Iron fertilization of the ocean and carbon storage in the deep sea.

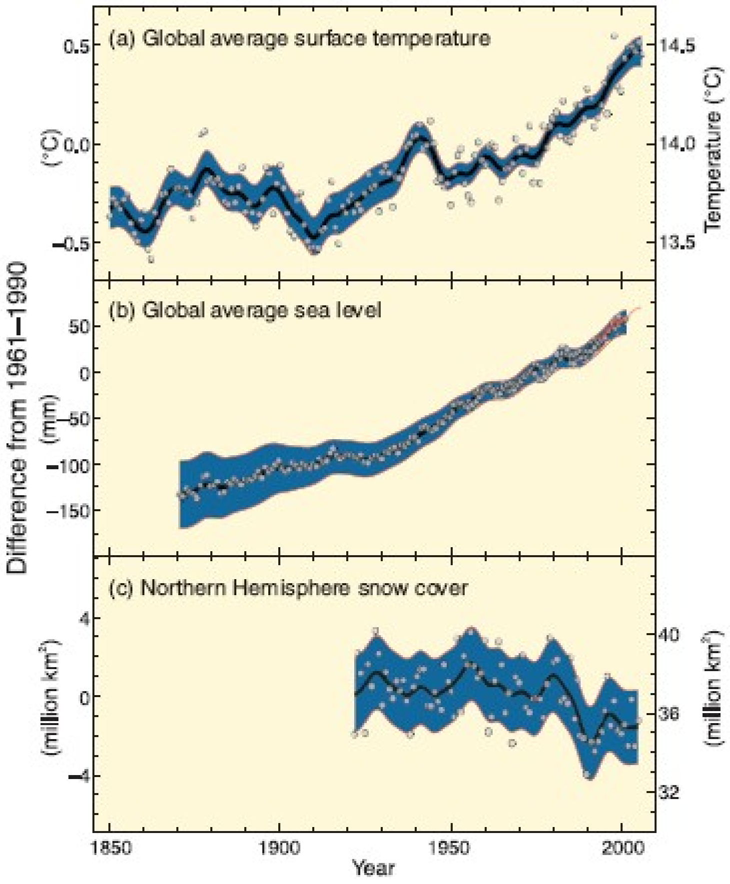
Why we need to take a cautious approach.

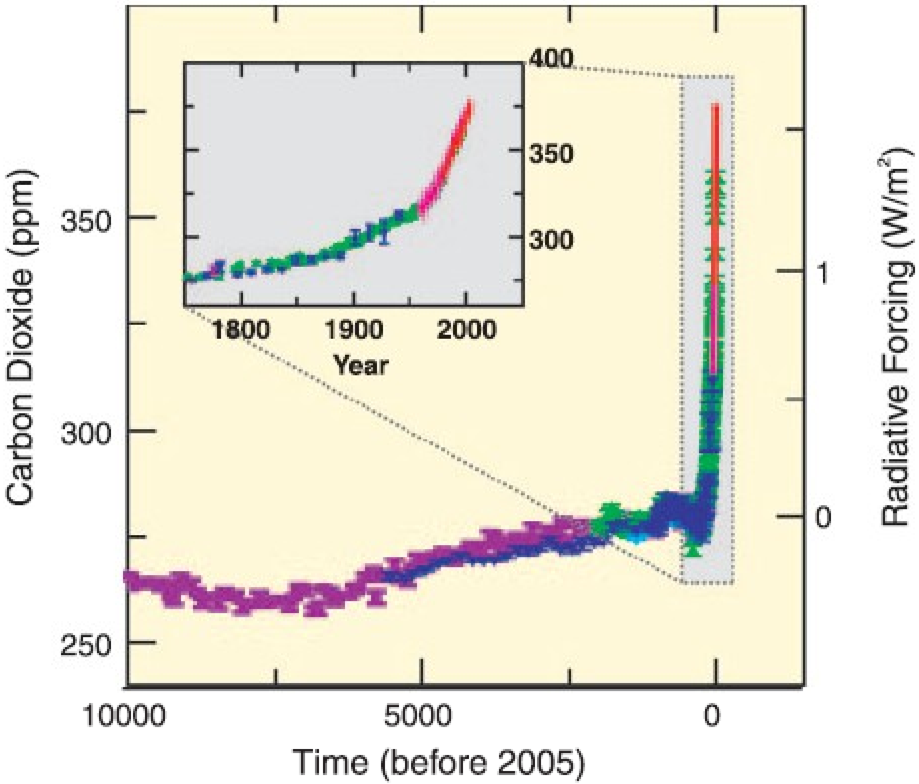
George Wolff, David Billett, Brian Bett, Jens Holtvoeth et al.

Environmental Sciences, University of Liverpool

National Oceanography Centre, Southampton

Change in atmospheric carbon dioxide





IPCC Synthesis Report, 2007

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Possible mitigation?

- Geo-engineering
- Carbon sequestration
  - Direct capture of CO_2 + injection to geosphere
  - Indirect means by fertilisation of the ocean and transfer of carbon to marine sediments

High nutrient, low chlorophyll (HNLC)regions

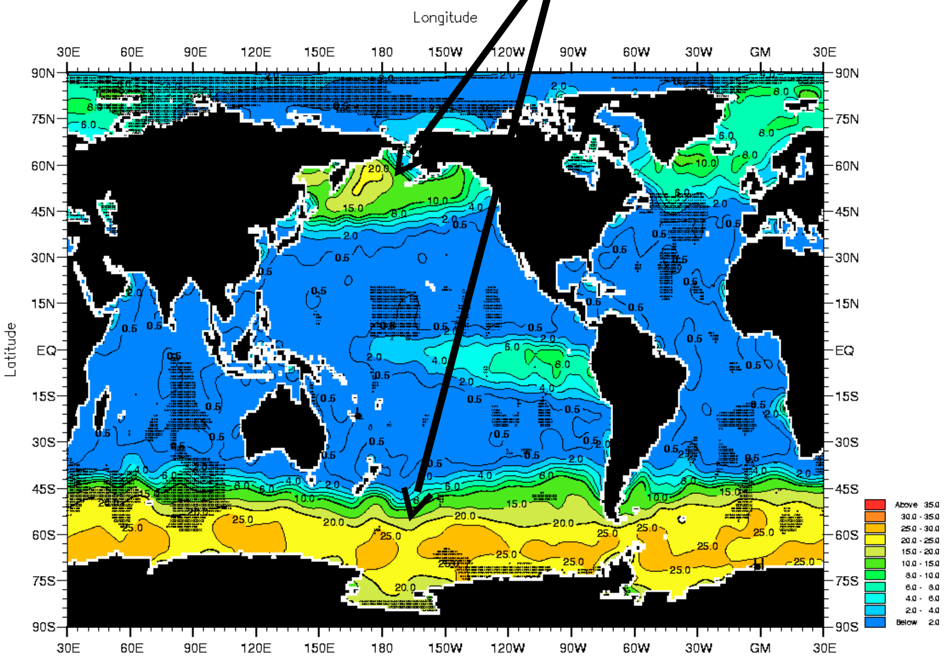


Fig. C2-1. Annual mean nitrate (μM) at the surface .
Minimum Value= 0.00 Maximum Value= 31.95

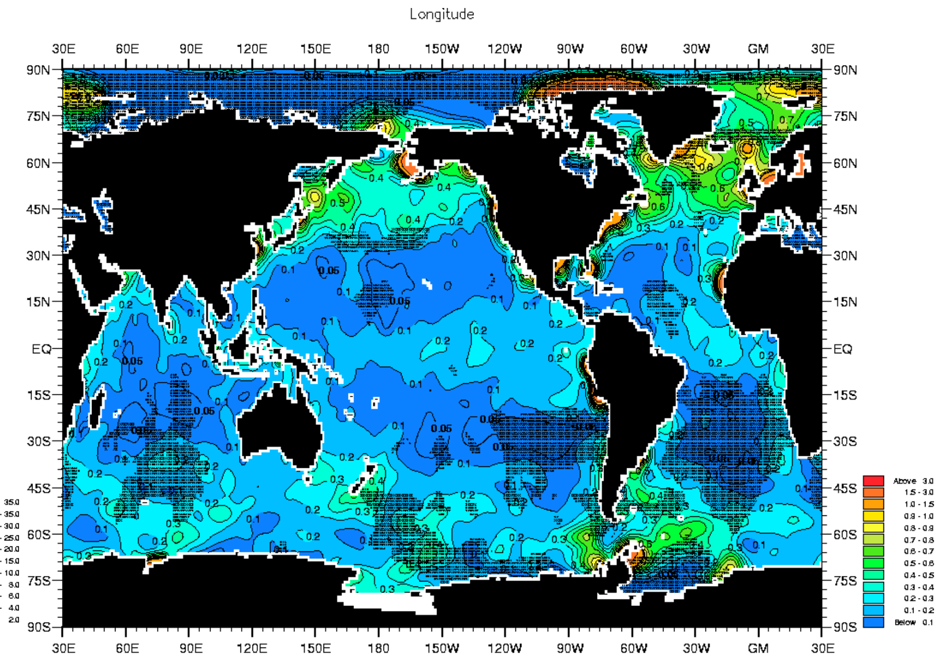


Fig. G2-1. Annual mean chlorophyll (μg/l) at the surface .
Minimum Value= 0.00 Maximum Value= 3.97

