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Modeling and Synthesis of Southern Ocean
Natural Iron Fertilization Workshop
Woods Hole, 27-29 June 2011

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Royal Netherlands Institute for Sea Research

Southern Ocean Iron Fertilization

Hein de Baar and many colleagues

Modeling and Synthesis of Southern Ocean
Natural Iron Fertilization Workshop
Woods Hole, 27-29 June 2011

Contents

- The *in situ* Iron Fertilization Experiments
  - Ironex I (1993) through SERIES 2002
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  - Galapagos Plume (1993)
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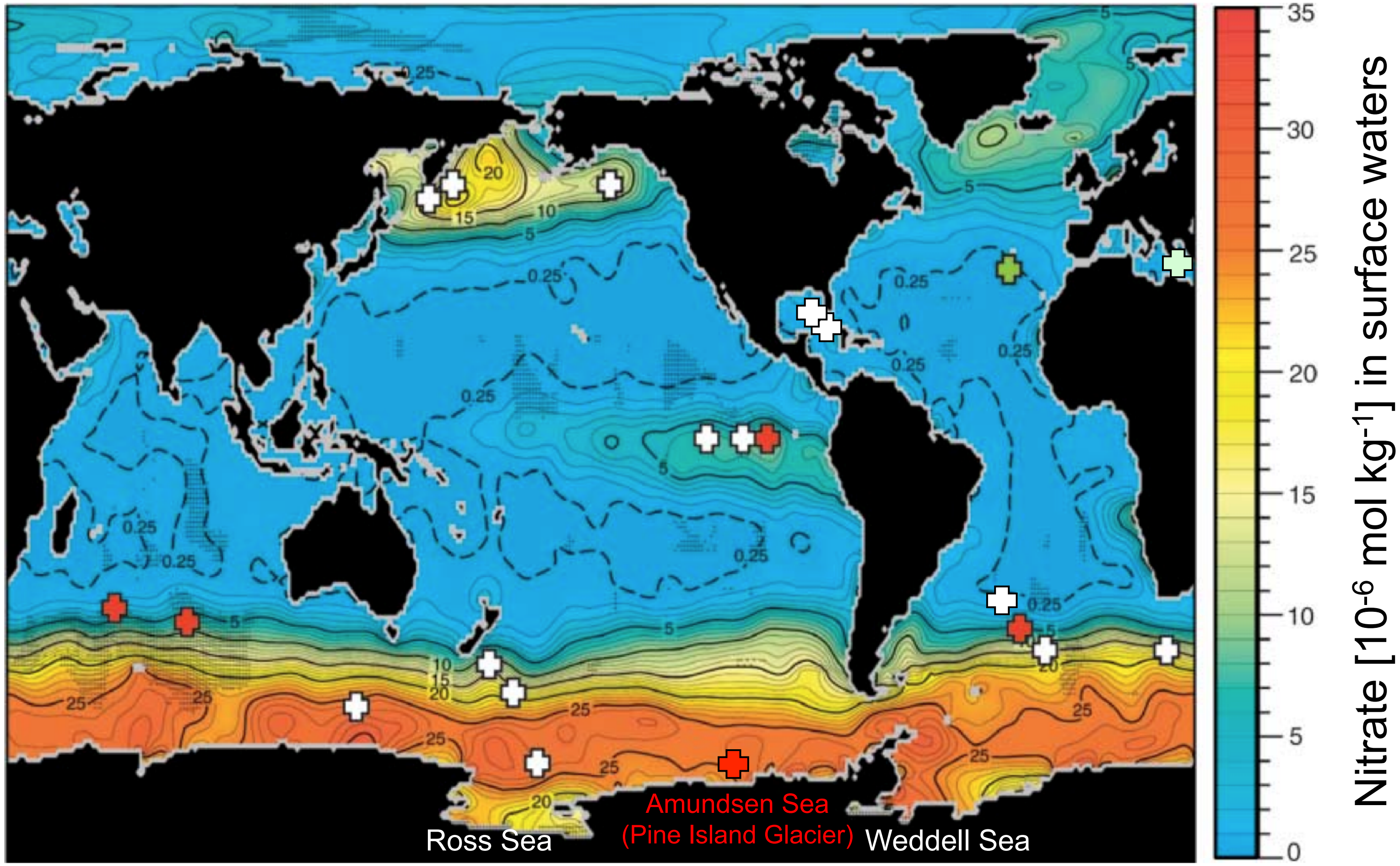
- Iron limitation is diffusion limitation of large diatoms
- Efficiency ratio Carbon : Iron (C:Fe ratio)
- Co-limitation with Manganese (Mn:P ratio versus ambient Fe)

- Iron Fertilization to Solve the fossil fuel CO_2 problem ?
  - (1988) Give me half a supertanker ....
  - (2011) GeoEngineering, London Convention, ISIS Consortium

NIOZ

Among 3 major High-Nutrient-Low-Chlorophyll (HNLC) regions only the Southern Ocean would (perhaps) yield long term deep carbon storage



13 Fe *in situ* addition experiments in 1993-2009 period; Ironex-1 to Lohafex

5 unperturbed natural Fe fertilization studies: Galapagos; Polar Front 1992; Crozet *Crozex* 2004-2005; Kerguelen *Keops* 2005; Pine Island Glacier *Dynalife* 2009

Not discussed today are:
- Fe + P addition experiment (FEEP 2004)
- P addition experiment (CYCLOPS 2002)

NIOZ

Hypotheses for HNLC condition

- Iron limitation
- Light limitation
- Grazing loss
- Other bio-limiting trace elements:
  - Cobalt ?

- Manganese co-limitation

What are your objectives

- fertilization experiments as a tool to unravel the functioning of the HNLC plankton ecosystem

- geo-engineering ocean fertilization for sequestration of CO_2 from the atmosphere to avoid global warming

depending on your objectives the design of research and experiment may be quite different

today we will shift back and forth between the two

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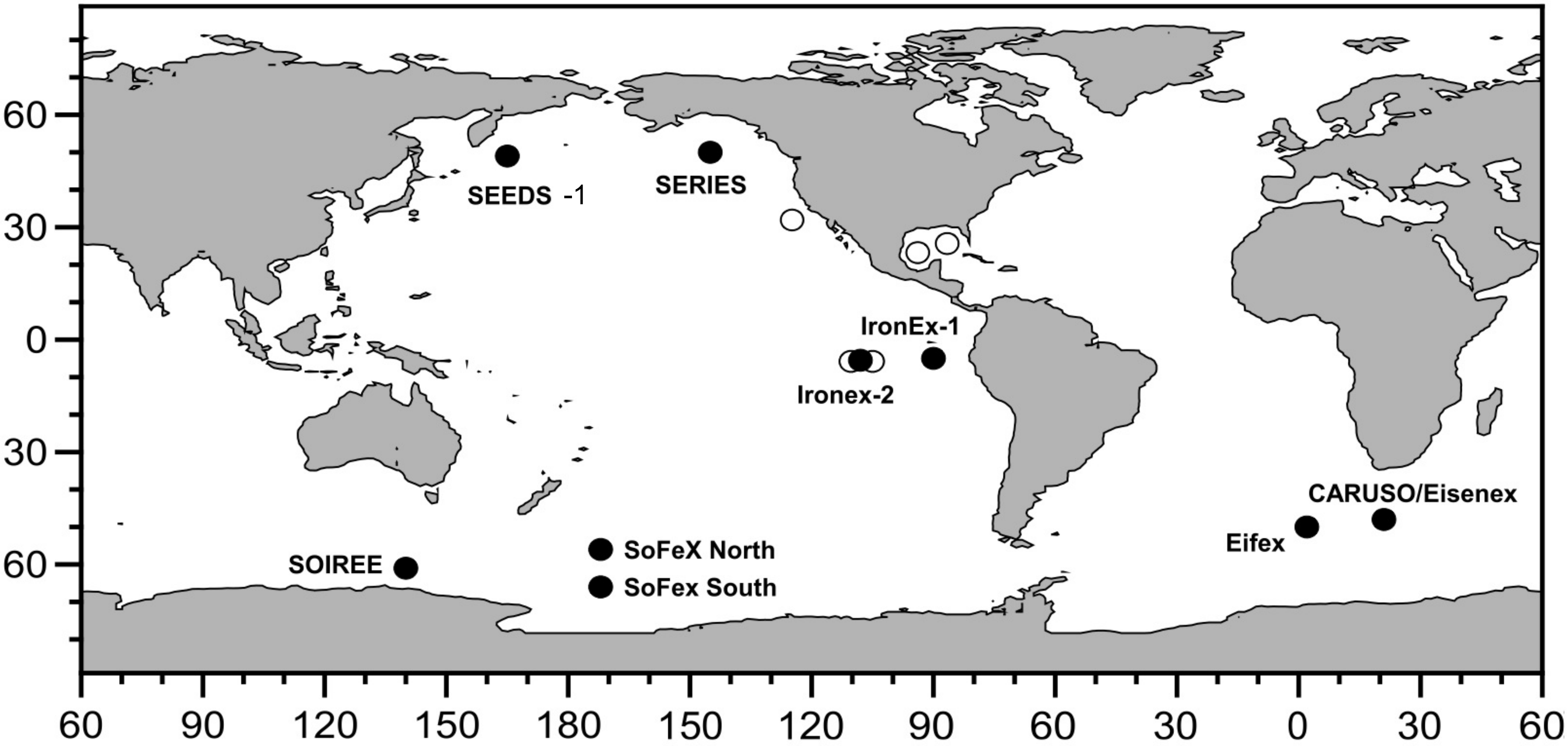
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 110, C09S16, doi:10.1029/2004JC002601, 2005

Synthesis of iron fertilization experiments: From the Iron Age in the Age of Enlightenment

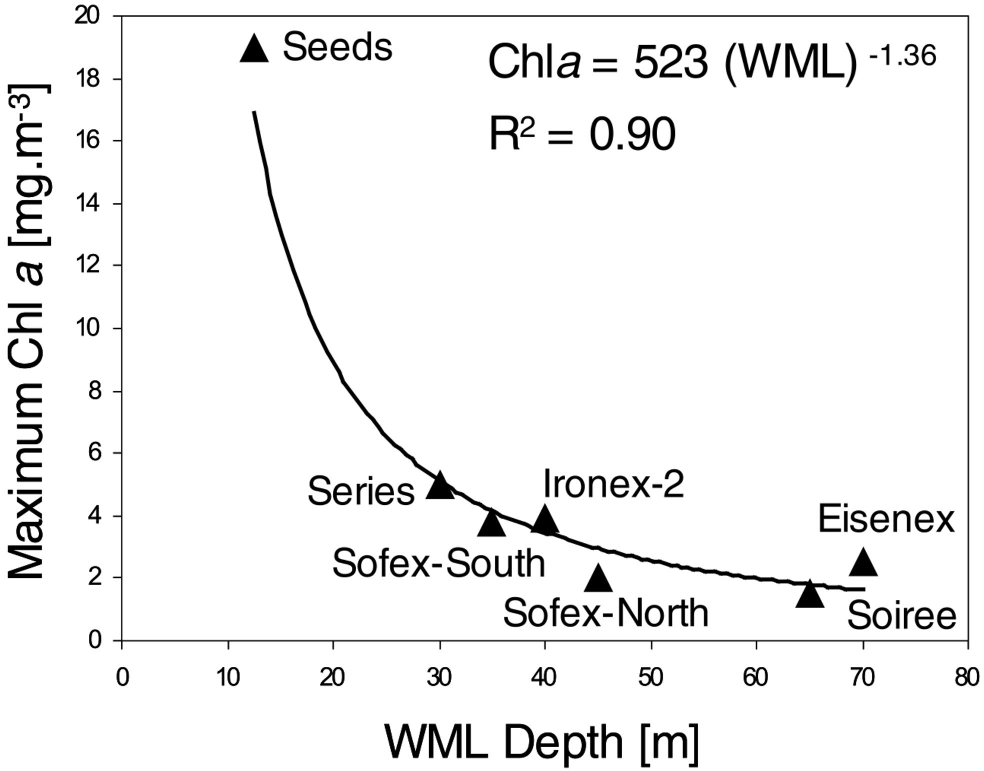
Hein J. W. de Baar,[1,2] Philip W. Boyd,[3] Kenneth H. Coale,[4] Michael R. Landry,[5] Atsushi Tsuda,[6] Philipp Assmy,[7] Dorothee C. E. Bakker,[8] Yann Bozec,[1] Richard T. Barber,[9] Mark A. Brzezinski,[10] Ken O. Buesseler,[11] Marie Boyé,[2,12] Peter L. Croot,[1,13] Frank Gervais,[7] Maxim Y. Gorbunov,[14] Paul J. Harrison,[15] William T. Hiscock,[16] Patrick Laan,[1] Christiane Lancelot,[17] Cliff S. Law,[18] Maurice Levasseur,[19] Adrian Marchetti,[20] Frank J. Millero,[16] Jun Nishioka,[21] Yukihiro Nojiri,[22] Tim van Oijen,[2] Ulf Riebesell,[13] Micha J. A. Rijkenberg,[1,2] Hiroaki Saito,[23] Shigenobu Takeda,[24] Klaas R. Timmermans,[1] Marcel J. W. Veldhuis,[1] Anya M. Waite,[25] and Chi-Shing Wong[26]

7 experiments available in 2004 for interpretation: Ironex-2 (1995), SOIREE (1999), CARUSO/Eisenex (2000), SEEDS-1 (2001), SoFeX-South (2002), SERIES (2002)



Ironex-1 (1993) premature subduction after 4 days, not used
SoFeX North (2002) very streaky due to Polar Front shear stress, cannot be quantified
Eifex (2004) no data available yet in 2004

Chlorophyll *a* response depends on depth of Wind Mixed Layer i.e. availability of light

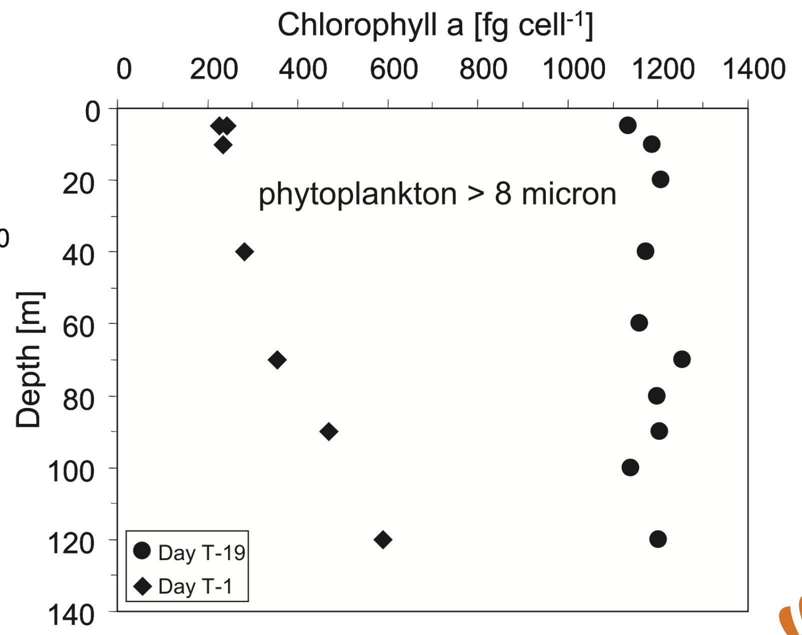


Also the major response is always an enhancement of the larger size classes of diatoms

Thus confirming what was already known from our bottle incubation experiments in 1988 (Buma, de Baar, et al, 1991)

However Chl *a* is NOT a good indicator of overall biomass

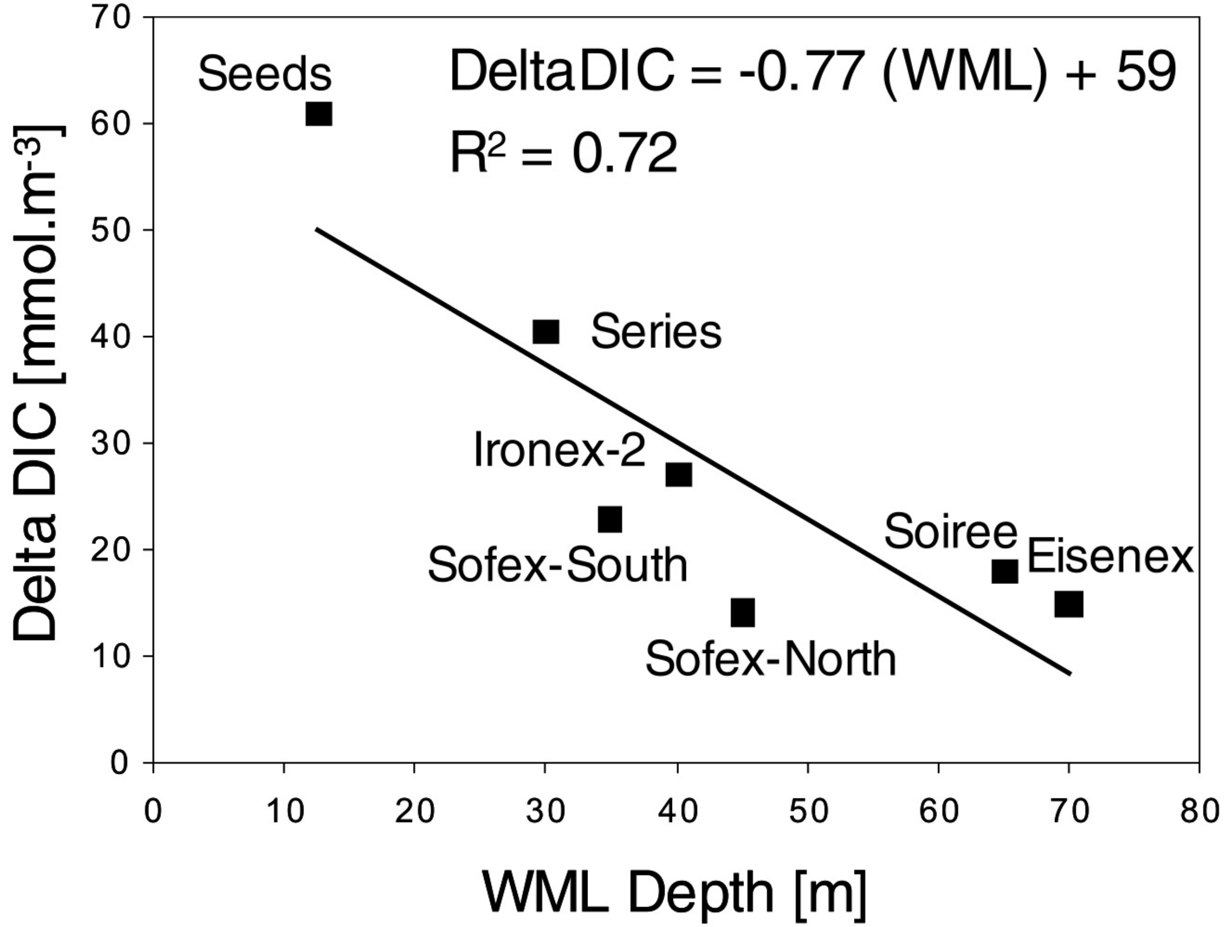
bio-synthesis of Chl *a* requires Fe
- at Fe limitation low Chl *a* per cell
- at Fe replete condition high Chl *a* per cell



Eisenex (2000): upon Fe addition a sixfold increase of cellular Chl *a* in the large diatoms > 8 micron

