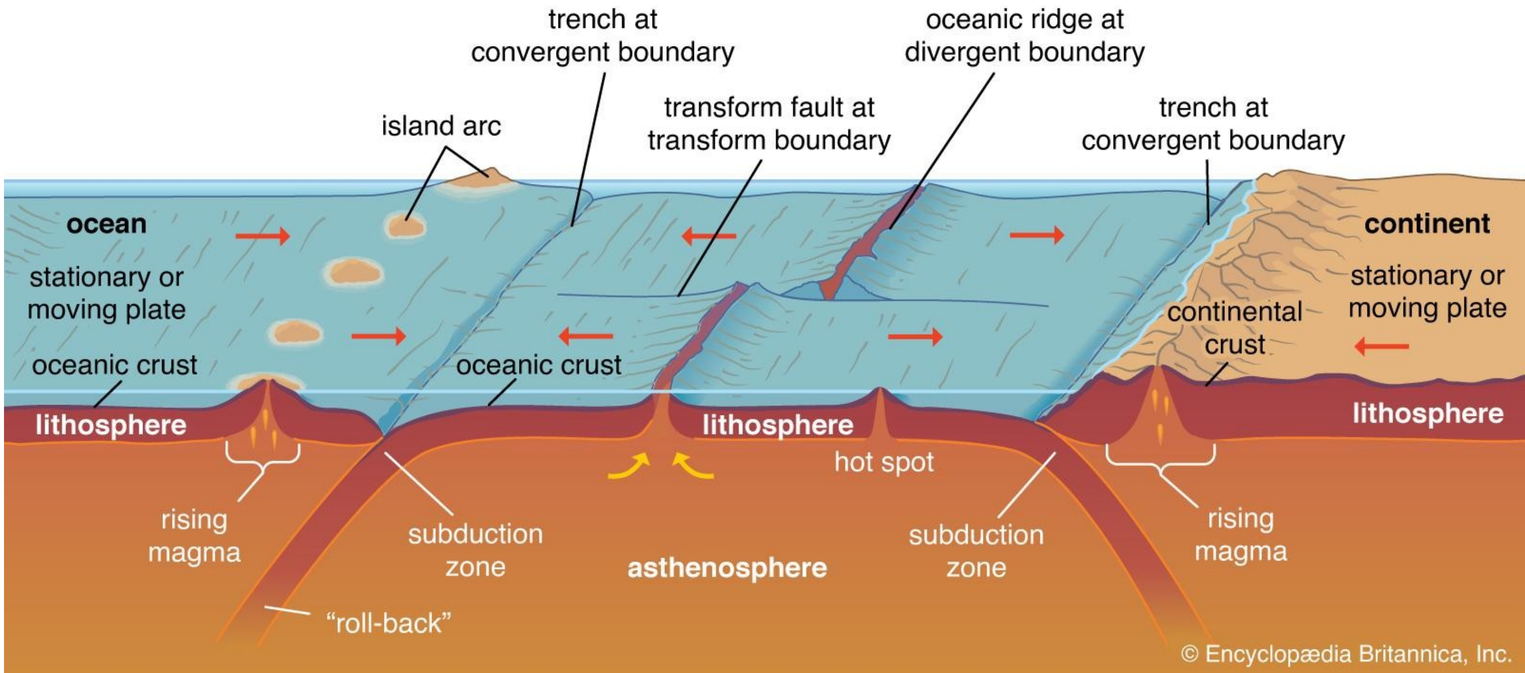
Magnabosco et al. 2019 in Deep Carbon Past to Present



Jones et al. 2018 Front in Microbiol

Deep Subsurface Environments



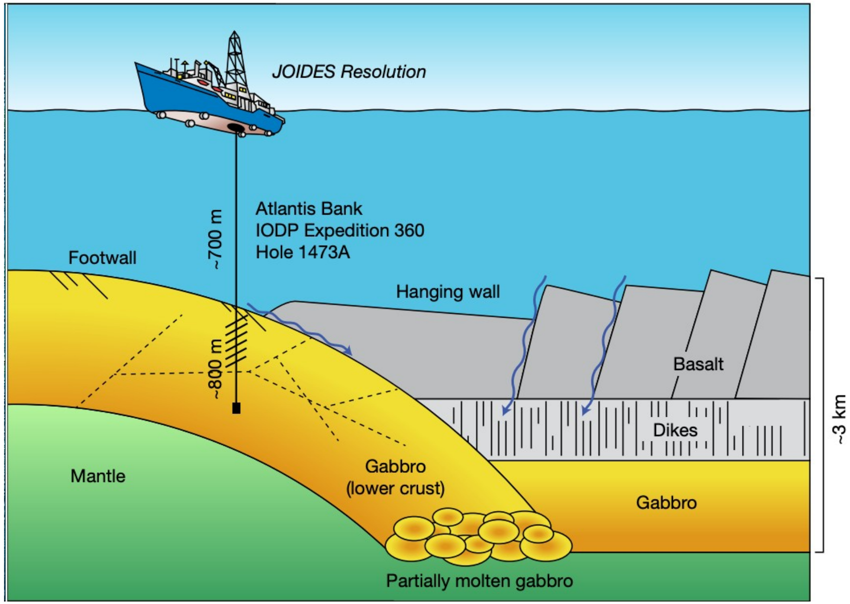


Marine Subsurface Environments: Oceanic Crust

Oceanic crust is about 6 km thick, composed of several layers and doesn't include the overlying sediment. It comprises the largest aquifer system on Earth, with an estimated fluid volume of roughly 2% of the total ocean.

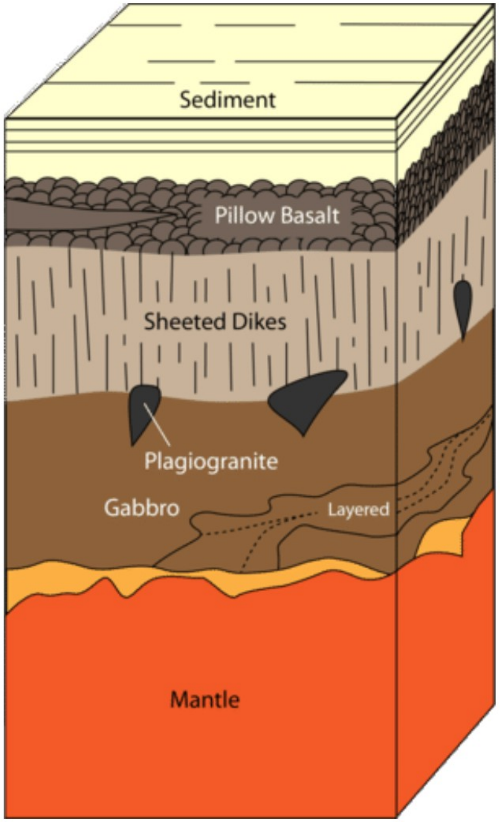
Oceanic crust differs from [continental crust] in several ways: it is thinner, denser, younger, and has a different chemical composition.

Nearly 70% of the ocean seafloor is exposed or shallowly buried (100 m of sediment) oceanic crust.