Nitrate (µM)

Chlorophyll (µg L-1)

Up to 30% of ocean area is HNLC

Iron deficiency limits phytoplankton growth in the north-east Pacific subarctic

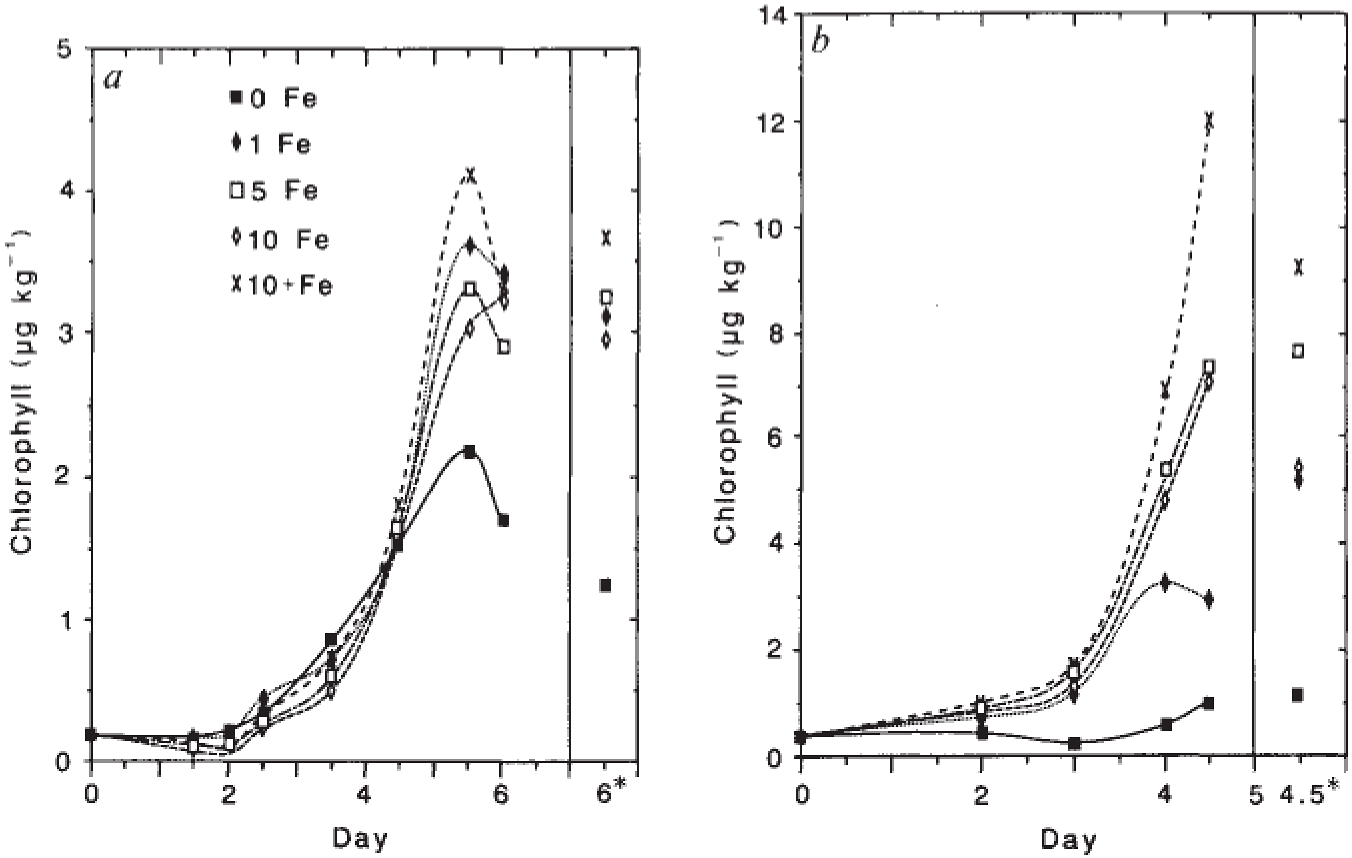
John H. Martin & Steve E. Fitzwater

Moss Landing Marine Laboratories, Moss Landing,
California 95039, USA

An interesting oceanographic problem concerns the excess major plant nutrients (PO_4, NO_3, SiO_3) occurring in offshore surface waters of the Antarctic[1–3] and north-east Pacific subarctic Oceans[4]. In a previous study[5], we presented indirect evidence suggesting that inadequate Fe input was responsible for this limitation of growth; recently we had the opportunity to seek direct evidence for this hypothesis in the north-east Pacific subarctic. We report here that the addition of nmol amounts of dissolved iron resulted in the nearly complete utilization of excess NO_3, whereas in the controls—without added Fe—only 25% of the available NO_3 was used. We also observed that the amounts of chlorophyll in the phytoplankton increased in proportion to the Fe added. We conclude that Fe deficiency is limiting phytoplankton growth in these major-nutrient-rich waters.

NATURE VOL. 331 28 JANUARY 1988

45.5⁰N 142.9 ⁰W 55.5 ⁰N 147.5 ⁰W



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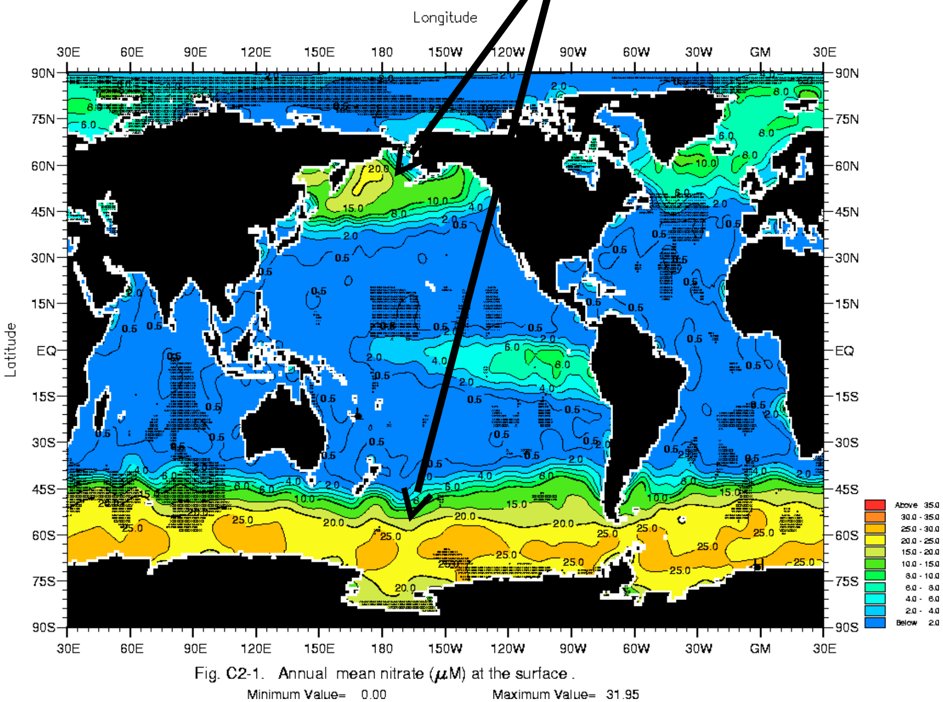
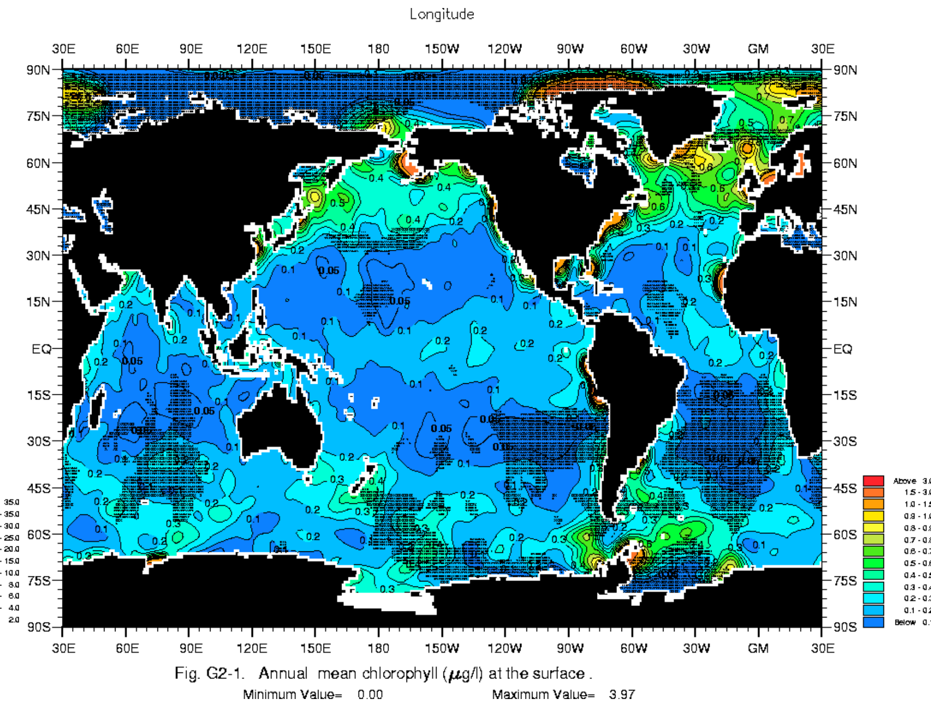
High nutrient, low chlorophyll (HNLC)regions



