Biogeography and metabolism across ocean gradients

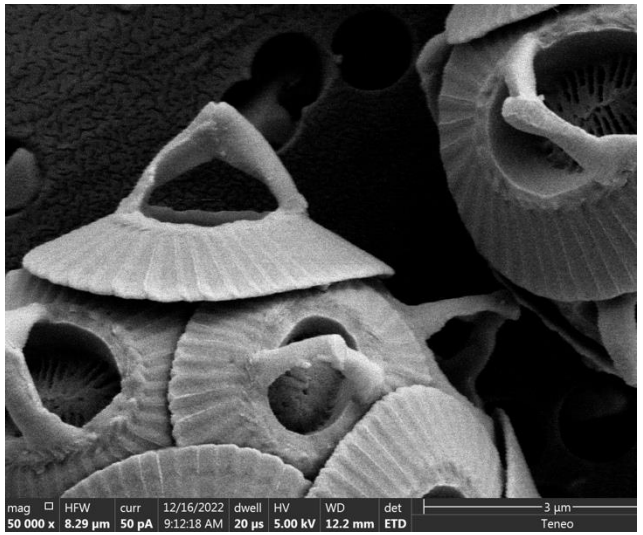


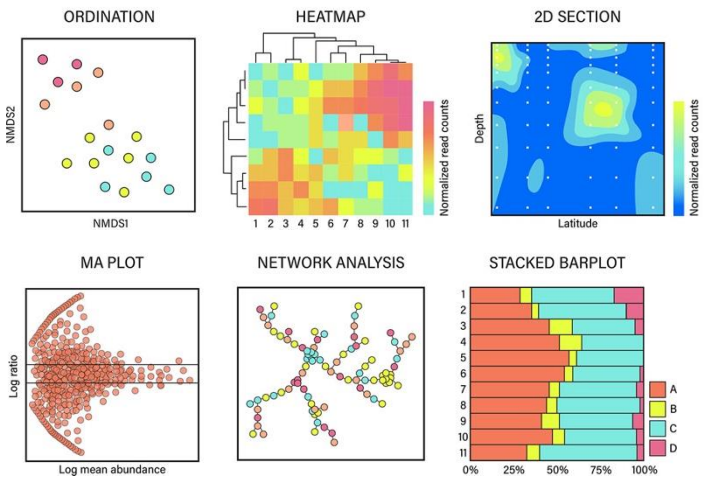


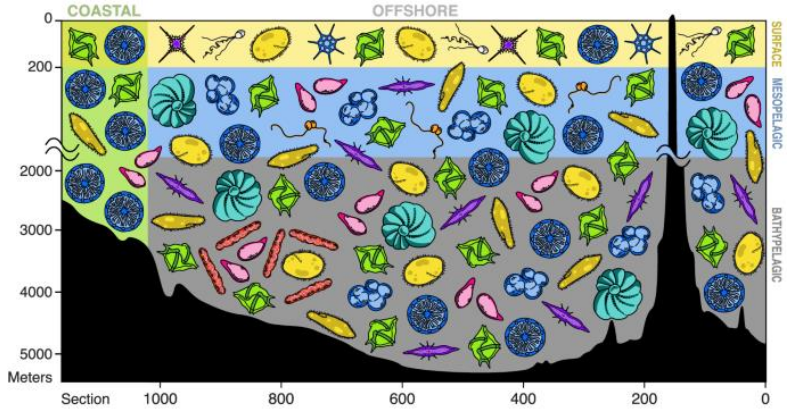
Natalie Cohen

Croucher Summer Course 2025

Outline







Inferring physiology from omics

Primary production, nutrient biomarkers, links to ocean biogeochemistry

Best practices in metatranscriptomics

From sample collection to data visualization

Microeukaryote metabolism across the ocean

Biogeography & ocean gradients

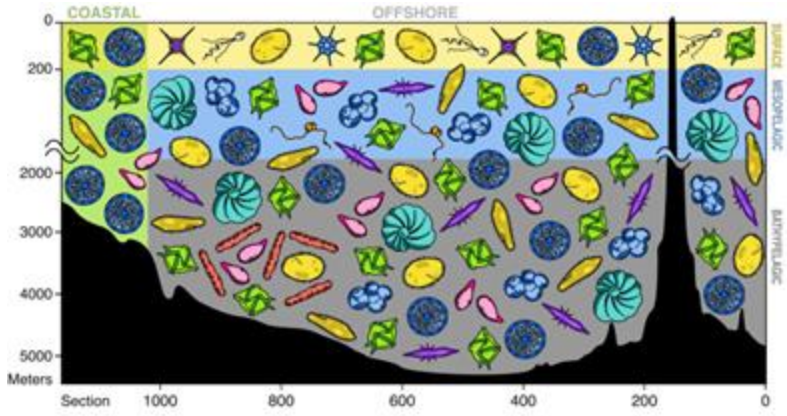
Outline

Inferring physiology from omics

Primary production, nutrient biomarkers, links to ocean biogeochemistry

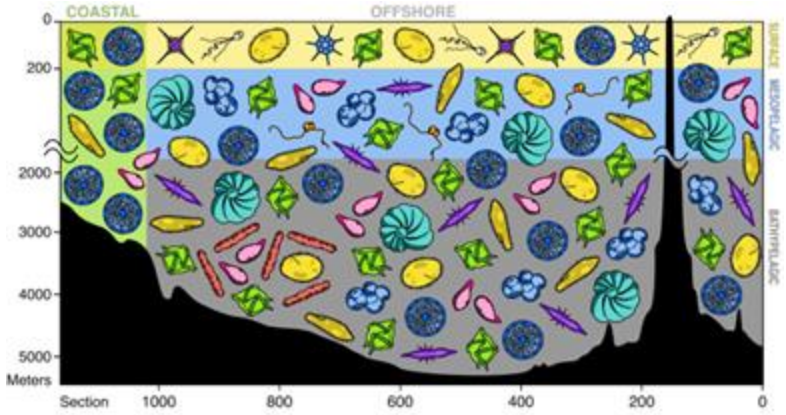
Best practices in metatranscriptomics

From sample collection to data visualization



Microeukaryote metabolism across the ocean

Biogeography & ocean gradients



Microeukaryote metabolism across the ocean

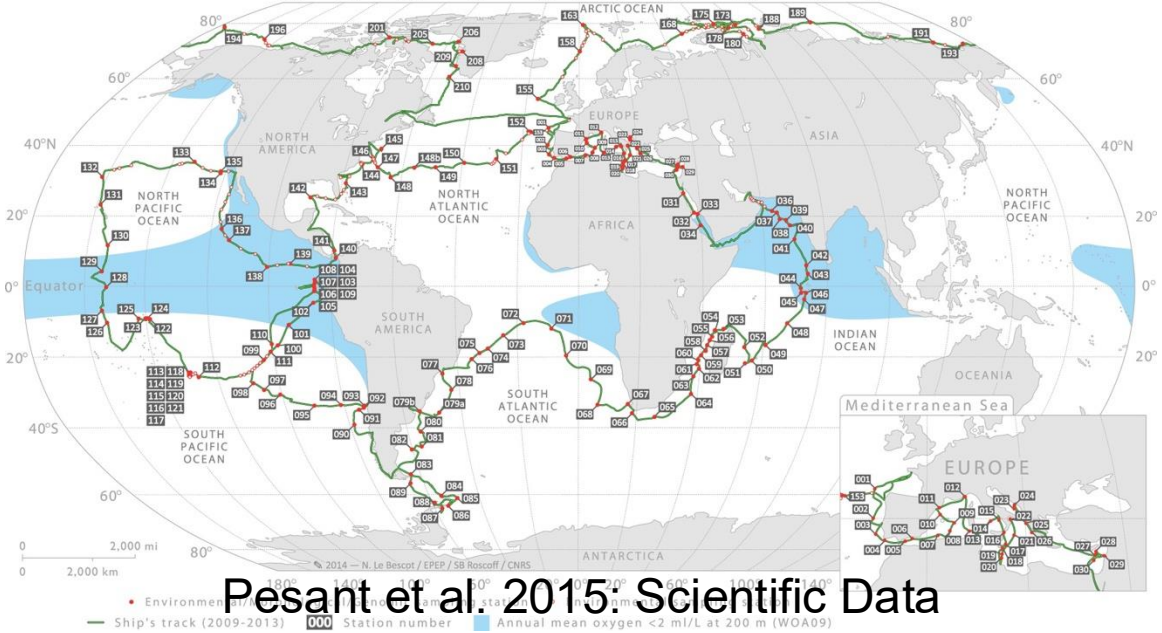
Biogeography & ocean gradients

- Biogeography
- Gradients
  - Vertical zonation
  - Latitudinal shifts
- Hydrothermal vents

What are the global patterns of microbial community composition and functional metabolism?

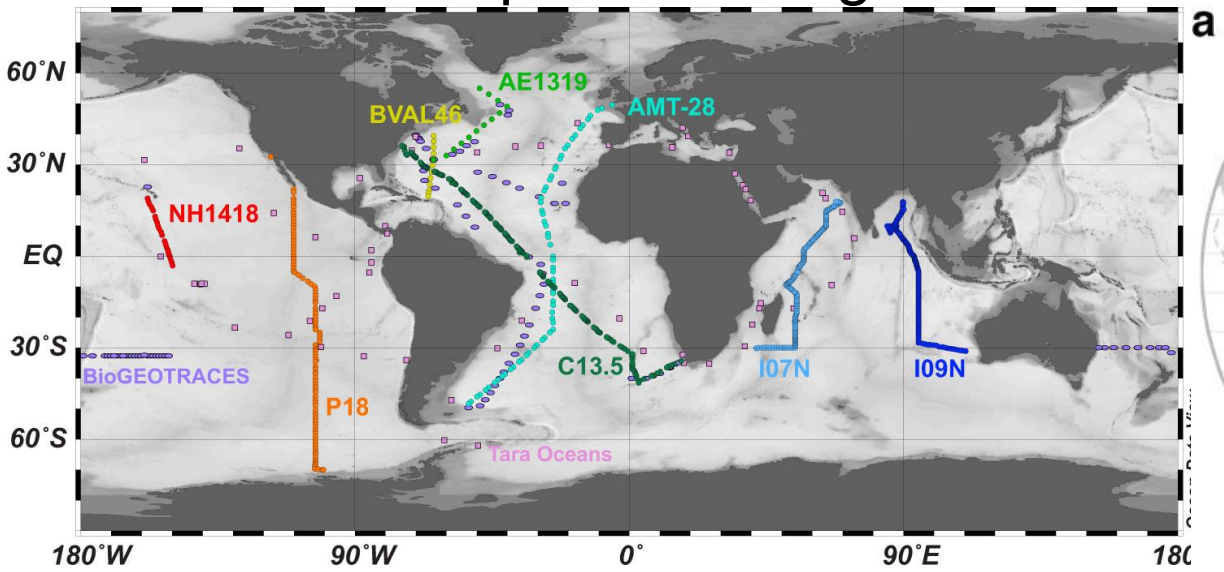
https://tara-oceans.mio.osupytheas.fr/ocean-gene-atlas/

Tara Oceans: 365 metagenomes



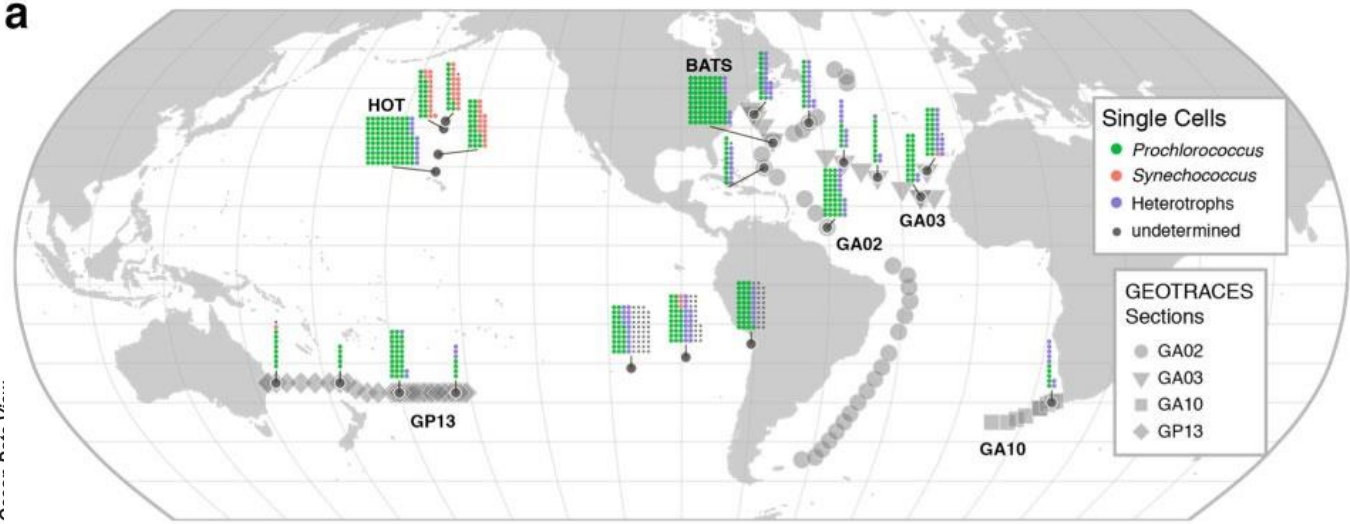
Pesant et al. 2015: Scientific Data

Bio-GO-ship: 970 metagenomes



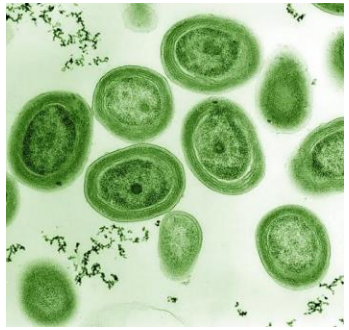
Larken et al. 2021 Scientific Data

BioGeotraces: ~700 single cell genomes



Berube et al. 2018 Scientific Data

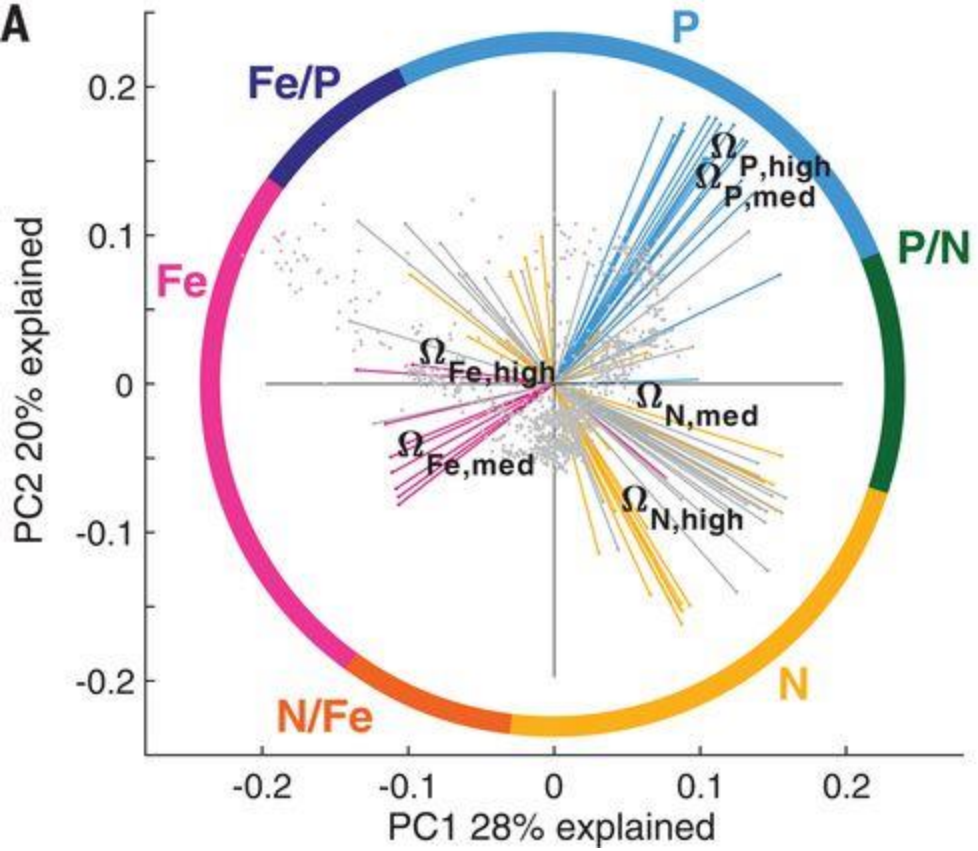
Global patterns of nutrient stress in *Prochlorococcus*

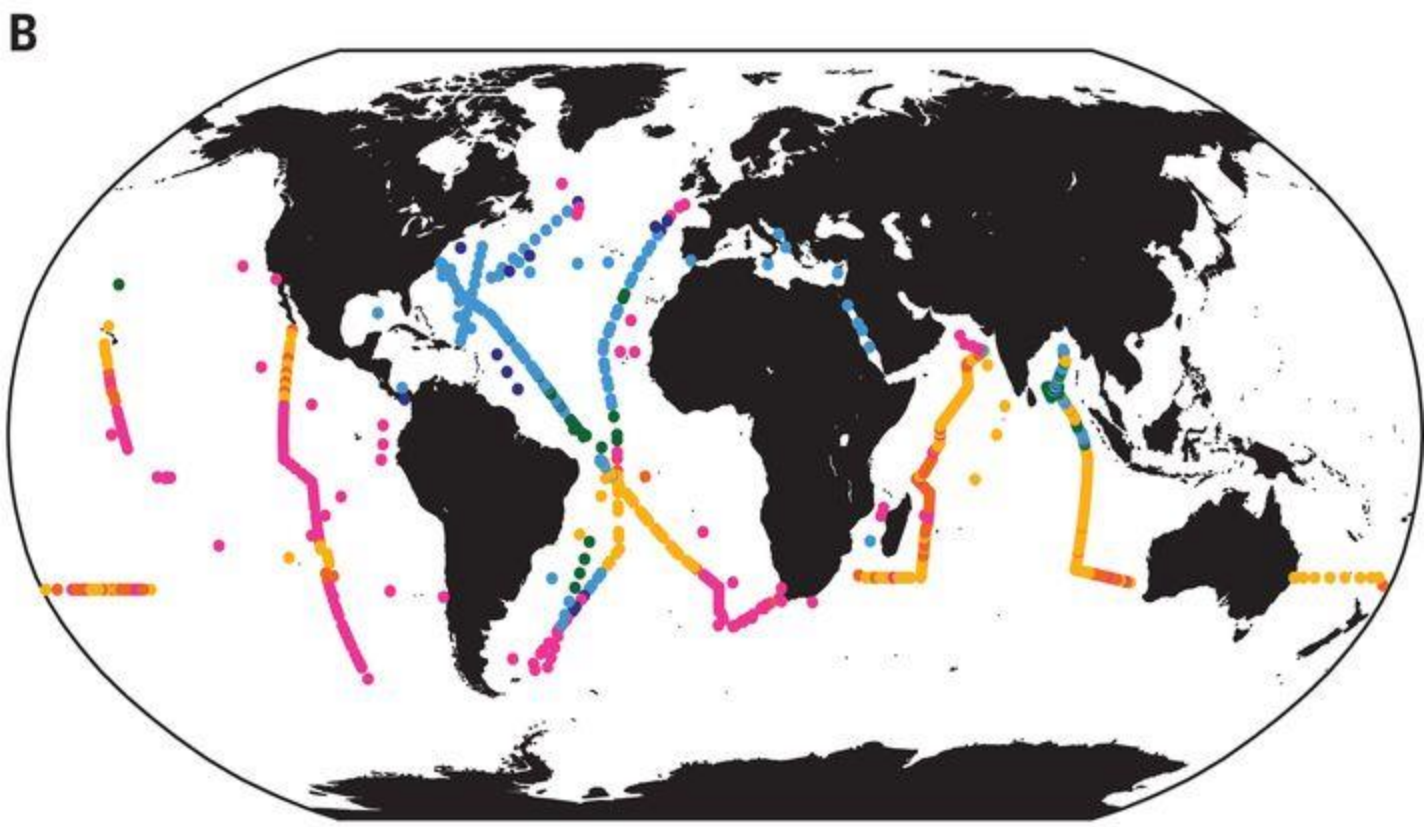


$\Omega_{type,severity}$	Function	Marker genes	Reference(s)
$\Omega_{Fe,high}$	Loss of Fe-containing proteins	HLIII-IV core genes	(*20*)
$\Omega_{Fe,medium}$	Fe uptake (transporters)	*cirA*, *expD*, *febB*, *fepB/C*, *tolQ*, *tonB*	(*19*)
$\Omega_{P,high}$	Alkaline phosphatase	*phoA*, *phoX*	(*12*, *15*)
$\Omega_{P,medium}$	P starvation regulation, arsenate toxicity, specific DOP assimilation	*arsR*, *acr3*, *chrA*, *gap1*, *mfs*, *phoB/E/R*, *ptrA*, *PMM707*, *PMM721*, *unkP1-5*	(*12*–*14*)
$\Omega_{N,high}$	Nitrite and nitrate assimilation and uptake	*focA*, *moaA-E*, *moeA*, *napA*, *narB*, *nirA*	(*17*)
$\Omega_{N,medium}$	Urea and cyanate utilization	*cynA/S*, *tauE*, *ureA-G*, *urtA*, *unkN1-2*	(*17*, *18*)

Ustick et al. 2021 *Science*

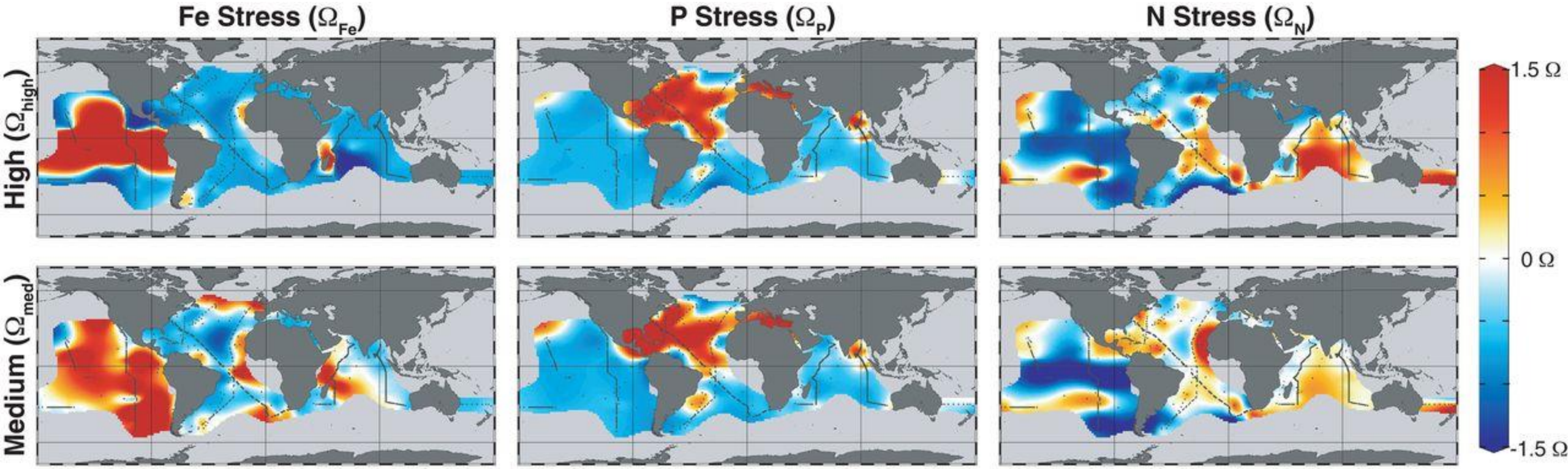
Global patterns of nutrient stress in *Prochlorococcus*