INTERNATIONAL OCEAN DISCOVERY PROGRAM

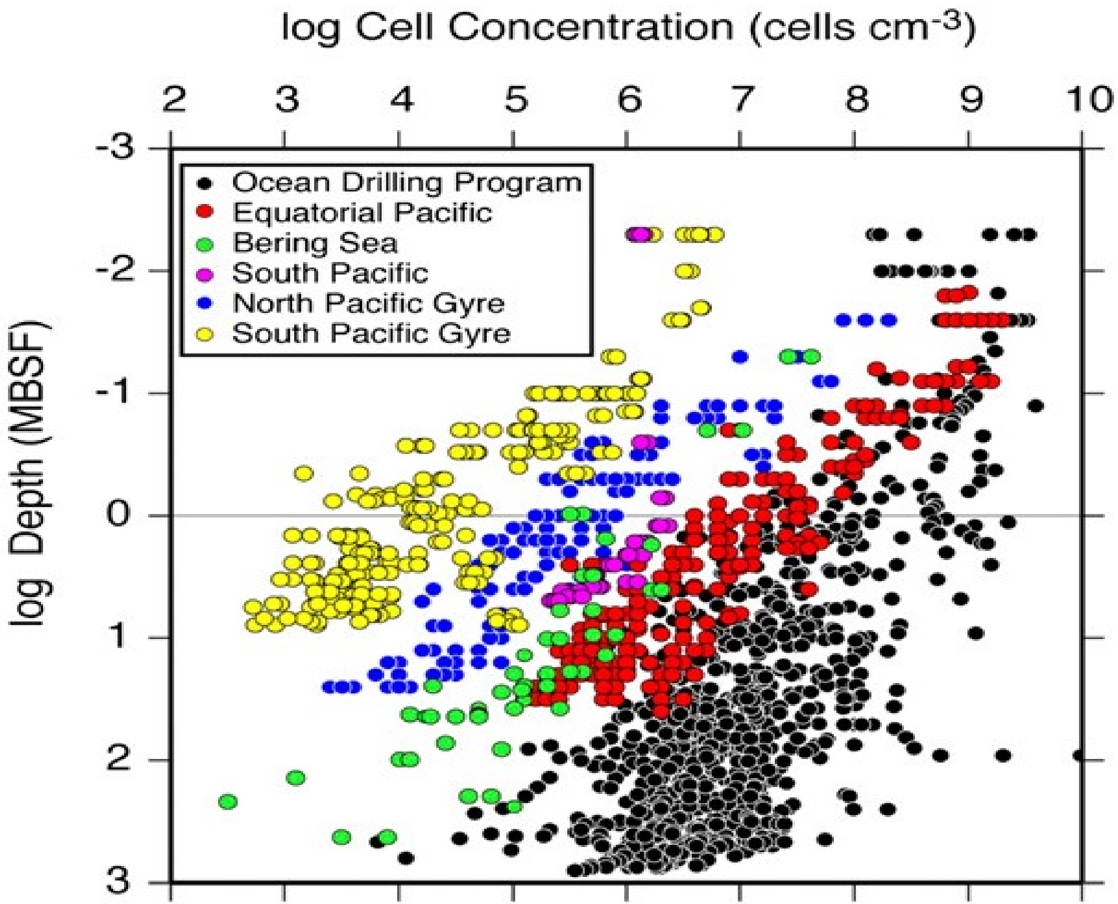
Oceanic Crust

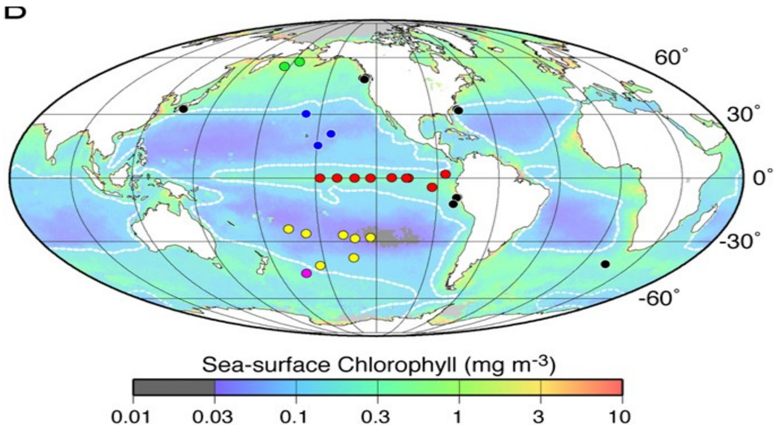


It has three layers:

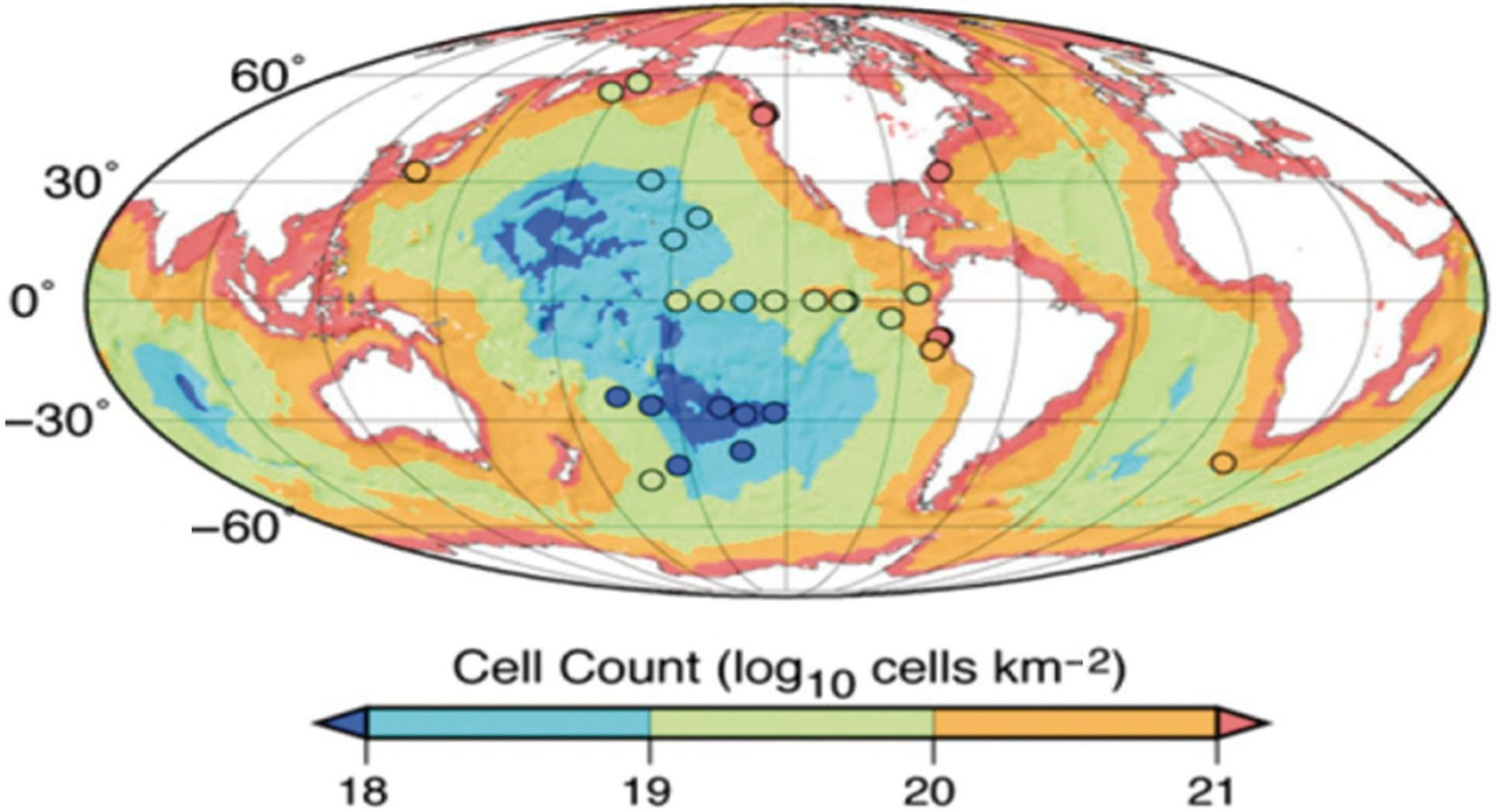
- *few hundred meters of extrusive and intrusive basalts, characterized by extensive fracturing, roughly 10% porosity*
- *a middle layer down to roughly 1.5 km below seafloor of sheeted dike complexes*
- *a deeper layer to roughly 4-km depth of igneous crystalline gabbroic rock*

The basalt porosity tends to decrease with age of the ocean crust as fractures are filled in by compression or mineral precipitation, although there are exceptions.

