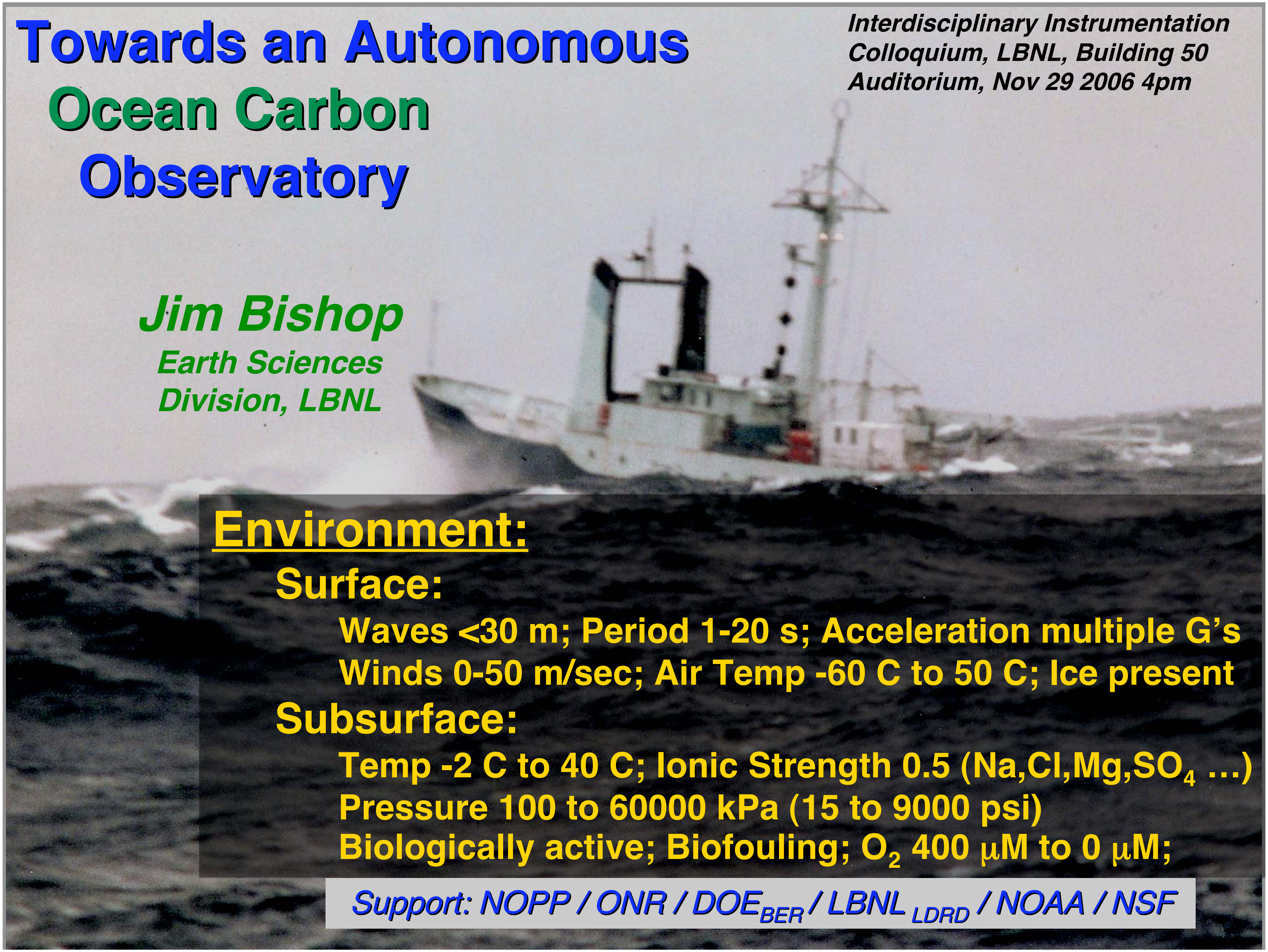


Towards an Autonomous Ocean Carbon Observatory

Interdisciplinary Instrumentation Colloquium, LBNL, Building 50 Auditorium, Nov 29 2006 4pm

Jim Bishop

Earth Sciences Division, LBNL

Environment:

Surface:

- Waves <30 m; Period 1-20 s; Acceleration multiple G's
- Winds 0-50 m/sec; Air Temp -60 C to 50 C; Ice present

Subsurface:

- Temp -2 C to 40 C; Ionic Strength 0.5 (Na,Cl,Mg,SO_4 …)
- Pressure 100 to 60000 kPa (15 to 9000 psi)
- Biologically active; Biofouling; O_2 400 μM to 0 μM;

Support: NOPP / ONR / DOE_{BER} / $LBNL_{LDRD}$ / NOAA / NSF

Special thanks to:

CARBON EXPLORER team

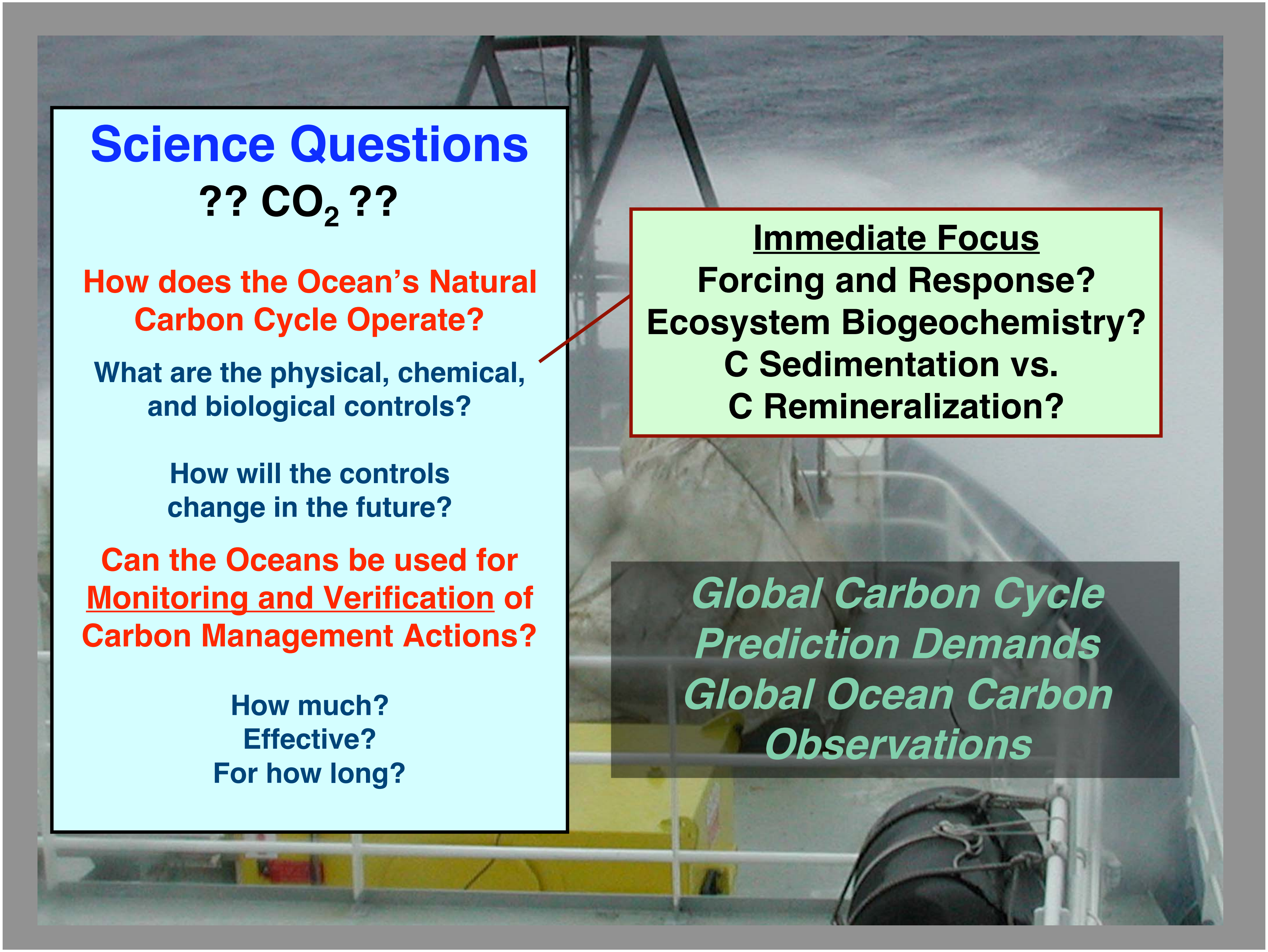
Todd Wood (ESD)
Russ Davis, Jeff Sherman (Scripps)
Casey Moore, Alex Derr (WETLabs Inc)

CARBON FLUX EXPLORER players

Derek Yegian, Zack Radding, Bill Edwards,
Sergio Zimmerman, Jean-Francois Beche,
Bryan Holmes, Russ Wells, Yoichi Kajiyama,
Bill Ghiorso, Todd Wood, Lloyd Regier (SIO).

PIC sensor
Alex Derr (WETLabs Inc)
Arlon Hunt, Todd Wood, Chris Guay,
Phoebe Lam (UCB),
Alexandra Thompson (UK Antarctic Survey)

DOC sensor
Craig Tindall, Paul Luke


Science Questions
?? CO_2 ??
How does the Ocean's Natural Carbon Cycle Operate?
What are the physical, chemical, and biological controls?
How will the controls change in the future?
Can the Oceans be used for Monitoring and Verification of Carbon Management Actions?
How much?
Effective?
For how long?
Immediate Focus
Forcing and Response?
Ecosystem Biogeochemistry?
C Sedimentation vs.
C Remineralization?
Global Carbon Cycle Prediction Demands Global Ocean Carbon Observations

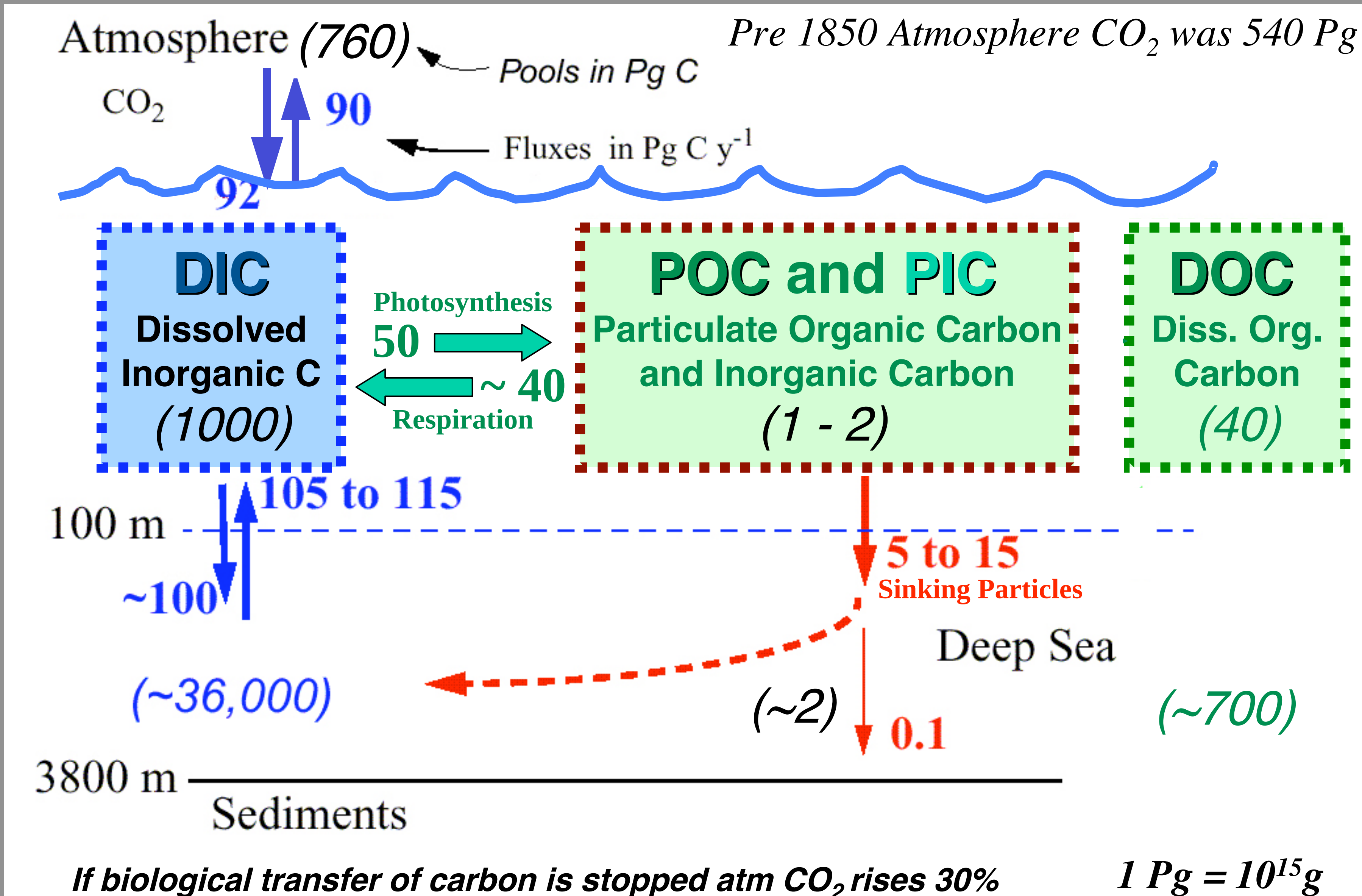
Oceanography of carbon exchange with the atmosphere: 2 processes

-Thermodynamic CO_2 uptake
aka "Solubility Pump"

- Biologically mediated CO_2 uptake
aka "Biological Pump"

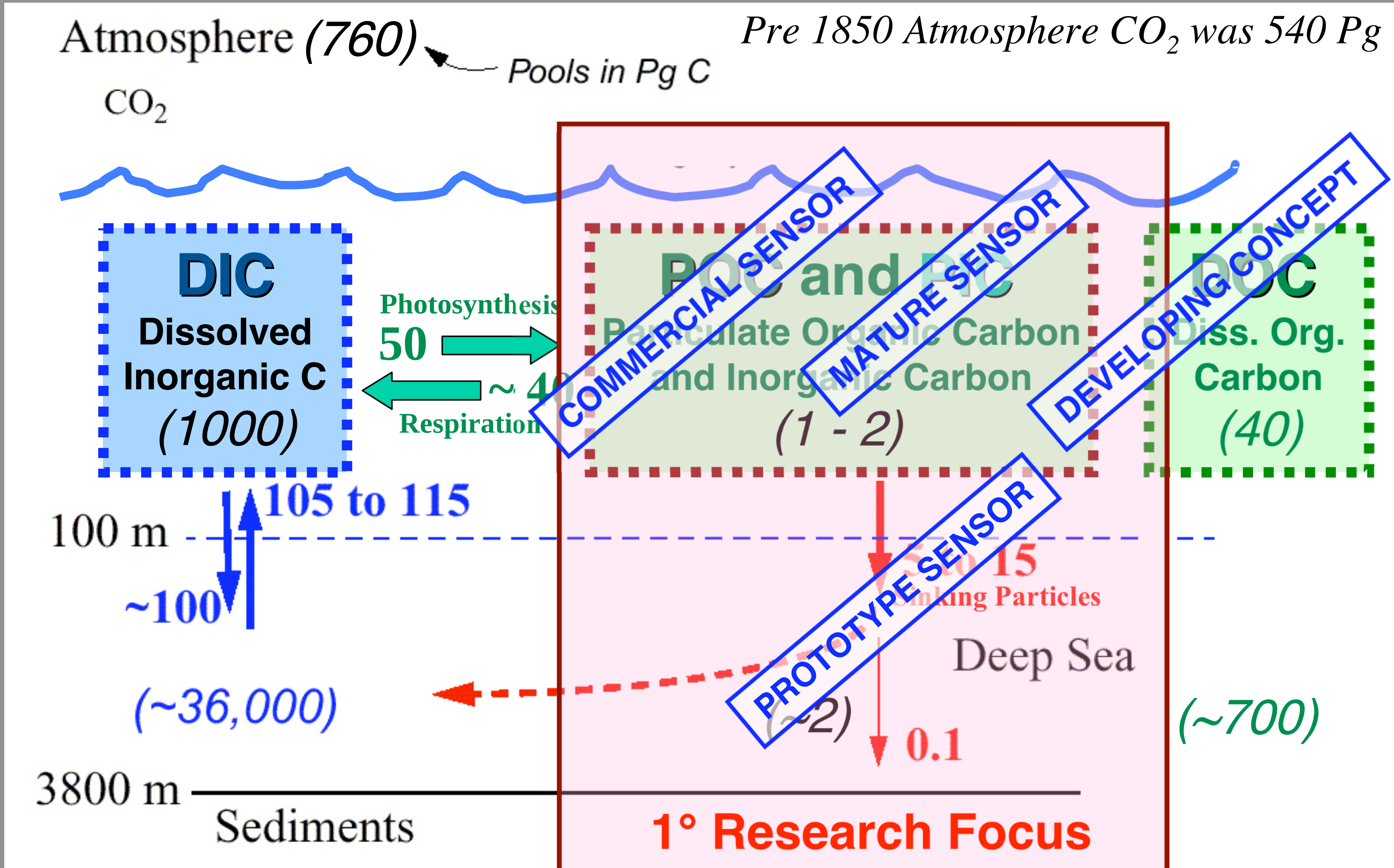
Ocean Carbon Cycle

Prediction?



Ocean Carbon Cycle

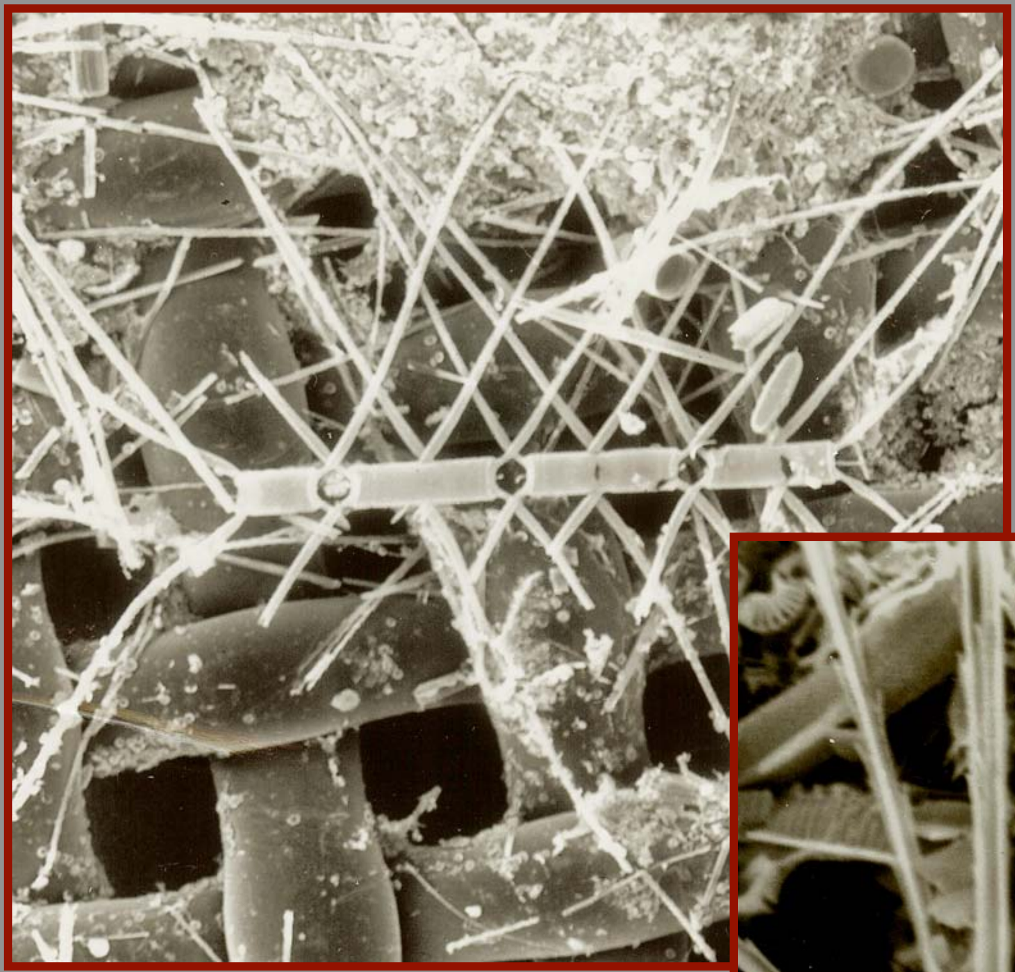
Prediction?

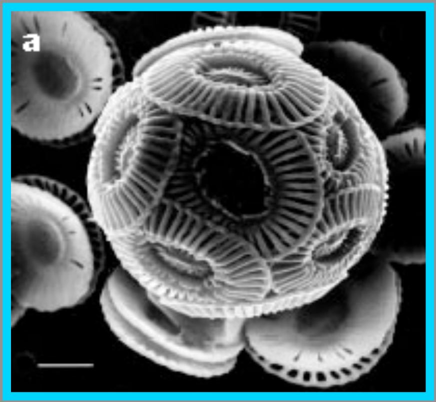


If biological transfer of carbon is stopped atm CO_2 rises 30%

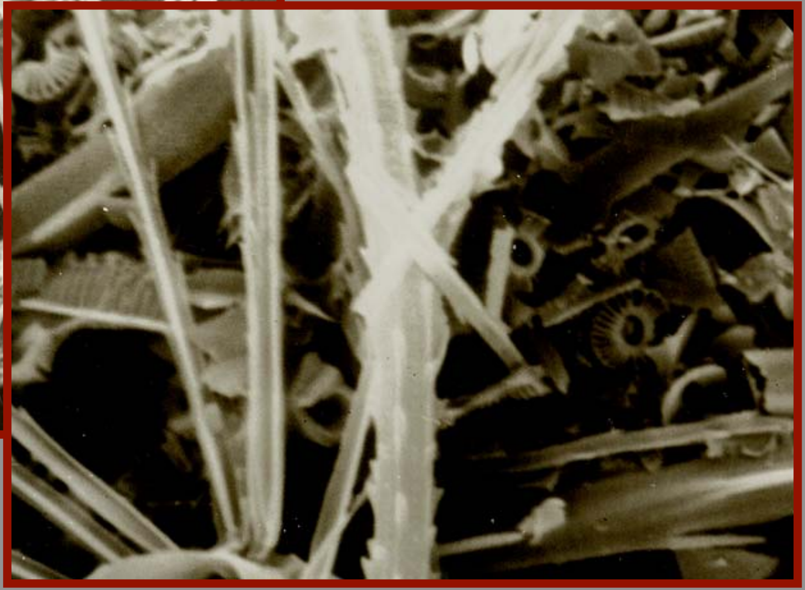
1 Pg = 10^{15}g

Why focus on PARTICLES?