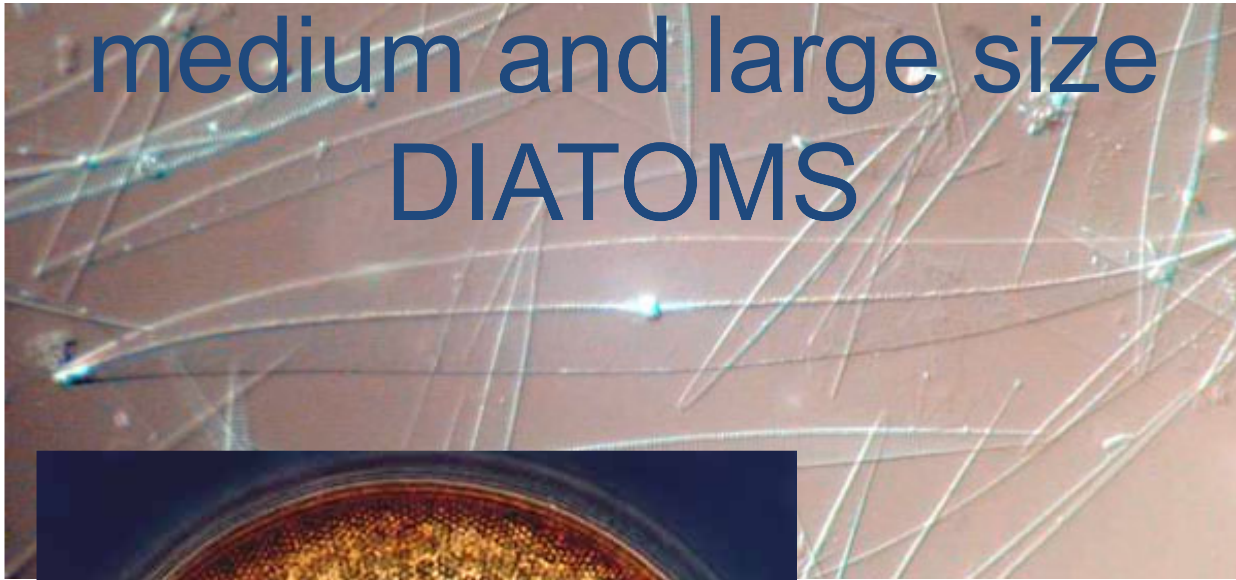
Decrease of total Dissolved Inorganic Carbon (DIC) is reliable quantitative indicator of net Biomass increase

$$DIC = [CO_2] + [HCO_3^-] + [CO_3^{2-}]$$

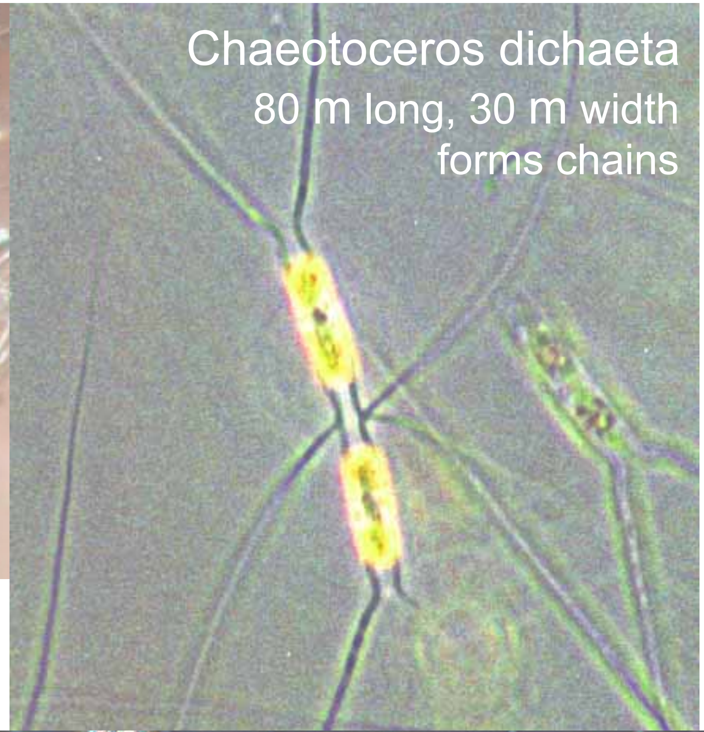


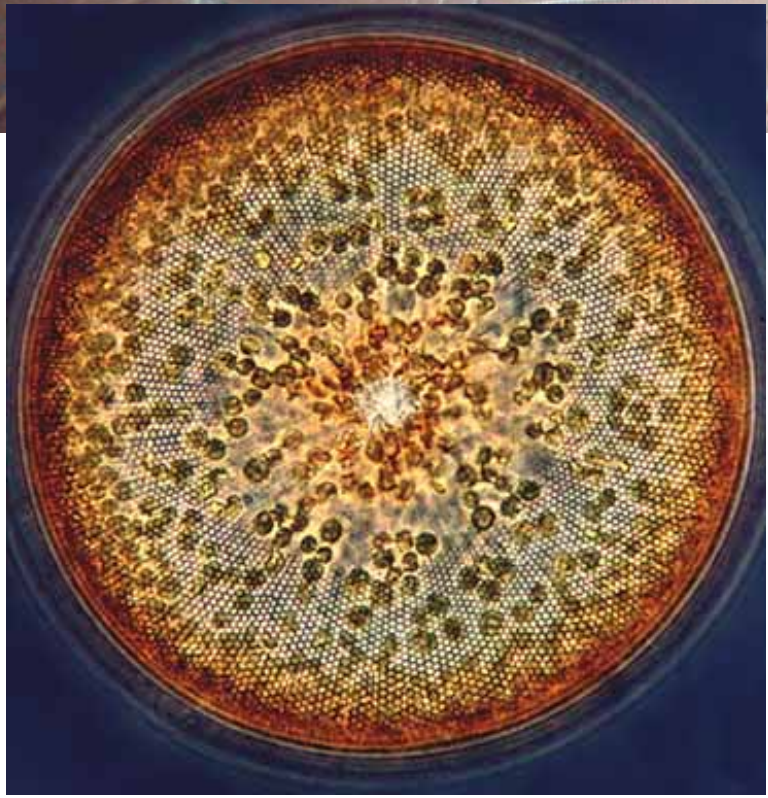
Net Biomass response depends on depth of Wind Mixed Layer i.e. availability of light