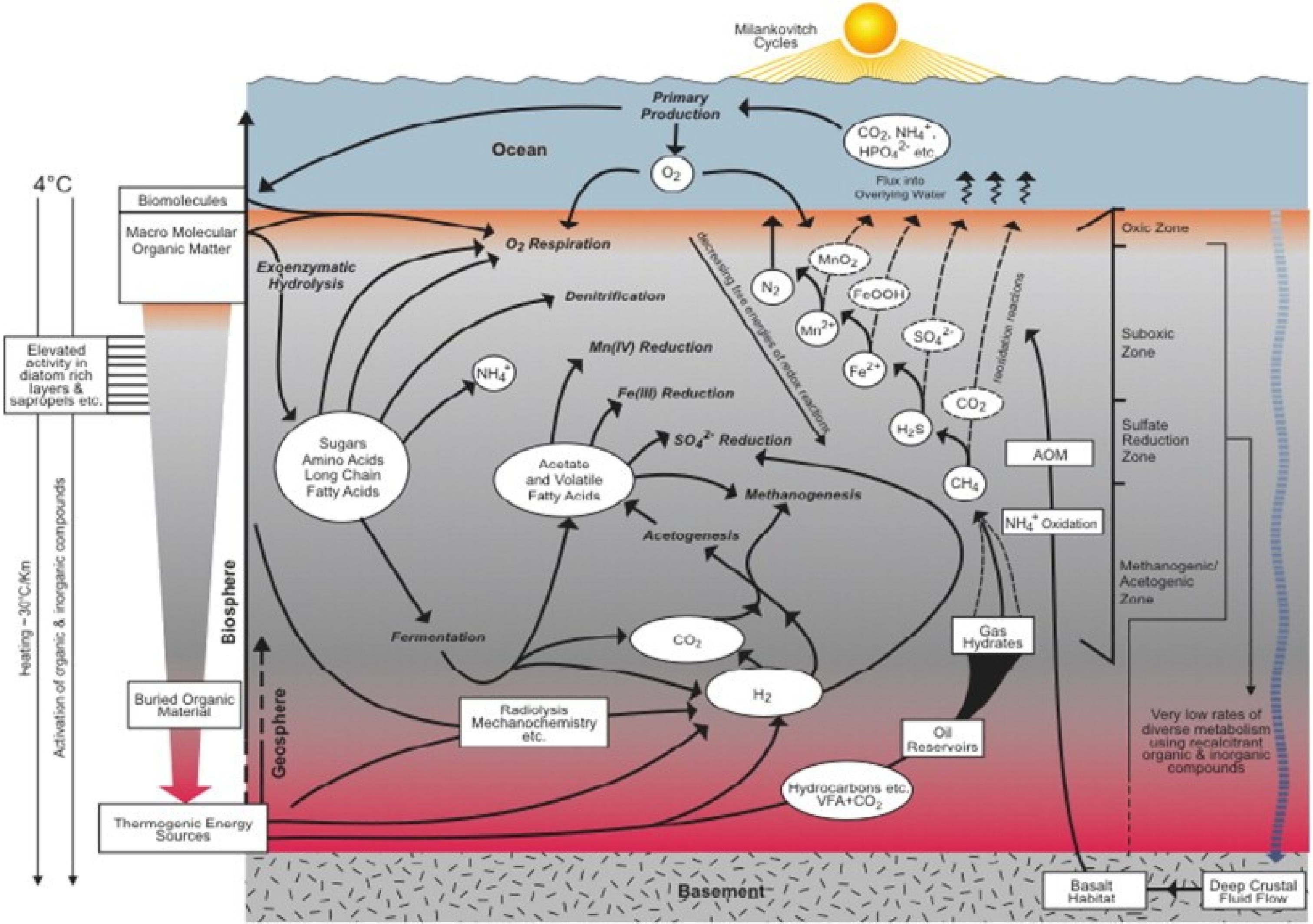




Kallmeyer et al. 2012 PNAS

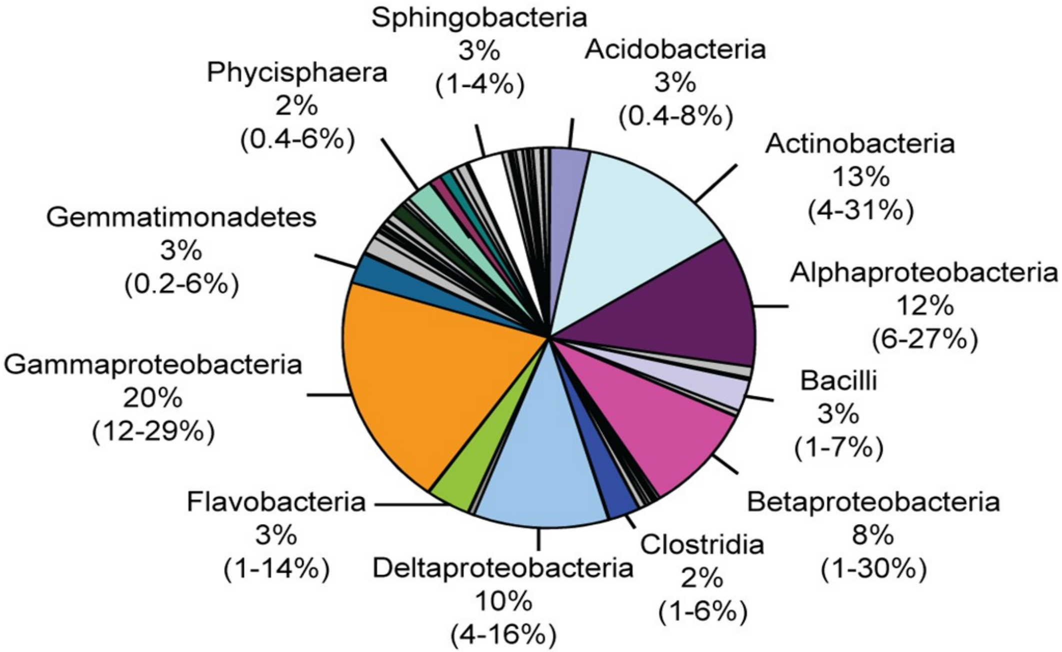


Kallmeyer et al. 2012 PNAS

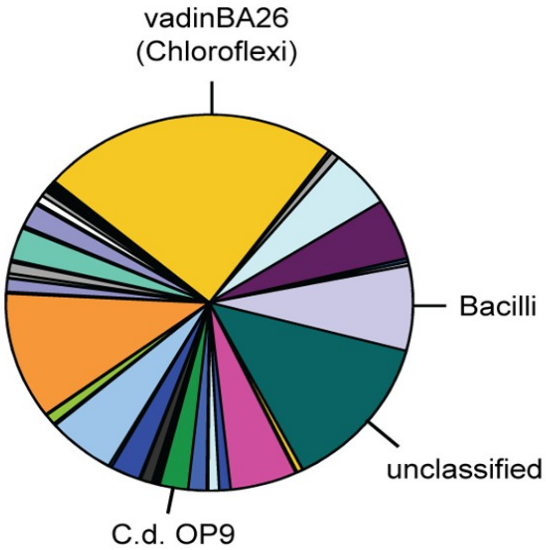


Kieft 2016 Their World: A Diversity of Microbial Environments

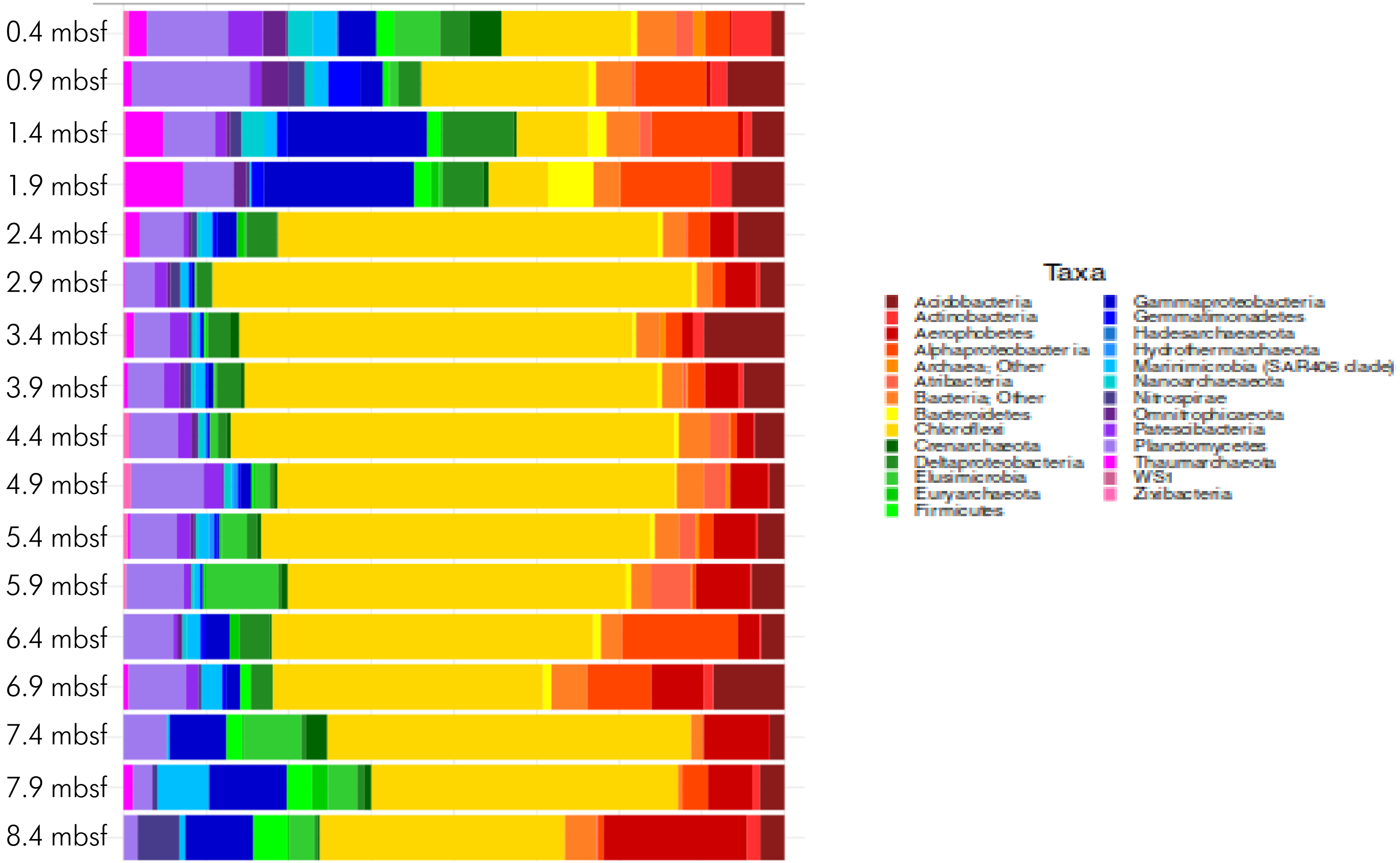
Deep-sea surface sediment



Deep subsurface sediment



Bienhold et al. 2016 PlosONE