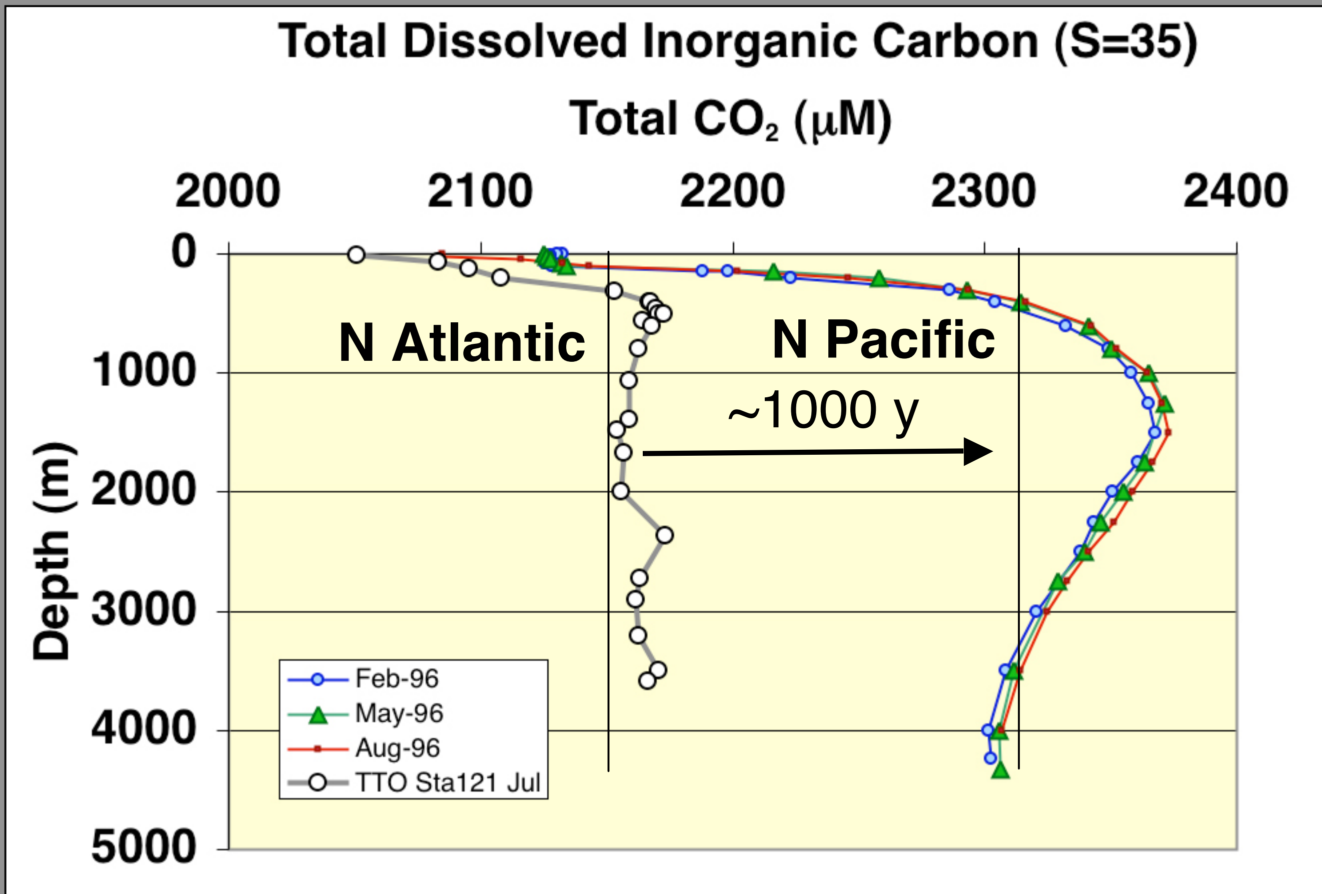
5 µm

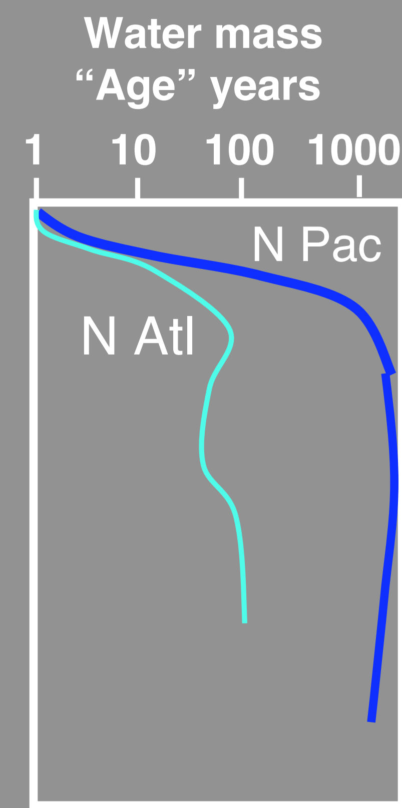


5 µm

50 µm

Dissolved Inorganic Carbon

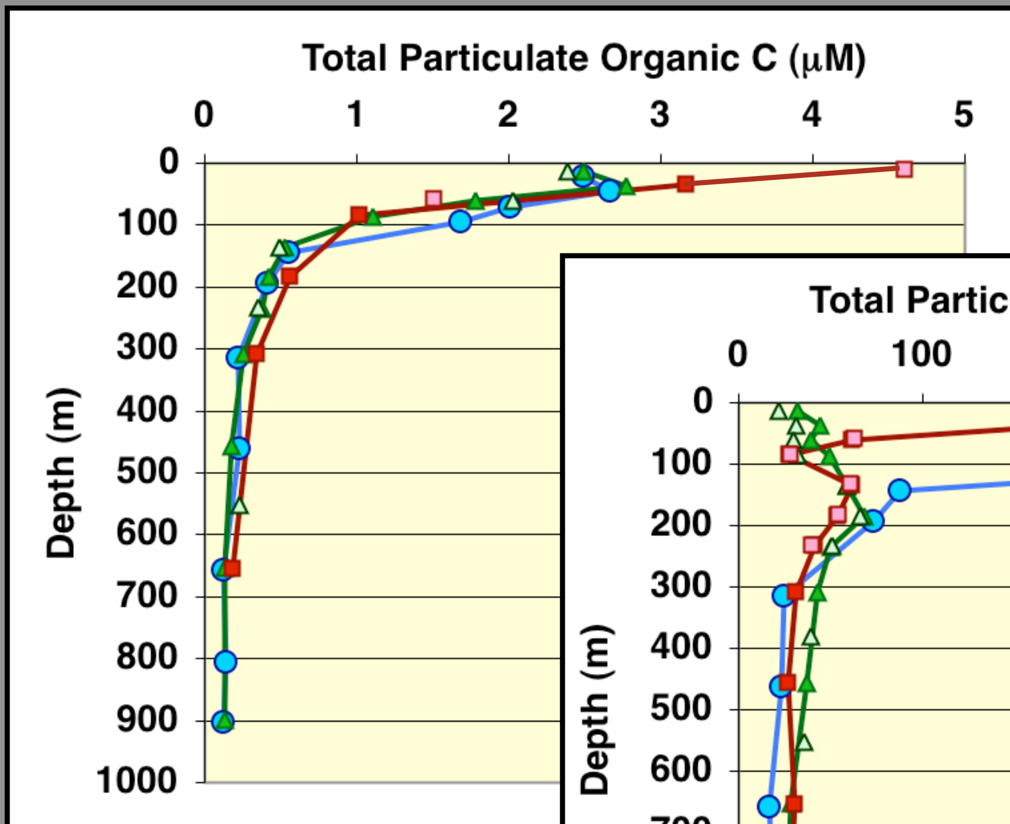


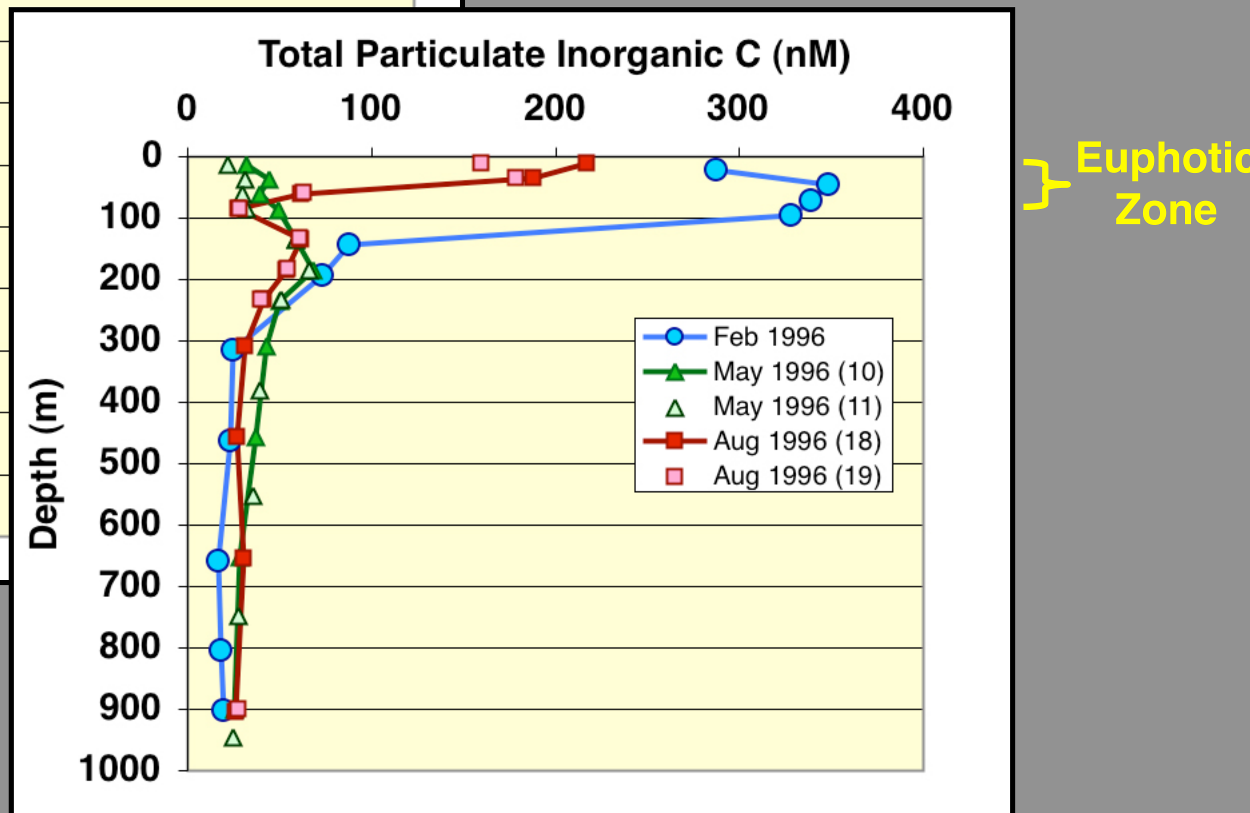


Age profile and ocean circulation mask local effects below 100 m.

PARTICLES (POC and PIC)

Seasonality seen well below the euphotic zone





Data from LBNL Multiple Unit Large Volume in-situ Filtration System (MULVFS)

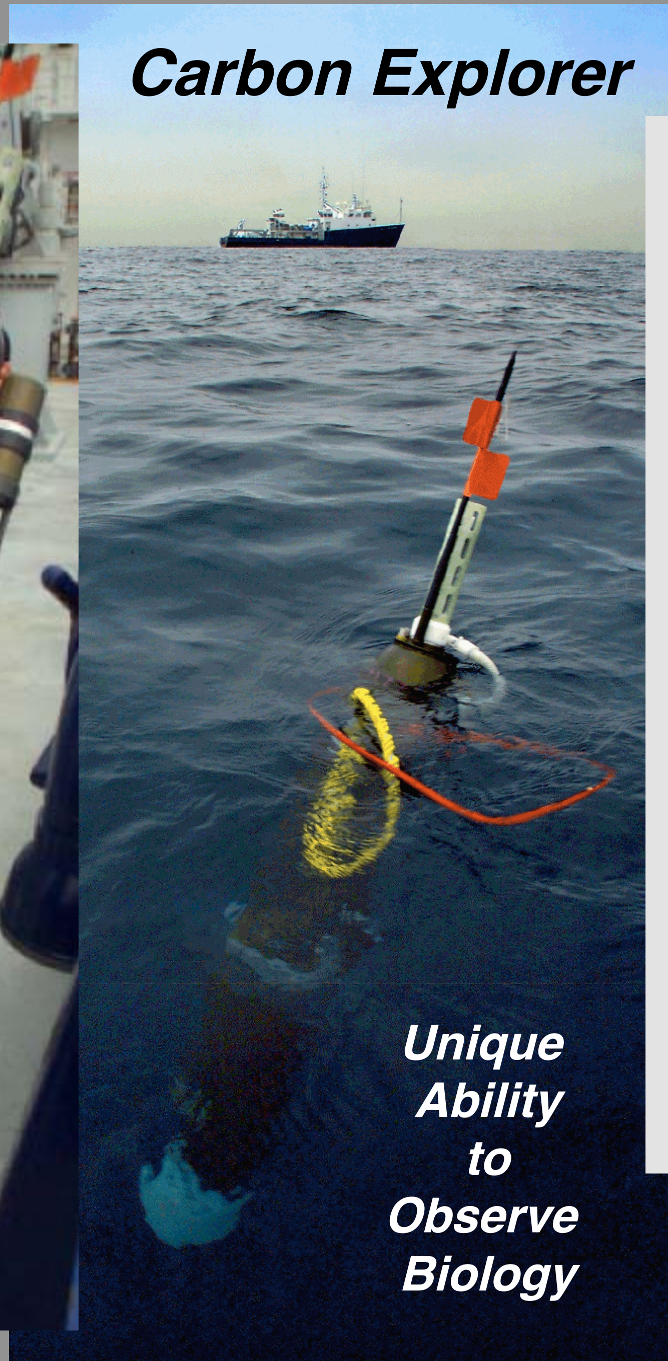
Aboard R/V Revelle:

Water Sampling

Carbon Explorers

Multiple Unit Large Volume in situ Filtration System

Carbon Explorer



Lagrangian float (souped up)

Fast Profiling
(diurnal profiles to 1000m)

Long Lived ~1 year

New: Real Time Bi-directional Satellite Telemetry

Temperature, Salinity
Particulate Organic Carbon
Particulate Carbon Flux Index
Scattering

(Particulate Inorganic Carbon)

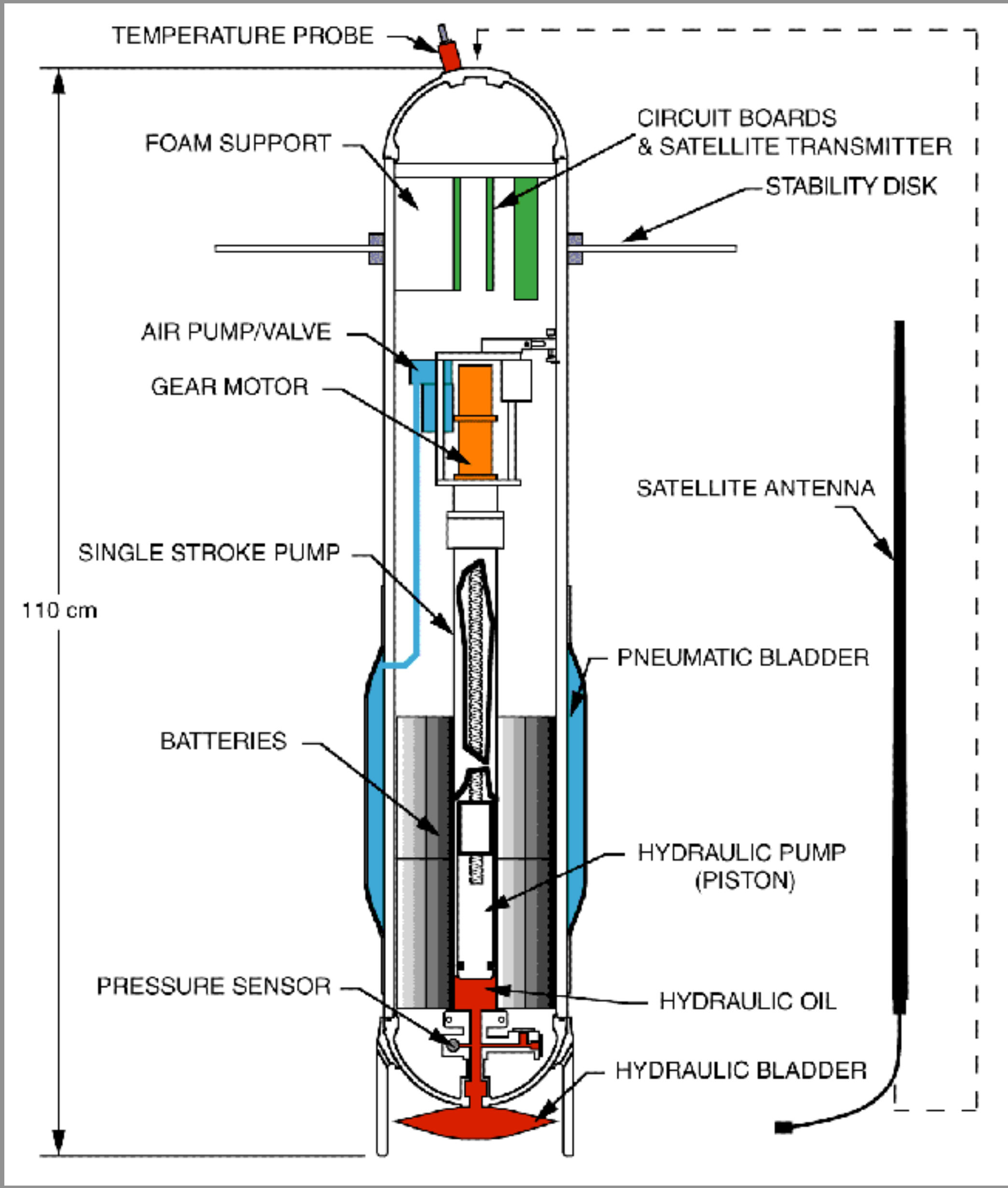
$25k per explorer = 1 ship day

The Sounding Oceanographic Lagrangian Observer (SOLO) is the active drive element of the Carbon Explorer and Carbon Flux Explorer

- A “float” in oceanography is engineered to to operate at a target depth below the surface. It is ballasted to be nearly neutrally buoyant in seawater and has the ability to adjust it’s density to sink to a target depth and rise again to the surface.

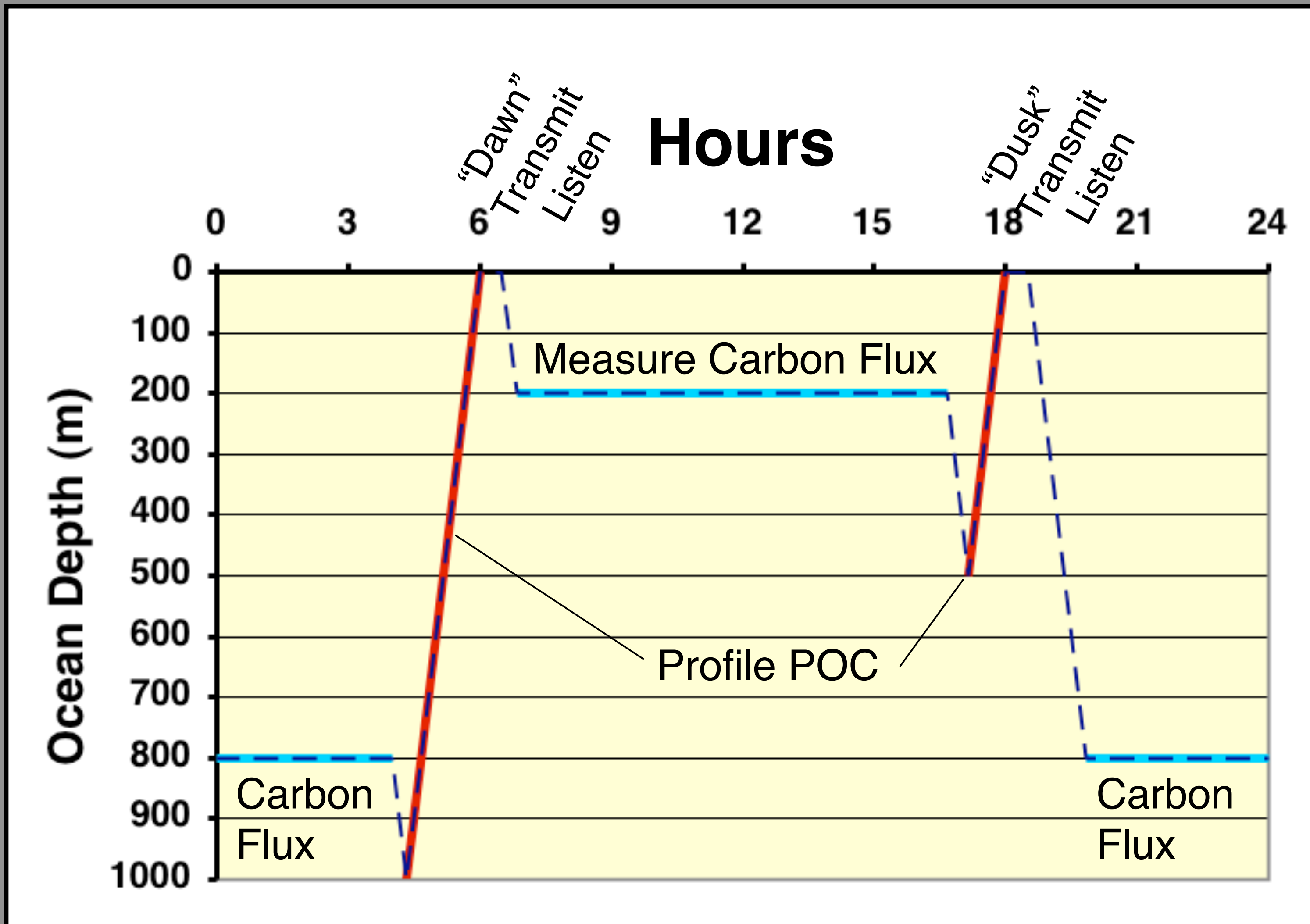
- It ‘s pressure case is less compressible than seawater, thus there is a predictable gain in buoyancy with depth. This means target depths may be reached fairly easily. The SOLO’s programming is adaptive.

