What can we learn from natural iron sources?

Stéphane Blain
Laboratoire océanographie et biogéochimie
CNRS-Université de la Méditerranée
Marseille (Fr)

Thanks to the KEOPS and CROZEX teams

What can we learn from natural iron fertilization?

NEWS
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Only mother nature knows how to fertilize the ocean

Web site Nature, Q. Schiermeier
Natural iron fertilization: what is it?

Two criteria:

enhanced supply of iron (field data) and enhanced biological activity

compared to the background of the region
Is natural iron fertilization a common process in the ocean?
“....In conjunction with this research a study will be made of the HNLC water west of the Galapagos Islands. This area is of interest since it appears to represent a natural enrichment experiment.”
Islands in HNLC waters

**Kerguelen I.**

**Crozet I.**

**Marquesas I.**

Blain et al. 2007

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Polar Front in the Atlantic Southern Ocean

(de Baar et al. 1995)
Coastal upwelling

Californian upwelling

Monterey bay

K.S. Johnson et al. 1999

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March 1997

March 1998

Dissolvable iron (nM)

Monterey Bay

S

Fe

Nitrate (uM)

Chlorophyll (mg m^-2)

Monterey Bay

Longitude (degrees west)

K.S. Johnson et al. 1999
Anticyclonic mesoscale Haida eddies in the eastern North Pacific Ocean

(W.K. Johnson et al. 2005)
Oligotrophic gyres

Boyle et al. 2005

Sedwick et al. 2005

Bergquist et al. 2006

Sarthou et al. 2007

Blain et al. subm.

Bergquist et al. 2006

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Guieu et al. 2002

Jickells et al. 2005
Oligotrophic gyres

Boyle et al. 2005
Sedwick et al. 2005
Bergquist et al. 2006
Sarthou et al. 2007

Blain et al. subm.
Bergquist et al. 2006

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Guieu et al. 2002
Oligotrophic gyres

Boyle et al. 2005

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Sedwick et al. 2003

BATS summer

BATS spring

Boyle et al. 2005

ALOHA Surface Fe Variability 1994-2002 (collapsed on annual cycle)

Boyle et al. 2005
Oligotrophic gyres

At DYFAMED site
(Med. Sea between Nice and corsica)

Bonnet et al. 2006

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Natural iron fertilization from above and N\textsubscript{2} fixation

Mars 2000

Mahaffey et al. 2003

Septembre 2000

Sarthou et al. 2003
What are the characteristics of iron supply to the ocean by natural processes?

How do they compare with those of purposeful additions?
What are the natural chemical forms of iron coming from below?

Natural speciation (KEOPS)

Dissolved phase dominated by organic complexation with an excess of ligands (Gueringa et al.)

Dissolution of lithogenic particulate Fe is a possible additional source.

Speciation after infusion

Fe(II)$_d$, Fe(III)$_d$, Fe(II)SO$_4$

Aggregation and sinking (Wells 2003, Nishioka et al. 2005)
**Natural iron supply**

**Iron fertilization symposium WHOI 26-27 sept 2007**

**What are the natural chemical forms of iron coming from above?**

<table>
<thead>
<tr>
<th>Mineral class</th>
<th>mineral</th>
<th>% in aerosol</th>
<th>% DFe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>illite</td>
<td>45</td>
<td>67.4</td>
</tr>
<tr>
<td></td>
<td>kaolinite</td>
<td>7</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>smectite</td>
<td>15</td>
<td>27</td>
</tr>
<tr>
<td>Clay</td>
<td>montmorillonite</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>oligoclase</td>
<td>6</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>orthoclase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>hematite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>beidellite</td>
<td></td>
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<tr>
<td>Clay</td>
<td>kaolinite</td>
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<tr>
<td>Clay</td>
<td>nontronite</td>
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<tr>
<td>Clay</td>
<td>montmorillonite</td>
<td></td>
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<tr>
<td>Clay</td>
<td>hematite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>goethite</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>Clay</td>
<td>magnetite</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Journet et al. subm.*
### Natural iron supply