medium and large size DIATOMS



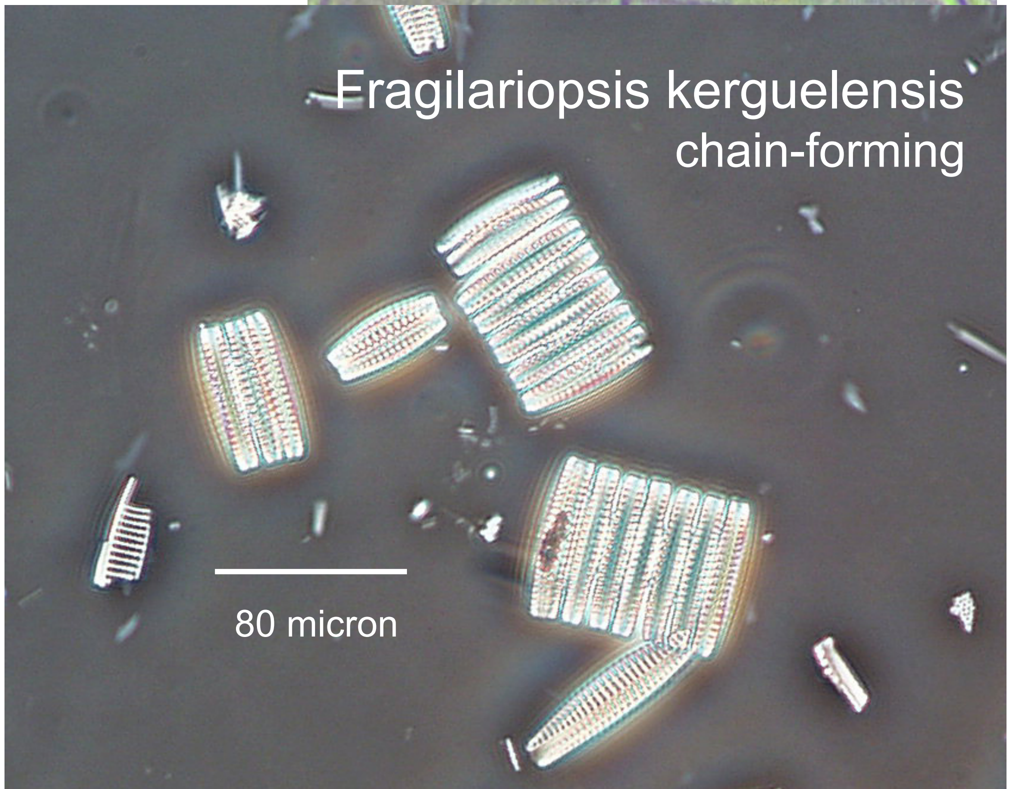
Pseudo-nitzschia



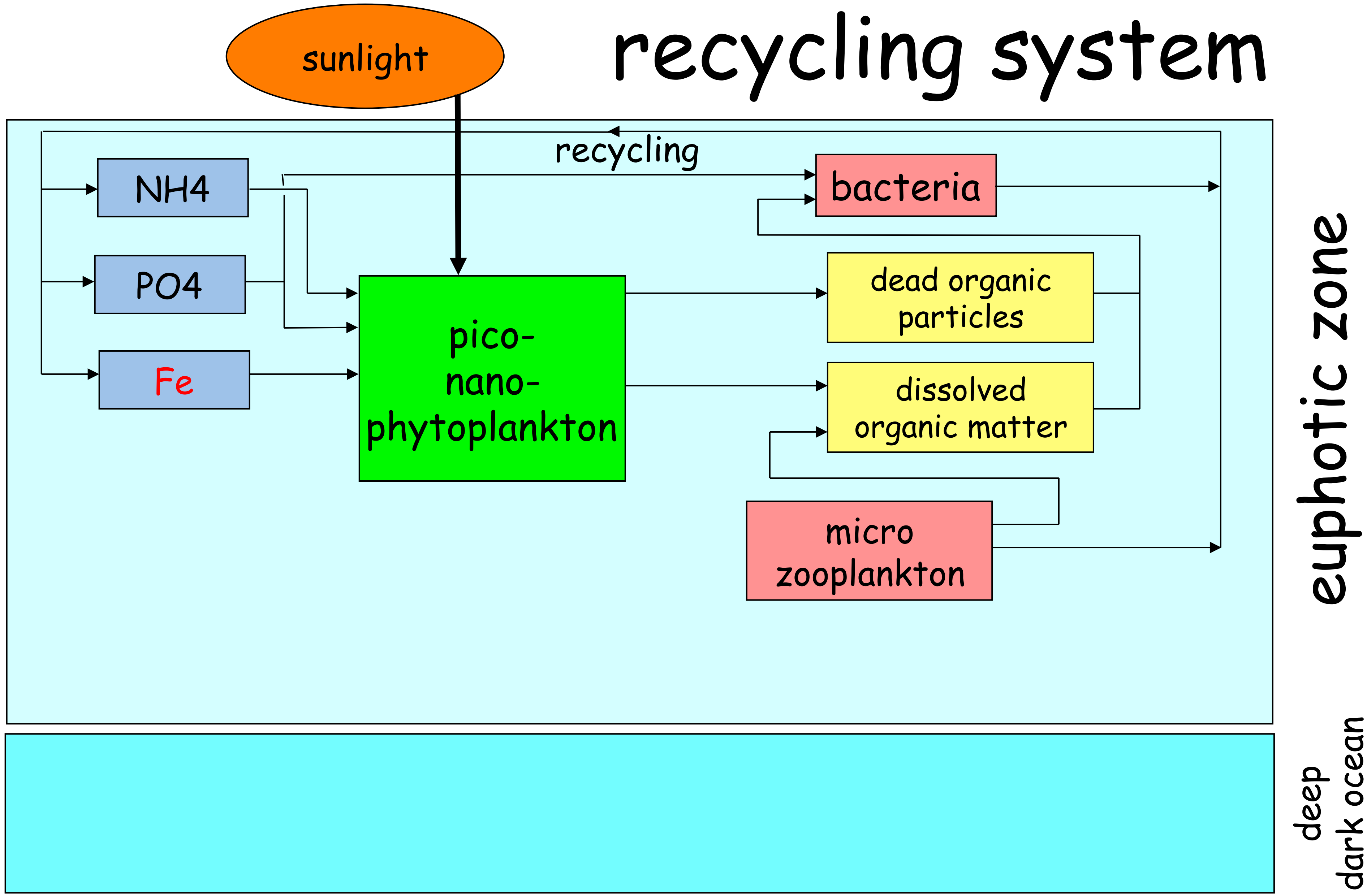


Actinocyclus

140 micron diameter

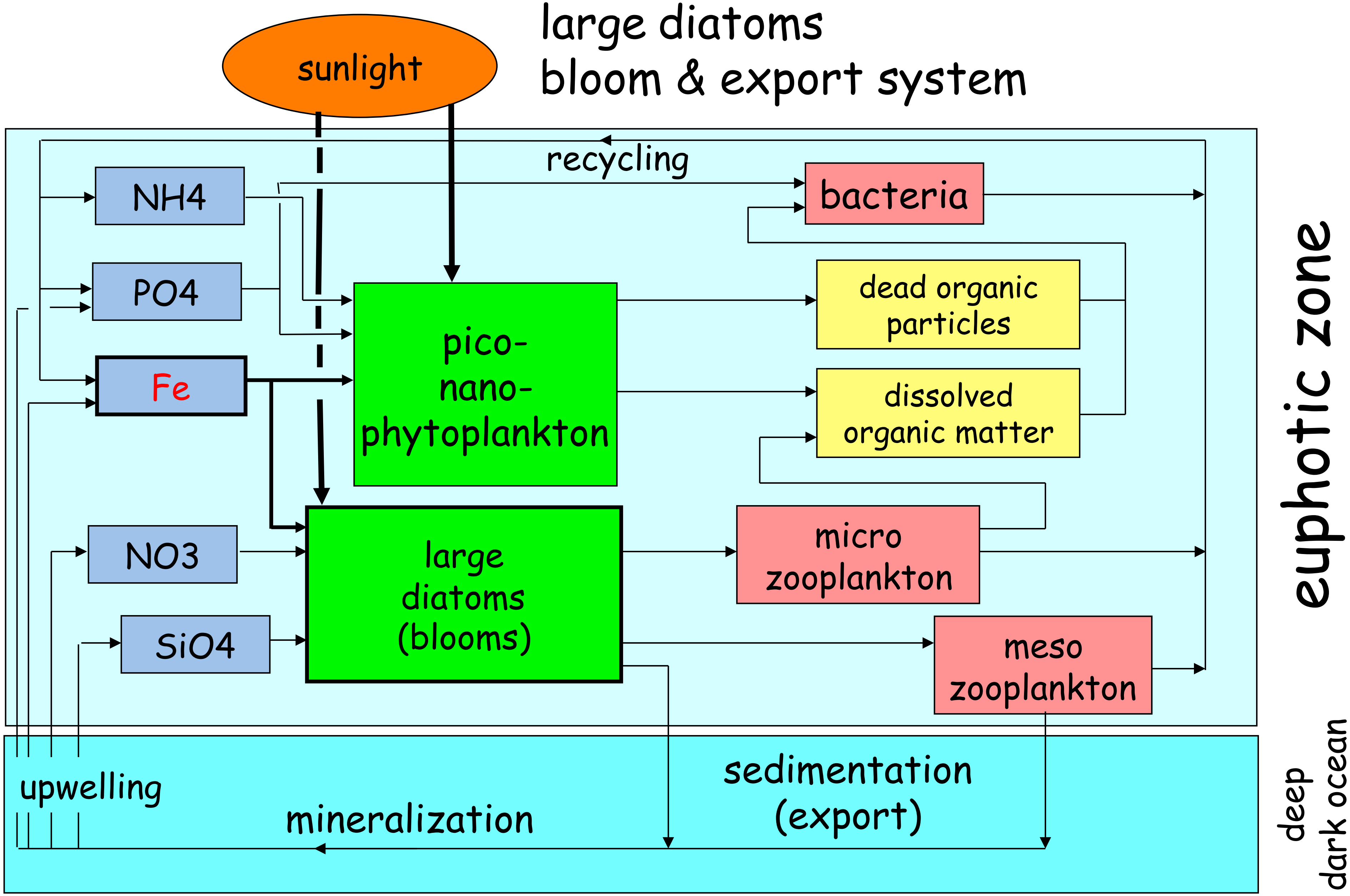


Fe depletion: recycling system

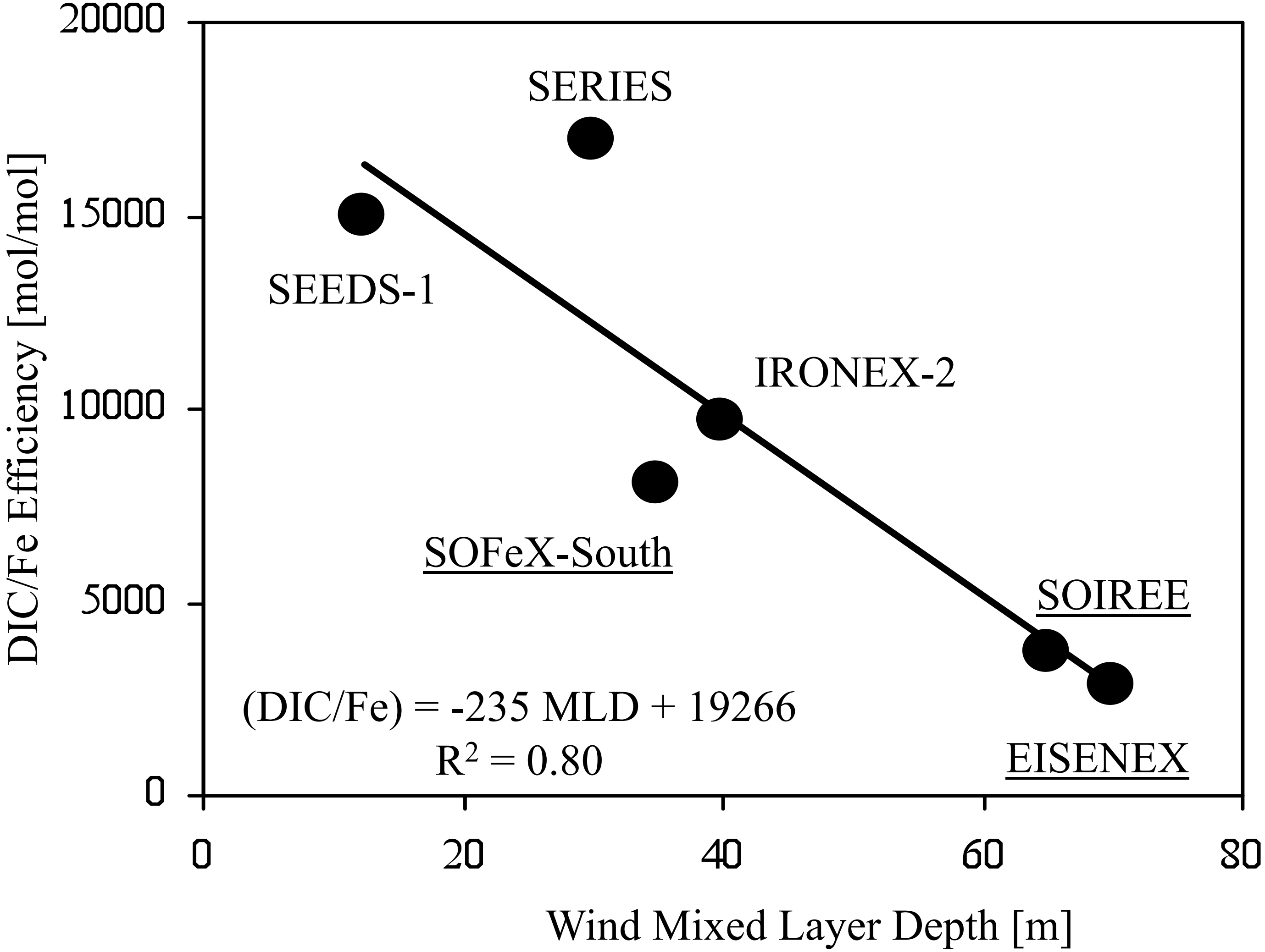


Fe supply: shift-up

large diatoms
bloom & export system

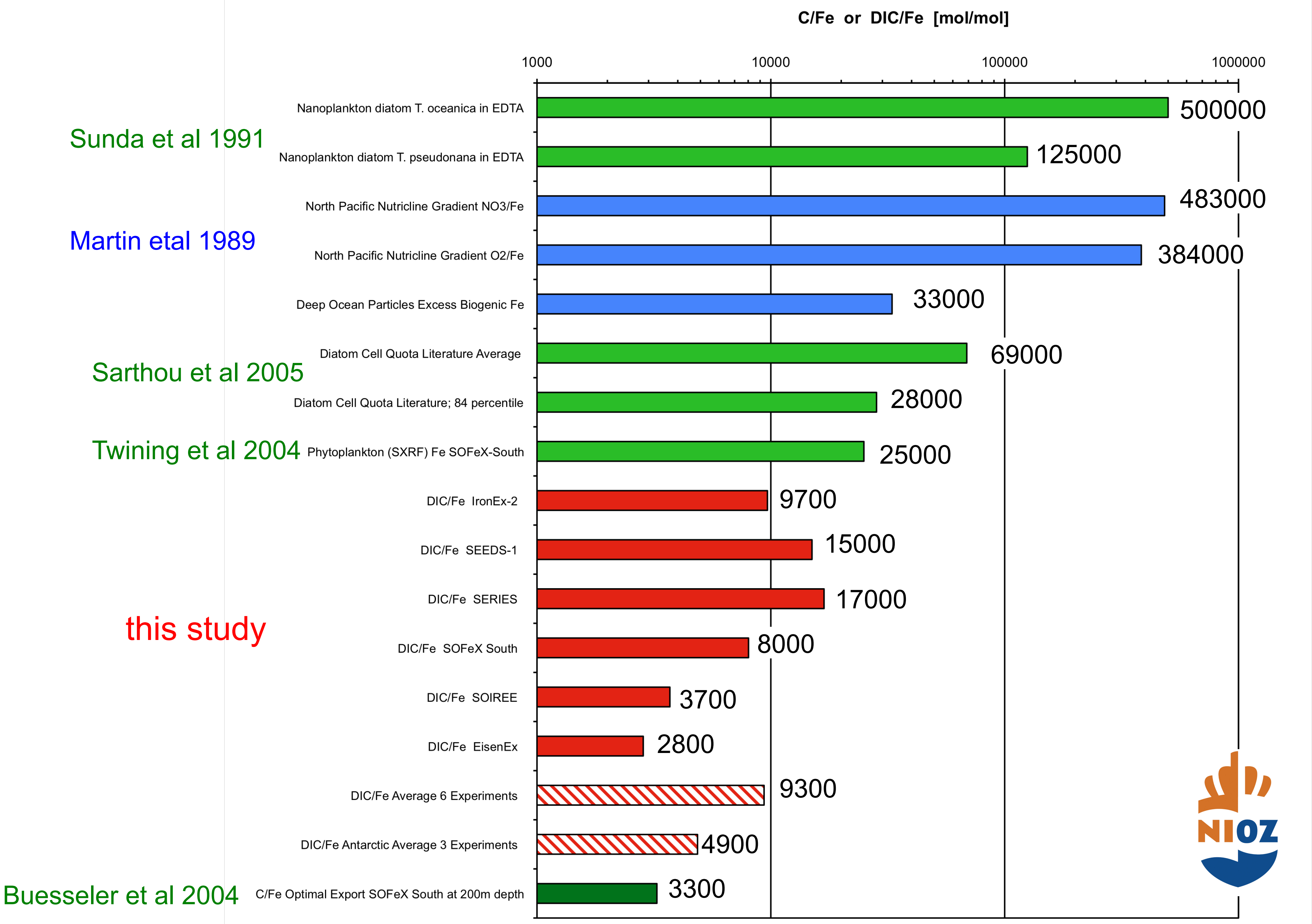


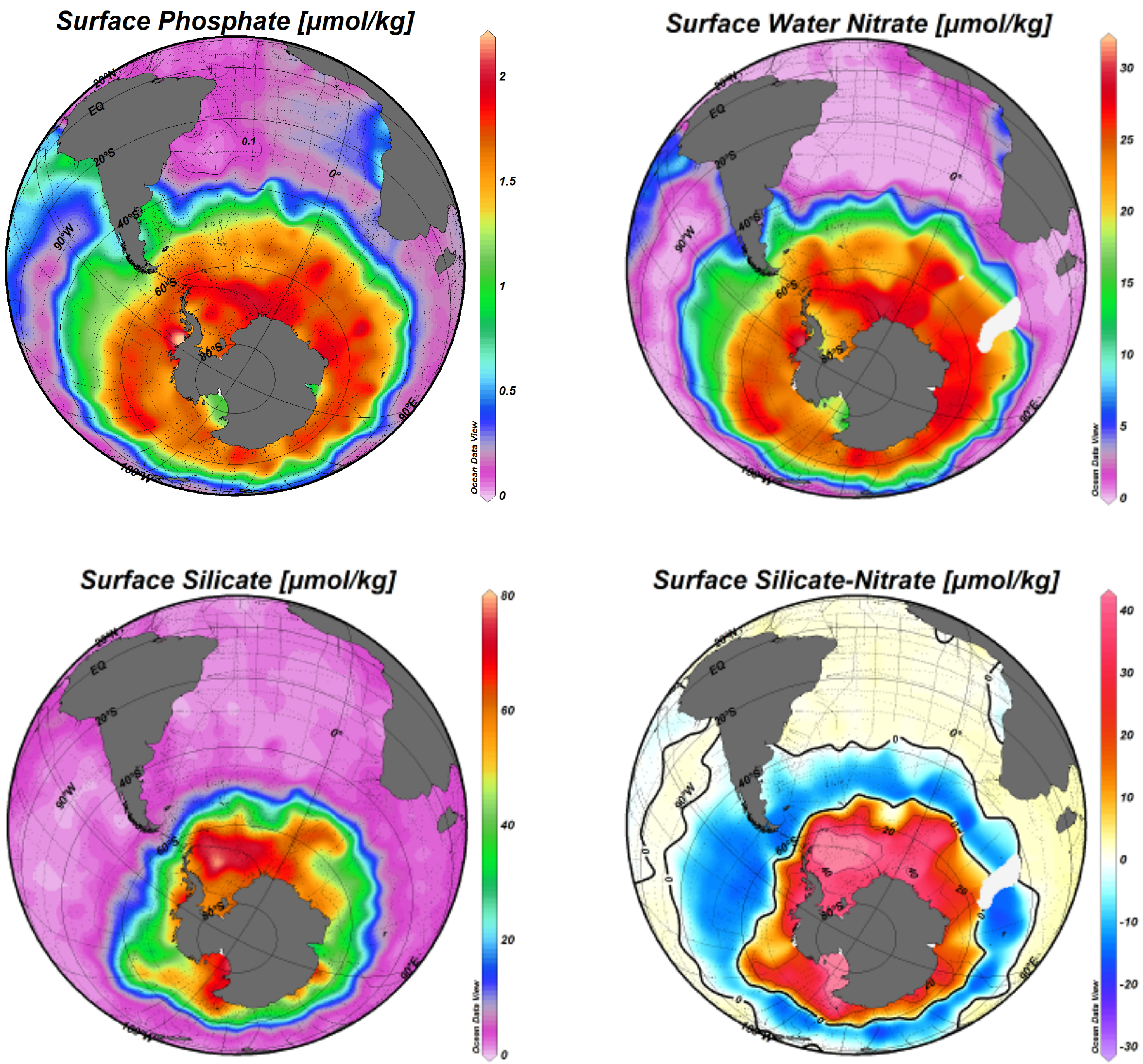
$$\text{DIC removal efficiency} = \frac{\text{DIC removal [mol]}}{\text{Fe addition [mol]}}$$



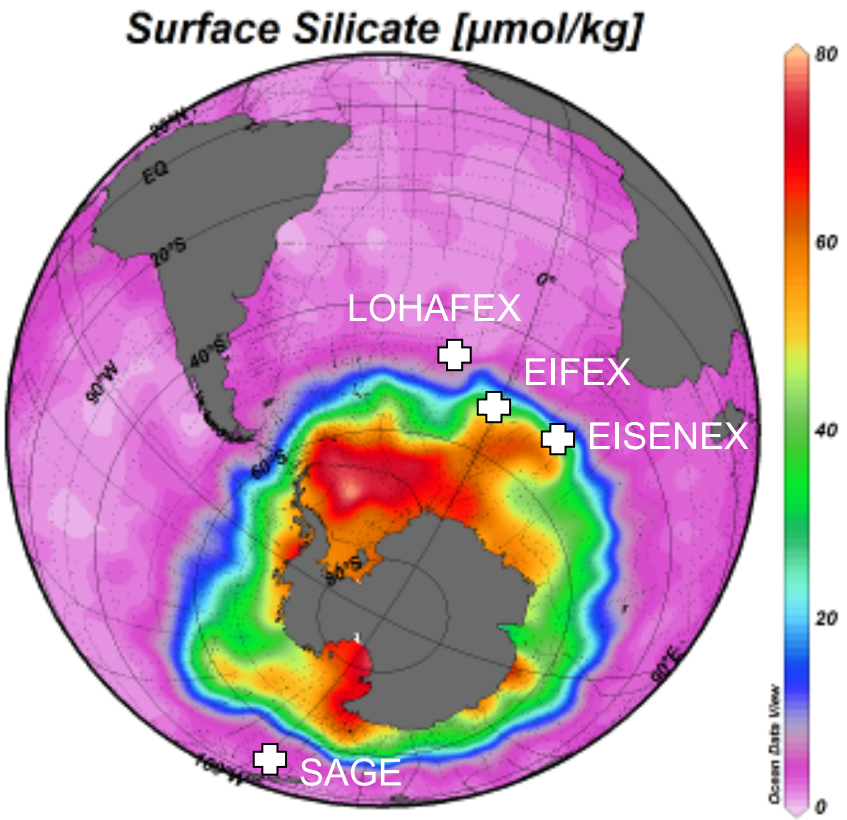
drawn after Table 3 of De Baar et al (2005)

C:Fe ratio values: from initial euphoria to reality



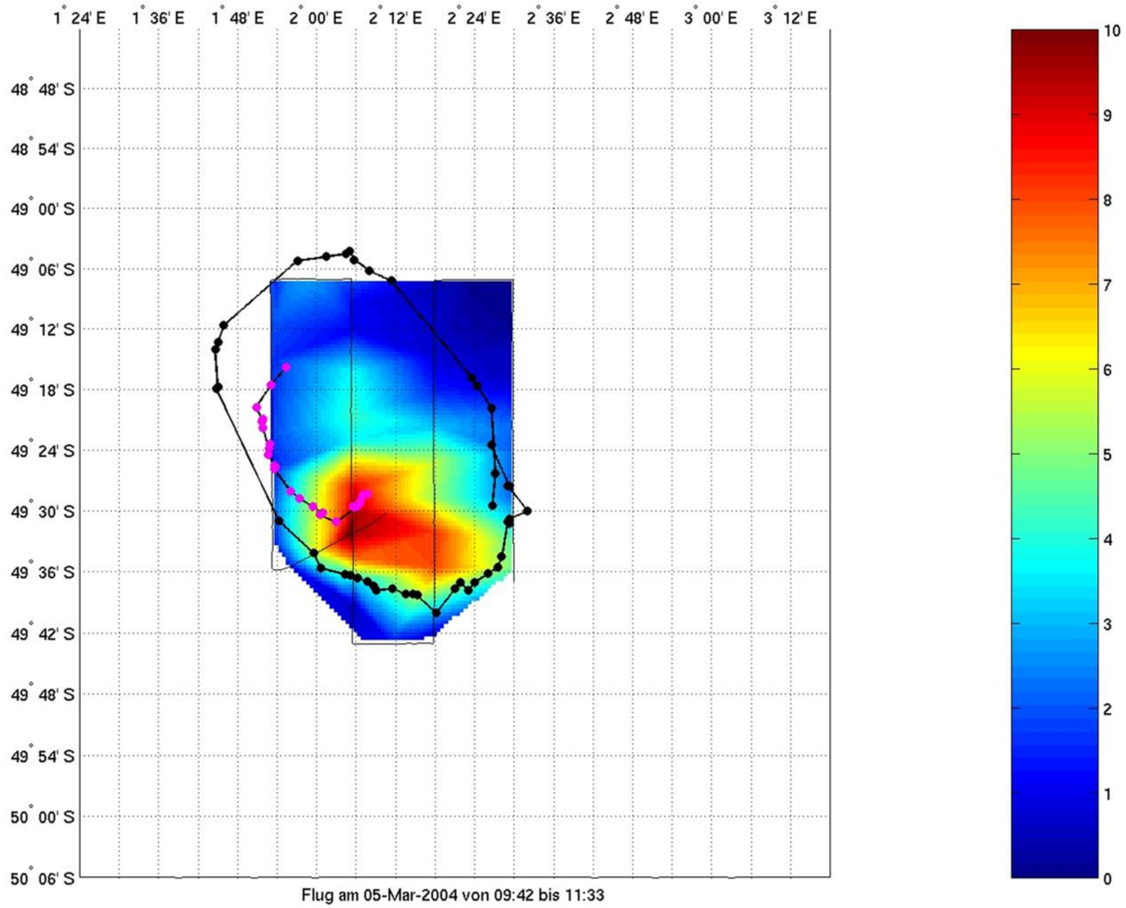

Surface Phosphate [µmol/kg]
Surface Water Nitrate [µmol/kg]
Surface Silicate [µmol/kg]
Surface Silicate-Nitrate [µmol/kg]
Ocean Data View
EQ
20°S
40°S
60°S
80°S
0°
90°W
90°E
180°W
0.1
0
0.5
1
1.5
2
5
10
15
20
25
30
40
60
80
-10
-20
-30

Iron enrichment experiments in Silicate depleted waters, will neither yield diatom blooms nor export of organic debris



	Initial Conditions			
Experiment	**PO4**	**NO3**	**SiO4**	
Eisenex	1.6	23.5	14.2	
Eifex	1.8	25	18.9	
Sage	0.7	9	0.9	Si-depleted
Lohafex	1.3	20	2	Si-depleted

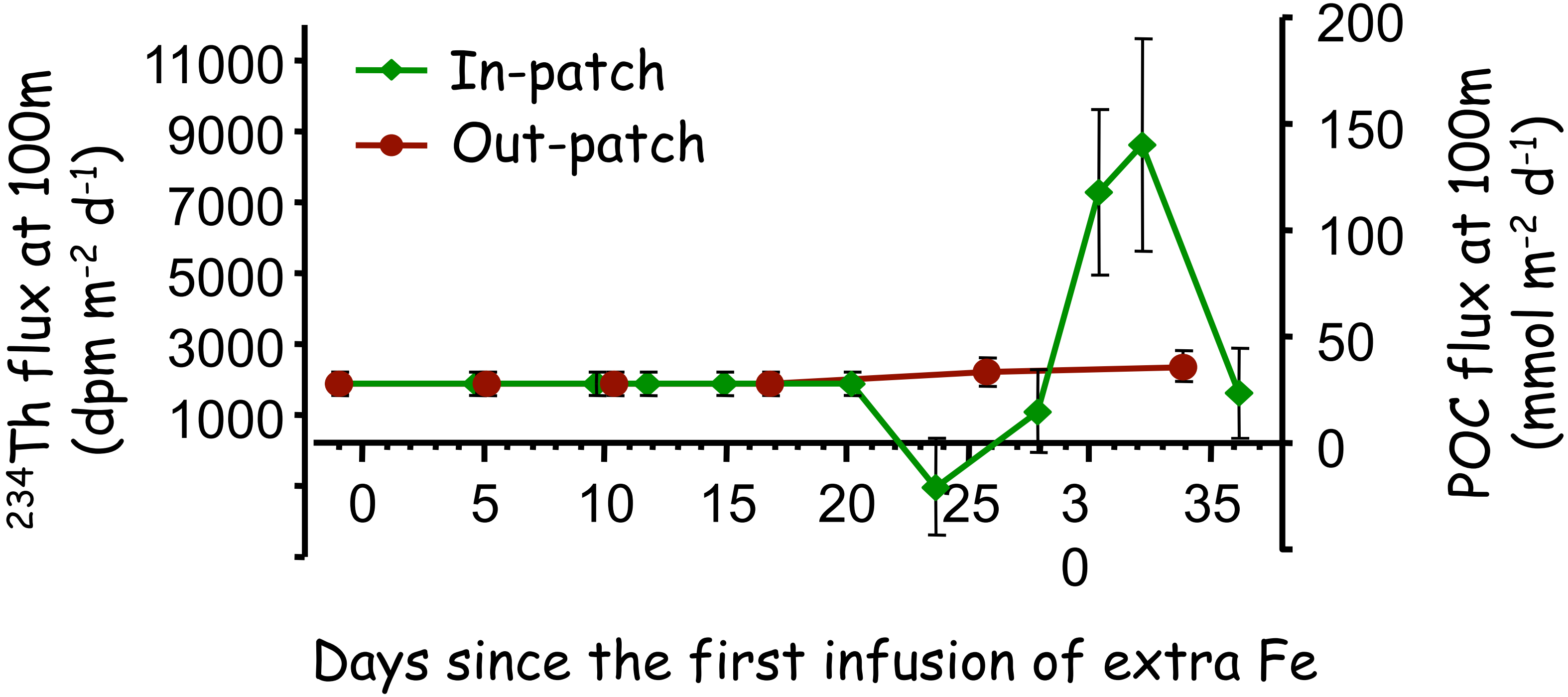
European Iron Fertilization EXperiment (EIFEX, Feb.-March 2004 at 59°S, 2°E)



An eddy located in a meander just south of the Polar Front was fertilized with Fe and monitored for 36 days afterwards. A phytoplankton bloom, dominated by diatoms, developed.

Chl-a LIDAR image obtained by helicopter 22 days after Fe infusion. Dots and line indicate the buoy track that closely followed the patch (Image V. Strass, AWI)

EIFEX in initial high Si waters:
big diatoms bloom and final massive export event

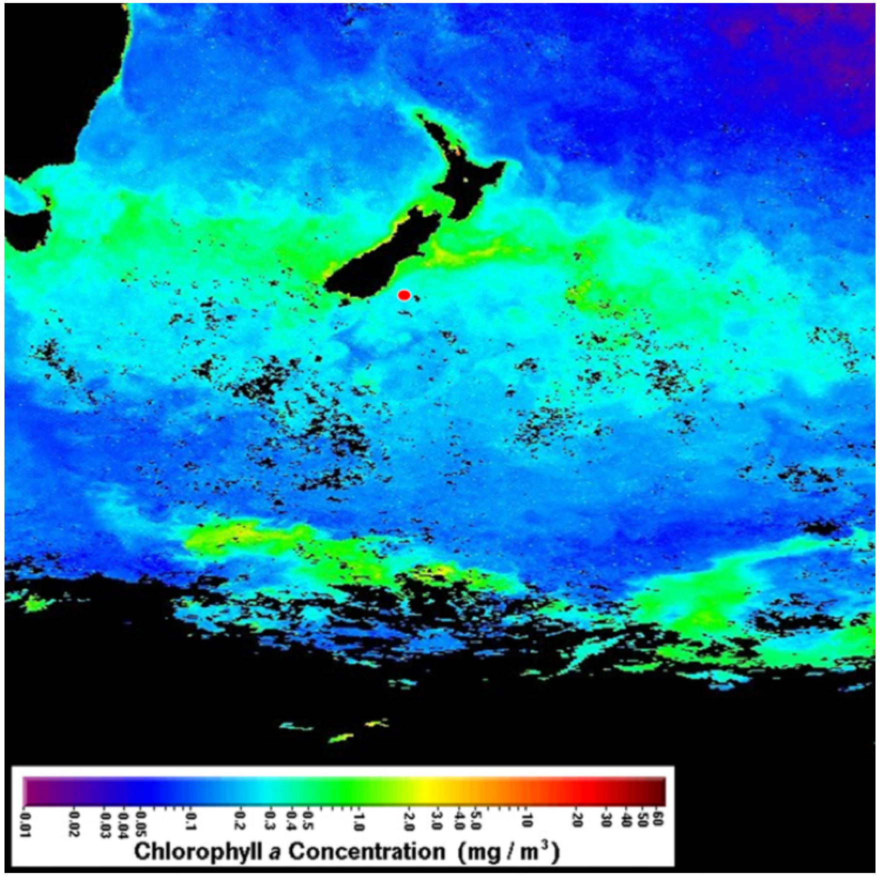


European Iron Fertilization EXperiment EIFEX:

Time series of ^{234}Th and particulate organic carbon (POC) export fluxes at 100m

Savoye et al. 2006

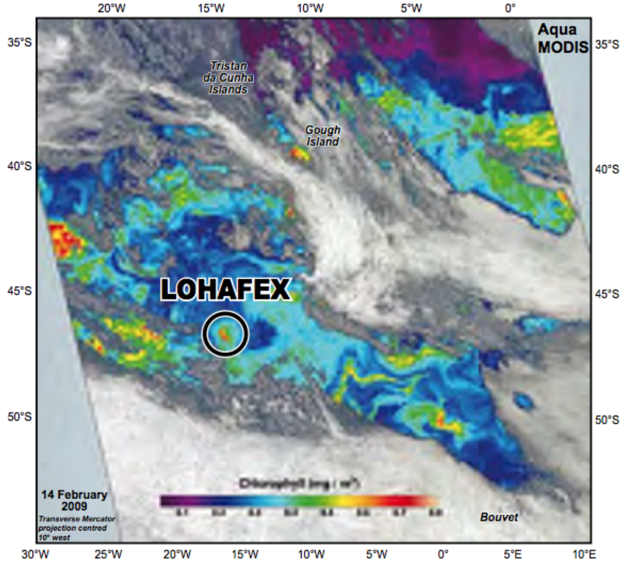
SOLAS air–sea gas exchange experiment (SAGE) 2004



- mostly ~twofold enhancement microbial loop
- no diatoms due to low initial Si surface waters
- no export into deeper waters

Harvey et al. (2011) DSR-2
Peloquin et al. (2011) DSR-2

LOHAFEX 2009



low Si thus no diatoms response;
modest bloom (Chl *a* maximum = 1.5 mg.m^{-3})
of very small picophytoplankton;
also some Phaeocystis, colonies after ~2 weeks,
next colonies disappear again,
likely due to intense grazing;
stimulation of many zooplankton,
doubling of faecal pellet production rate

Inside-Patch double abundance of:

"..*Themisto gaudichaudii*, an active, aggressive, indiscriminate carnivore which attacks organisms much larger than itself with its formidable clawed appendages.."