- The volume of the float is about 15 L and it can adjust it’s volume by 0.2 L.



SOLO engineered at Scripps

Carbon Explorers can sample diurnal processes for a year



Typical Mission Profile

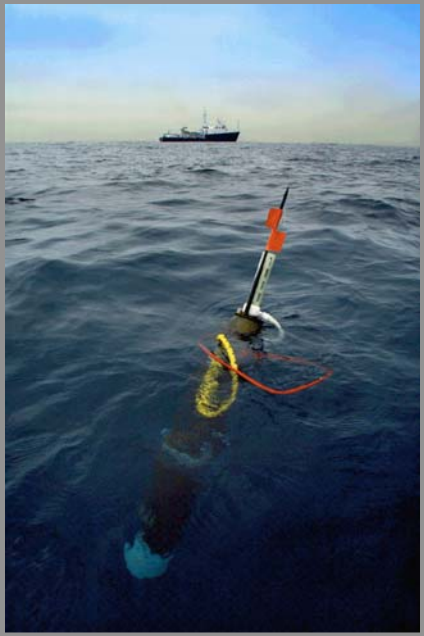
First Explorers gave fundamental and new insights to the Ocean Carbon Cycle

First 6 Robot Carbon Explorers

- First obs. of natural iron fertilization of marine biomass by Asian dust (Bishop et al., Science **298, 817-821,**2002)

  50 years of ship visits to same site in N Pacific - missed dust storm events that happen once every 3 years. Intense dust storm in 2001 resulted in a short-lived transient biological growth response - contrary to what had been previously believed.

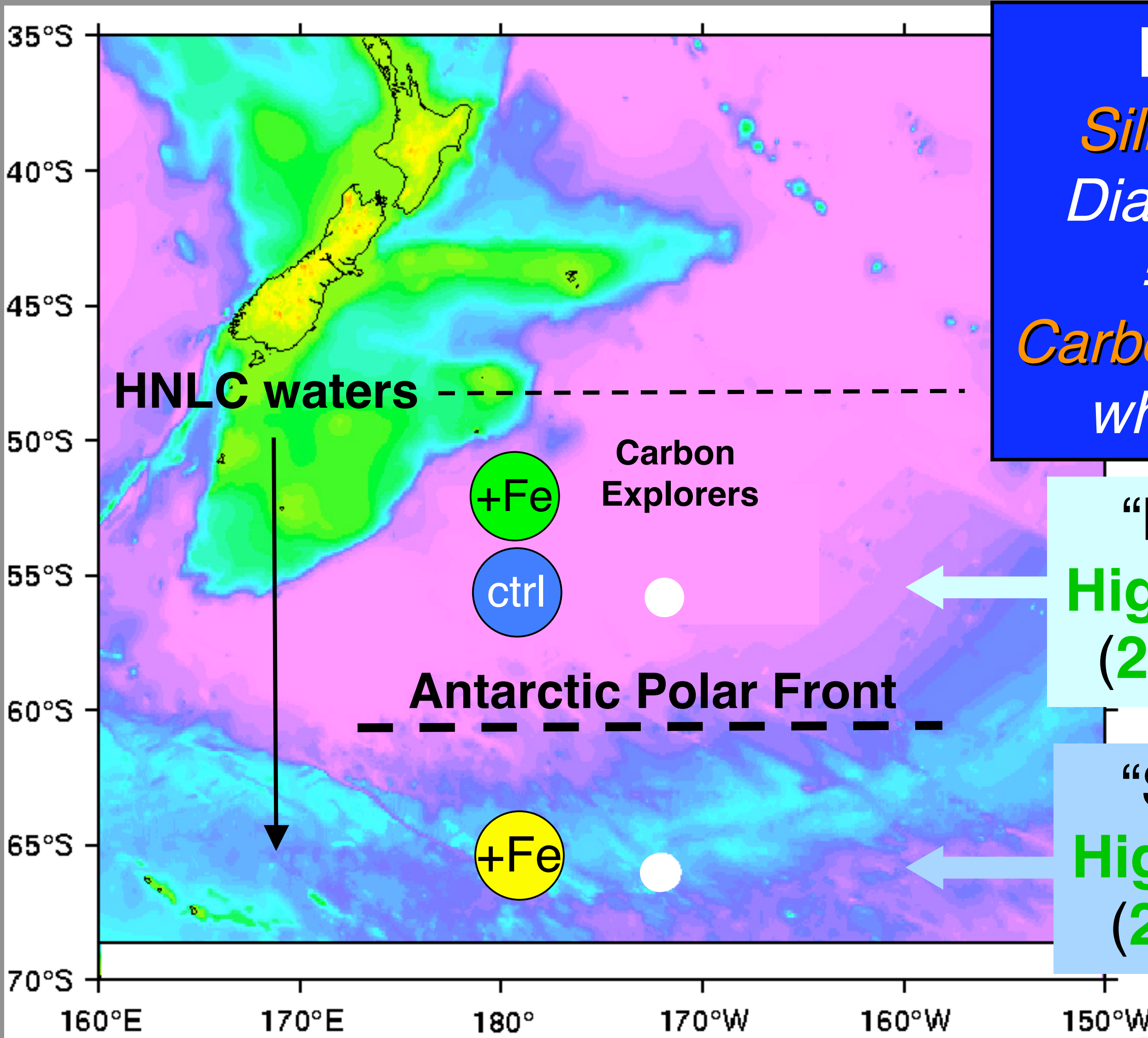
- First obs. of purposeful iron-stimulation of carbon biomass and carbon sedimentation in Southern Ocean (Bishop et al. Science, **304, 417-420,** 2004).



Some results follow

"Being there matters"

2002 Southern Ocean Iron Experiment (SOFeX)



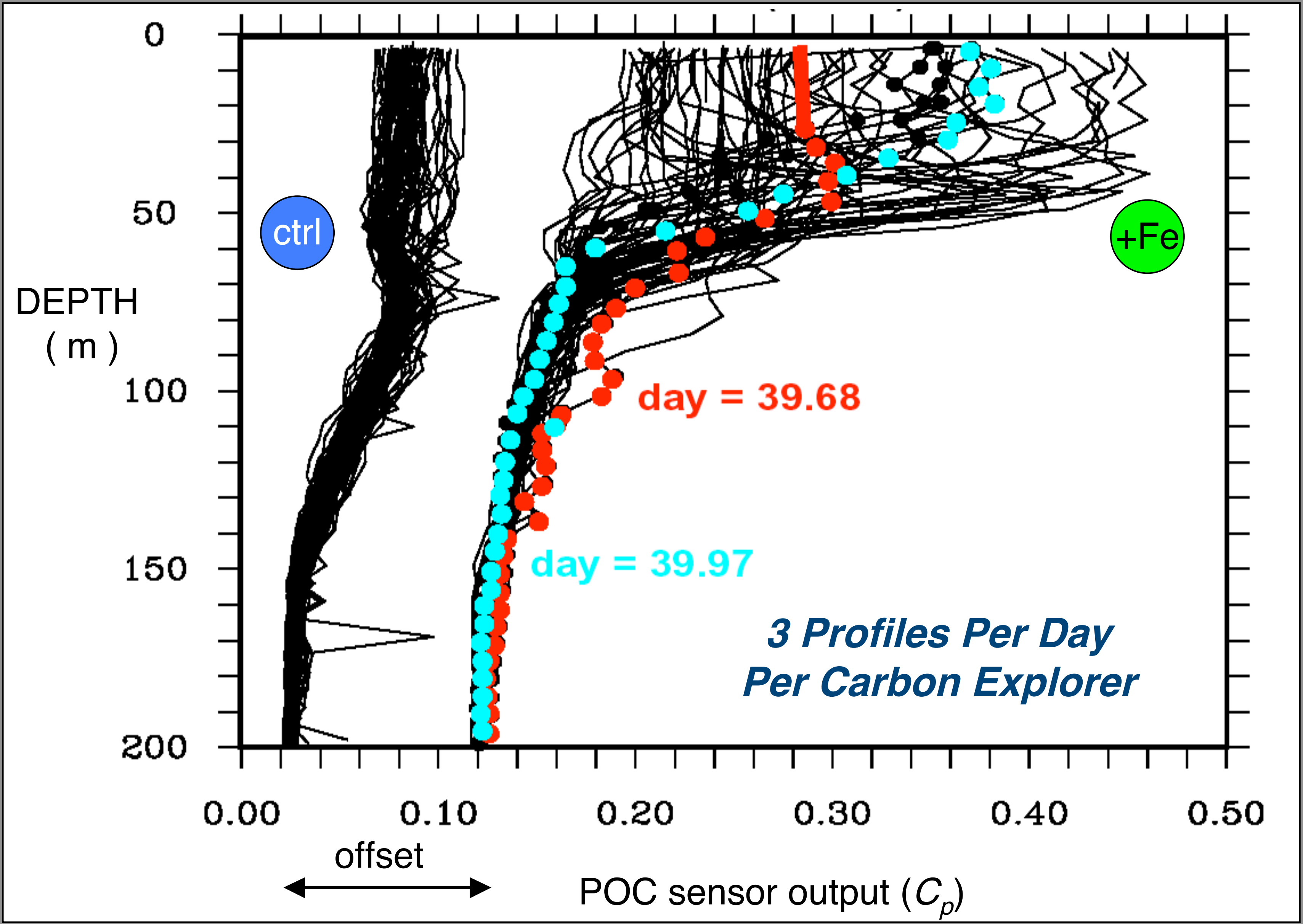
Hypothesis:
Silica Limitation of Diatom productivity => Little Extra Carbon Sedimentation when iron added.

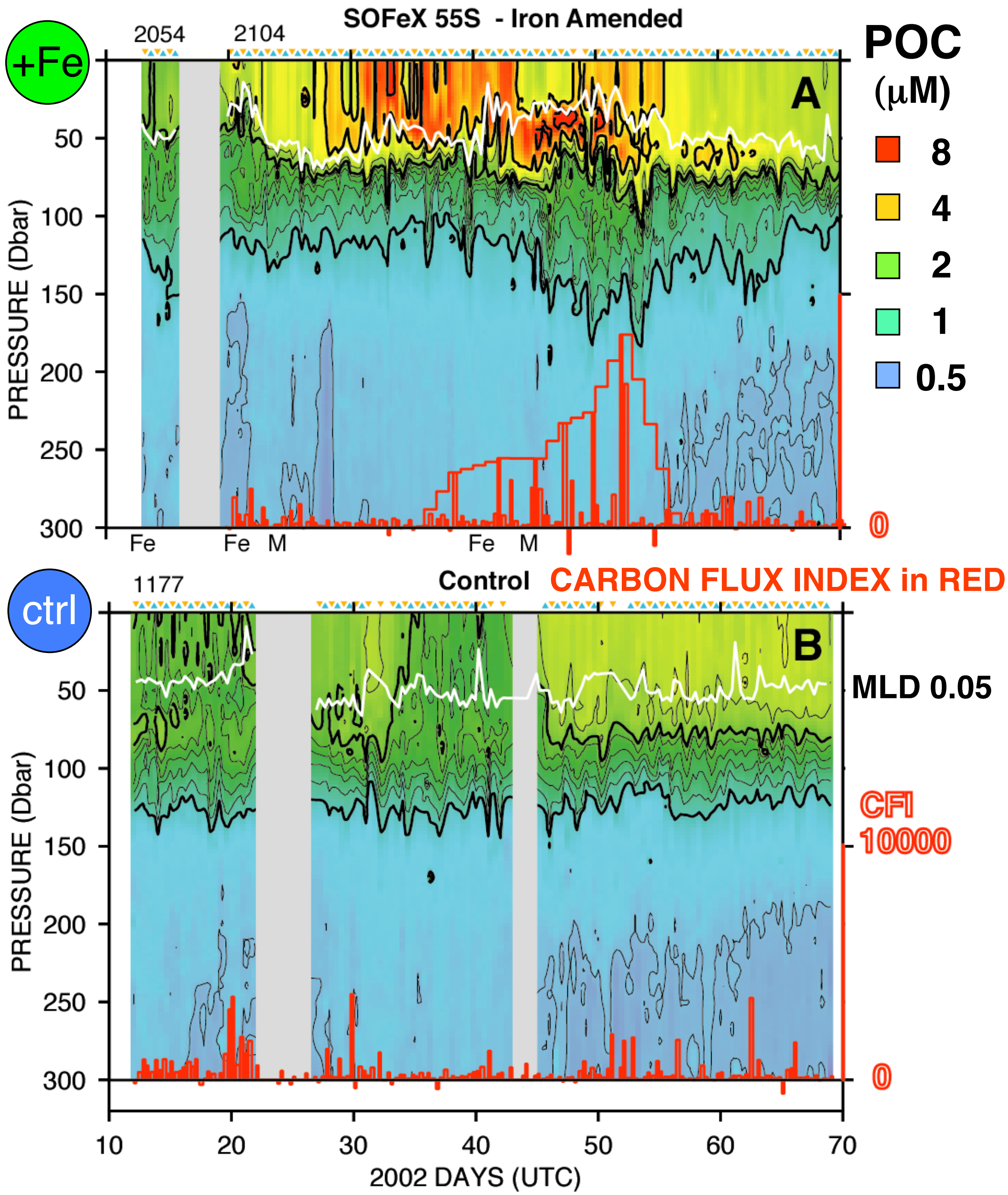
"North" (55°S)
High NO_3 : Low Si
(**22** μM : **2.5** μM)

"South" (66°S)
High NO_3: High Si
(**27** μM : **60** μM)

Bishop et al. Science, ***304, 417-420,*** *2004*

POC profiles from Carbon Explorers : First 4 weeks
Clear record of biomass enhancement





SOFeX

"North Patch" (55 S)

High NO_3 : Low **Si**

(**22** μM : **2.5** μM)

- *Carbon Export at 55S was Enhanced as a result of iron amendment*
- *Fe added : C Exported mole ratio >1:10^4*
- *SOFeX Hypothesis Contradicted*

  Export surprisingly strong N of the Polar Front

Bishop et al. Science, ***304, 417-420,*** *2004*

The Year Beyond SOFeX

QUESTIONS

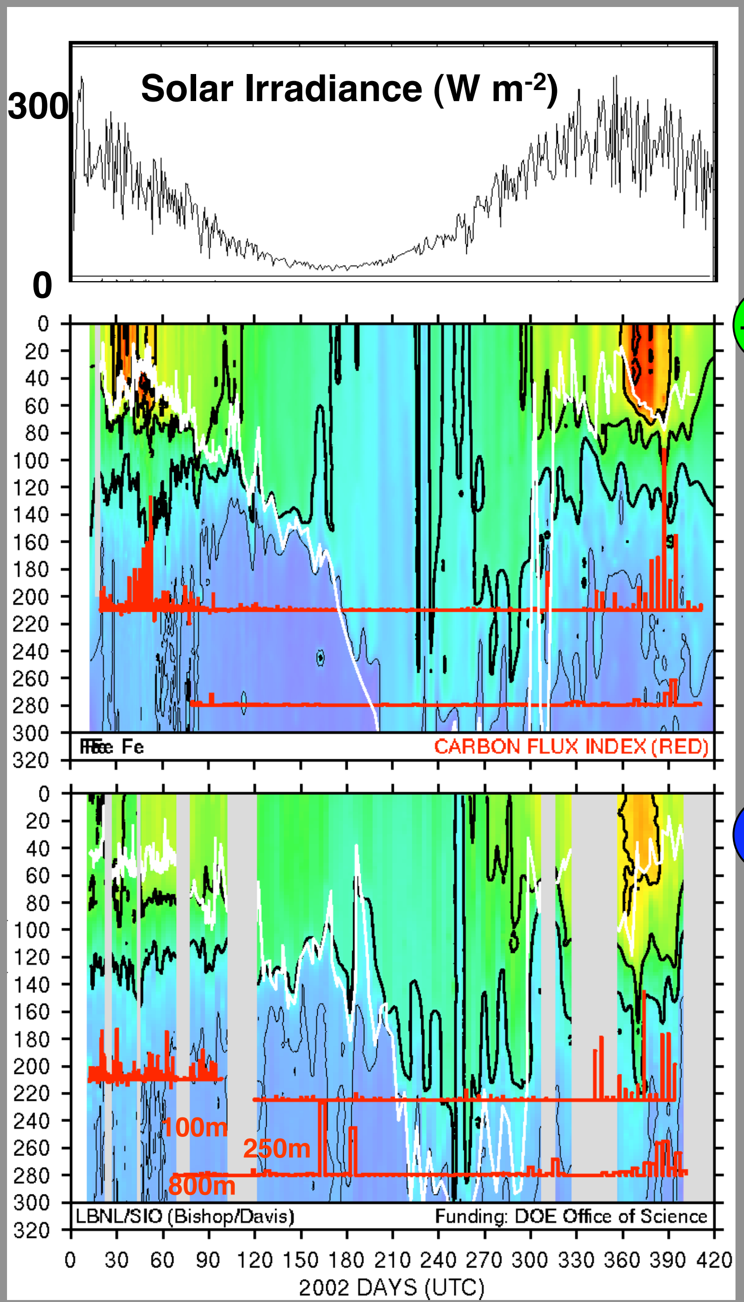
55°S (North of Polar Front):

Will both Explorers observe the same biological variability?

Is surface biomass a predictor of carbon flux?

66°S (South of Polar Front):

What happens during total darkness and in the presence of pack ice?



55°S (North of Polar Front)

Daily records of POC & Carbon Flux Summer -> Winter -> Summer.

NEW FINDINGS (2 float ENSEMBLE)

C Flux at 800 m is <u>not</u> related to overlying biomass.

Not explained by surface fluxes or forcing or hydrography.

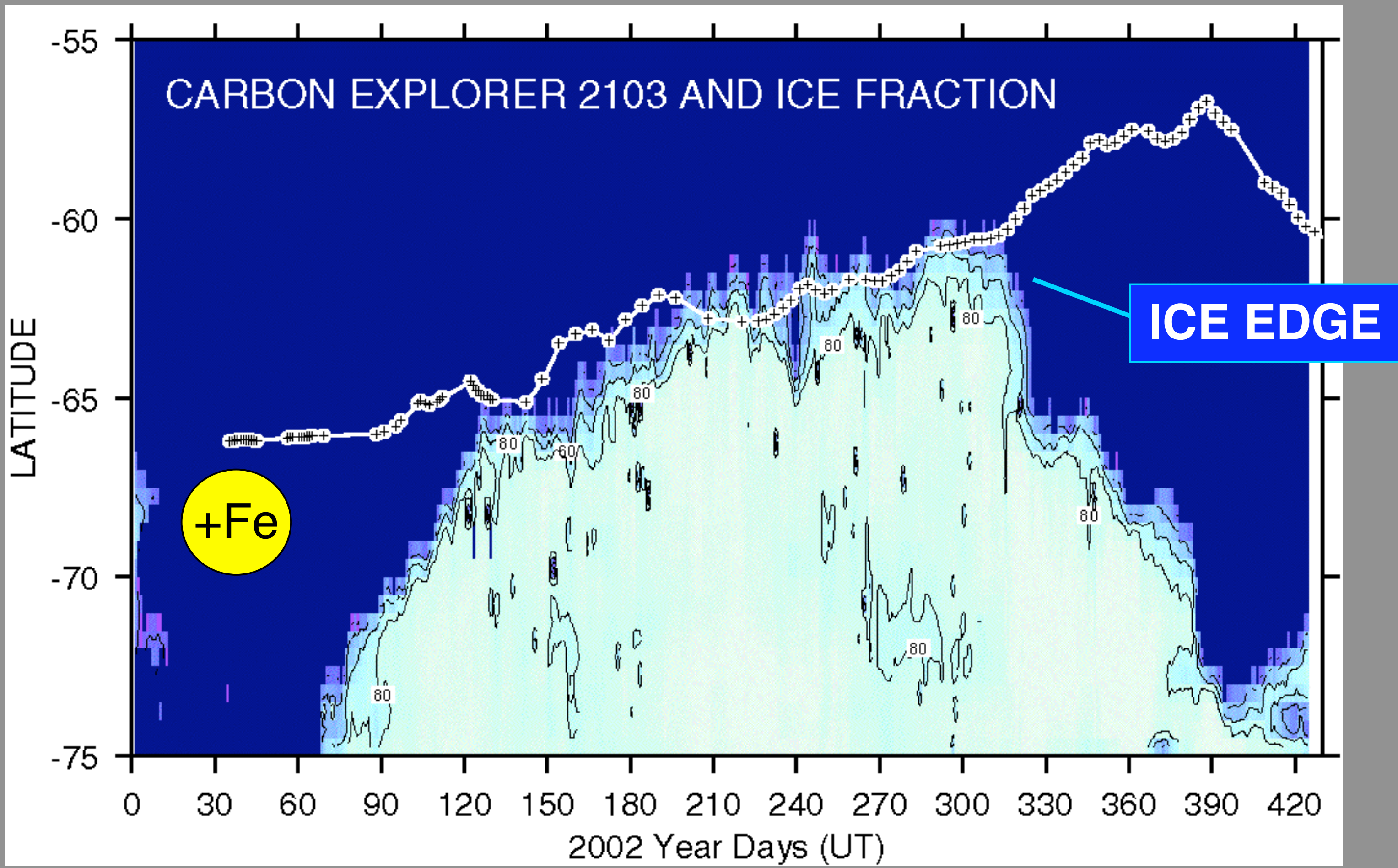
Hypothesis: Small differences in mixing led to big differences in light and hence differences in biology and flux coupling.