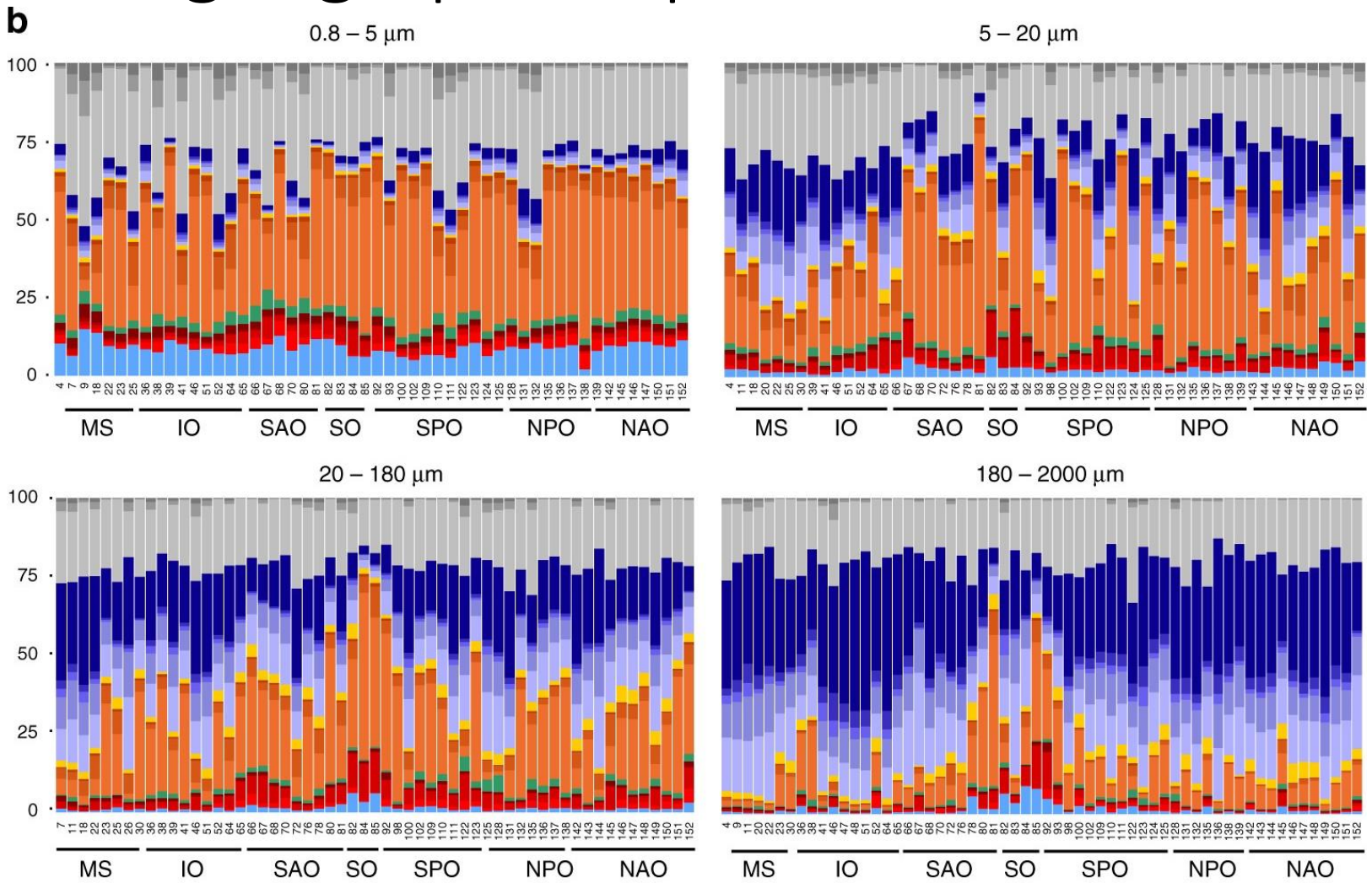
Ustick et al. 2021 *Science*

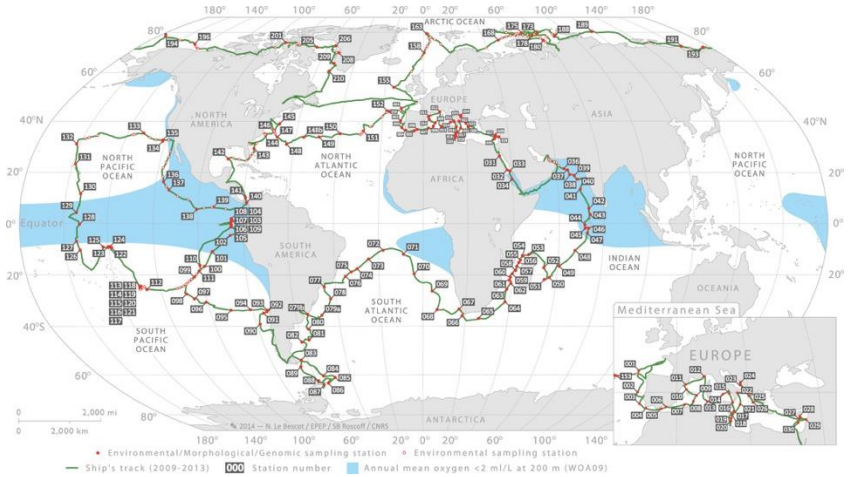
Global patterns of nutrient stress in *Prochlorococcus*



Ustick et al. 2021 *Science*

Biogeographical patterns in microeukaryote composition

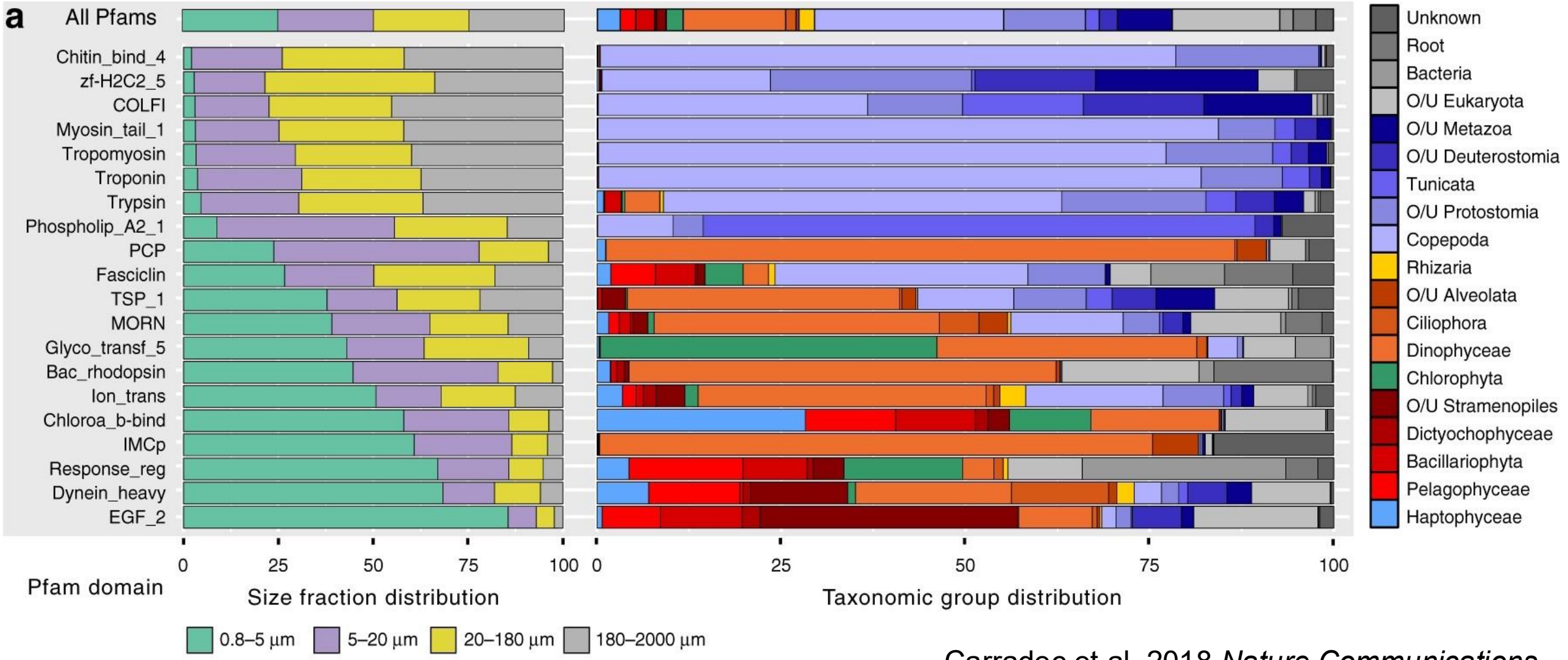




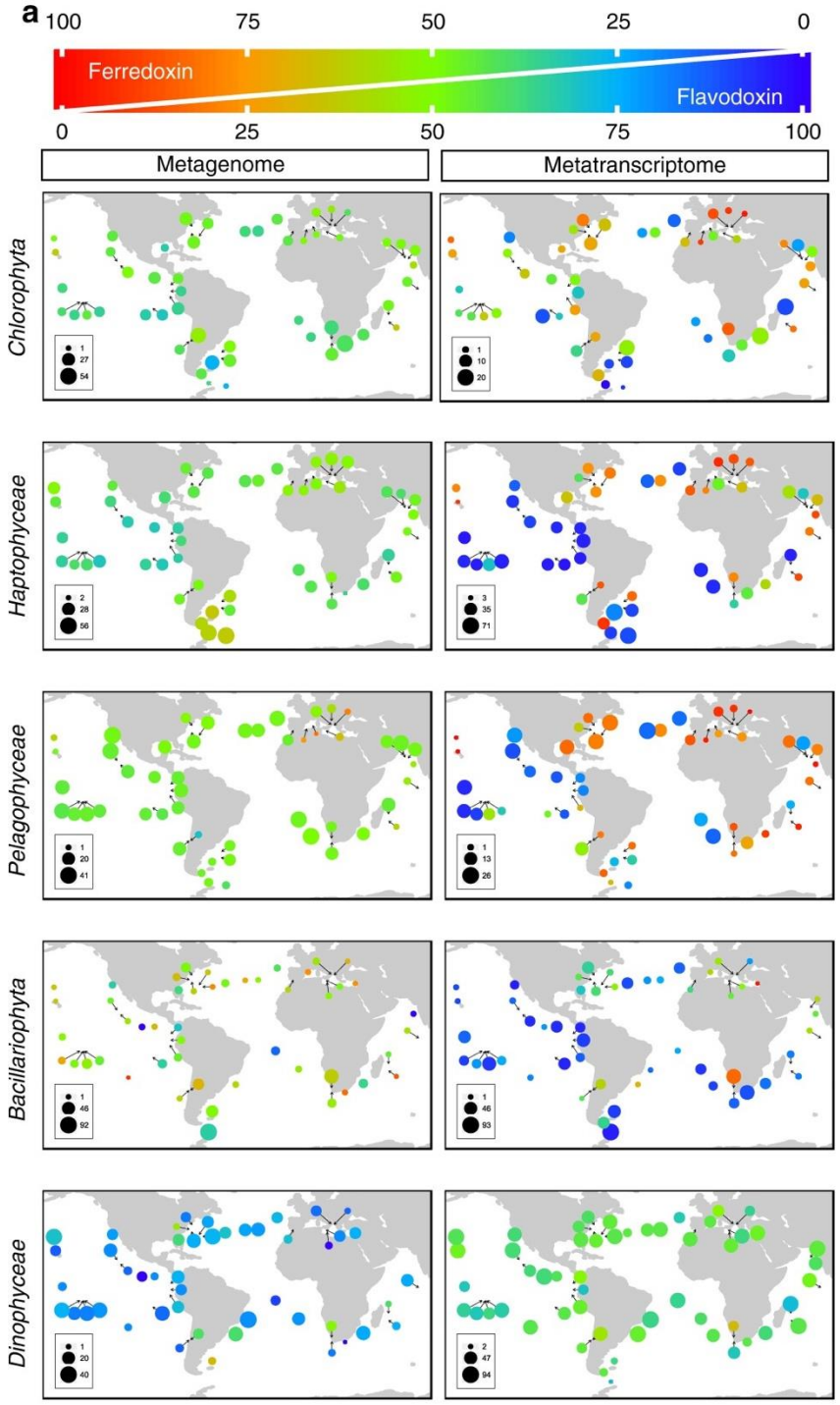
48.3% of the unigenes had taxonomic annotations

Carradec et al. 2018 *Nature Communications*

Biogeographical patterns in microeukaryote function



Carradec et al. 2018 *Nature Communications*



Links between metagenomes and metatranscriptomes

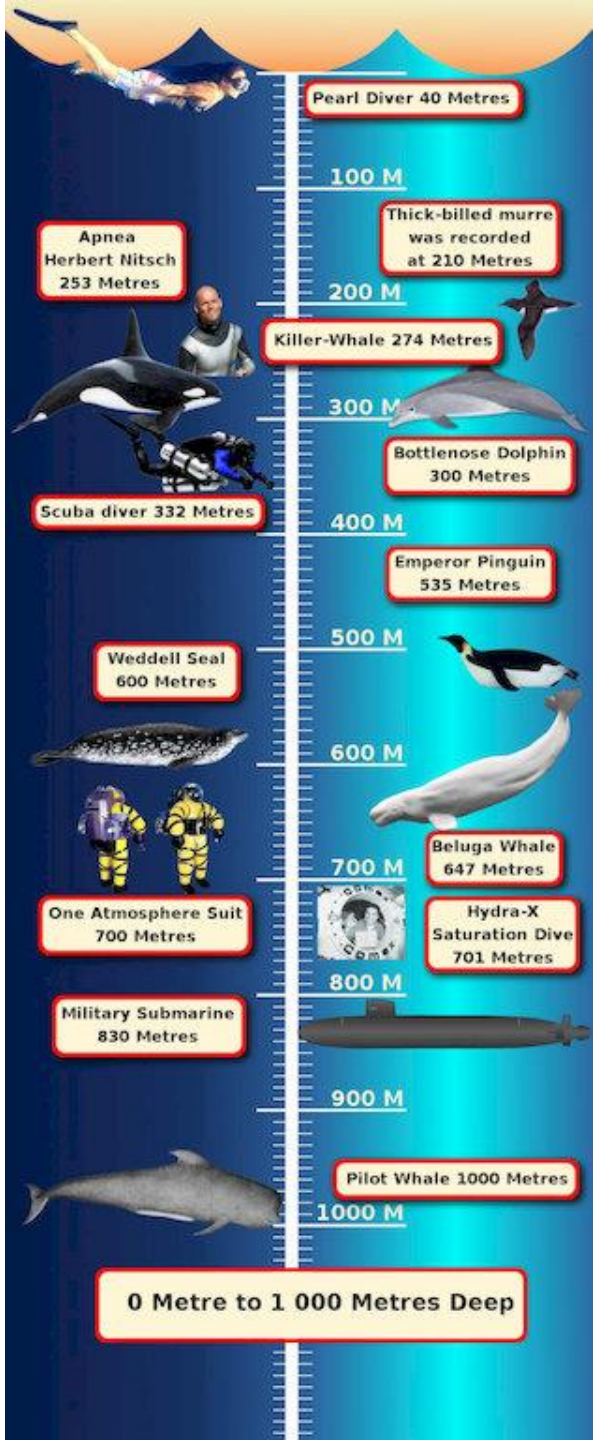
- Gene abundance shows little variation, except in diatoms
- Haptophytes, chlorophytes, and pelagophytes will transcriptionally regulate flavodoxin and ferredoxin
- Diatoms tend to express flavodoxin genes. Species may be adapted to iron regimes rather than relying on transcriptional flexibility
- Dinoflagellates show muted patterns across ocean

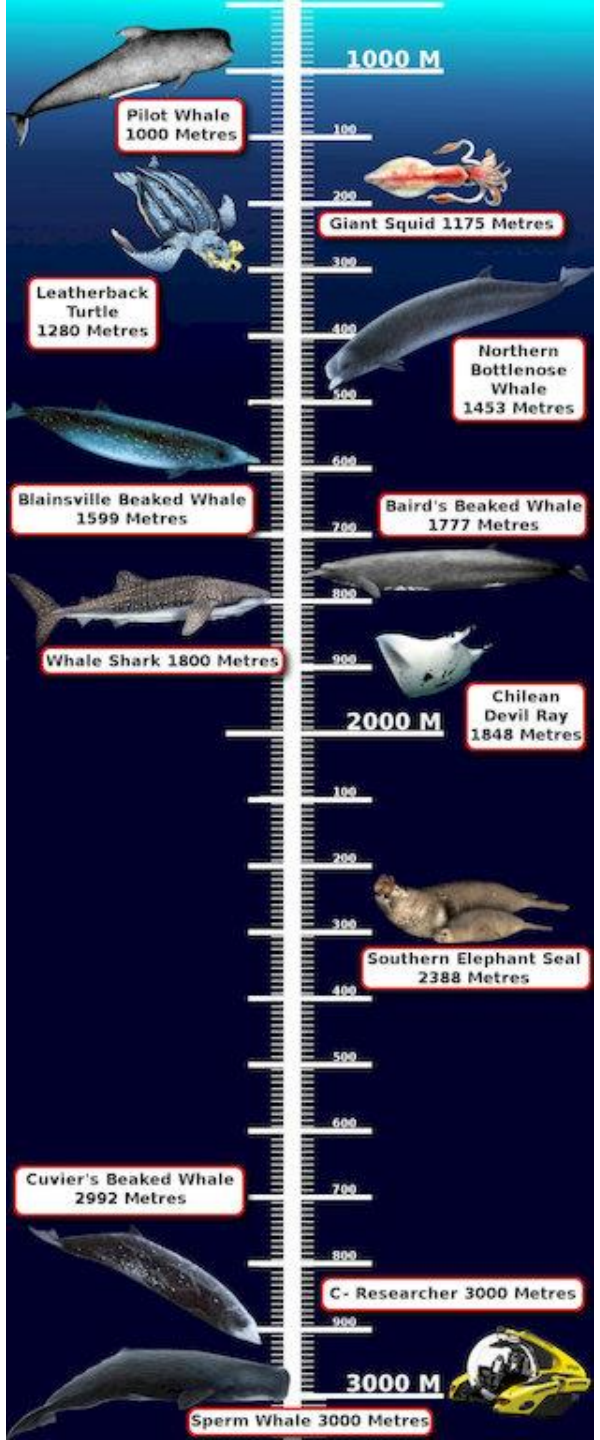
Nutrient limitation is dealt with differently among these taxa

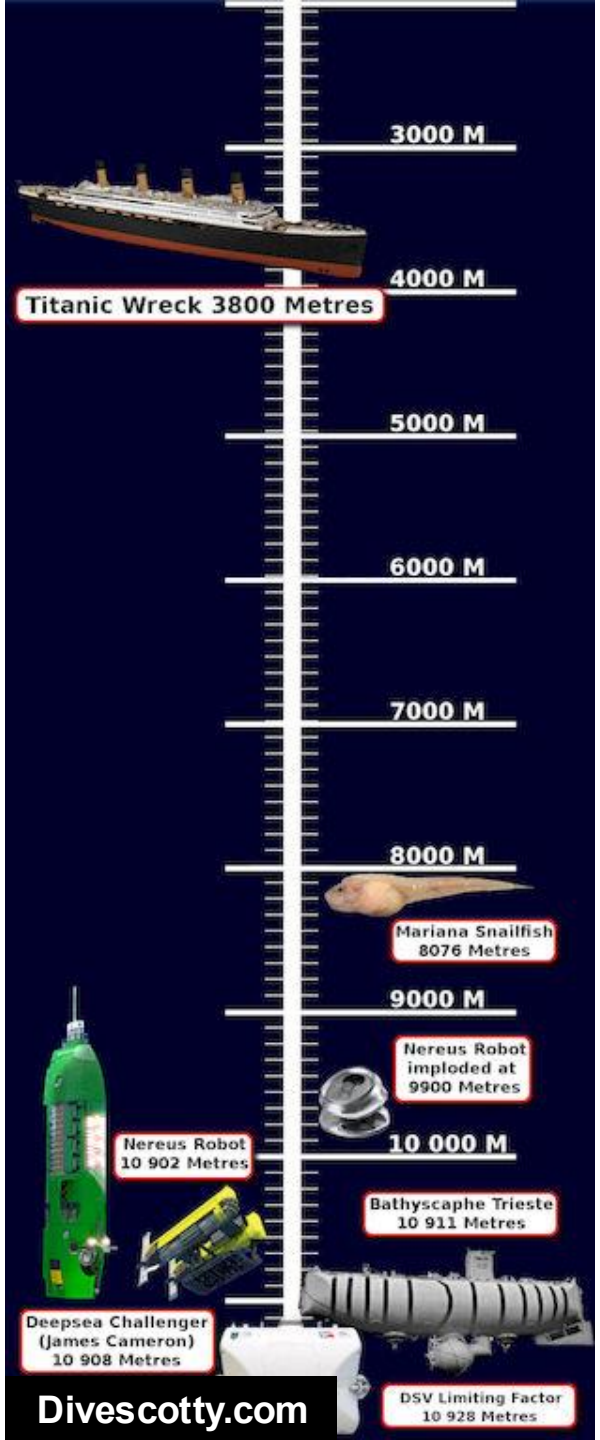
Carradec et al. 2018 *Nature Communications*

What have we learned from survey-based omic expeditions?