Nitrate (μM)



Chlorophyll (μg L-1)

rtin’s hypothesis – oceanic Fe supply limits productiv
Addition of Fe relieves limitation + draws down C

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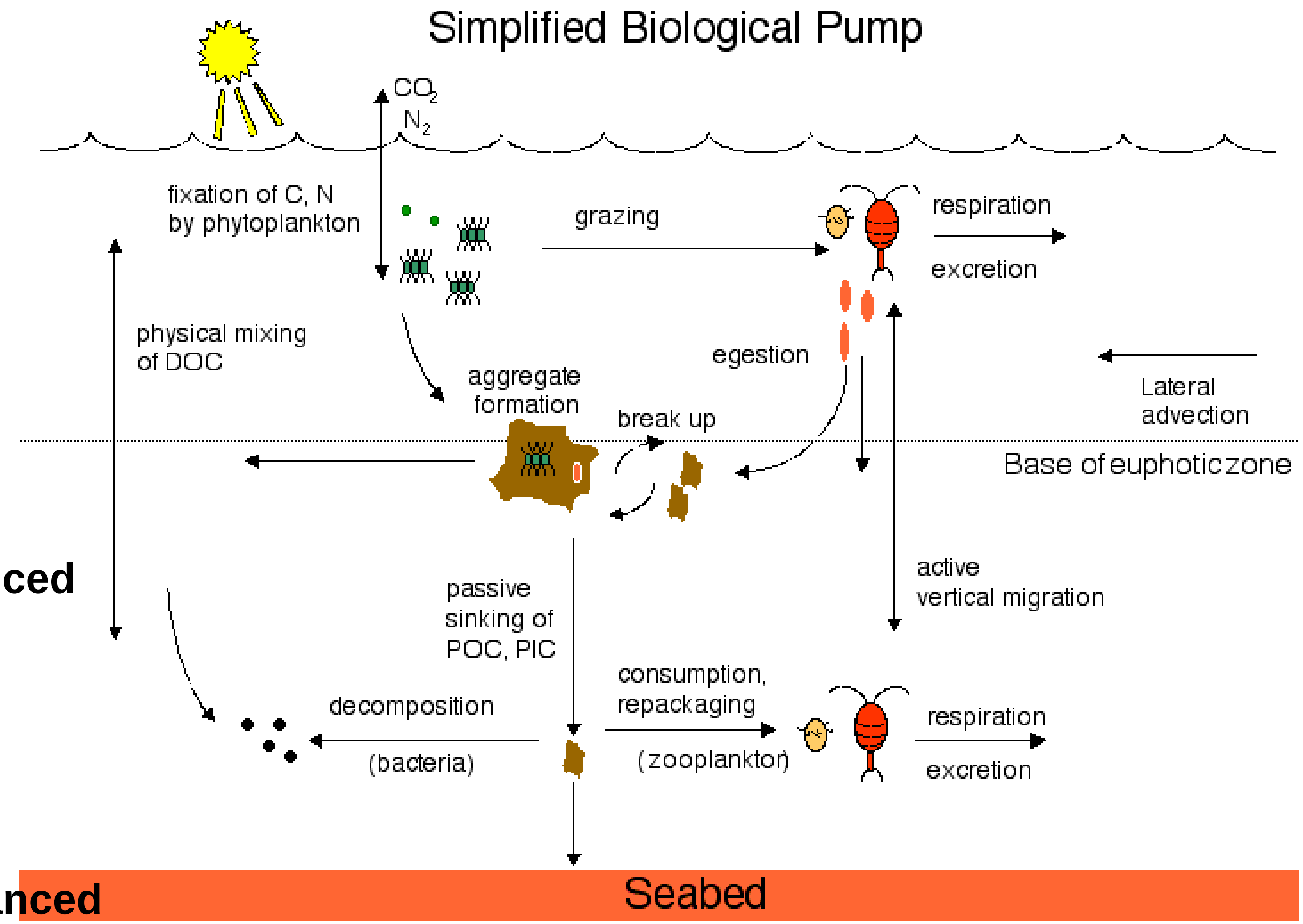
After OCTET workshop, 2000



+Fe

Enhanced flux

Enhanced burial

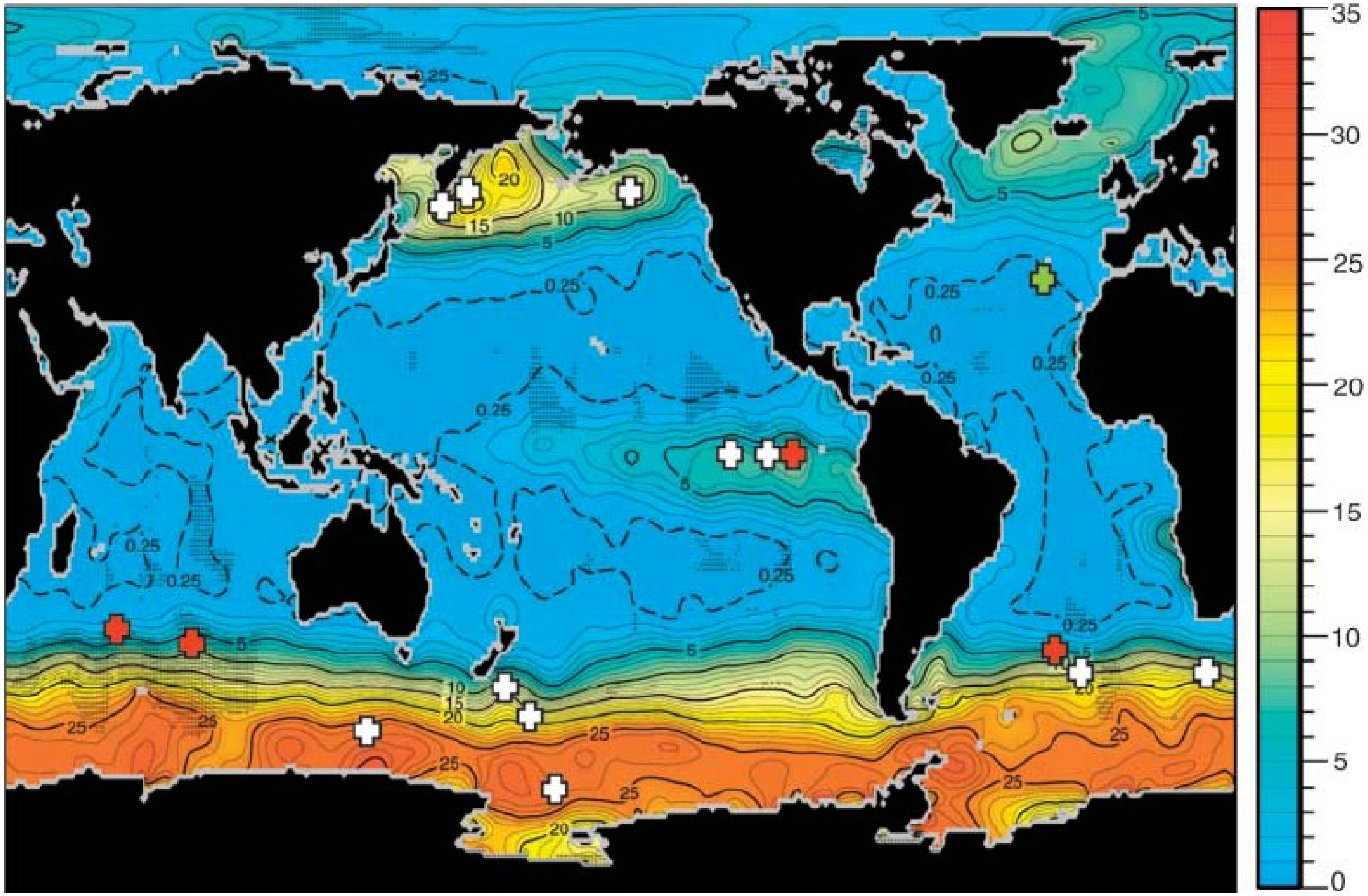
Enrichment with iron leads to enhanced export of carbon as organic particles from surface water