Mazzocchi et al (2009)
GLOBEC Newsletter

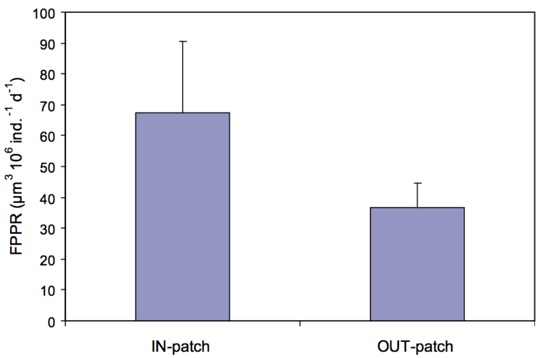
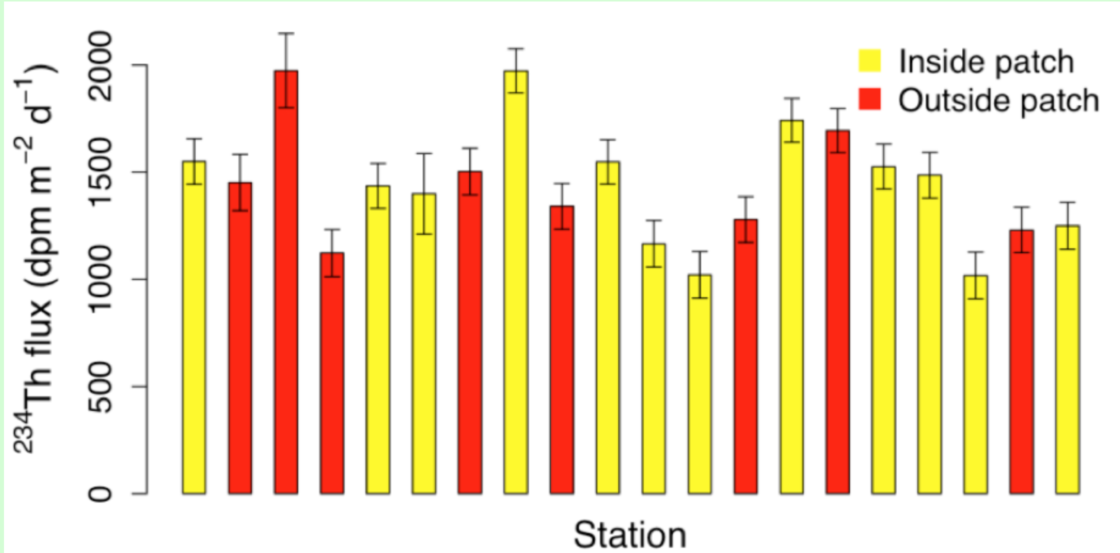


Figure 6. Faecal pellet production rate (as volume, µm^3 x 10^6 ind.$^{-1}$ d^{-1}) in Calanus simillimus *averaged at the stations inside the fertilised patch (days 4–36 after fertilisation) and outside the patch (days 16–35).*



Export by ^{234}Th deficiency method:
no significant difference Inside-patch and Outside-patch
Confirms that for Carbon sequestration you need
high-Silicate waters supporting blooms of large diatoms

Rutgers van der Loeff, unpublished results

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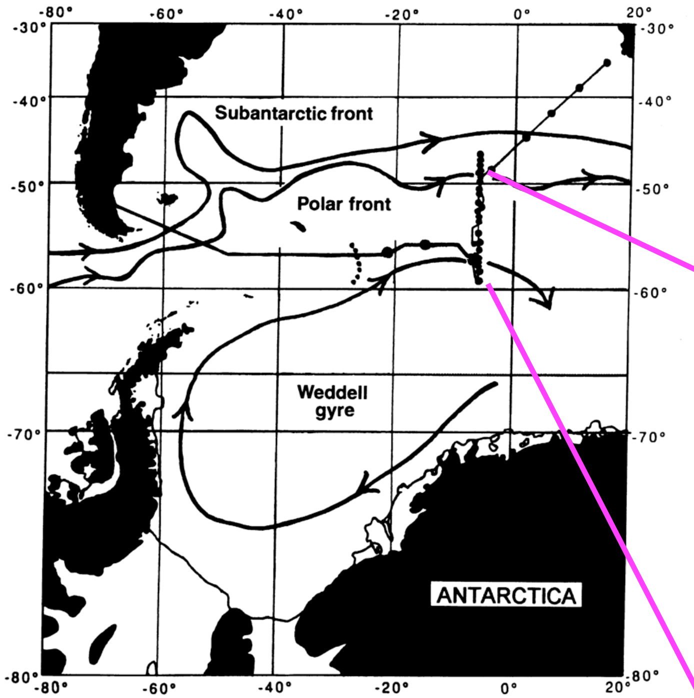
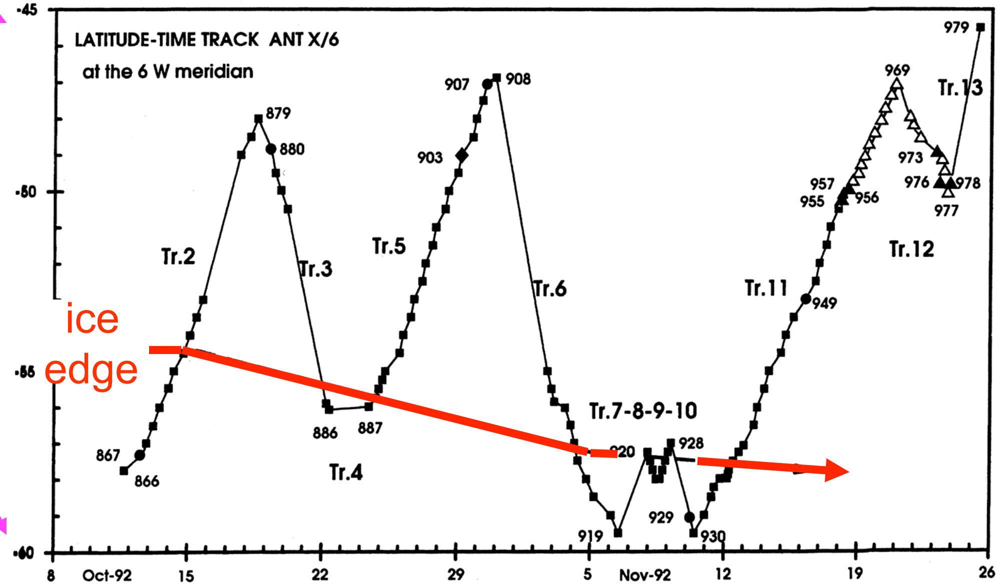
NIOZ

The natural iron fertilization studies:
2) Polar Front (1992) austral spring development

1995

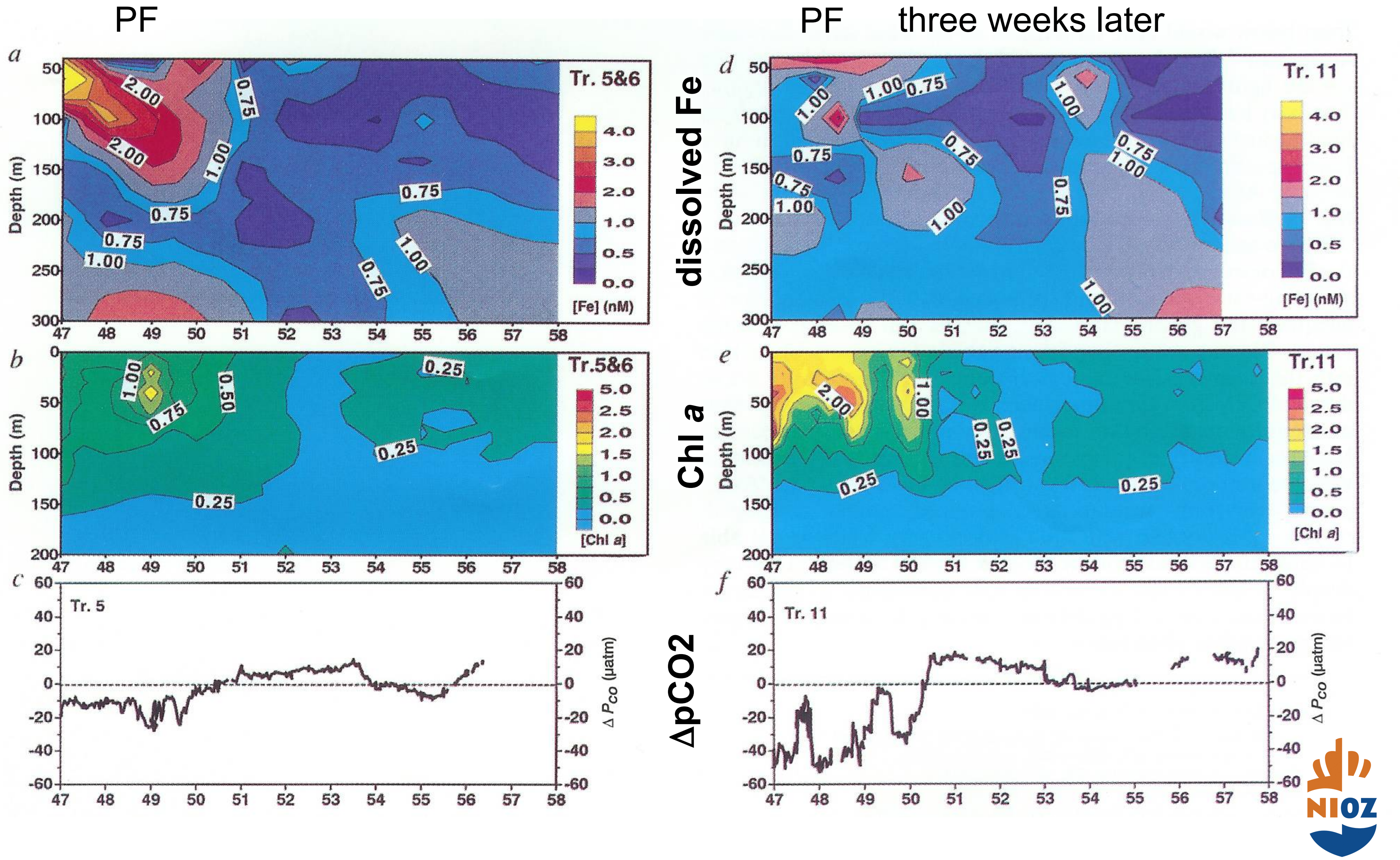




1000 kilometres

two months austral spring evolution

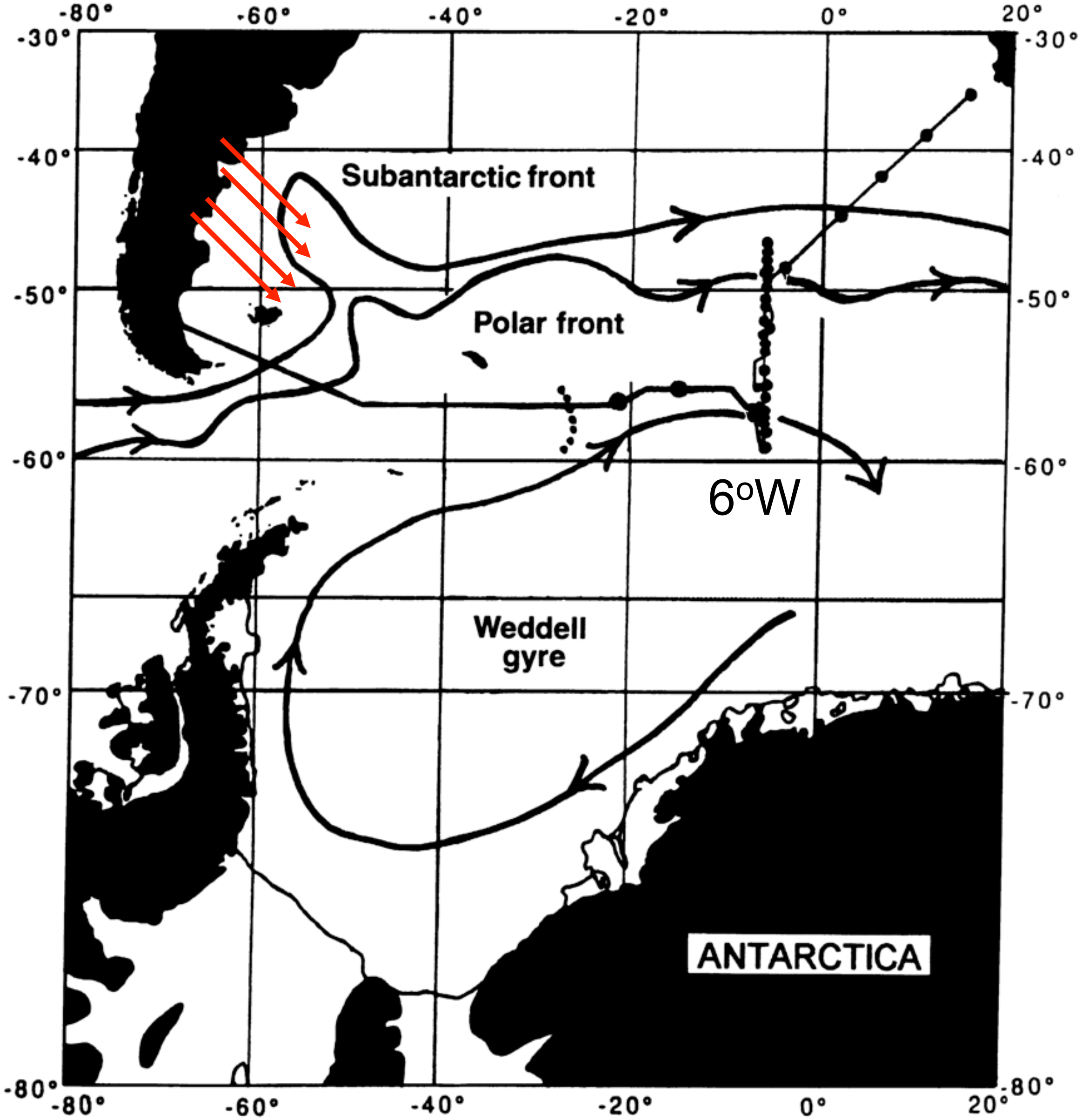
natural iron fertilization at the Polar Front
large diatoms blooms grow and use iron and CO_2



Perhaps the extra Fe at the Polar Front at 6 °W comes from strong dust storms input off Patagonia, (Argentina)

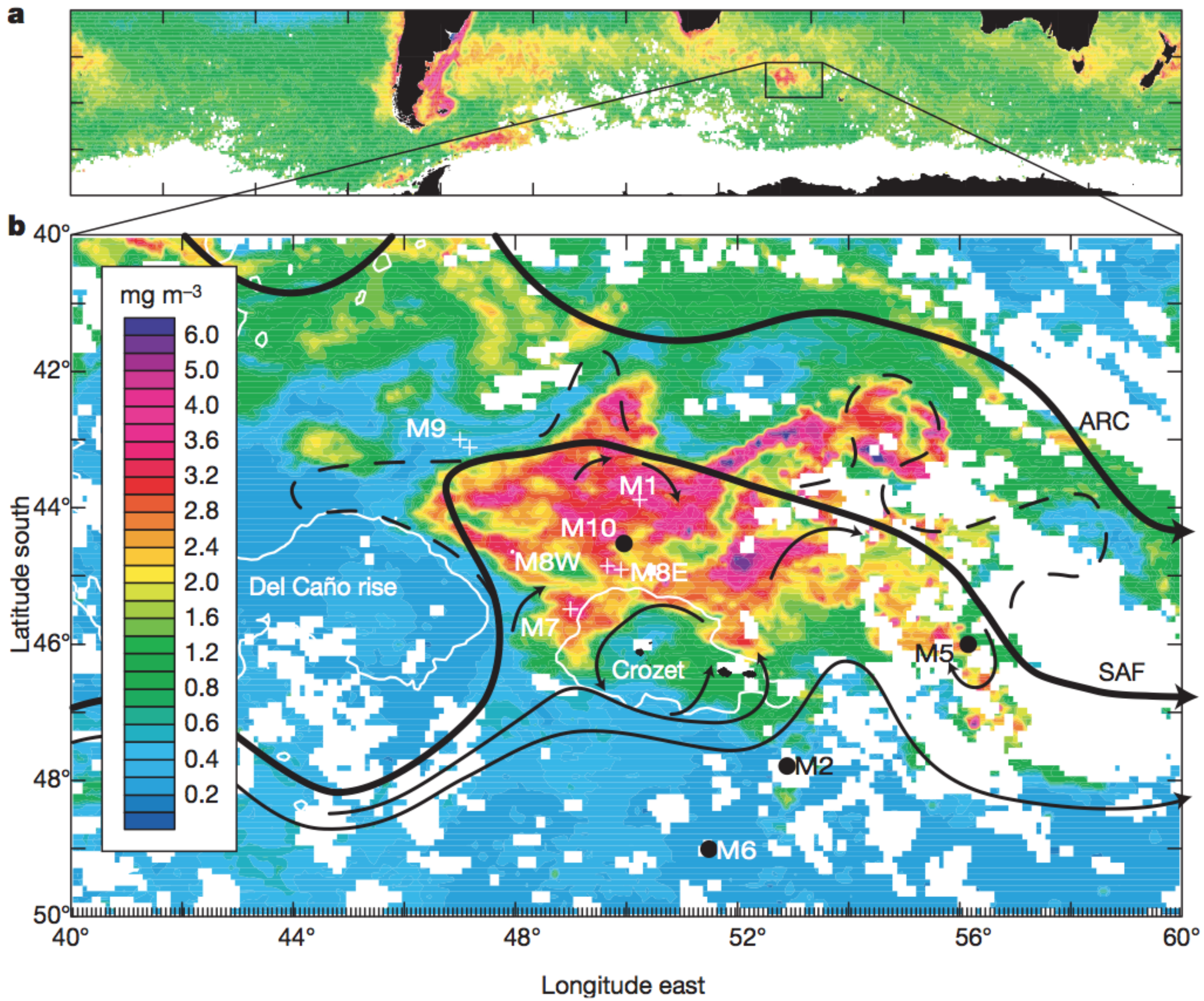
soil and dust comprises about 4% iron by weight

if only small part of this dust dissolves in seawater you will find higher concentrations of dissolved Fe