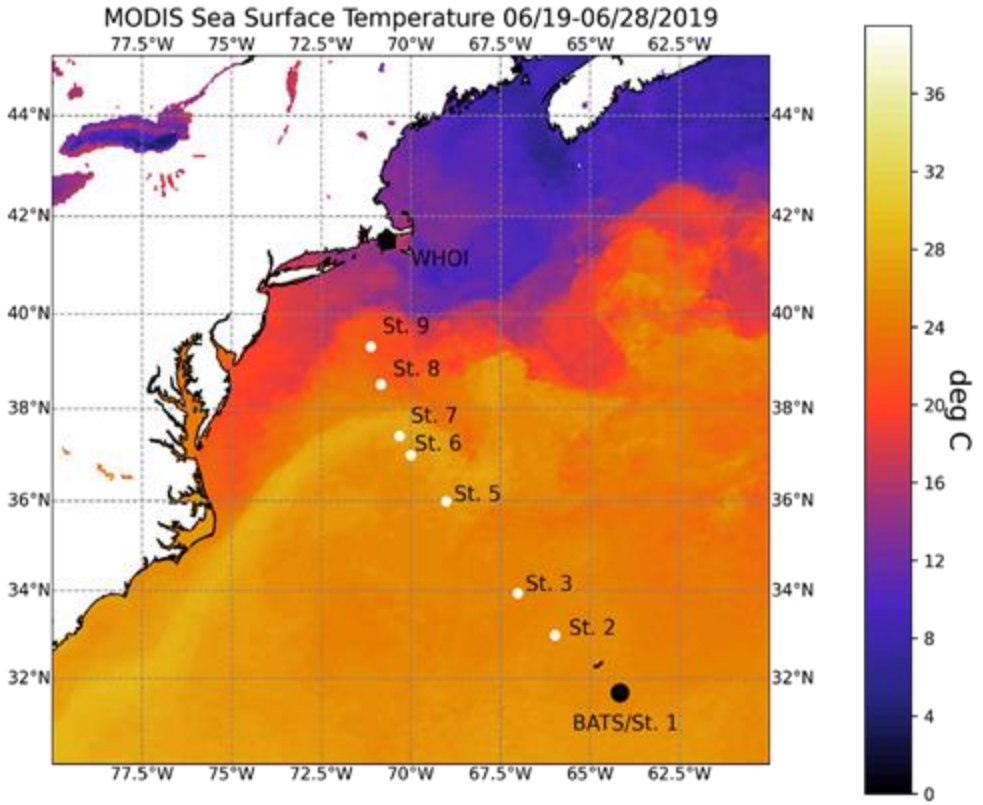
- Zones of nutrient limitation impart a signature on genomes
- Most of the genetic material is unannotated
- Of the annotated fractions, some differences in latitude
- Size fraction reveals different community members and function
- Differences in genome adaptation and transcriptional responsiveness among phytoplankton groups


Pearl Diver 40 Metres
100 M
Thick-billed murre was recorded at 210 Metres
Apnea Herbert Nitsch 253 Metres
200 M
Killer-Whale 274 Metres
300 M
Bottlenose Dolphin 300 Metres
Scuba diver 332 Metres
400 M
Emperor Pinguin 535 Metres
500 M
Weddell Seal 600 Metres
600 M
Beluga Whale 647 Metres
700 M
One Atmosphere Suit 700 Metres
Hydra-X Saturation Dive 701 Metres
800 M
Military Submarine 830 Metres
900 M
Pilot Whale 1000 Metres
1000 M
0 Metre to 1 000 Metres Deep

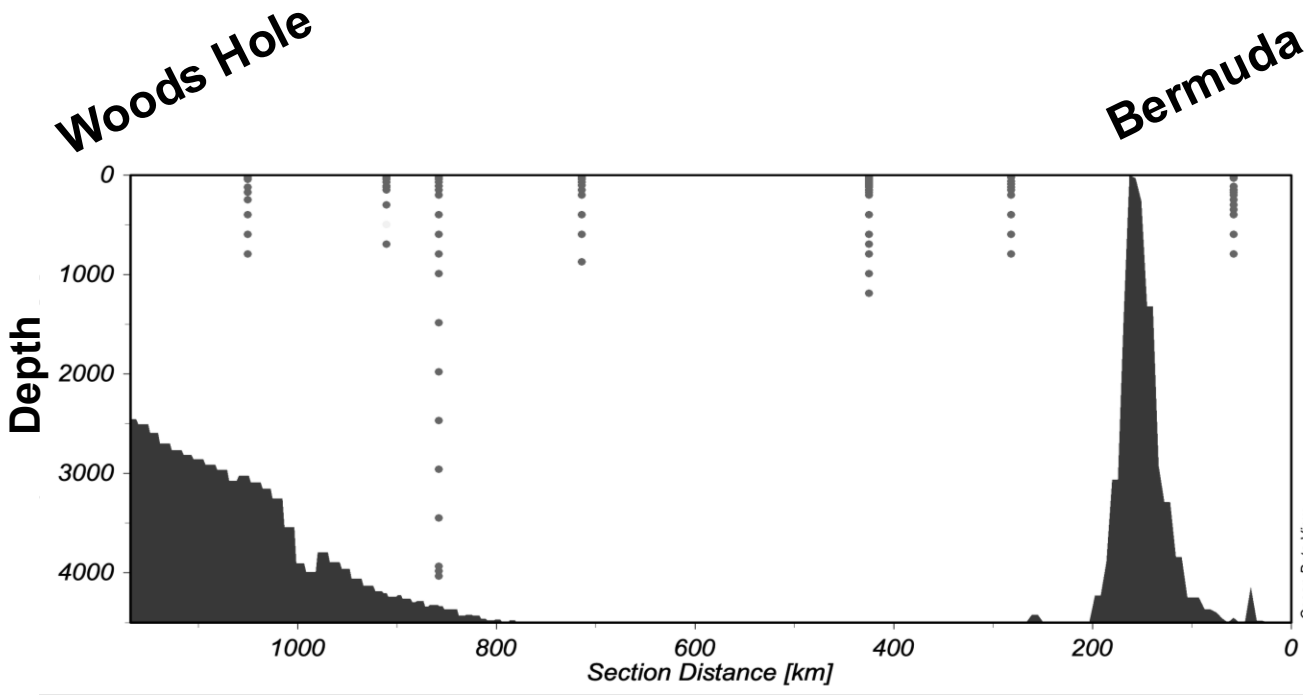

1000 M
Pilot Whale 1000 Metres
Giant Squid 1175 Metres
Leatherback Turtle 1280 Metres
Northern Bottlenose Whale 1453 Metres
Blainsville Beaked Whale 1599 Metres
Baird's Beaked Whale 1777 Metres
Whale Shark 1800 Metres
2000 M
Chilean Devil Ray 1848 Metres
Southern Elephant Seal 2388 Metres
Cuvier's Beaked Whale 2992 Metres
C- Researcher 3000 Metres
3000 M
Sperm Whale 3000 Metres


3000 M
4000 M
Titanic Wreck 3800 Metres
5000 M
6000 M
7000 M
8000 M
Mariana Snailfish 8076 Metres
9000 M
Nereus Robot imploded at 9900 Metres
10 000 M
Nereus Robot 10 902 Metres
Bathyscaphe Trieste 10 911 Metres
Deepsea Challenger (James Cameron) 10 908 Metres
DSV Limiting Factor 10 928 Metres
Divescotty.com

How are communities structured along a coastal-offshore transition zone?



BATS-WHOI – June 2019



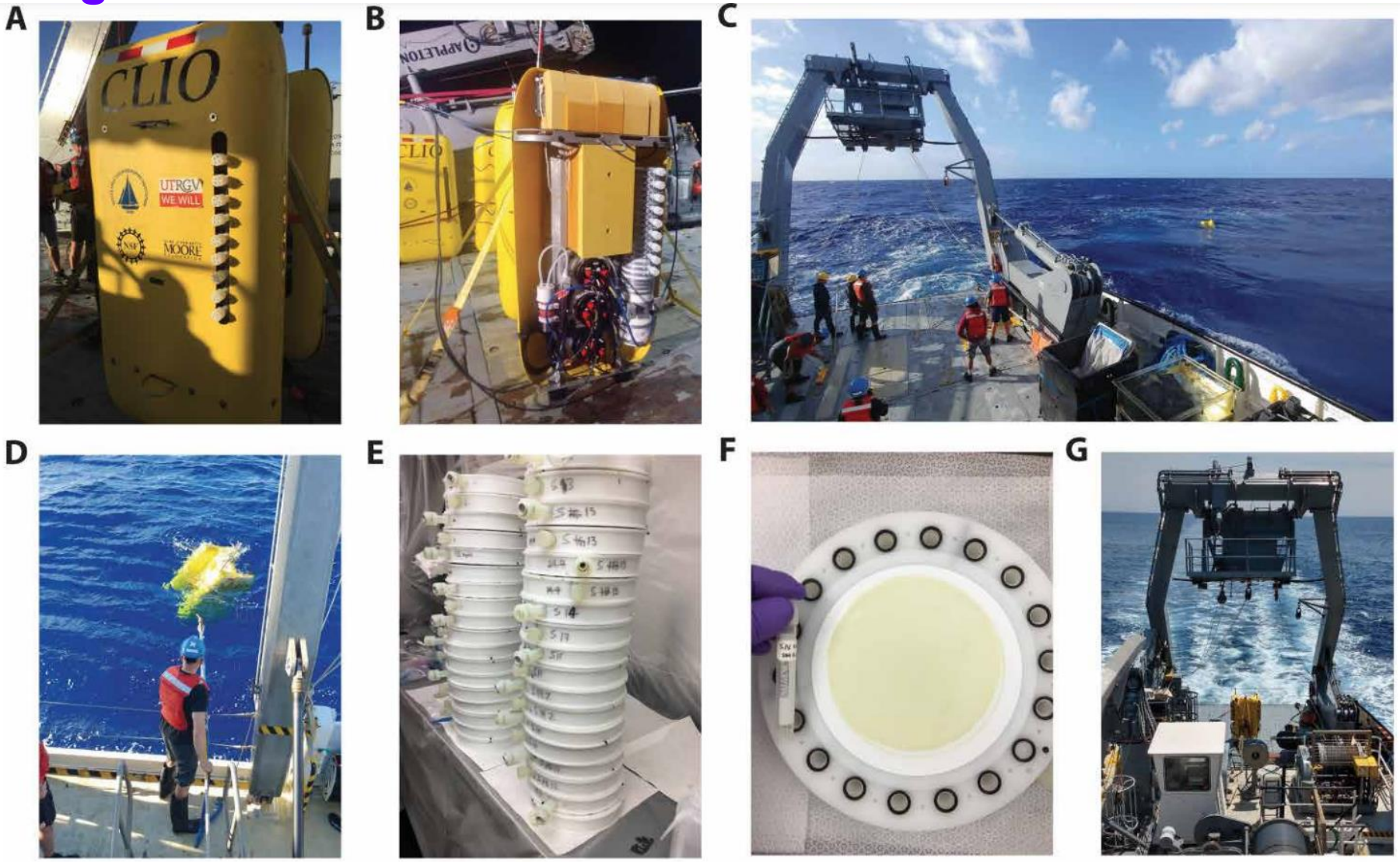
Cohen et al. 2024 *Nature Communications*

Microeukaryotes are undercharacterized!

Bermuda Atlantic Time Series station (BATS)
R/V *Atlantic Explorer*

SIMONS FOUNDATION

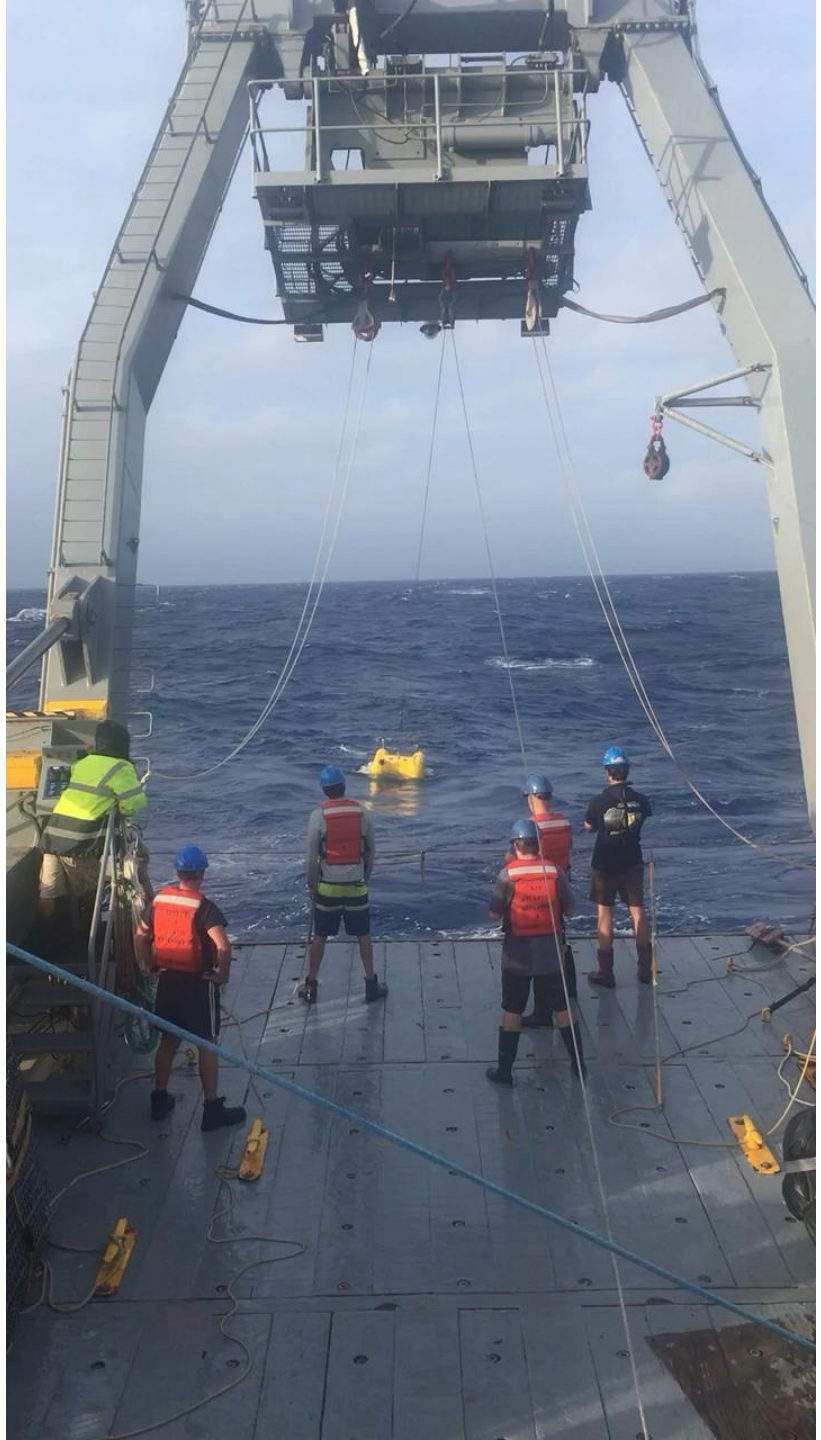
Biogeochemical AUV Clio: *in situ* microbial biomass collection



Avg 2,320 L per dive
Took ~13 hours
8-18 depths
0.2-51 µm
11 days

- Lagrangian drift
- Vertical movement to max 6,000 meters
  - <5 cm resolution
- Outfitted with physicochemical sensors
  - Collects bulk seawater

Cohen et al. 2024 *Nature Communications*



AUV *Clio*



Mak Saito (WHOI), Mike Jukuba (WHOI), Chip Breier (UTRGV)

Assembling and annotating large metatranscriptomes

1.8 billion sequences
11 million open reading frames
77,438 proteins

Arianna Krinos (WHOI)



Database = PhyloDB + NCBI RefSeq genomes + EukProt

allenlab.ucsd.edu
ftp.ncbi.nih.gov/refseq
Richter et al. 2022

Harriet Alexander (WHOI)



eukrhythmic

EUKulele

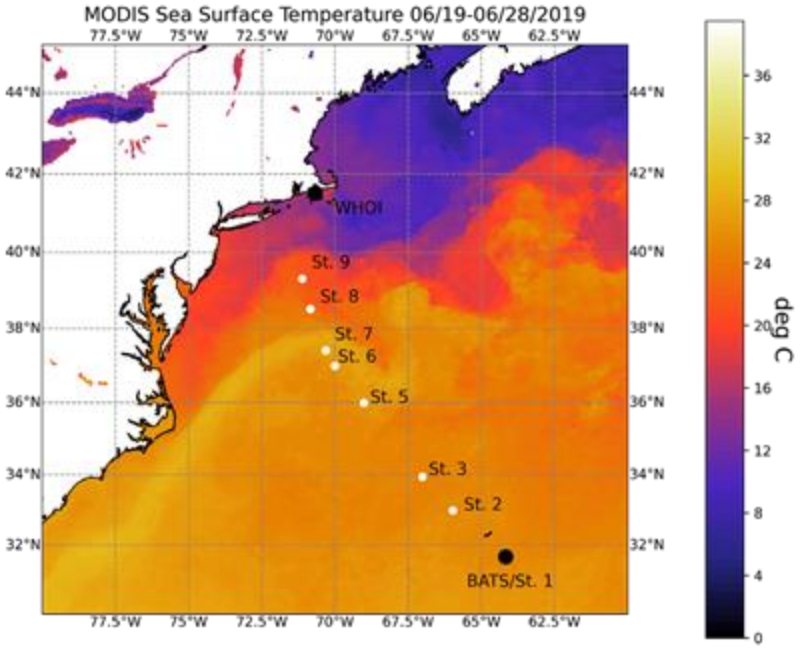


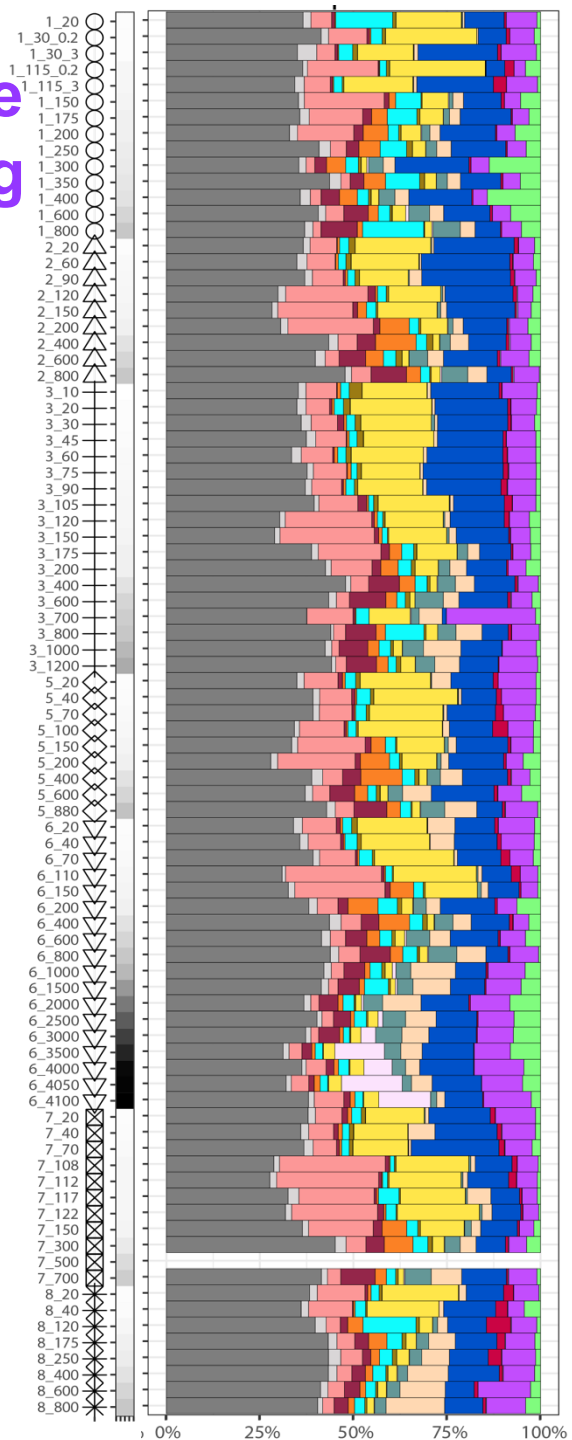
eukulele.readthedocs.io

Cohen et al. 2024, Krinos et al. 2021, Cohen et al. 2022
Krinos et al. 2023

github.com/AlexanderLabWHOI/EUKulele
github.com/AlexanderLabWHOI/eukrhythmic

What was the microeukaryote community composition along the western North Atlantic?





Bermuda (offshore)

Woods Hole (coastal)

proteins

Haptophytes

Dinoflagellates

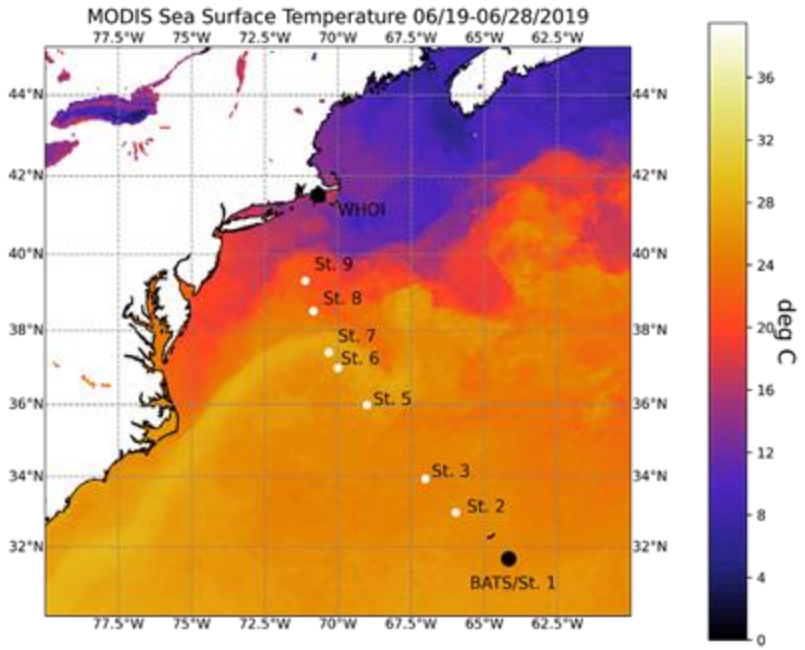
Stramenopiles

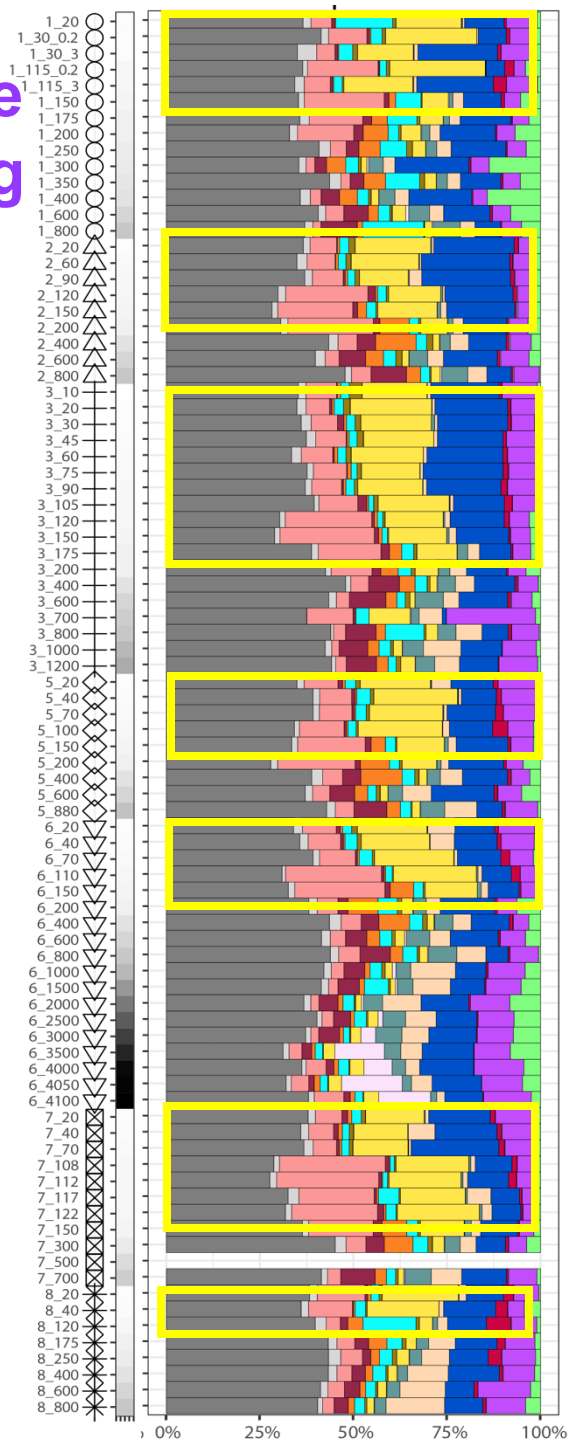
depth
4000
3000
2000
1000

site
1
2
3
5
6
7
8

Cohen et al. 2024 *Nature Communications*

What was the microeukaryote community composition along the western North Atlantic?





Bermuda (offshore)

Woods Hole (coastal)

proteins

Haptophytes

Dinoflagellates

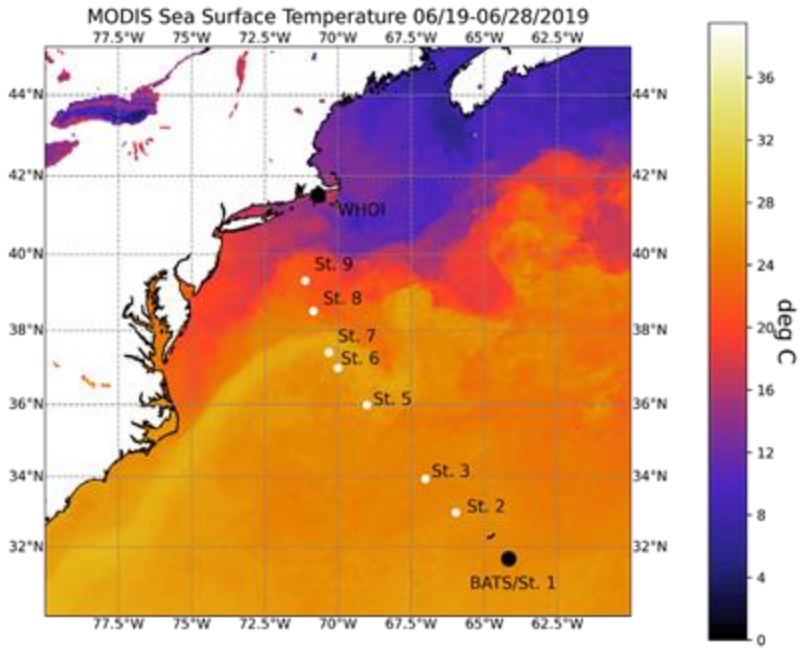
Stramenopiles

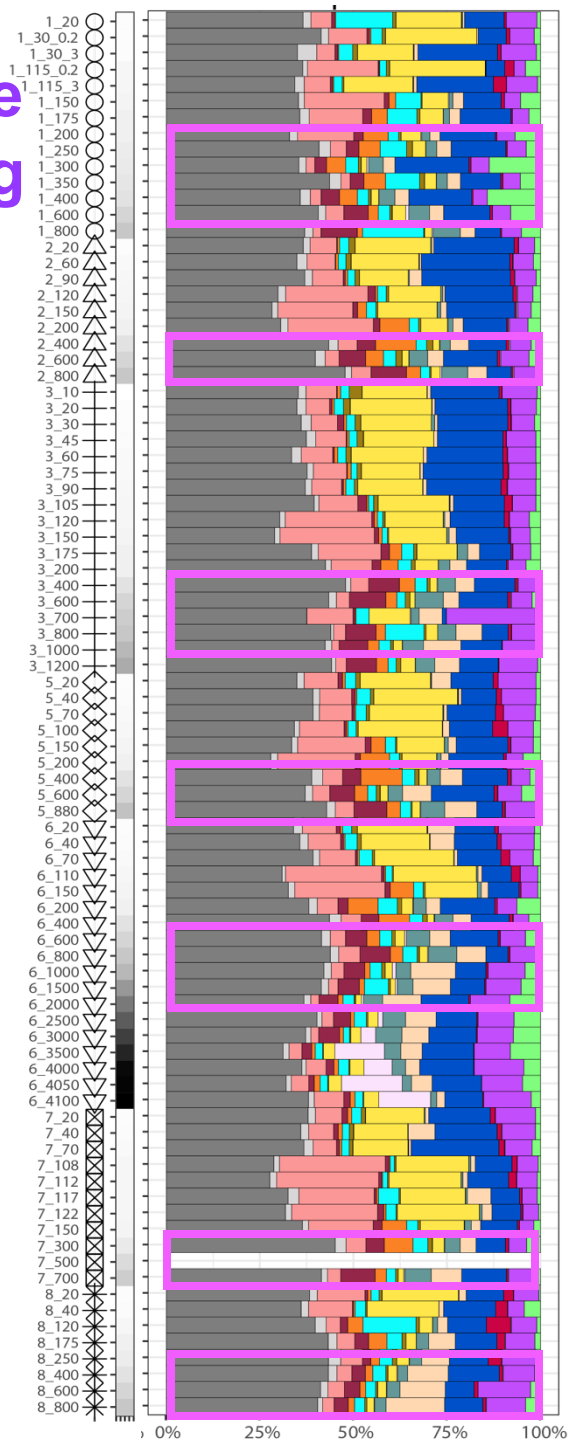
depth
4000
3000
2000
1000

site
1
2
3
5
6
7
8

Cohen et al. 2024 *Nature Communications*

What was the microeukaryote community composition along the western North Atlantic?