Hypothesis: Light limitation over winter starves zooplankton of food. Zooplankton grazing thus more efficient. Fewer particles sink to deep water.

NEW QUESTION

Biology both records different next year. Why?

Carbon Explorer Journey at 66°S



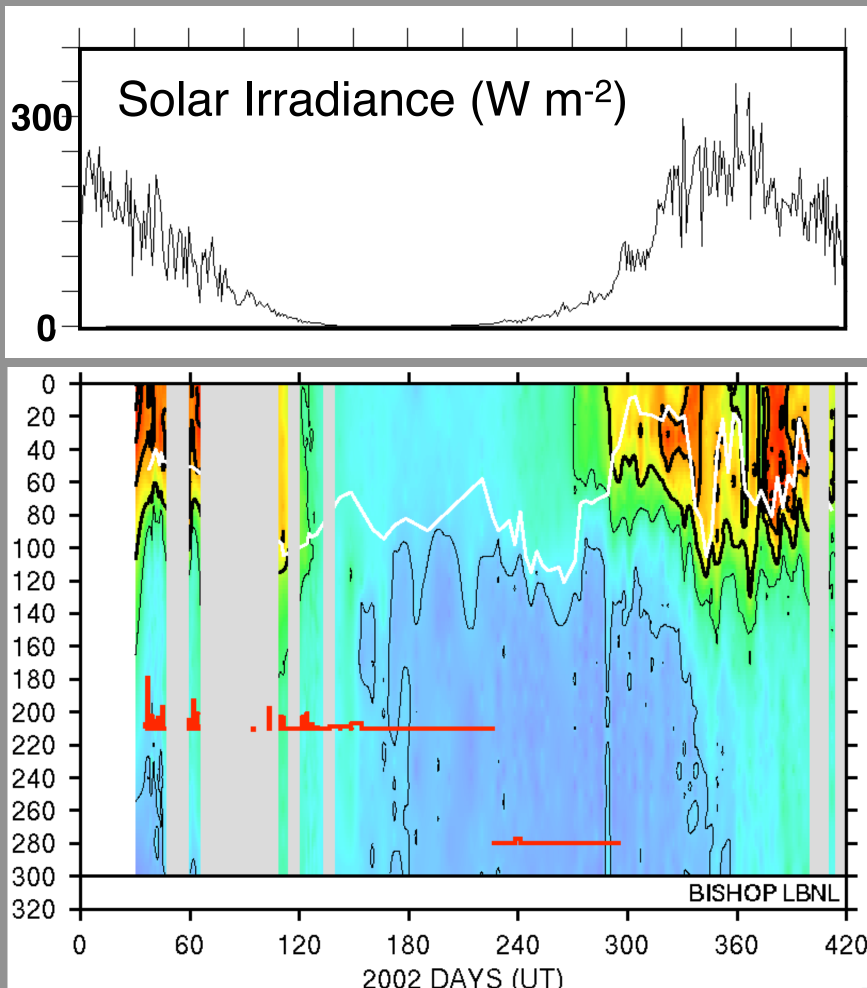
Explorer 2103 braved ice for two winters

New Findings:

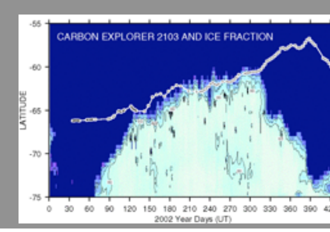
66°S (South of Polar Front)

NEW FINDINGS

- **First winter obs. of Ice and POC.**
  - 0.5 m of ice formed.
  - POC levels dropped 15x
- **Strong POC recovery on thermal restratification and then sea ice melting.**
- **Seasonality in subsurface waters.**
  - Diagnostic of export
- **Higher sfc biomass, low Carbon Flux**
  - More efficient grazing.
  - Lower sedimentation than at 55°S.



POC & CFI to Day 300,
Scattering systematics shown



Carbon Explorers

have captured important fast biological processes of the carbon cycle for the first time.

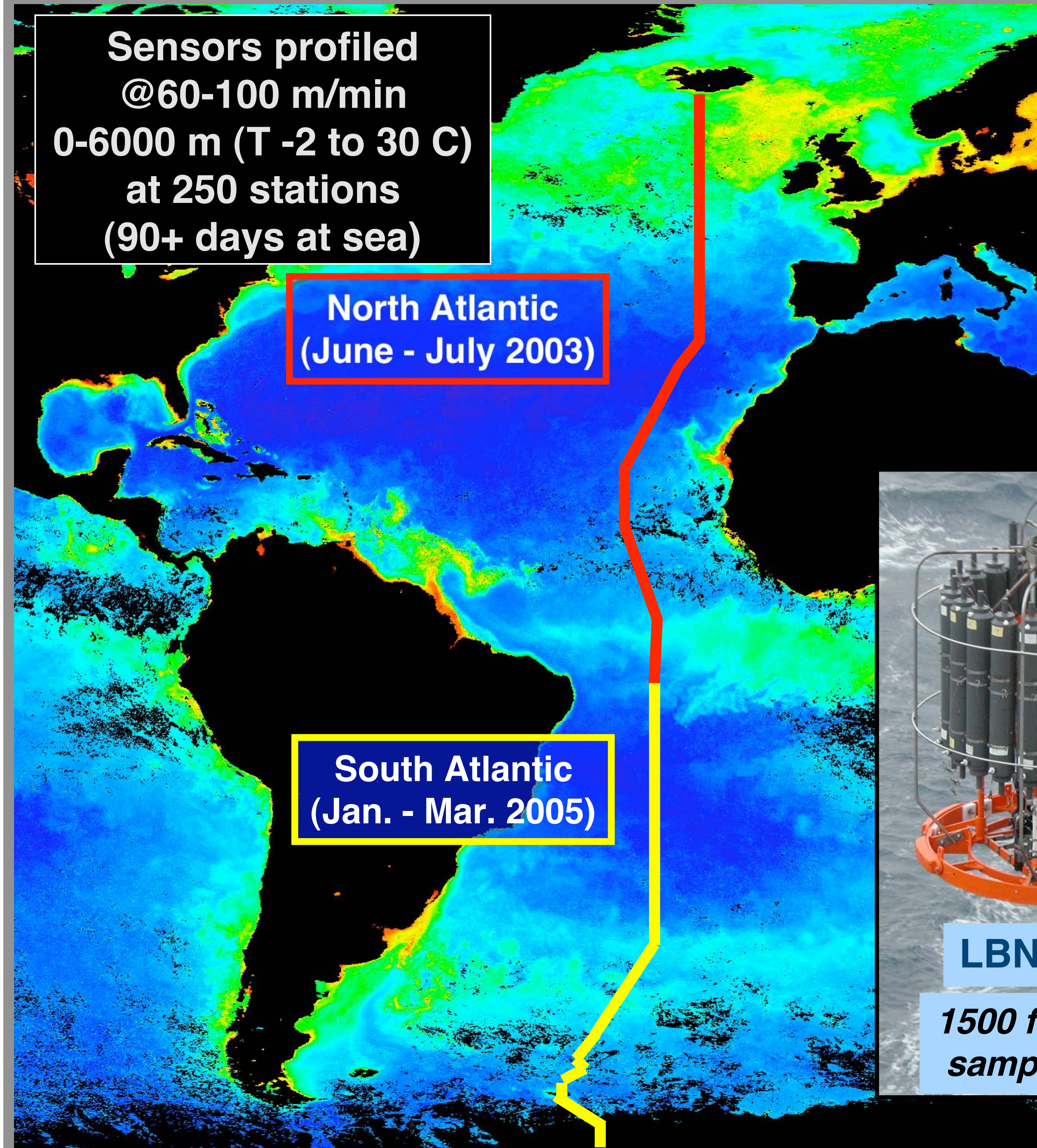
They have done this in real time


PART II
Development and Validation of sensors
NOAA
R 104
Ship expeditions are opportunities for
testing and operational proof of new sensors
Aboard NOAA’s R/V Ron Brown

Carbon Inventory

NOAA CLIVAR
Repeat Hydrography
Program

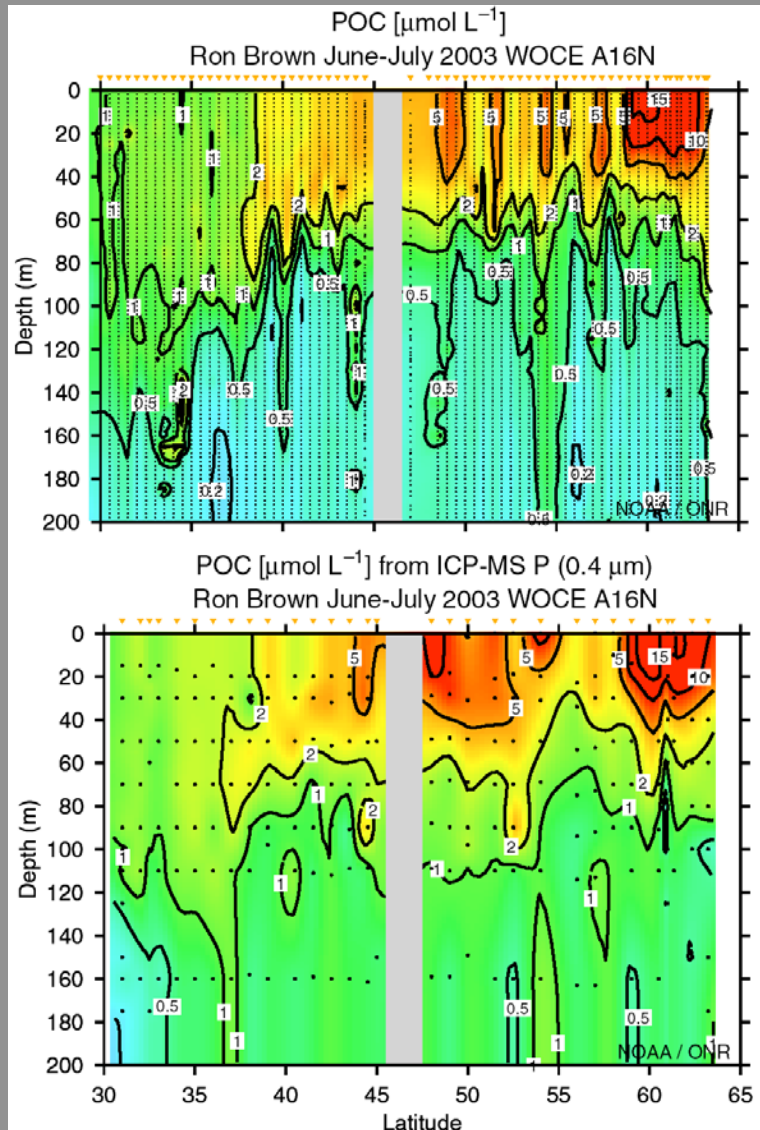
Ship Surveys
A16N in 2003
A16S in 2005



June 2003: *POC sensor*

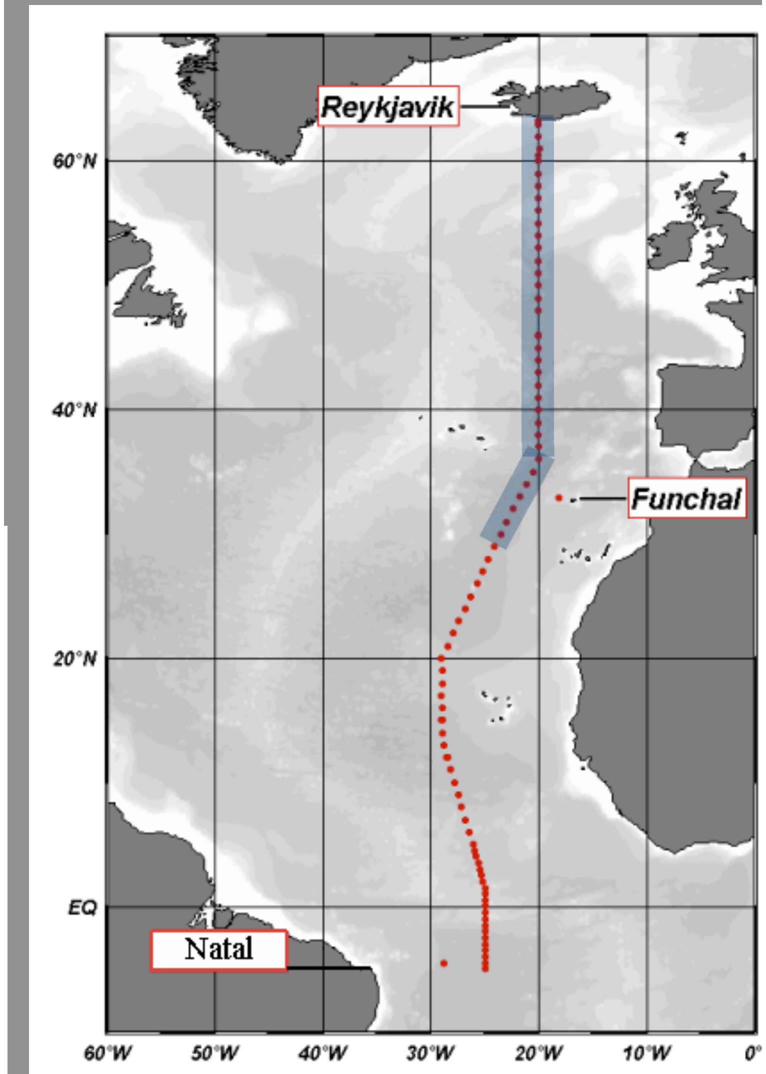
North Atlantic

Real time Transmissometer estimate of POC
Using Bishop 1999 Calibration
Contoured *April 2004*



POC Estimated from filtered samples
Analyzed by ICP-MS Aug - Nov 2004

Results agree!



For the first time, absolute transmissometry is possible to full ocean depth

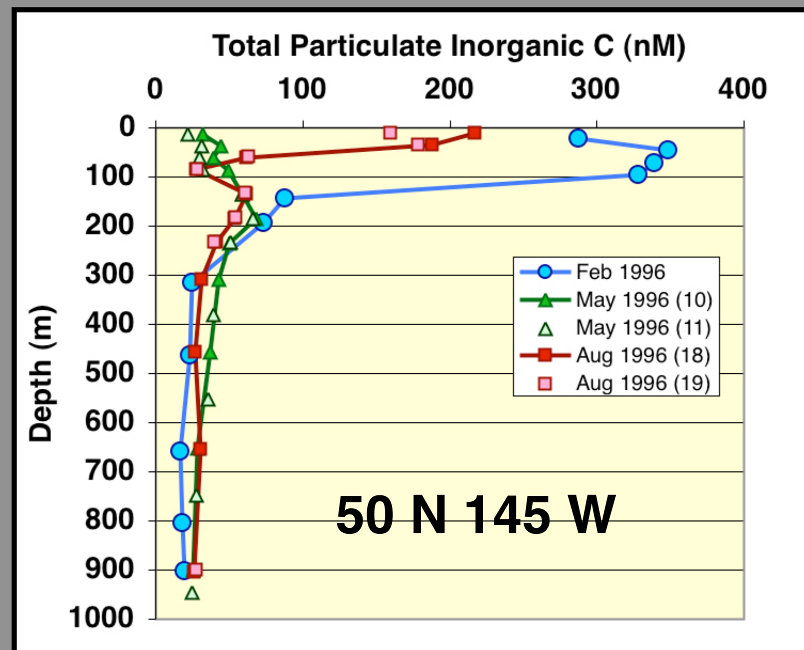
POC Sensor: stable, commercially available, and has very consistent response to POC over wide range of ocean conditions.

Exception: sensitivity 40% low South of S Ocean polar front (T < 3C) where particle size distributions are very different.

PIC sensor vs. Particulate Ca by ICP- MS.

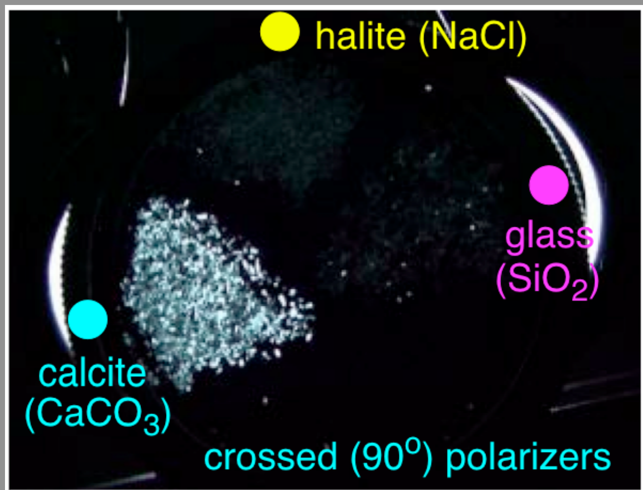
PIC variability is extreme (0.01 to 30 μM)

… and is hard to follow from ships

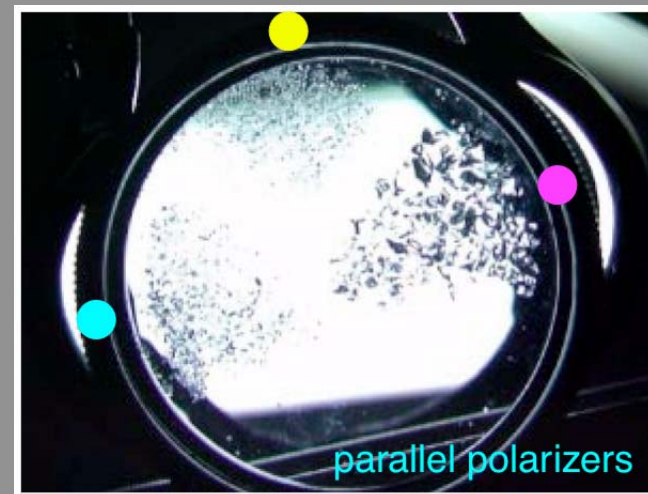


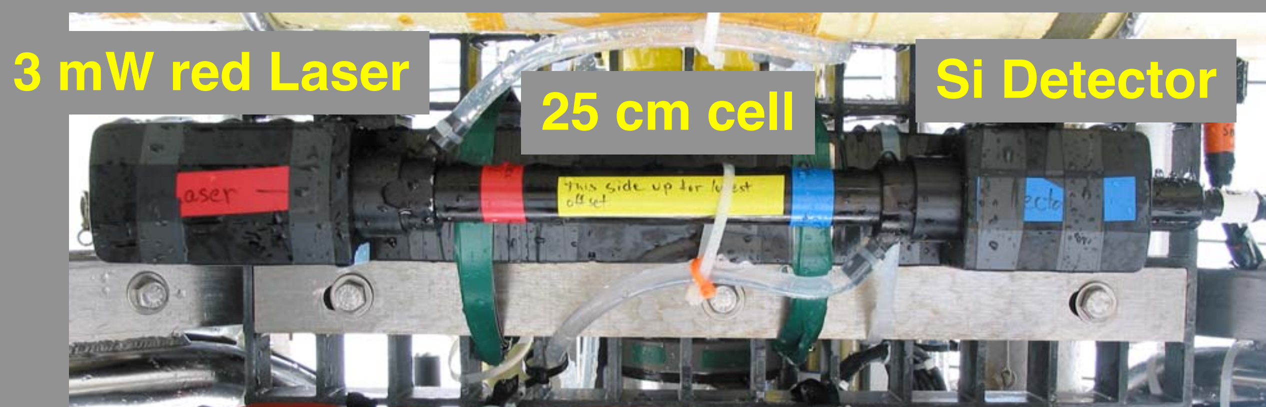
"PIC is also the ballast that helps organic aggregates sink into the deep sea." (Armstrong et al. 2003)

Sensor for particulate inorganic carbon (PIC).



Concept:
Calcite and
Aragonite
'lights up' in
crossed
polarized
transmitted light
.

