Progress Towards an International BioGeoSCAPES Program and Development of the Biogeochemical AUV Clio

The BioGeoSCAPES community

Mak Saito, Al Tagliabue, Maite Maldonado, Naomi Levine, Adrian Marchetti, Alyson Santoro, Ben Twining, Harriet Alexander, Martha Gledhill, and many others

Clio AUV Project - Chip Breier and Mike Jakuba

UNOLS Annual Meeting New Orleans November 2022

BioGeoScapes

Ocean metabolism and nutrient cycles on a changing planet

Dinoflagellate artwork by Dean Jacobson

my background

- Trace metal biogeochemist and microbiologist researcher
- Interested in interface between chemistry and biology and connection to global biogeochemical cycles
- Participant and Chief Scientist on many UNOLS expeditions
- Lead PI for the recently awarded Accel-Net BioGeoSCAPES
- Science user PI for AUV Clio development
- Science PI for BCO-DMO (Biological Chemical Oceanography Data Management Office)

today's outline

- Introduction:
  - What is BioGeoSCAPES?
  - Background on Microbial Biogeochemistry
- Brief GEOTRACES history
- Prior 'omics efforts
- Accel-Net BioGeoSCAPES activities
- Development of new biogeochemical AUV Clio

BioGeoSCAPES

Ocean metabolism and nutrient cycles on a changing planet

OCEAN METABOLISM – at the heart of the planetary support system

Intracellular processes | Organisms & assemblages | Ecosystem-scale cycling and feedbacks

Mission Statement: To improve our understanding of the functioning and regulation of ocean metabolism and its interactions with nutrient cycling within the context of a hierarchal seascape perspective.

Why? To constrain biological feedbacks on a changing planet

BioGeoSCAPES
Ocean metabolism and nutrient cycles on a changing planet

• New Technologies Come of Age: ‘Omics and Micronutrients

‘OMICS REVOLUTION

- The use of new biological “omics” methods has transformed our understanding of biological communities and their activities.
- **Genomic**, **transcriptomic**, **proteomic**, **metabolomic**, and **lipidomic** measurements are now routinely made, but often not simultaneously.

MICRONUTRIENTS

- Significant advances have enabled the quantification of metal micronutrients in seawater
- This has led to significant insights into biogeochemical controls on biology.

Despite these advances, rarely are these new measurements conducted simultaneously.

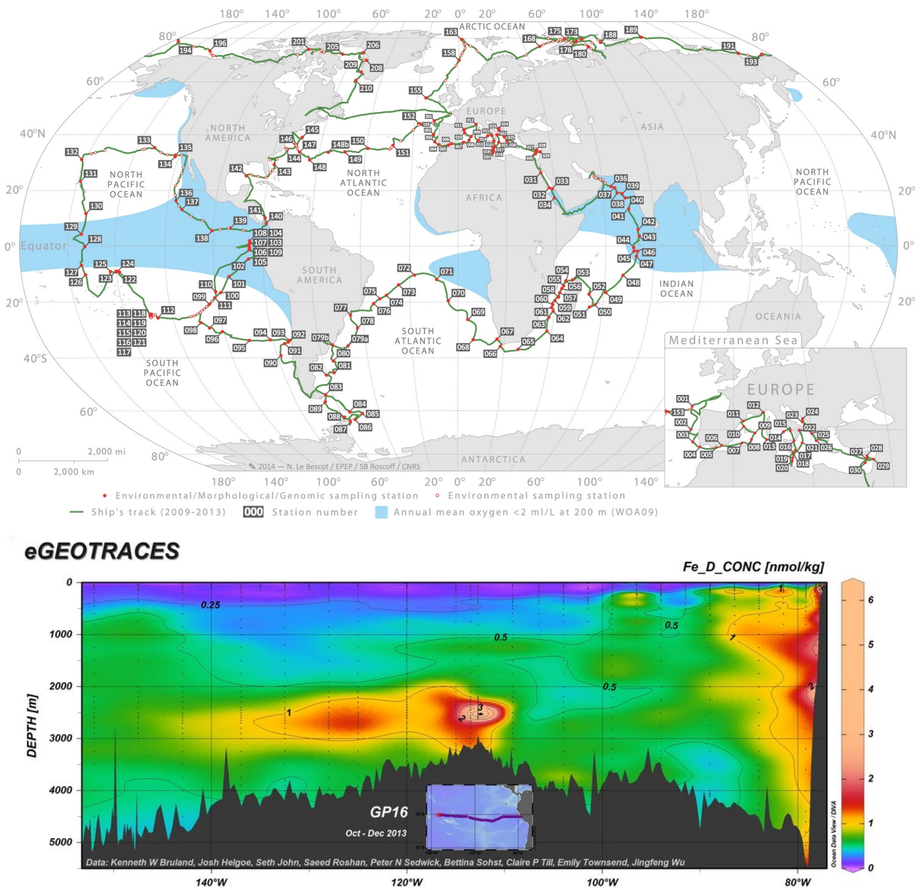


Figure 1. Revolutions in ‘omics (top) and trace metal measurement technology (bottom) has enabled major ocean discoveries within recent decades. (Pesant et al., 2015; Resing et al., 2015)

BioGeoSCAPES
Ocean metabolism and nutrient cycles on a changing planet

- Vision
  - An integrated approach combining ‘omics approaches (genomics, transcriptomics, proteomics, lipidomics and metabolomics) and chemical measurements (nutrients, micronutrients, biogeochemistry)
  - Global-scale quantification of microbial communities
  - Understanding ocean metabolism and its influence on ecosystem health and biogeochemical cycles.

<u>BioGeoSCAPES</u>

- International, community-driven effort (www.BioGeoSCAPES.org)
- Full-depth, basin-scale ocean sections, time-series, process studies
- Rich biological and chemical datasets and improved integration between observations and models

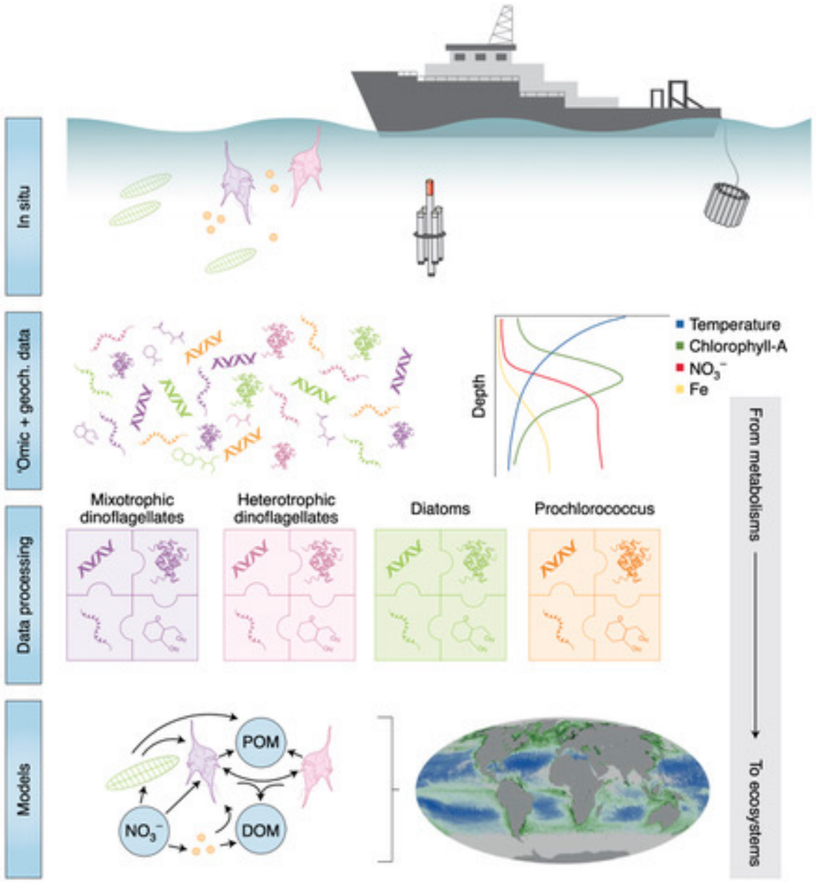


Figure 2. BioGeoSCAPES will integrate *in situ* ‘omic and geochemical observations with data science and models to transform our understanding of ocean microbial biogeochemistry. From Levine and Leles, 2021.

BioGeoSCAPES
Ocean metabolism and nutrient cycles on a changing planet

• Connections to existing infrastructure, technology, and partnerships

- BioGeoSCAPES will connect with the development of both biogeochemistry and **biomedical infrastructure** and technology development.
- The study of trace metal micronutrients and ‘omics in ocean environments are active fields in the US and beyond.
- Infrastructure includes multiple sampling modes: Trace metal rosette and winch, submersible filtering pumps, autonomous underwater vehicle, analytical sequencers, and mass spectrometers.
- **Intercalibration** and **data science** initiatives needed for implementation

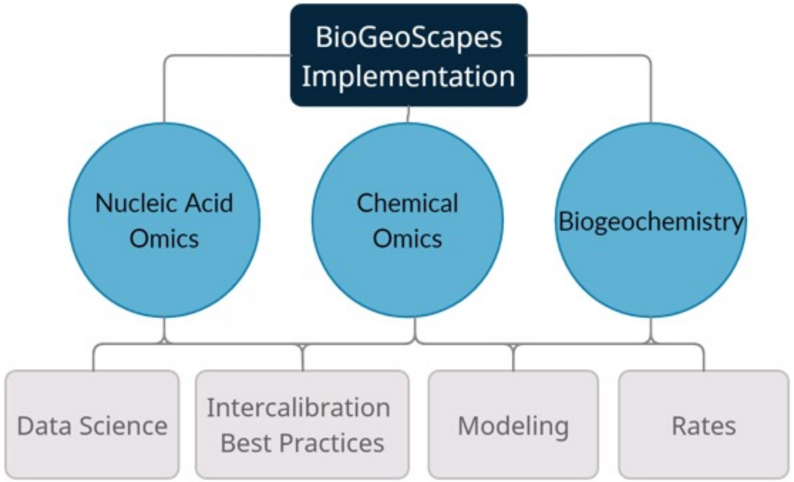


Figure 3. Three examples of science domains (blue) that will be integrated into BioGeoSCAPES science, relying on four enablers (grey).

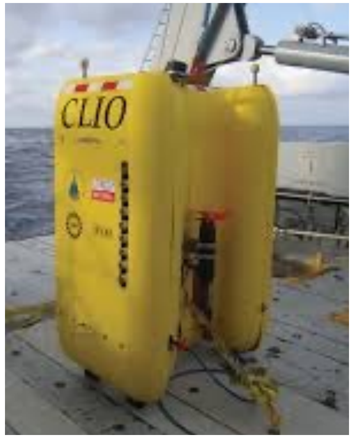


Figure 4. The autonomous underwater vehicle CLIO designed for biogeochemical sampling on global ocean basin scales.

International Momentum for BioGeoSCAPES

Nation with Ambassadors
Australia
Belgium
Canada
Chile
China
Denmark
Finland
France
Germany
India
Israel
Italy
Japan
Portugal
Russia
South Africa
Spain
Sweden
Taiwan
The Netherlands
Turkey
United Kingdom
United States

Completed National Meetings:

Australia
Canada
China
France
Japan
United Kingdom
United States

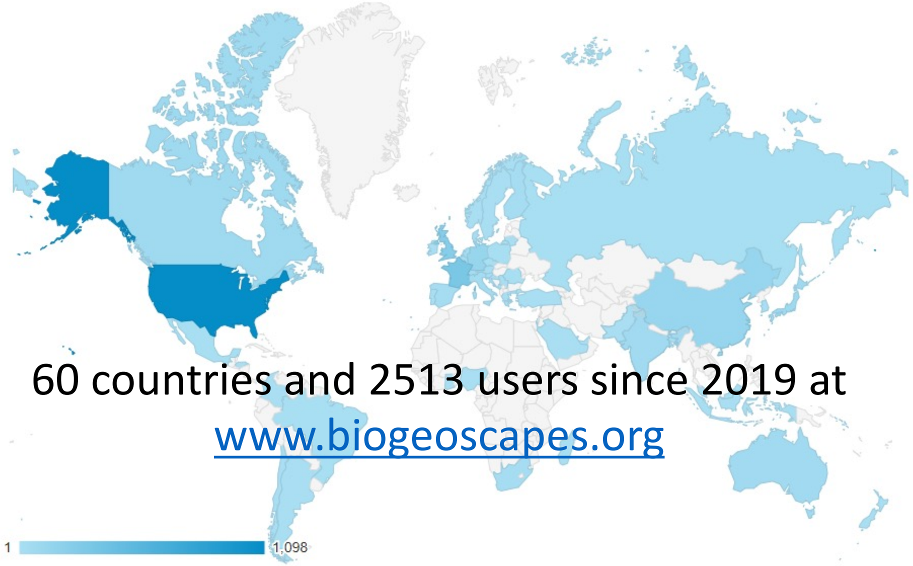
International BioGeoSCAPES meetings

- Early meetings starting in 2010
- Pan EU Workshop Croatia 2022
- Royal Society Marine Microbes in a Changing Climate 2022
- Sessions at Ocean Science meetings 5 sessions and 44 abstracts in 2022

Proposals:

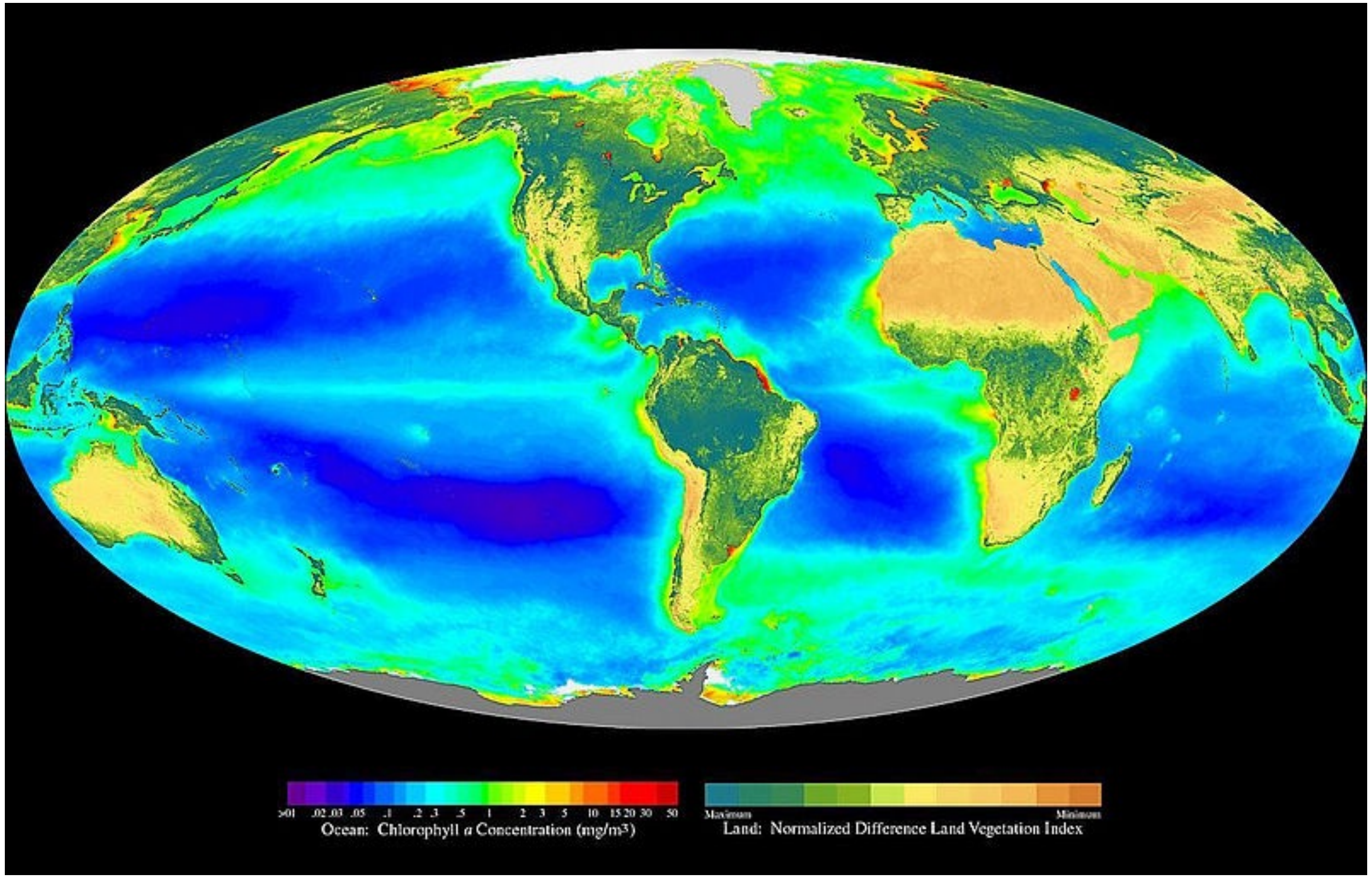
EU, US, and Canadian proposals submitted to further development of BioGeoSCAPES