+ burial in sediments leads to carbon sequestration

Purposeful Fe Addition Experiments in HNLC ocean regions
Testing Martin's Hypothesis

- Ironex-I, 1993
- Ironex-II, 1995
- SOIREE (Southern Ocean Iron Release Experiment), 1999
- EisenEx (Iron Experiment), 2000
- SEEDS (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study), 2001
- SOFeX (Southern Ocean Iron Experiments - North & South), 2002
- SERIES (Subarctic Ecosystem Response to Iron Enrichment Study), 2002
- SEEDS-II, 2004
- EIFEX (European Iron Fertilization Experiment), 2004
- LOHAFEX 2009

Testing Martin's hypothesis with Fe additions (white crosses)



Annual mean surface nitrate concentrations µM, from Boyd et al., 2007 *Science* **315**, 612

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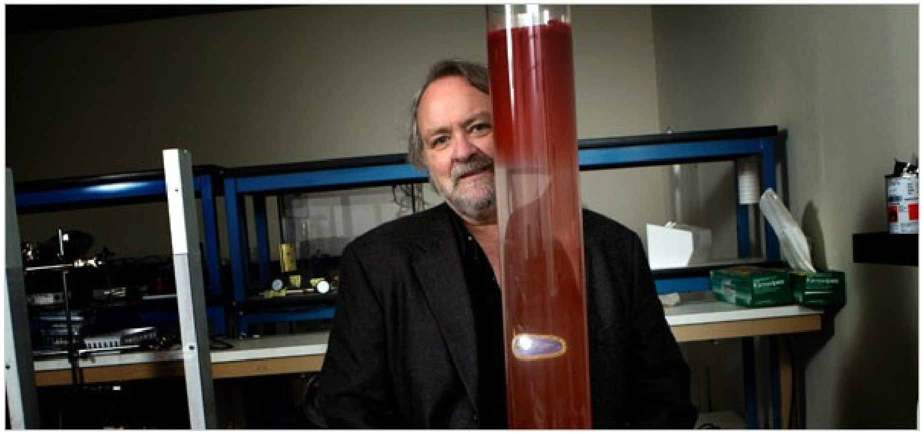
LOHAFEX 2009

- Largest purposeful addition ever
- 300 km2
- 6 Tonnes Fe into core of eddy of area ~ 10000 km-2
- 39 days

Would ocean fertilisation work?

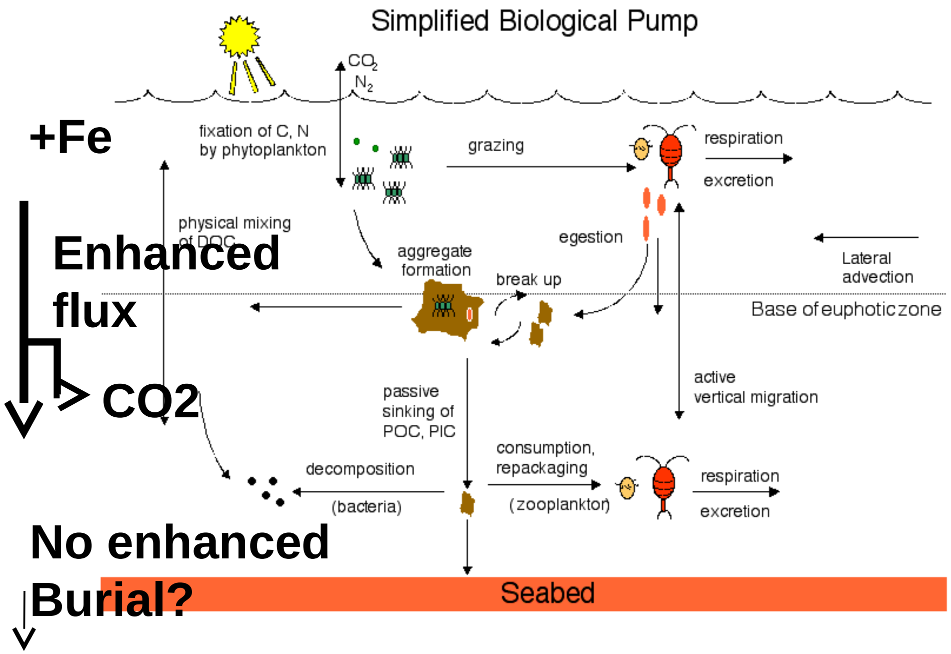
- Lab-based studies show Fe:C ratios of 2 – 7 x 10-6 (Sunda & Huntsman, 1995)
- Upscaled to the HNLC ocean ~ 3 Gtonnes CO2 y-1
- $1 – 2 per Tonne CO2
- $5 per Tonne makes a profit!



Recruiting Plankton to Fight Global Warming
Russ George, CE of Planktos
(New York Times – 1/5/2007)

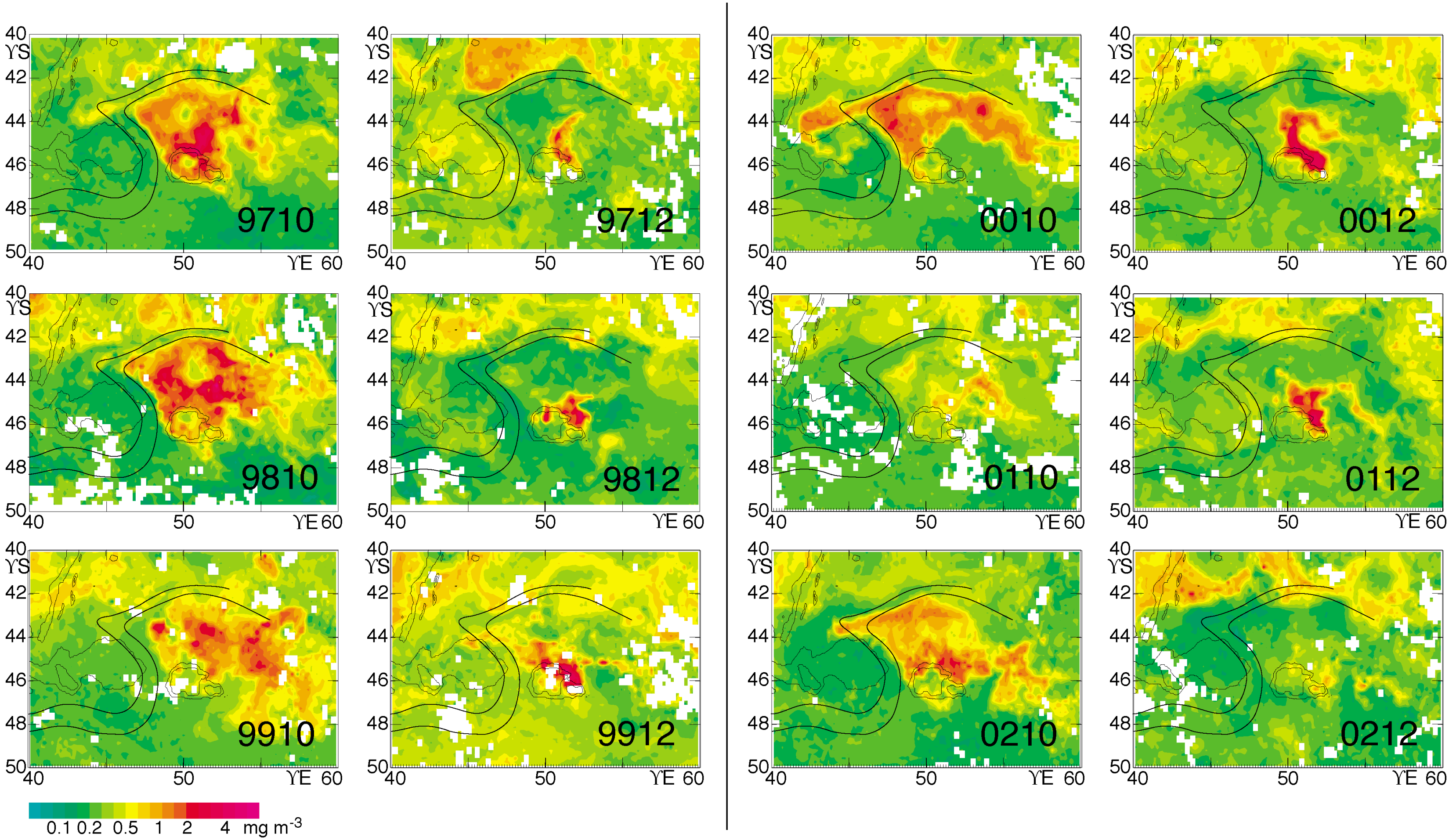
Would ocean fertilization work?