The natural iron fertilization studies:
3) Crozex at Crozet Island Plateau (2004-2005)

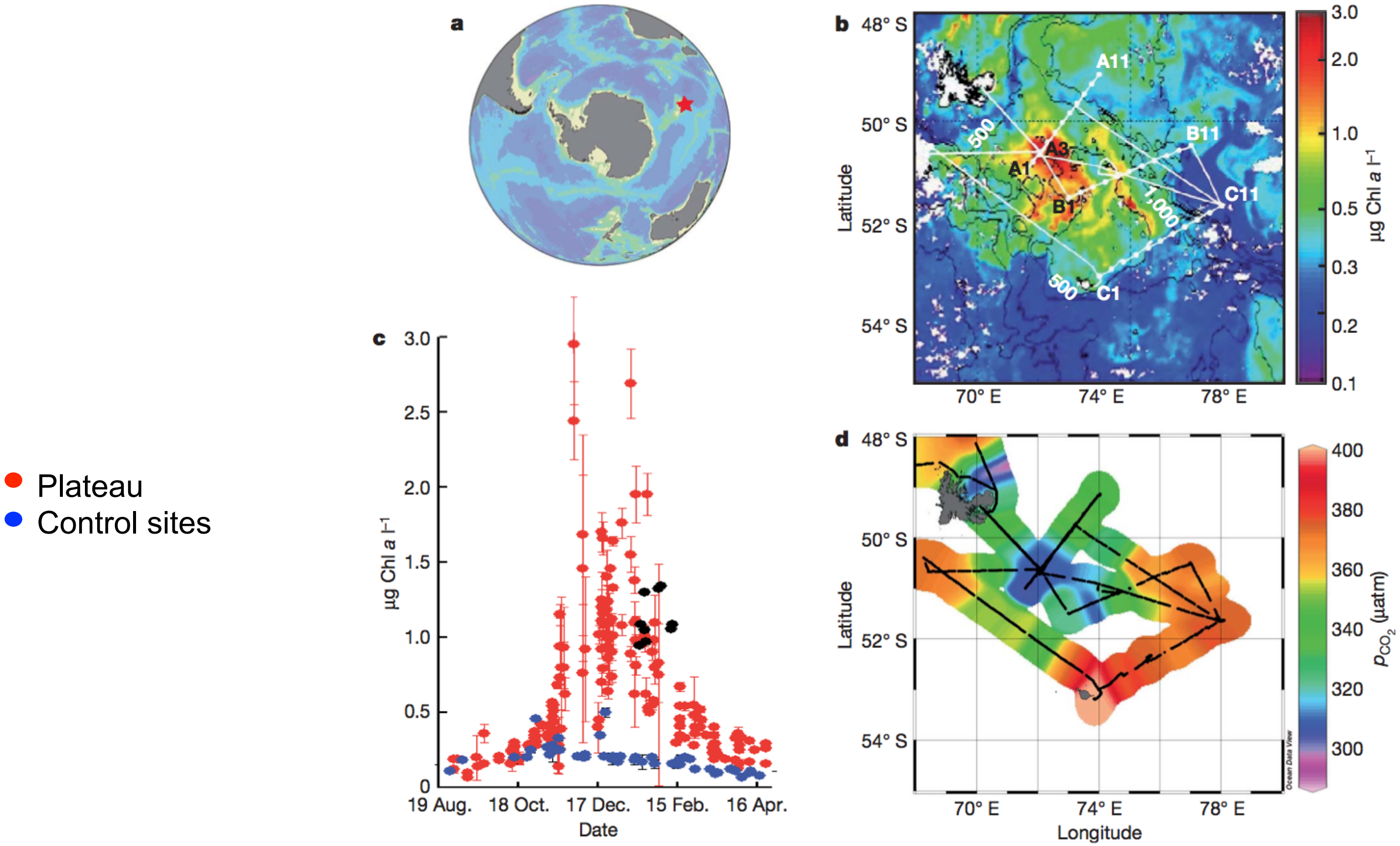
Chlorophyll *a* observed from satellite



C:Fe export efficiency will be discussed

Pollard et al. (2009)

The natural iron fertilization studies:
4) Keops at Kerguelen Plateau (2005)



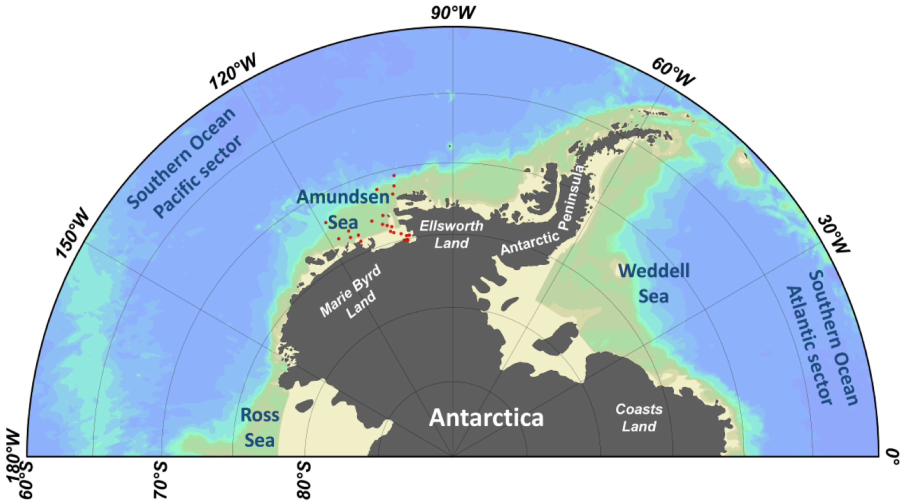
" The addition of DFe occurs slowly and continuously during natural fertilization, whereas purposeful additions of large amounts of iron within a short period lead to the loss of most (80–95%) of the added DFe during mesoscale enrichment experiments. "
Blain et al. (2007)

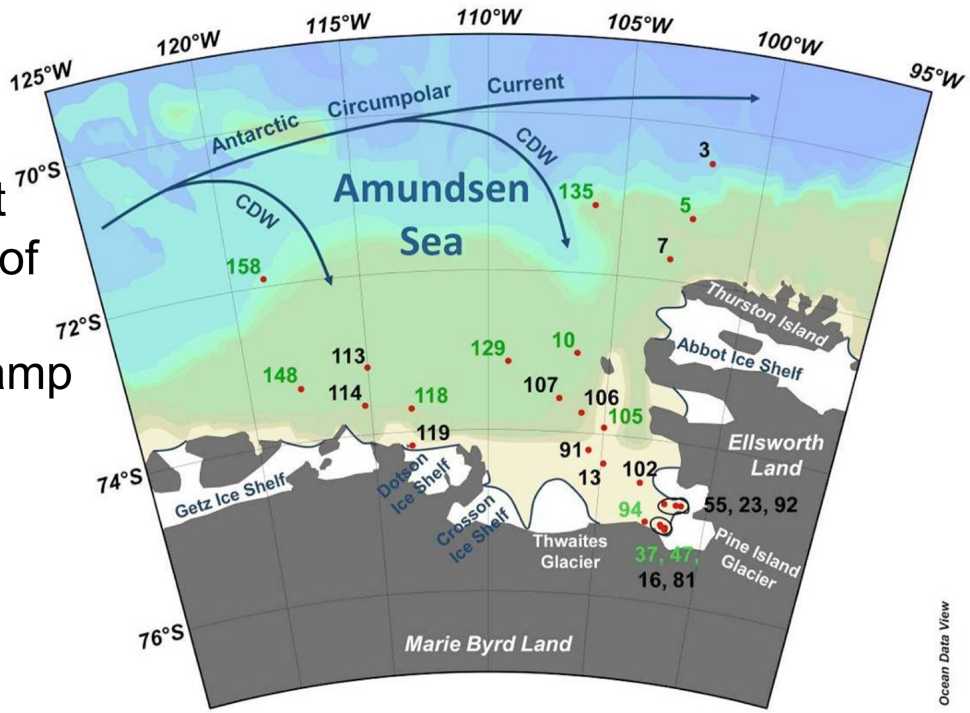
C:Fe export efficiency will be discussed

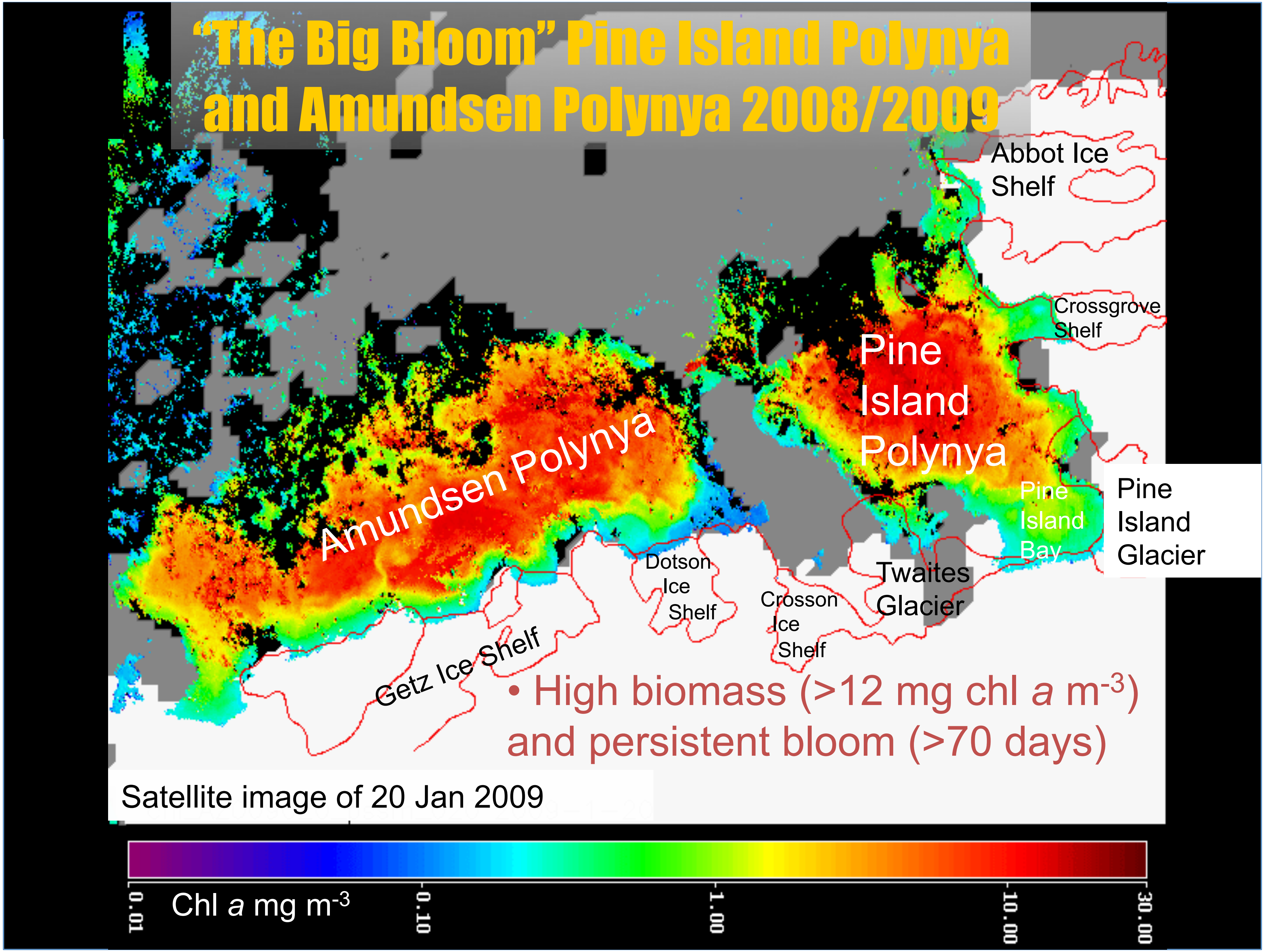
The natural iron fertilization studies:
5) DynaLife at Pine Island Glacier and Polynia

February 2009 cruise aboard Nathaniel Palmer

Collaborative project with Stanford group of Kevin Arrigo, Anne-Carlijn Alderkamp





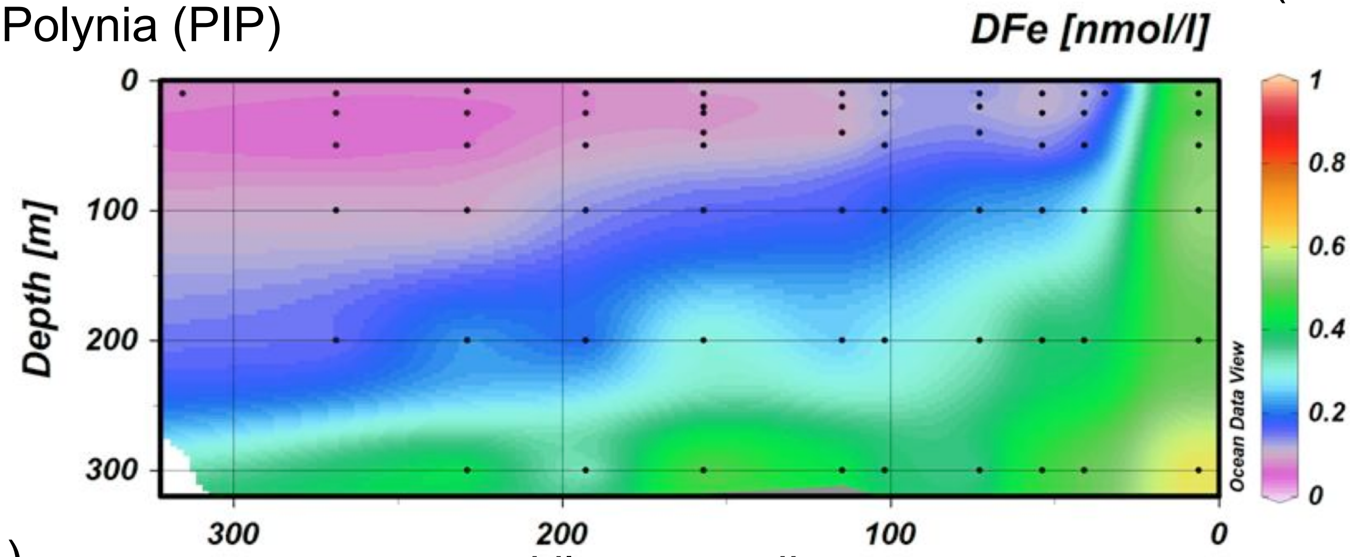


"The Big Bloom" Pine Island Polynya
and Amundsen Polynya 2008/2009
Abbot Ice Shelf
Crossgrove Shelf
Pine Island Polynya
Amundsen Polynya
Pine Island Bay
Pine Island Glacier
Twaites Glacier
Dotson Ice Shelf
Crosson Ice Shelf
Getz Ice Shelf
• High biomass (>12 mg chl a m-3)
and persistent bloom (>70 days)
Satellite image of 20 Jan 2009
Chl a mg m-3
0.01
0.10
1.00
10.00
30.00

Strong supply by the glacier of dissolved Fe and particulate 'Total Dissolvable' Fe

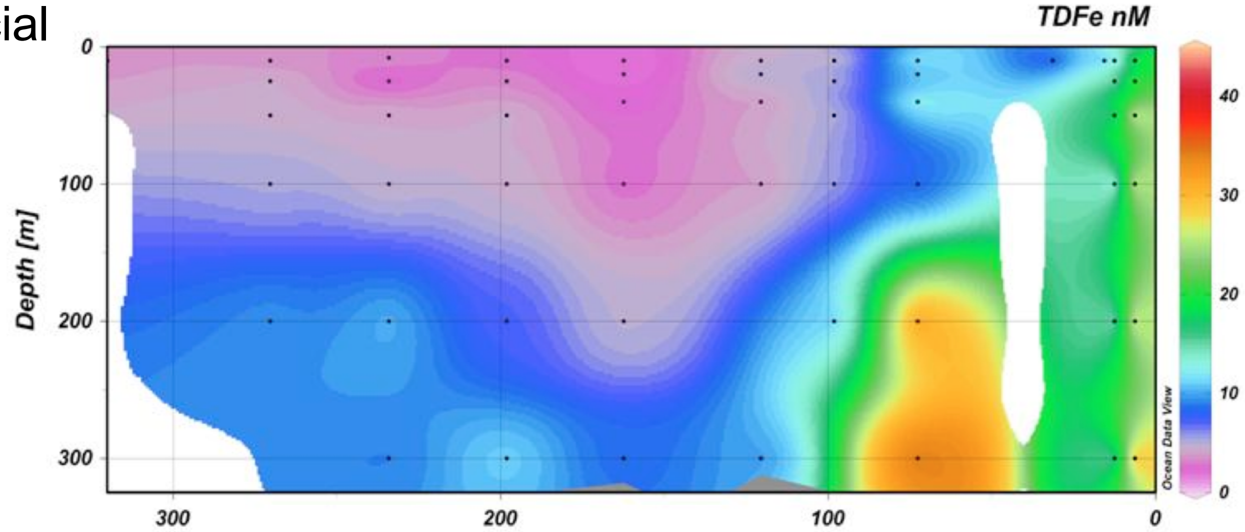
Pine Island Polynia (PIP)

Pine Island Glacier (PIG)

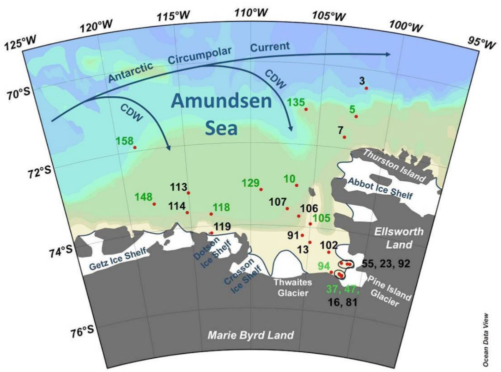


kilometers distance

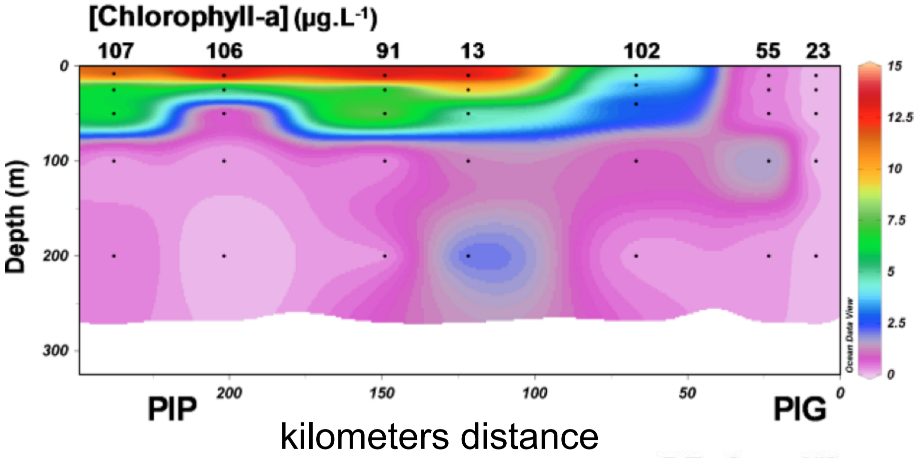
Gerringa et al. (2011), submitted, DSR II special