2018 International Interest Meeting at National Academies Center in Woods Hole, MA USA

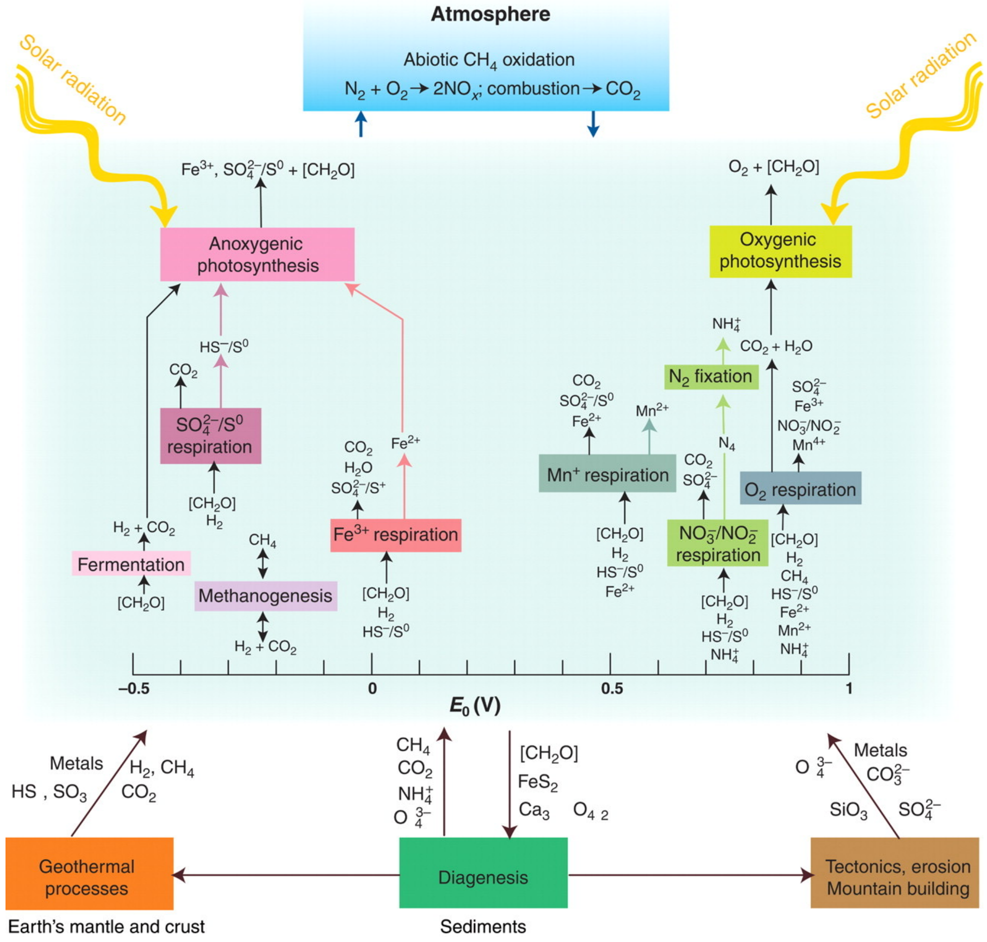


60 countries and 2513 users since 2019 at www.biogeoscapes.org

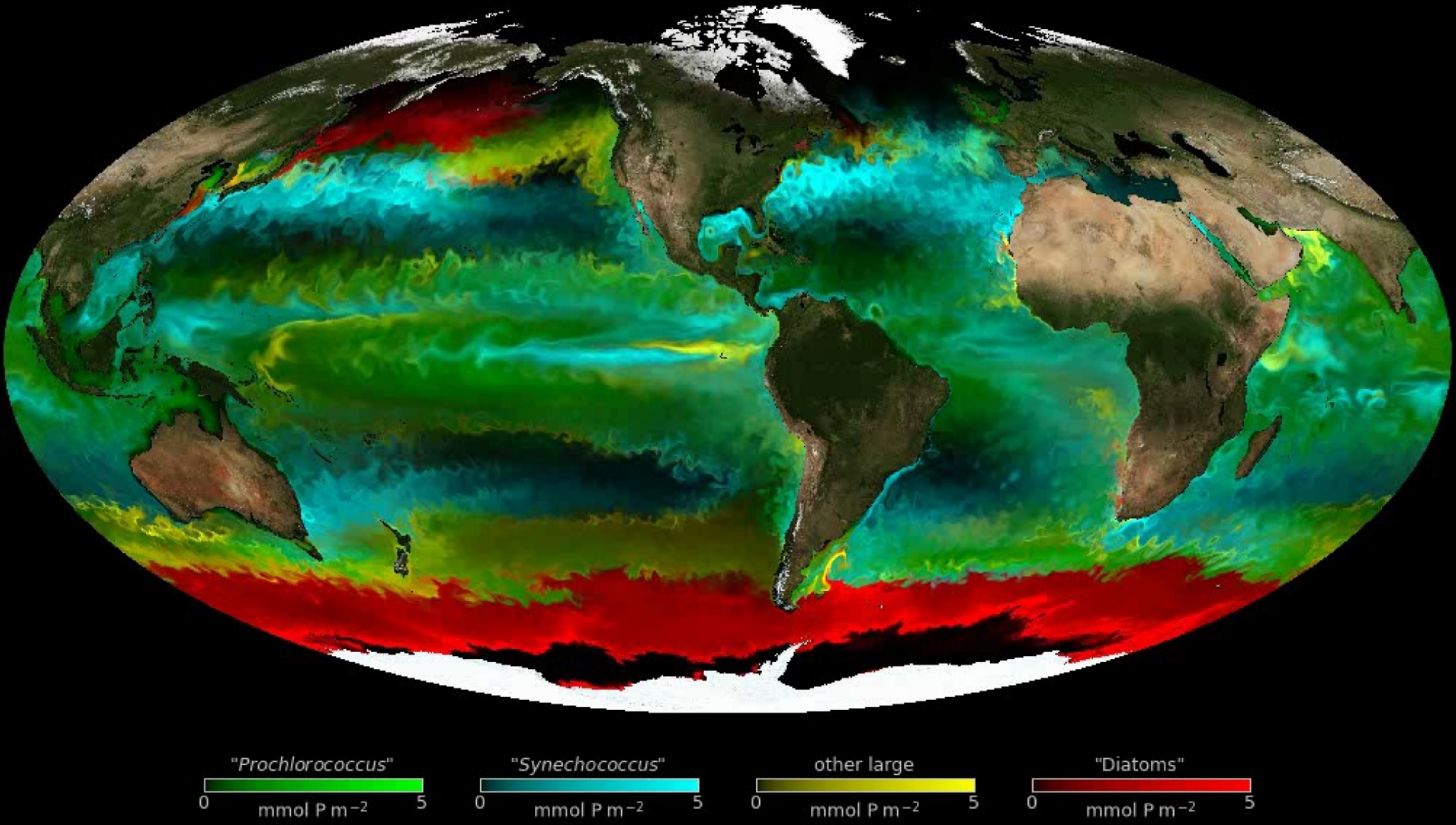
Biogeochemical cycles define and enable a habitable planet



The Microbial Engines That Drive Earth's Biogeochemical Cycles



In essence, microbes can be viewed as vessels that ferry metabolic machines through strong environmental perturbations into vast stretches of relatively mundane geological landscapes. The individual taxonomic units evolve and go extinct, yet the core machines survive surprisingly unperturbed. [Falkowski, Fenchel, DeLong, 2008](#)



Darwin Project MIT

Four modes of human environmental impacts

Biogeochemical cycles constitute Earth's life support systems, yet are not as well known or understood

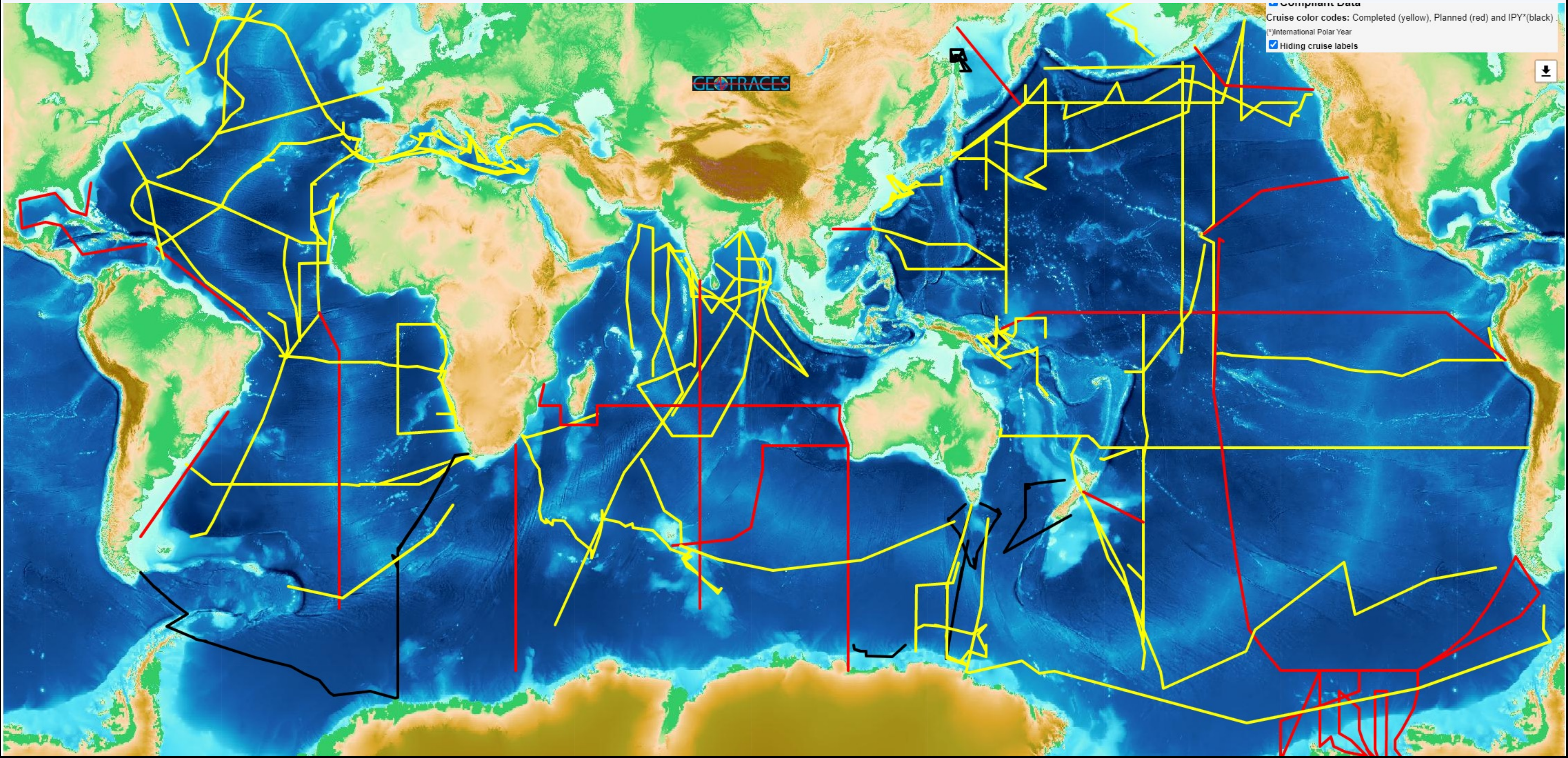
Ocean biogeochemical cycles are currently being impacted, *damaged*, by multiple means:

Ocean acidification, Ocean deoxygenation, eutrophication by agricultural and sewage nutrient releases, aerosol pollution, changes in CO_2 uptake due to climate change, nitrous oxide production

Illustration by Ichiko Sugiyama; from Saito in prep

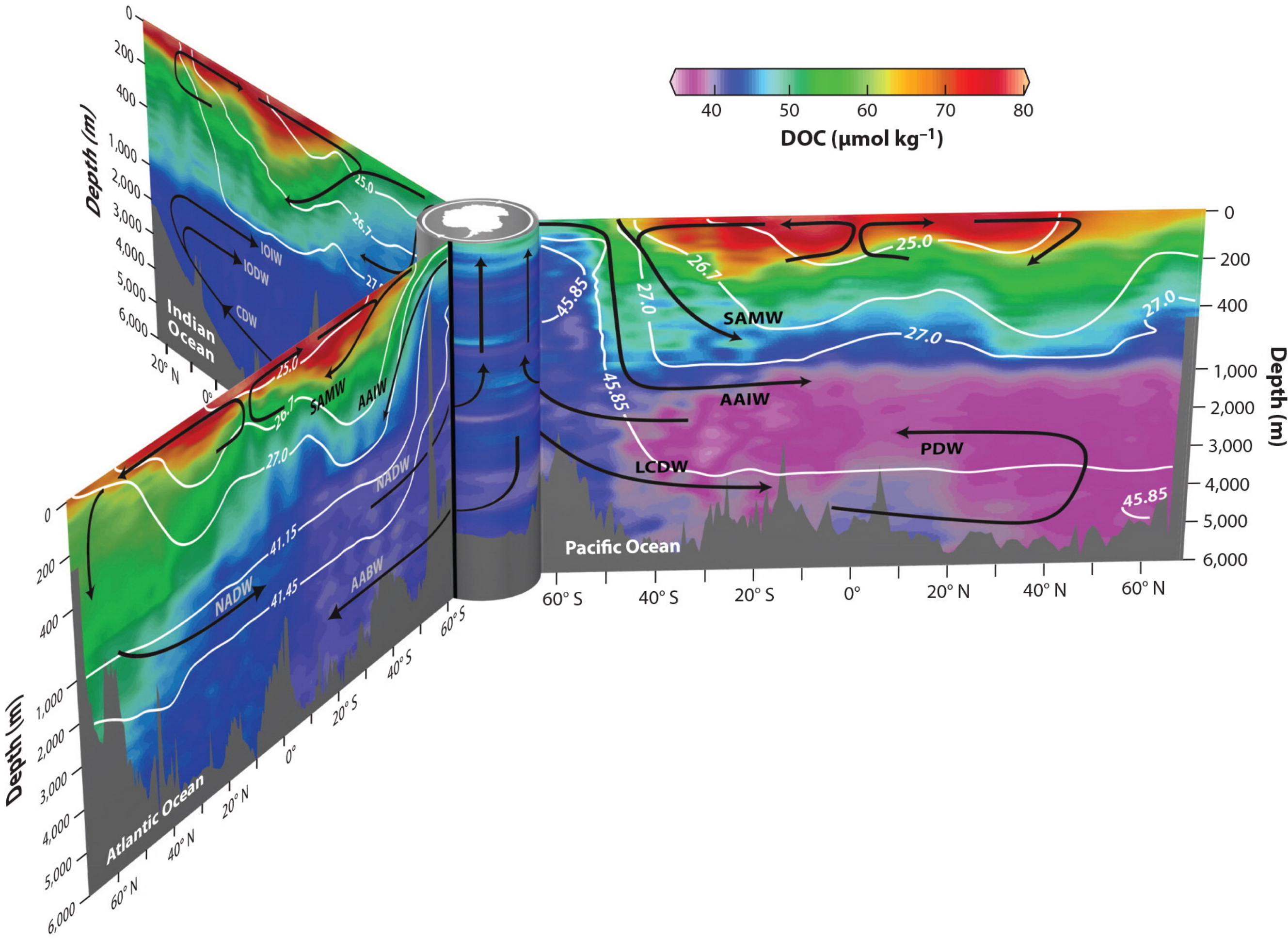
GEOTRACES Ocean Section Expeditions

Mission: To identify processes and quantify fluxes that control the distributions of key trace elements and isotopes in the ocean, and to establish the sensitivity of these distributions to changing environmental conditions.



Chemical maps of the oceans

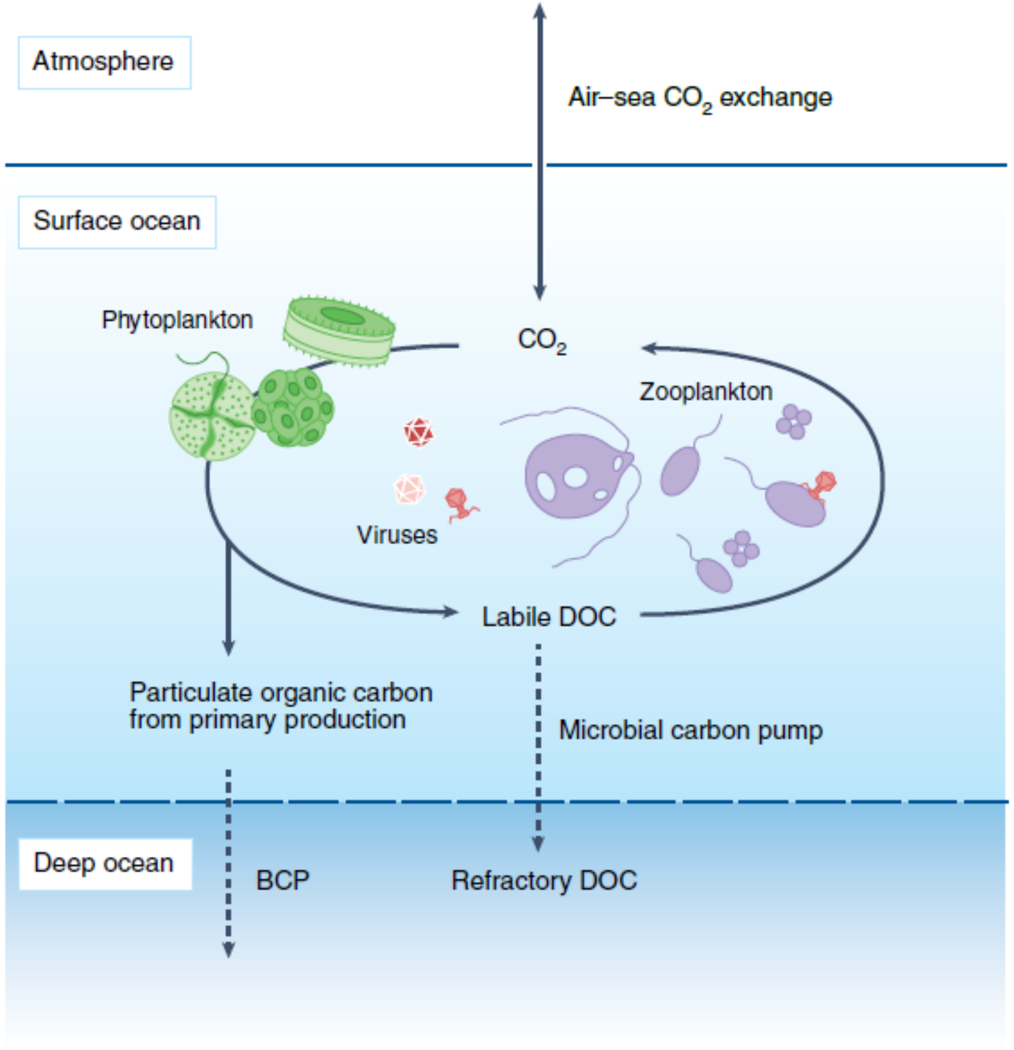
- JGOFS developed major nutrients sections
- More challenging analytes:
  - DOC - Dissolved Organic Carbon
- Data like this inspired many GEOTRACERs to develop this for micronutrients iron, zinc, etc.
- Ocean Section visualizations a powerful tool to see invisible attributes (chemistry and microbiology)