- All Southern Ocean experiments:
  - **show notable increases in biomass,**
  - **photosynthetic rate**
  - **decreases in DIC + nutrients**
- But, evidence regarding enhanced export to the deep ocean?
  - **scarce + generally to a few hundred metres (Boyd et al., 2007, *Science* 315, 612)**
- Export efficiency to the deep ocean?
- Real cost (need high Fe:C)?



- Lenton & Vaughn (*Atmos. Chem. Phys.* 9, 5539-5561. 2009) argue Fe fertilization only worthwhile on a millennial timescale
- Güssow et al. (*Marine Policy* 34: 911-918. 2010) argue that further research is needed as Fe

HNLC region shows some enhanced production



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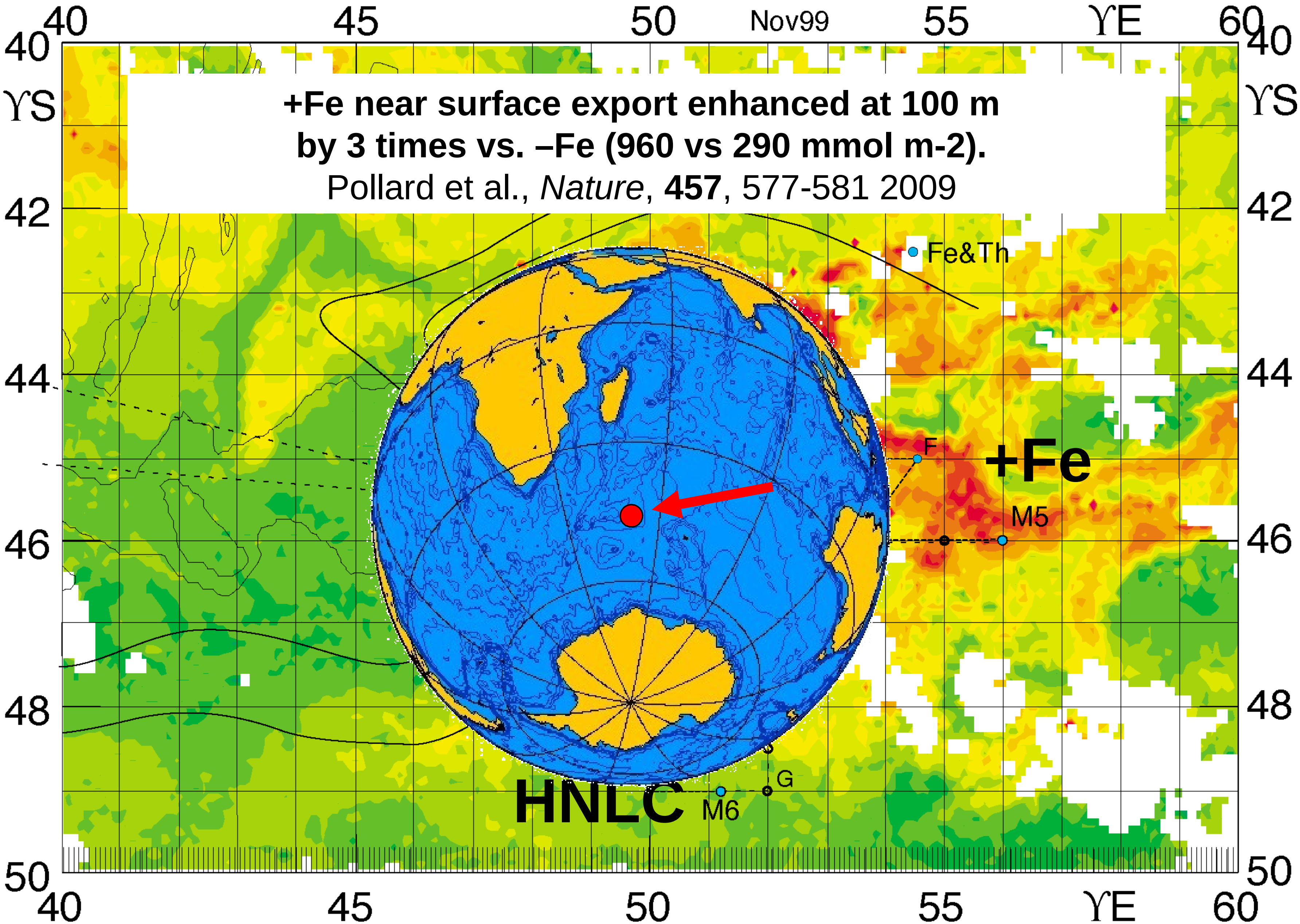
Natural Enrichment

- KEOPS (the KErguelen Ocean and Plateau compared Study) – Blain et al., 2007 *Nature* **446**, 1070
- CROZEX (CROZet natural iron bloom and EXport experiment) – Pollard et al., 2009 *Nature* **457**, 577
- Show widely varying Fe/C sequestration efficiency
  - KEOPS 1.5 x 10-6 (Close to geo-engineering requirements)
  - CROZEX 1.1 x 10-4 to 8.7 x 10-5
  - vs. ~ 10-2 to 10-4 for purposeful additions (may be too high because much of added Fe is lost or is oxidised and unavailable).



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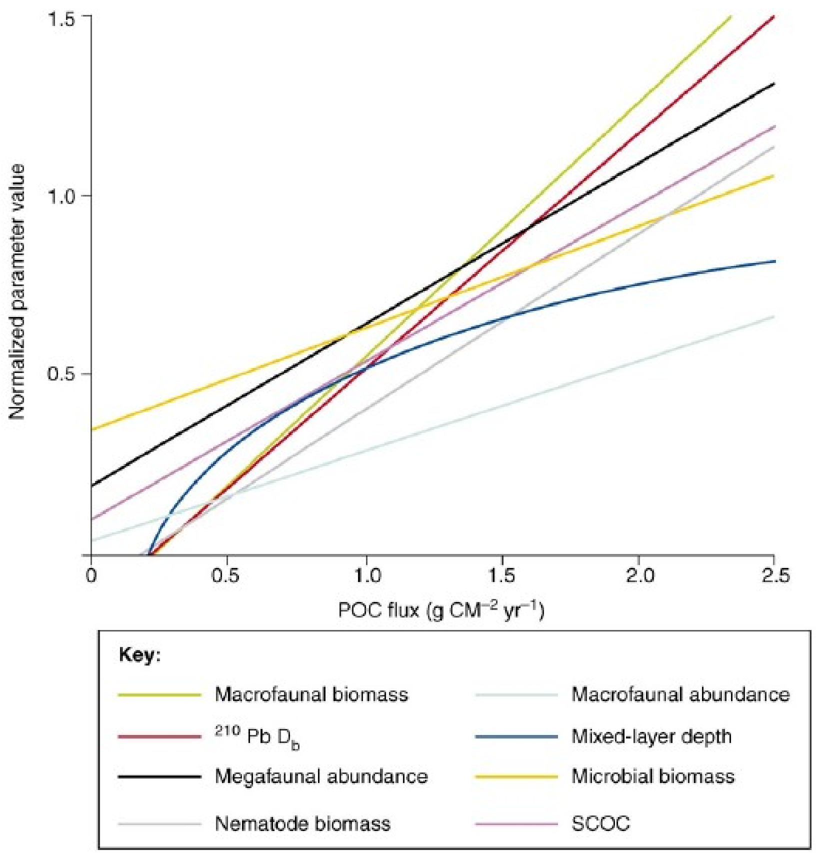
Additional carbon flux to the sea floor

- **Does iron fertilisation impact ocean ecology and should we care? (Buesseler et al., 2008)**
- Crozet Plateau is an ideal test site - two abyssal locations @ 400 km, with profoundly different export fluxes, one iron fertilised, the other HNLC