Bermuda (offshore)

Woods Hole (coastal)

proteins

Haptophytes

Dinoflagellates

Stramenopiles

Picozoa

Radiolaria

Foraminifera

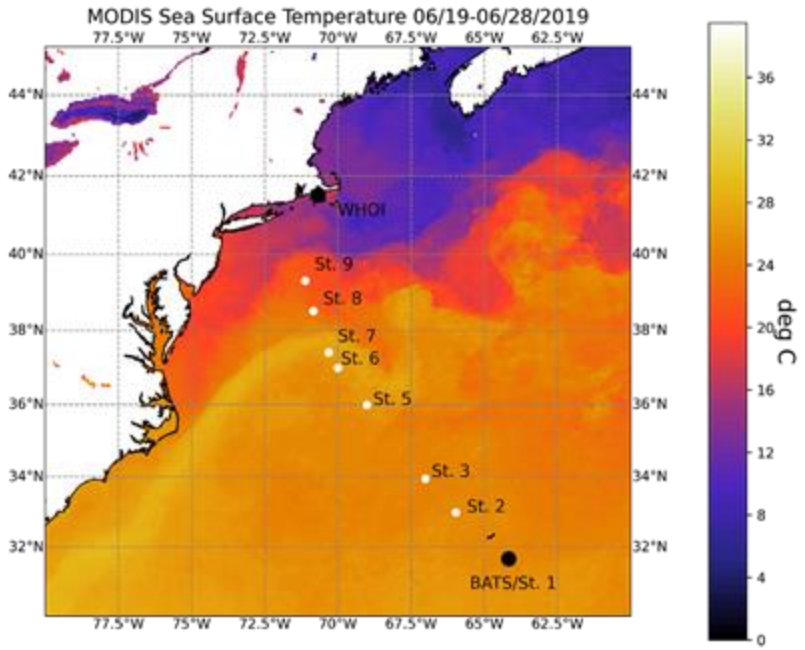
Discoba

depth
4000
3000
2000
1000

site
1
2
3
5
6
7
8

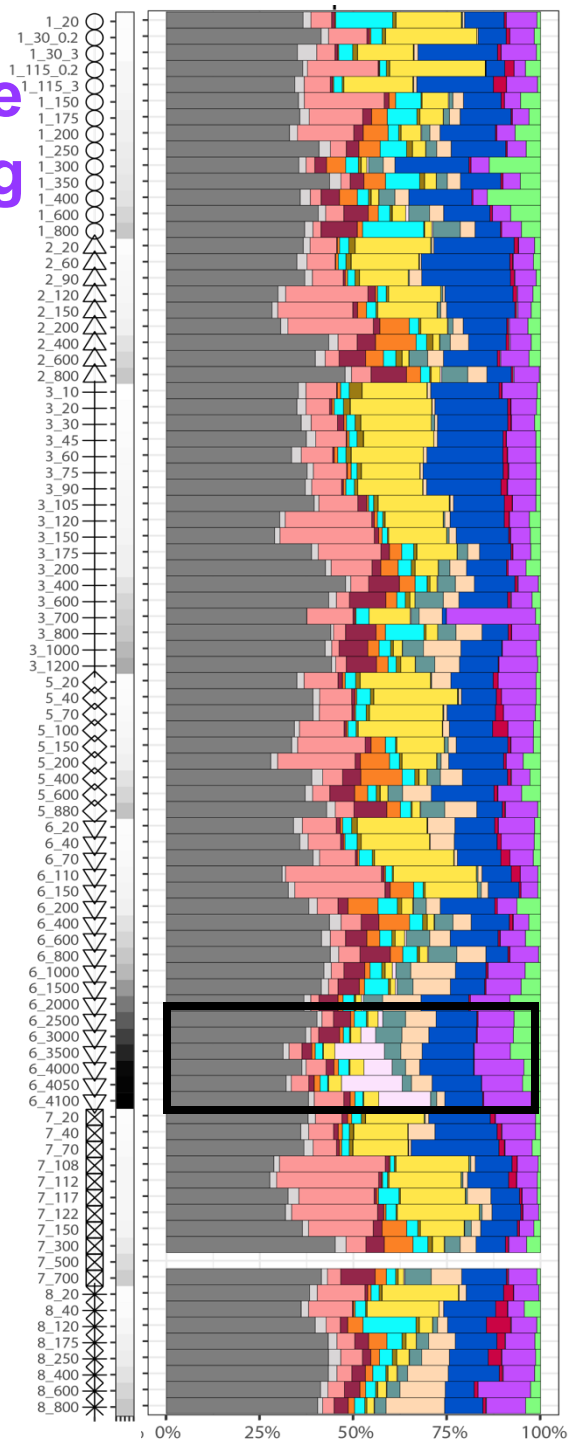
Cohen et al. 2024 *Nature Communications*

What was the microeukaryote community composition along the western North Atlantic?



Proteins indicate shifts in community composition with depth

Cohen et al. 2024 *Nature Communications*



Bermuda (offshore)

Woods Hole (coastal)

proteins

Haptophytes

Dinoflagellates

Stramenopiles

Picozoa

Radiolaria

Foraminifera

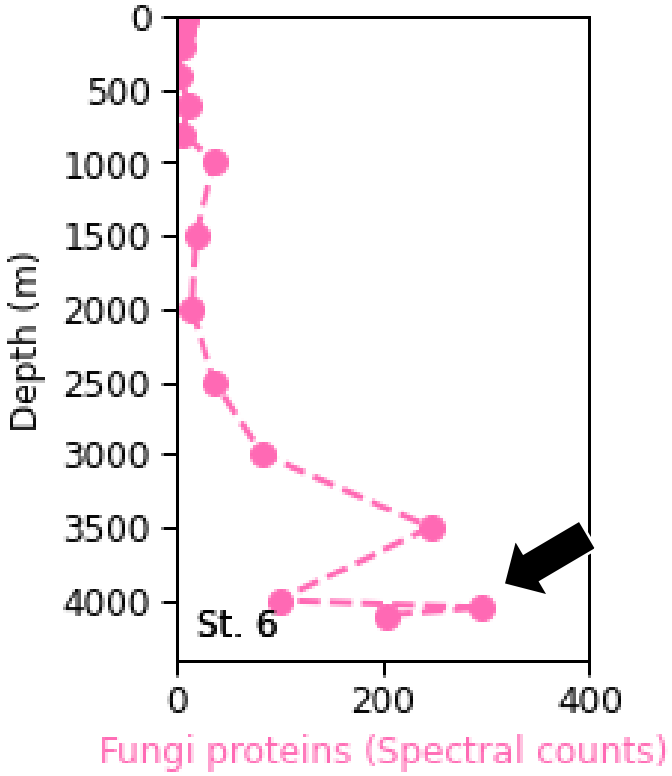
Discoba

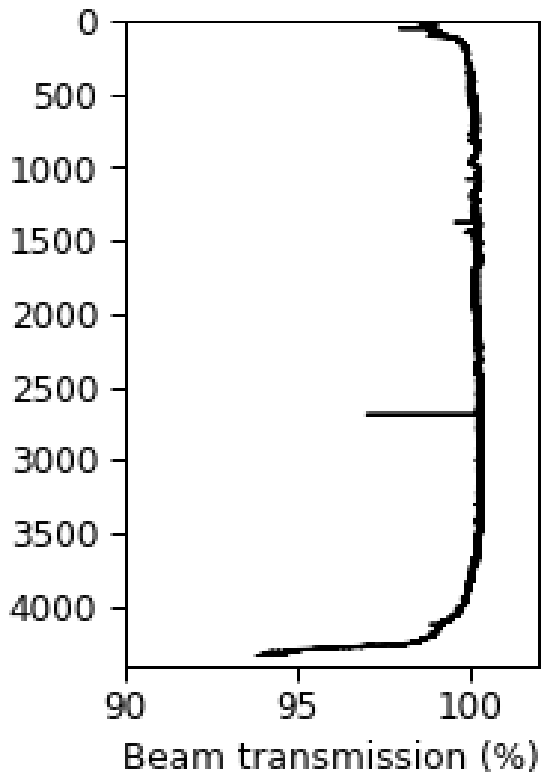
Fungi

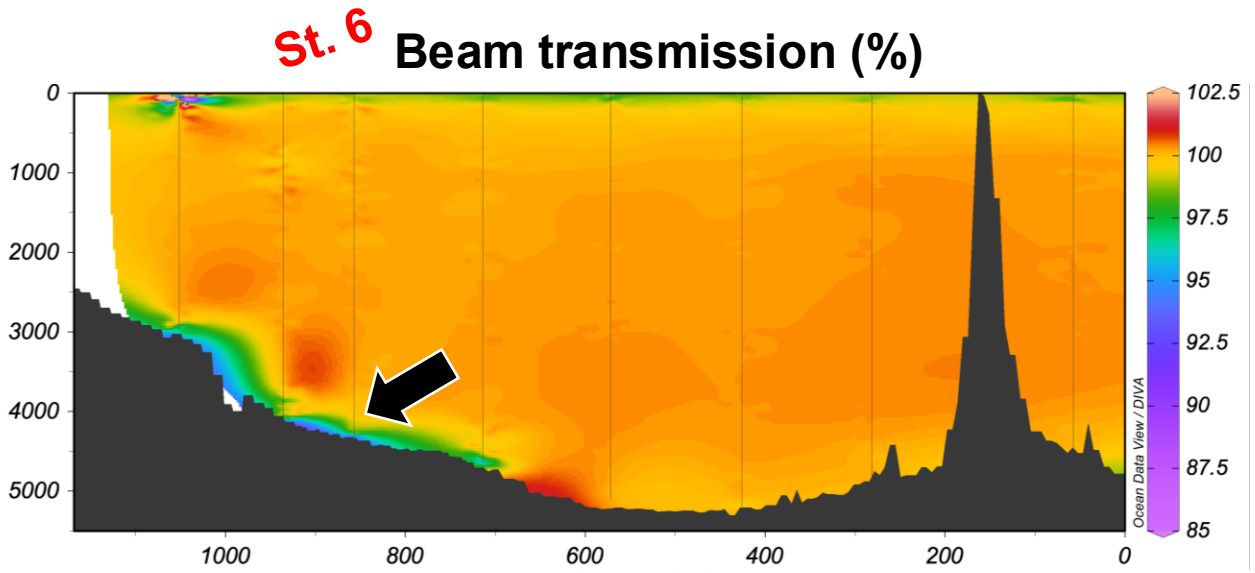
depth
4000
3000
2000
1000

site
1
2
3
5
6
7
8

Fungi within a nepheloid layer



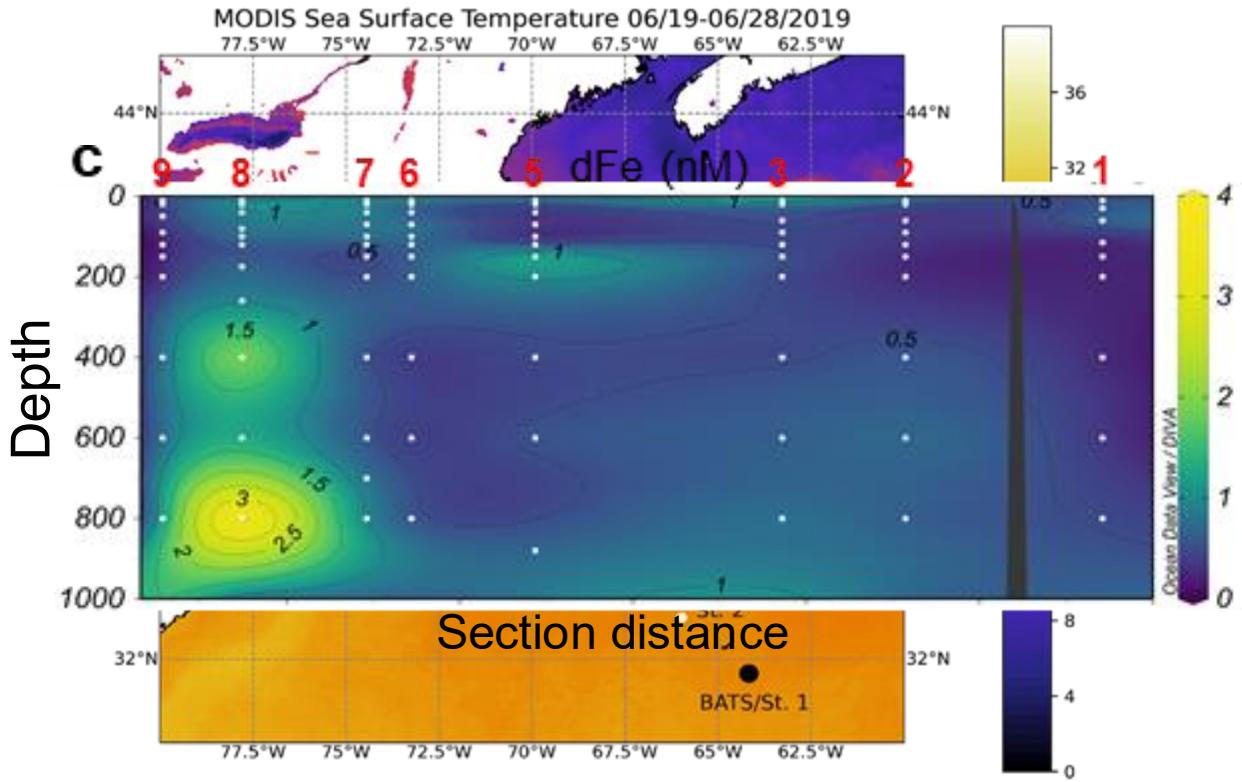




Lithogenic material with enrichment of organics (Lam et al. 2015)
Particulate metal concentrations elevated (Noble et al. 2016)
Fungi are consumers of organics throughout the water column (Bachy et al. 2022)

Cohen et al. 2024 *Nature Communications*

Nitrogen stress near coastline, phosphate stress offshore

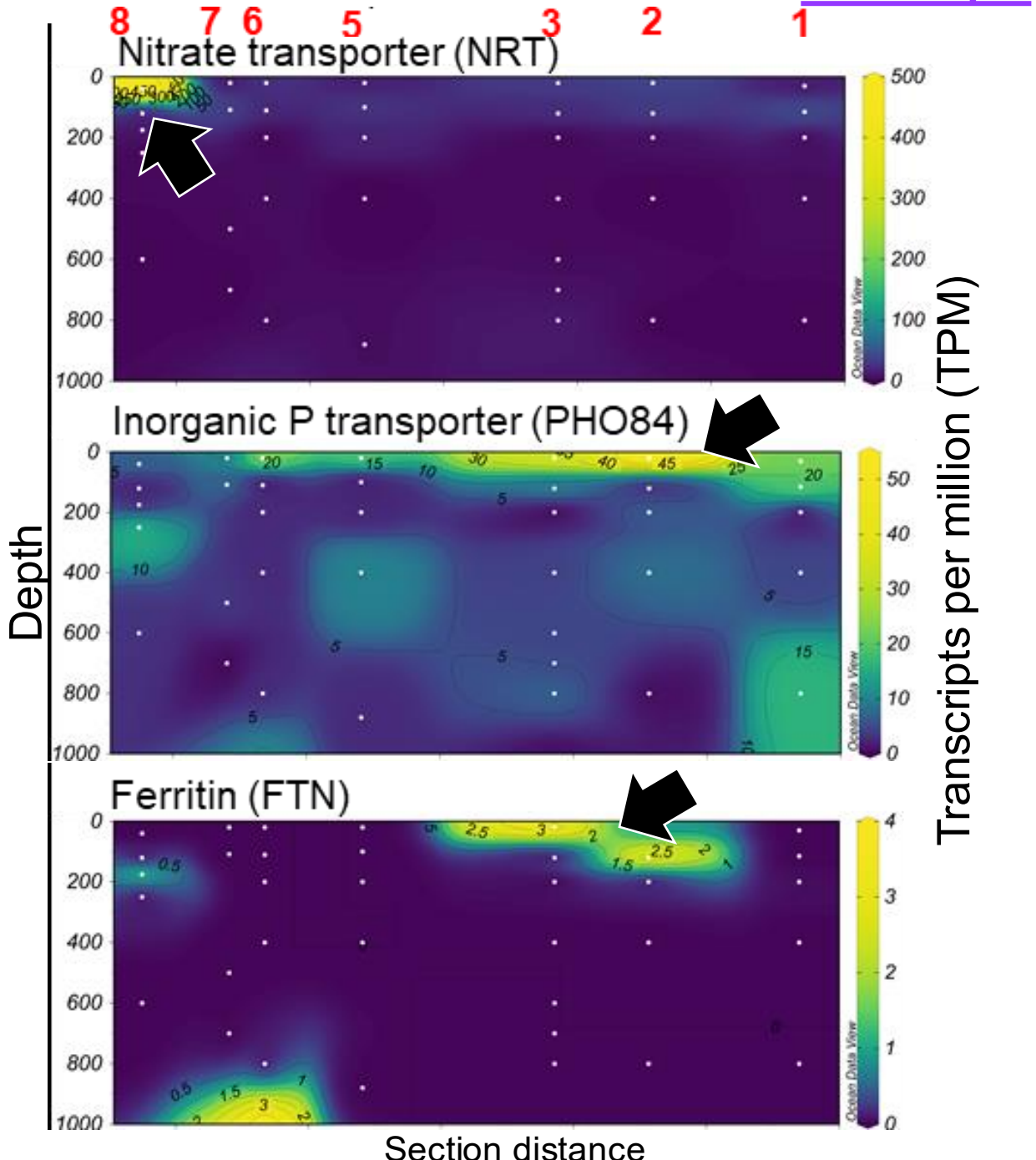


Aeolian-sourced Fe and N may promote P stress

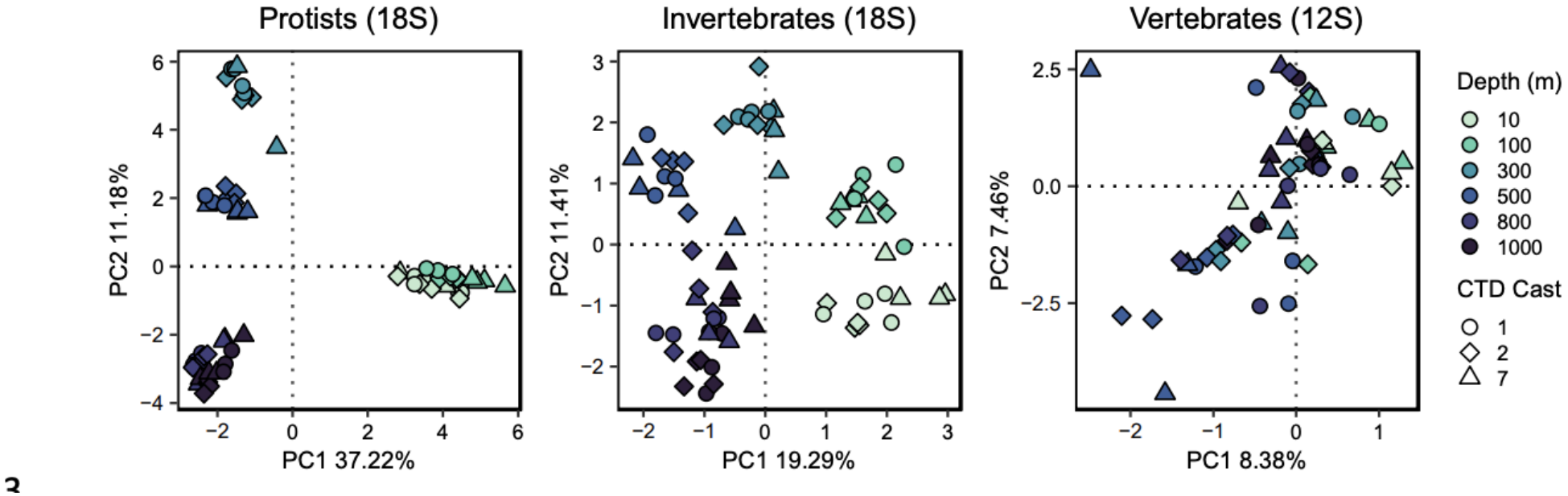
(Baker et al. 2003)

Cohen et al. 2024 *Nature Communications*

transcripts



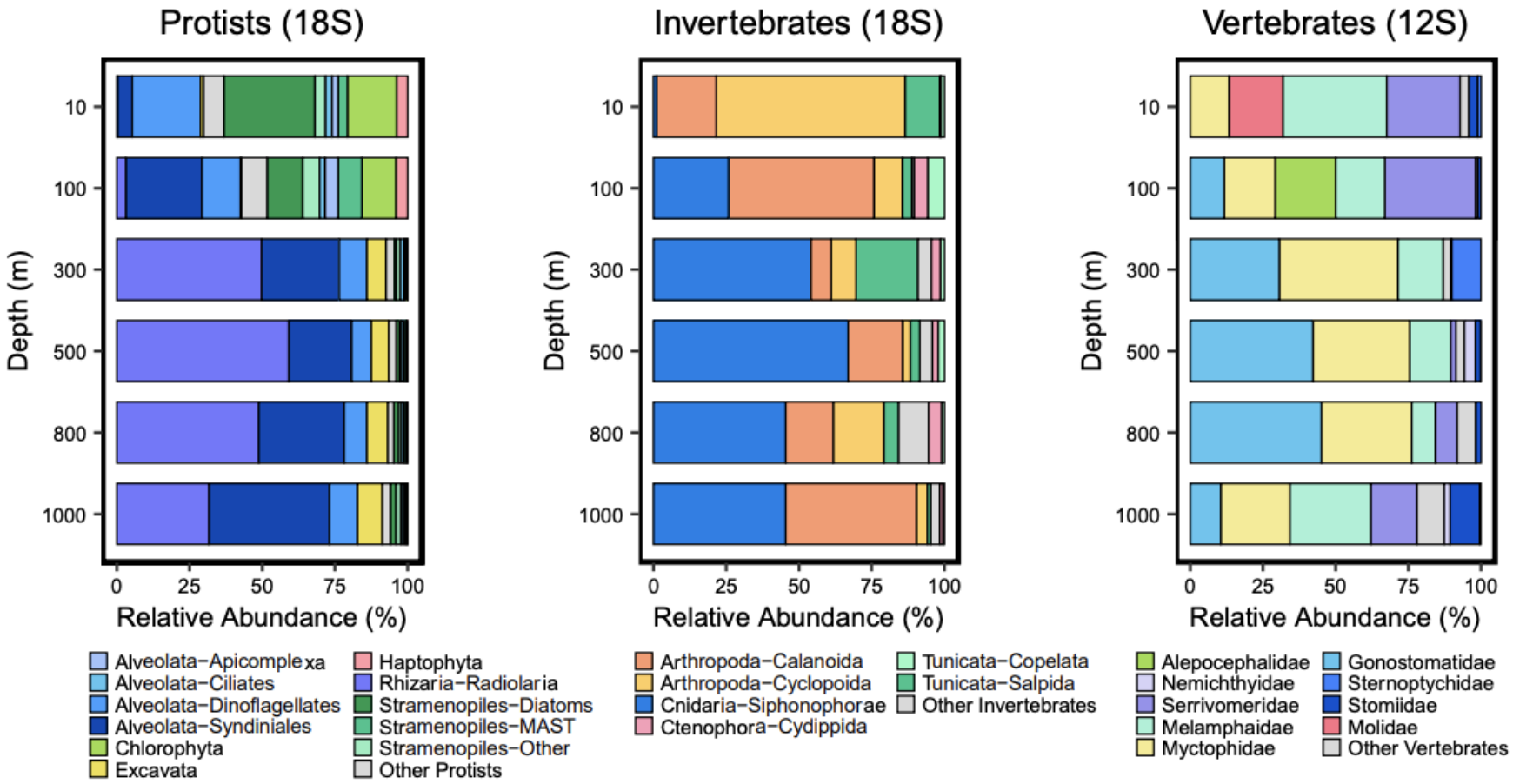
Mesopelagic eukaryote biodiversity



- eDNA/amplicon sequencing – microeukaryotes, invertebrates, vertebrates
- from the Northwest Atlantic continental slope