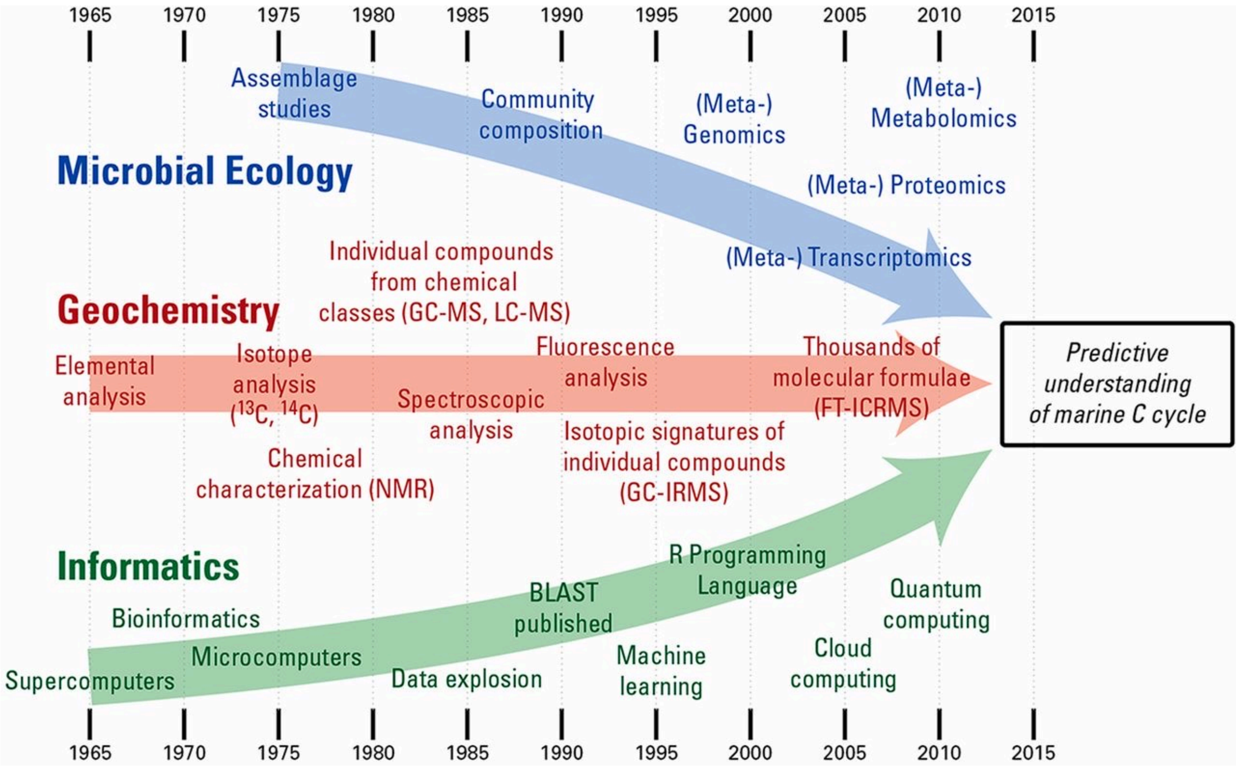


Hansell DA. 2013.
Annu. Rev. Mar. Sci. 5:421–45

Cycling of carbon molecules

Interest in Incorporating Organic Geochemistry into BioGeoSCAPES

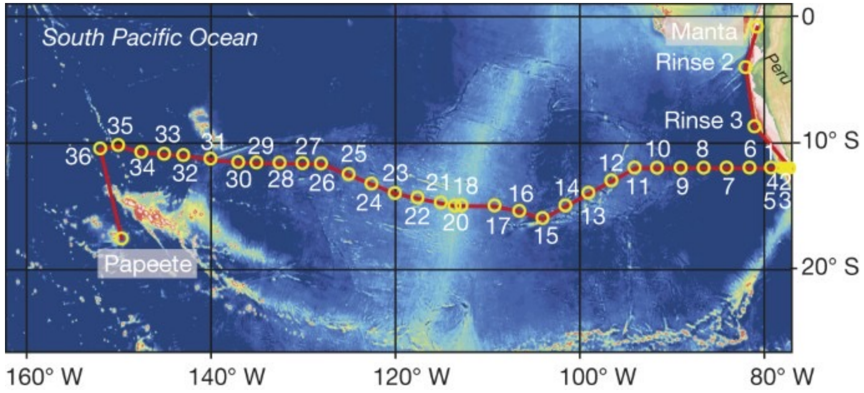




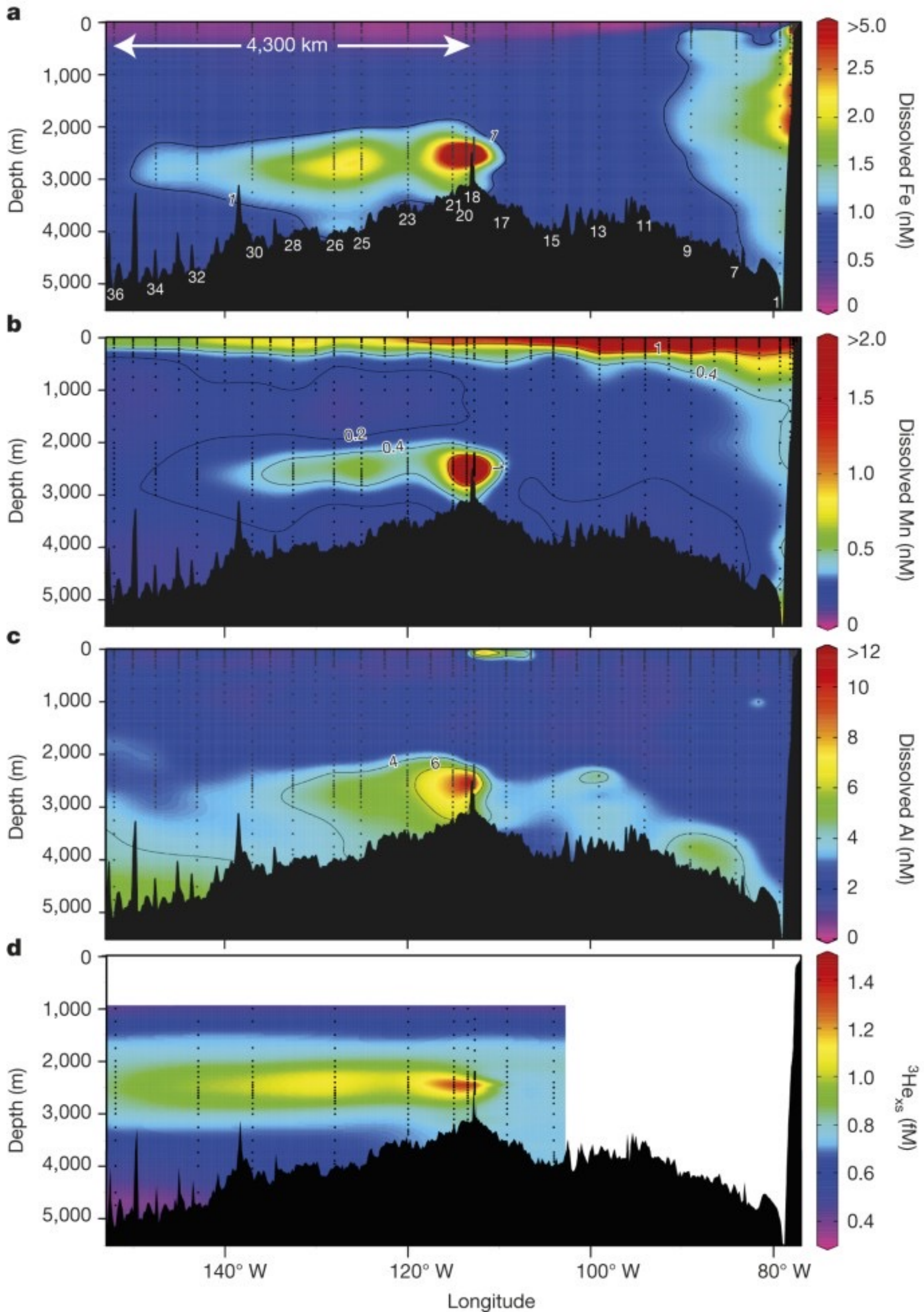
Moran et al., 2016, 2022

GEOTRACES discovered massive hydrothermal metal plumes throughout the oceans

- Previously thought to be 10's of km long, based on localized vent expeditions
- Different international expeditions discovered plumes 1000's of km in scale

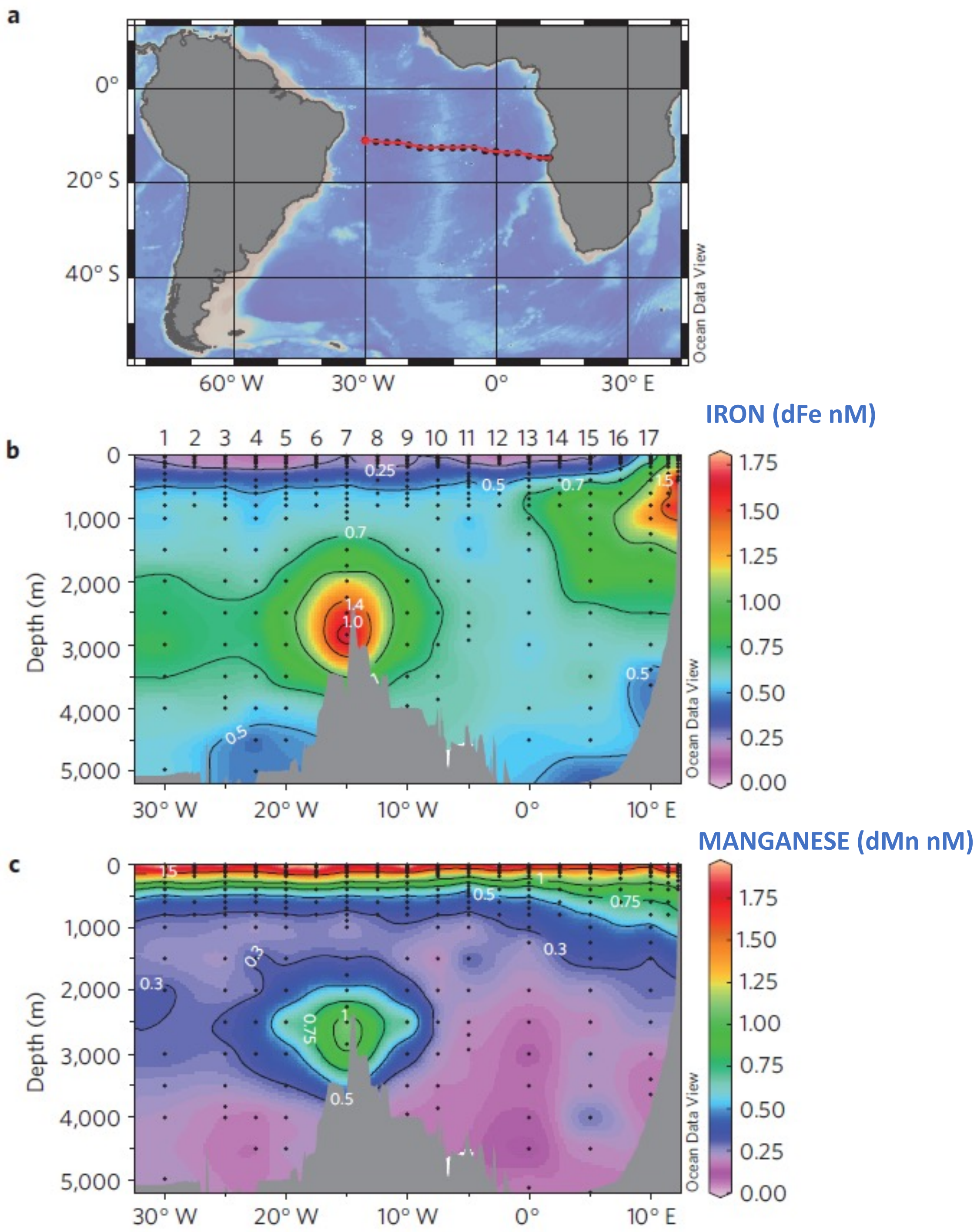


US GP15 Expedition Resing et al., 2015; R/V Roger Revelle



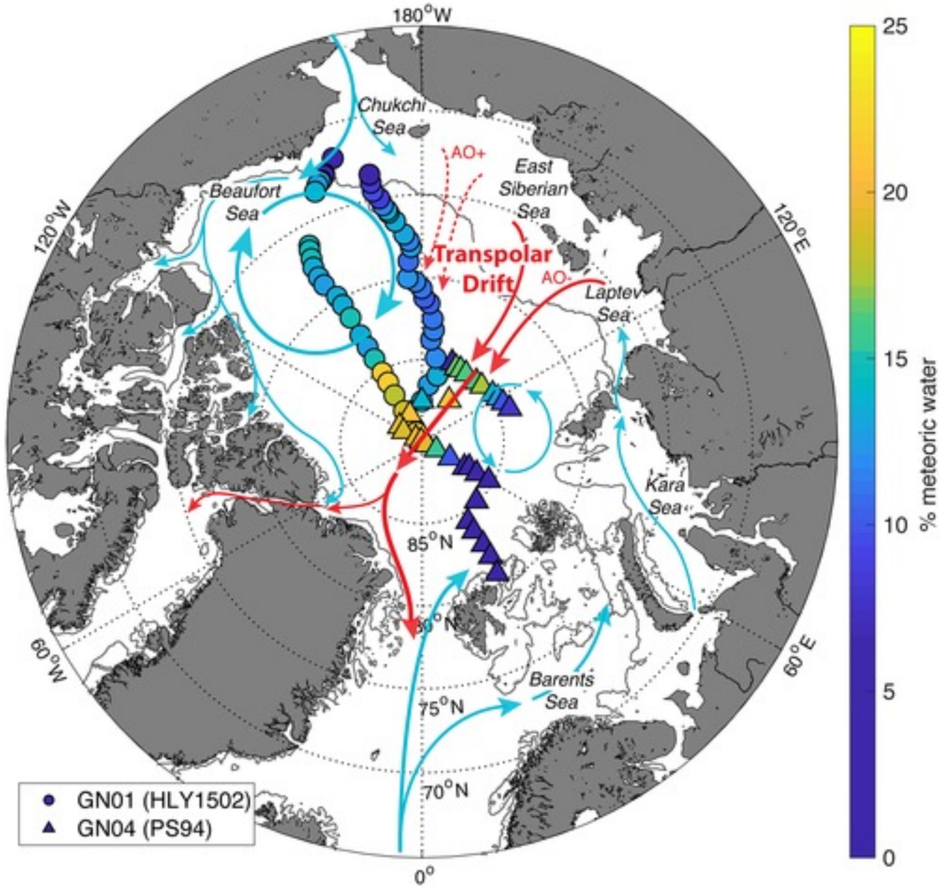
Challenges of field work

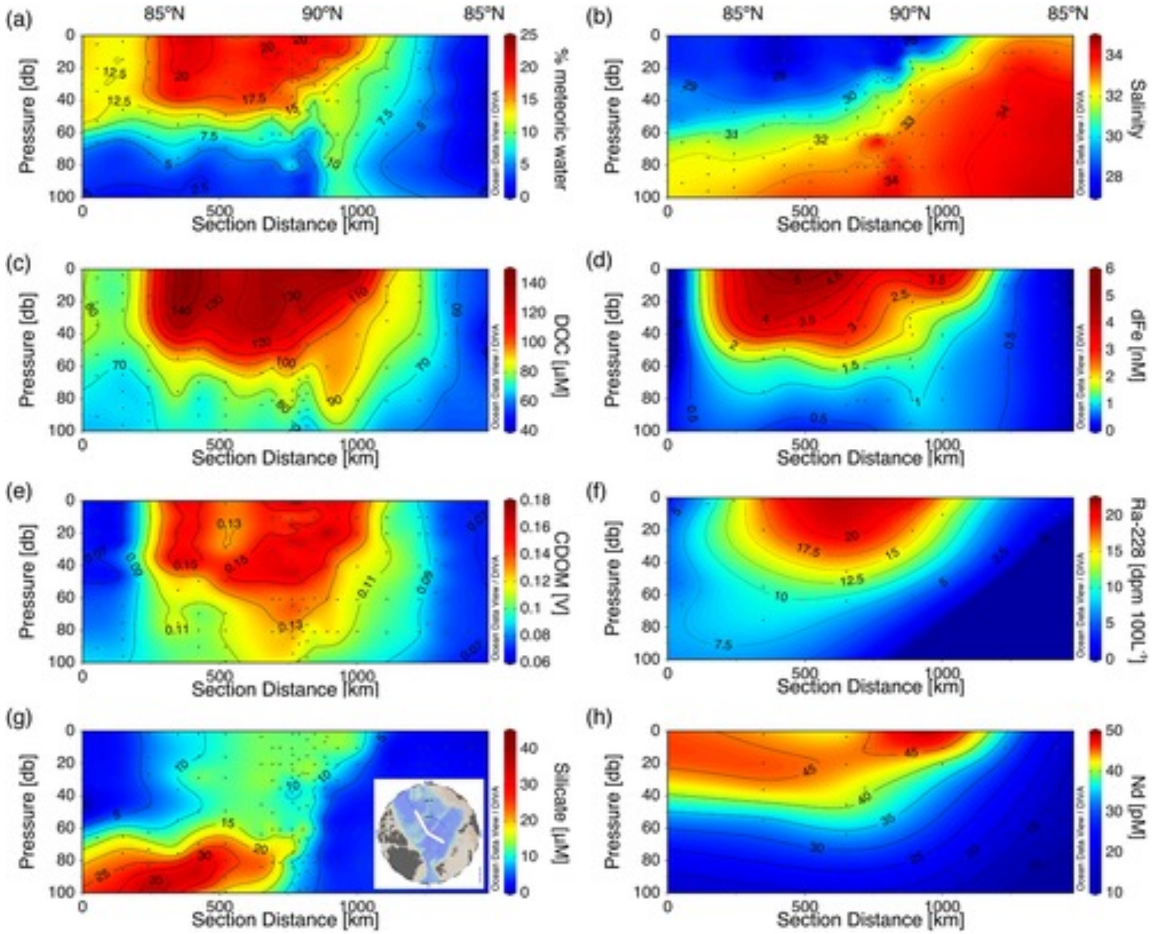
- R/V Knorr 2007 “CoFeMUG” expedition
- Our first attempt at full depth metal profiling
- SeaMac winch 5000m amsteel ¼” line
- Non-conducting trace metal rosette
- Winch broke at Stn 3 (level winder), birds nest of tangle. Electrician and bosun recovered the package and repaired the winch!
- Became a GEOTRACES compliant section



Saito et al., 2013

GEOTRACES discovered "rivers of metals" in the Arctic Ocean Transpolar Drift and increased metal input due to permafrost melt and climate change



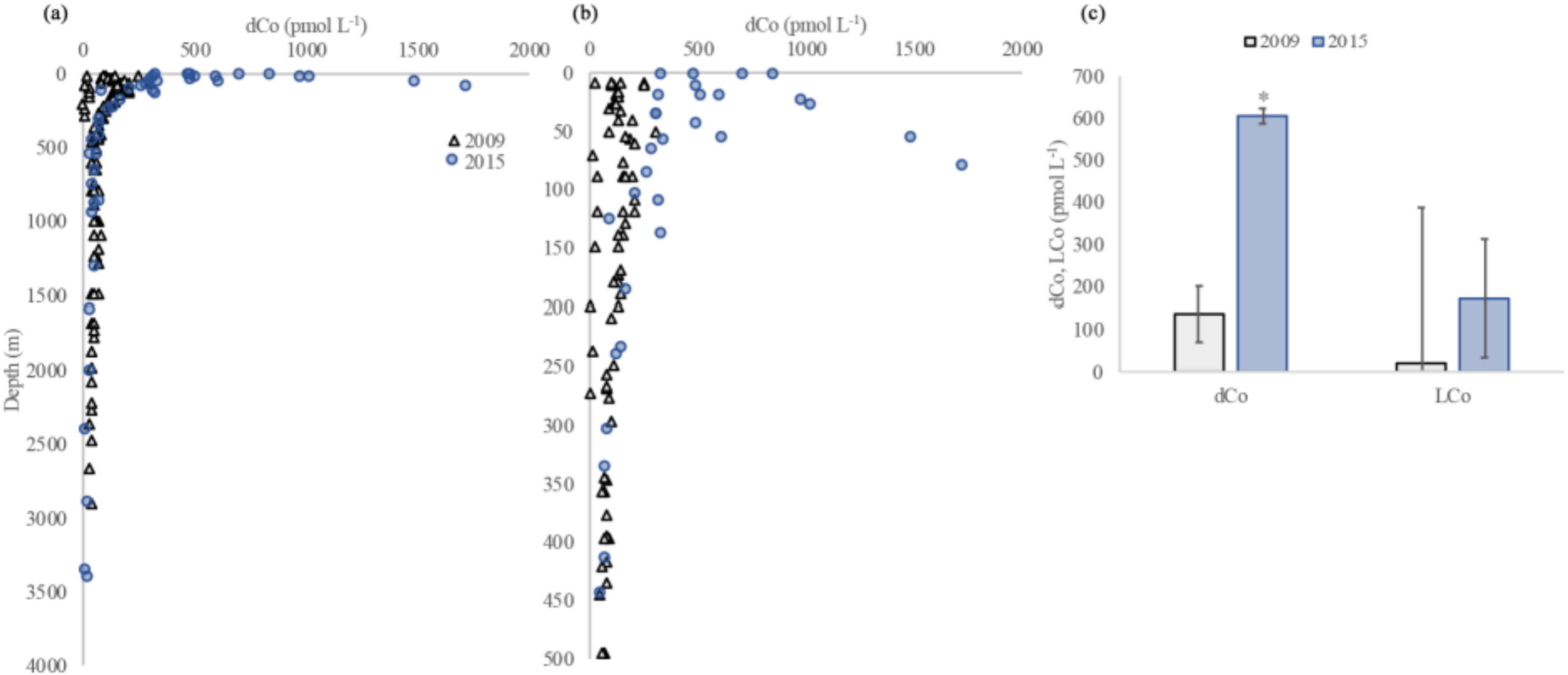


US and German expeditions, Charette et al., 2020; Kipp et al., 2018; USCG Healy

Climate Change Effects:
Increasing Cobalt in the Arctic Ocean due to Permafrost Melt

Comparing Canadian and US GEOTRACES

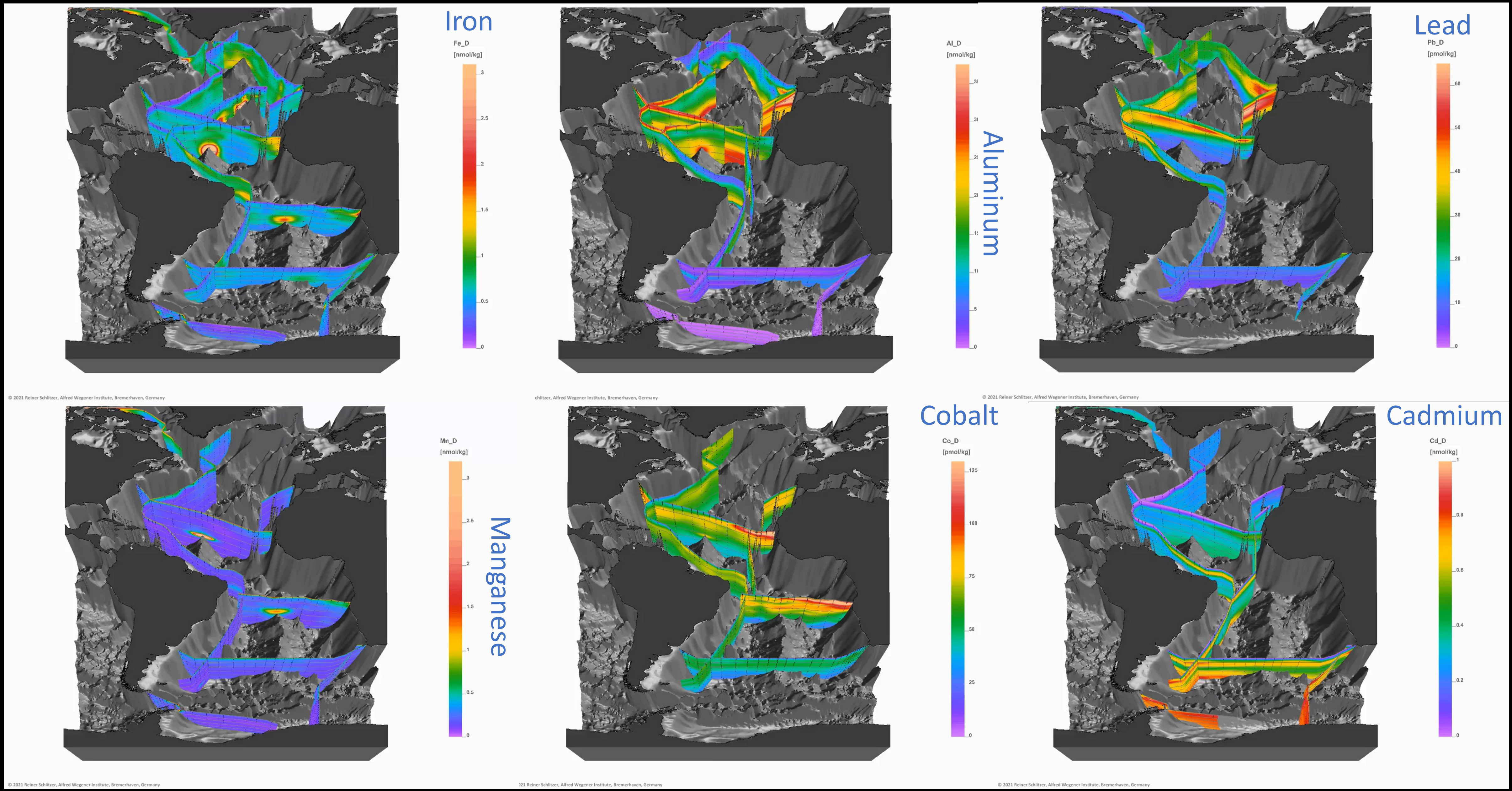
R. M. Bundy et al.: Elevated sources of cobalt in the Arctic Ocean **4761**