Buesseler et al., *Science*, **319**, 161-162, 2008

Smith et al. *TREE*, **23**, 518, 2008

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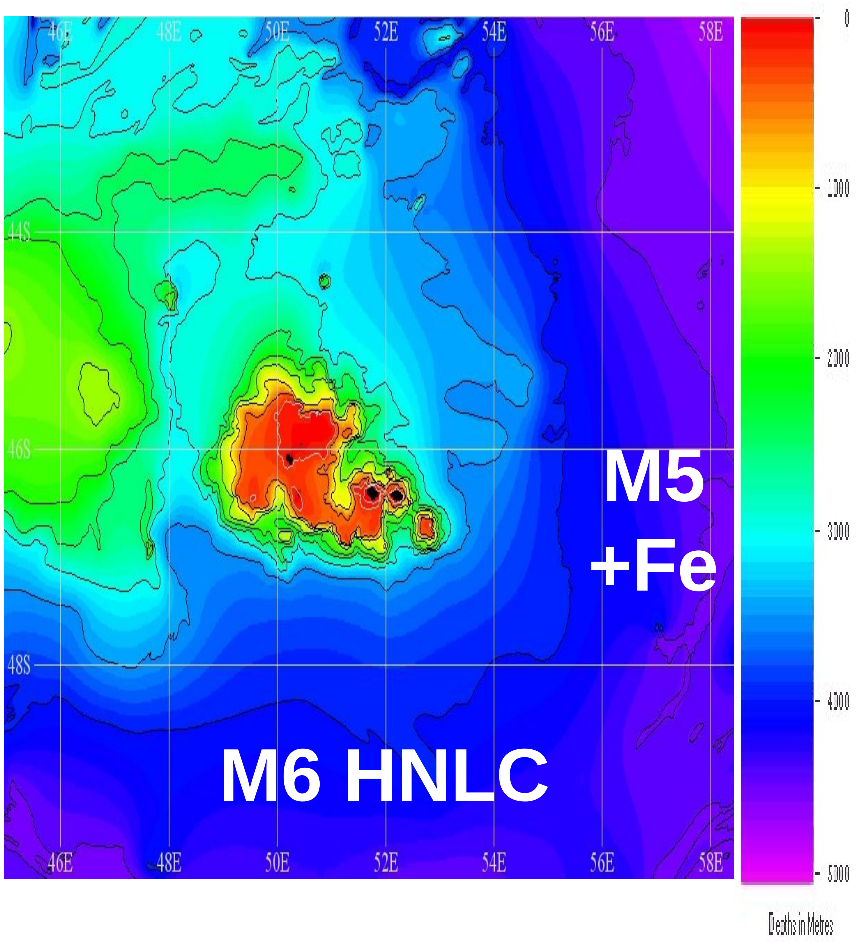
Hypotheses

- Iron fertilisation of HNLC waters leads to enhanced POM fluxes and enrichment sea floor (4000 m) at +Fe, but not at HNLC
- The benthic community responds to enrichment at +Fe.
- The composition of the POM flux influences the composition of the benthic megafaunal community.



Methodology

Benthic biology

- megafauna

Benthic chemical diversity

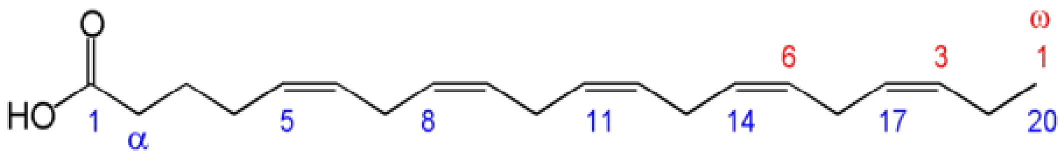
- biochemical composition of major fauna
- carotenoids, lipids
- comparison with incoming OM flux (sediment traps, SAPS) and sediments
- isotopic composition of bulk OM and specific compounds

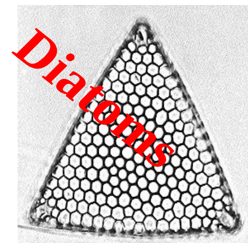
Diversity - holothurians

- *Abyssocucumis abyssorum* (filter feeder) vs. *Molpadia* (head down feeder)

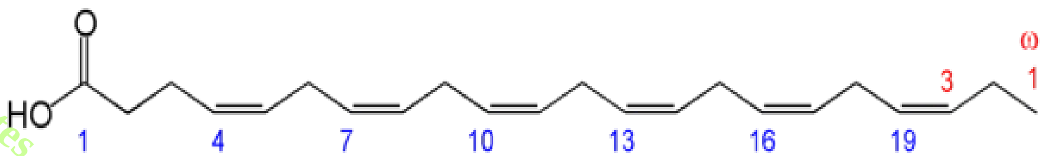
Lipids - Polyunsaturated Fatty Acids

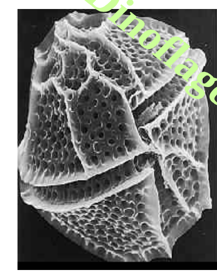
Eicosapentaenoic acid:
C20:5(n-3)





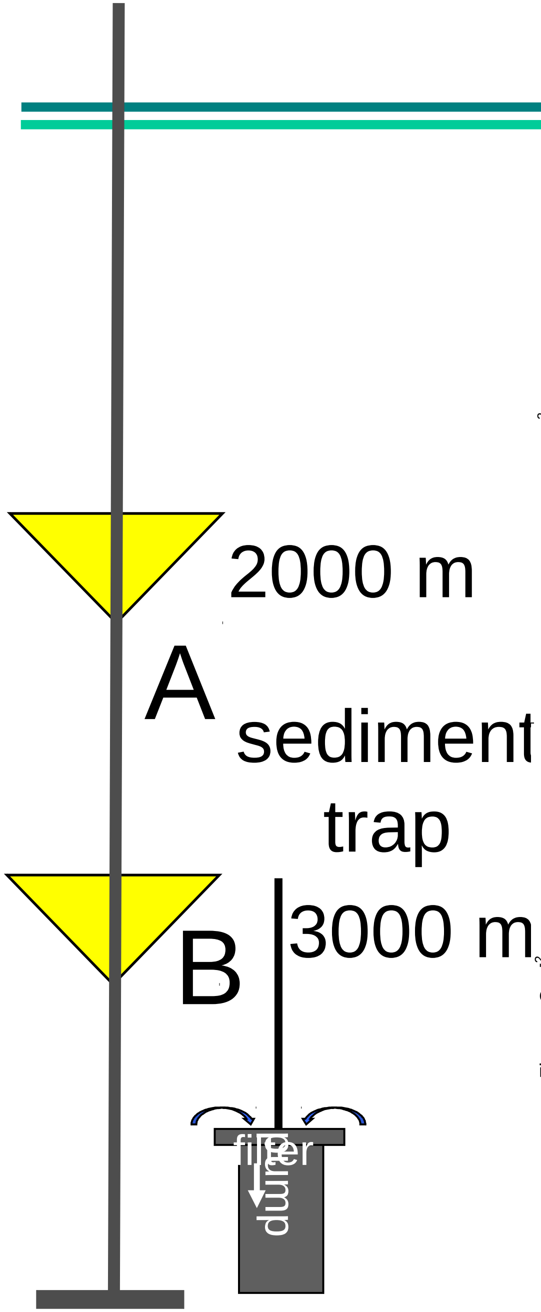
Docosahexaenoic acid:
C22:6(n-3)



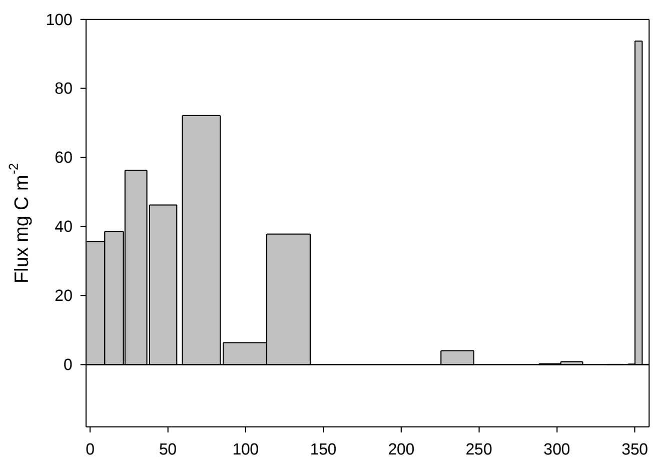


Chemical structure of two PUFAs (polyunsaturated fatty acids). C20:5 (n-3) is a diatom biomarker and C22:6(n-3) is common in dinoflagellates.