Yang et al. *biorxiv*

Mesopelagic eukaryote biodiversity

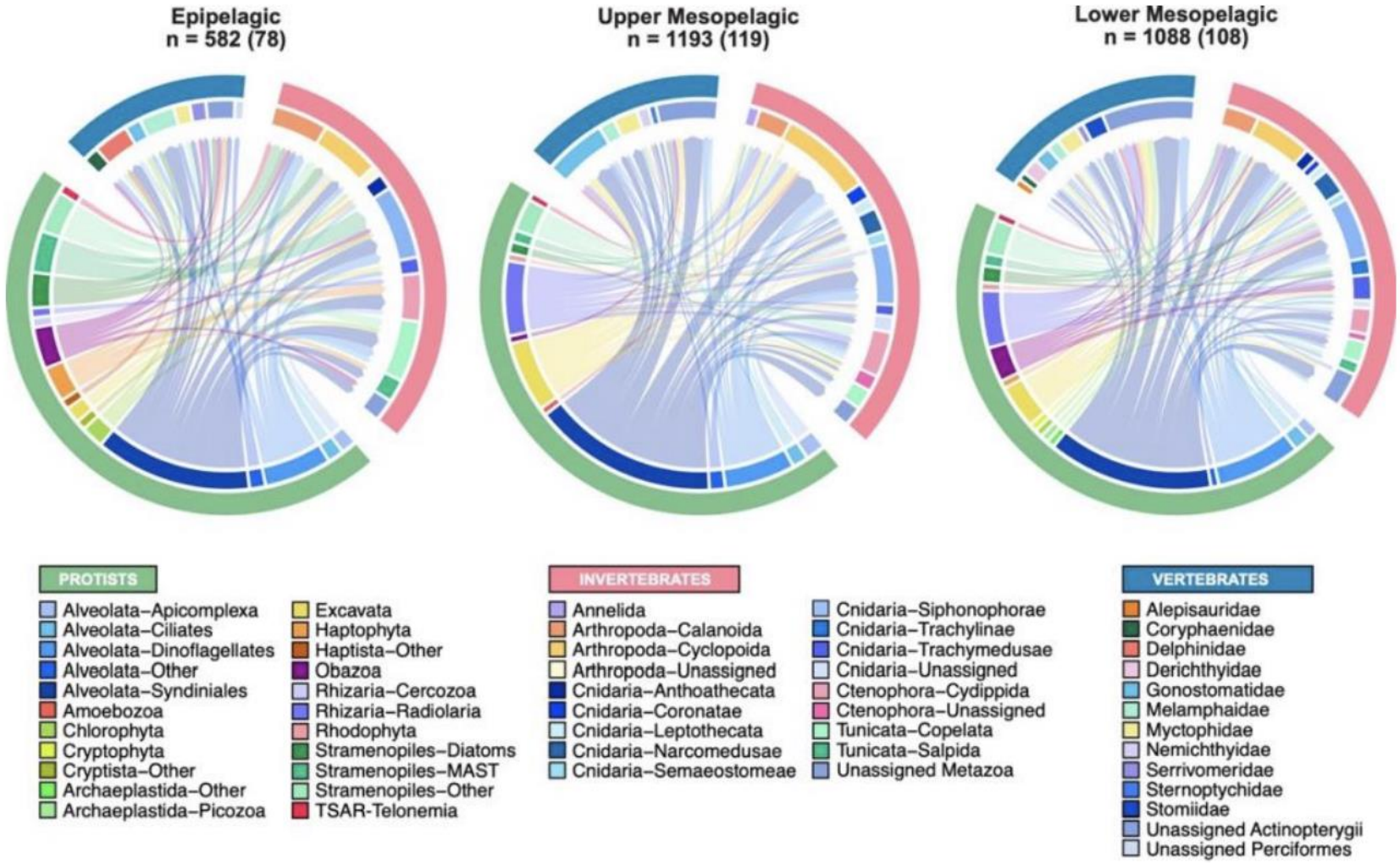


- Diatoms, certain copepods at surface
- Radiolaria and siphonores at depth

Yang et al. *biorxiv*

Mesopelagic eukaryote trophic interactions

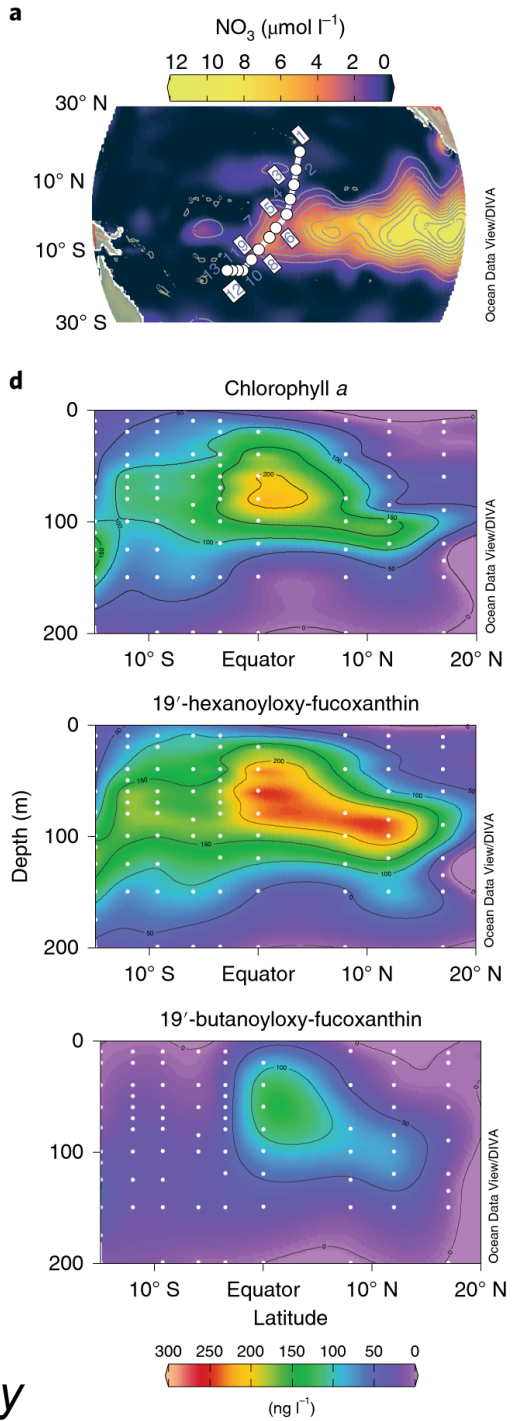
- Interactions across taxa with depth
- Parasites and hosts

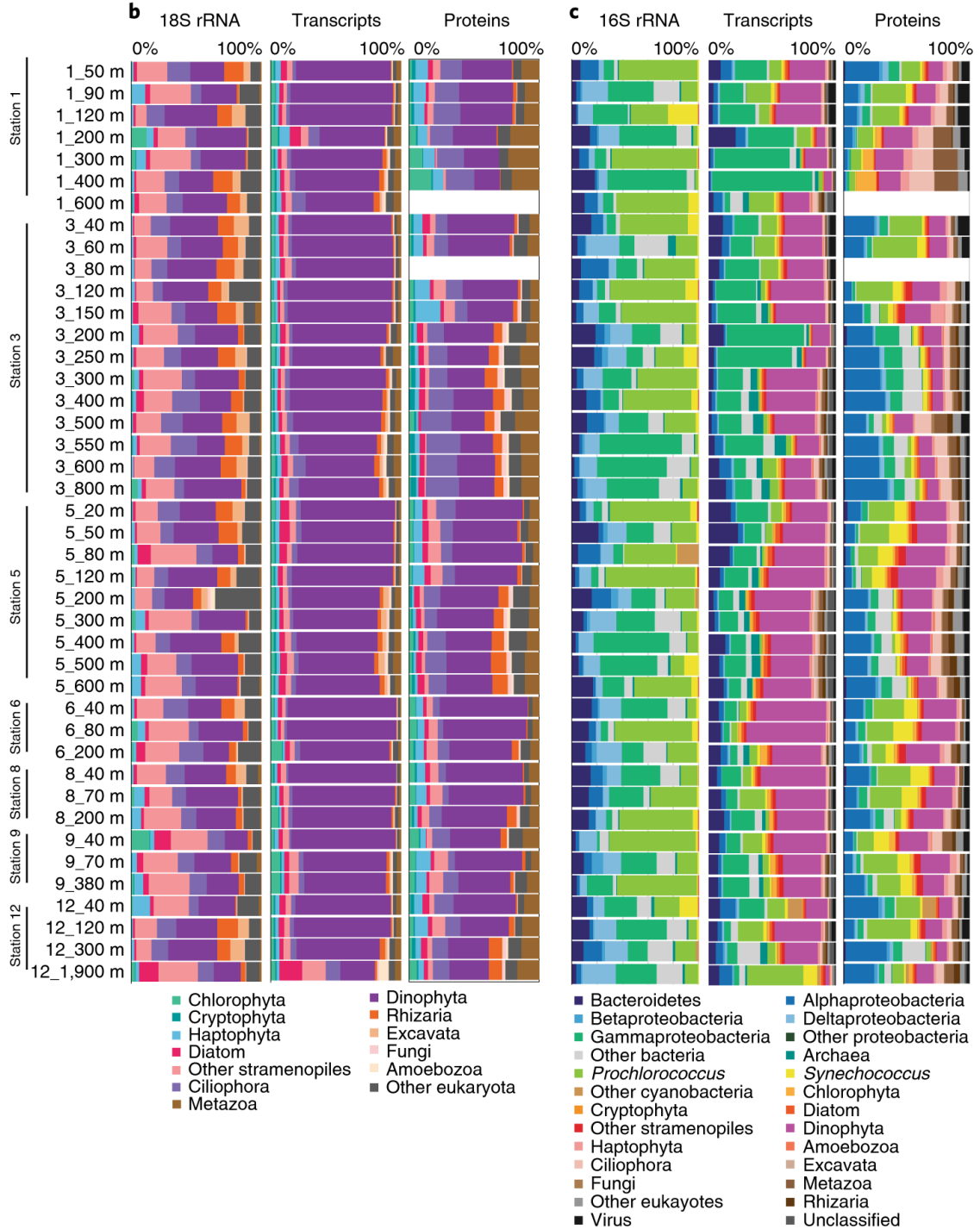


Yang et al. *biorxiv*

How is taxonomy and function impacted along a nutrient gradient?

- Sampled across a low nitrogen-low iron gradient
- Mostly dinoflagellates in the surface and mesopelagic
- Cyanobacteria rapidly decrease in relative abundance below 100 m

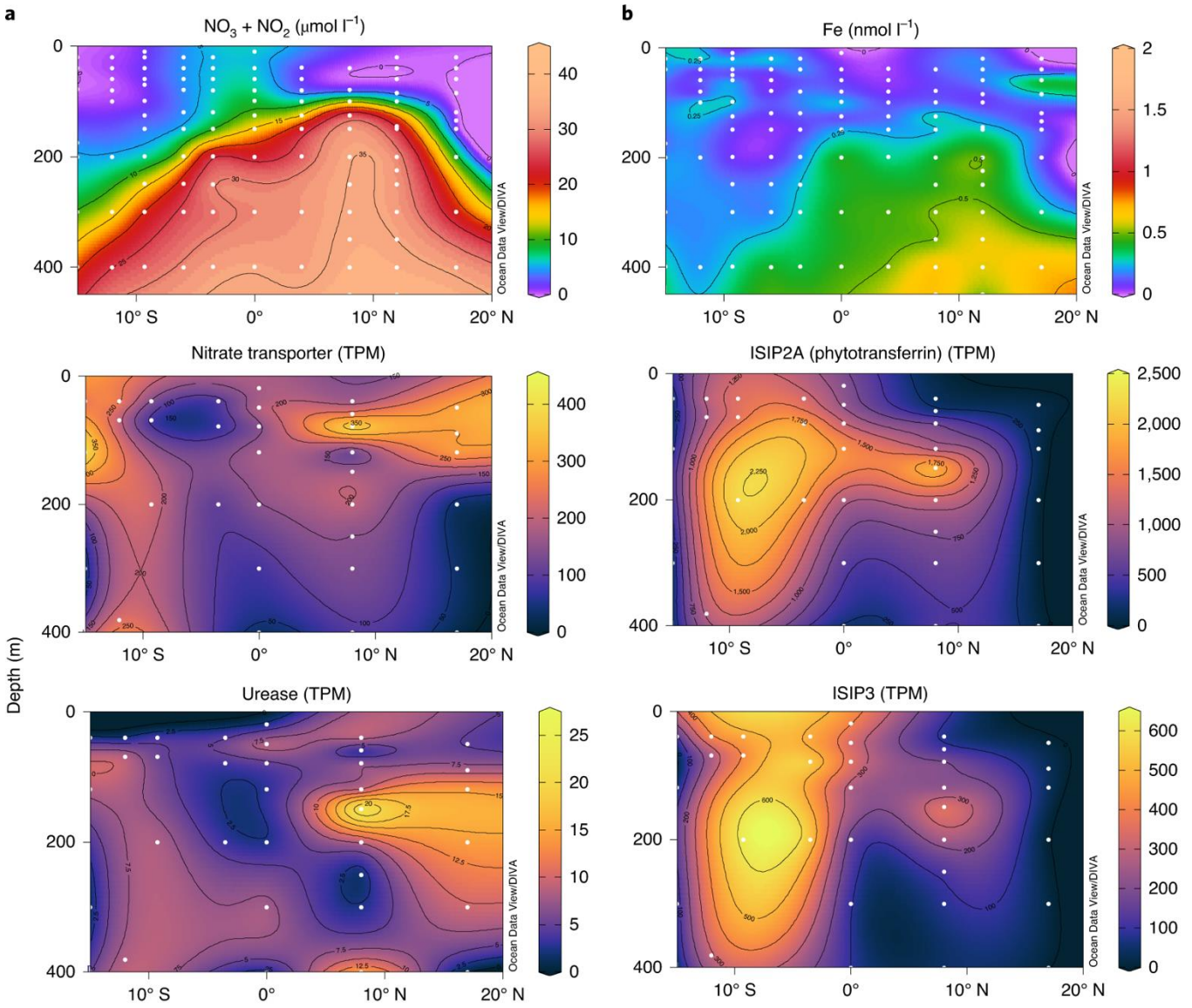




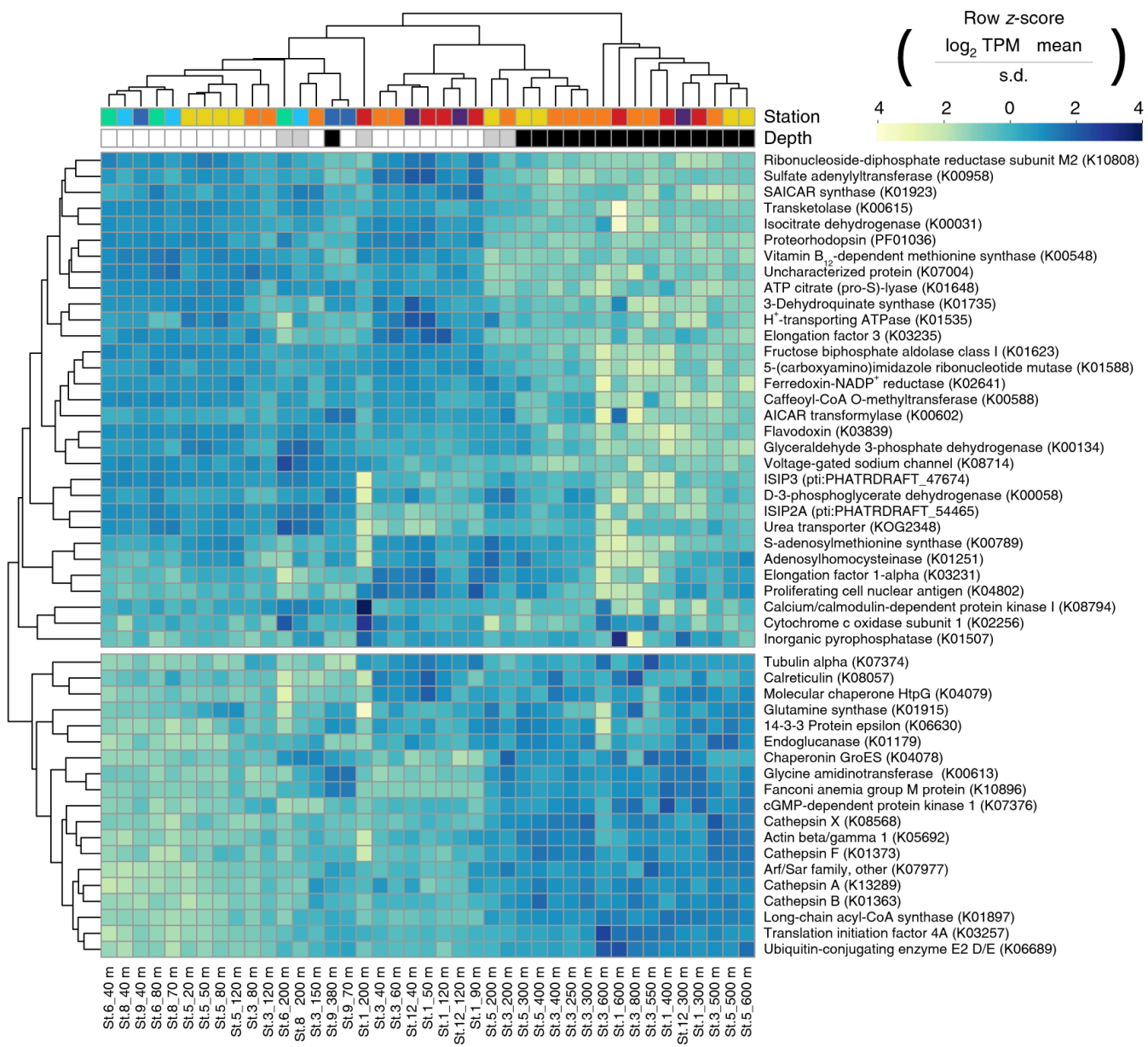
Cohen et al. 2021 *Nature Microbiology*

Alternating nitrate and iron stress

- Nitrate transporters, urease, urea transporter in oligotrophic gyres
- Iron transporters, a different urea transporter in the equatorial (low Fe) region
- Dinoflagellates are relatively abundant and responsive to changes in nutrient conditions



Cohen et al. 2021 *Nature Microbiology*

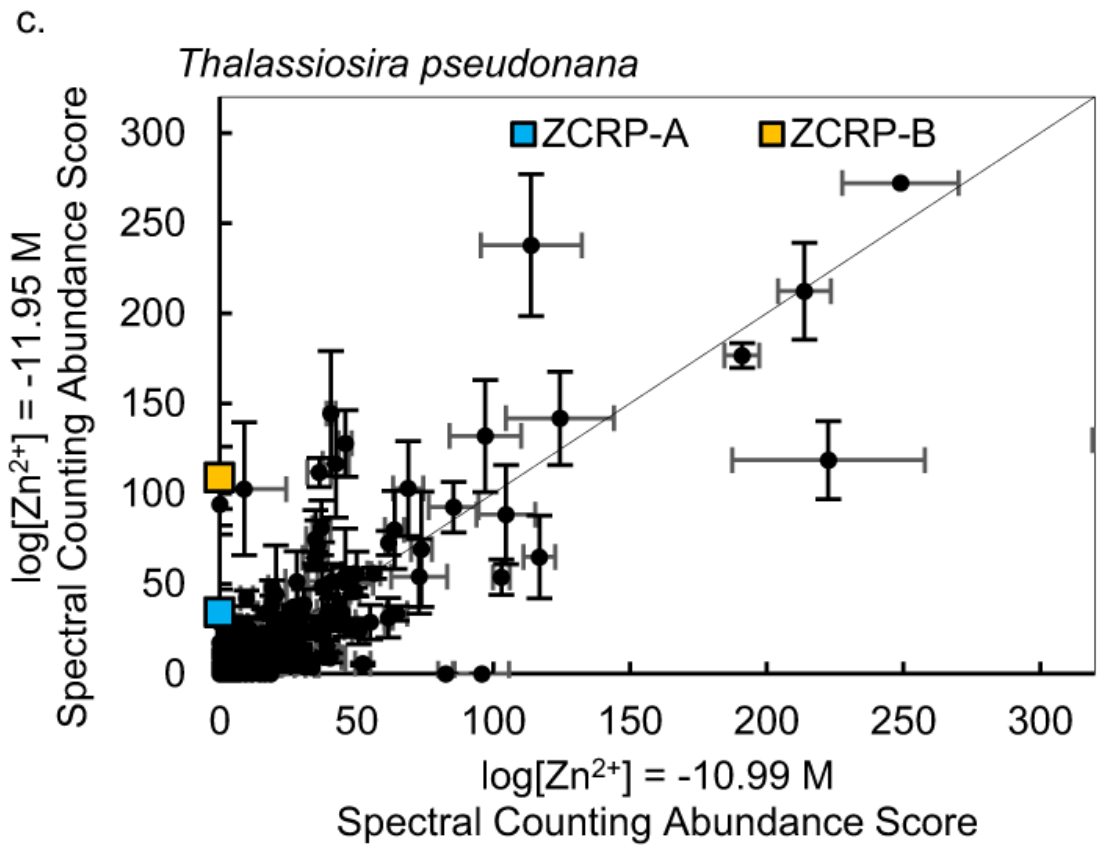


Distinct transcriptomic signatures in surface vs. mesopelagic

- Surface dinoflagellates engaged in photosynthesis, rhodopsin, iron transport
- Deep communities invested in cytoskeletal components, proteases (cathepsins) potentially involved in phagotrophy
- Same dinoflagellate genus/species?