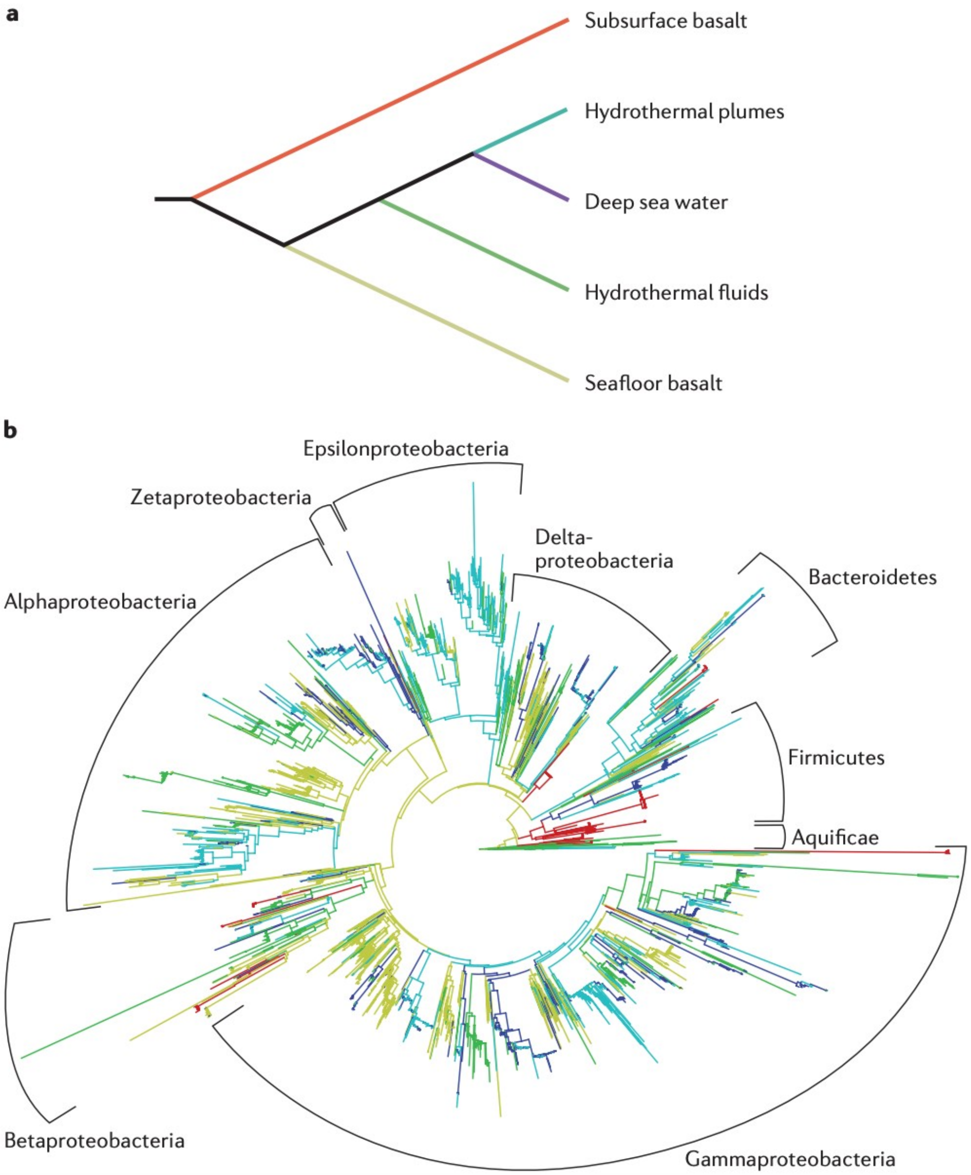


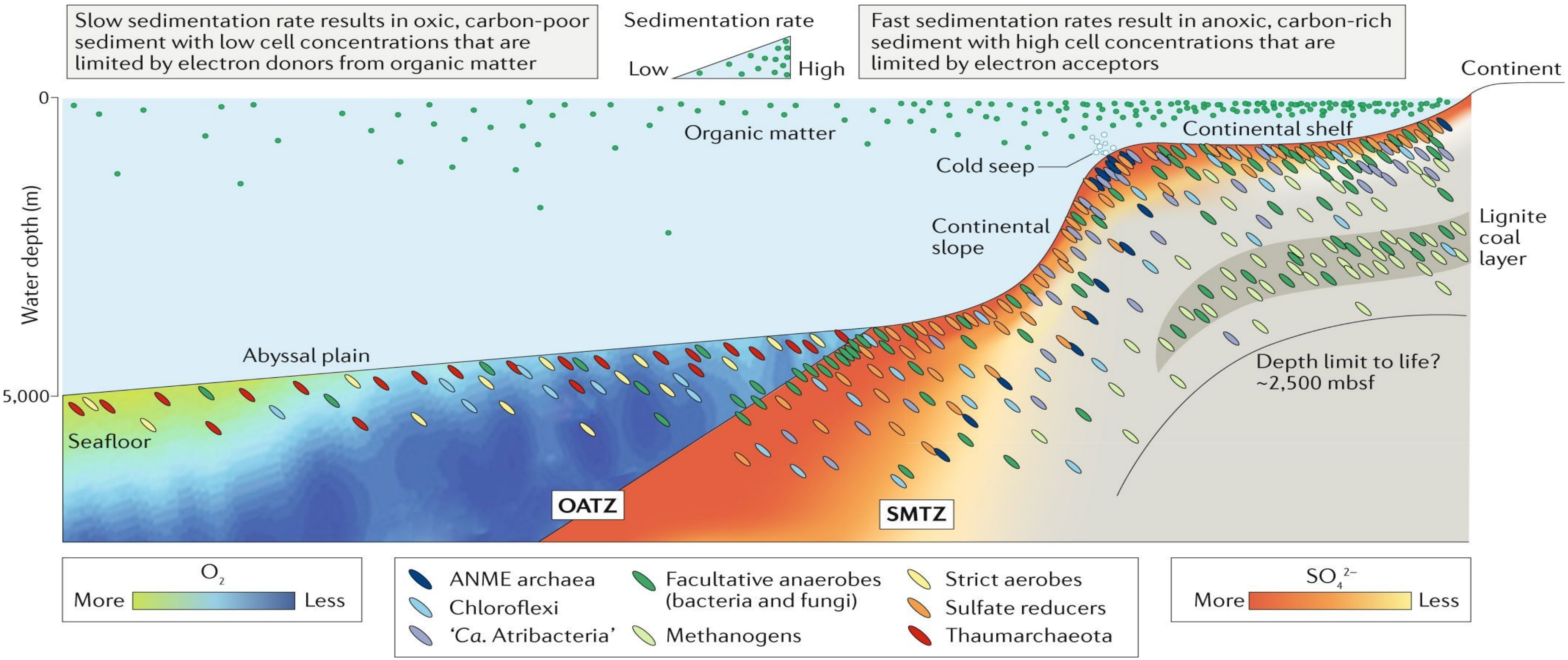
Biddle, Ash and Giovannelli, unpublished

Marine subsurface Environments

Bacterial communities on seafloor basalts are often dominated by the phyla Proteobacteria (in particular, the classes Alphaproteobacteria and Gammaproteobacteria), Actinobacteria, Bacteriodetes, Chloroflexi, Firmicutes and Planctomycetes