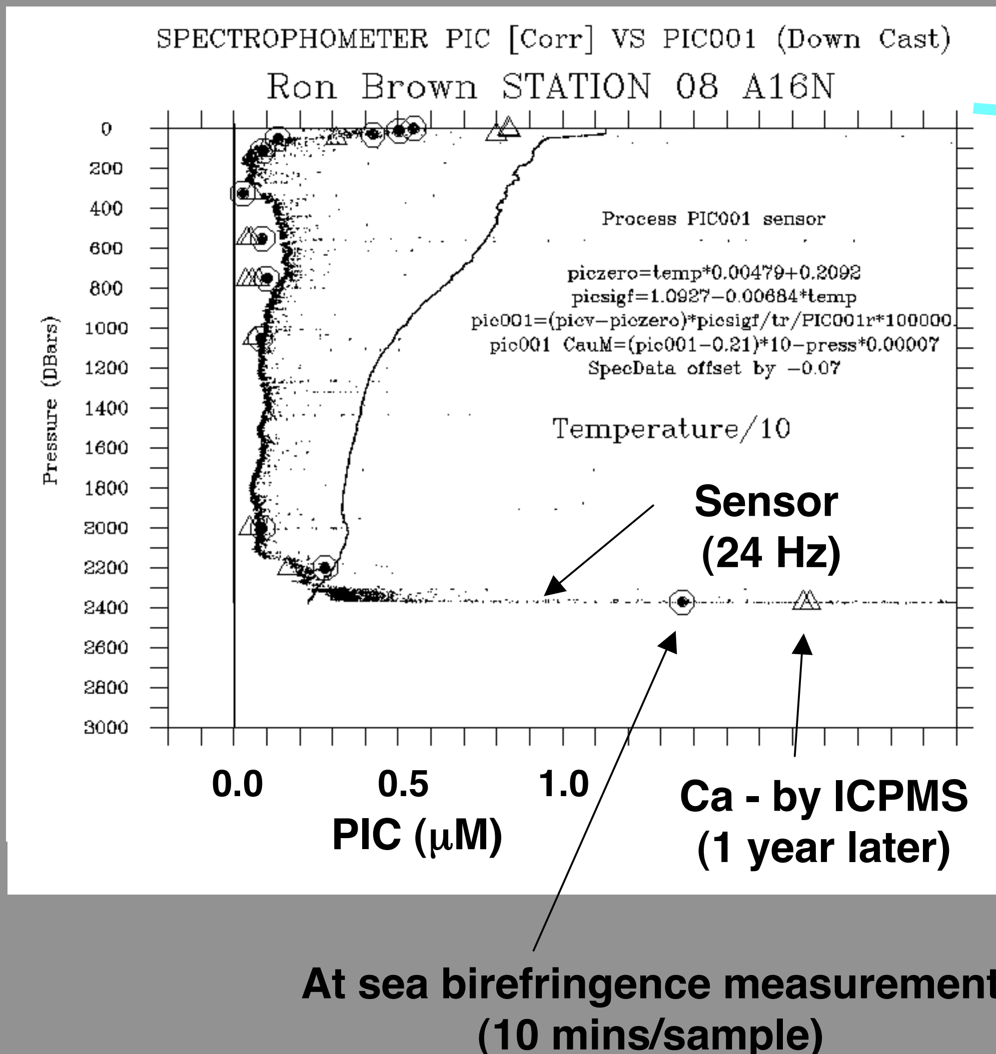


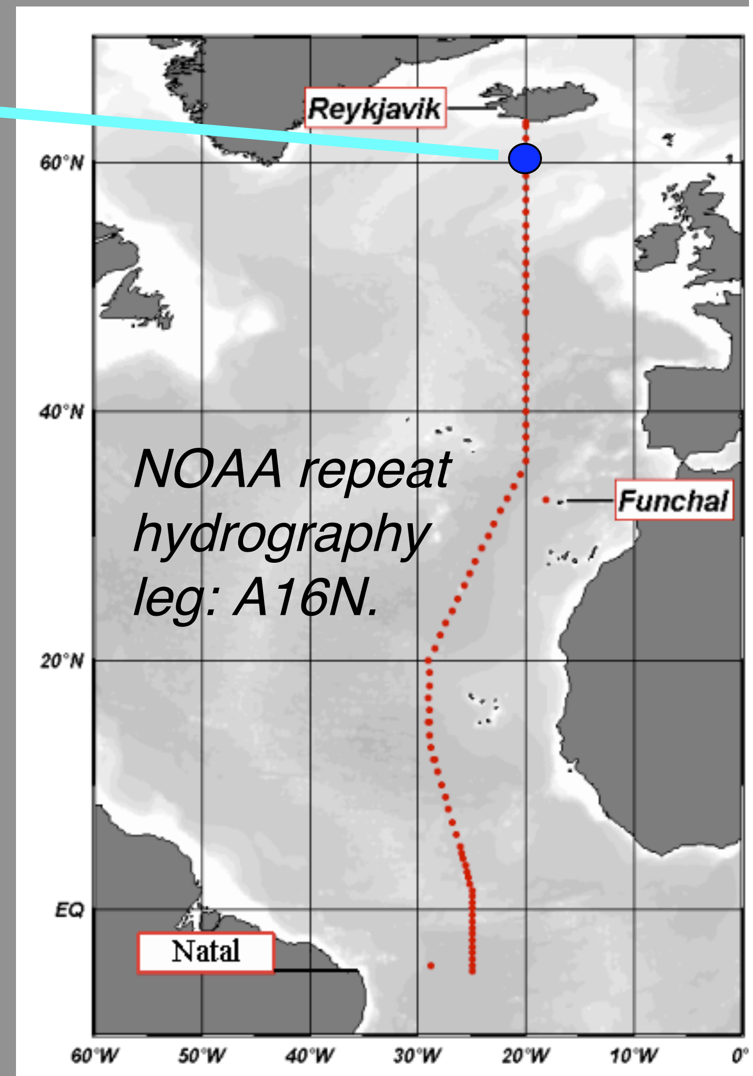


ONR / NOAA/ NOPP / WETLabs, Inc.

LBNL developed concept patented

June 2003: First operational test: *PIC sensors calibrated and operationally tested at stations along the survey track*





serial no 001

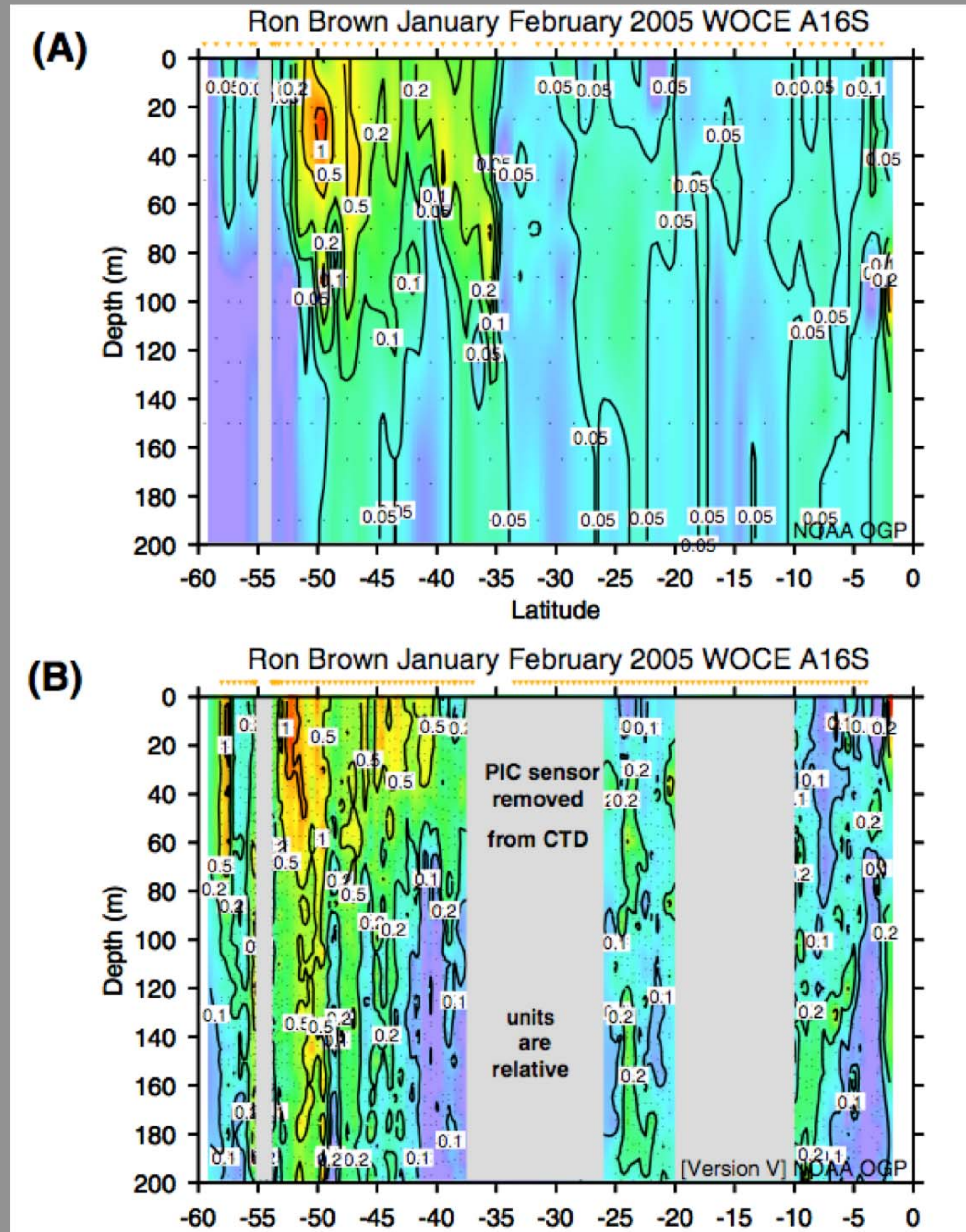
Stable to ~100 nM, major T hysteresis issues

Jan 2005

South Atlantic Ocean

refined

Stable to 10-20 nM



Filtered $CaCO_3$ by ICP-MS

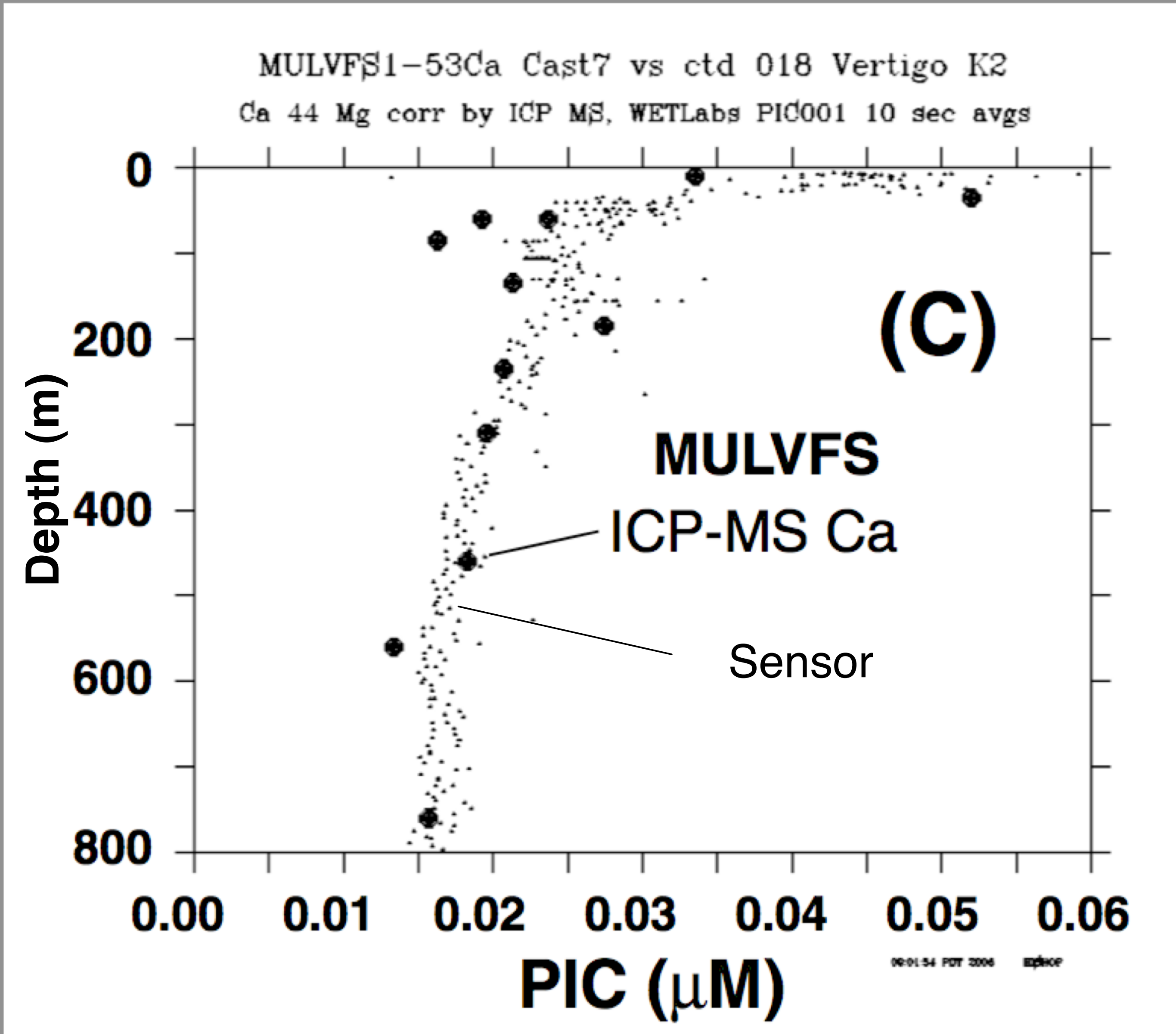
PIC Sensor

(real time)

AUGUST 2005

refined again

can detect variations of PIC in deep waters



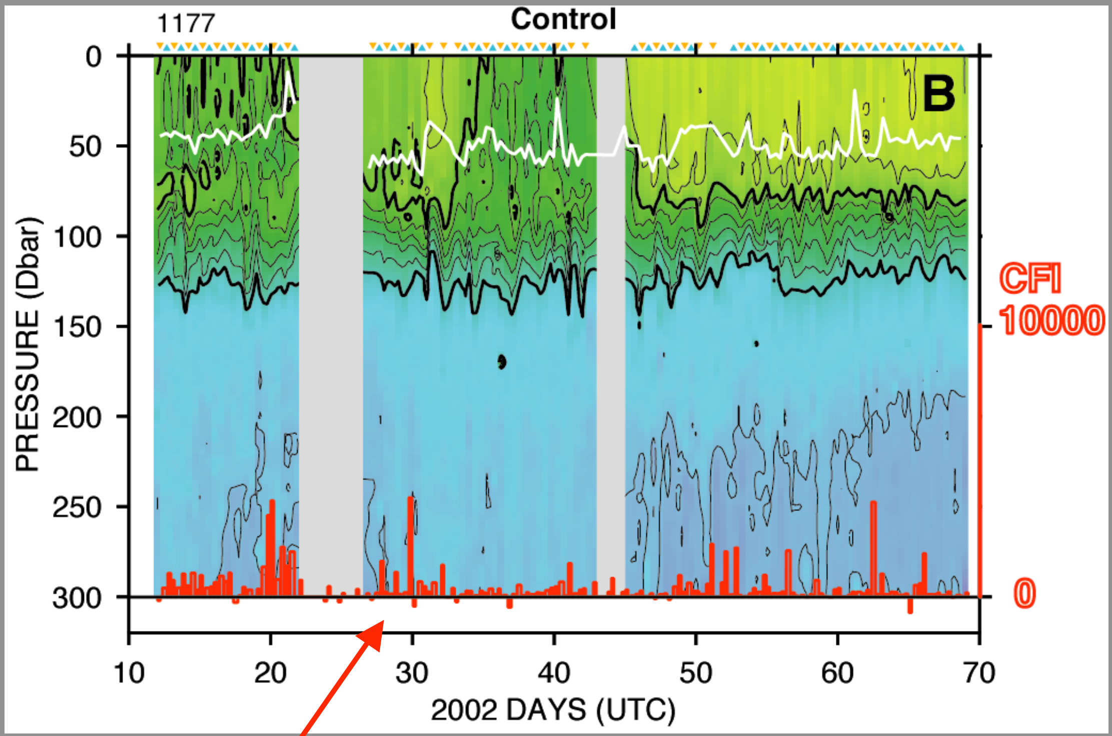
Sensor now precise to several nM

PIC Sensor is nearly ready for operational deployment on the Carbon Explorer.

Work in progress to verify sensor calibration response over wide range of ocean conditions.

Results so far look good.

GOING BEYOND CARBON FLUX INDEX



Carbon Explorer data

What explains the spikes?

Instrument Development

Sedimenting particles fall into the funnel and accumulate on a glass surface and are imaged at 15 μm resolution by an upward looking digital camera. Periodically, the surface is cleaned.

Instrument integrated with float

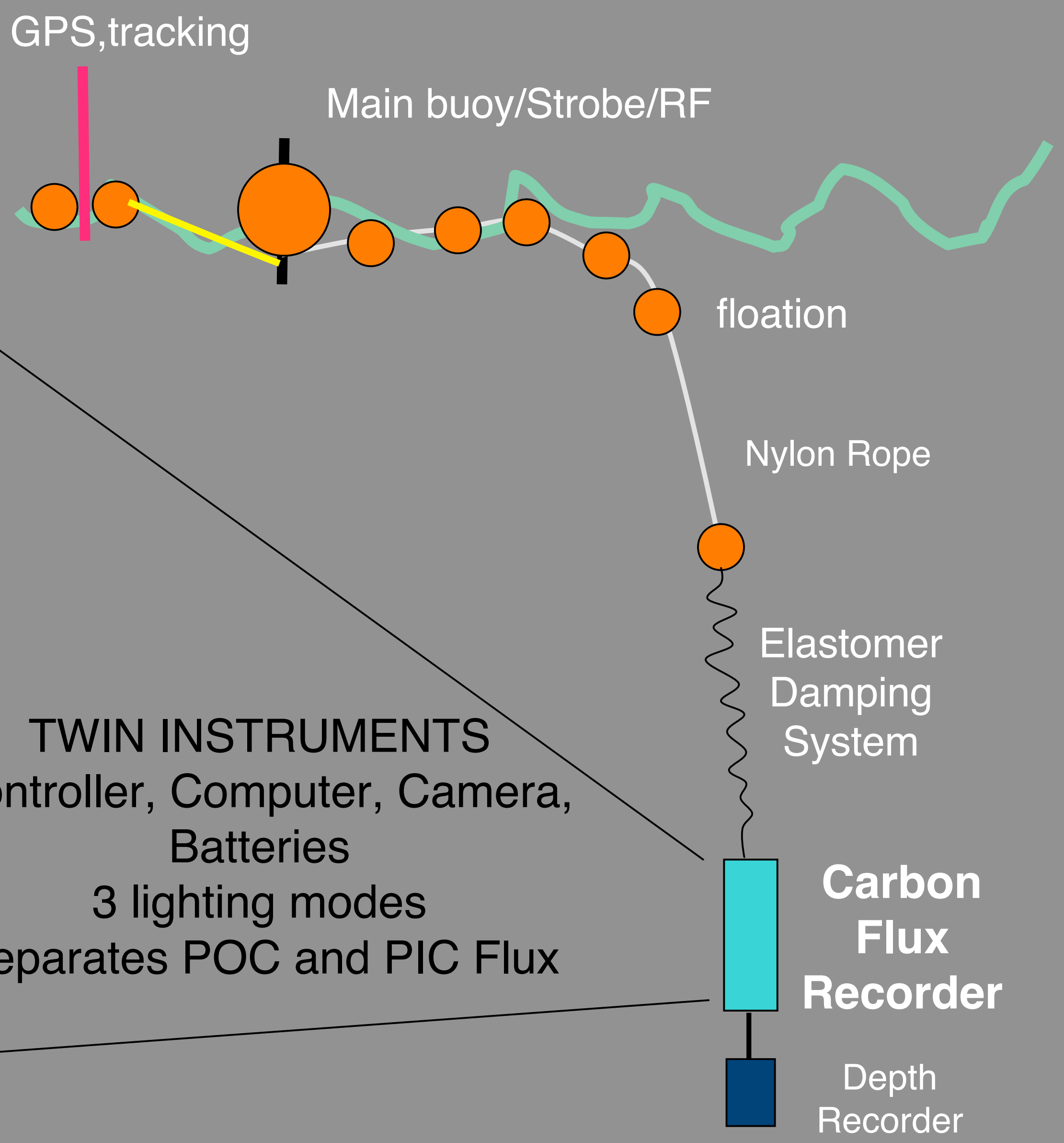
Carbon Flux Explorer

Instrument and ballasting design for free vehicle achieved at LBNL

Support DOE Office of Science, Office of Biological and Environmental Research

J Bishop LBNL

Optical Carbon Flux Instrument development & testing



TWIN INSTRUMENTS
Controller, Computer, Camera,
Batteries
3 lighting modes
Separates POC and PIC Flux

Support DOE Office of Science, Office of Biological and Environmental Research

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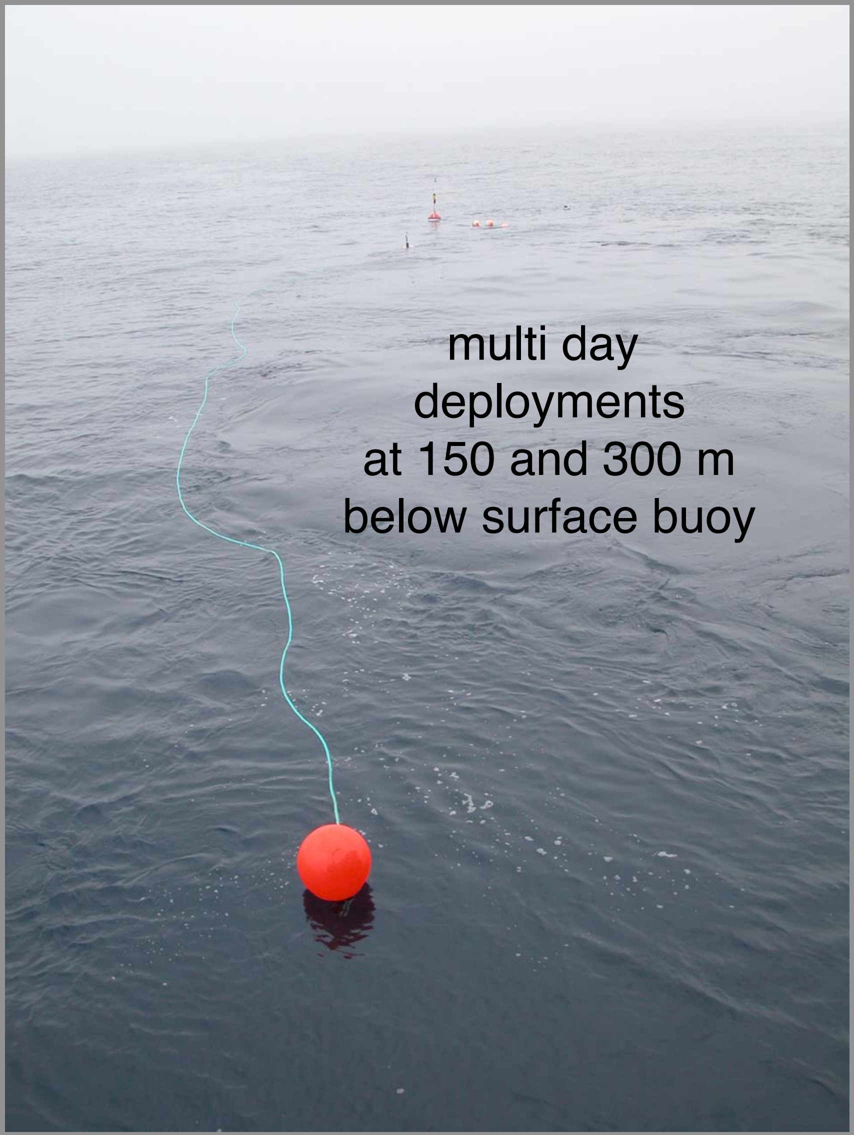
Optical Sediment Trap Results Oyashio 2005