Randie Bundy et al., 2020

GEOTRACES Data Products: 3D Ocean Sections of Elements and Isotopes

www.egeotraces.org



GEOTRACES and intensive ship use

Results from GP-15

- Typically 1 cruise every 2-3 years in US
- Long in duration, usually max ship duration
- Multiple wire time ops, full depth CTDs, Trace Metal Rosettes, submersible McLane pumps
- ~30-40 PIs funded per cruise

Results from GP-15

- Pacific Ocean Meridional transect (Alaska – Tahiti)
- Sample bottles filled: 15,758
- GoFlo bottles racked inside lab van: 1,700
- Bottle rinses: 47,274
- Longest work day: 39 hours
- GoFlo bottles lost to sea: 1 (RIP #45);
- Pallets filled with seawater samples: 12.5

R/V Revelle loading Nov 2022

Competition for wire-time is a major factor, Super stations can be 3-4 days in length

The Omics revolution: Omics as powerful new tools in Ocean Science

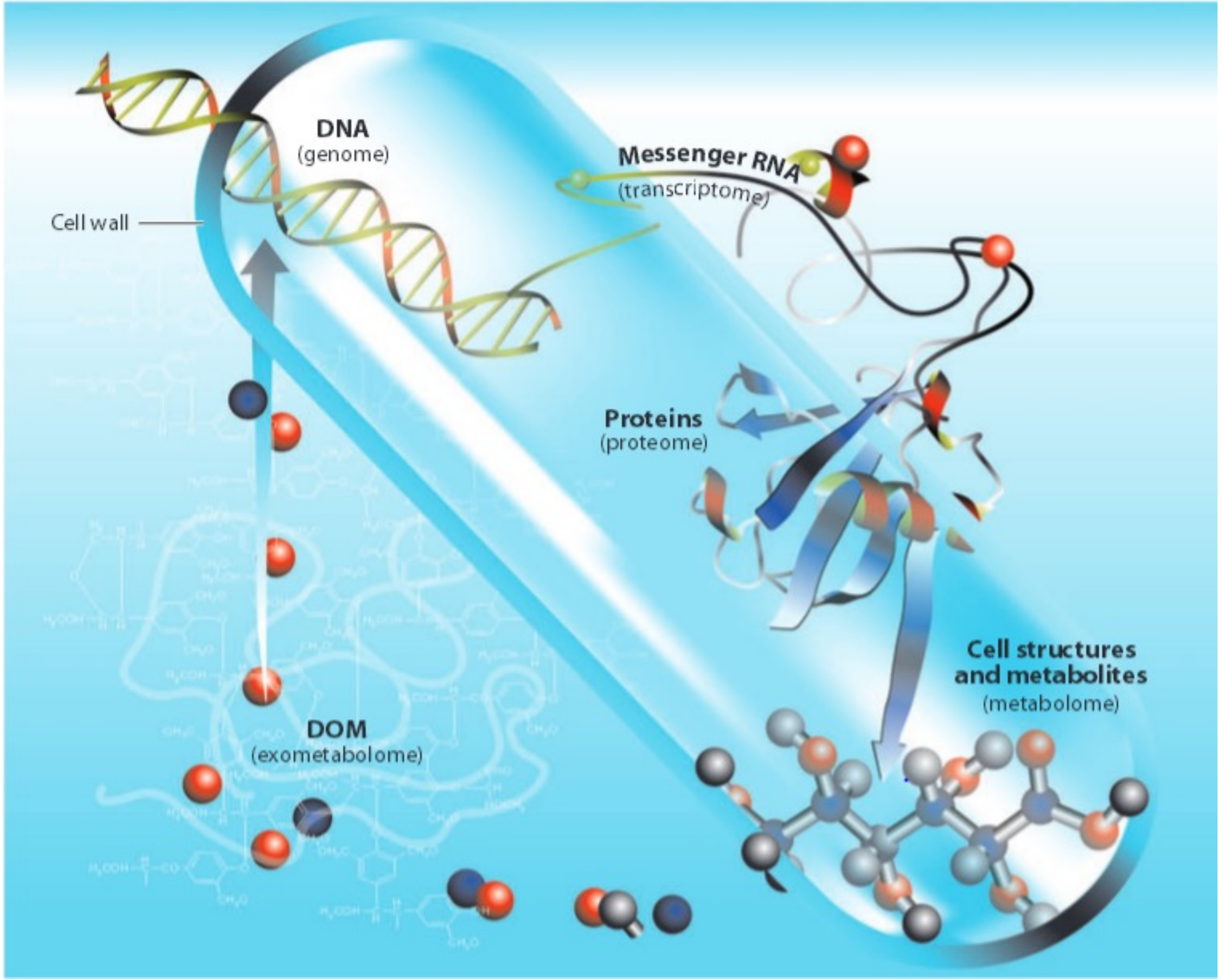


Figure from Kujawinski, Annual Reviews 2011

- Genomics
- Transcriptomics
- Proteomics
- Metabolomics

Allow new insights on:

- *Who is there?*
- *What are they doing?*

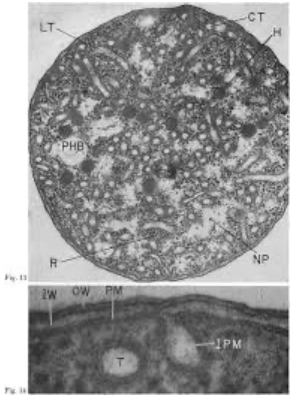
<u>"Meta" omics</u> = analysis of diverse biological communities in natural samples

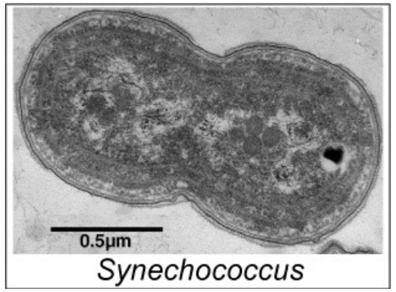
- Metagenomics
- Metatranscriptomics
- Metaproteomics
- Meta-Metabolomics??

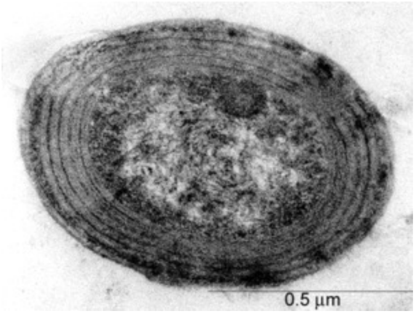
Discovery of major ocean microbes is recent and ongoing

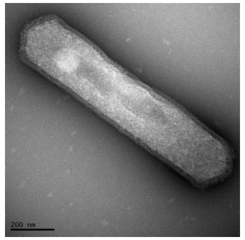
These microbes and other microbes have a major role in controlling C, N, and S cycling in the oceans

1971	Nitrospina and Nitrococcus
1978	Synechococcus
1985	Crocosphaera
1988	Prochlorococcus
2002	Pelagibacter
2003	Planctomycetes anammox
1992/ 2005	Thaumarchaeota
2008	UCYN-A Atelocyanobacterium
2004/ 2009	SUP05 Thioglobaceae
1996	SAR202
1990's	SAR86







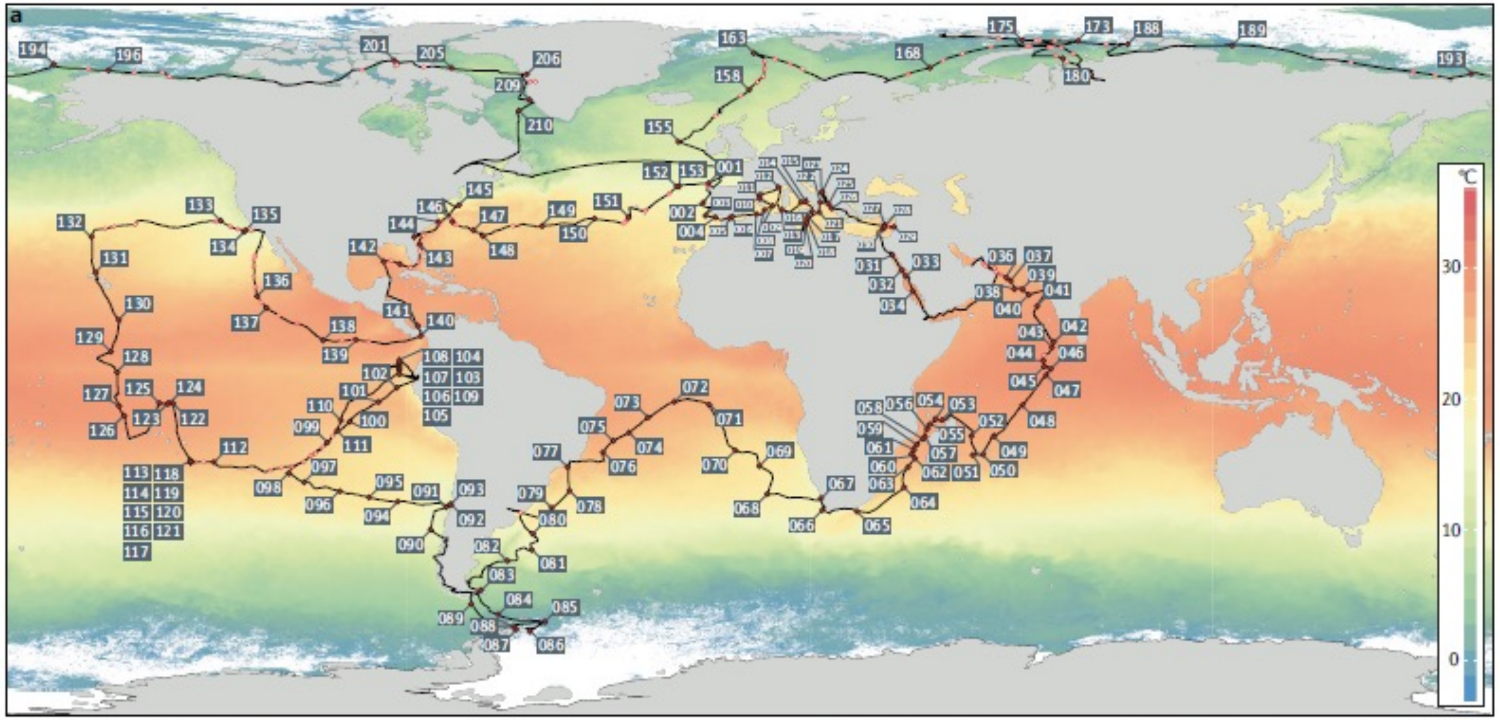


Blue text identified by DNA sequence
Black text by cultured microbes

Review Article | Published: 12 May 2020

Tara Oceans: towards global ocean ecosystems biology

>60 Terabases sequenced
DNA and RNA, various size fractions, mostly shallow samples



Tara Oceans (2009–2013)
- 140,000 km sailed
- >35,000 plankton samples collected
- 210 sampling stations
- >60 terabases of DNA and RNA sequenced
- ~7 million images captured
- 120 crew members and scientists on-board
- 52 stopovers in 37 countries
- 35,000 schoolchildren on board at stopovers

- Global coverage
- Datasets have been extensively used yielding many discoveries
- Yet smaller ship platform makes profiling and chemical (metal) work difficult

environmental microbiology reports

Environmental Microbiology Reports (2019) **11**(1), 35–37

doi:10.1111/1758-2229.12721

Crystal ball: the microbial map of the ocean

Alyson E. Santoro*

Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, CA, USA.

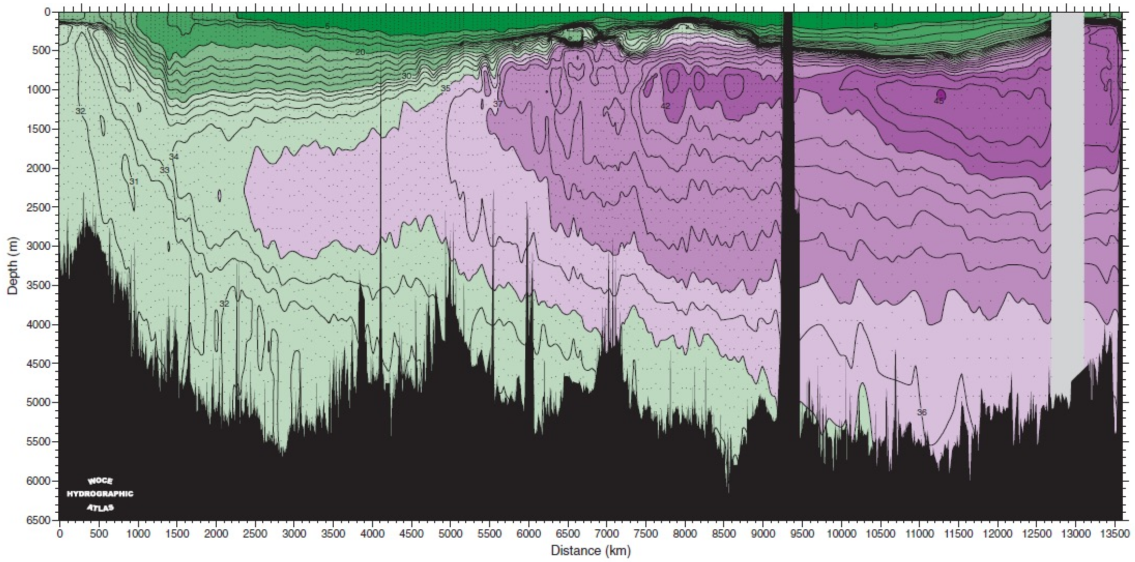


Fig. 1. Nitrate concentration (μmol kg^{-1}) in the Pacific Ocean along World Ocean Circulation Experiment (WOCE) section P16 at 150°W longitude, from the Southern Ocean to the Bering Sea. From the WOCE Pacific Ocean Atlas (Talley, 2007).

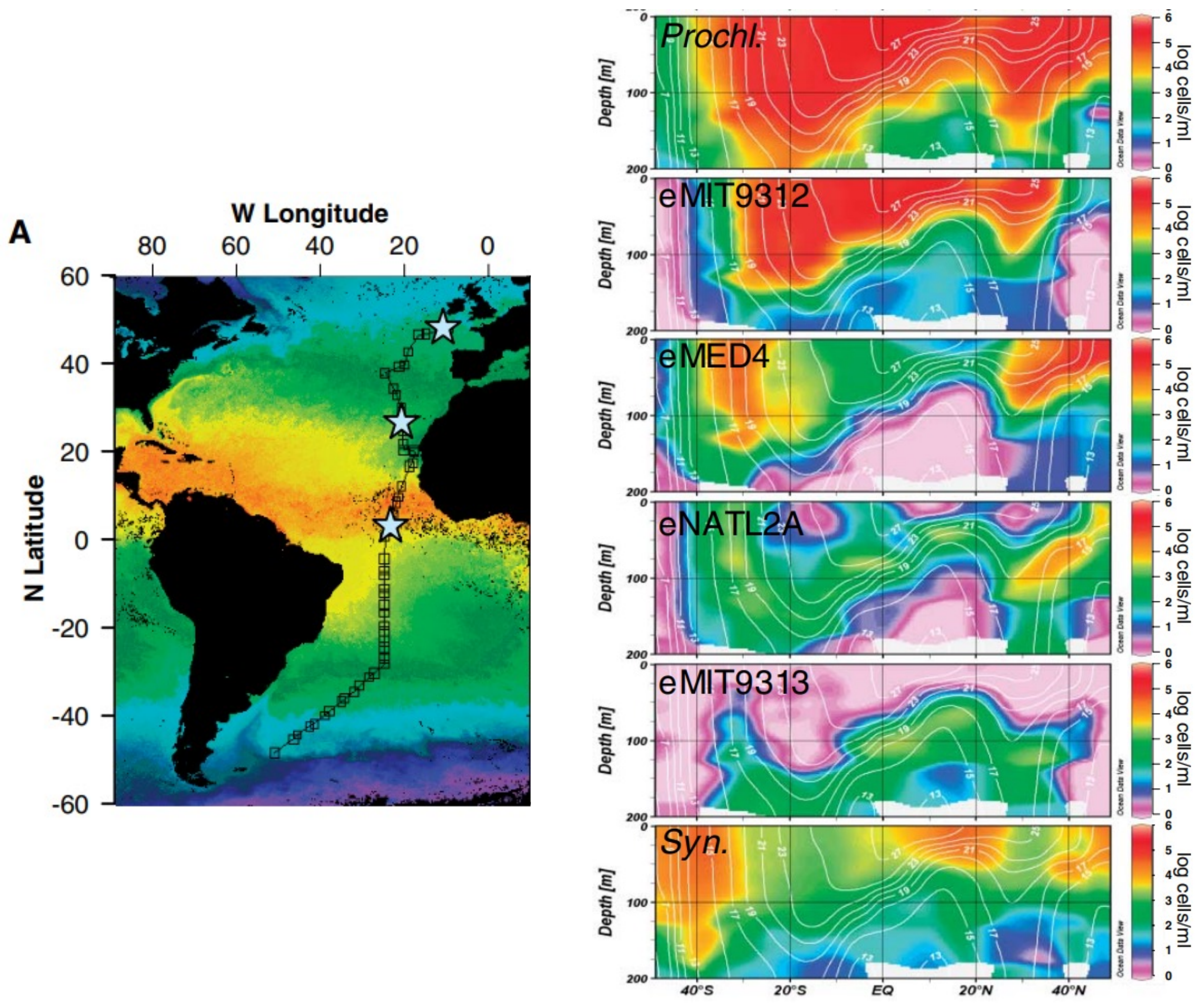
But these pioneering expeditions fall flat, literally, when it comes to mapping microbes at the spatial resolution necessary for relating their distributions to the three-dimensional structure of the ocean's circulation. Constrained by budgets and

Throughout history maps have been used to shape opinions, wield power, and understand the world. A microbial map of the ocean would be no different.

Where are the microbes?