Edwards et al 2011Nat Rev Microbiol





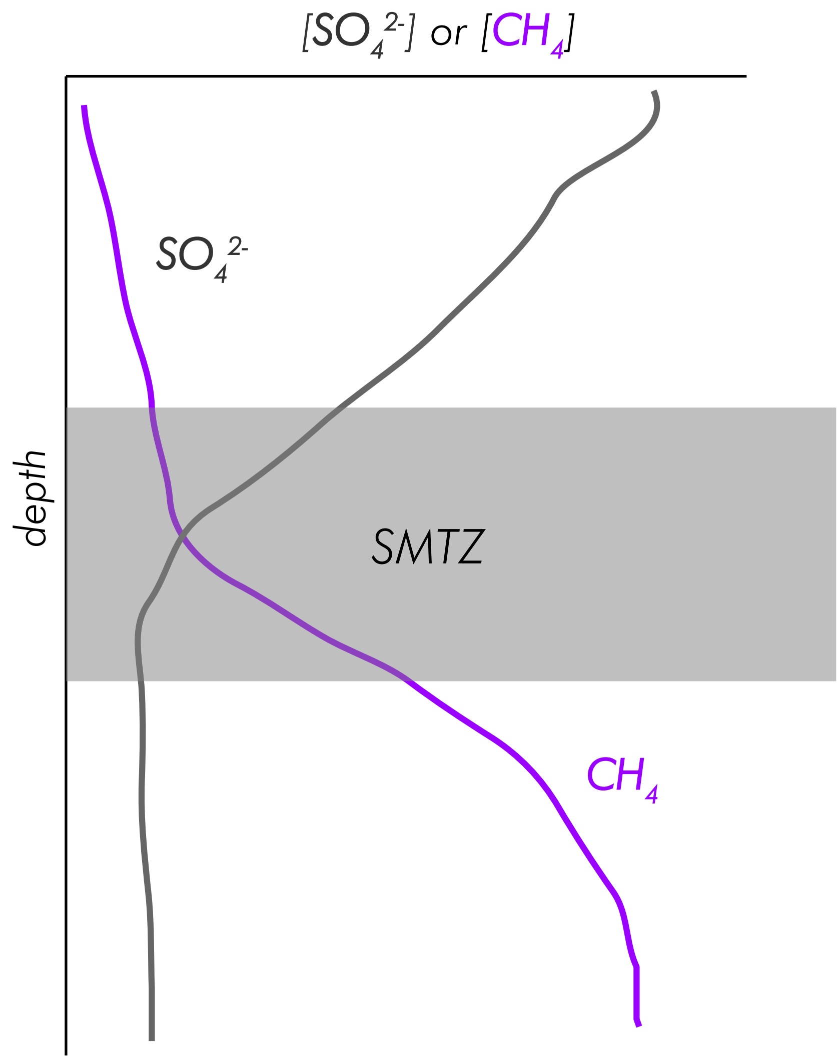
Orsi et al 2018

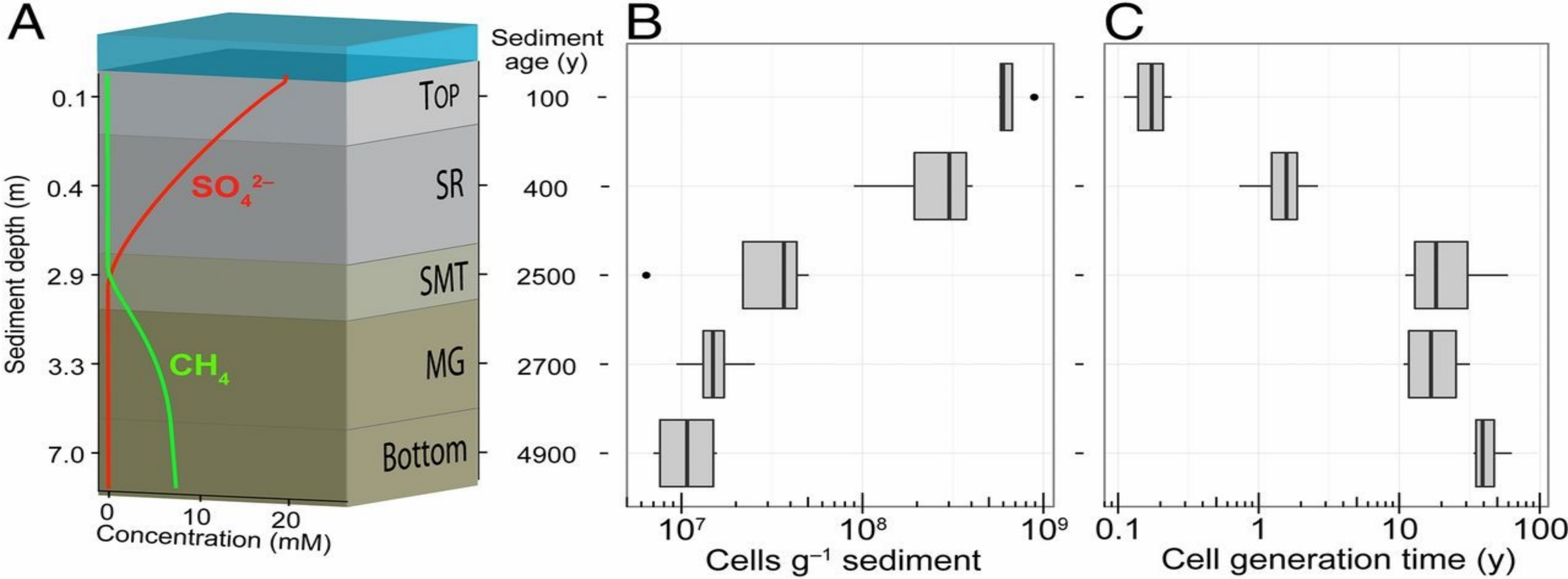
The **Sulfate-Methane Transition Zone** (SMTZ) is one of the most important zone in marine subsurface sediments together with the oxic-anoxic interface

It is a geochemically defined zone in marine sediments between the minima of sulfate and the maxima of methane concentrations.

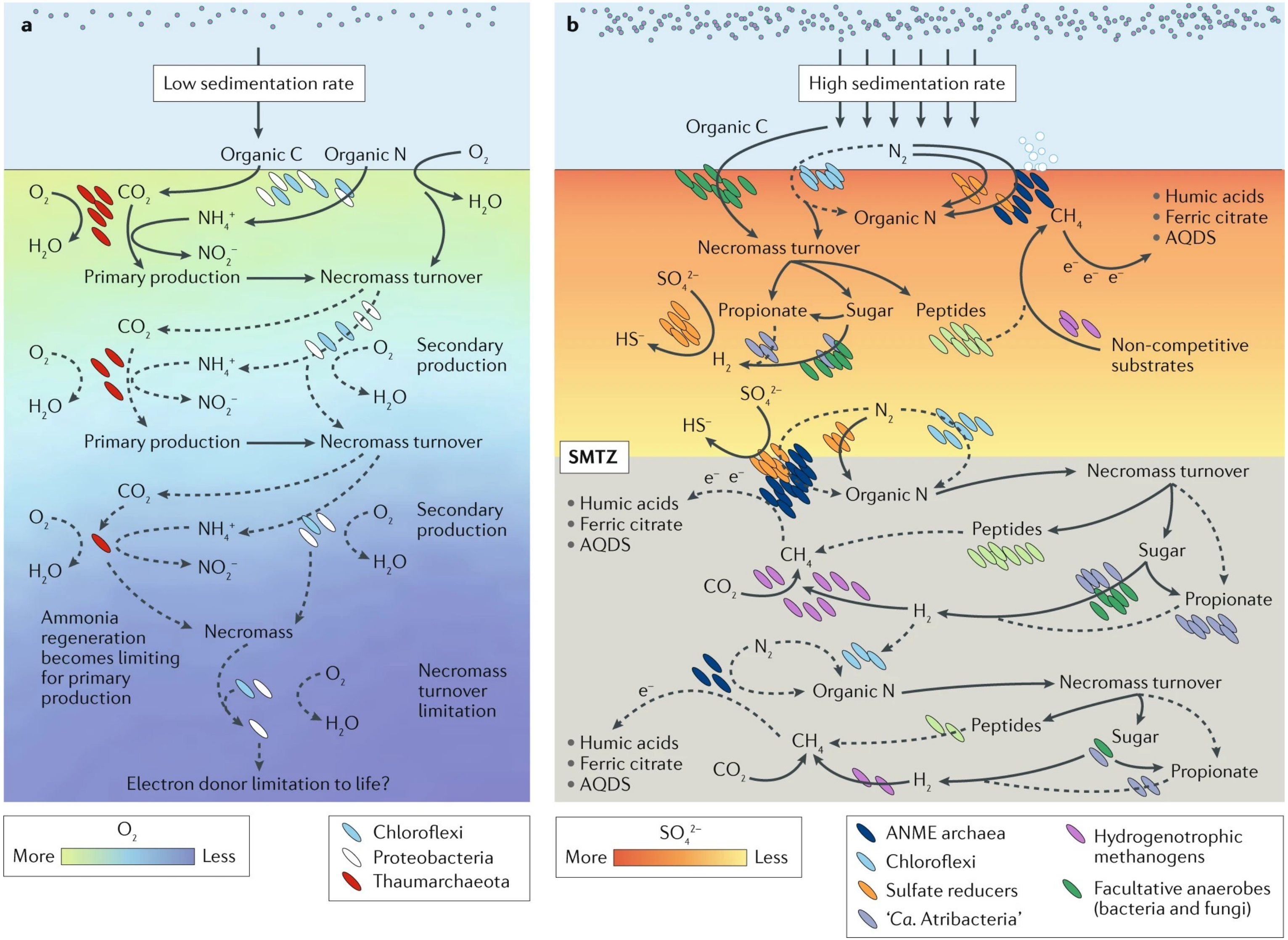
The SMTZ is an area of intense metabolic activity, where anaerobic methane oxidizers (ANME) is believed to play a key role in removing methane in partnership with sulfate reducing bacteria (SRB)

The SMTZ has a variable depth globally, and it is dependent upon sediment lithology, productivity of the overlaying water column and metabolic activity of the microbial community