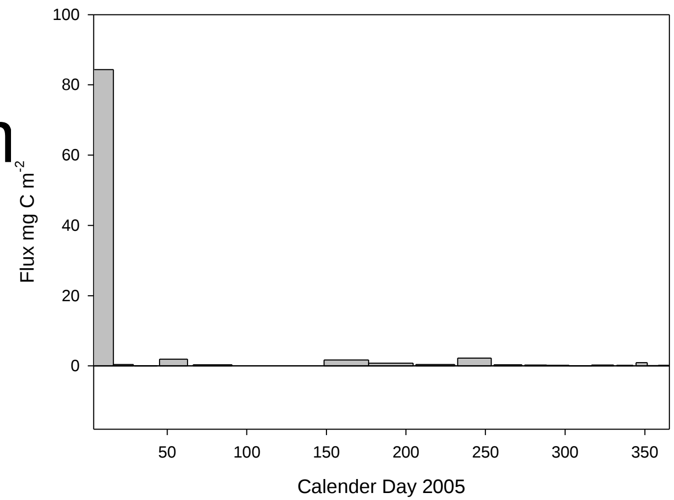
Fluxes



+Fe



HNLC



m-2y-1
m-2y-1)

C m-2y-1
m-2y-1)

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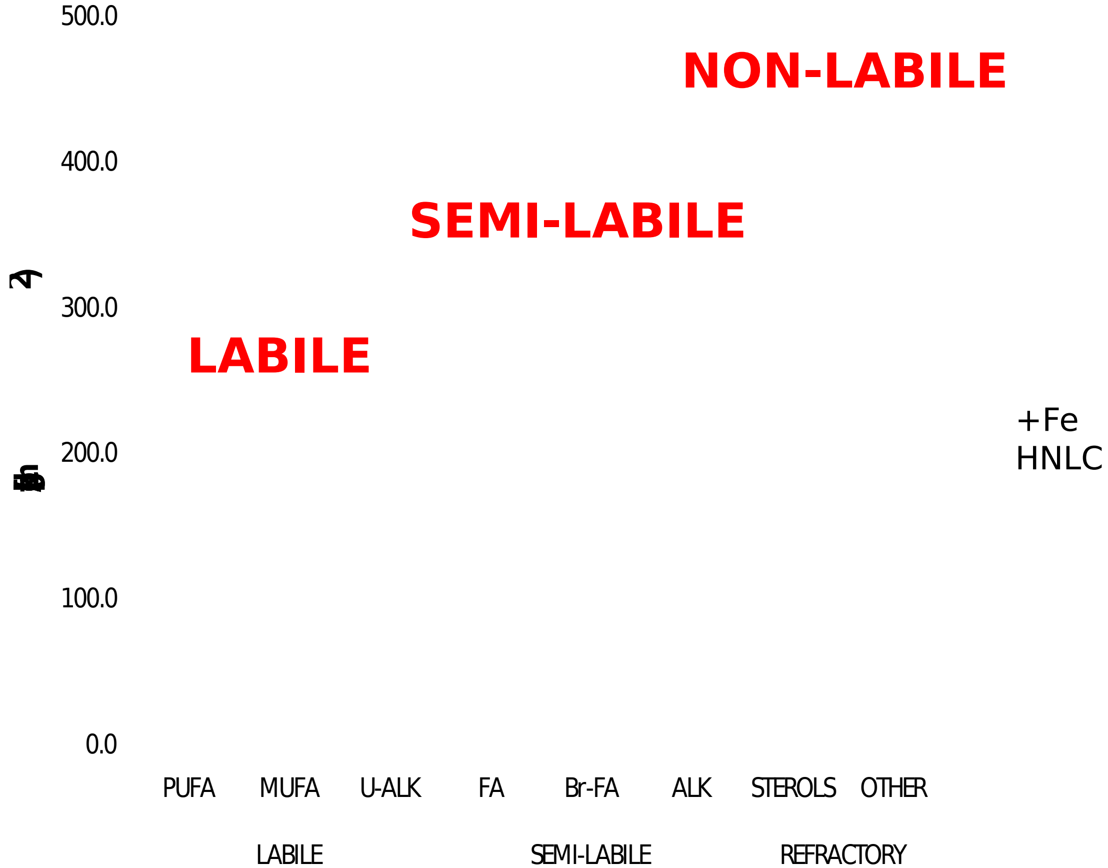
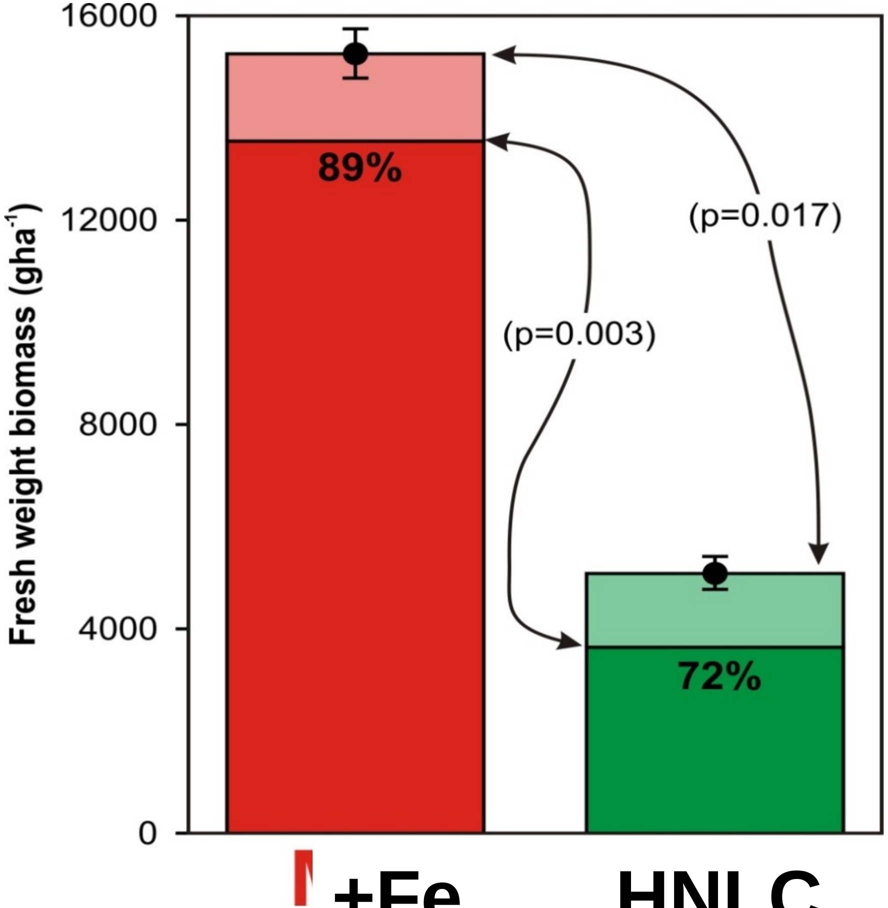
Composition – lipid biomarkers

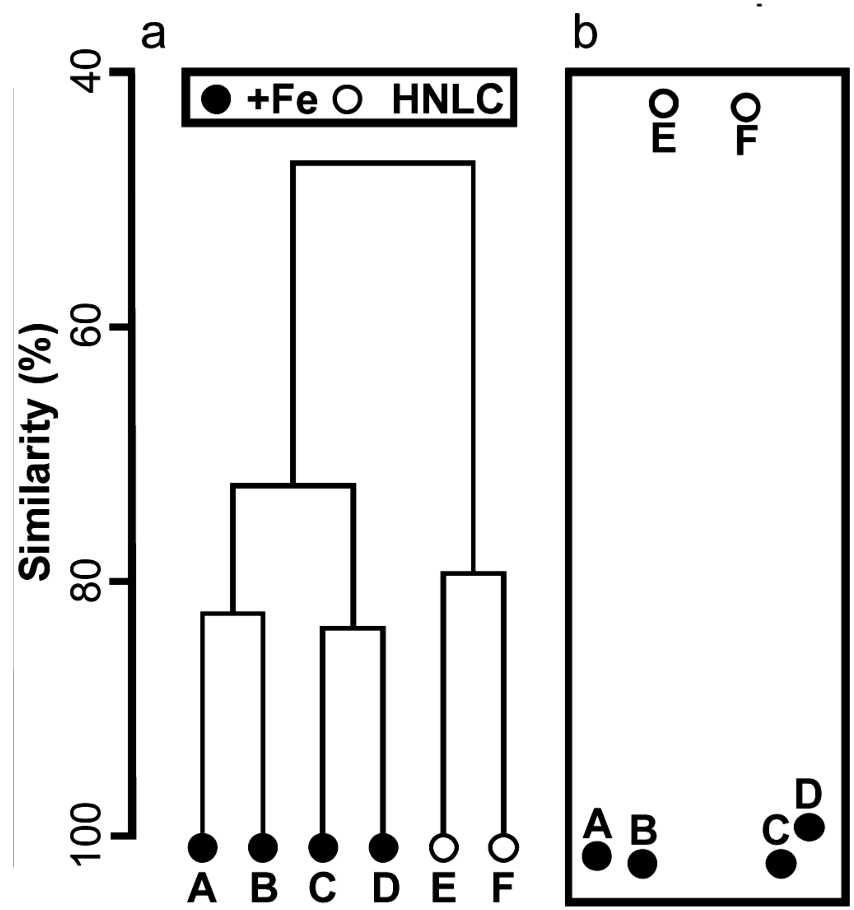


Fluxes of labile + semi-labile POM are significantly higher at +Fe vs. HNLC.
(Friedman's test, n=6, p=0.014)