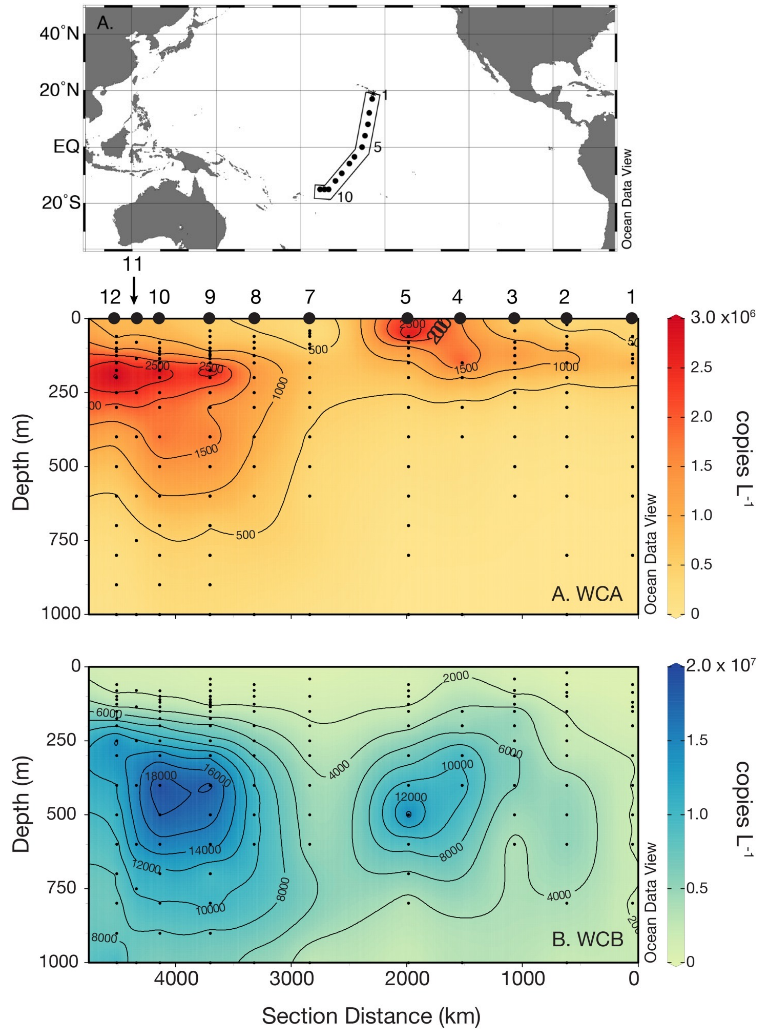
Relatively few sections done so far, **none full depth**

Prochlorococcus in the North Atlantic



Johnson et al., 2006

Ammonia Oxidizing Archaea in the Central Pacific

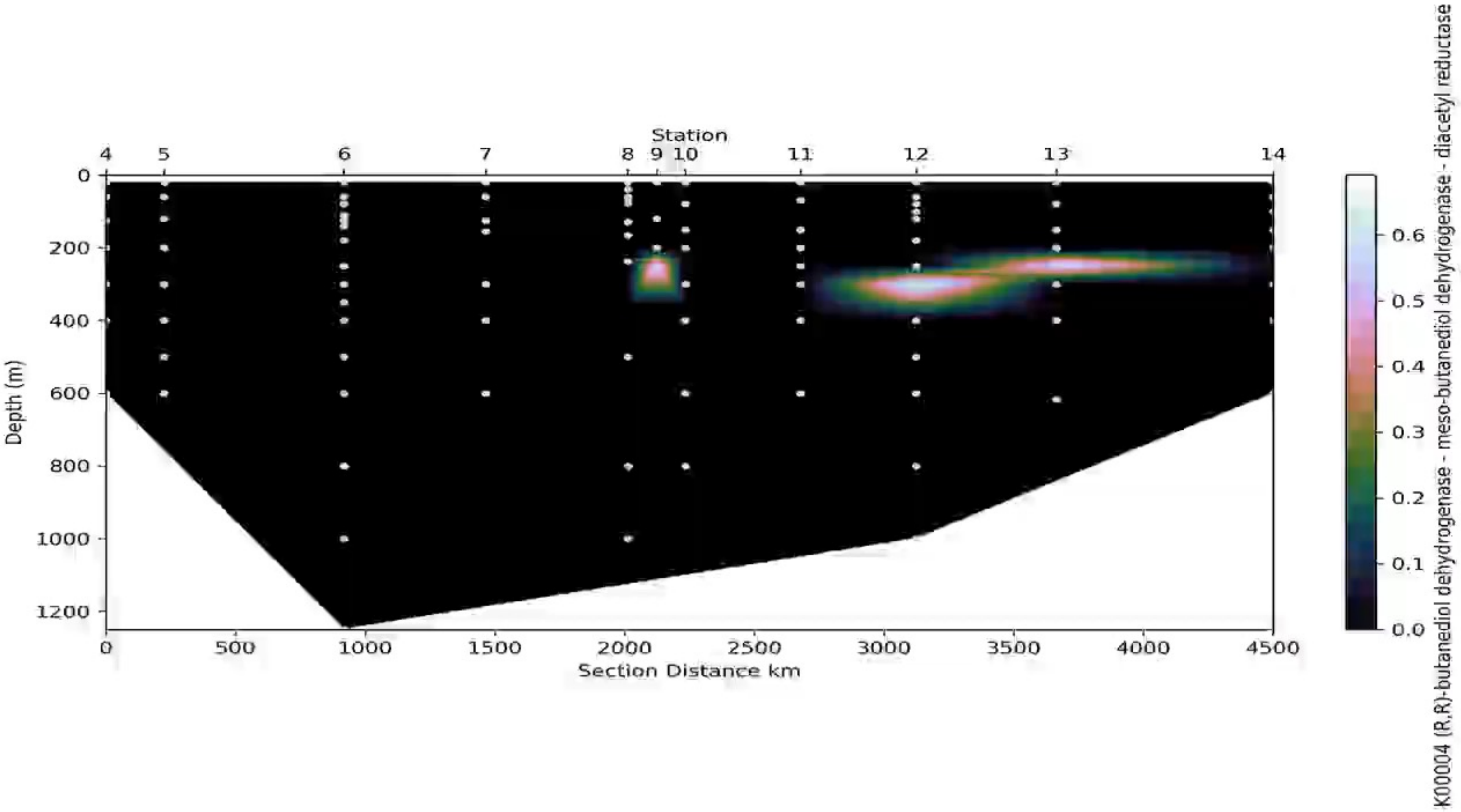


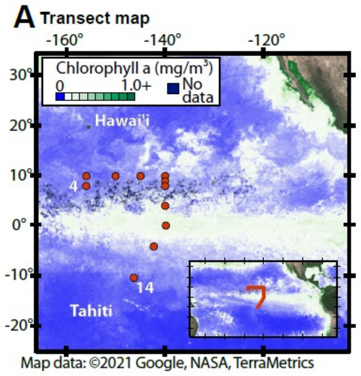
Santoro et al., 2017

What are the microbes doing? Biogeochemical Functions

Other Omics provide complementary capabilities: Central Pacific Ocean Protein section profiles

~100,000 microbial proteins from the ProteOMZ expedition by KO group Saunders et al., 2022





BioGeoSCAPES
Ocean metabolism and nutrient cycles on a changing planet

Recent Accel-Net Implementation Award:

Developing an international program to study ocean metabolism and nutrient cycling by microbes in a changing planet (BioGeoSCAPES)

Mak Saito, Harriet Alexander, Heather Benway, Maite Maldonado, Naomi Levine, Alyson Santoro, Alessandro Tagliabue, Ben Twining

- Just awarded summer of 2022 for 5 years
- Grant supports development of International Networks-of-Networks
- Accel-Net = Acceleration of Networks
- Does not fund science research activities

The plan

1. Why is BioGeoSCAPES needed now?

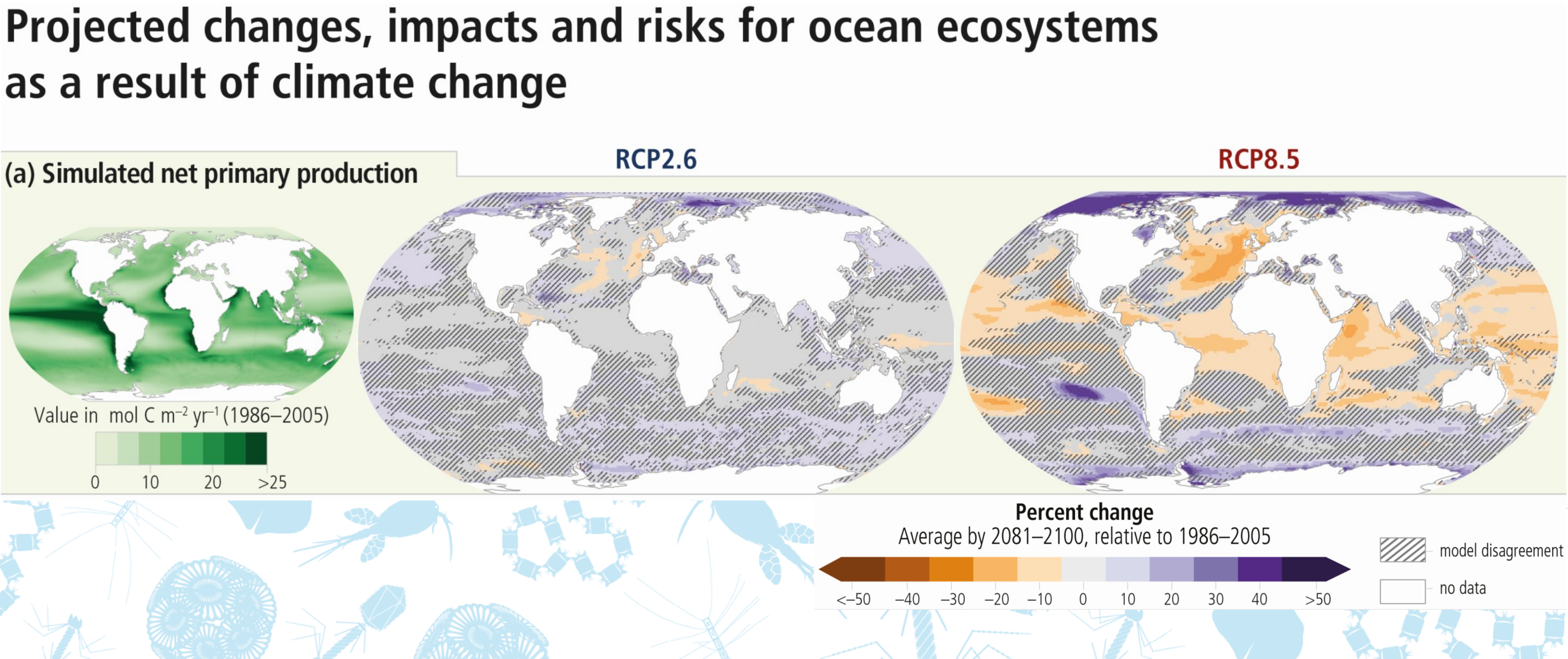
2. BioGeoSCAPES planning activities enabled by US AccelNet grant

Why BioGeoSCAPES now?

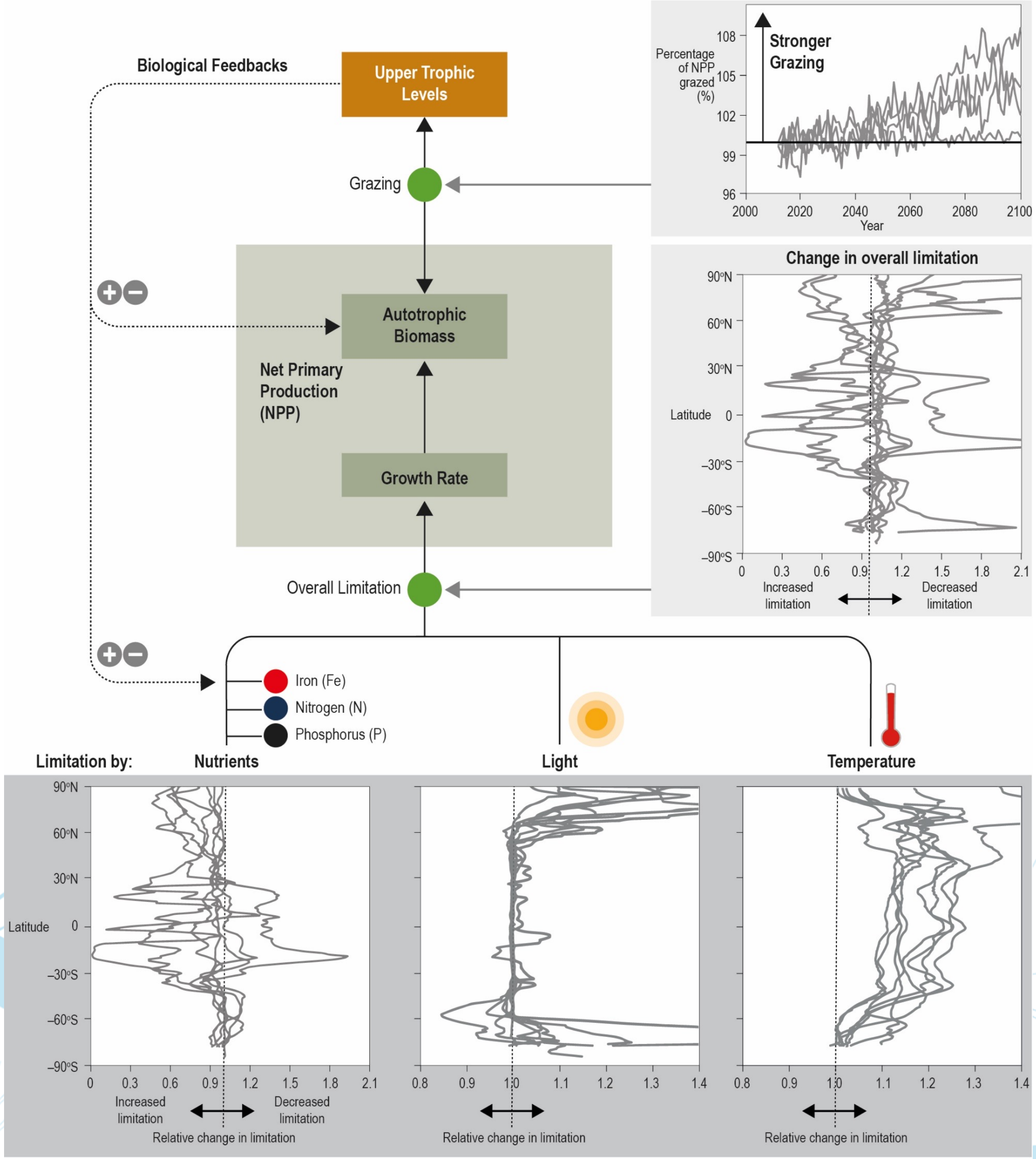
- Ocean conditions, nutrient cycles and productivity are changing

  → improved science needed to understand and predict impacts, and to inform possible responses

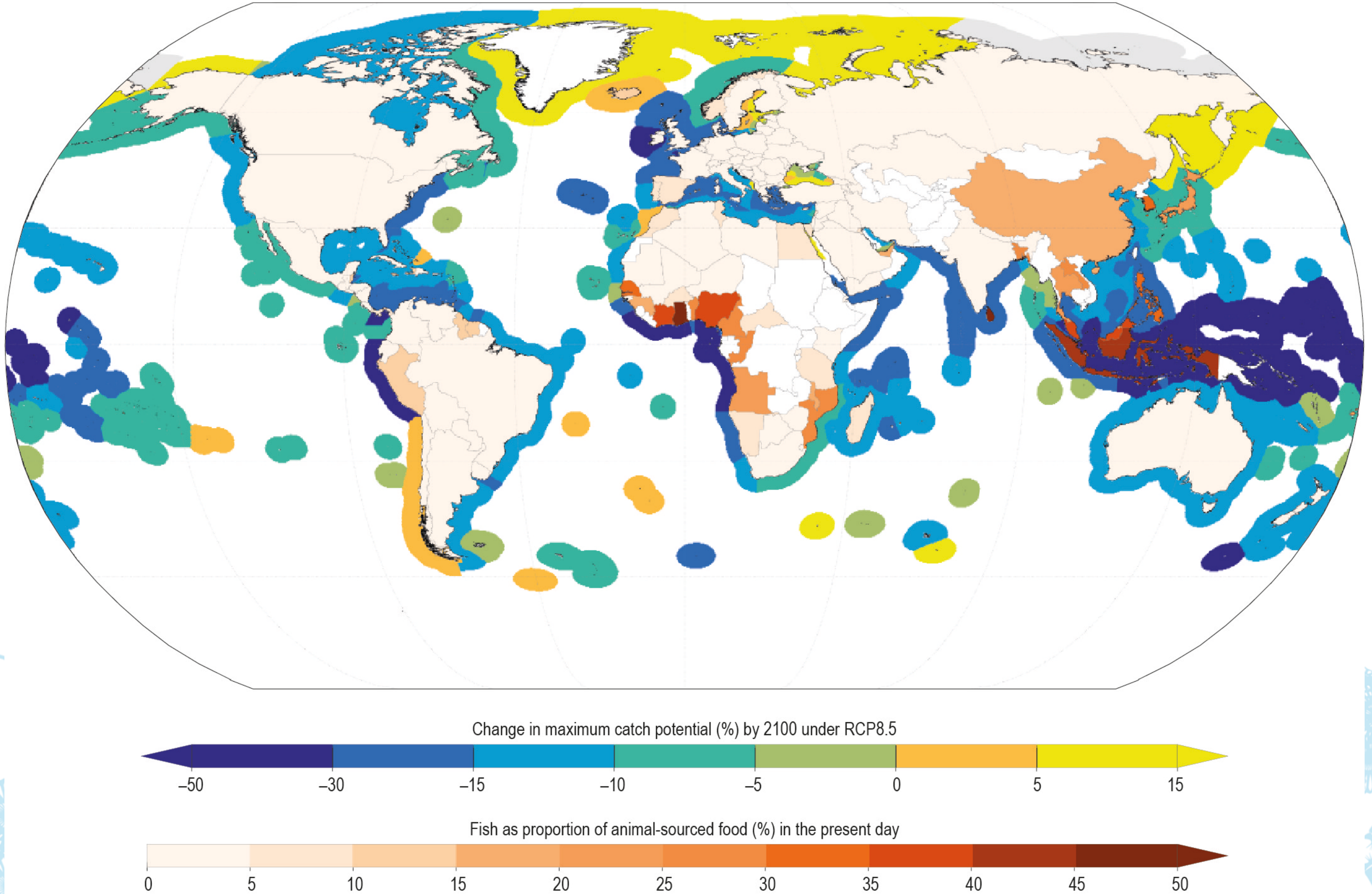
IPCC Special report on the ocean and cryosphere in a changing planet (2019)



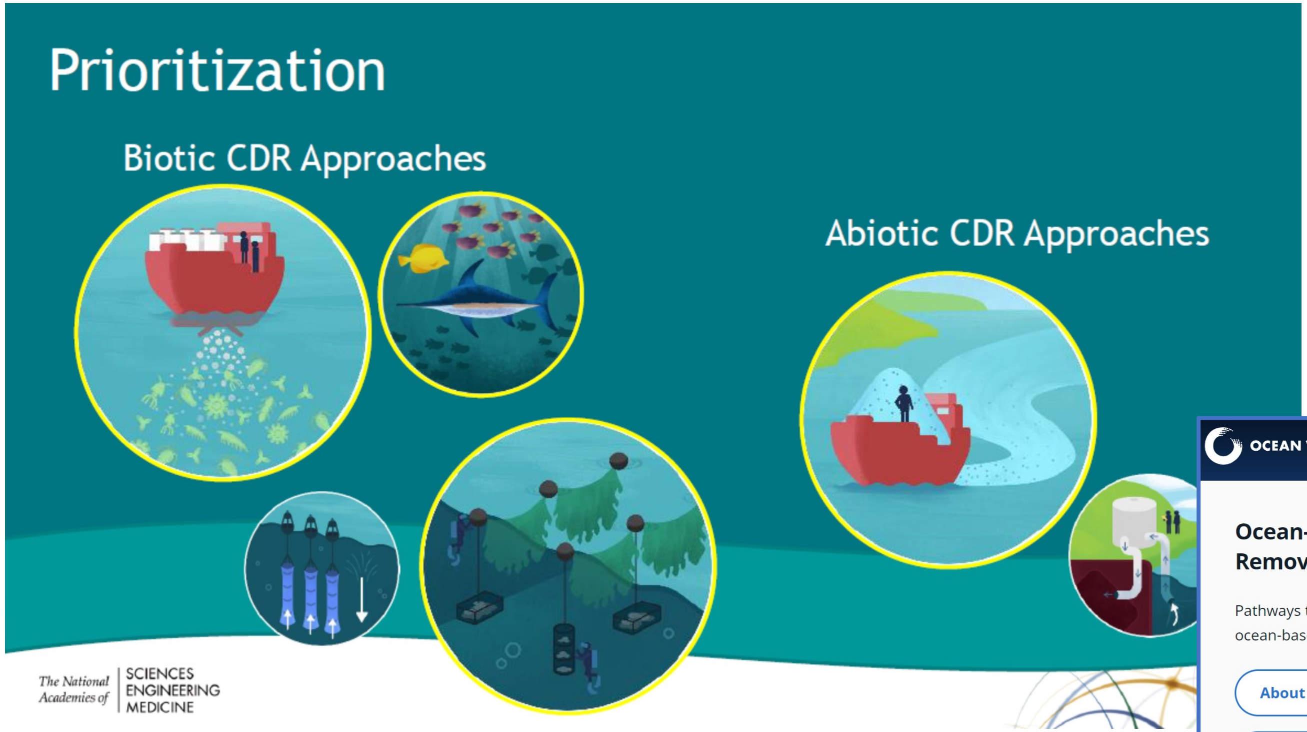
Models disagree on changes in grazing and resource limitation