Starnawski et al. 2017 PNAS



Orsi 2018 Nat Microbiol

Continental subsurface

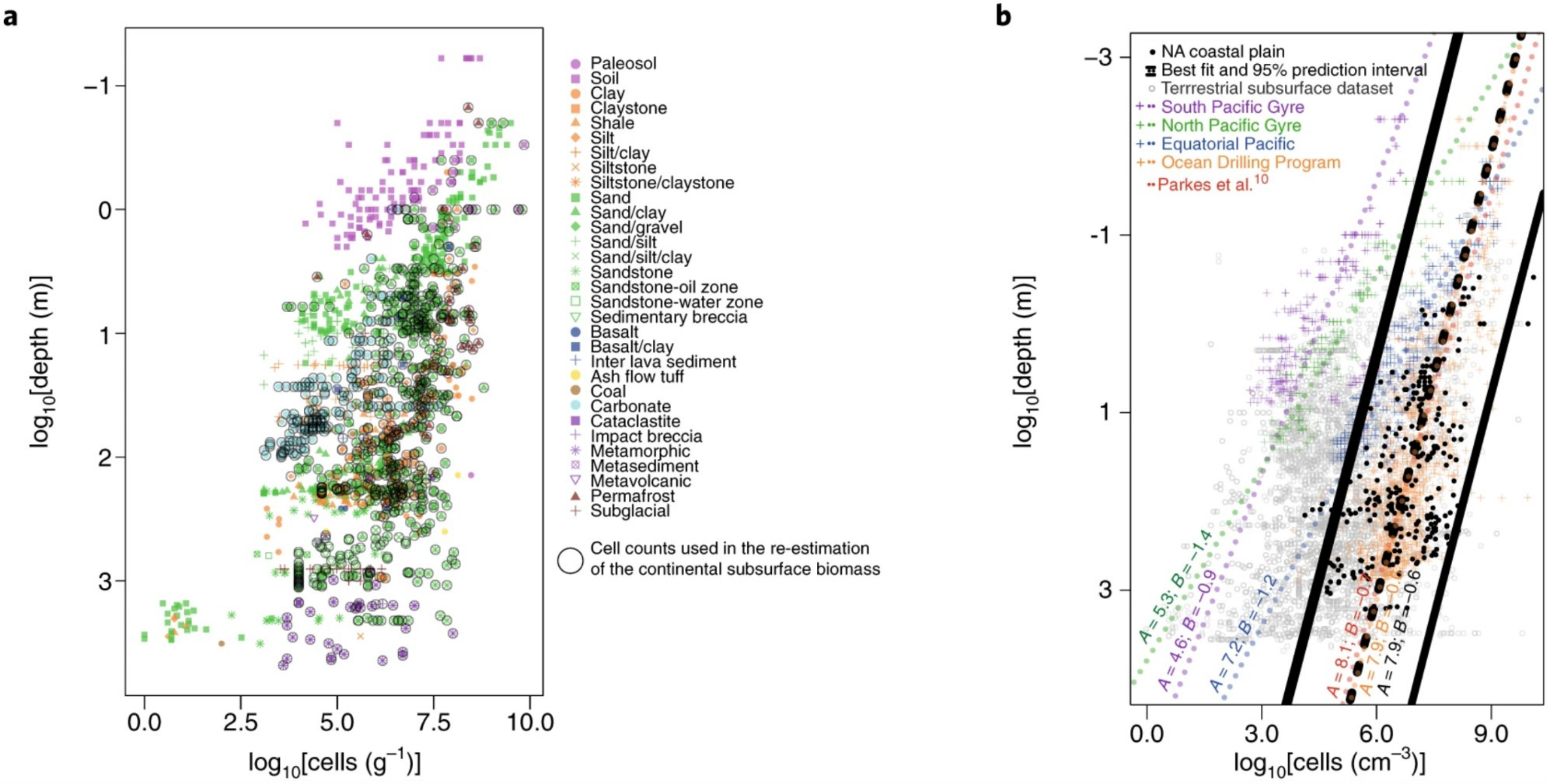
The Continental subsurface is characterized by higher crustal thickness (~40 km) compared to the marine crust (6-8 km)

The composition in therm of bedrock is more varied, and includes the entire spectrum of volcanic rock as well as metamorfic and sedimentary rocks

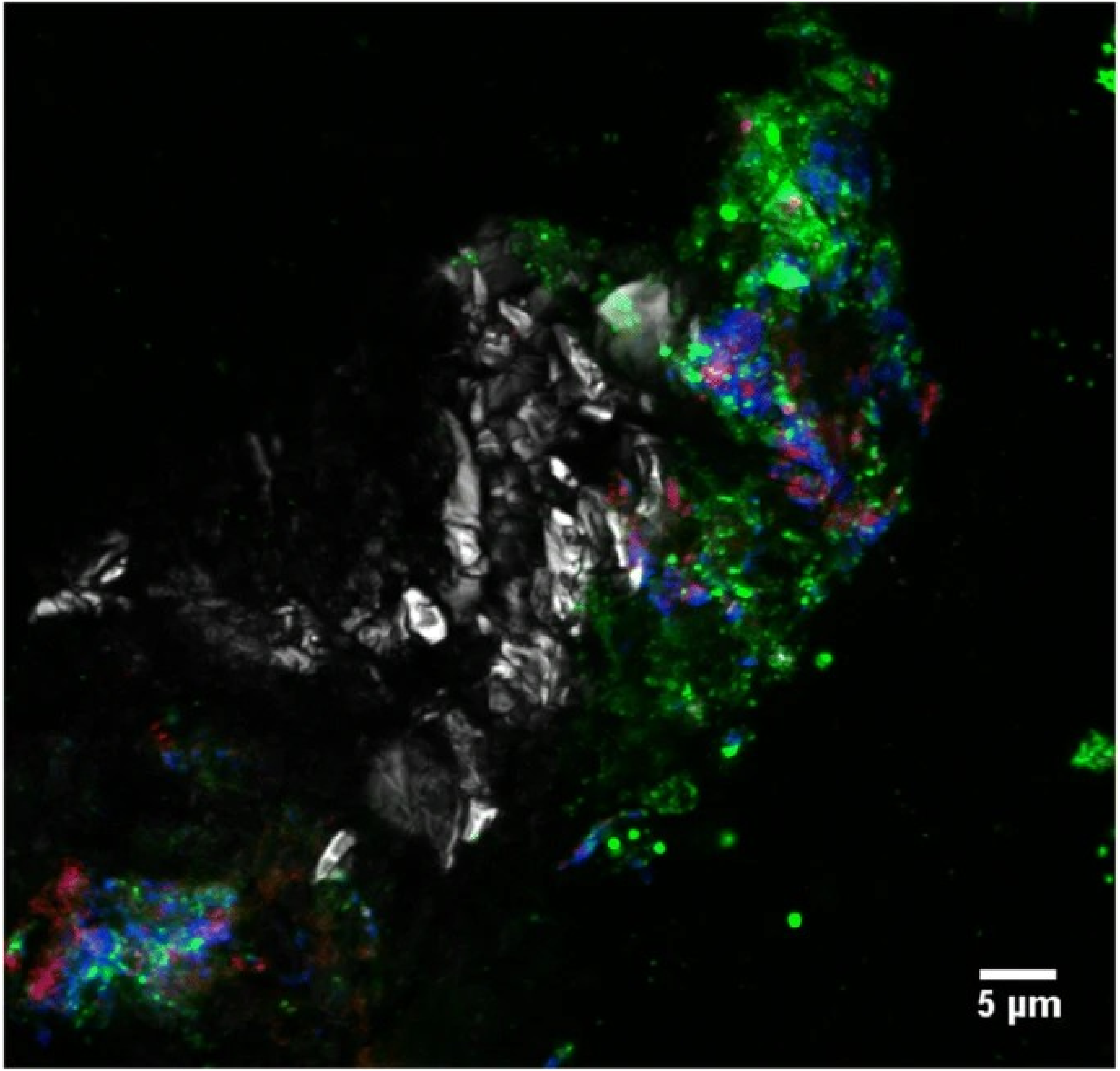
While the continental crust appears to host a more diverse suite of ecological niches (and might thus be more biologically diverse) we have comparatively less studies compared to the marine subsurface

On the other had, we have more studies in crystalline bedrocks, while the majority of the marine studies are in sedimentary environments