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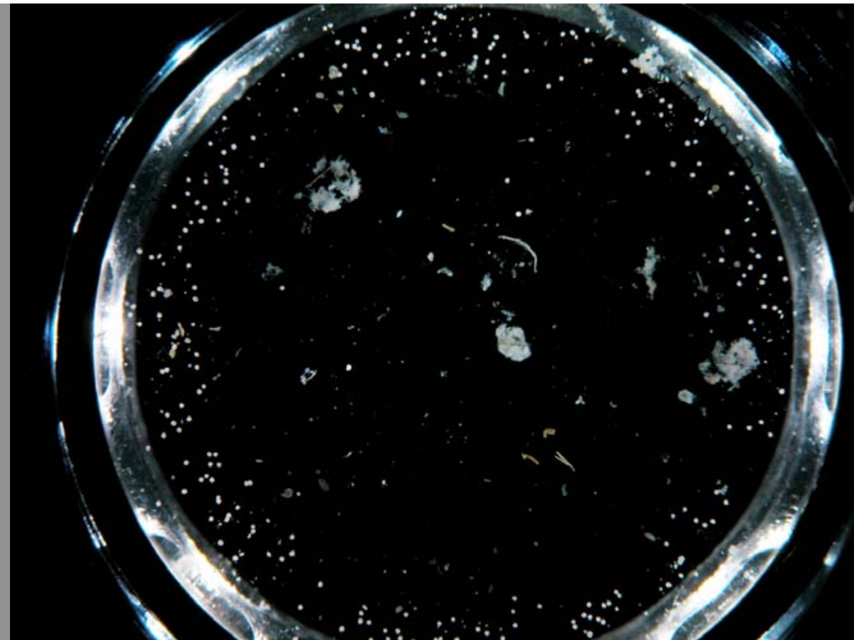
3 modes
of illumination

15 μm
resolution

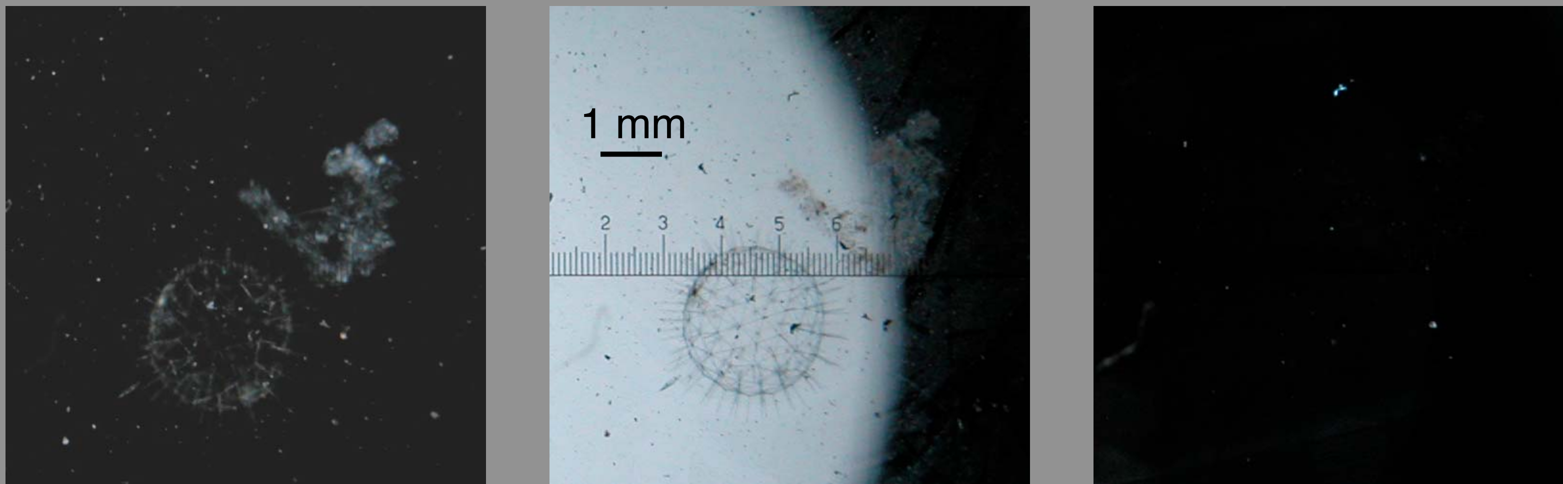


Dark Field

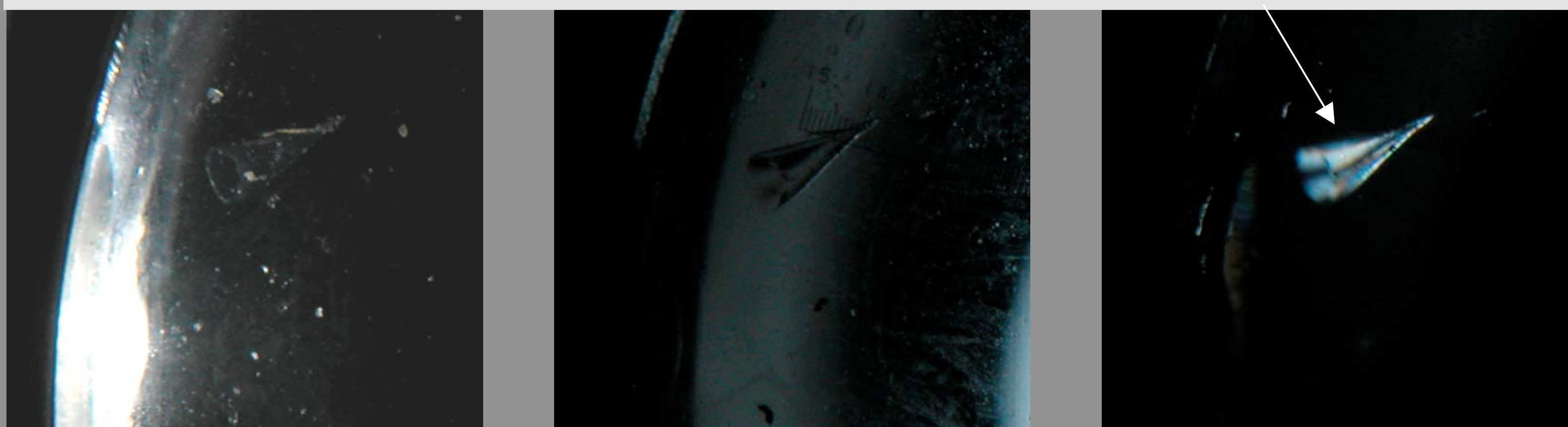
Transmitted

Cross Polarized

Radiolarian shell and aggregate (amorphous SiO_2)



Pteropod shell ($CaCO_3$, aragonite) ‘lights up’ under polarized transmitted light due to mineral birefringence



DARK Field BCK POL

R/V WECOMA SEPT 2006

DARK FIELD IMAGES

1146 UTC 2246 L

time series of 60 images
@ 25 min intervals
with cleaning every 2.5 hours
images shown are just before
each cleaning step

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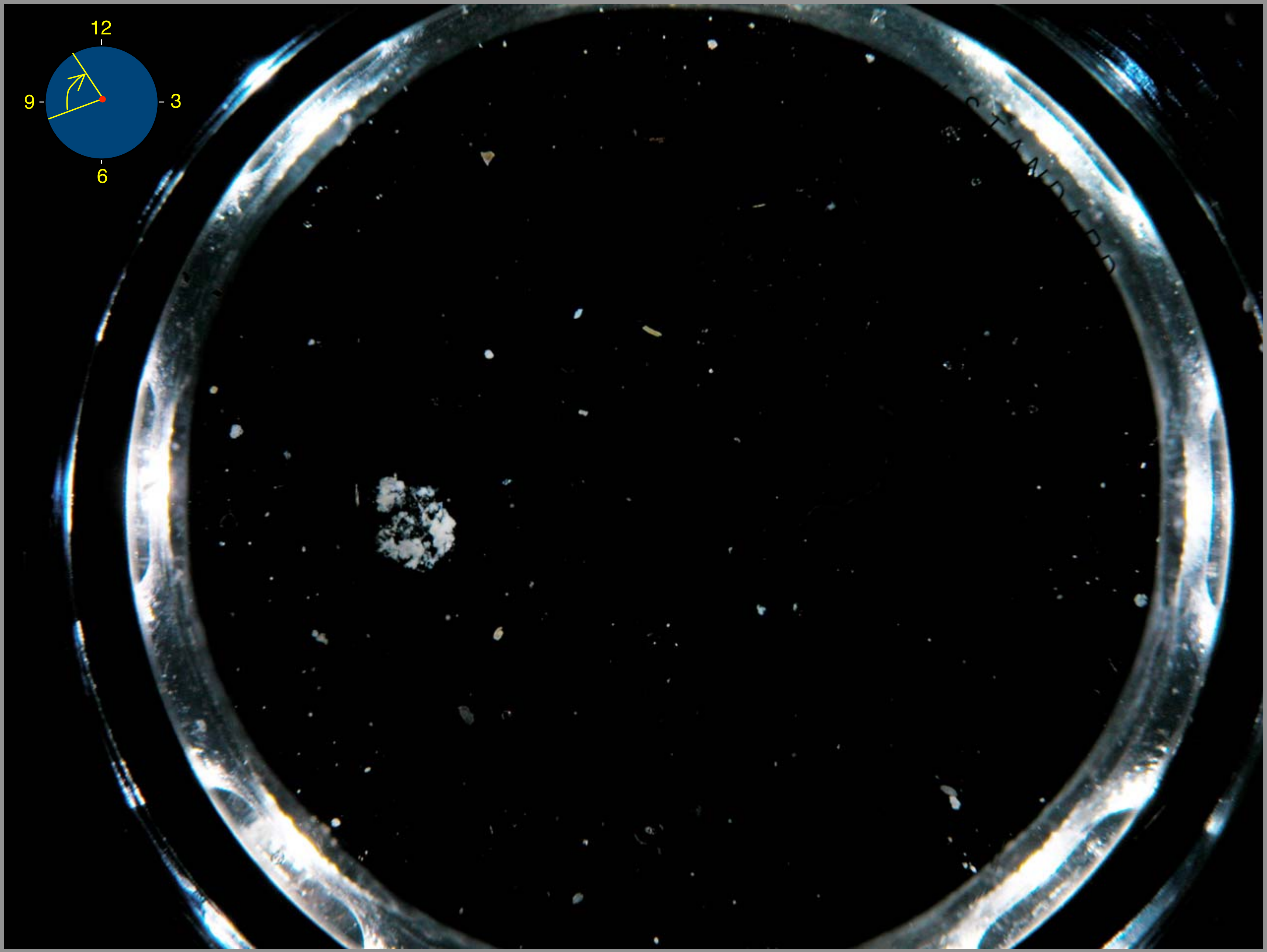
J Bishop LBNL

DARK FIELD IMAGES

1146 UTC 2246 L



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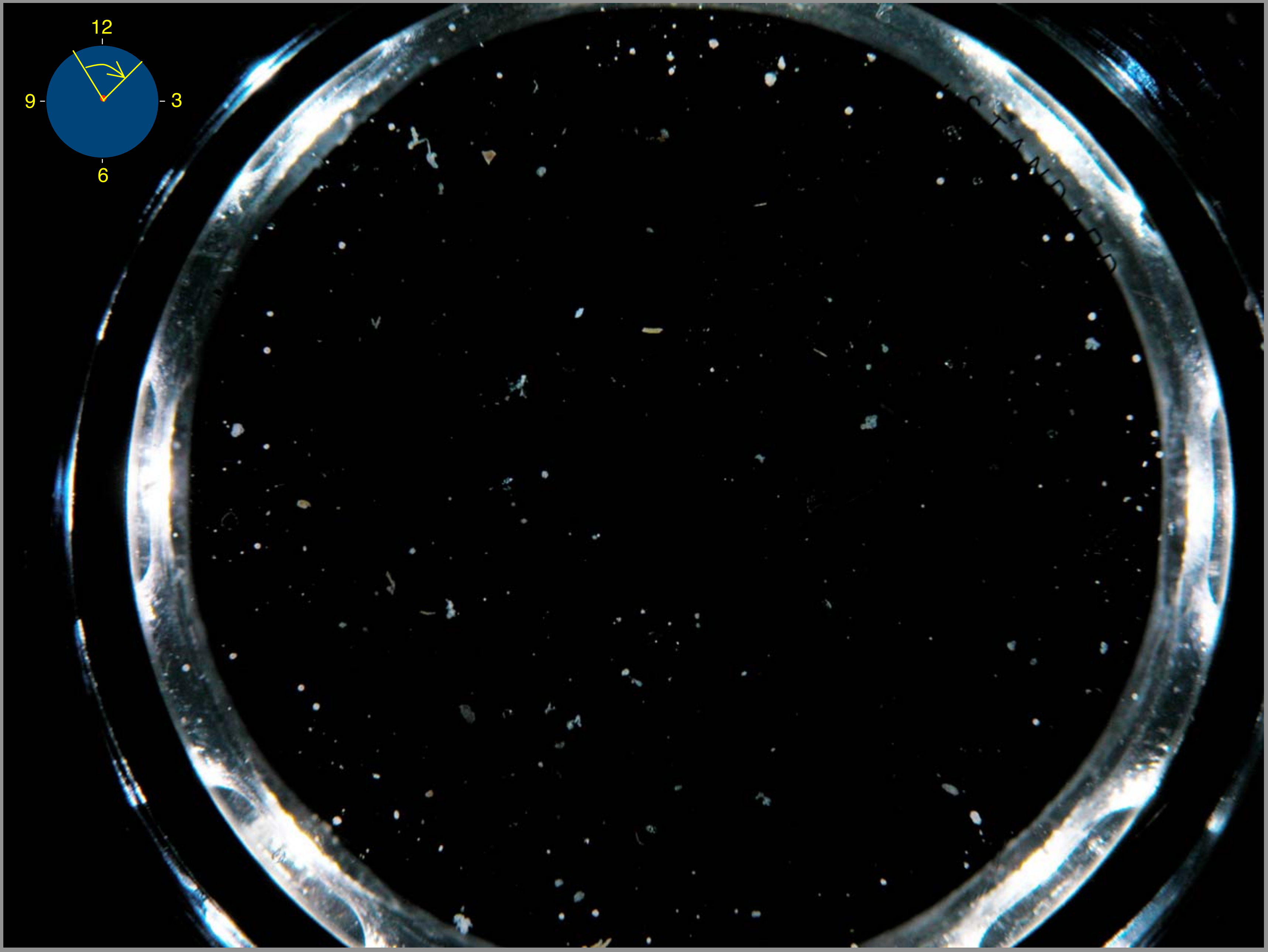
1422 UTC 0122 L



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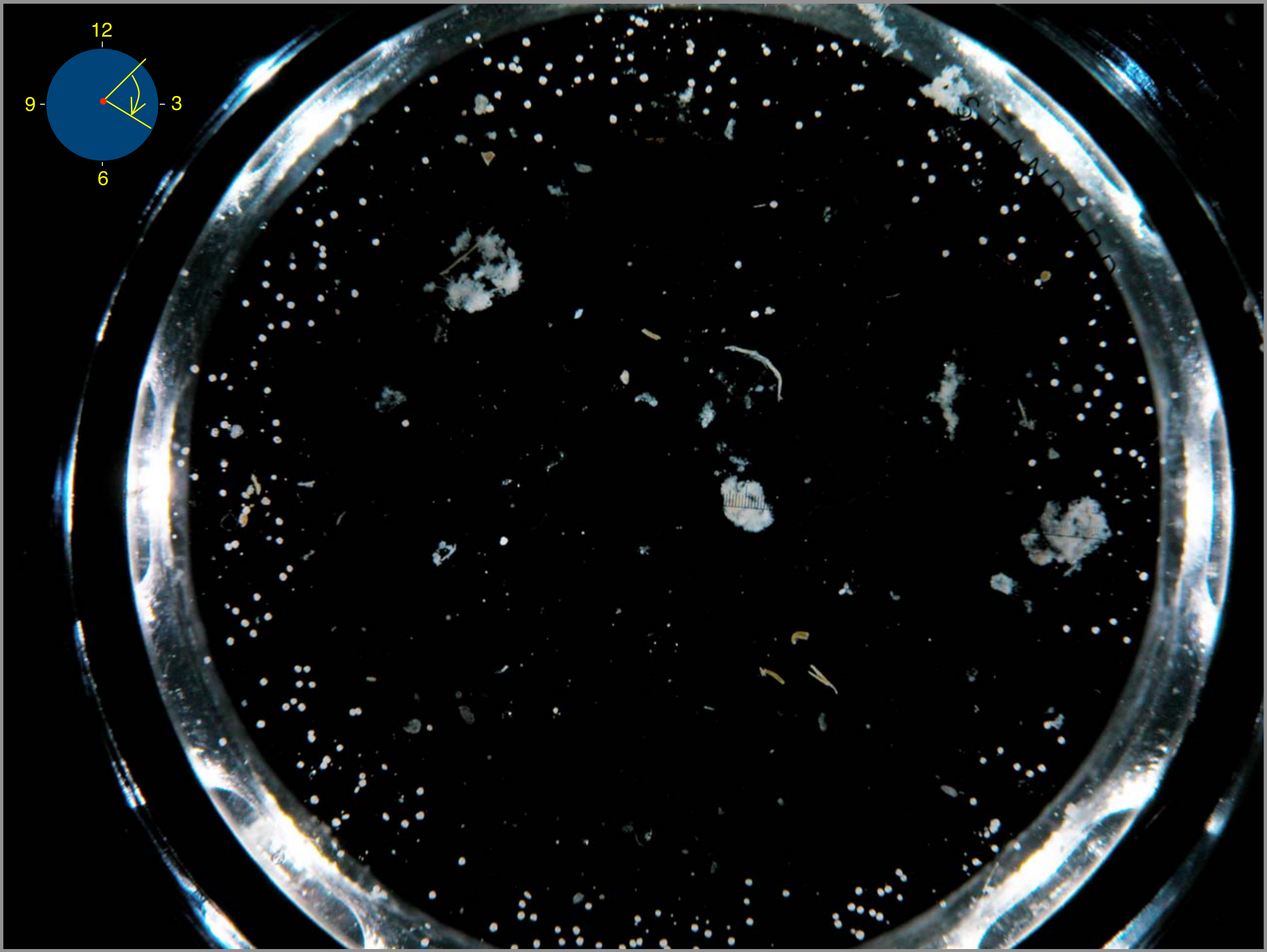
1658 UTC 0358 L



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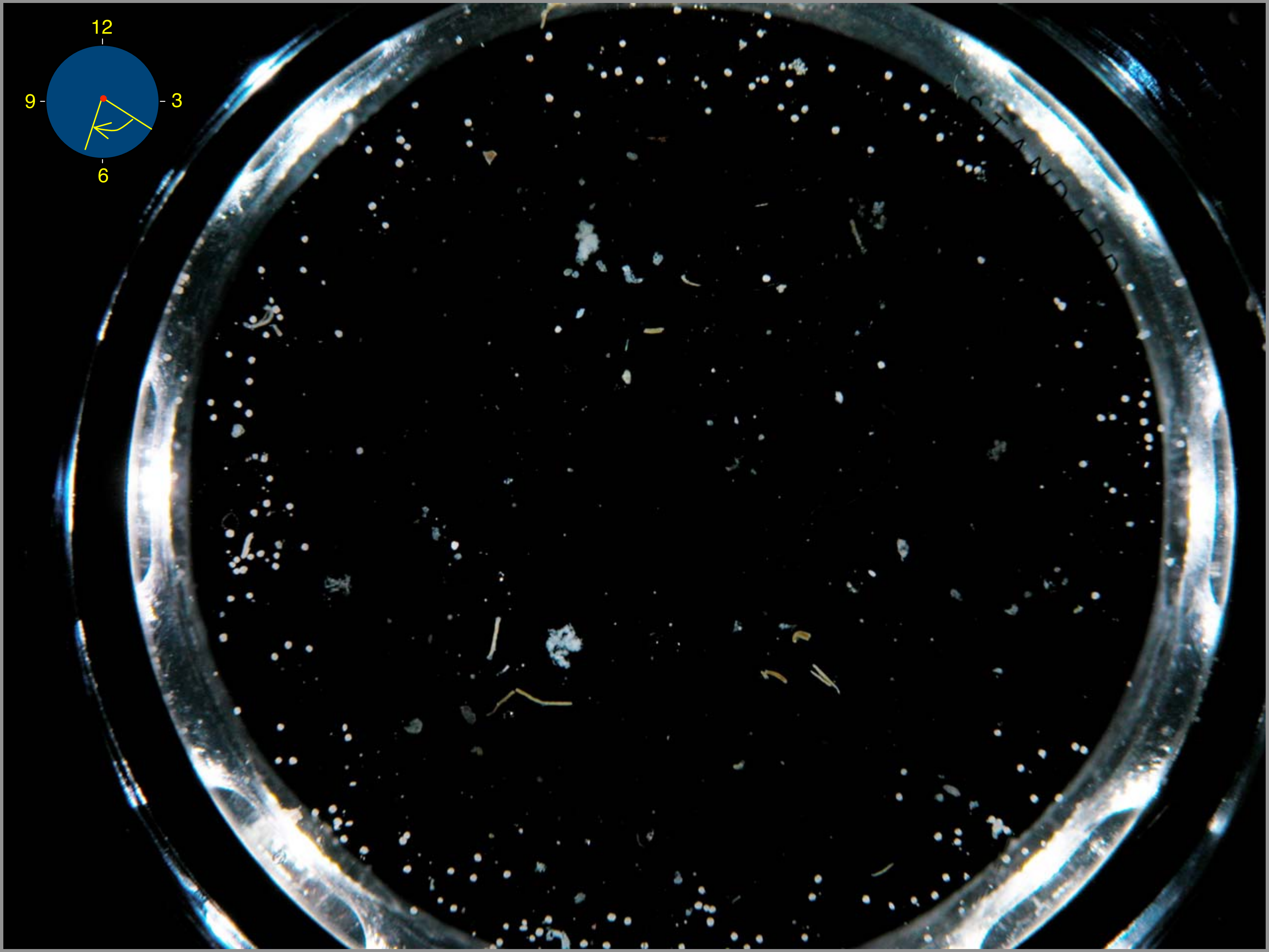
1933 UTC 0633 L