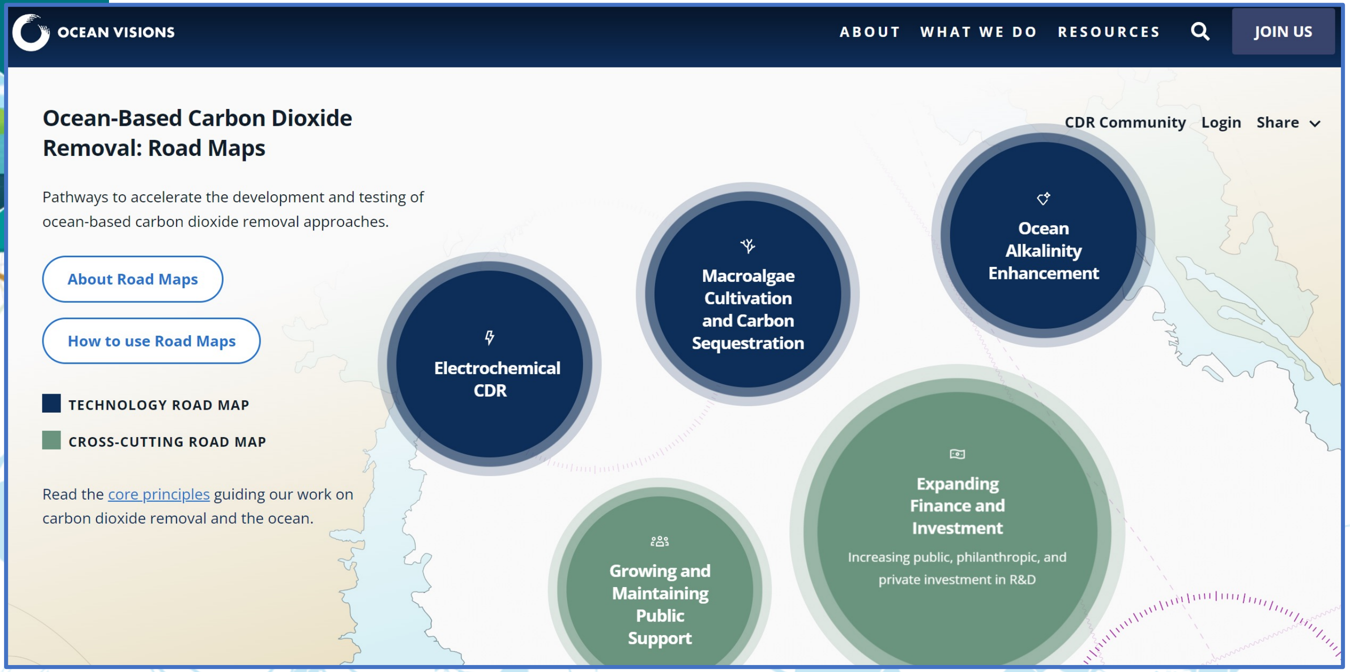


The largest fishery declines may impact the most vulnerable populations



Improved understanding of ocean metabolism needed to inform marine carbon dioxide removal





Why BioGeoSCAPES now?

- Ocean conditions, nutrient cycles and productivity are changing
  → improved science needed to understand and predict impacts, and to inform possible responses

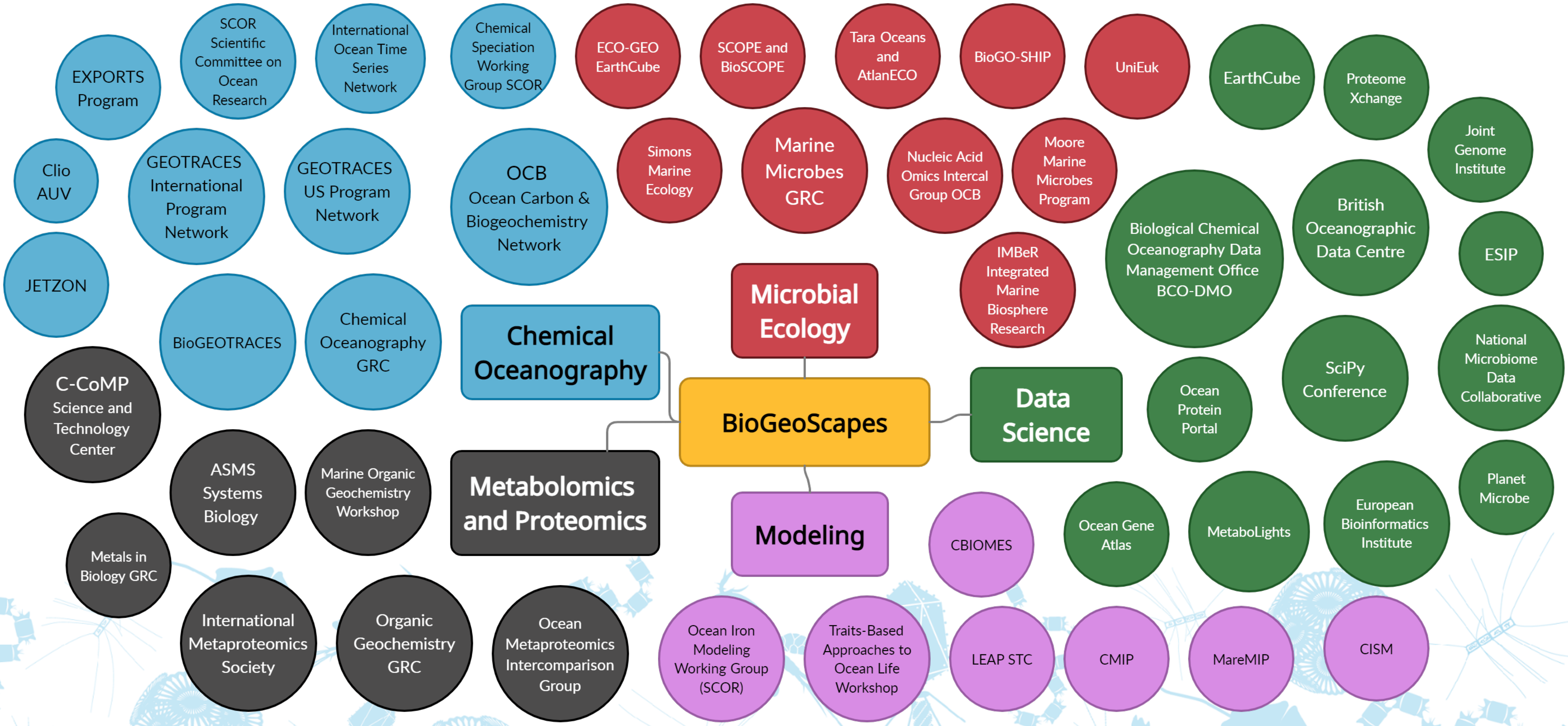
- Maturing analytical and computation capabilities
  → ability to measure key microbial and geochemical process across the global ocean

- UN Decade of Ocean Science for Sustainable Development
  → sustainable management of ocean resources

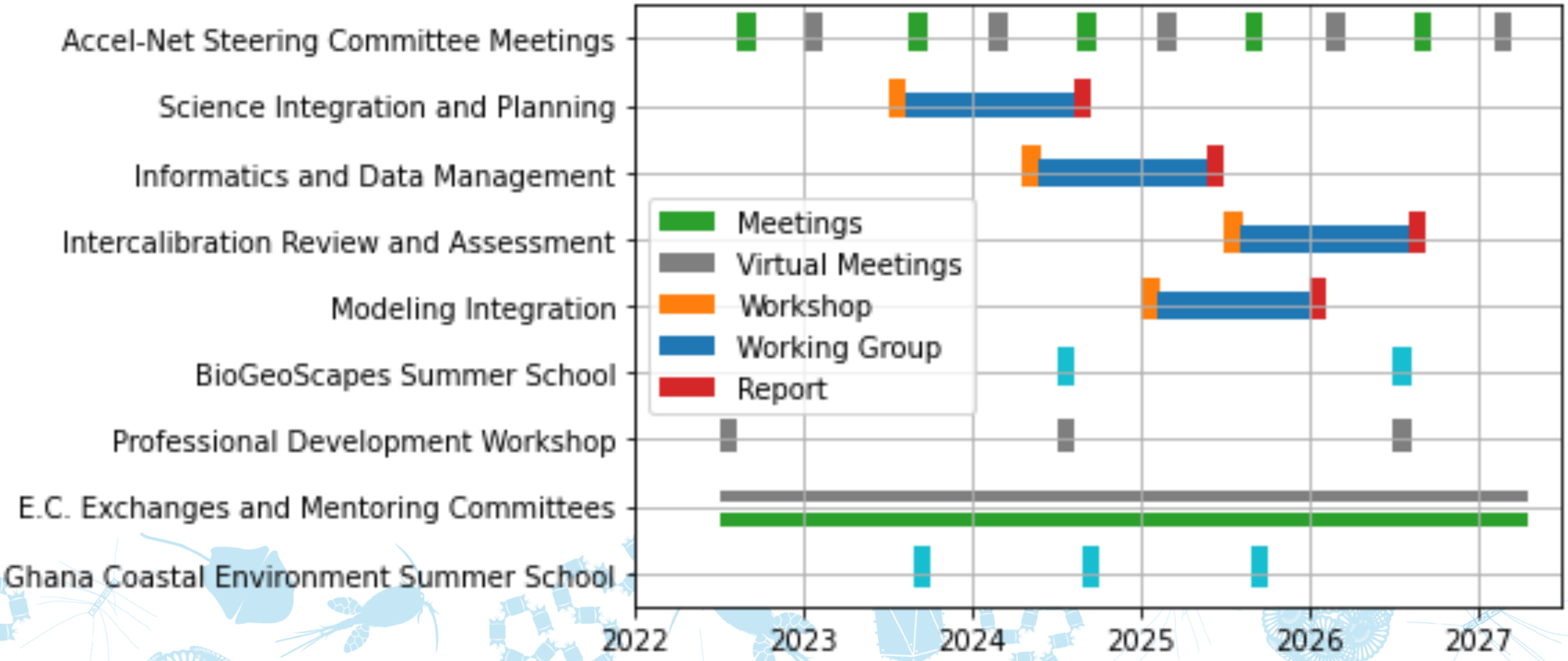
BioGeoSCAPES challenges

- Bridging across scales and disciplines
- Physical and chemical sampling strategies to match biology
- Standardizing sampling and analytical protocols
- Integrating ‘omics-based technology with physiological studies and rate measurements
- Breaking boundaries between oceanography and ‘omics data sets – new mathematical/integrative tools?
- Training new generation of ‘omics-enabled oceanographers

A network of networks



Timeline of AccelNet Activities



International planning activities

Science and implementation plan **2023**

Informatics and data management

Model integration

Intercalibration review and assessment

Each will need an international working group of planners, organizer, and writers

Capacity building

- International early career exchanges (ca. 5/yr; 2wks – 3 months)
- BioGeoSCAPES summer schools (ca. 2 over 5 yrs)
- Professional development workshops (ca. 3 over 5 yrs)
- Mentorship program: evidence-based team mentoring program (nrmnet.net)
- Early career representation on all planning committees
- Emphasis on equity and inclusiveness

Partnership with Coastal Ocean Environment Summer School in Ghana and Nigeria

COASTAL OCEAN ENVIRONMENT SUMMERSCHOOL IN GHANA

Coastal Ocean Environment Summer School In Nigeria and Ghana

HOME ABOUT 2022 SCHOOL (IN NIGERIA) PAST SCHOOLS TESTIMONIALS RESOURCES CONTACT & APPLY

Collection and analysis of coastal metagenome samples

The topics covered in the school include:

- –Coastal and estuary dynamics
- –Physical Oceanography
- –Tides
- –Organic and isotope biogeochemistry
- –Satellite and field oceanography
- –Numerical modeling of the ocean
- –Data analysis techniques
- –Oil and gas basin development
- –Mineral Geochemistry
- –Fisheries management
- –Pollutant dispersal
- –Maritime affairs
- –Scientific Python
- –Ocean Data View
- –Atmospheric Science
- –Sediment coring and spectroscopy
- –Cloud computing

A ‘franchise’ model?

A ‘franchise’ model?

- Ocean basin-scale expeditions
- Coastal observations
- Time-series studies
- Laboratory physiology measurements
- Integrated modeling

Driven by research goals

All underlain and enabled by intercomparable measurements

BioGeoSCAPES outcomes

- Baseline understanding of microbial communities and their metabolic function
- New tools for data integration, visualization and analysis
- Quantified biological and biogeochemical hierarchies structuring ocean metabolism at different scales
- Key biological feedbacks represented in ocean ecosystem models
- Foundation for study of future anthropogenic impacts on the ocean, and its resilience to change
- Train new generation of scientists worldwide for increased capacity in omics, bioinformatics, modelling, and biogeochemistry

BioGeoSCAPES Summary

- Development of the BioGeoSCAPES program is open to all interested parties – participation and input are actively sought!
- There is a lot of community-building work ahead of us
- We need to identify compelling, understandable goals for the program to excite funders and colleagues, and to focus subsequent efforts
- Get involved / stay in touch: Join the mailing list at www.biogeoscapes.org

New Autonomous Underwater Vehicle Clio : A Microbial Biogeochemistry Vehicle

Chip Breier U. Texas Rio Grande Valley, Lead PI

Mike Jakuba WHOI, Lead Vehicle Engineer

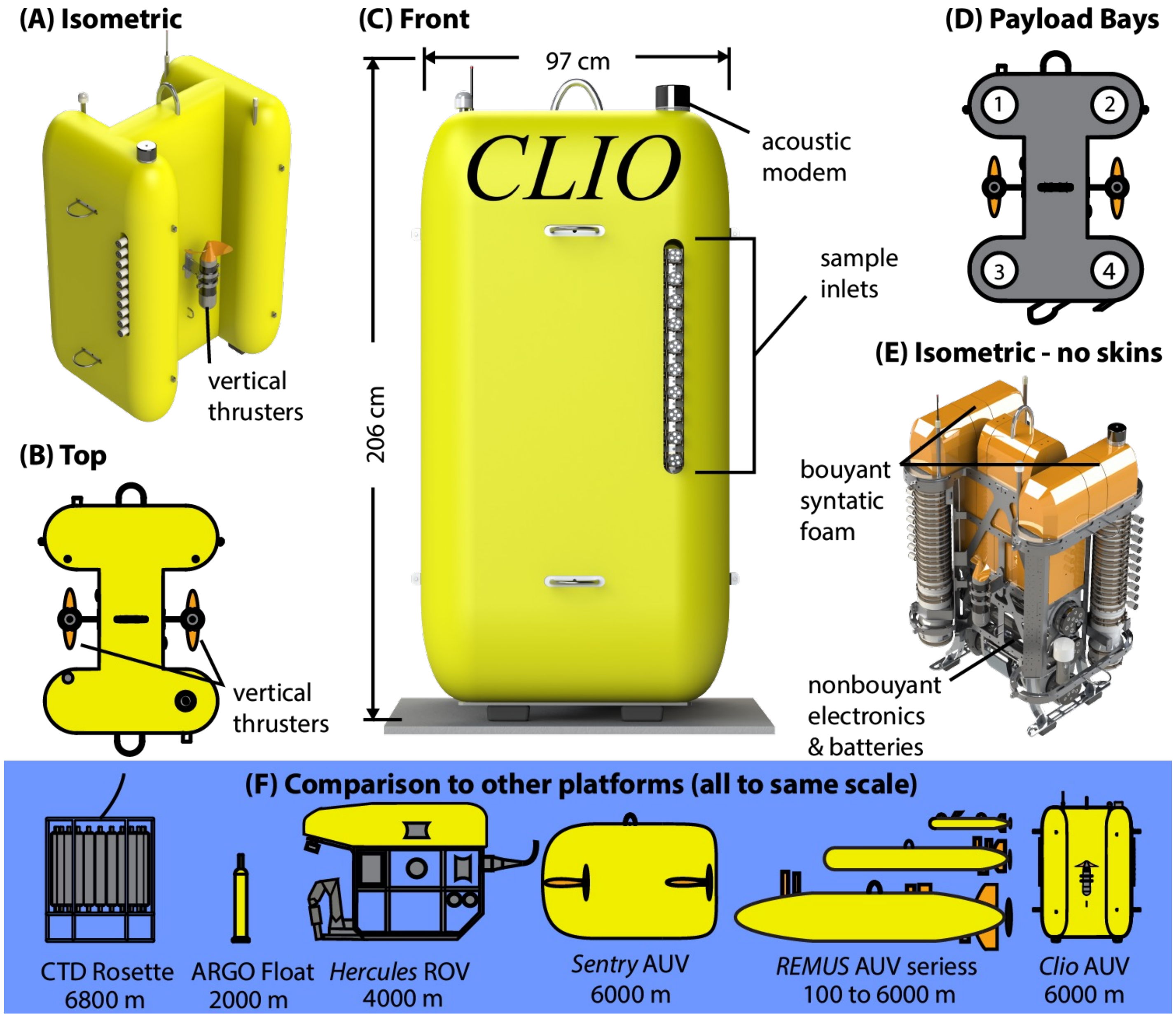
Mak Saito WHOI, Embedded Science User

Inspired by the operational challenges faced by GEOTRACES

Clio: A purpose designed robot

Designed to:

- Dive to 6000m
- Stop and hold depth at any arbitrary depth
- Process seawater to collect multiple sets of samples for nutrients, trace metals, the carbon system, and 'omics measurements
- Repeat these tasks during dives repeated across an ocean basin.