Deep Subsurface Environments



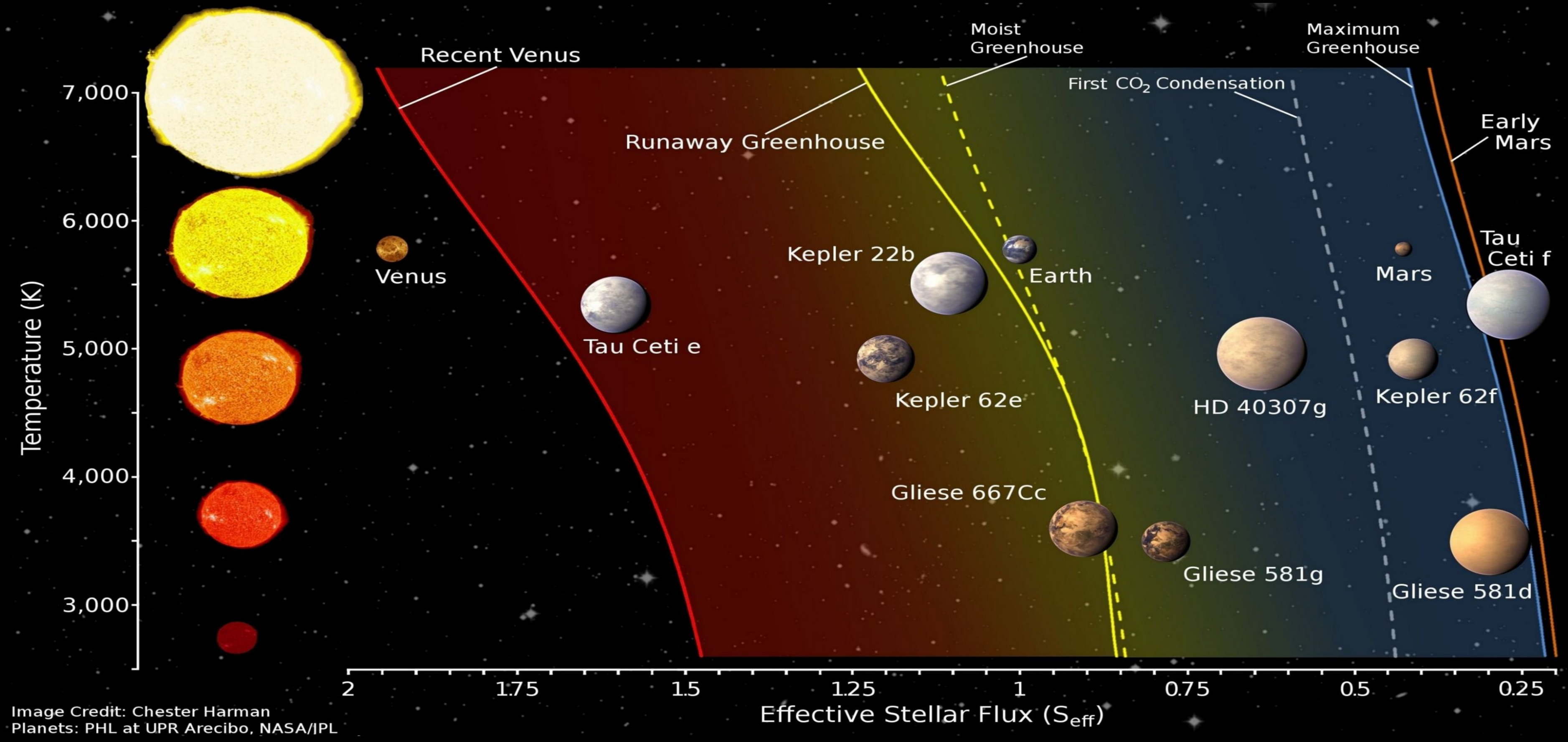
Magnabosco et al. 2018 Nat Geosci

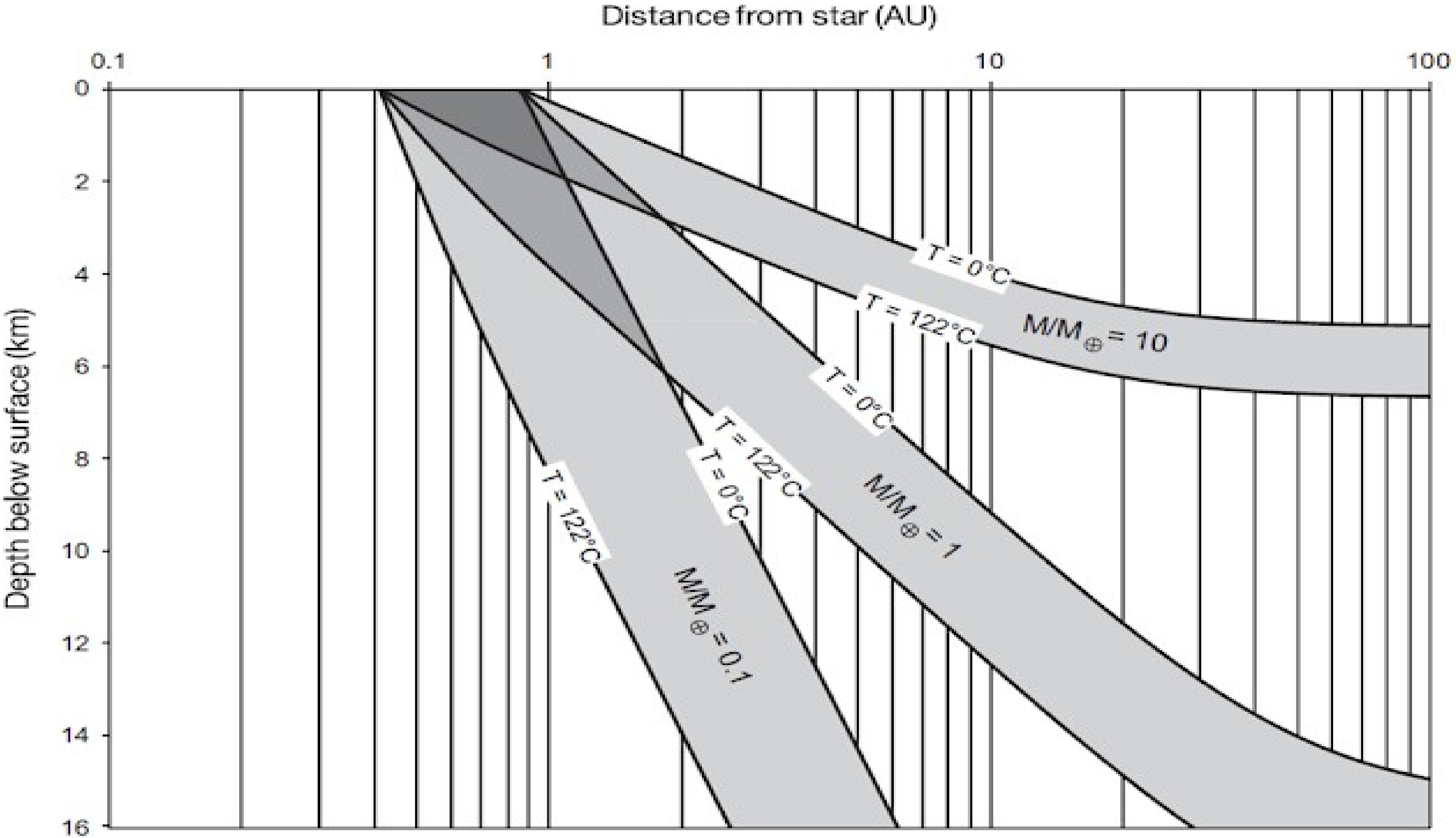


Hard porous rock subsurface biofilm at 139.4 mbs of the Iberian Pyrite Belt. In red, members of Bacteria domain detected with EUB338 I-II probe; in blue, members of Archaea domain detected with ARC915 probe; in green groups of EPS detected with ConA lectin; in gray, reflection. Scale bar, 5 µm

Escudero et al. 2018 Int Microbiol

Habitable Zone





McMahon et al. 2013 Planet Space Sci

Science

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REPORT

Radar evidence of subglacial liquid water on Mars

R. Orosei[1,*], S. E. Lauro[2], E. Pettinelli[2], A. Cicchetti[3], M. Coradini[4], B. Cosciotti[2], F. Di Paolo[1], E. Flamini[4], E. Matt

+ See all authors and affiliations

Science 03 Aug 2018:
Vol. 361, Issue 6401, pp. 490-493
DOI: 10.1126/science.aar7268