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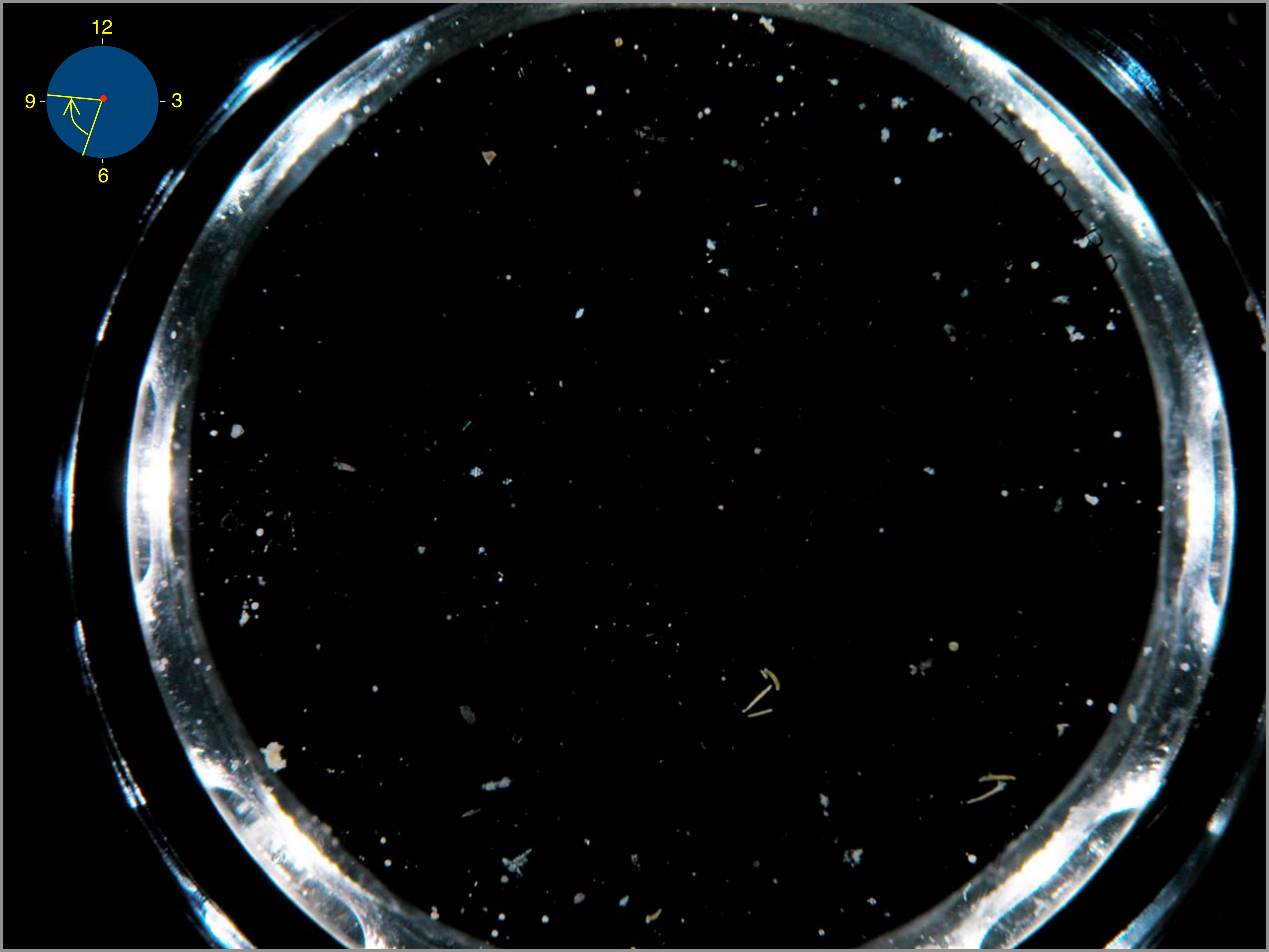
2208 UTC 0908 L



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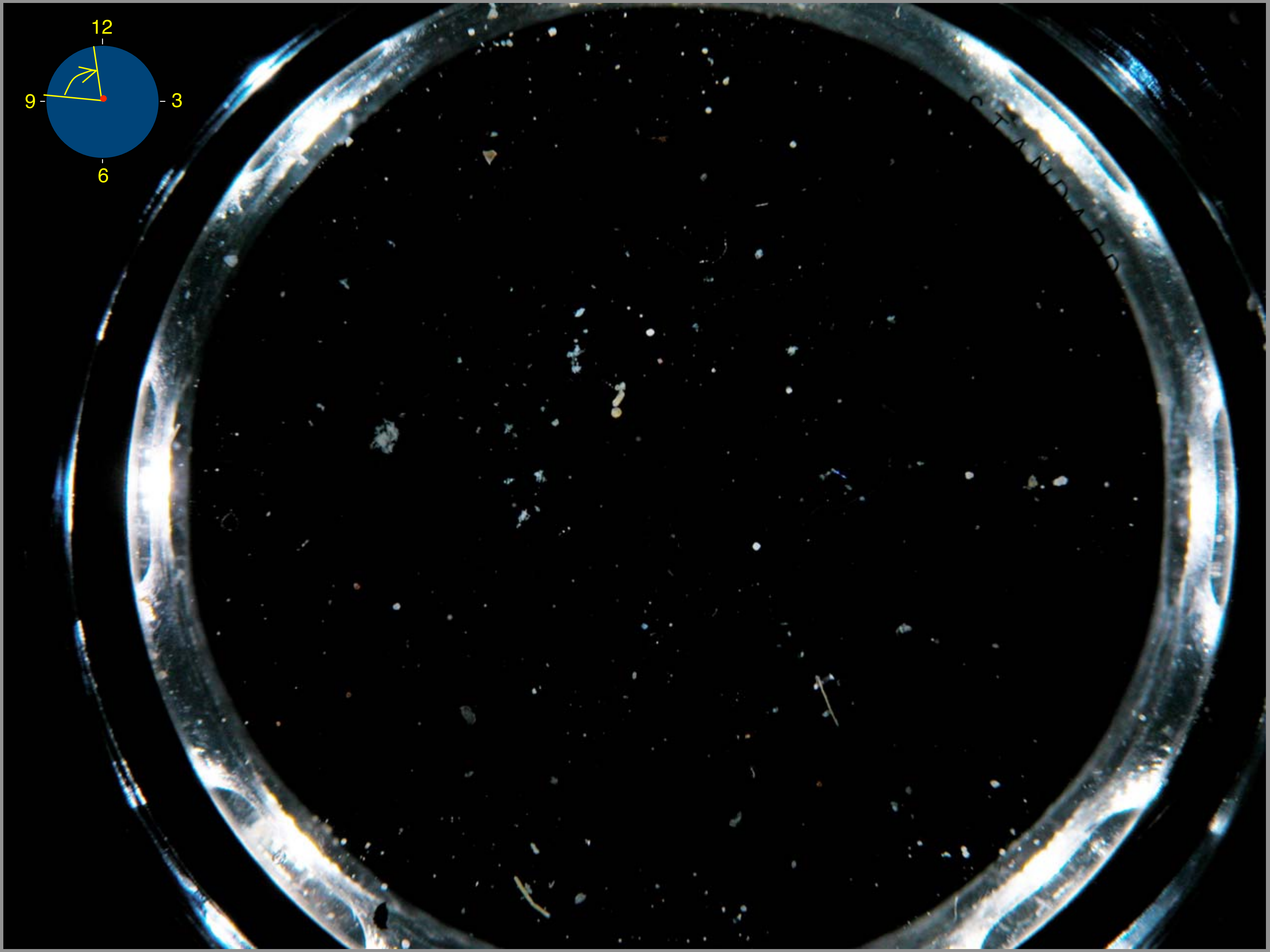
J Bishop LBNL

0044 UTC 1144 L



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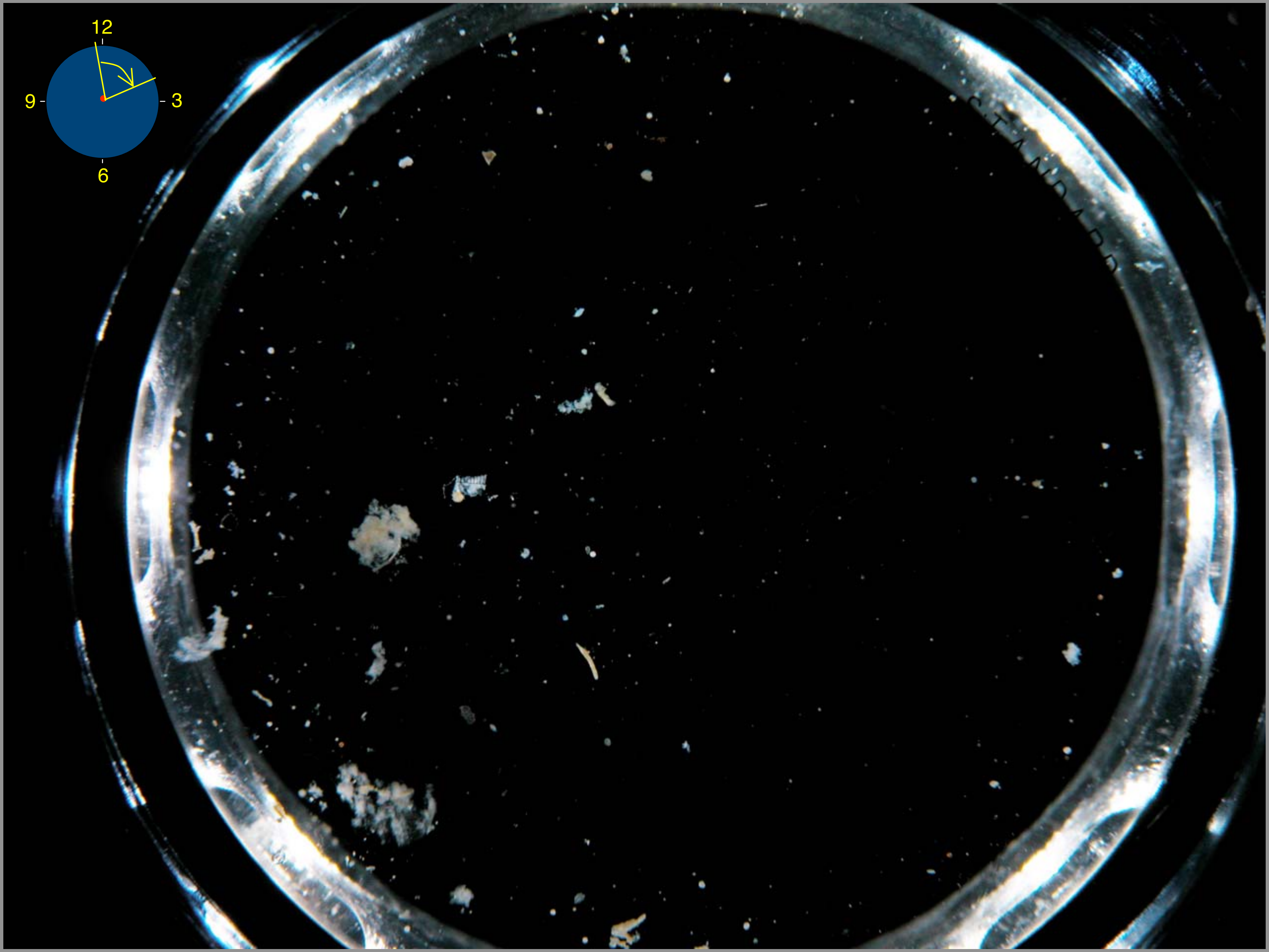
0319 UTC 1419 L



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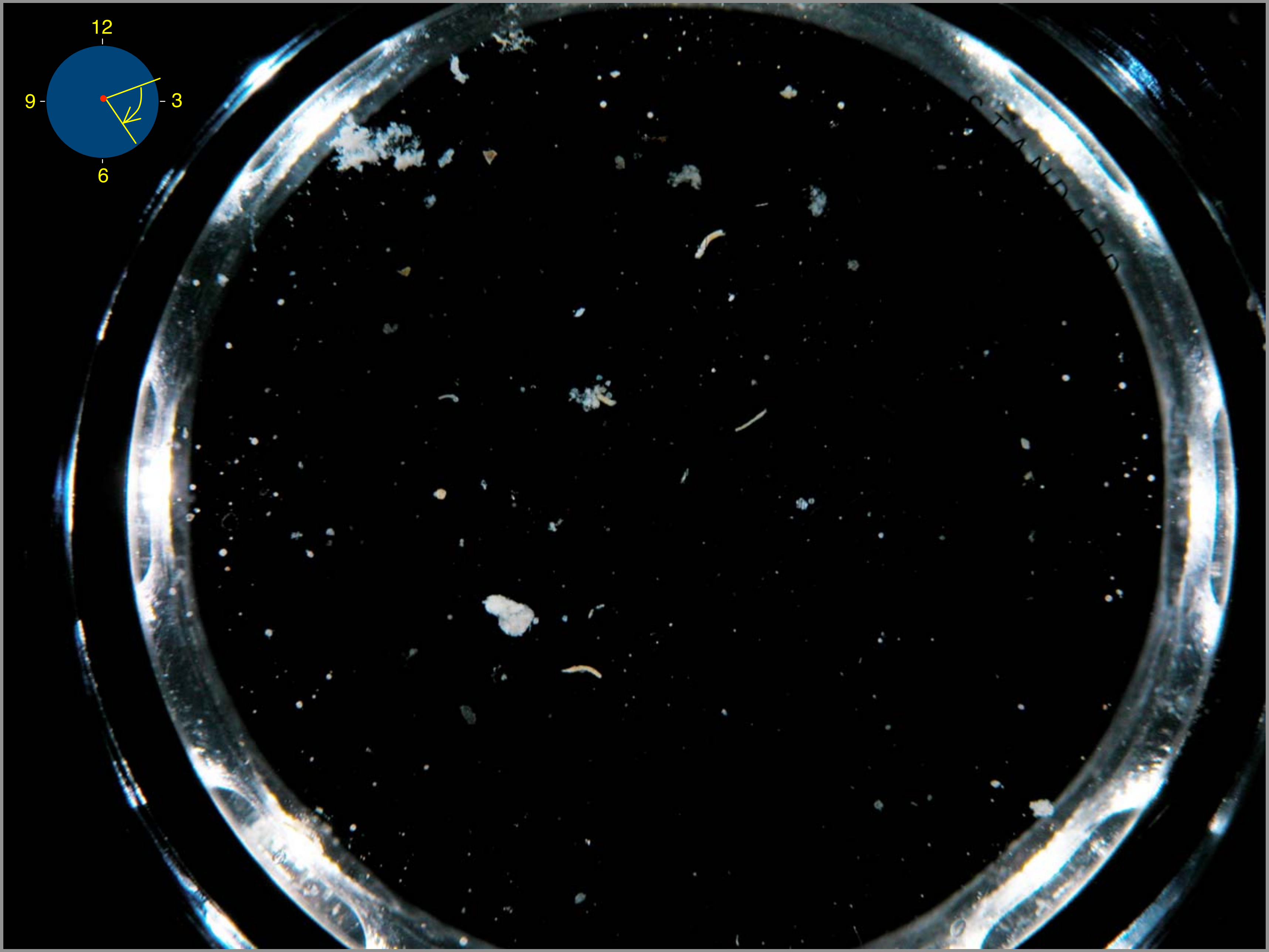
J Bishop LBNL

0555 UTC 1655 L



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QUANTITATIVE ANALYSIS

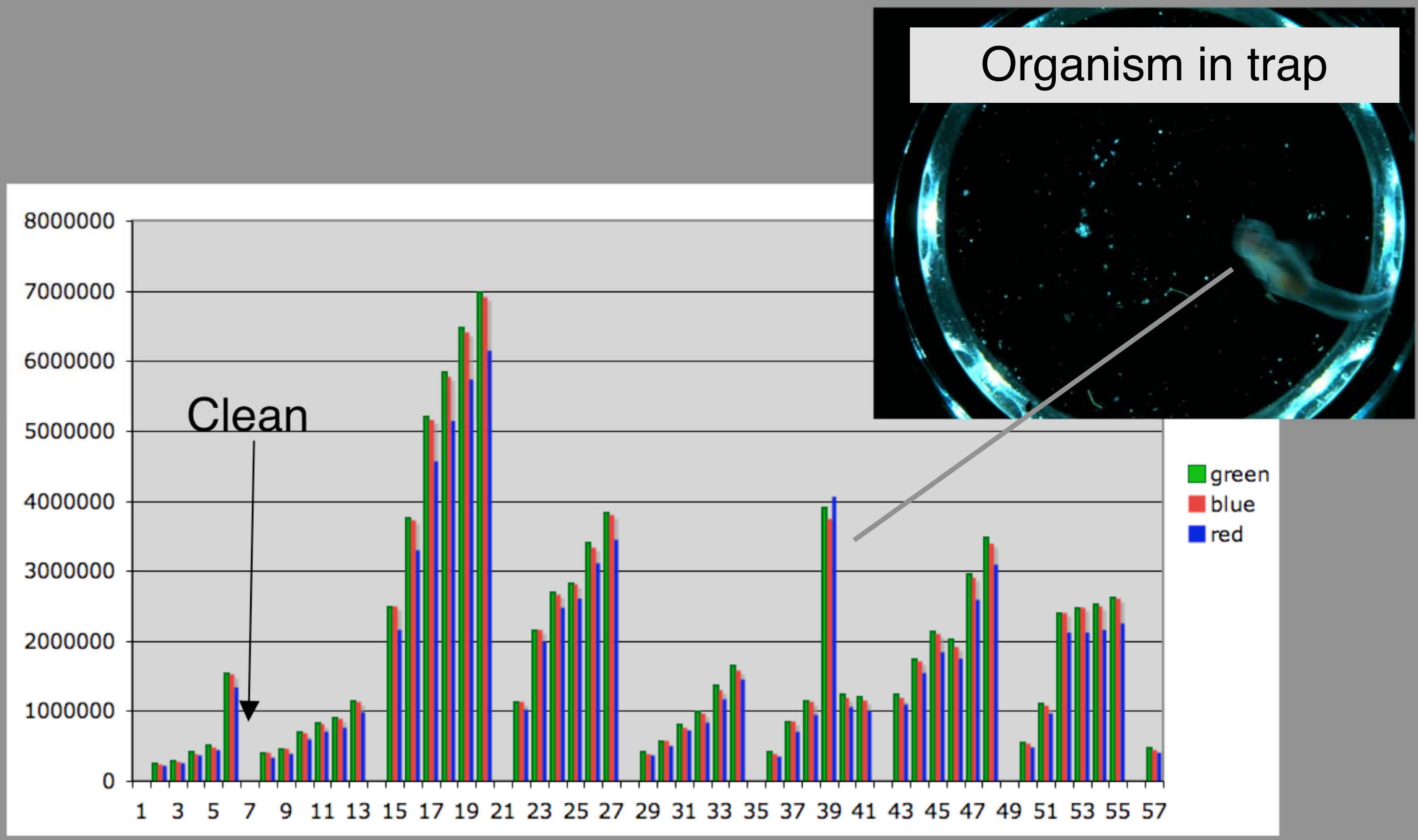
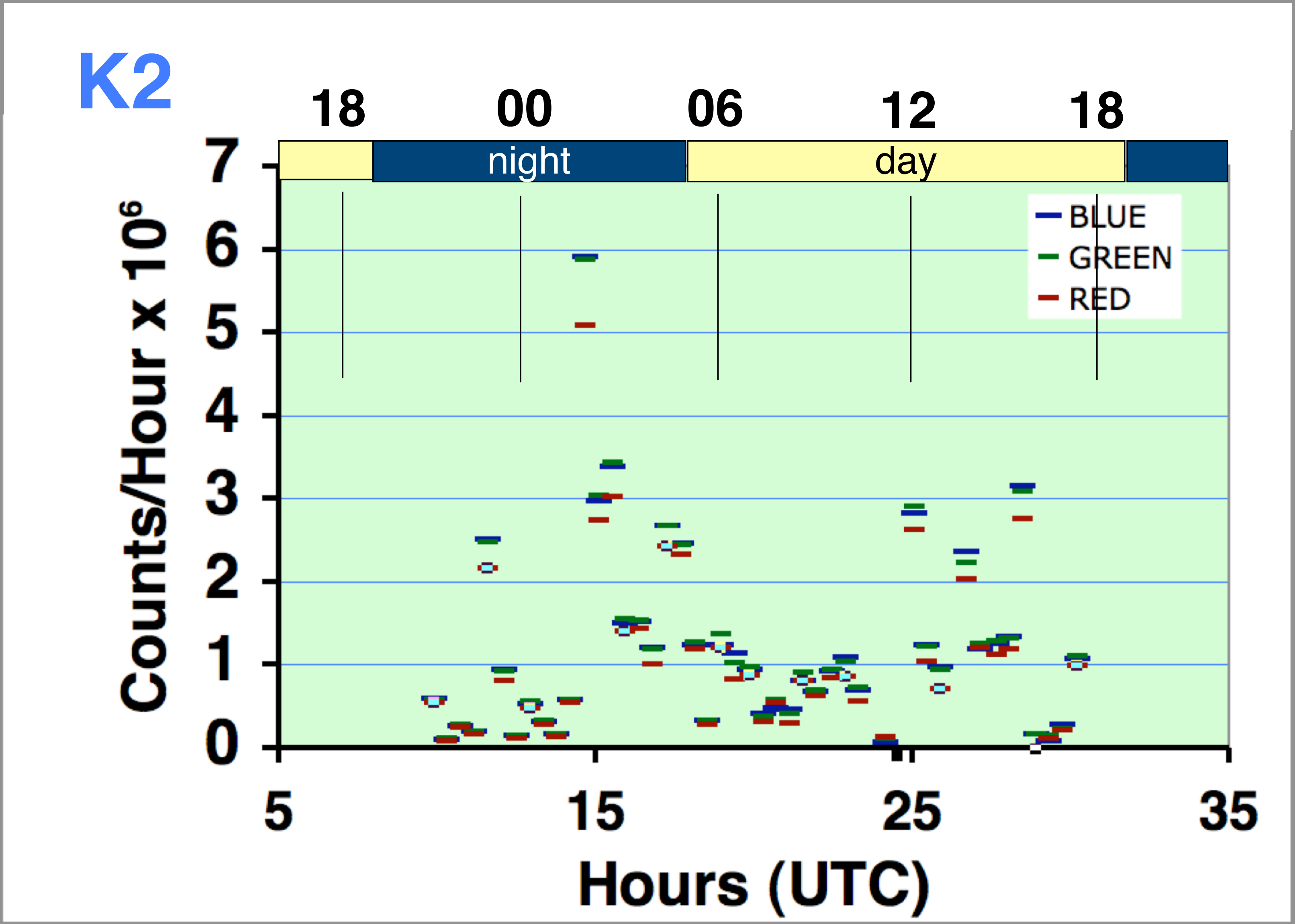