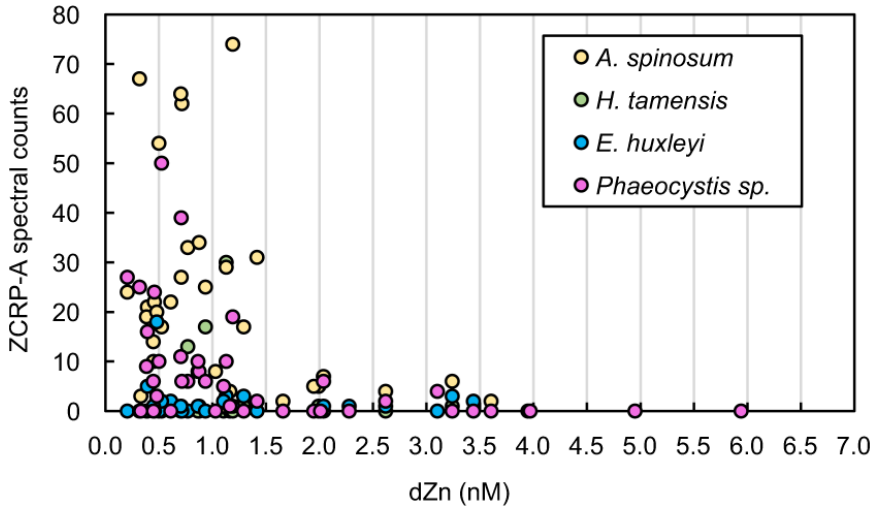
Cohen et al. 2021 *Nature Microbiology*

Development of zinc stress biomarkers and application in the central Pacific Ocean

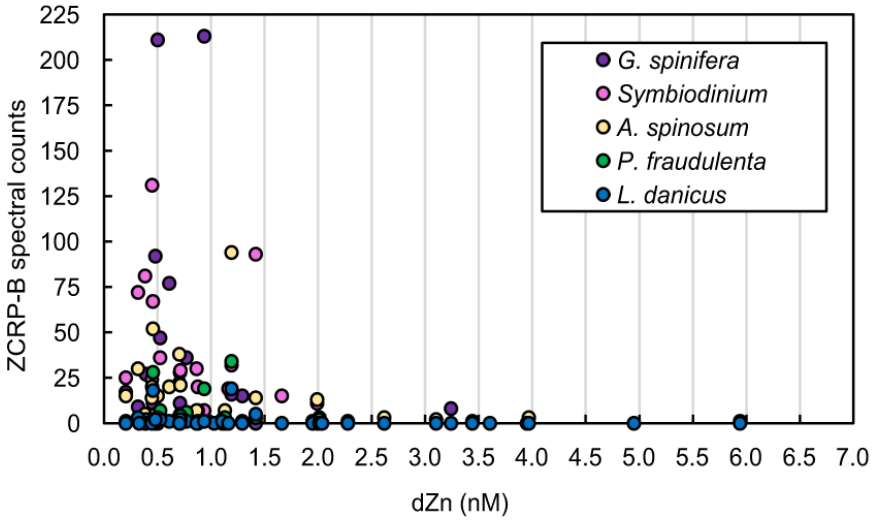


Kell et al. 2022 *Nature Communications*

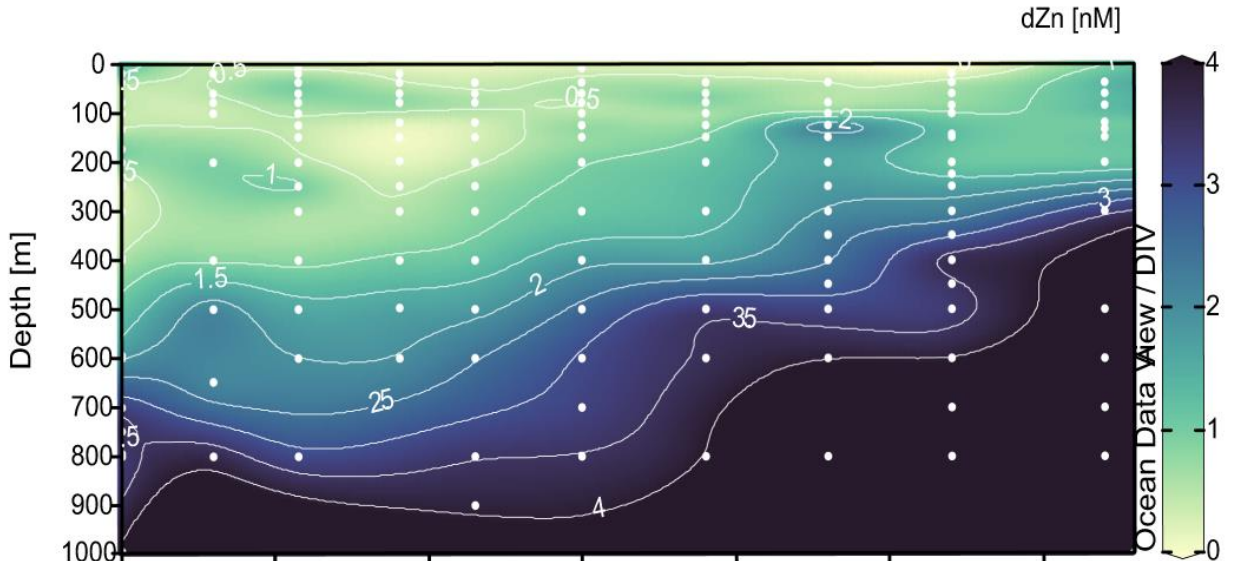
Development of zinc stress biomarkers and application



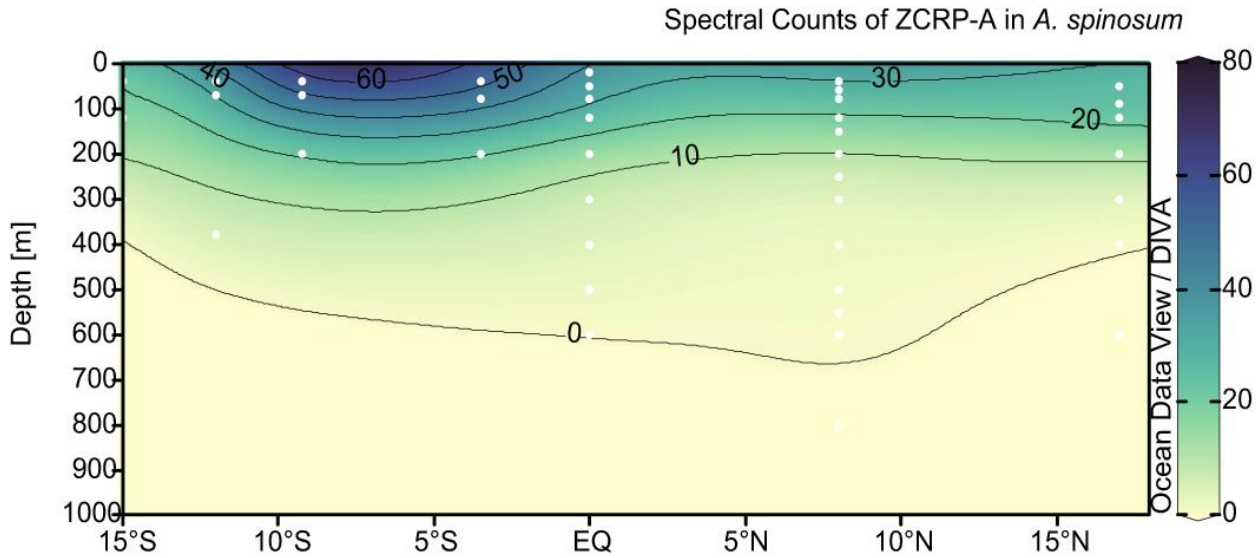
g.



c.



d.



Kell et al. 2022 *Nature Communications*

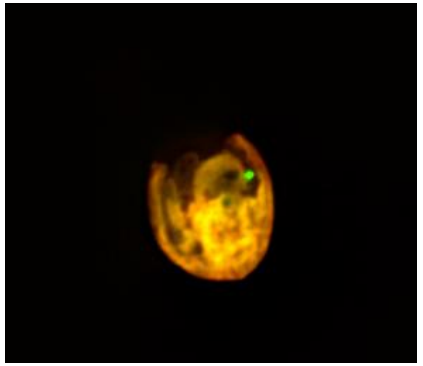
Tracking mixotrophy using omics

a machine learning method to determine trophic mode of in situ planktonic populations based on metatranscriptomics

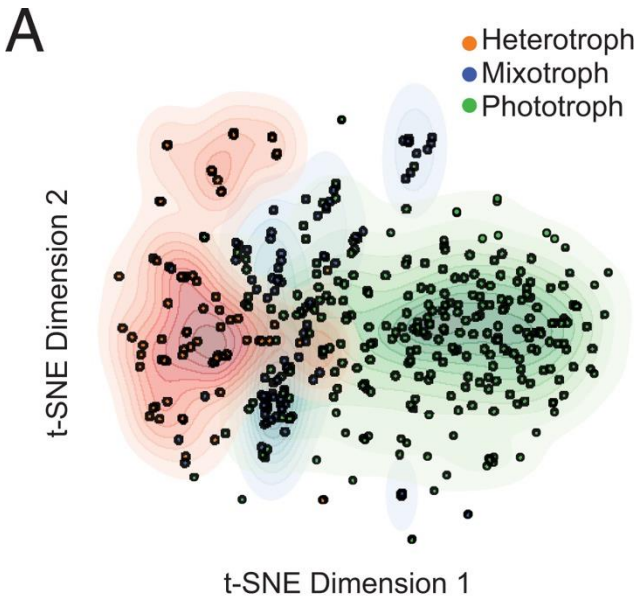
Trained using cultured representatives

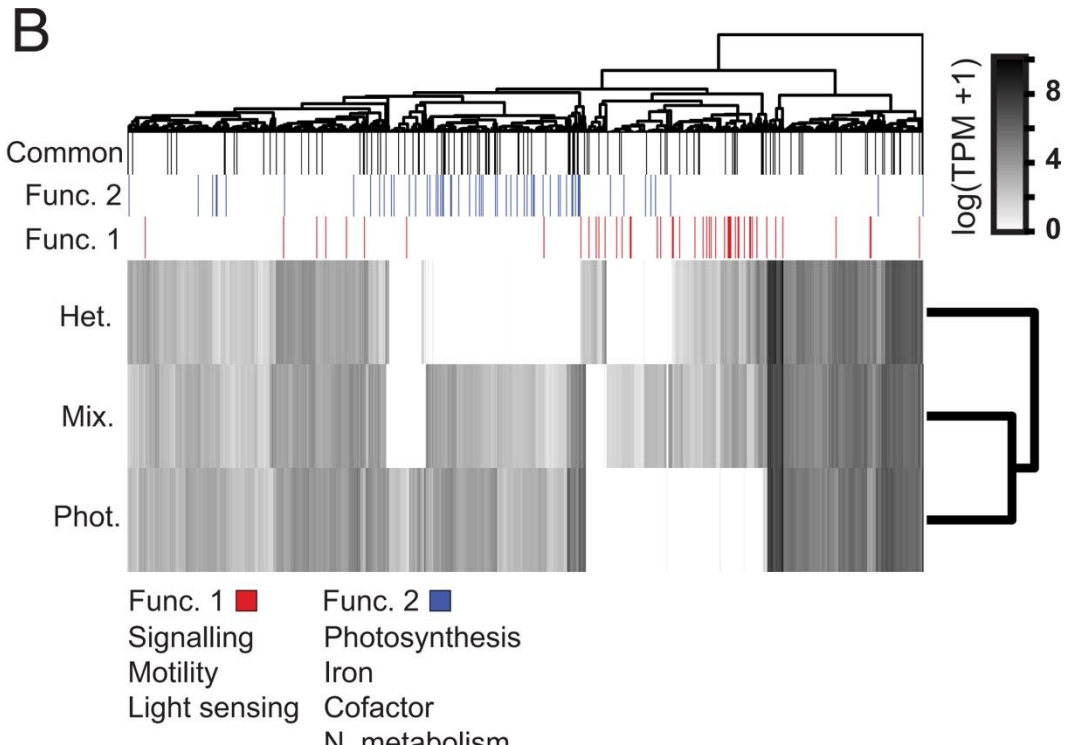
Genes involved in phagotrophy are not specific to this process

Gene models could be wrong!



Low probability of being heterotrophic (Burns et al. 2018)

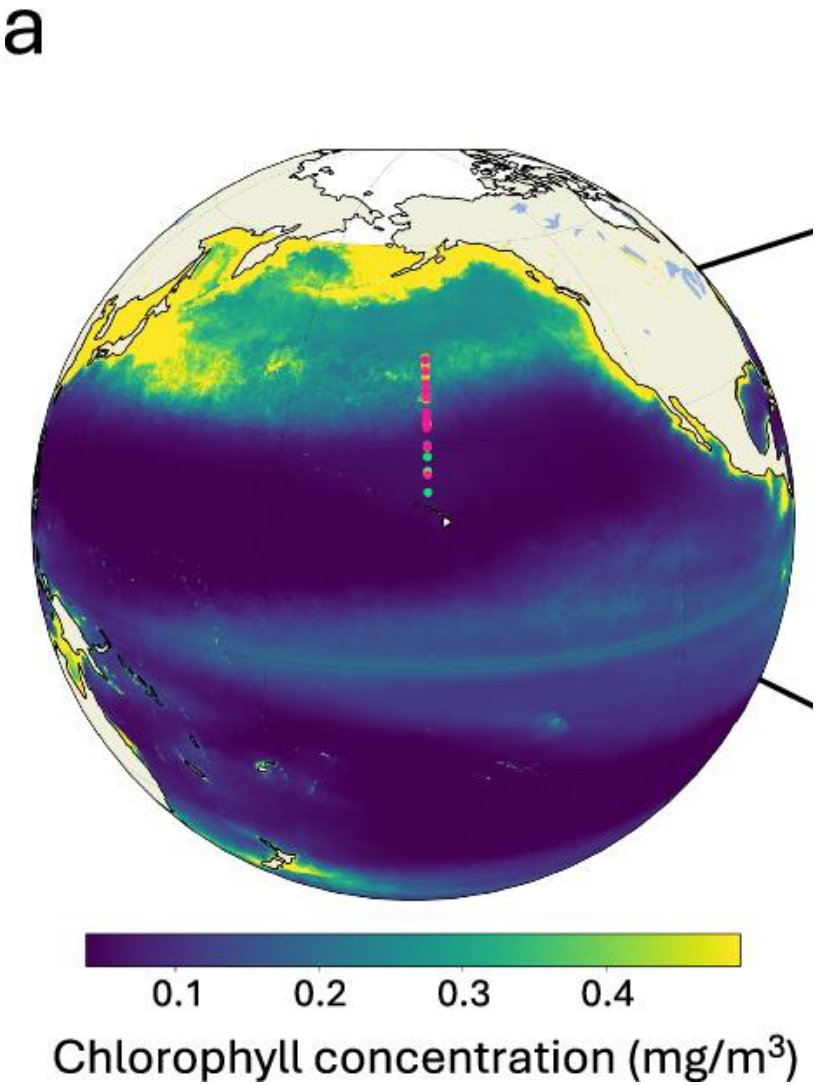




Lambert et al. 2022 *PNAS*

Tracking mixotrophy using omics

Applied to the North Pacific Ocean.
Resolved by taxa bins



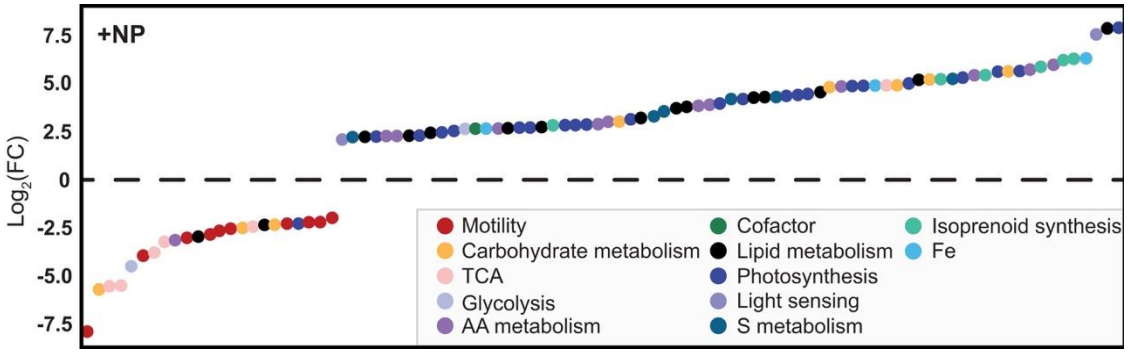
Lambert et al. 2022 *PNAS*

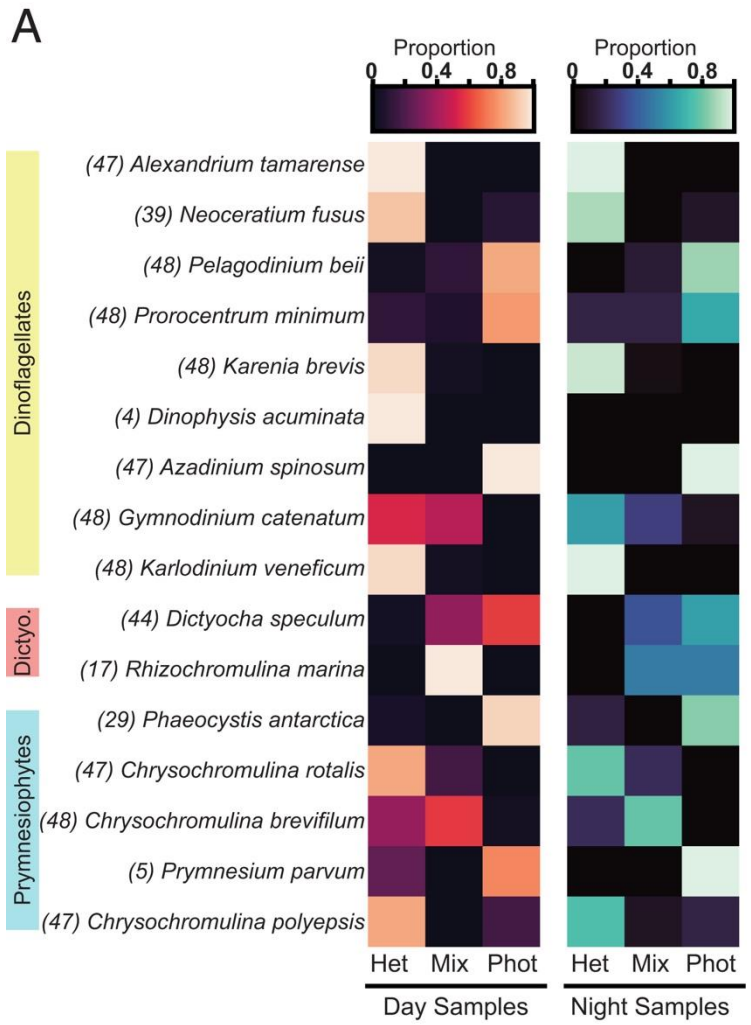
Tracking mixotrophy using omics

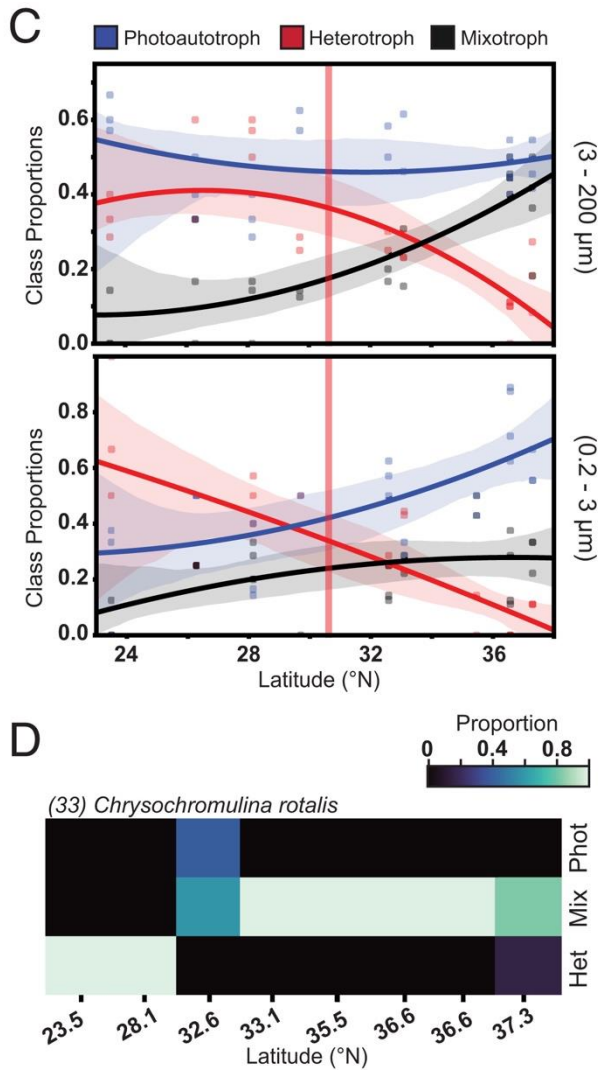
Applied to the North Pacific Ocean. Resolved by taxa bins

Organisms did not shift trophic mode based on day/night

Mixotrophic microeukaryotes shift their trophic mode in response to natural a nutrient gradient







Lambert et al. 2022 *PNAS*

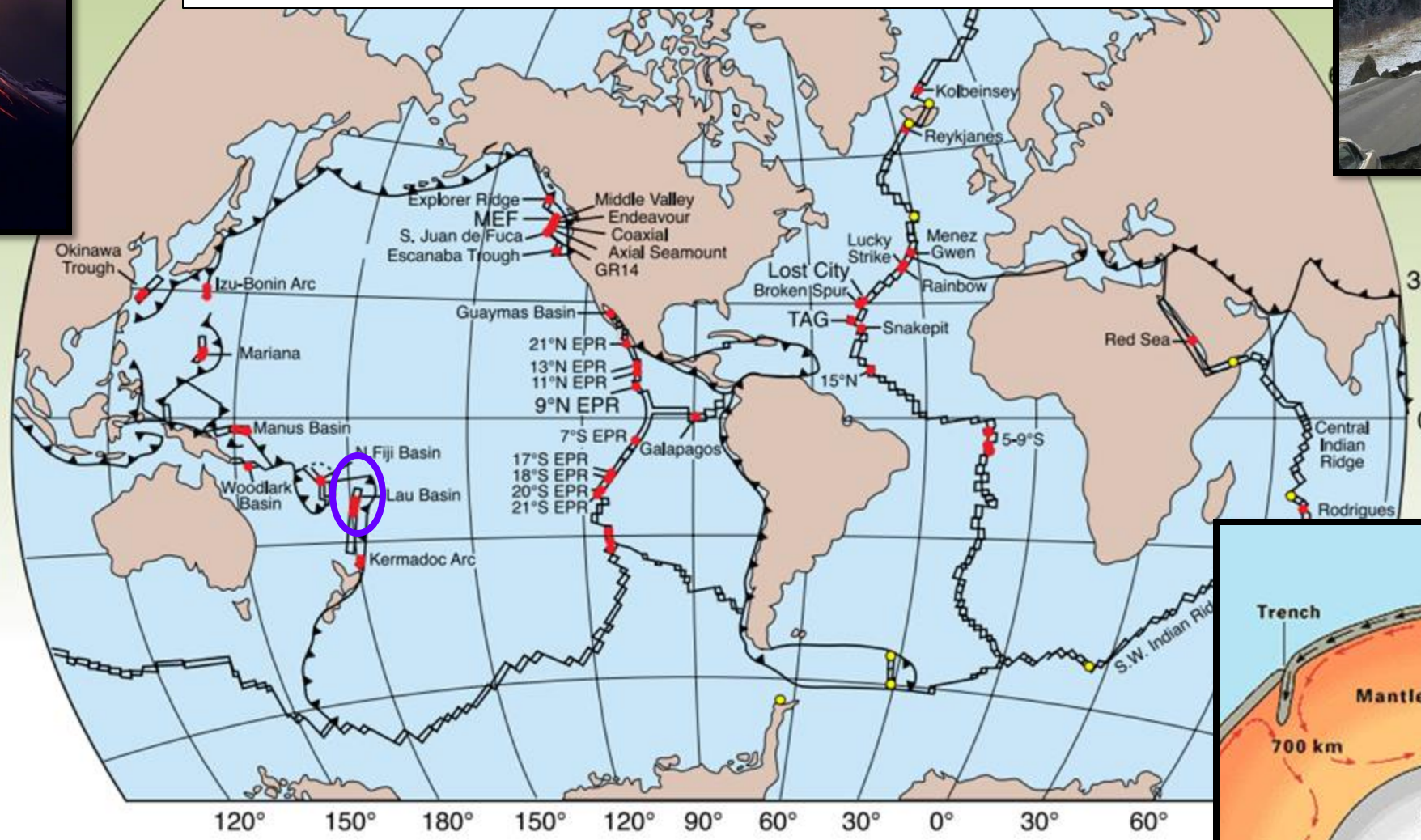
What have we learned from large omic investigations across gradients?