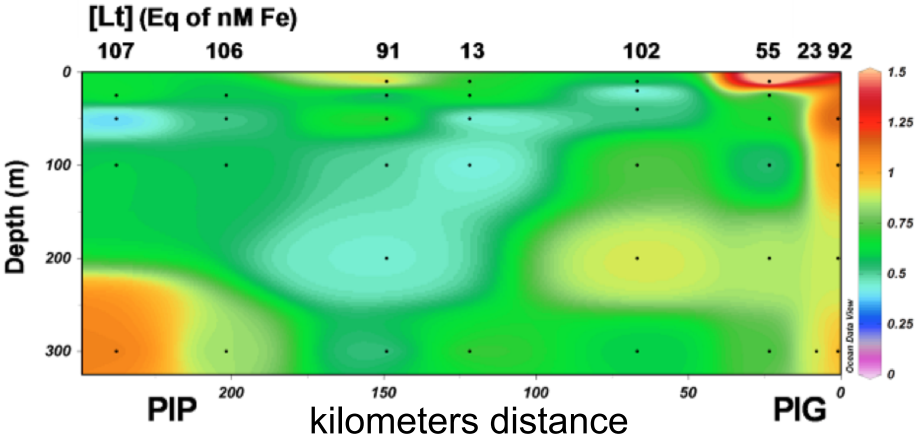
kilometers distance

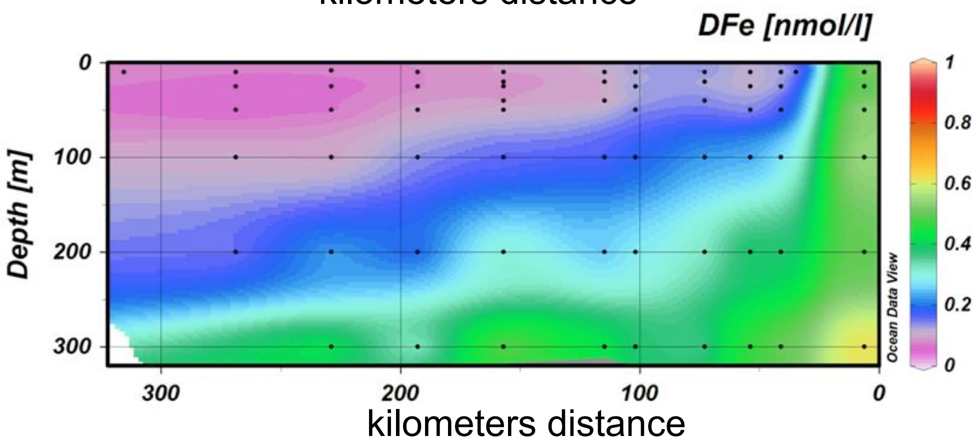


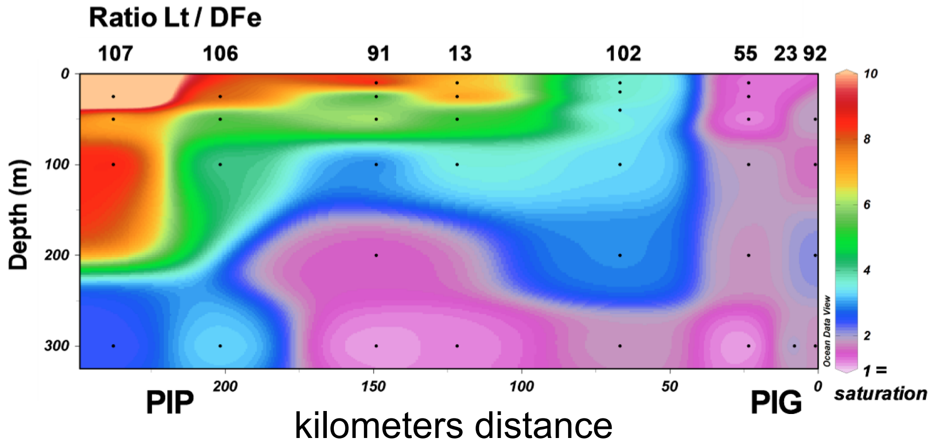
Intense diatom bloom in the Pine Island Polynia

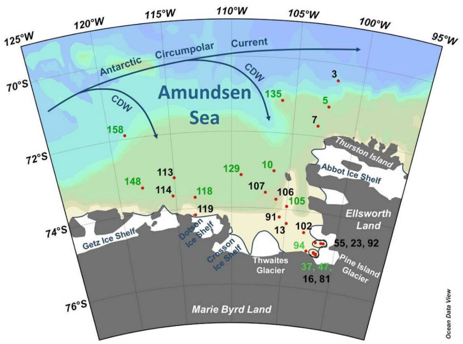


Organic ligand [Lt] that is binding the dissolved Fe has high abundance near Pine Island Glacier









Thuroczy et al. (2011), submitted, DSR II special

Excess organic ligand plotted as ratio Lt /DFe
near glacier hardly any excess Lt

akin to *in situ* Fe fertilization exps

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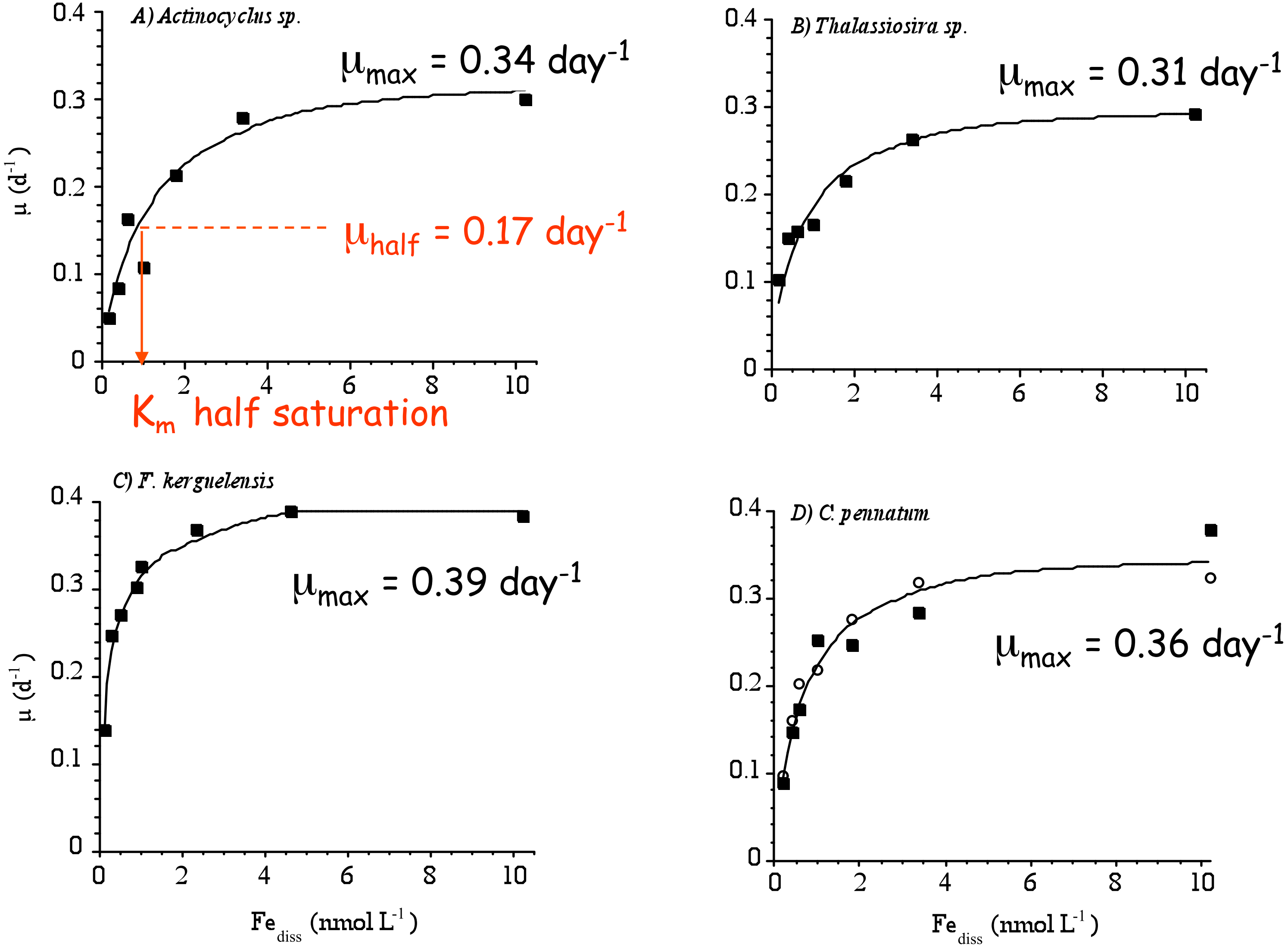
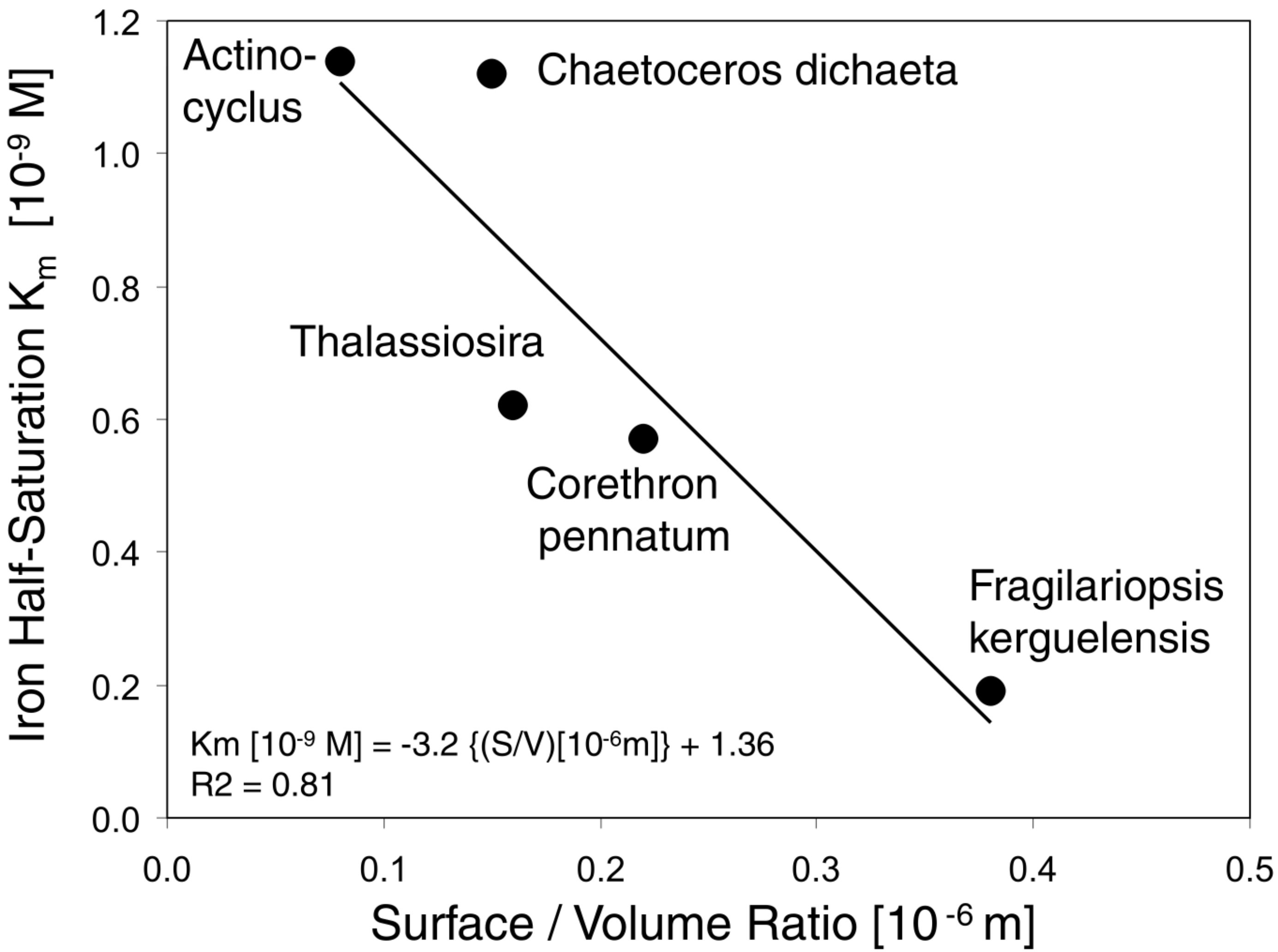
Iron Requirement for Growth of Large Diatoms:

growth curves for dissolved Fe [nM] in pristine (EDTA-free) Antarctic seawater

Monod: $\mu = \mu_{max} \{[Fe]/(K_m + [Fe])\}$



Timmermans et al. (2004), Limnol. & Ocean., 49, 2141



← bigger diatoms need higher ambient dissolved Fe

De Baar et al. (2005)

Available online at www.sciencedirect.com

Iron Content of Growing Diatoms

DEEP-SEA RESEARCH
PART I

Deep-Sea Research I 51 (2004) 1827–1850

www.elsevier.com/locate/dsr

Cellular iron contents of plankton during the Southern Ocean Iron Experiment (SOFeX)

Benjamin S. Twining[a,*,1], Stephen B. Baines[a], Nicholas S. Fisher[a,c], Michael R. Landry[b]

- intracellular Fe concentration **$Q = 0.234$ mol m^{-3}** of diatoms in the Fe-replete SOFeX-South patch
- corresponding element ratio C : Fe = 25000 : 1 of diatoms in the Fe-replete SOFeX-South patch

- this is the first ever reliable Fe cell quota

Cell Demand [mol Fe s^{-1}] = Diffusive Supply [mol Fe s^{-1}]

at steady state one expects the product of the specific growth rate μ with intracellular Fe concentration Q and cell volume V to be equal to the diffusive supply of dissolved Fe to the cell:

growth demand = diffusive supply

$$\mu \, Q \, V = 4 \, \pi \, r \, D \, \alpha \; [Fe]$$

where

μ [sec^{-1}] is specific growth rate,

Q [moles m^{-3}] the intracellular Fe concentration,

V [m^3] is the volume of an individual cell,

r [m] the cell radius of a round (spherical) cell,

D [m^2 s^{-1}] molecular diffusion coefficient of Fe in seawater,

α dimensionless geometric correction factor for diatoms having non-spherical shape

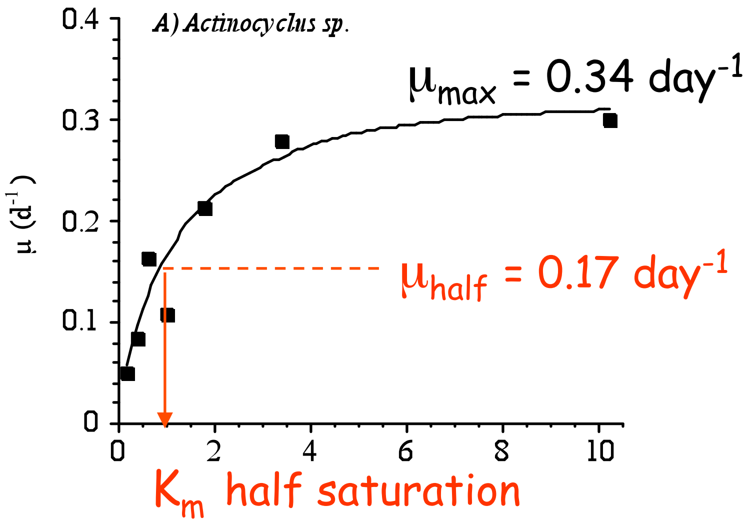
Fe [mol m^{-3}] the bulk concentration of dissolved Fe in seawater

De Baar et al., in press

Now substituting for dissolved [Fe] the Km [mol m^{-3}] at half of the maximum growth rate i.e. at

$\{0.5\ \mu_{max}\}$ of the Monod equation

$$\mu = \mu_{max} \{[Fe]/(Km + [Fe])\}$$



At half maximum growth rate:

cellular demand [mol Fe s^{-1}] = diffusive supply rate [mol Fe s^{-1}]

$$0.5\ \mu_{max}\ Q\ V = 4\ \pi\ r\ D\ \alpha\ \ [Km]$$

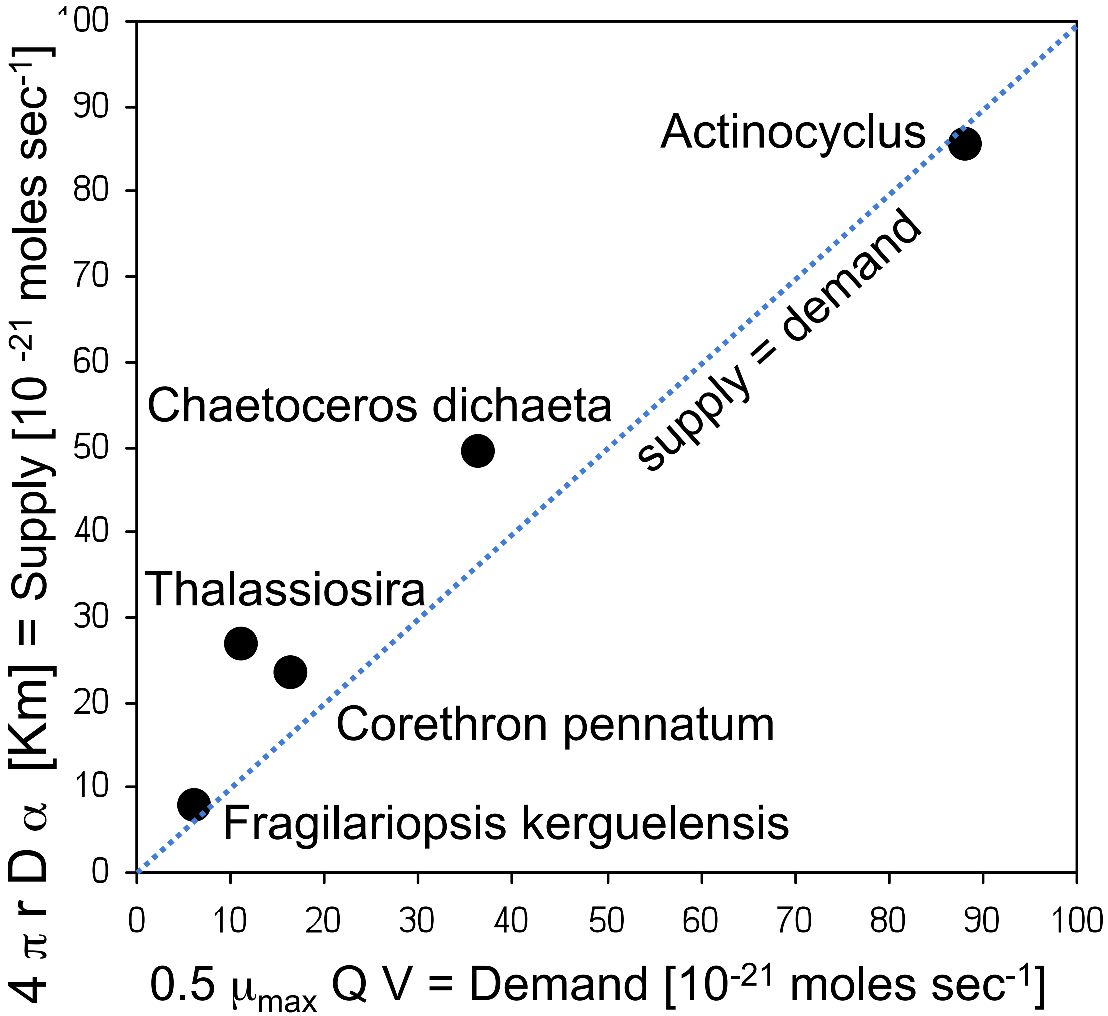
Klaas Timmermans
L&O, 2004

Q = 0.234 mol m^{-3}
Benjamin Twining,
DSR, 2004

Klaas Timmermans
L&O, 2004

De Baar et al., in press

Diffusion Supply = Demand for Growth



growth rate of large oceanic diatoms is controlled by the Fe concentration in ambient seawater

De Baar et al., in press

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  - (2011) GeoEngineering, London Convention, ISIS Consortium

2008 Theme Section with 12 articles on ocean iron fertilization

Vol. 364: 269–282, 2008
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MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published July 29

Contribution to the Theme Section 'Implications of large-scale iron fertilization of the oceans'