Image cycle number

60 cycles / 24 hours

Dark Field OST Aug 5-6 2006



Support DOE Office of Science, Office of Biological and Environmental Research

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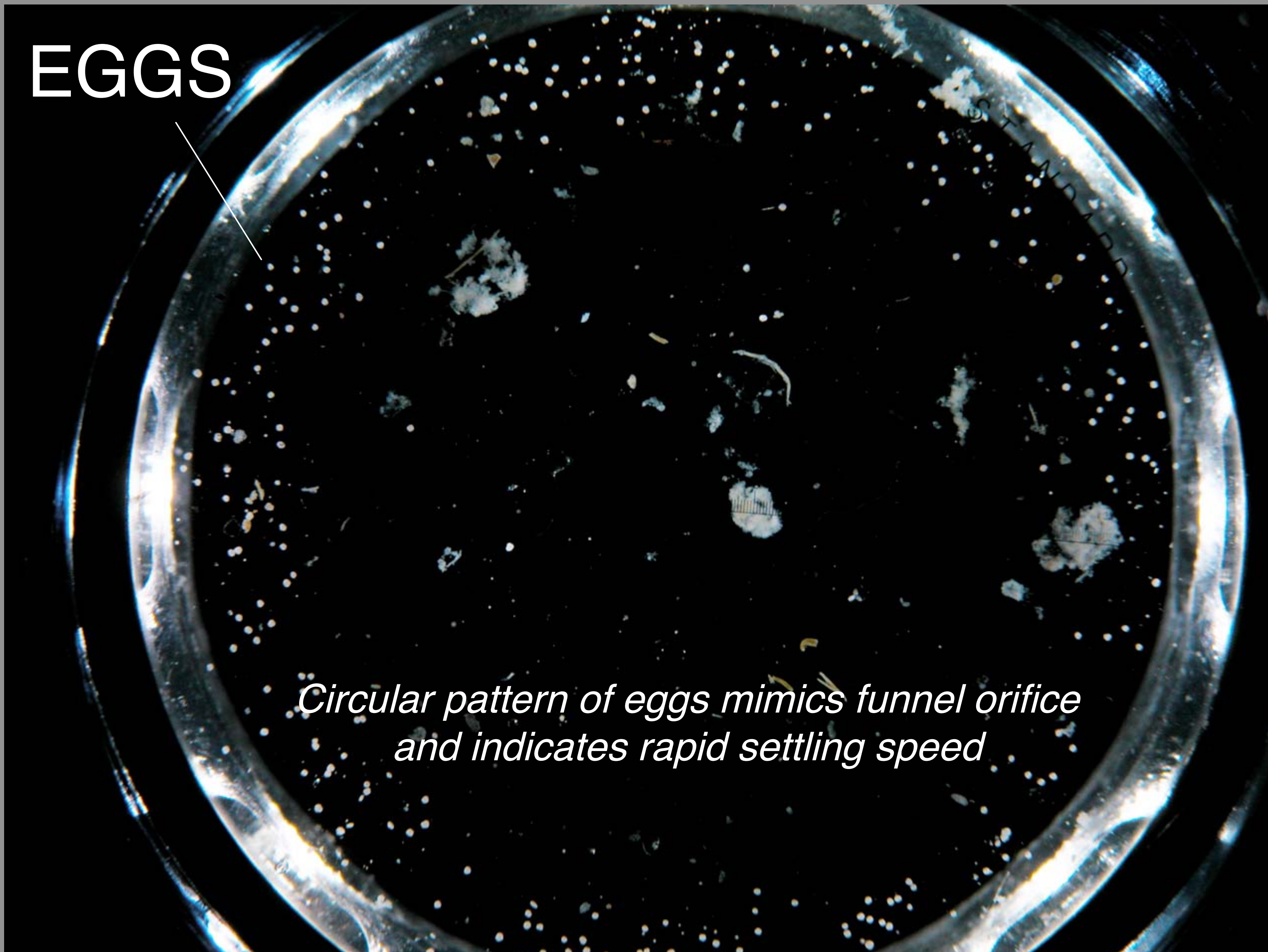
Recognition of specific classes 1658 UTC 0358 L



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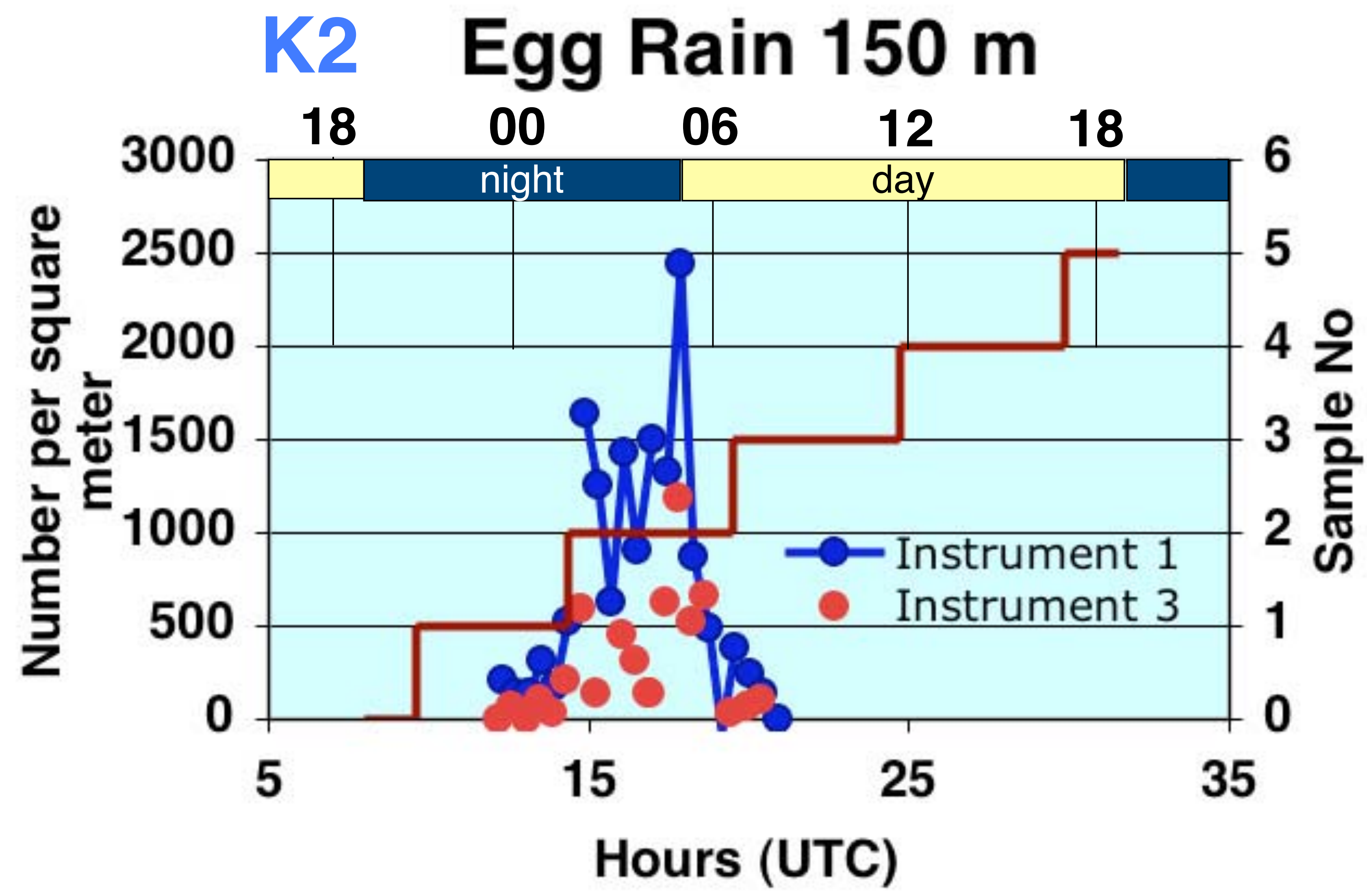

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“Swimmers”

1:37 **2** 6:30 **3** 11:45 **4** 16:50 **5** 18:30

Inst 1

Inst 3

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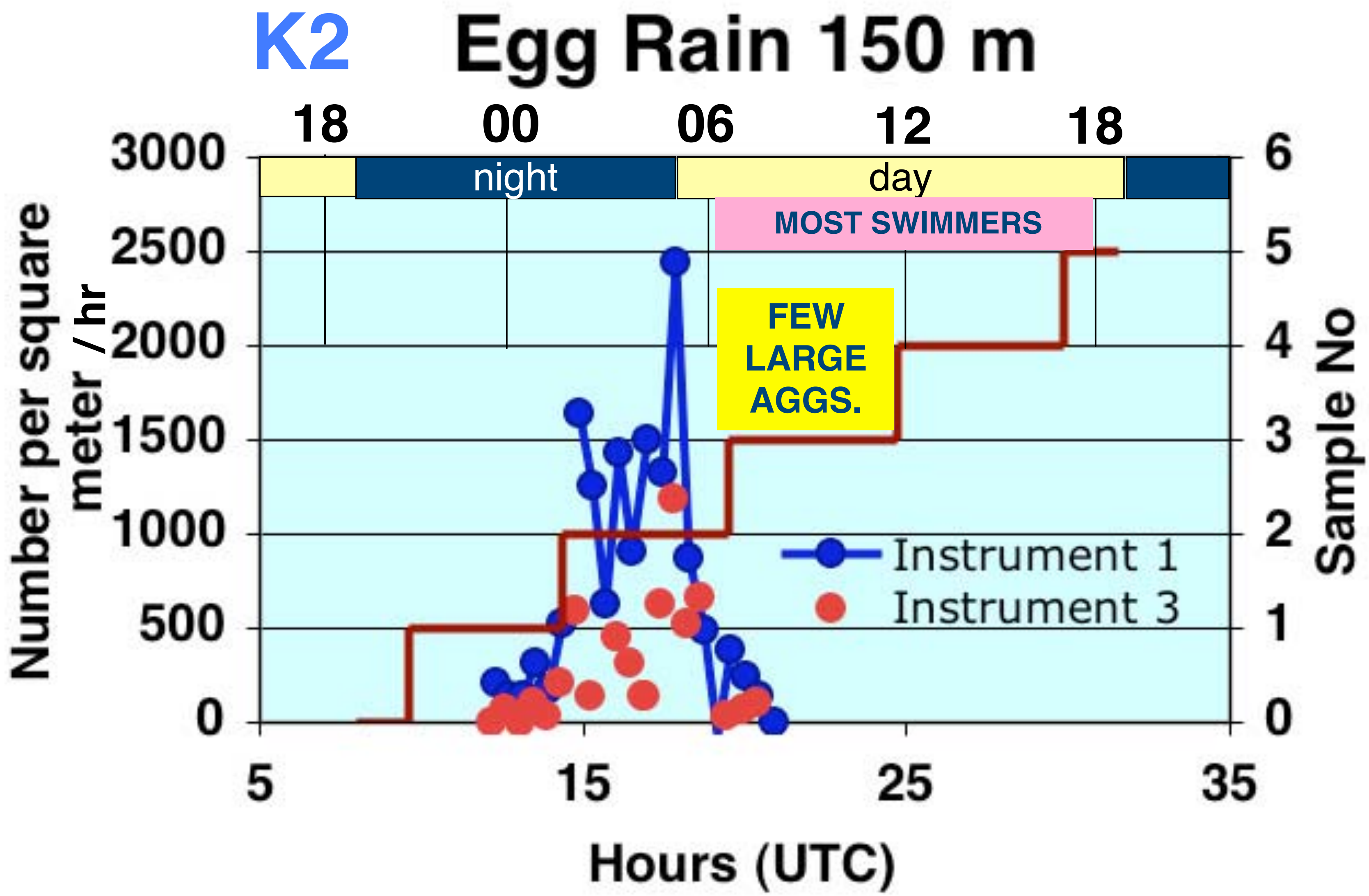

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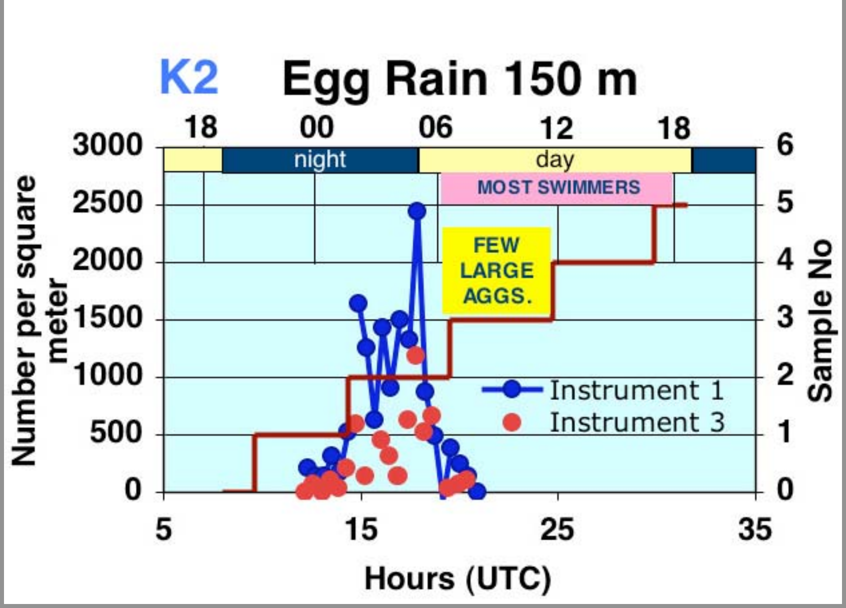
Summary:

(3) OPTICAL TRAP:

NEW!!! 24 minute flux !!!

high frequency detail of particle sedimention. Food Web (egg rain event, diurnal swimmers, etc.)



Competing technology collects samples averaged over days and cannot relay results in real time

And …

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The first robotic ocean Carbon <u>Flux</u> Explorer successfully tested at Scripps; August 2006.

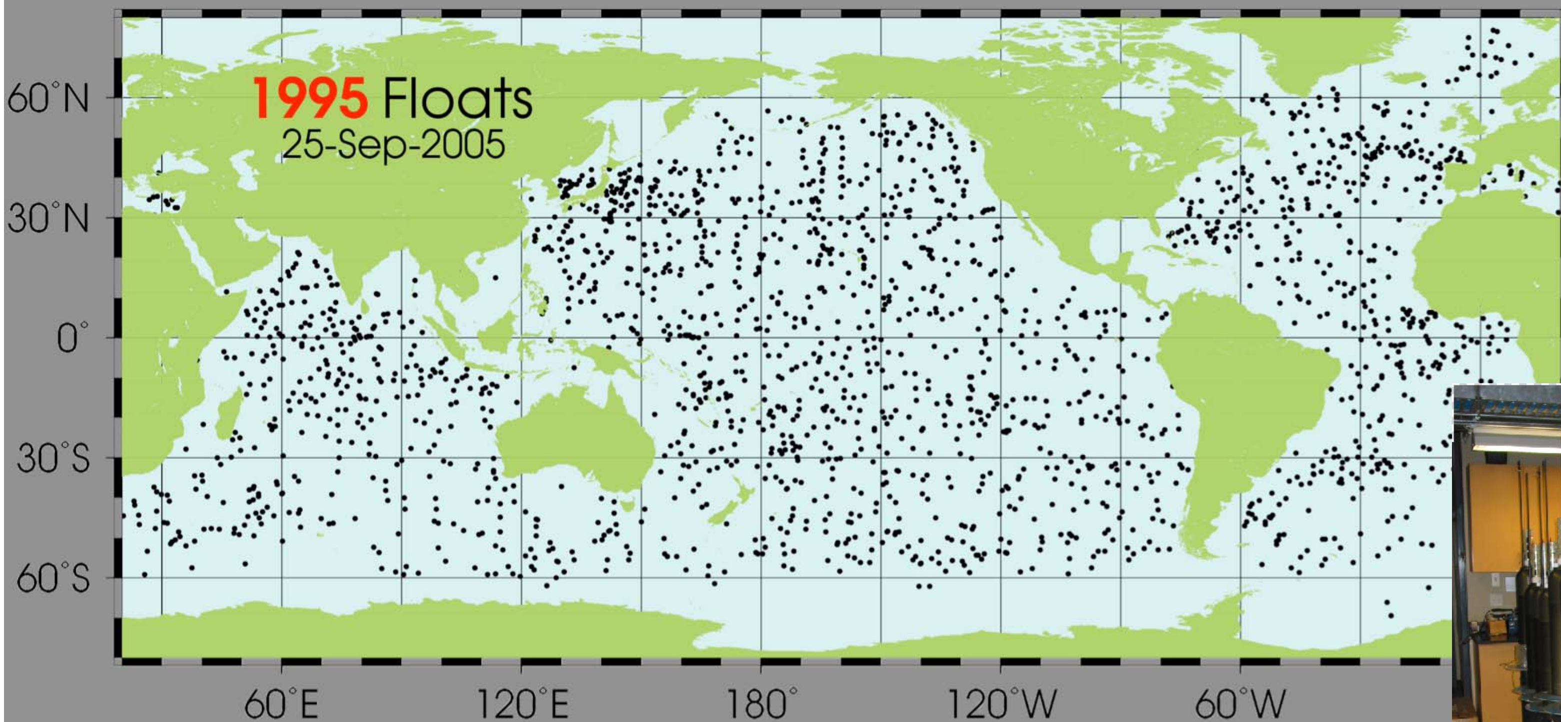
80 kg vehicle ballasted to 10 g.
underwater trim is vertical to +/- 2 degrees.
Most work was done at LBNL.

Carbon Flux Explorer nearly ready for
its first week - month long deployments.

To do: minor but critical engineering
details for first prototype, ship tests
system packaging, robustness,
optimize power budget,
algorithm for reduction of image data
prior to satellite transmission
(still 2400 to 9600baud).

And … the biological issues
of biofouling and ‘swimmers’

The Future: ***A "Carbon" - Argo?***



2432 Floats
27 March 2006

2721 Floats
28 Nov. 2006

Argo is a global project aimed at real time assessment of the ocean's heat and fresh water budgets.

Prospects for a "Carbon" Argo are Excellent

Carbon Explorer Track record

2 N Pacific OSP	2001	
1 Cal current	2001	
4 SOFeX	2002	- 1 at 66S
2 N Pacific OSP	2003	
3 N Atlantic A16N	2003 -	1 at 60 N
1 HOT (lost on launch)	2004	

—

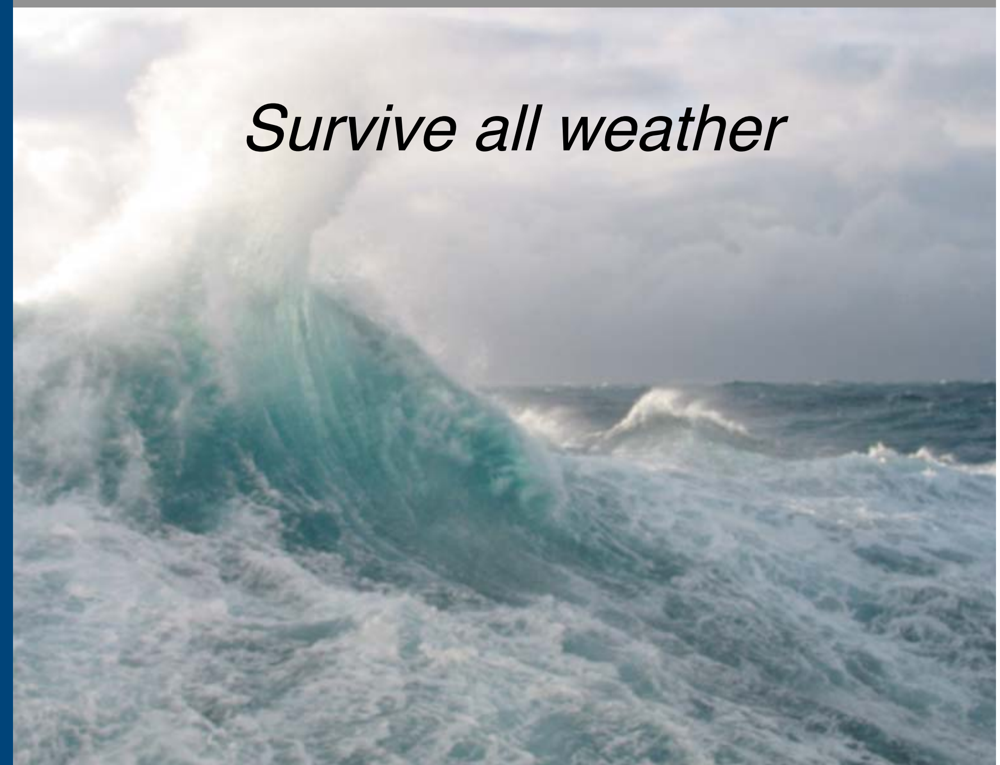
No major biofouling problems

POC sensor / scattering sensor
~7 float-years of data

Sensors outlive battery life of float

PIC sensor - 1 test on Carbon Explorer

Orbcomm telemetry saves power but was poor poleward of 55. Irridium will fix



Sensor STATUS

POC

Sensor is mature.

PIC

Operational validation on CTD's [CLIVAR A16N, S]

POC & PIC flux:

1-2 years for fully autonomous float ops.

DOC components:

Possible!

pCO_2, TCO_2, NO_3, O_2...

June 22 2005

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We are now ready for investment in an enhanced ocean carbon observing system that is …

Fast

Real Time

Robotic

High Frequency

Free Ranging

Low Cost

LBNL has and can have a significant advantage in these areas.

Science Questions

?? CO_2 ??

How does the Ocean's Natural Carbon Cycle Operate?

What are the physical, chemical, and biological controls?

How will the controls change in the future?

Can the Oceans be used for <u>Monitoring and Verification</u> of Carbon Management Actions?

How much?
Effective?
For how long?

Forcing and Response?
Ecosystem Biogeochemistry?
C(z): Sedimentation vs. Remin.?

Ocean Acidification?
Circulation Changes?
Warming?

"New" Carbon Math

Atmosphere - Ocean Sink

=

Land Sink - Emissions

Could be Known In Real Time