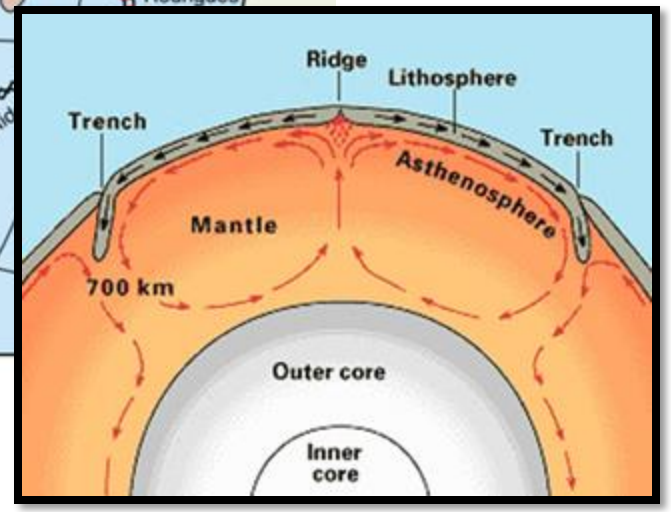
- Distinct community composition and functional metabolism at depth
  - Location dependent, potentially database dependent
- Changes in nutrient regime is evident in transcripts/proteins
- Can track shifts in metabolism and trophic mode
- Provides valuable biogeochemical insights when paired with direct observations (rate measurements, geochemistry)

Hydrothermal activity is associated with plate boundaries







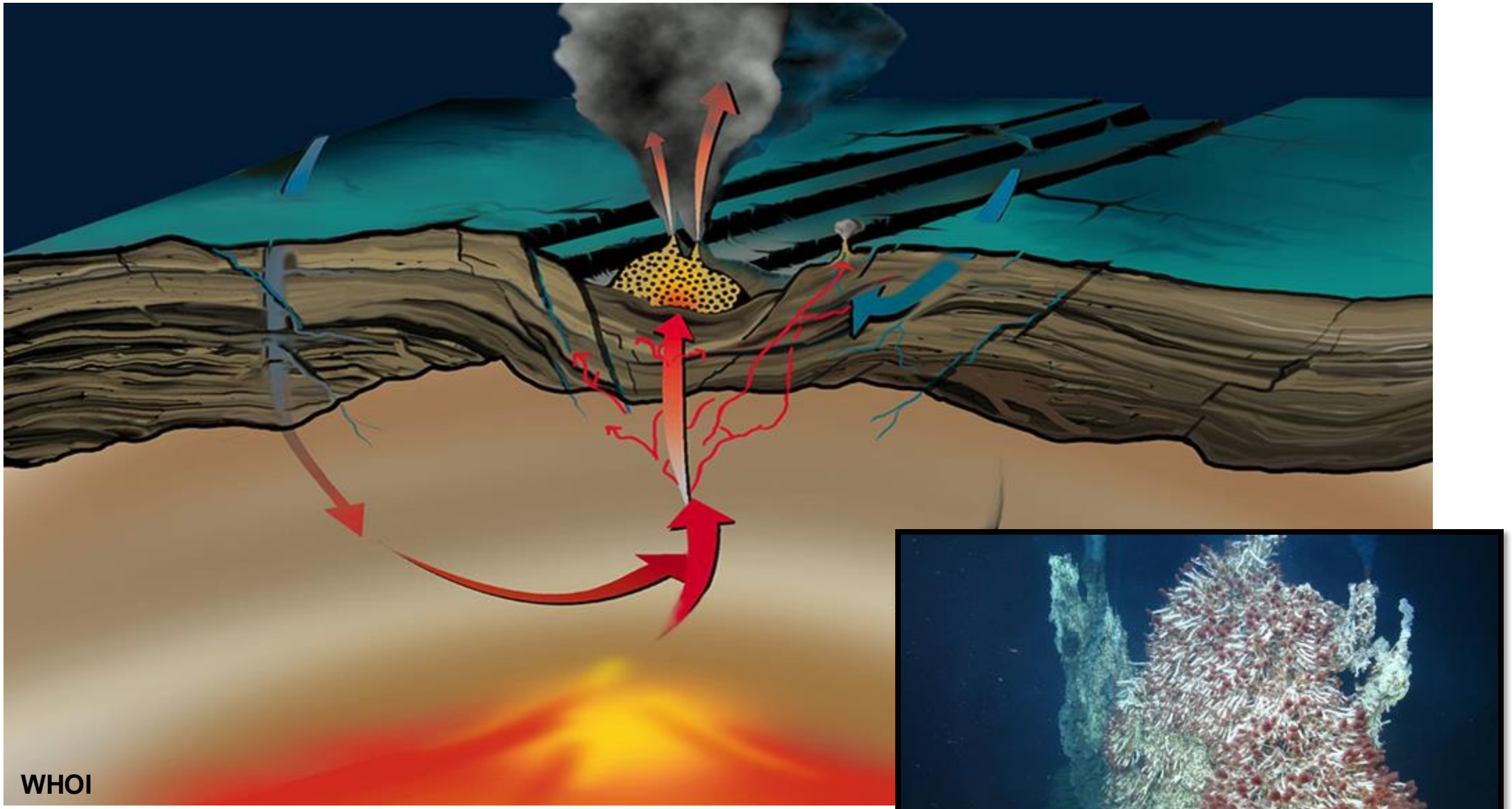


United States Geological Survey

https://www.youtube.com/watch?v=xFAu8CqCtR8

Tivey 2007 *Oceanography*

Plate tectonics: the structure of the earth's crust


WHOI
UMass

Biogeochemical & economic importance of hydrothermal systems

Hydrothermal Fe stimulates phytoplankton blooms!

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-09973-6 OPEN

Hydrothermal vents trigger massive phytoplankton blooms in the Southern Ocean

Mathieu Ardyna[1,2], Léo Lacour[1,3], Sara Sergi[4], Francesco d'Ovidio[4], Jean-Baptiste Sallée[4], Mathieu Rembauville[1], Stéphane Blain[5], Alessandro Tagliabue[6], Reiner Schlitzer[7], Catherine Jeandel[8], Kevin Robert Arrigo[2] & Hervé Claustre[1]

Article | Open Access | Published: 22 February 2021

Massive Southern Ocean phytoplankton bloom fed by iron of possible hydrothermal origin

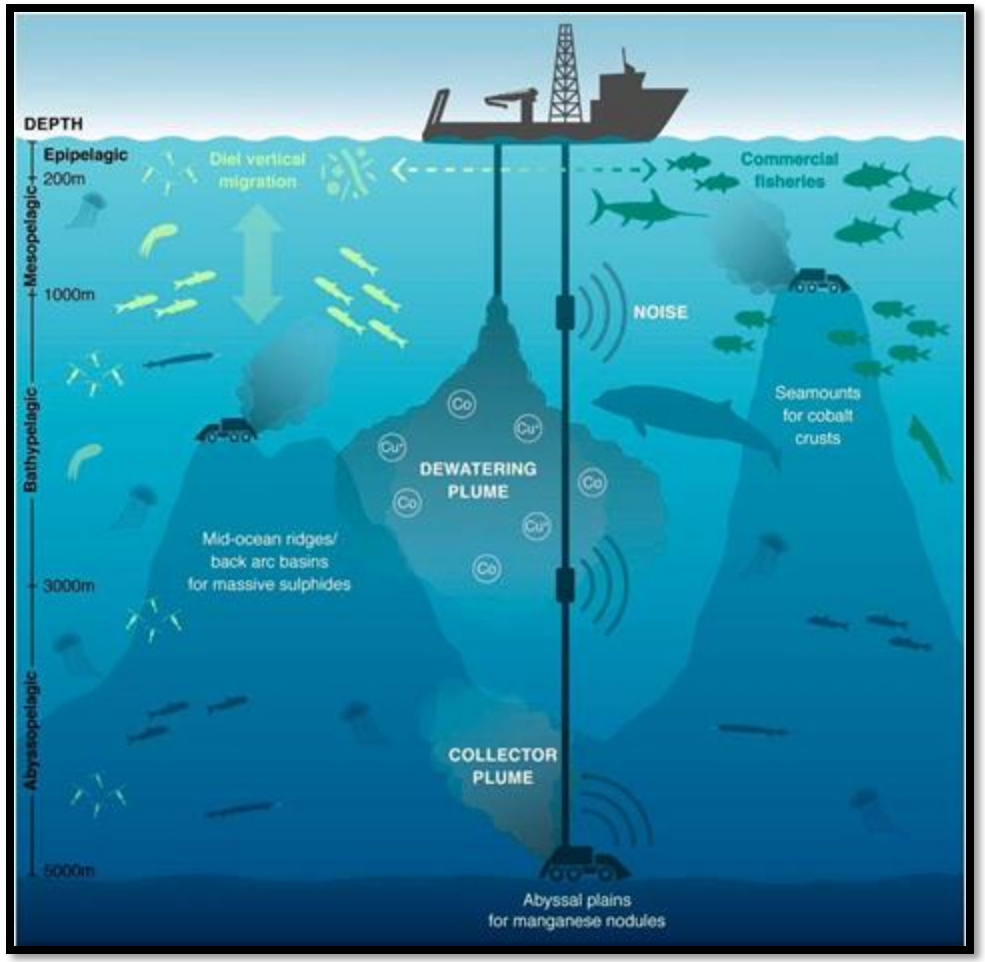
Casey M. S. Schine, Anne-Carlijn Alderkamp, Gert van Dijken, Loes J. A. Gerringa, Sara Sergi, Patrick Laan, Hans van Haren, Willem H. van de Poll & Kevin R. Arrigo

Nature Communications **12**, Article number: 1211 (2021) | Cite this article

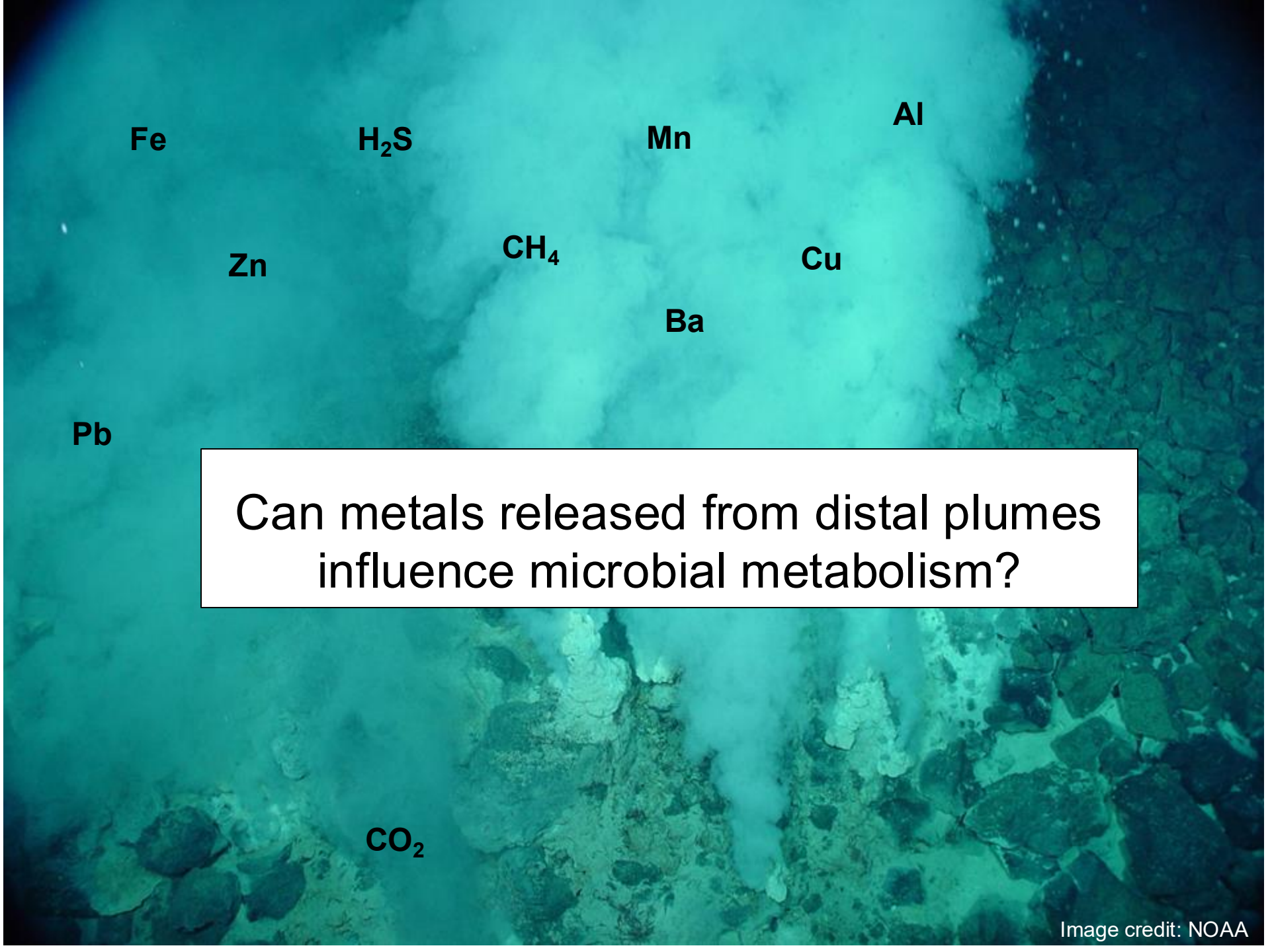
1022 Accesses | **30** Altmetric | Metrics

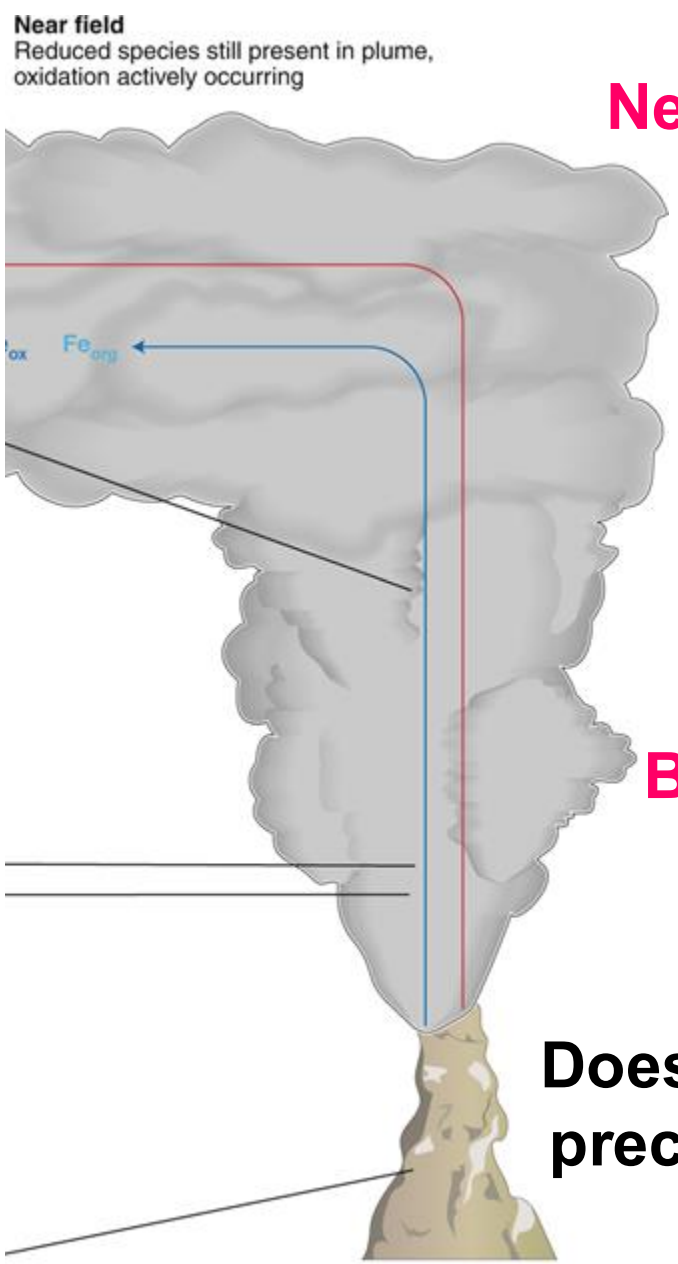
Ardyna et al. 2019 & Schine et al. 2021 *Nat Comm*

Deep sea mining to meet increasing economic demands?



Drazen et al. 2020 *PNAS*


Fe
H_2S
Mn
Al
Zn
CH_4
Cu
Ba
Pb
Can metals released from distal plumes influence microbial metabolism?
CO_2
Image credit: NOAA



Near field

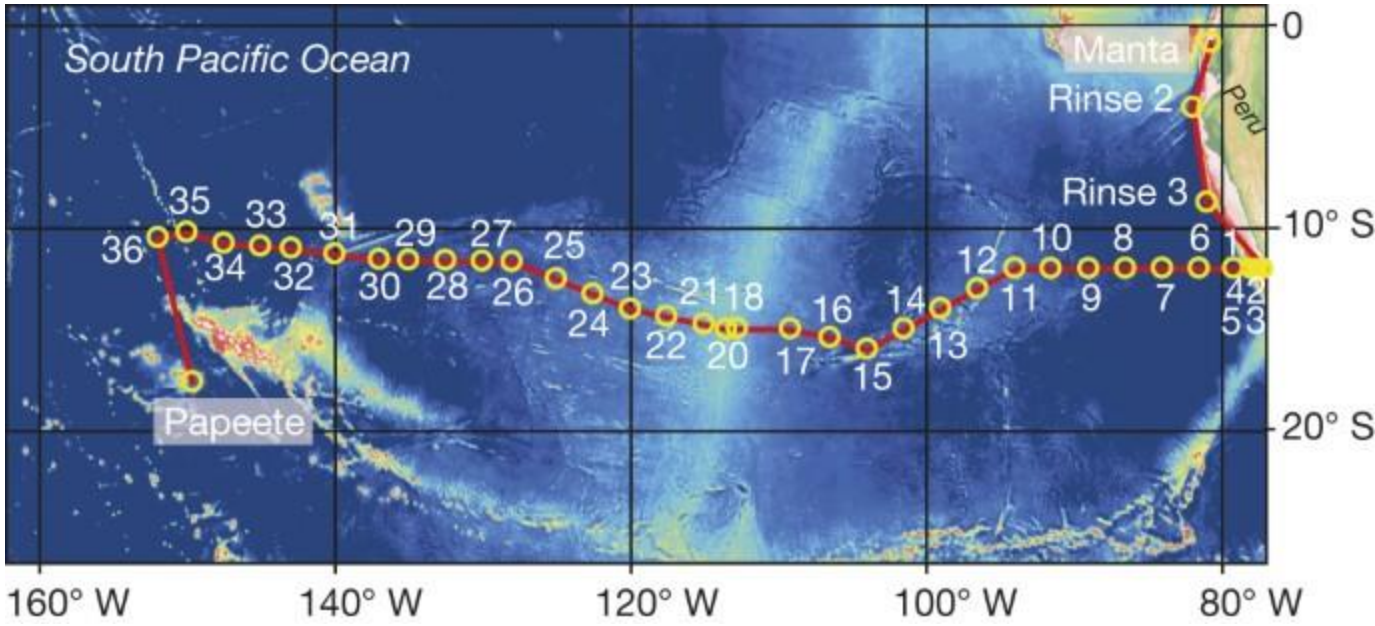
Buoyant plume

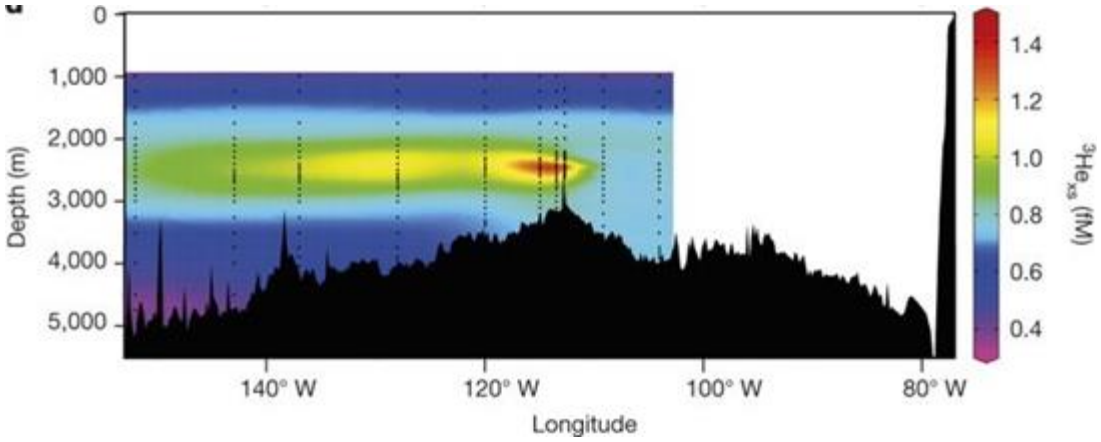
Doesn’t it all precipitate?

Gartman & Findlay 2020 *Nat. Geos.*

Hydrothermal Fe is transported over thousands of km!

OMG!



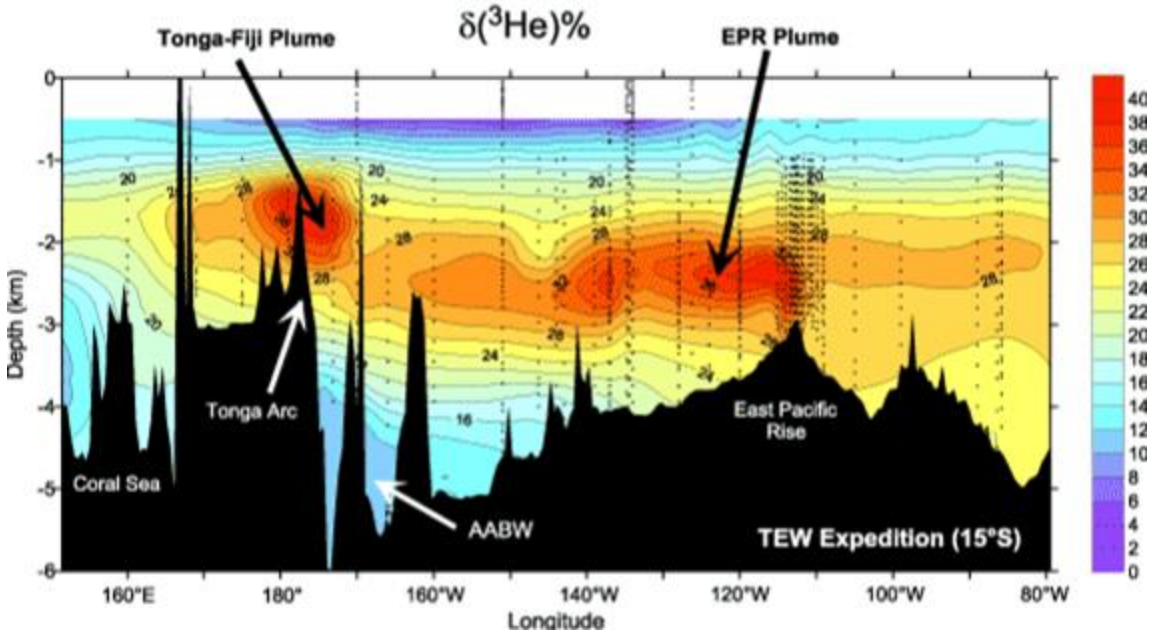


Marker for hydrothermal activity

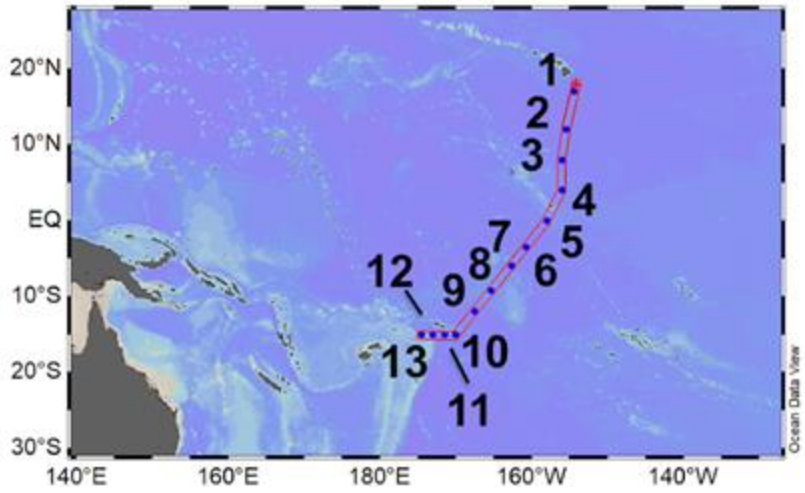
Resing et al. 2015 *Nature*

Intense hydrothermal signal off the Tongan Ridge

Do hydrothermal vents in the Northeast Lau Basin produce metal plumes?