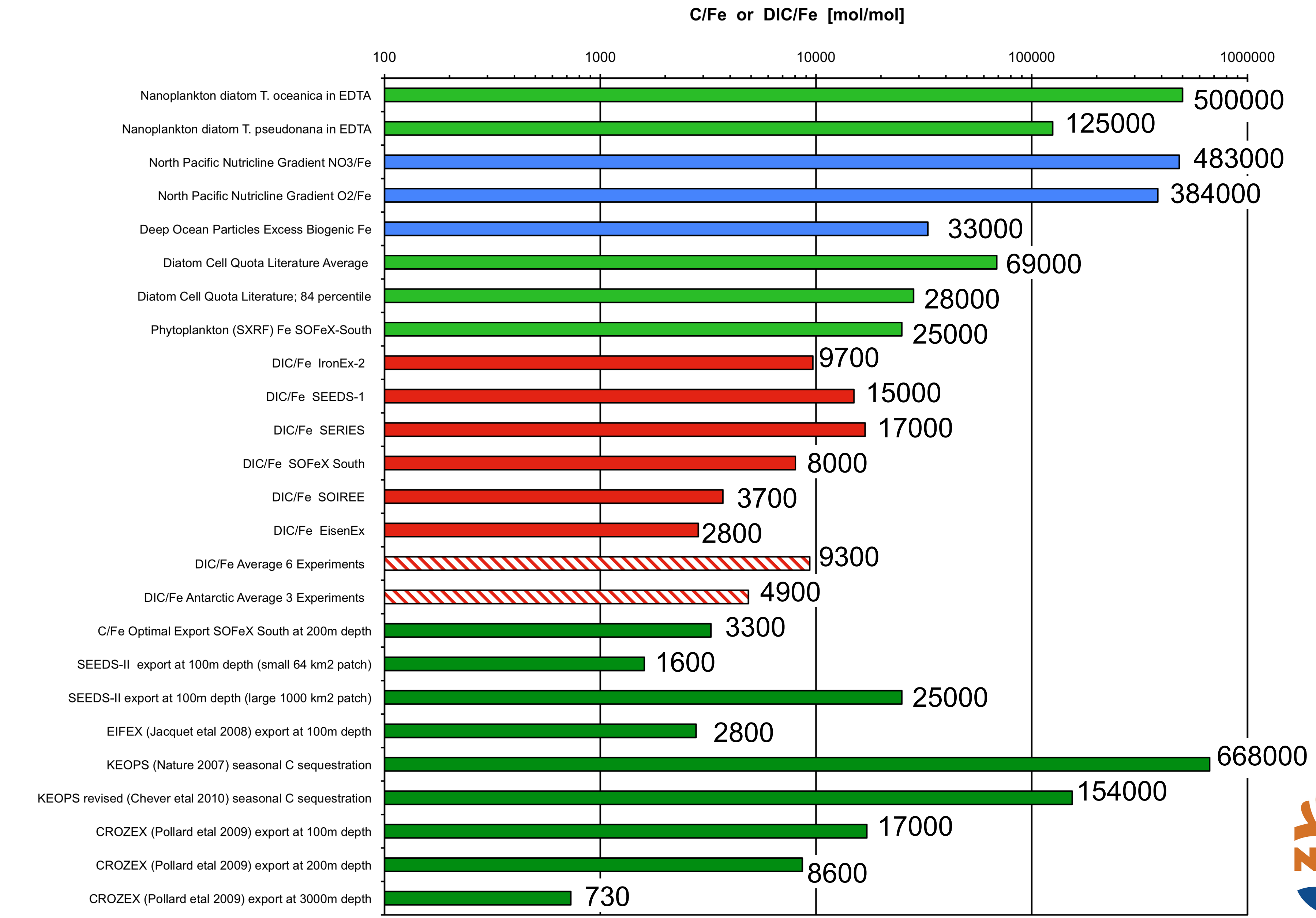
OPEN ACCESS

Efficiency of carbon removal per added iron in ocean iron fertilization

Hein J. W. de Baar[1,2,*], Loes J. A. Gerringa[2], Patrick Laan[2], Klaas R. Timmermans[2]

True element ratio values	Complete equation	Eq. no.
$(C{:}Fe)_{large\text{-}diatoms\text{-}optimal}$		
Efficiency ratio values		
$(\Delta DIC{:}Fe)_{NCP}$	$(\Delta DIC_{in\text{-}patch} - \Delta DIC_{control\text{-}station}){:}Fe$	(1)
$(C{:}Fe)_{gas\text{-}flux\ efficiency}$	$(Flux_{fertilized\text{-}patch} - Flux_{control\text{-}station}) / Fe_{added}$	(2)
$(C{:}Fe)_{export\text{-}efficiency\text{-}100m}$	$(C_{export\text{-}in\text{-}patch} - C_{export\text{-}control\text{-}site})_{100m}{:}Fe$	(3)
$(C{:}Fe)_{export\text{-}efficiency\text{-}250m}$	$(C_{export\text{-}in\text{-}patch} - C_{export\text{-}control\text{-}site})_{250m}{:}Fe$	

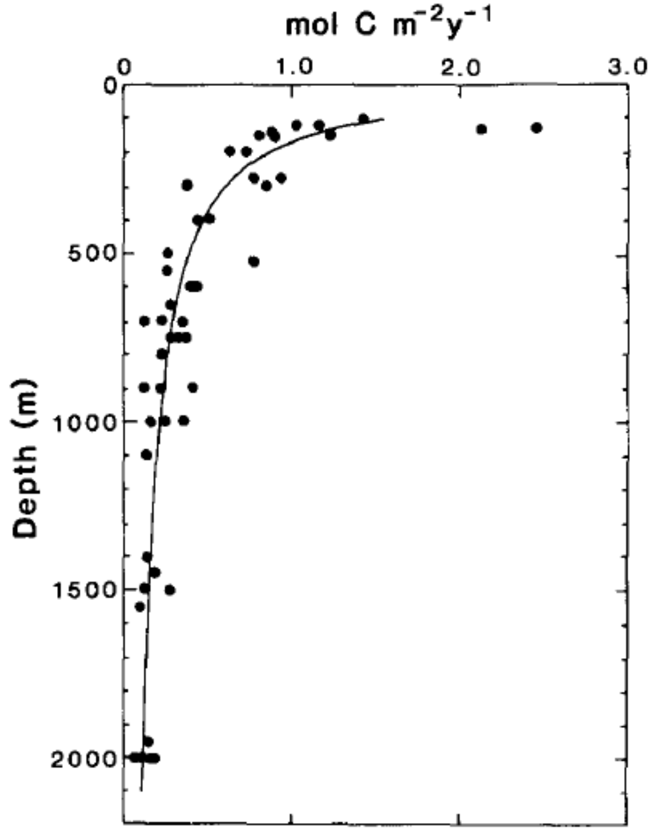
Extra C:Fe efficiency values of EIFEX, KEOPS, CROZEX



NIOZ

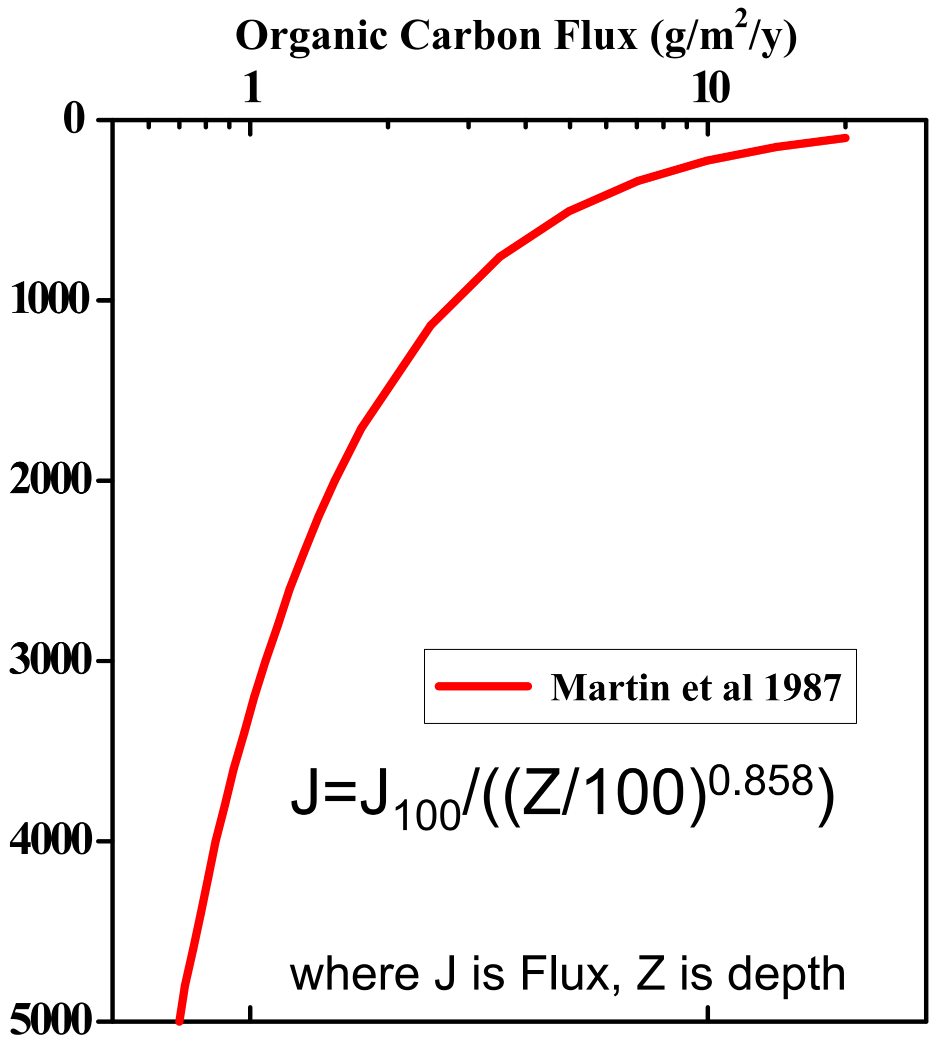
C:Fe efficiency of export decreases with increasing depth due to underway respiration/mineralization:

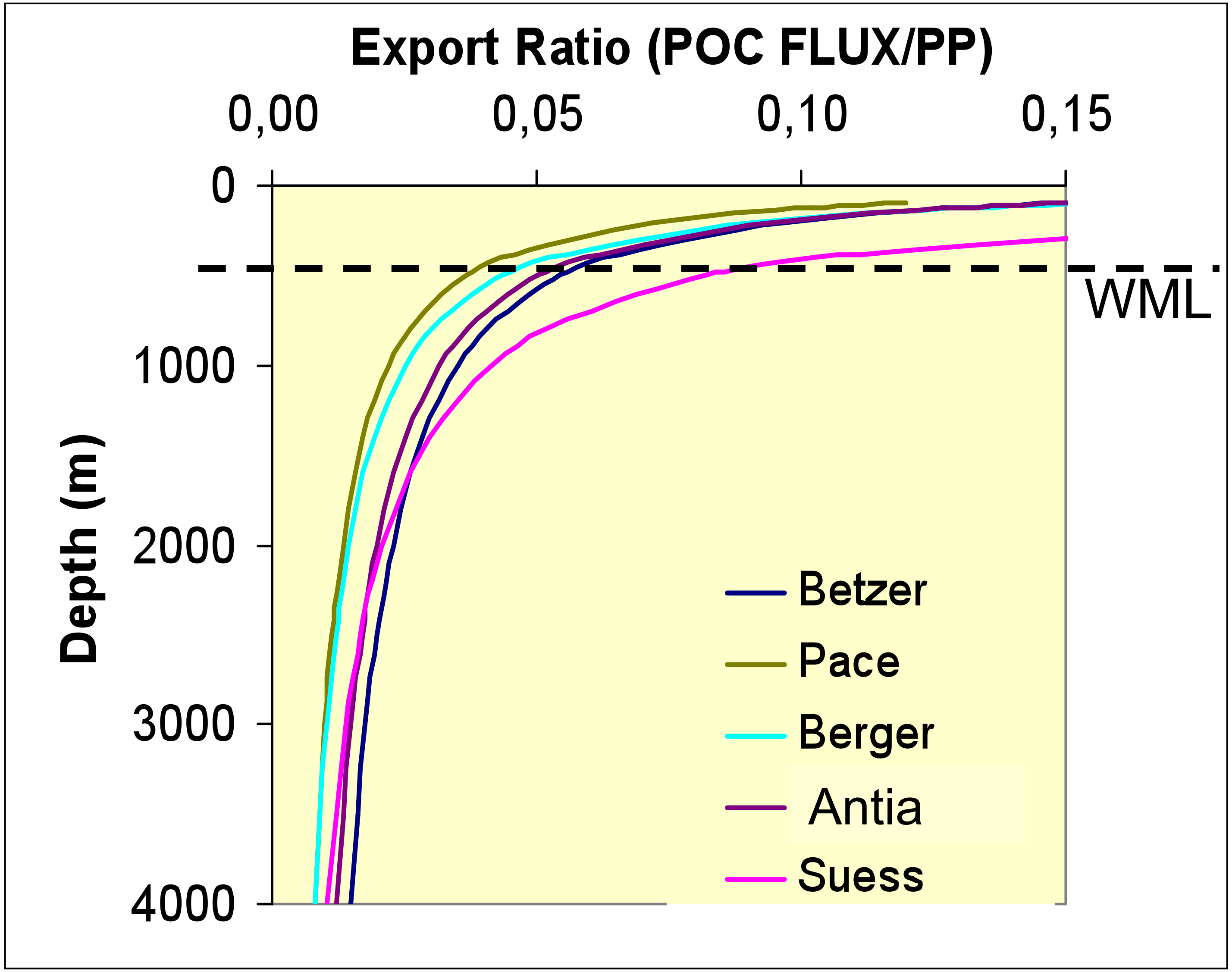
downward particulate flux as a function of depth



Sediment Trap Fluxes
Open Ocean Composite

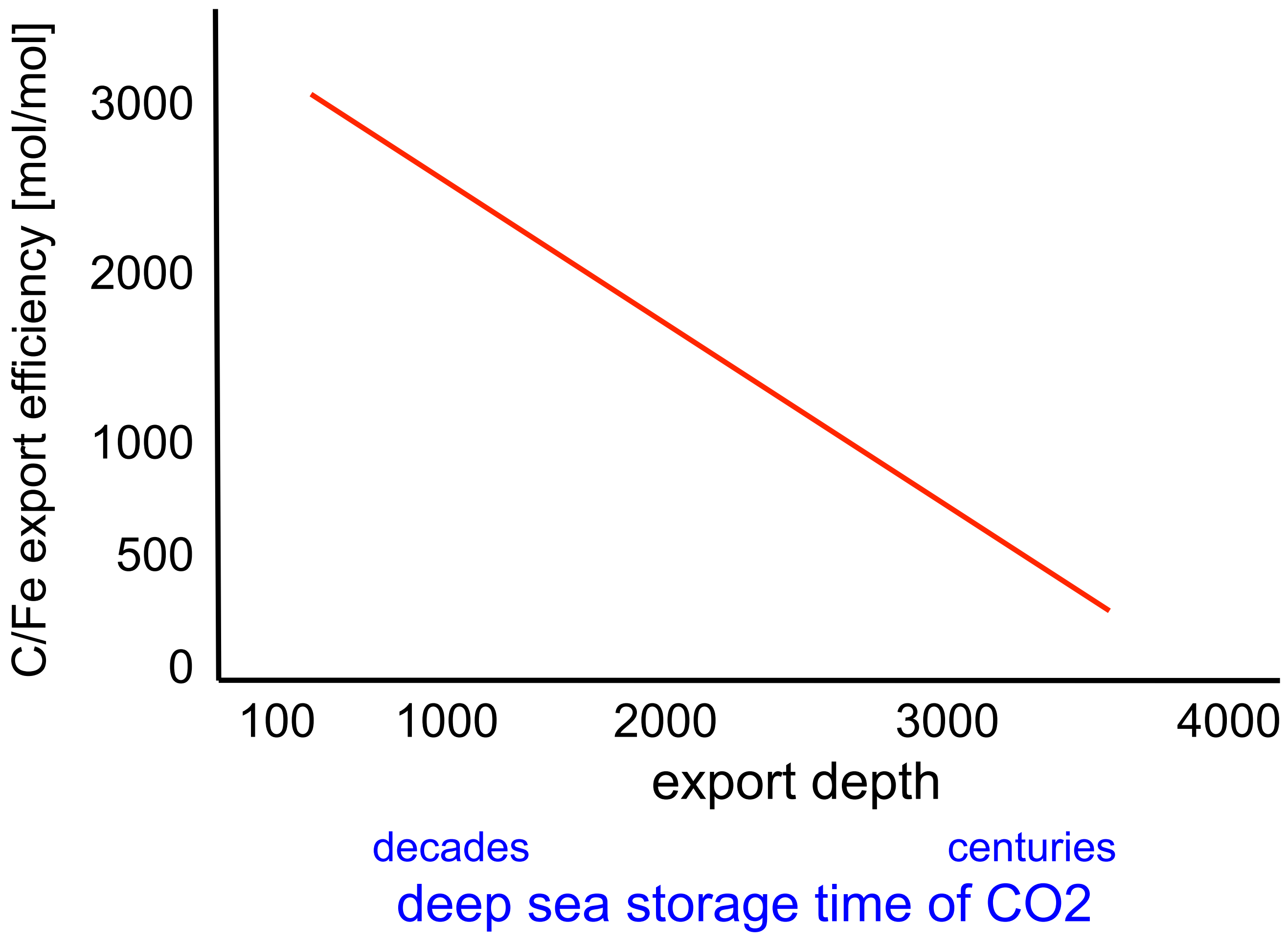
Martin et al (1987) VERTEX: Carbon cycling in the northeast Pacific, Deep-Sea Research, 34, 267-285





Significance of the mixed layer depth

Inverse trend between C/Fe export efficiency and deep sea CO2 storage time: not favorable



