Iron studies during JGOFS

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- Fe and JGOFS - historical perspective
- Fe limitation and the Biota
- Biogeochemical cycling of Fe
- Reappraisal - Fe supply and the global C cycle?
IRON and CLIMATE

Marine biota play a key role in climate by regulating atmospheric CO₂ levels.

One means of regulation is via the BIOLOGICAL PUMP.

The PUMP works most efficiently when all of the available nutrients are utilised.
The Vostok ice core provided tantalising evidence of the impact of changes in Fe supply on atmospheric CO2 (Martin, 1990)
Historical perspective

- S. Ocean Paradox - Gran, Hart
- Trace metal chemistry and contamination (Patterson, Bruland, Martin) - improved techniques
- Shipboard Fe enrichments - Martin, de Baar
- The link to climate - Fe Hypothesis - Martin
- *In situ* Fe enrichments - SF$_6$ - Watson, Duce, Liss, Martin
JGOFS Sites in relation to (modelled) dust deposition

Field studies/surveys

Time-series

(g m^{-2} yr^{-1}) N. Mahowald et al. (1999)
JGOFS STUDIES IN HNLC POLAR WATERS

There were also major studies conducted in tropical (EQPAC) and subpolar (N PACIFIC) HNLC waters
Fe limitation and the biota

1) Shipboard Fe enrichments

2) Oceanic surveys - spatial relationships

3) Molecular and other proxies of Fe stress

4) *In situ* mesoscale Fe additions
Shipboard Fe Enrichments

[Graph showing chlorophyll concentration over days with and without iron added.]

S. Ocean - Martin, de Baar……
EqPac - Coale, Price…..
NE Pacific - Martin, Coale…….
Oceanic surveys - spatial relationships

de Baar et al. (1995) - Polar Front (Atlantic sector)
Iron, chlorophyll and CO$_2$ drawdown
Molecular and other proxies of Fe Stress

LaRoche et al. (1996)
NE Pacific
Flv can substitute for Fd to alleviate iron stress by reducing the cell’s Fe requirements

Other proxies
FRRF - biophysical (Falkowski....)
Nutrient uptake kinetics (Coale, Timmermans....)
**In situ** Fe enrichments - (10 km length-scale)

IronEx I - subducted after 3-4 days, increase in $F_v/F_m$

IronEx II - chlorophyll 0.3 to $>3$ mg m$^{-3}$, CO$_2$ and DMS
Fe limitation and mesoscale Fe enrichments in the S. Ocean

Largest inventory of unused nutrients
Deep-water formation
Other limiting factors? Mixed layers, Si, Krill?

SOIREE Summer, Pacific sector
Eisenex - Spring, Atlantic sector
SOFEX - Summer - Pacific sector.
*In situ* experiments have yielded similar trends

- **Cell size**
- **Cellular chlorophyll**
- **Increased growth rate, C fixation,** $F_v/F_m$
- **Altered Si:C uptake ratio’s**
- **Floristic shifts**

**DMSP**

**C fixation**
But there have also been different trends between tropical and polar HNLC in situ experiments.

Iron-binding ligands and their production
In situ experiments permit the concurrent examination of many parameters, permitting the construction of Fe budgets and validation data for models.
Fe budget from SOIREE (Bowie et al. 2001)

**Atmospheric flux**
- SOIREE Fe enriched patch (140°E, 61°S)
- 180 pM d⁻¹
- 1073 pM
- 1110 pM
- 11.9
- 3.3
- 6.5

**Diffusive flux**
- 0.1 pM d⁻¹
- negligible
- 72 pM d⁻¹
- 0.85 pM d⁻¹
- 0.72 pM d⁻¹
- 0.79 pM d⁻¹

**Particulate Fe** (inorganic and detrital)
- 1073 pM

**Dissolved Fe**
- 1110 pM

**Sinking biogenic Fe** (from sediment trap data, mostly diatom aggregates)
- 58 pM
- 25.2 pM
- 19 pM

**Sinking mesozooplankton biogenic Fe** (predicted from biogenic budget)

**Biogenic Fe**
- 11.9
- 3.3

**Patch area**
- 56 to 200 km²

**Four Fe infusions over 13 d**
- (ferrous sulphate solution)
- 0.004 pM d⁻¹
- 185 pM d⁻¹

**Upwelling**
- 0.004 pM d⁻¹

**Sinking non-biogenic Fe**
- 72 pM d⁻¹

**SOIREE Fe enriched patch**
- OUT patch
- IN patch

**Upper mixed layer**
- 65 m
Numerical modelling of SOIREE (Hannon et al., 2001)
Biogeochemical cycling of Fe

What are the relative contributions of

Atmospheric inputs

Upwelling

Martin
Dust deposition is dominant in the NE Pacific

de Baar; Measures
Upwelling is the dominant driver in the S. Ocean
Remote-sensing (TOMS, SeaWiFs) has enabled us to monitor episodic dust events from source to sink
Other iron supply mechanisms

Ice melt (Sedwick, DiTullio)
Offshore transport of Fe in eddies (Crawford, Whitney)
Coastal ocean - geomorphology (Bruland, Hutchins)

Upwelling - Cromwell undercurrent (Coale, Chavez)
(Measures & Vink, 2001) Dissolved Fe profiles: little decrease in DFe during the ‘growth season’

Relatively flat profile compared to macro-nutrients

THE ‘FERROUS’ WHEEL (Kirchman, 1997)

Evidence that the microbial loop rapidly recycles Fe

Heterotrophic bacteria
Heterotrophic nanoflagellates
Viruses ??
IRON AND THE OCEANIC C CYCLE

What has been learnt during JGOFS

The Fe Hypothesis

Tenet 1 - Fe would increase phytoplankton growth

Tenet 2 - Fe would increase C sequestration

Modelling - yes, Field data ??
Modeling

Watson et al. (2000)

SOIREE
CO2 drawdown
Si:C uptake ratio’s

Glacials
predicted timing and magnitudes match records well

Glacial terminations
Fe supply - 50% of 80 ppm CO2 change
In situ experiments display increases in chlorophyll, but not always increases in export - WHY?

Fig. Courtesy K. Buesseler
Time-series of Photosynthetic competence provides some clues
SOIREE vs. polar blooms

Few data available on the temporal evolution of polar blooms

Mooring data in the vicinity of the APFZ (60S, 170W) from 10 bio-optical arrays provides excellent coverage

Why the exceptional longevity of SOIREE?

Fe Patch increased from 50 to 1100 km²

IN
HNLC waters
hi Si
low Fe
low diatoms
low Chl

OUT
low Si
hi Fe*
hi chla
hi diatoms

Stretching via horizontal flows
Mixing of water by horizontal diffusion
DOES ‘DILUTION’ OF CELLS PREVENT AGGREGATION
The Future

• Improved global/seasonal coverage of DFe profiles
• Better understanding of Fe biogeochemistry - Fe:C ratios, scavenging, remineralisation length scales
• More data to explore the links between Fe supply, bloom termination and export (and C sequestration)
• Use of SF$_6$ approach for other manipulations - DISCO, FeCycle
• The Fe-phytoplankton link is an example of what can be achieved for other key groups - N Fixers, Calcifiers...
Conclusions

• During JGOFS *in situ* mesoscale expts have confirmed the key role that iron plays in the ocean C Cycle
• Expts have placed JGOFS field studies into context - IronEx II and EQPAC
• Iron supply results in similar trends in tropical - polar HNLC waters
• Some divergences remain - Fe-L production