Lupton et. al 2004 *Geochem. Geophys. Geosys.*



Are the metals released influencing microbial metabolism?

Automated pre-concentration & multi-elemental detection of total dissolved metals

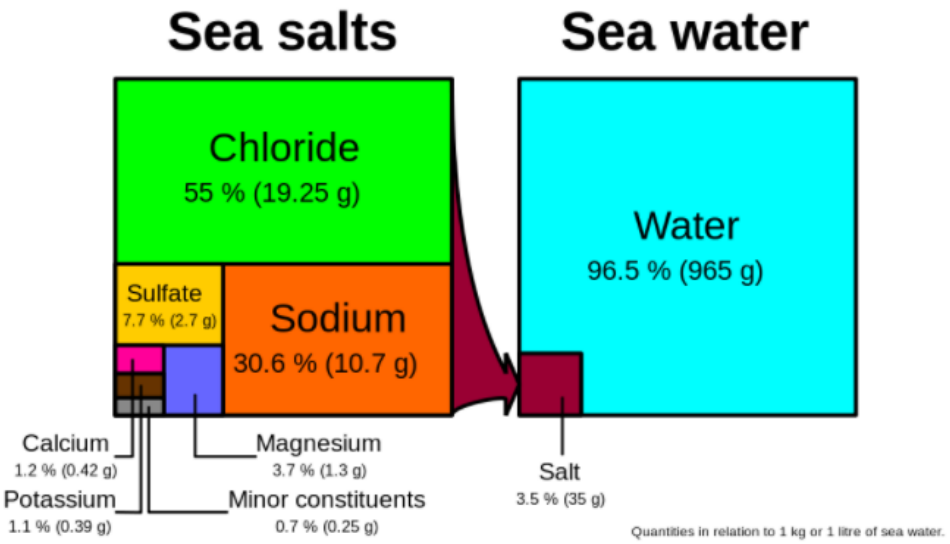


Figure 5.3.1 *The relative proportions of ions in seawater. (By derivative work: Tcncv (talk) Sea_salt-e_hg.svg: Hannes Grobe, Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; SVG version by Stefan Majewsky (Sea_salt-e_hg.svg) [CC BY-SA 2.5], via Wikimedia Commons)*

geotraces-gp15.com

Roger Williams University



Elemental Scientific



Thermo Scientific

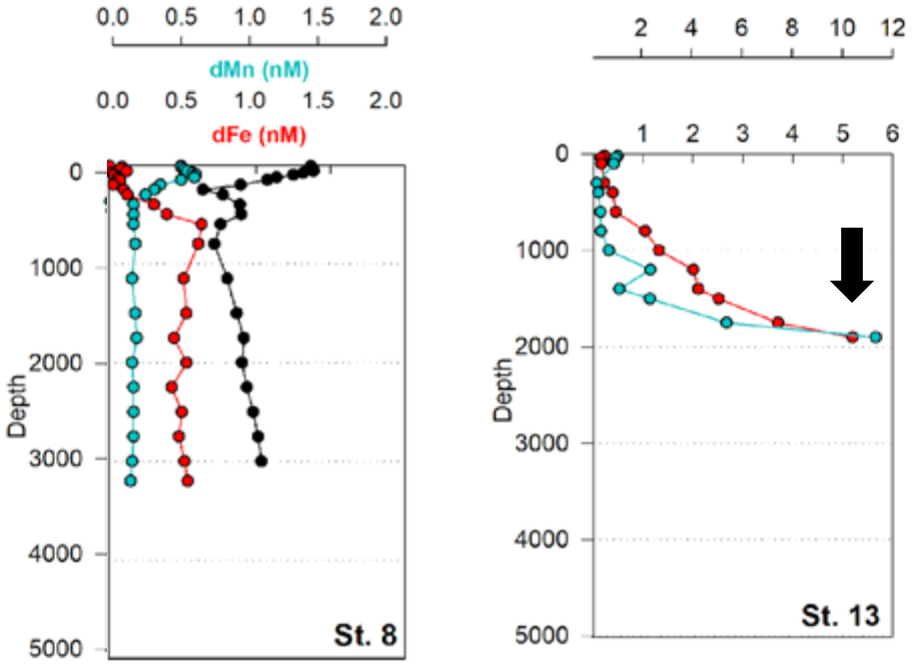
Inductively coupled plasma mass spectrometry (ICP-MS)

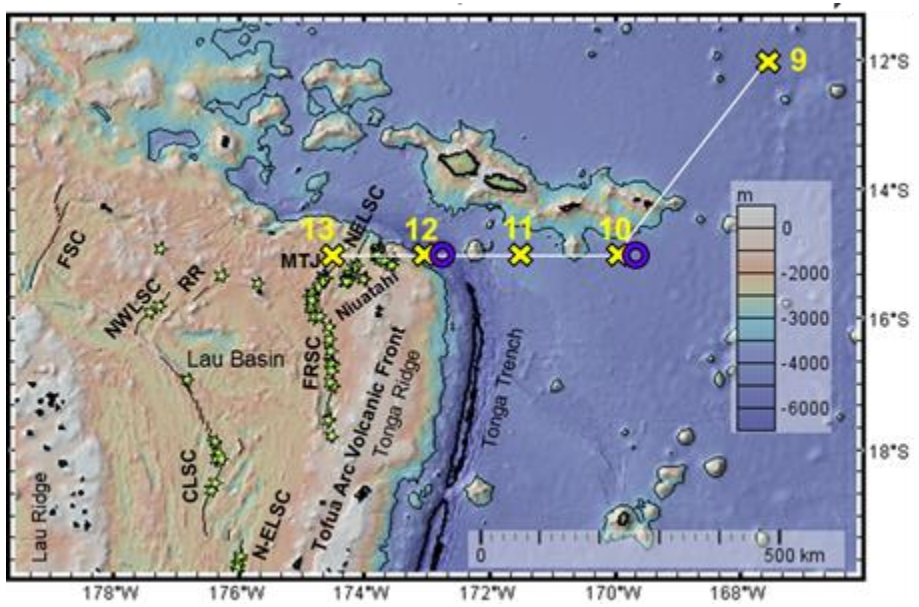
Fe & Mn signatures indicate distal hydrothermal plumes

Metal maximum at 1,900m!

Multiple hydrothermal plumes present

Many sources!



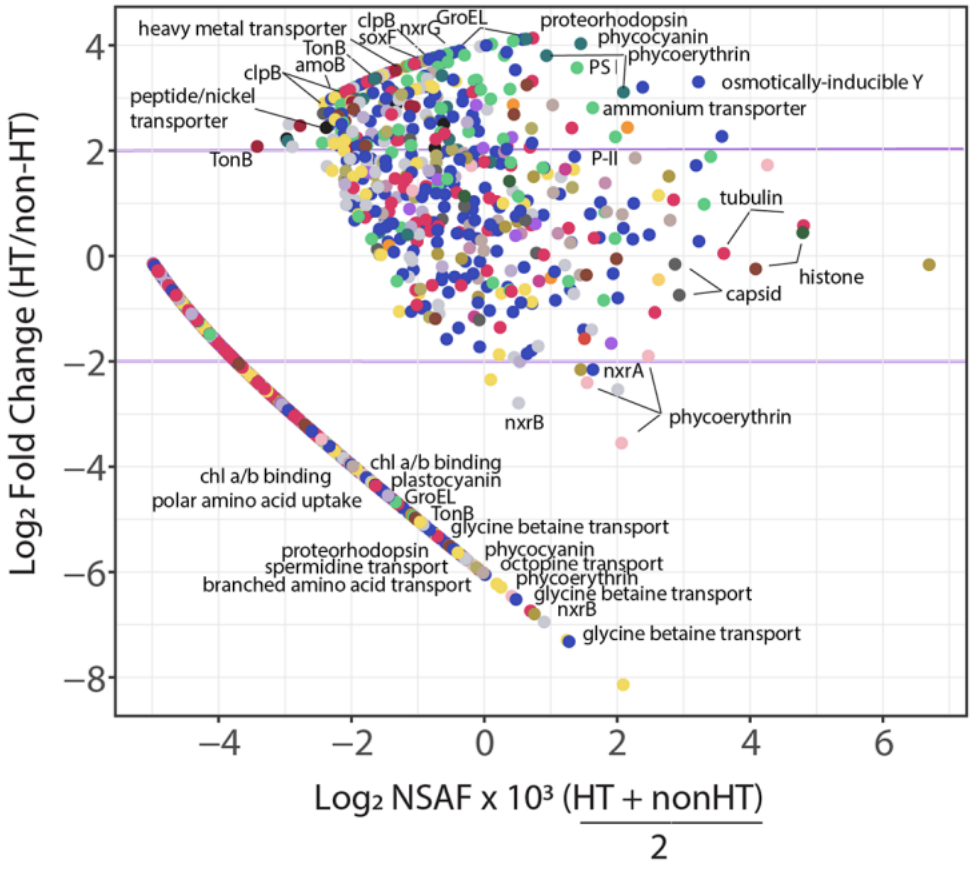


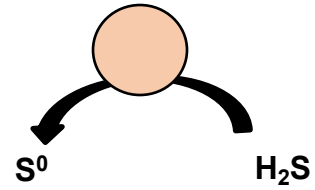
Cohen et al. 2021 *Biogeosciences*

InterRidgeVent Database – Beaulieu et al. 2013

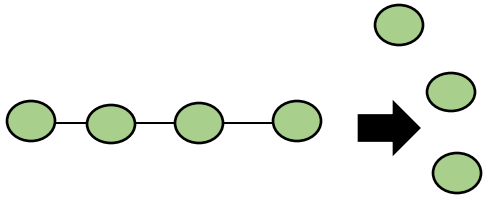
^{3}He from Lupton et. al 2004 *G*^{3}

How are microbes influenced by plumes?

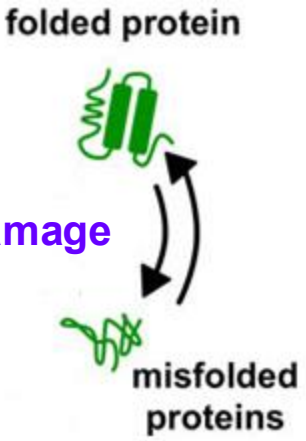




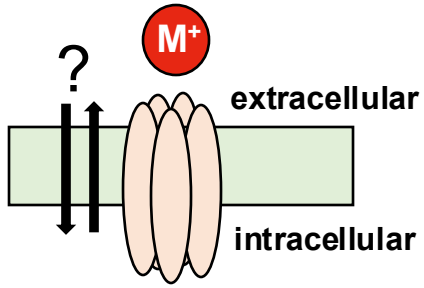
Chemosynthesis



Protein breakdown



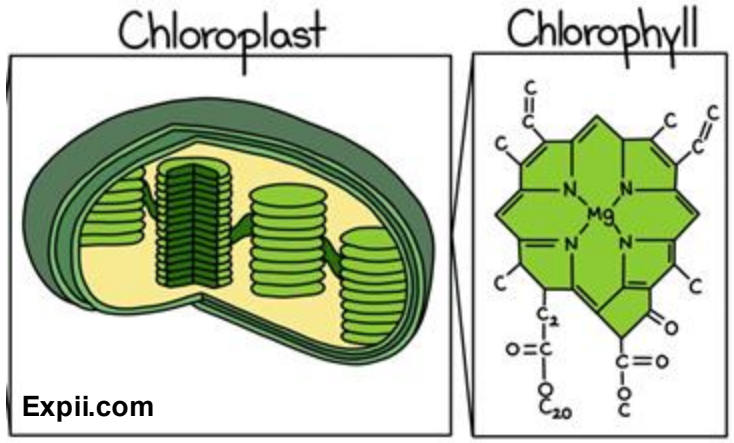
Resistance to damage



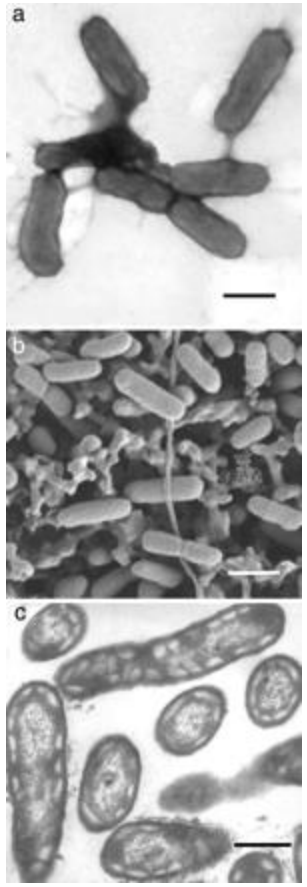
Metal transport

Cohen et al. 2021 *Biogeosciences*

Source of light in the deep dark ocean?



Why do we have photosynthetic proteins in the plume?



Beatty et al. 2005 PNAS



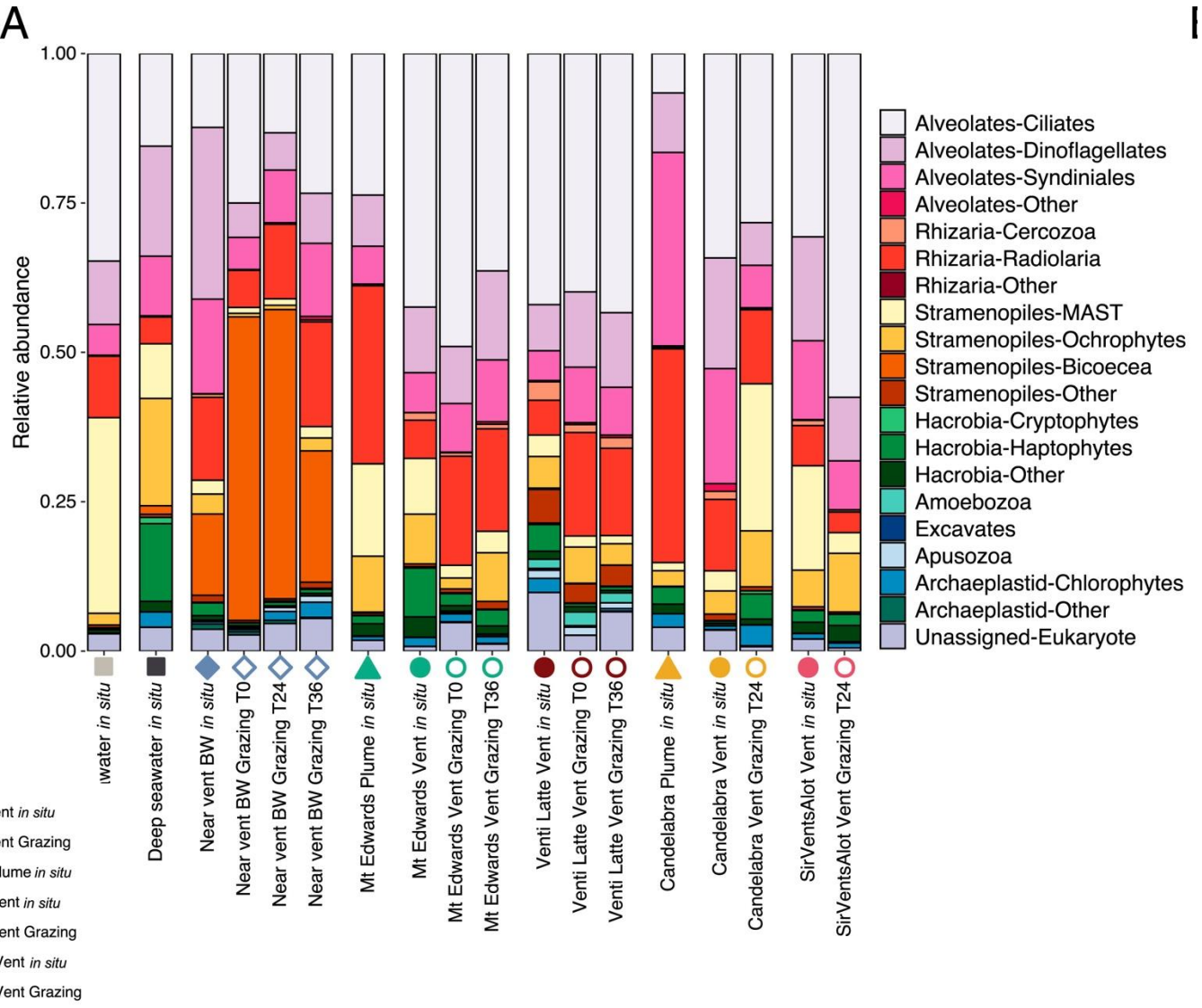
Van Dover et al. 1994 EOS

Using geothermal light?

Green sulfur bacteria from hydrothermal vents use low light to grow…..

Microeukaryote grazing at hydrothermal vents

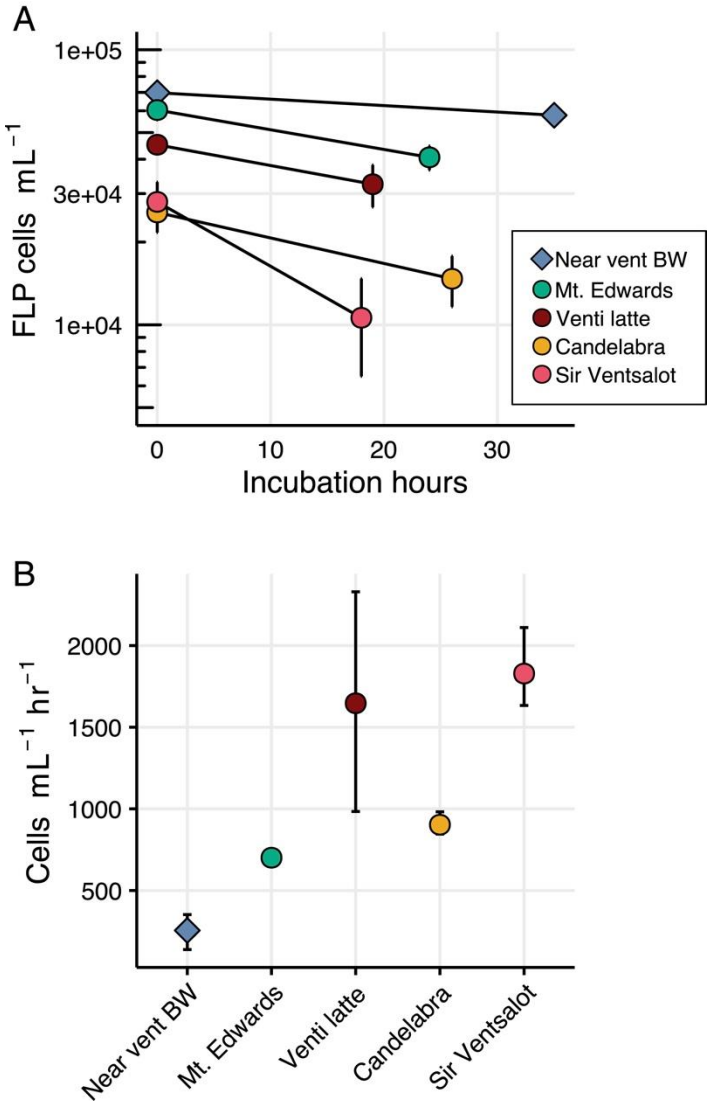
- Microeukaryotes are a link between primary producers and higher trophic levels in vent ecosystems
- Paired grazing experiments with amplicon sequencing to quantify protistan grazing
- Worked with vent fluids from the Gorda Ridge spreading center in the northeast Pacific Ocean



Hu et al. 2021 *PNAS*

Microeukaryote grazing at hydrothermal vents

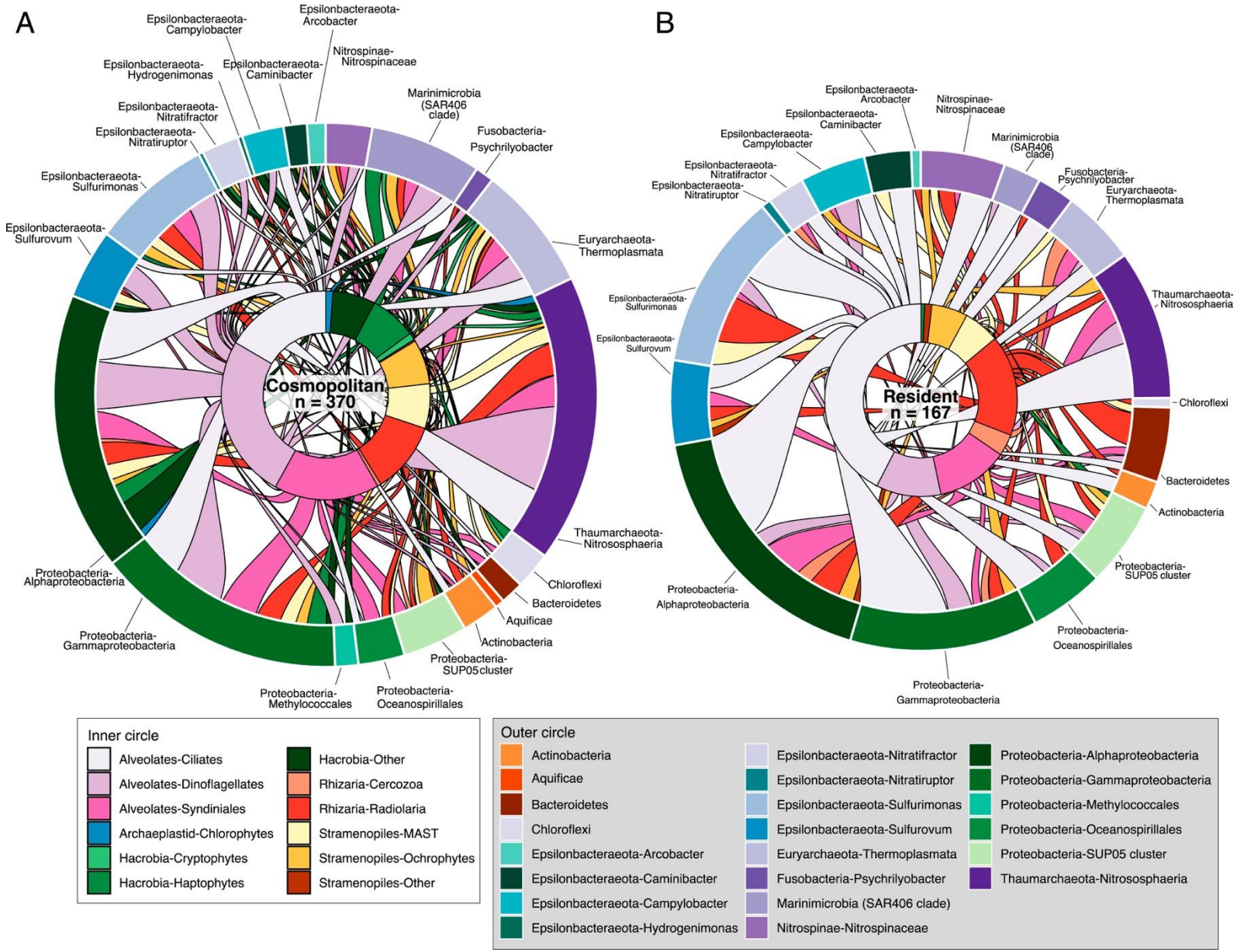
- Increased grazing in vent fluid compared to background deep seawater
- Microeukaryotes are important consumers of primary production at vent sites



Hu et al. 2021 *PNAS*

Microeukaryote grazing at hydrothermal vents

- Identified interactions between archaea/bacteria and microeukaryotes
- Resident ciliates especially interacted with bacterial counterparts
- Adds to relatively little that is known about deep sea eukaryotes



Hu et al. 2021 *PNAS*

How has omics shaped our understanding of microbial biogeography and ocean gradients?

- Patterns in nutrient stress, genomic adaptations and transcriptional activity across ocean provinces revealed
- Evidence for changing community composition with depth in the North Atlantic and dinoflagellate dominance in the central Pacific
- Microeukaryote metabolism reflects shifting nutrient stressors across latitudinal and coastal-offshore gradients
- Hydrothermal vents create complex and chemically rich gradients at the sea floor
  - Distal plumes may contain remnants of hydrothermal influence
  - Microeukaryotes are important grazers in these ecosystems