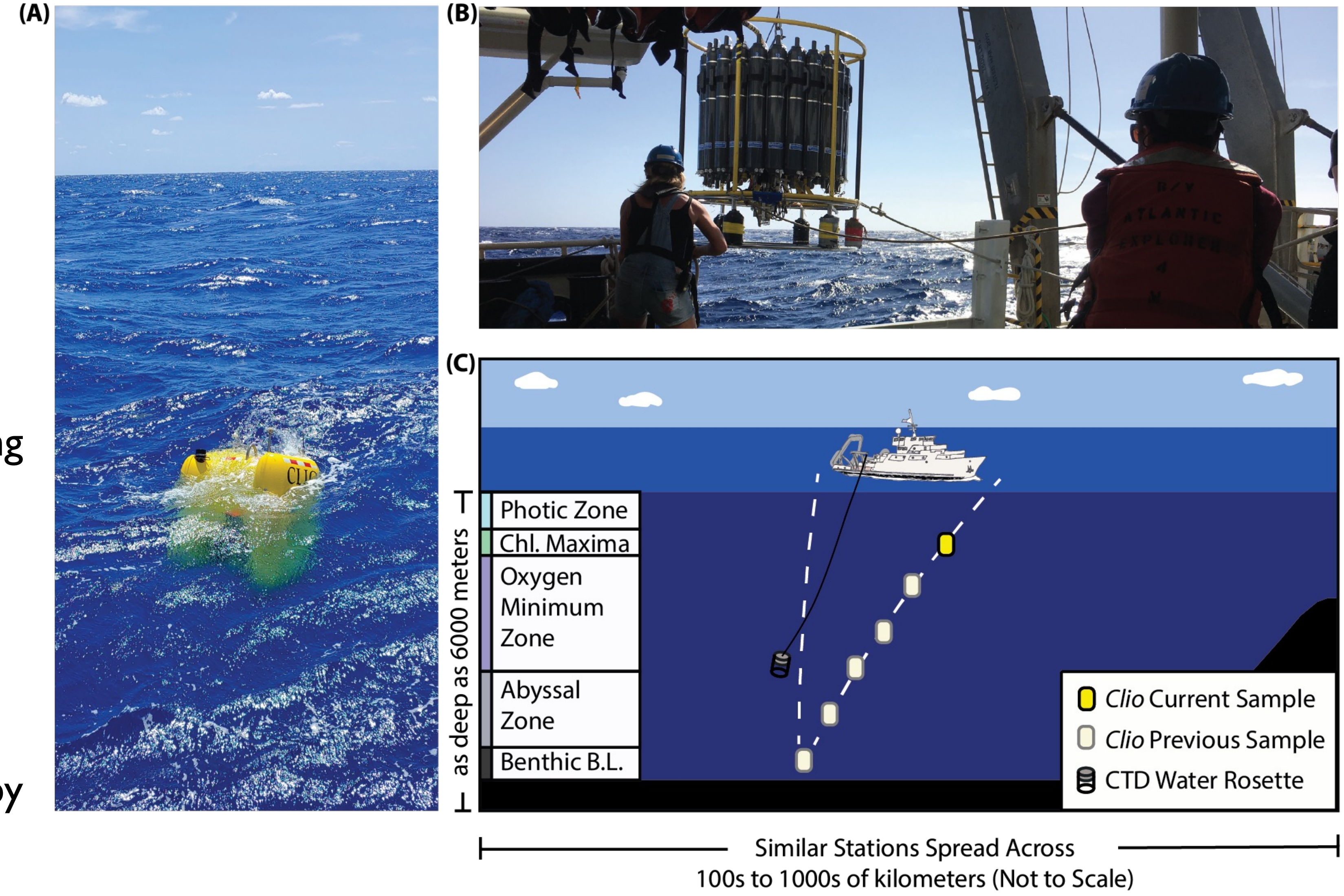


Breier et al, Science Robotics, 2020

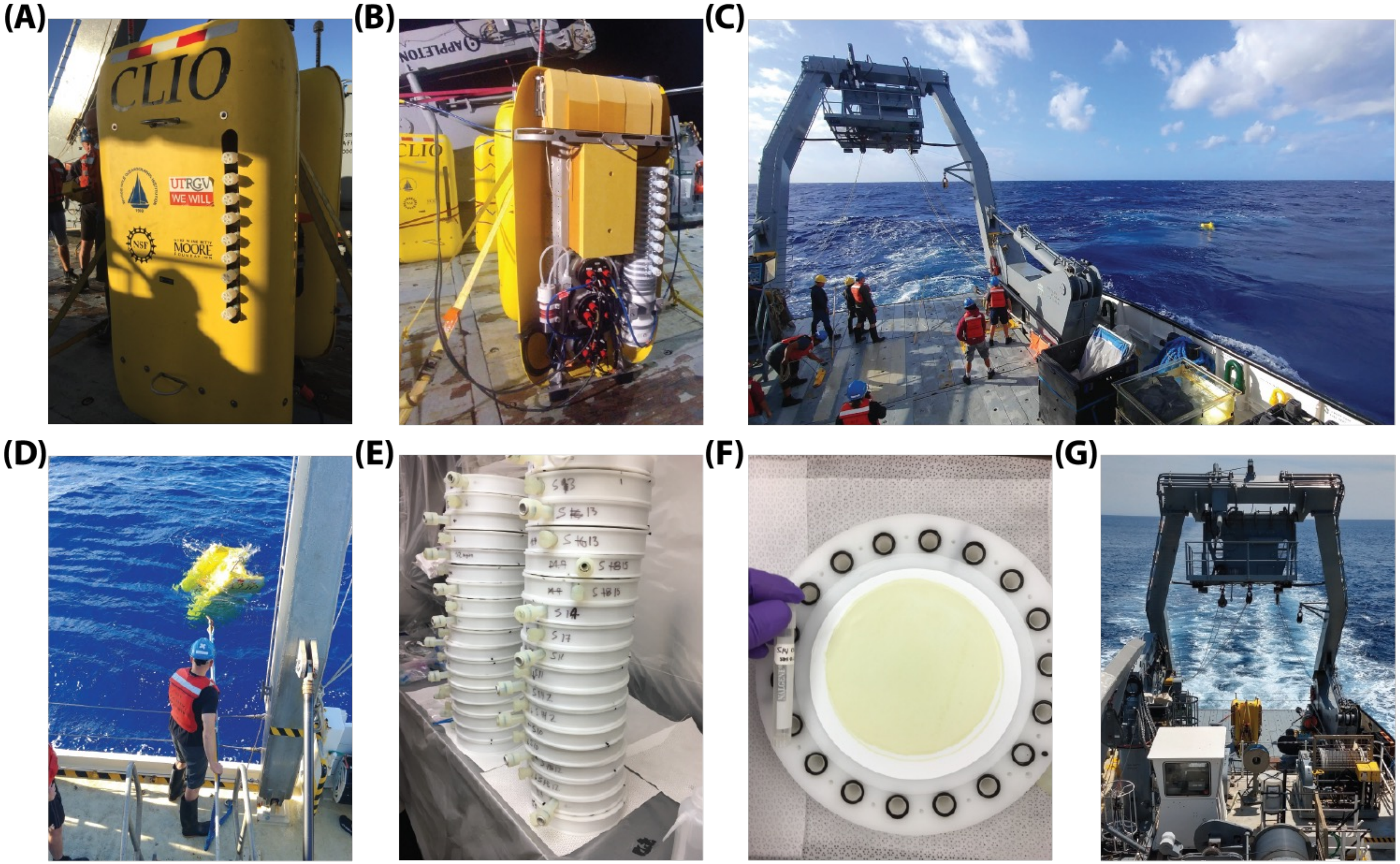
Clio: Design Operations

Intended to:

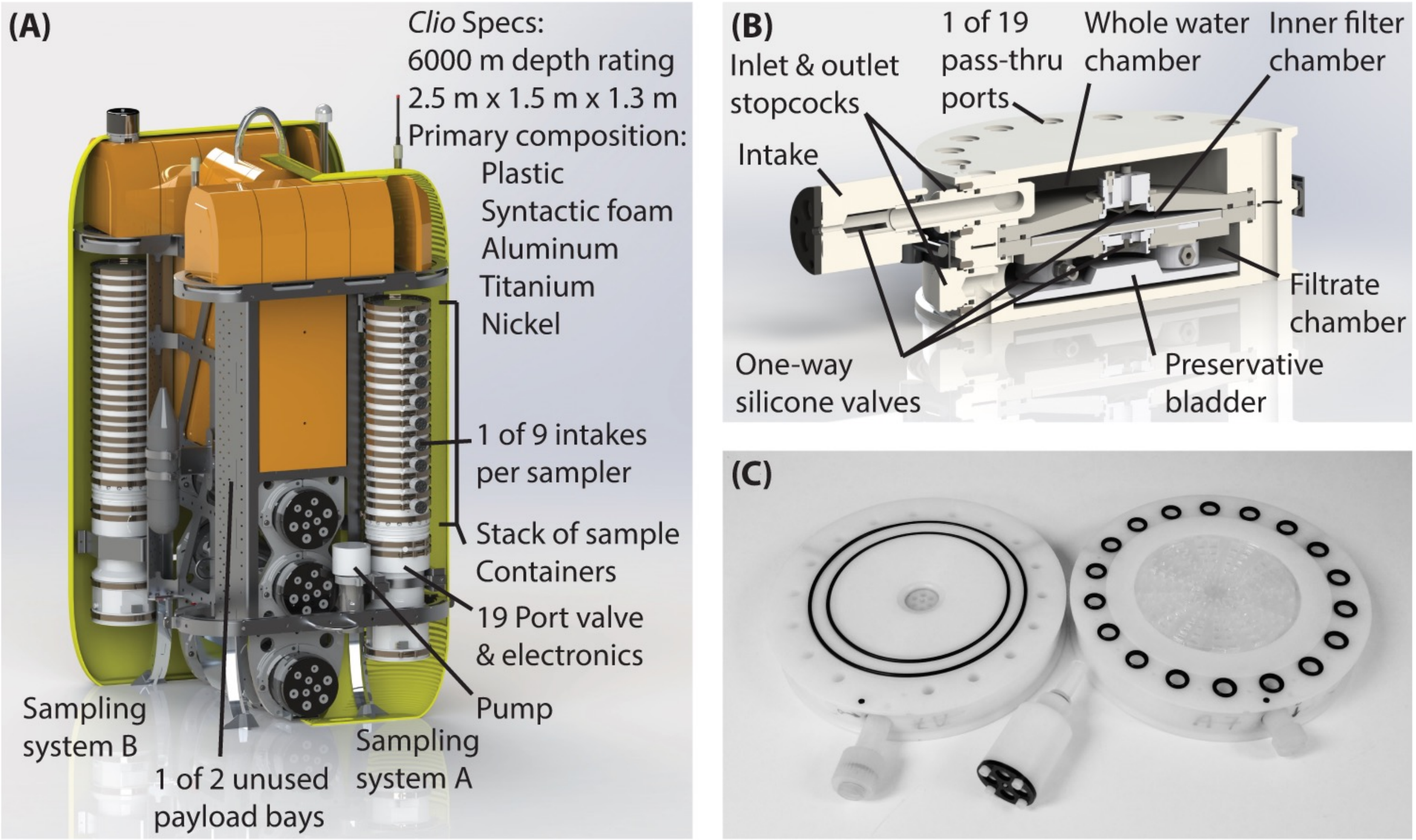
- Improve sample and sensor data collection for measurements normally performed by wire-based methods.
- Improves resolution by isolating sample collection from host ship motion.
- Frees ship for parallel data collection tasks.
- On an Ocean Section cruise Clio would reduce wire time by 50% and cruise duration by 1/3rd for equivalent number of samples



Clio: Typical Operational Cycle



Clio: Robotic Sampling Systems



Clio AUV: Conception to Validation

Clio Sampling and Sensing Payload

Table 1. An Example *Clio* Dive Sampling Plan and Payloads

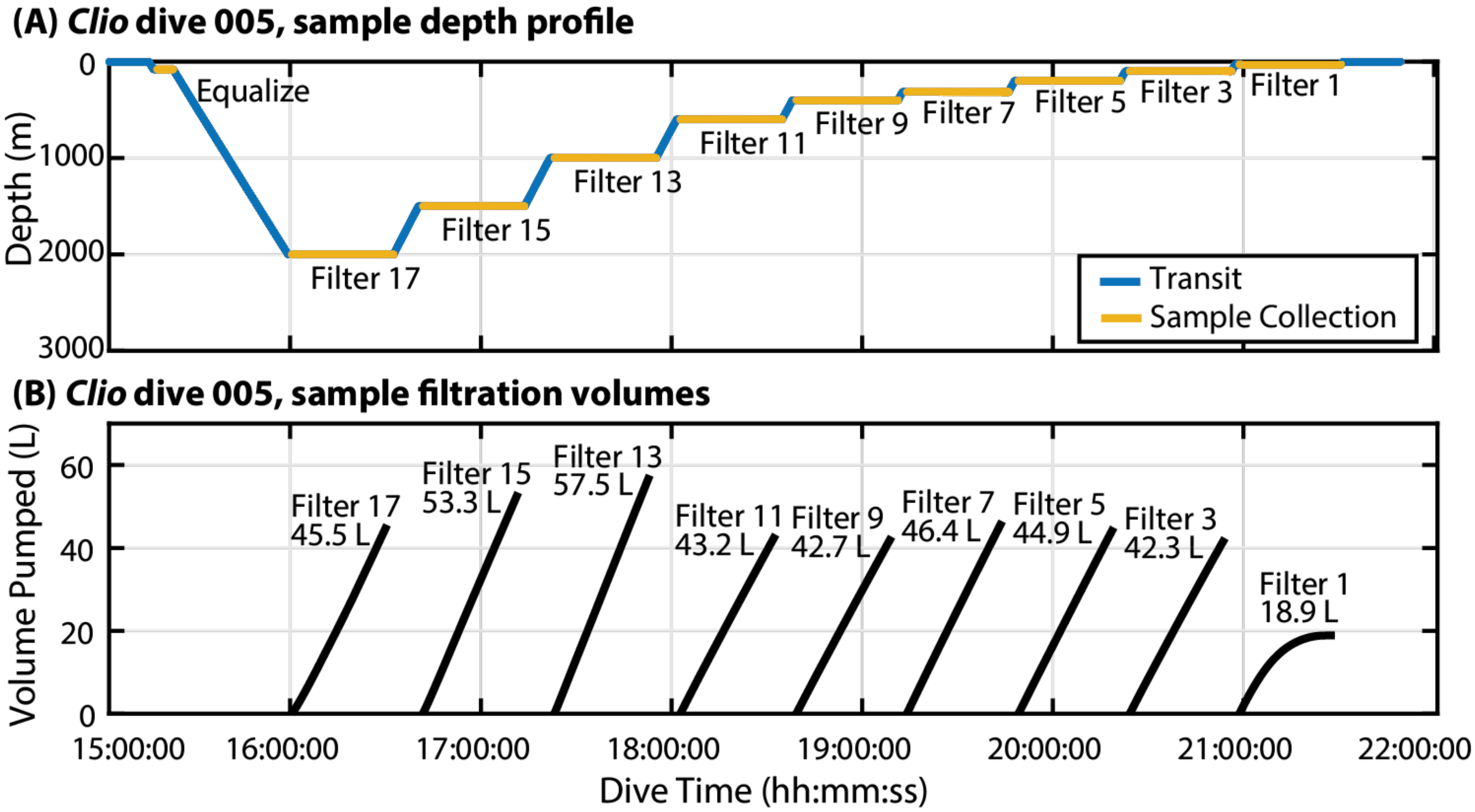
	Reconfigurable Science Payload Bays								
	This Proposal				Possible Use of Additional Payload[1]			Sensor Payload	
	Science Bay 1 SUPR-Omics[2]	Science Bay 2 SUPR-Metals			Science Bay 3 SUPR-Carbon		Science Bay 4 SUPR-Rad	Current	Future Reconfigurable
	Particles[3] (150 L)	Whole Water (200 mL)	Particles[3] (150 L)	Filtrate (200 ml)	Particles[3] (>150 L)	Filtrate (250 ml)	Particles[3] (>150 L)	Seabird 49 Fastcat CTD Wetlabs 25 cm transmissometer Wetlabs ECO Fl chlorophyll-a Anderra 4330 optode Unisense O2-STOX	UV Nitrate Methane Wetlabs ECO 470 Wetlabs ECO 532 Wetlabs ECO 650 Wetlabs AC-S Particle Camera
Media	SUPOR[4]	seawater	SUPOR[4]	seawater	QMA[5]	seawater	QMA		
Derived Analyses	DNA/RNA Proteomics	FISH Cell Count	Metals	Metals Nutrients	POC	DOC	Th,Po,Pb		
Samples	9	9	9	9	9	9	9		
Tot. Filtered	1350 L		1350 L		1350 L		1350 L		
Energy	504 Whr		504 Whr		504 Whr		504 Whr		

[1] *Alternatively additional payload could also be used for other sample types or sensors.*

[2] *With in situ preservation.* [3] *Multiple size classes per sample possible.*

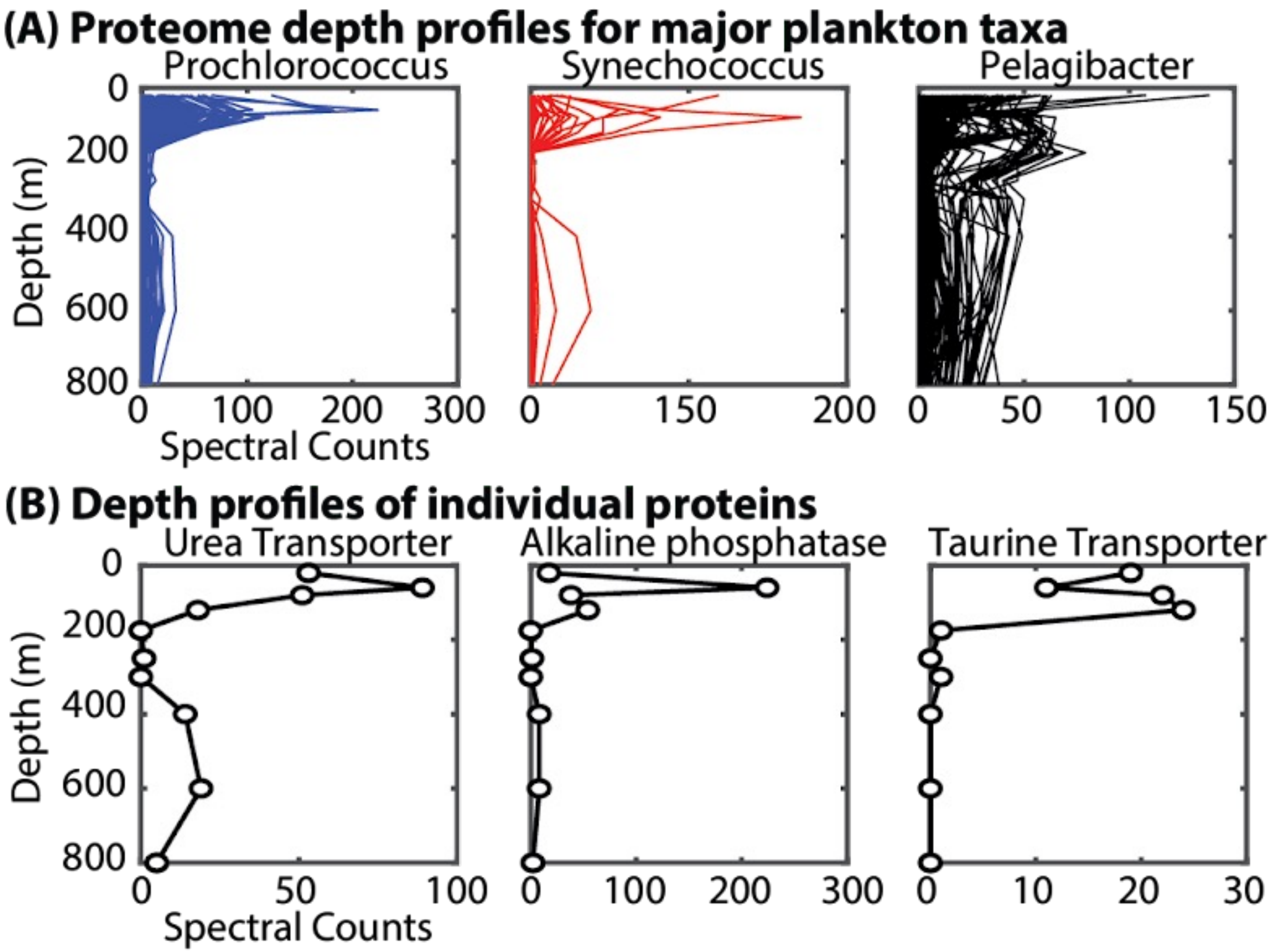
[4] *Omnipore PTFE filters are a possible substitute.* [5] *Either 47 or 142 mm diameter.* [6] *Operational blank*

Clio: Typical Sampling Dive Profile



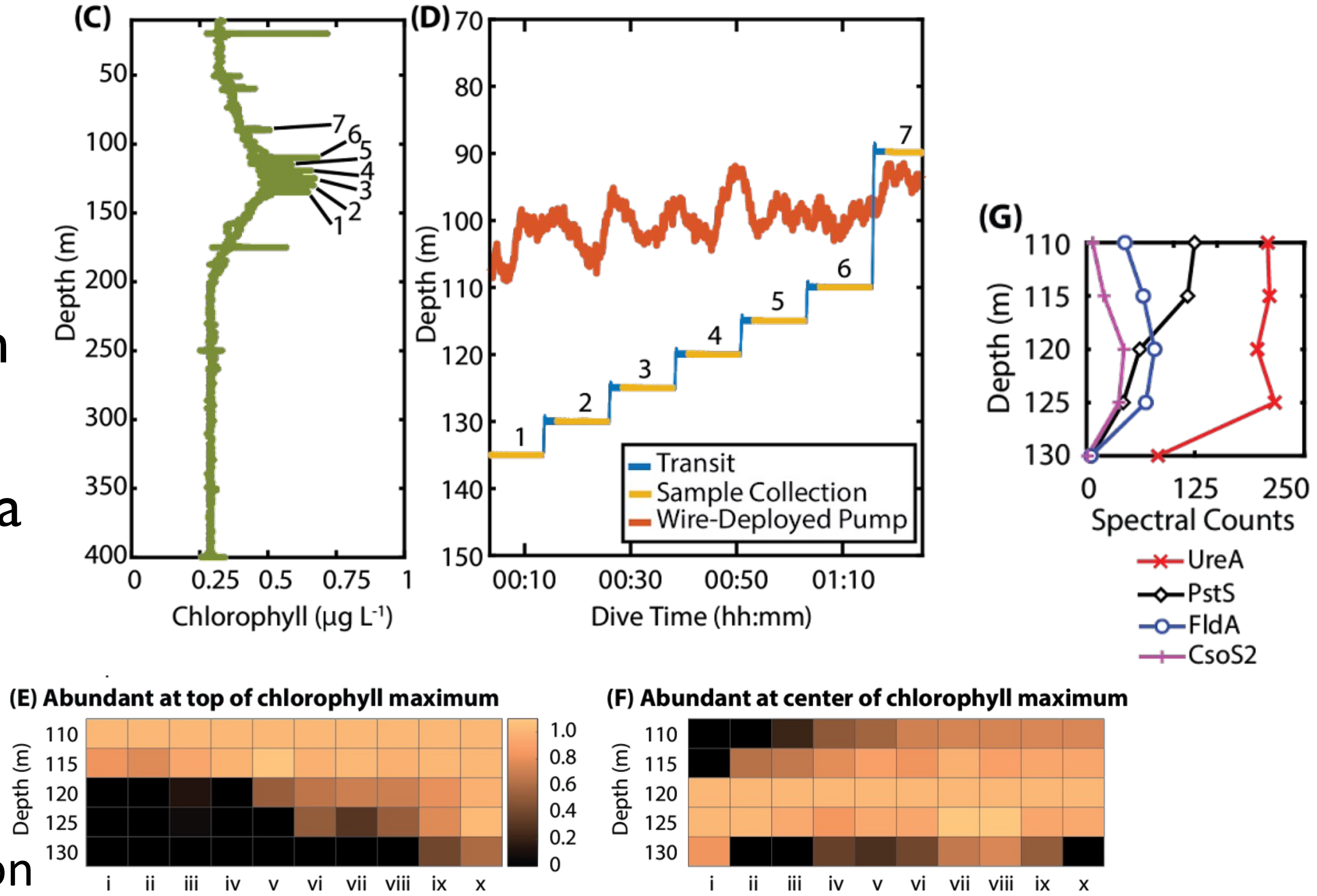
Clio: Proteomics Profiles

- Protein profiles by major microbial taxa.
- Select nutrient response proteins from *Prochlorococcus* and *Pelagibacter.*
- Select correlations with the deep chlorophyll maximum.