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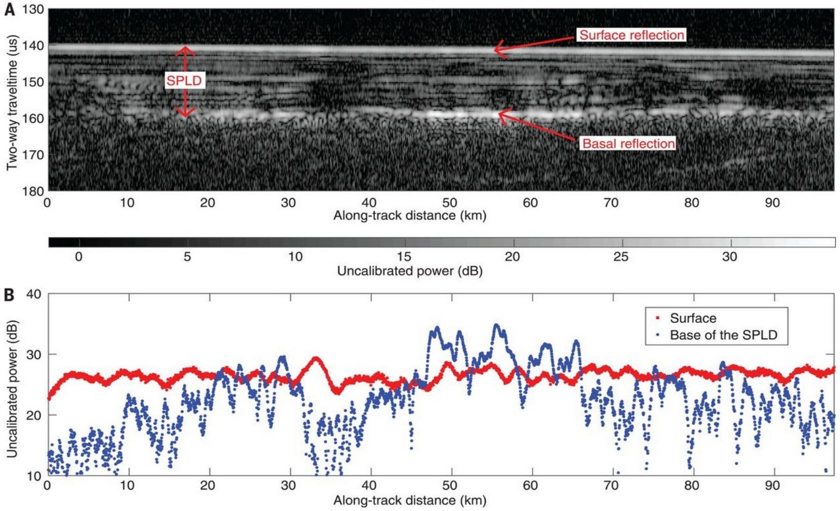
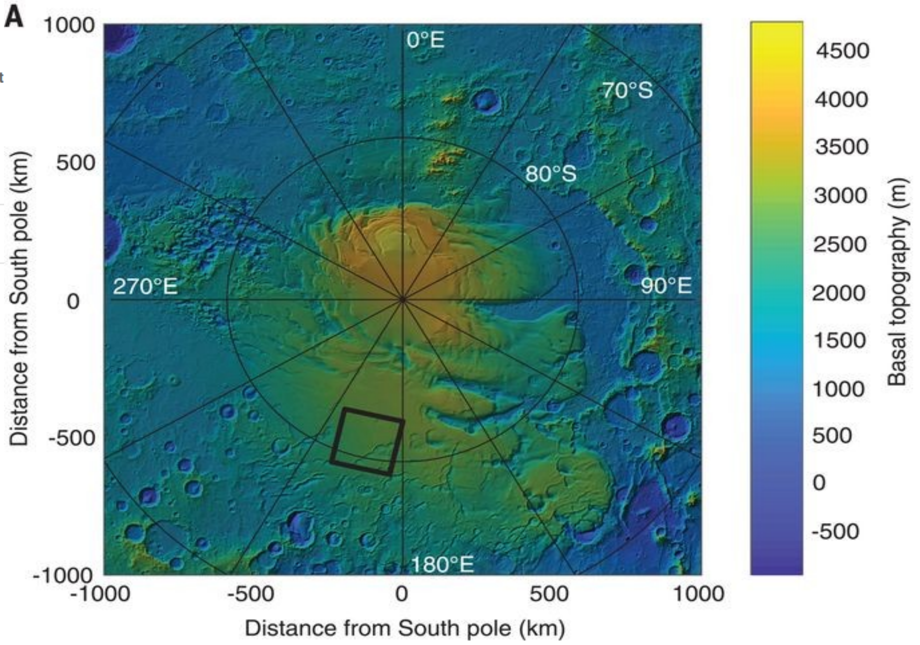
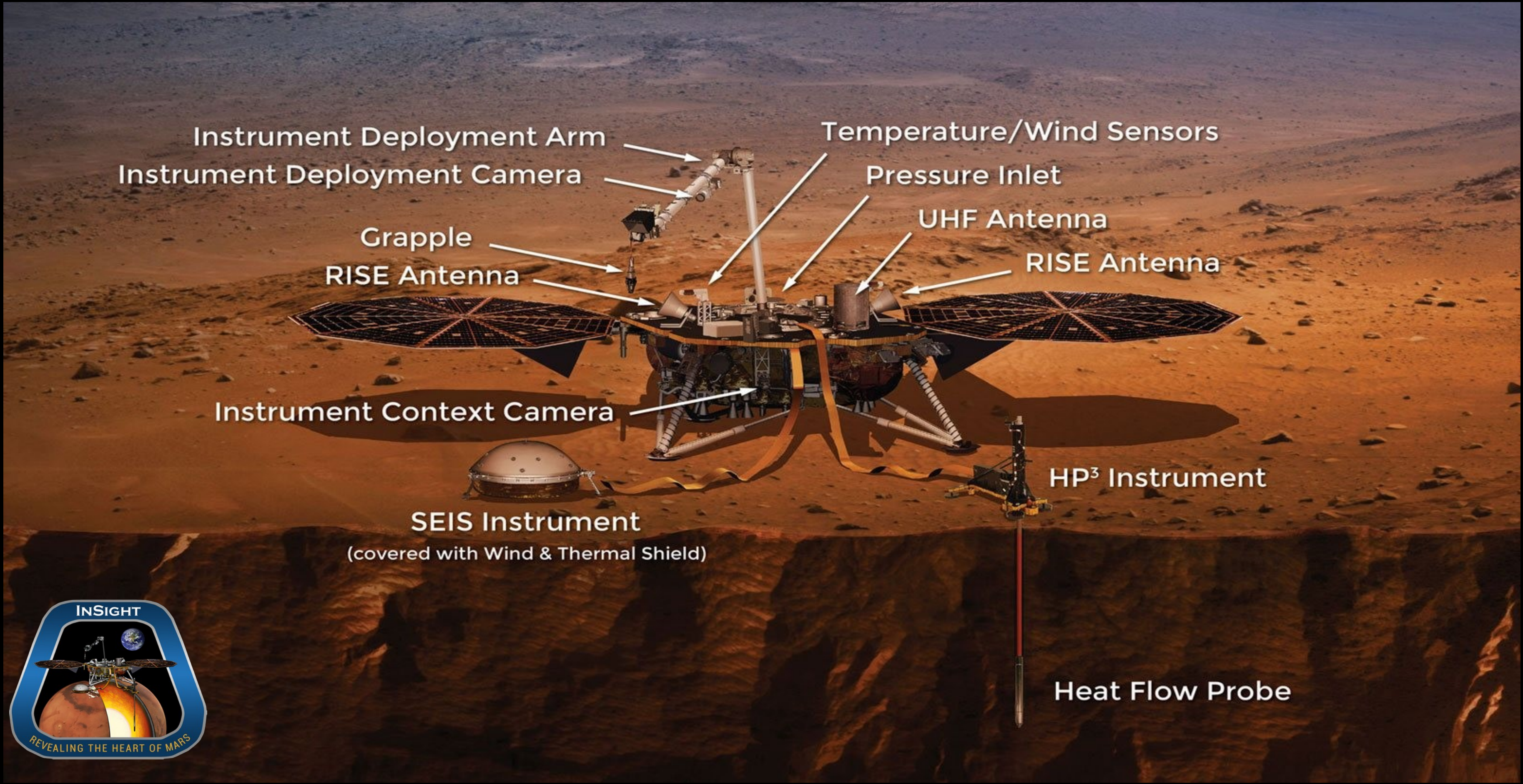
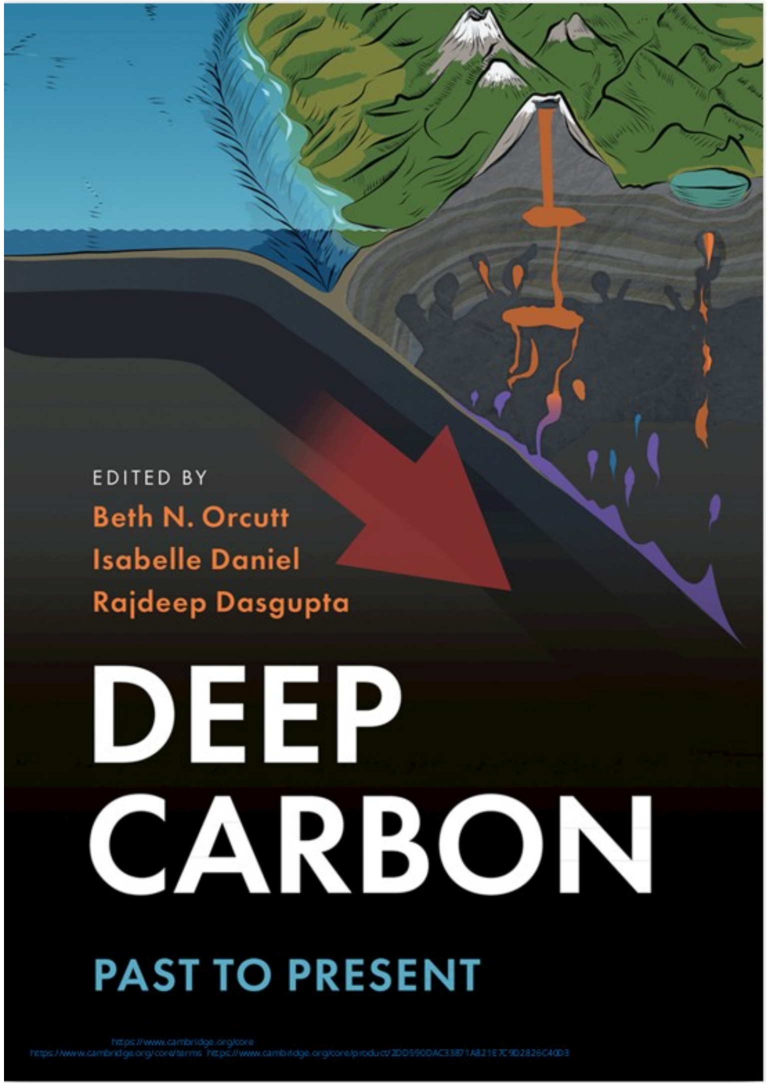




Orosei et al. 2018 Science



https://mars.nasa.gov/insight/



DEEP CARBON
Past to present

EDITED BY
Beth Orcutt
Isabelle Daniel
Rajdeep Dasgupta

Cambridge University Press

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Readings

Sunagawa, S., Coelho, L. P., Chaffron, S., Kultima, J. R., Labadie, K., Salazar, G., et al. (2015). Structure and function of the global ocean microbiome. Science 348. doi:10.1126/science.1261359

Bertagnolli, A. D., and Stewart, F. J. (2018). Microbial niches in marine oxygen minimum zones. Nat Rev Microbiol 16, 723–729. doi:10.1038/s41579-018-0087-z

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Magnabosco, C., Lin, L.-H., Dong, H., Bomberg, M., Ghiorse, W., Stan-Lotter, H., et al. (2018). The biomass and biodiversity of the continental subsurface. Nature Geoscience, 1. doi:10.1038/s41561-018-0221-6