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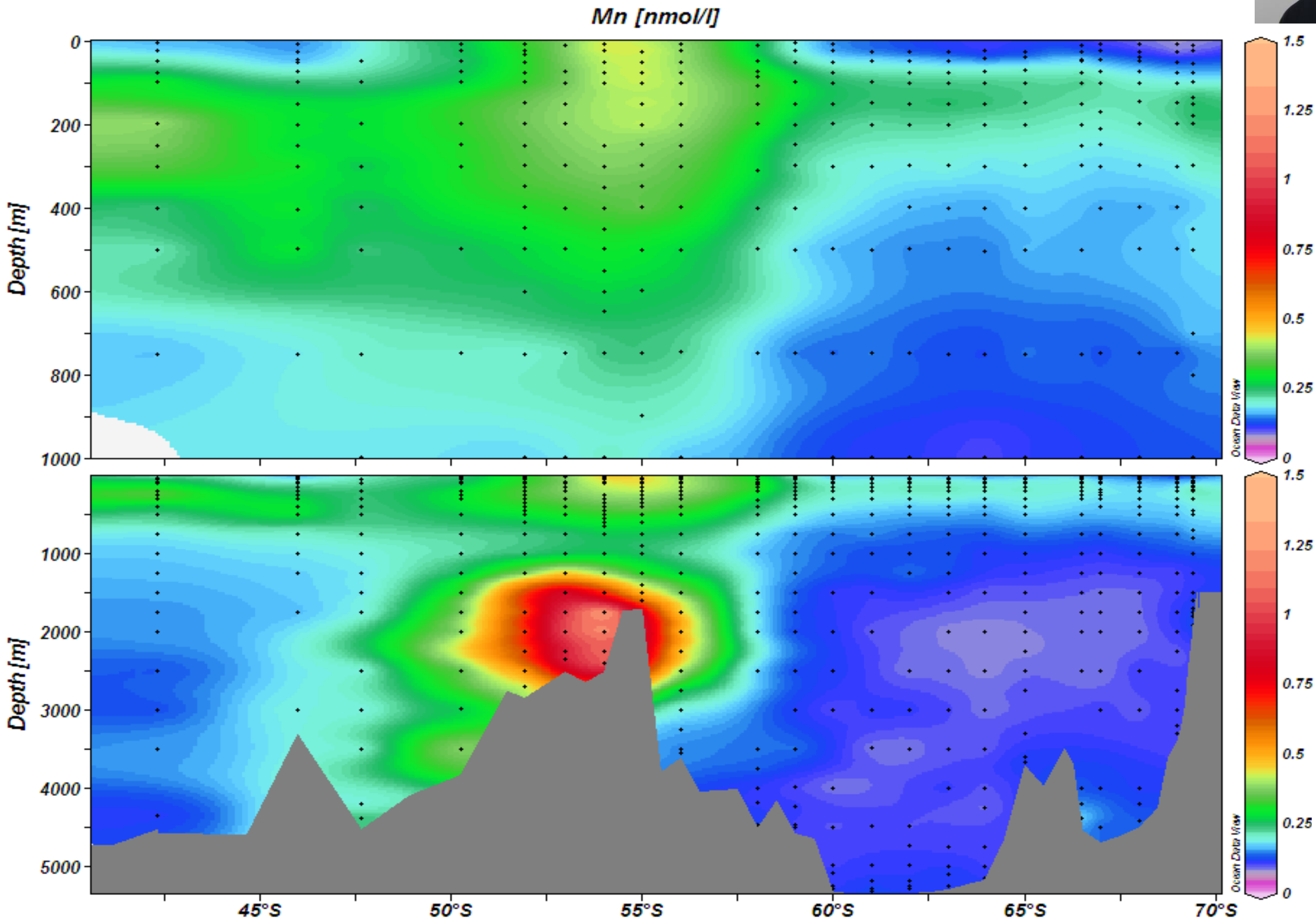
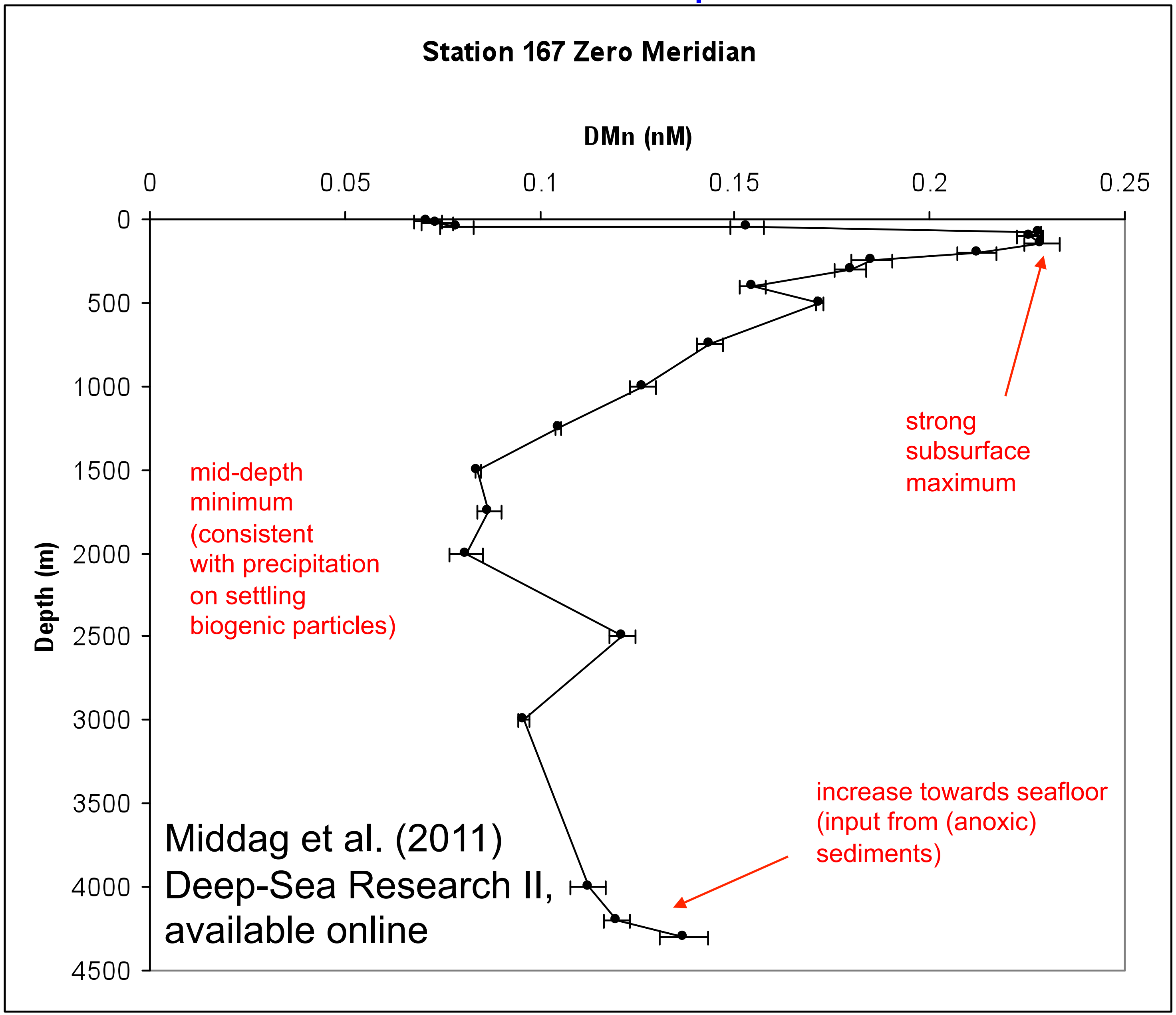
Dissolved Manganese at Antarctic Zero Meridian

Rob Middag et al. (2011) Deep-Sea Research II, available online



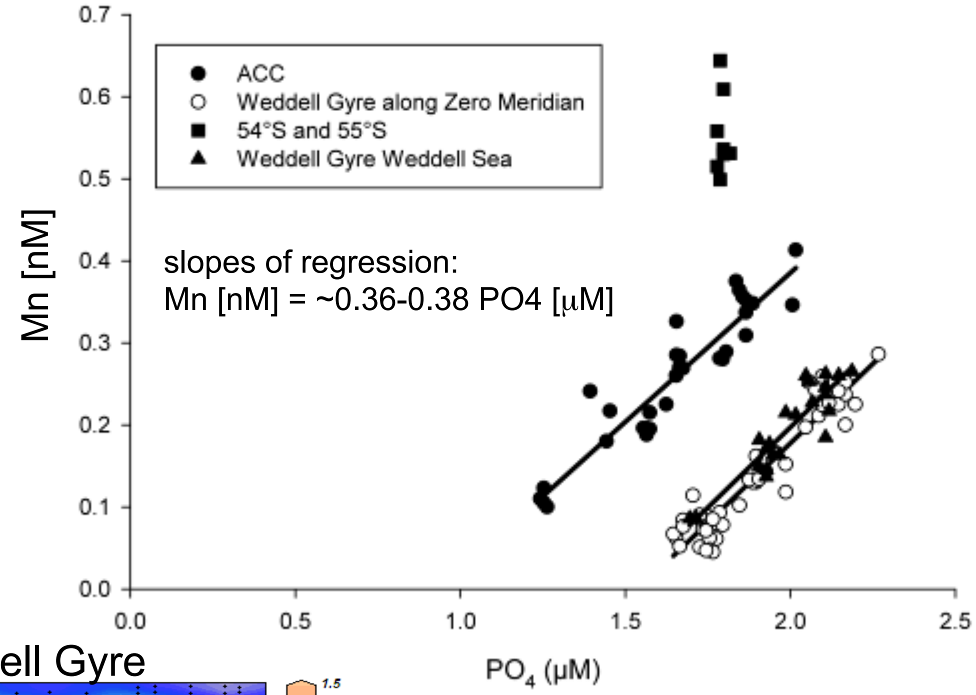
Antarctic station shows very low Mn in upper euphotic zone as well as in deeper waters

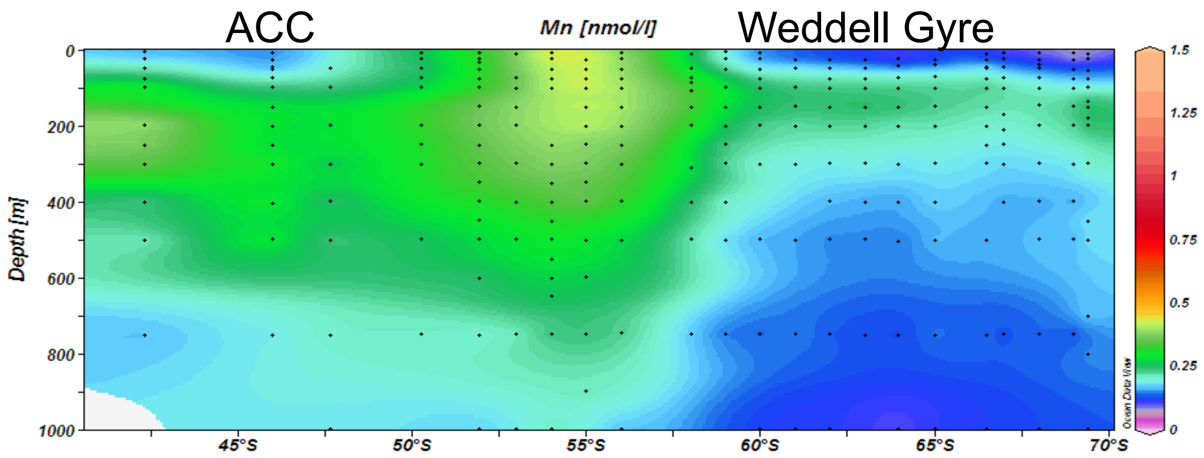


Zero meridian and Weddell Sea upper waters: Mn minima covariance with phosphate minima

Mn-PO4 correlation is the first-ever ocean tracer evidence of the otherwise known biological role of Mn

Middag et al., Deep-Sea Research II, available online

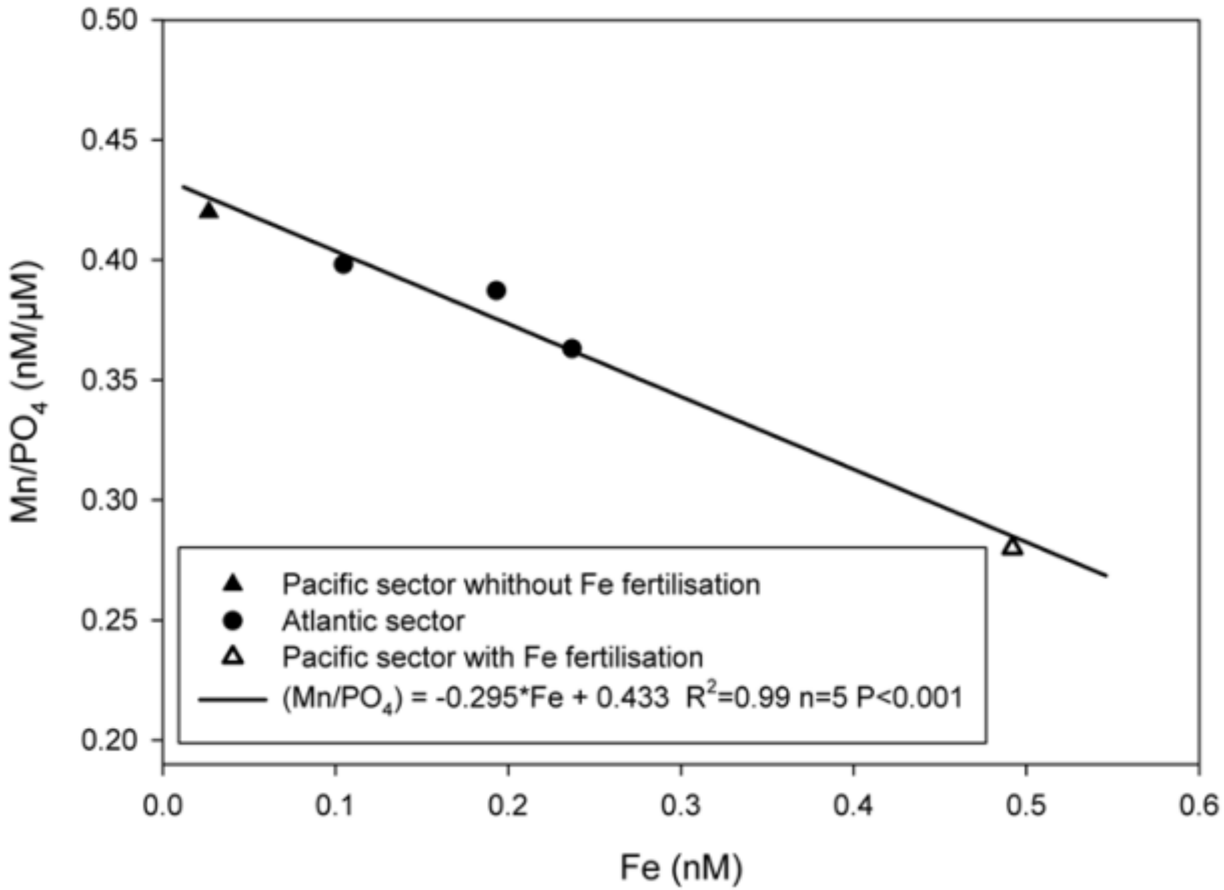




55° S

exclude 54-55 °S due to recent dust input, as also shown from Fe, Al and air mass trajectories

Biological uptake ratio Mn/P increases
with decreasing ambient iron (Fe) availability



● Mn/P slope
in Atlantic sector
as function of
ambient Fe

agrees well with

independent data of

▲ △ Mn/P ratio
of phytoplankton
in Pacific SOFeX
in situ Fe
fertilization experiment

Middag et al., Deep-Sea Research II, available online

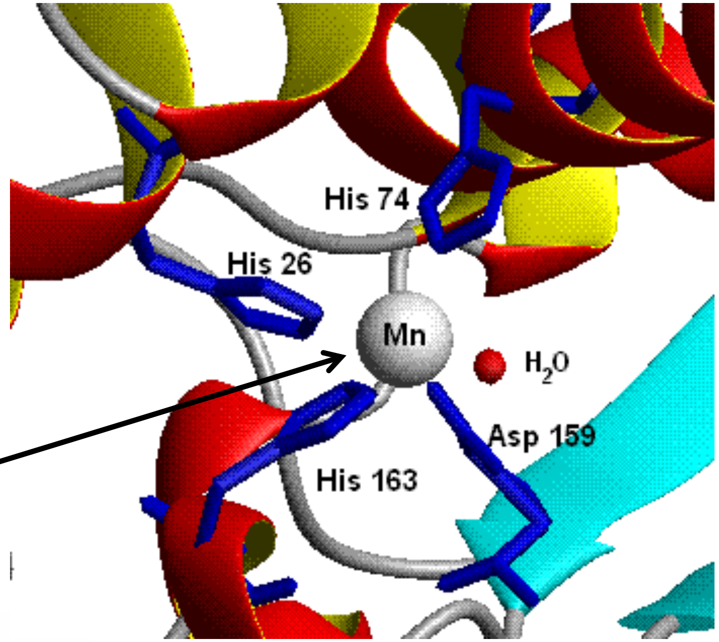
NIOZ

intracellular biochemistry explanation:
Fe is needed for electron transport in photosynthetic pathway

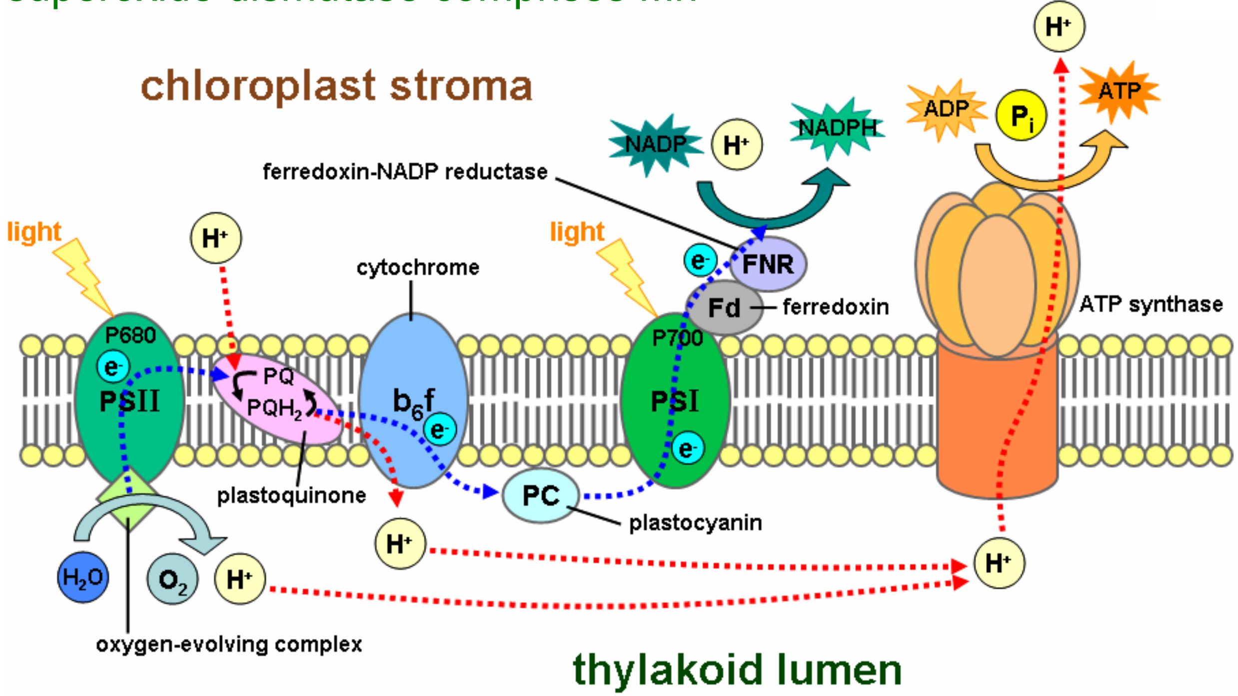
at Fe limitation this transport is hampered, the excess energy goes into superoxide radicals O_2^- which are highly toxic by agressive reactivity

superoxides are damaging for the cell, extra superoxide dismutase enzyme (SOD) is produced

superoxide dismutase comprises Mn



Structure of the active site of Mn-based superoxide dismutase



Photosynthetic electron transport chain of the thylakoid membrane

superoxide radical O_2^-

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Iron Fertilization to Solve the fossil fuel CO_2 problem ?

(1988) Give me half a supertanker ....
this assumed an export efficiency of C:Fe = ~500000

(2002) SoFeX South experiment
cellular Fe quota (akin to Redfield stoichiometry) C:Fe = ~25000 (Twining et al., 2004)
export efficiency at 200m depth C:Fe = 3300 (Buesseler et al., 2004)

(2004) CROZEX
export efficiency at 3000m depth C:Fe = 730 (Pollard et al., 2009)

Thus far the evidence of C/Fe efficiency is unfavorable

(2007) GeoEngineering becomes subject of debate

(2007 onwards) London Convention (IMO) struggles with rulings on fertilization experiments

(2011) ISIS Consortium: In-Situ Iron Studies of the Ocean http://isisconsortium.org/

ISIS Consortium Institutions

(including names of MOU signatories)

as of April 7, 2011

http://isisconsortium.org/

Woods Hole Oceanographic Institution
    Susan K. Avery, President and Director, January 11, 2011
National Oceanography Centre
    Professor Ed Hill OBE, Executive Director, January 21, 2011
Université Pierre et Marie Curie, Paris, France
    Jean-Charles Pomerol, President, April 7, 2011
University of Maine
    Michael J. Eckardt, Vice President for Research, December 30, 2010
University of Plymouth, Marine Institute
    Prof. Martin J. Attrill, Director of the Marine Institute, January 11, 2011
School of Ocean and Earth Science and Technology, University of Hawaii
    Brian Taylor, Dean SOEST, January 11, 2011
Antarctic Climate and Ecosystems Cooperative Research Centre
    Anthony J. Press, C.E.O., January 13, 2011
University of Illinois at Urbana-Champaign
    Robert Easter, Interim Chancellor; Walter K. Knorr, Comptroller; Don Wuebbles, Professor;
    Robert Rauber, Professor and Dept. Head, January 14, 2011
Moss Landing Marine Laboratories
    Jerry Garmo, Deputy Chief Operating Officer, January 14, 2011
Xiamen University
    Chongshi Zhu, President, January 18, 2011
University of Massachusetts Boston
    Winston E. Langley, Provost and Vice Chancellor for Academic Affairs, January 18, 2011
University of Rhode Island
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NIOZ-Royal Netherlands Institute for Sea Research
    Hermann Ridderinkhof, Deputy Director, February 10, 2011


Antarctic Ocean
20 Febr 2008 (0°W, 58°S)
Icebreaker Polarstern
Thank you
for your attention