Clio: High Resolution Sampling

- High vertical resolution sampling within the deep chlorophyll maximum.
- Comparison to depth resolution achievable with wire-based techniques.
- Clio can hold depth with a precision <5 cm
- Capable of *adaptive* sampling



Clio AUV: Conception to Validation

Clio the BGC AUV
37 Tweets

Clio the BGC AUV @BgcAuv · Jun 23, 2019
I had to lie to twitter.

21:03

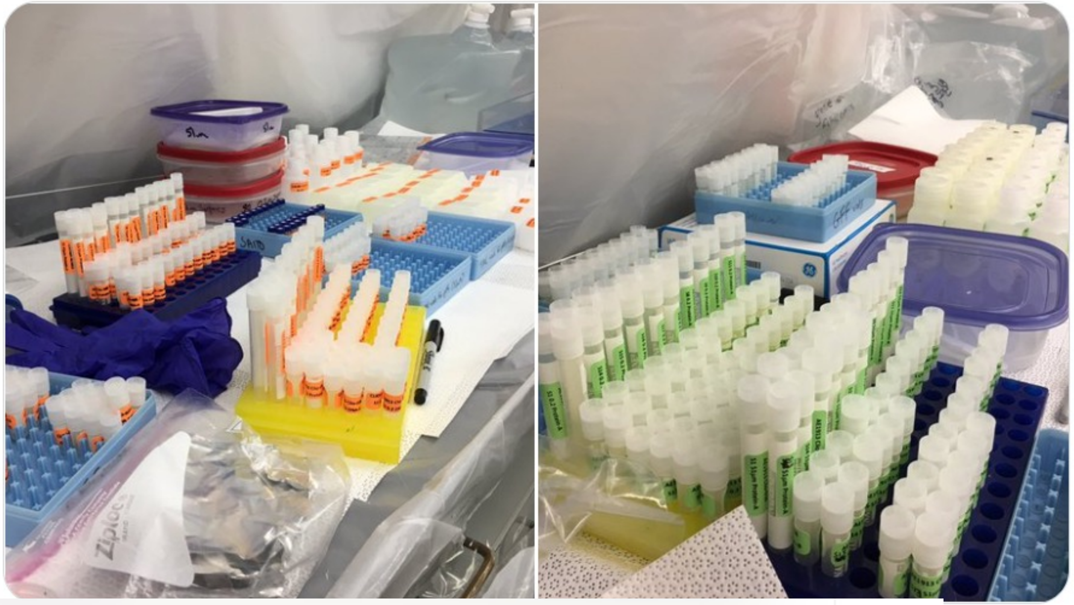
Are you a robot?

I'm not a robot

Clio the BGC AUV
37 Tweets

Following

Clio the BGC AUV @BgcAuv · Jun 25, 2019
My biogeochemists pick nice bright label colors for my payloads, they love me!

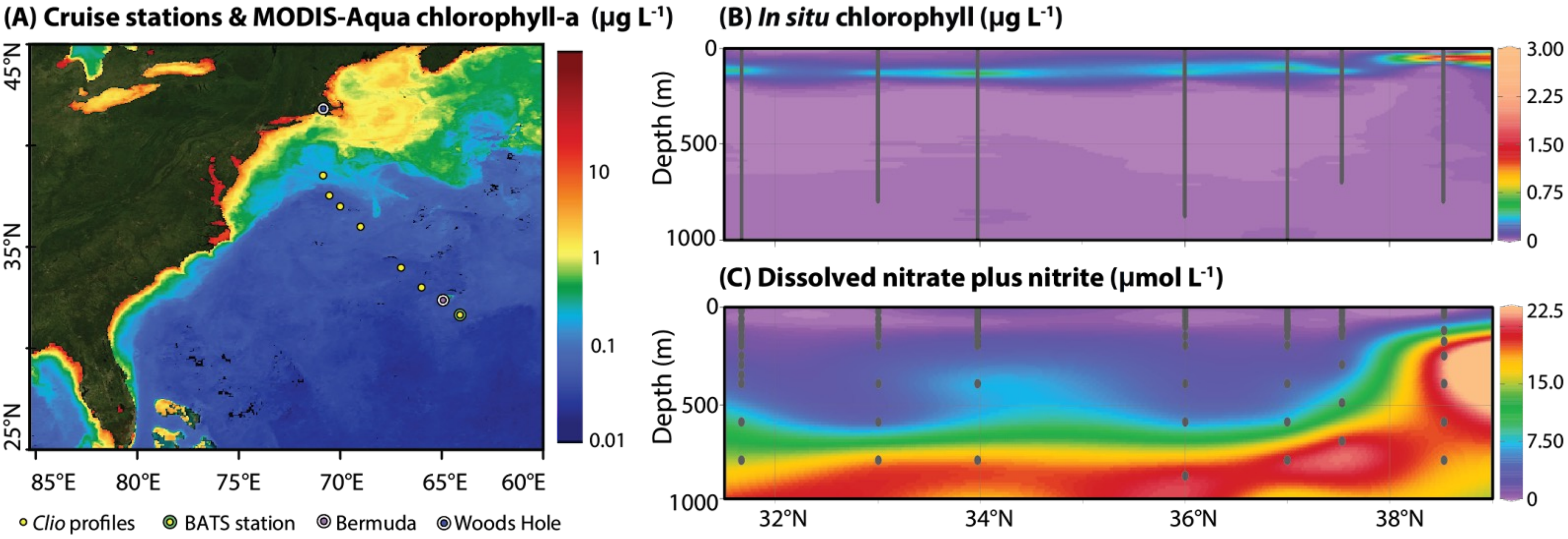


Clio the BGC AUV
37 Tweets

Following

Clio the BGC AUV @BgcAuv · Jun 26, 2019
One of my engineers wanted me to say "Clio is smart now, it thinks on its own and adaptively selects where to sample using chlorophyll sensor data". I told them yeah sure no prob, but it's weird to talk about oneself in the third robot.

Clio: First Ocean Sectional Cruise



In June 2019, *Clio* completed its first sectional cruise in a series of 9 dives spanning a 1,144 km transect between Bermuda and Woods Hole, Massachusetts, USA, through the Sargasso Sea and the Gulf Stream yielding large multi-omic and metals datasets

Natalie Cohen et al., in prep

Clio Summary and the Importance of Sample Return

- Many ecologically and biogeochemically relevant parameters require *returned* samples for analysis
- Micronutrients, Omics, DOM – critical biogeochemical parameters for which there are no *in situ* sensors
- Parallel to biomedicine: Few bedside/clinic complex diagnostics. Sample collection and centralized laboratories are critical. Theranos company bankruptcy is a recent example of overpromises.
- Few chemical and biological AUVs, Clio could be part of Deep-Submergence laboratory
- Employ robotic sampling tools to facilitate ocean biogeochemical studies as well as speed biochemical mapping and exploration efforts so we can better understand the ocean's relationship to a changing climate.

Conclusions and Take Home Messages

Potential Scientific Uses of BioGeoSCAPES

- Discovery of ocean microbial biogeochemistry on a scale previously not possible
- Develop baseline and record of environmental changes
- Develop technologies, standards, and best practices that will improve the understanding of the ocean carbon cycle and CDR verification methods

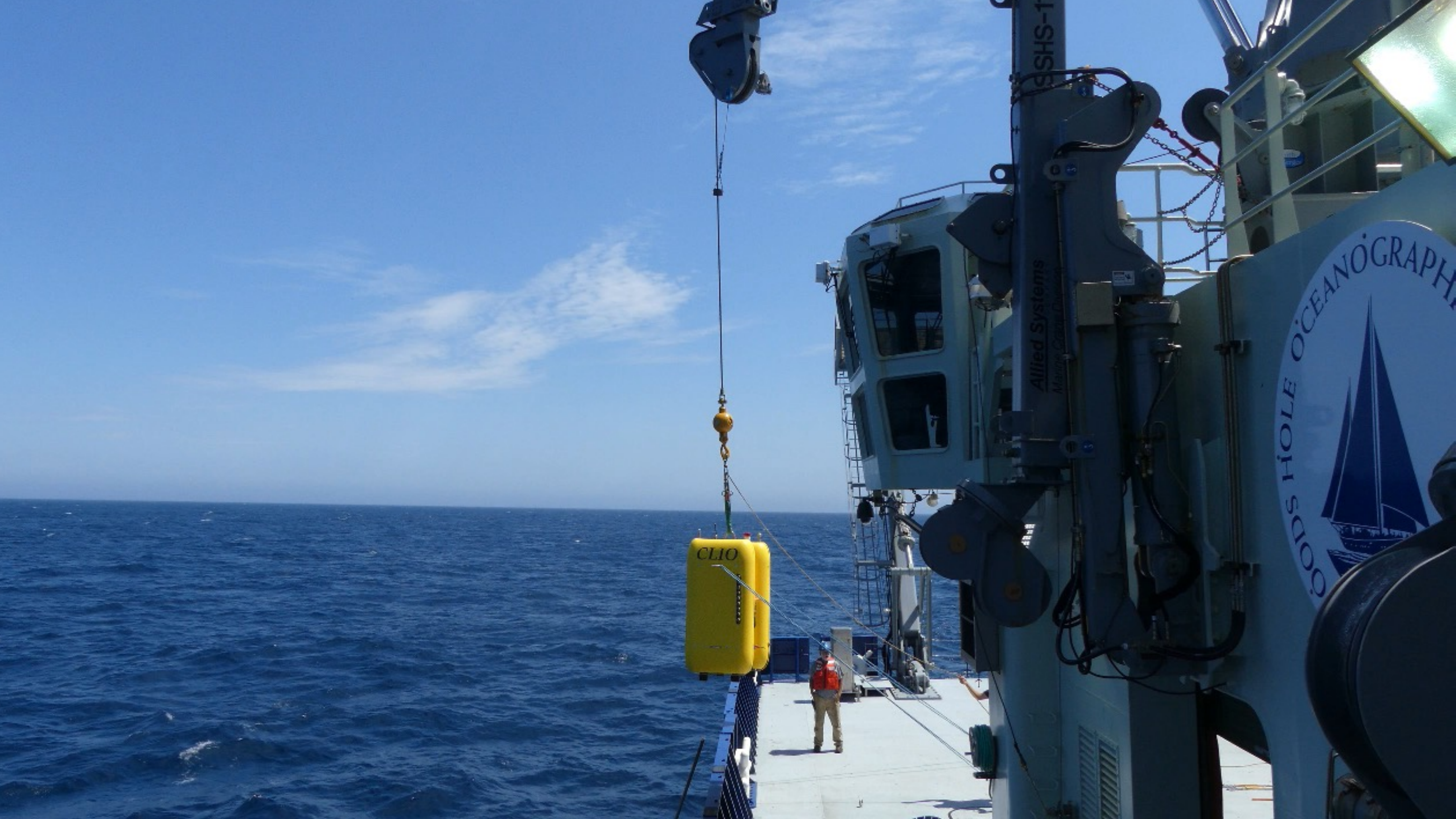
Potential UNOLS ship needs by BioGeoSCAPES

- Complex sampling operations: Full depth sampling, use of multiple sampling devices and AUVs
    - CTD, Trace Metal Rosettes, In Situ pumps, AUVs
    - Complex deck ops and multiple winch use
    - Successful incorporation of Biogeochem AUVs would allow more efficient use of ships
- Process cruises: coastal sampling and/or time series, diel (around the clock sampling)
- Employing a “Franchise model” could mean more frequent expeditions than GEOTRACES and more ship requests

Thank you for listening!

BioGeoSCAPES
Ocean metabolism and nutrient cycles on a changing planet

NSF


CL10
Allied Systems

International Momentum for BioGeoSCAPES

Nation with Ambassadors
Australia
Belgium
Canada
Chile
China
Denmark
Finland
France
Germany
India
Israel
Italy
Japan
Portugal
Russia
South Africa
Spain
Sweden
Taiwan
The Netherlands
Turkey
United Kingdom
United States

<u>Completed National Meetings:</u>

Australia
Canada
China
France
Japan
United Kingdom
United States

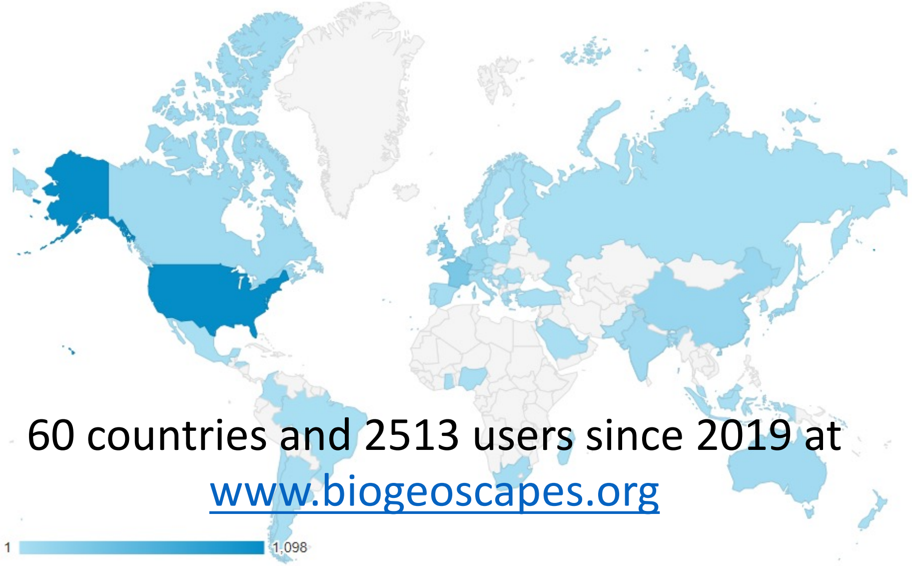
<u>International BioGeoSCAPES meetings</u>

- Pan EU Workshop Croatia 2022
- Royal Society Marine Microbes in a Changing Climate 2022
- Sessions at Ocean Science meetings 5 sessions and 44 abstracts in 2022

<u>Proposals:</u>

EU, US, and Canadian proposals submitted to further development of BioGeoSCAPES

2018 International Interest Meeting at National Academies Center in Woods Hole



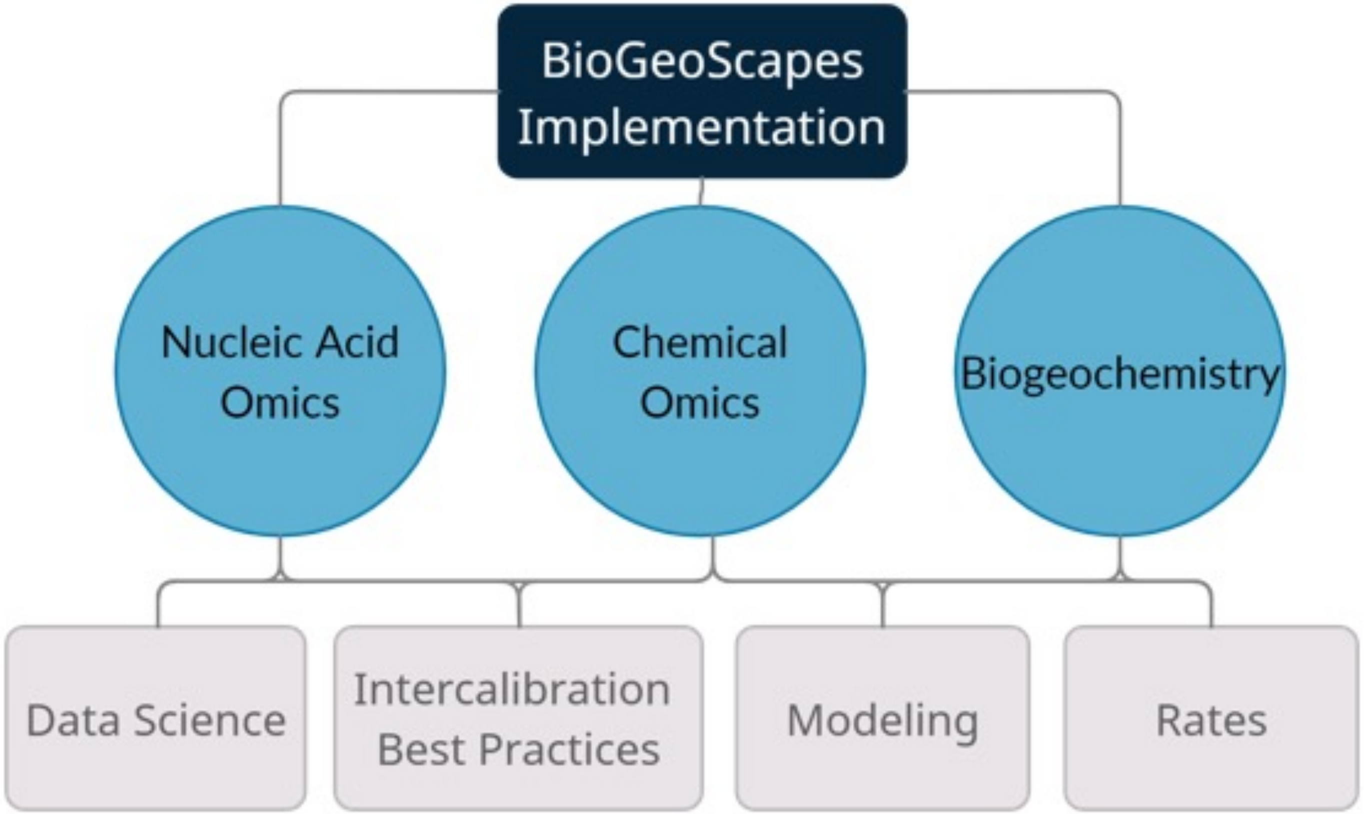
60 countries and 2513 users since 2019 at www.biogeoscapes.org

Resource depletion
Ecosystem and diversity loss
Toxicity
CO2
N,P
Biogeochemical Cycle

Towards an international program

<u>NSF AccelNet Implementation proposal:</u> Development of an International Network for the Study of Ocean Metabolism and Nutrient Cycles on a Changing Planet (BioGeoSCAPES)

Mak Saito (PI), Alyson Santoro, Naomi Levine, Heather Benway, Harriet Alexander, Ben Twining



AccelNet project goals

- <u>Strengthen</u> connectivity of international BioGeoSCAPES network
- <u>Identify</u> primary science drivers for an international BioGeoSCAPES program
- <u>Plan</u> components of a FAIR data infrastructure to support integration of environmental and omics data
- <u>Increase interaction</u> between modelers and observationalists to <u>facilitate integration</u> of BioGeoSCAPES data and numerical models
- <u>Synthesize</u> omics standardization and intercalibration activities and <u>build consensus</u> on best practices to ensure omics data are intercomparable
- <u>Build</u> technical, analytical, and leadership capacity, transfer knowledge, and <u>strengthen international collaboration</u>