nthos catch data – biomass & taxon compositi

Trawl (OTSB14) catch data





+Fe **HNLC**

3.5 **1**

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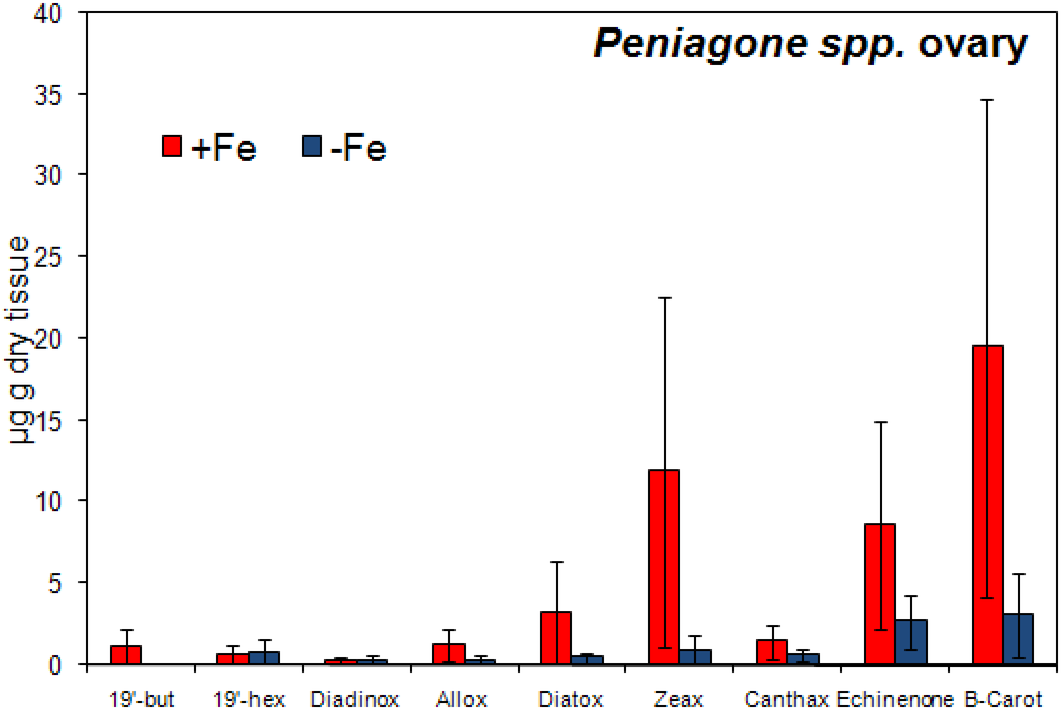
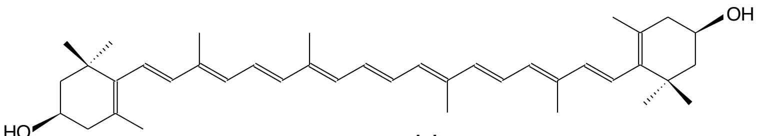
s catch– Top 10 megafauna - biomass & abund

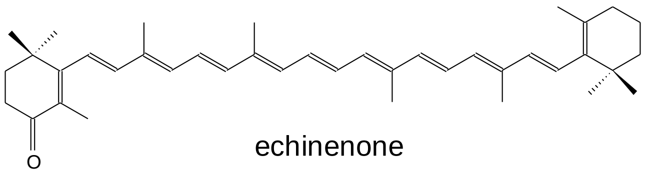
Species Name	Density (+Fe) (individuals ha-1) n=4	Biomass (+Fe) (wet wt g ha-1) n=4	Rank (+Fe) Abundance/ (Biomass)	Density (HNLC) (individuals ha-1) n=2	Biomass (HNLC) (wet wt g ha-1) n=2	Rank (HNLC) Abundance/ (Biomass)
Peniagone crozeti	259.6	910.5	**1 (3)**	11.05	23.47	
Ophiuria lienosa	194.7	53.43	2	162.3	64.25	1
Amphioplus daleus	128	35.69	3	37.93	6.615	5
Peniagone challengeri	69.17	137.1	**4**	5.591	9.894	
Ophiuria irrorata loveni	41.32	38.53	5	18.7	17.61	
Kolga nana	0	0		17.43	3.276	
Peniagone affinis	3.675	29.57		94.61	497.4	**3 (1)**
Peniagone willemoesi	1.833	4.544		95.58	134.2	**2 (3)**
Ophiotrema tertium	0.035	7x10-4		61.08	7.633	4
Psychropotes longicauda	12.57	1195	(1)	2.536	105	(5)
Molpadiodemas aff atlanticus	28.32	962.9	(2)	0	0	
Molpadiodemas morbillus	8.672	460.3	(4)	0	0	
Benthodytes sordida	5.07	308.7	(5)	3.458	131	(4)
Styracaster robustus	6.807	52.11		13.15	230.1	(2)

Ovarian tissues - carotenoids

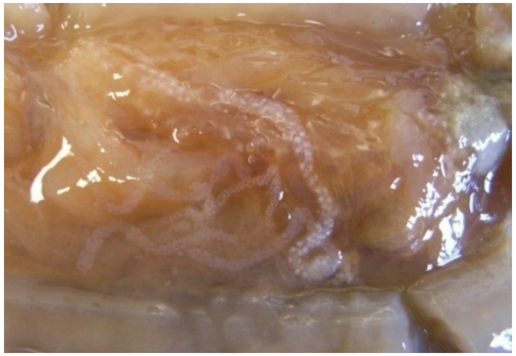




zeaxanthin



echinenone



ncentrations of key carotenoids in ovarian tissues higher at +Fe in *Peniagone* sp
species have similar maximum egg size (~ 500 µm diameter), but at +Fe, *P. cro*
significantly higher gonad index than *Peniagone* spp. at –Fe.
vated carotenoid concentrations impart increased fecundity.
nent supply and the ability of *P. crozeti* to assimilate them may be critical in
minance at +Fe?

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Conclusions

- Iron fertilisation of HNLC waters around Crozet + algal bloom leads to enhanced POM fluxes and enrichment at the sea floor (4000 m) at +Fe, but not at -Fe.
  - **Yes.**
- The benthic fauna respond to enrichment at +Fe.
  - **Yes.**
- The molecular composition of the POM flux influences the composition of the benthic megafaunal community.
  - **Maybe?**

Conclusions

Natural Fe fertilisation influences the biomass and community composition of large invertebrates in the deep sea

Long term geoengineering would be expected to do the same

Wolff G.A., Billett D.S.M., Holtvoeth J., Bett B.J., et al.(2011) The effects of natural iron fertilisation on deep-sea ecology: The Crozet Plateau, Southern Indian Ocean.

PLoS One, **6**, e20697. DOI: 10.1371/journal.pone.0020697

Acknowledgements

Does Iron Fertilisation Work?

Natural enrichment

- Enhanced C flux to deep ocean
- No enhanced C burial – remineralised by benthos
- Evidence of impact on benthic ecosystem in terms of biomass, species dominance and richness and carbon metabolism?

Purposeful addition

- Enhanced production
- Limited evidence for export, because of time, grazing + other factors?
- Timing re. diatom bloom?
- Fe speciation differs to natural (Laglera and van den Berg, 2009, *L&O* **54**, 610)

Sedimentary Setting

- Phytodetritus was evident at the sea floor at +Fe but not at HNLC.
- Chlorophyll concentrations higher in +Fe *vs* HNLC surficial sediments.
- Chlorophyll/ phaeopigment in surficial sediments 1.89 vs. 0.64 at +Fe and HNLC, respectively – implies fresher material at +Fe.