<table>
<thead>
<tr>
<th>Mode of addition</th>
<th>Flux of DFe (µmol m^-2 d^-1)</th>
<th>Flux of TFe (µmol m^-2 d^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>more or less continuous</td>
<td>&lt; 10^-1</td>
<td>1 ?</td>
</tr>
</tbody>
</table>
| **Natural**  
  From below | ![Image](image1) | ![Image](image2) |
| pulsed | ![Image](image3) | ![Image](image4) |
| **Natural**  
  From above | ![Image](image5) | ![Image](image6) |
| pulsed | ![Image](image7) | ![Image](image8) |
| **Acidic FeSO_4** | ![Image](image9) | ![Image](image10) |
| pulsed | ![Image](image11) | ![Image](image12) |

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Iron is never supplied alone, macronutrients are also added.

From deliberate release
Macronutrient entrainment during SERIES

From below

From above

Silicic acid

(Law et al. 2007)
FeSO$_4$ addition is a poor imitation of the natural processes of fertilization, but is it an important issue? Yes it is.
What can we learn from natural iron fertilization on carbon sequestration in the ocean?
$CO_2$ sink

**OISO cruises, South Indian**

1998-2007  
(Courtesy N. Metzl)

- oiso1
- oiso2
- oiso3
- oiso4
- oiso5
- oiso6
- oiso8

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**CO2 sink**

**Carbon sequestration**

**Jouandet et al.**

**Kerguelen S.**

**Bakker et al.**

**Crozet**
## Carbon export

<table>
<thead>
<tr>
<th>Experiment</th>
<th>duration</th>
<th>excess of C export at 100m</th>
<th>excess of C export at 200m</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOIREE</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>Charette and Buesseler, 2000</td>
</tr>
<tr>
<td>EisenEx</td>
<td>22</td>
<td>0</td>
<td>0</td>
<td>Rutgers van der Loeff and Vöge, 2001</td>
</tr>
<tr>
<td>SOFeX-S</td>
<td>27</td>
<td>7 ± 3</td>
<td>-</td>
<td>Buesseler et al, 2005</td>
</tr>
<tr>
<td>KEOPS</td>
<td>~ 90</td>
<td>11 ± 5</td>
<td>14 ± 8</td>
<td>Savoye et al. (2007)</td>
</tr>
<tr>
<td>CROZEX</td>
<td>~ 90</td>
<td>9.4 ± 1.5</td>
<td></td>
<td>Morris et al. (2007)</td>
</tr>
<tr>
<td>EIFEX</td>
<td>36</td>
<td>13 ± 13</td>
<td></td>
<td>Savoye (unpublished)</td>
</tr>
</tbody>
</table>

**Efficiency** = \[
\frac{\text{Excess of carbon export (mol)}}{\text{Excess of DFe supply (mol)}} \times 100%
\]

\[
\begin{align*}
\text{Efficiency} & = \frac{70,000 \pm 40,000}{668,000} \\
& = 10.46\% \\
\end{align*}
\]

Compared to 4,300 for SO exp. (de Baar et al. 2006)
KEOPS: Fraction of the int. PP exported at 100 m was twice lower in the bloom than in HNLC waters

(Savoye et al. 2007)

but

KEOPS: The fraction of the Cexp that was transferred below 450 m was higher below the bloom than in HNLC waters

(Jacquet et al. 2007)

C and Fe cycles coupling

KEOPS: No preferencial remineralization of C and Fe in the mixed layer and also in the seasonal thermocline of the Kerguelen bloom

(Obernosterer et al. 2007, Sarthou et al. 2007)

but

FECYCLE

During the unperturbated experiment in the subantarctic, Preferencial remineralisation of C versus Fe was observed below the MLD

(Boyd et al. 2005, Frew et al. 2005)
Bacteria play a crucial role in coupling/decoupling C and Fe cycles in fertilized systems.
Natural iron fertilization does not only increase the rates of the biogeochemical processes but it drives a complete change of the ecosystem.

New parameterisations, new laws?

There is large variety of natural iron fertilized sites in the ocean with a large potential for new findings.

The short term mesoscale iron fertilization experiment was a powerful tool for research in oceanography. The second generation of experiments should be more “subtle” to make their results more comparable with natural processes.

The mode of iron addition, planned in large scale / commercial iron fertilization, does not imitate a natural process of fertilization.