Evolution of the Biological Pump

Andy Ridgwell
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Decreased atmospheric $\text{pO}_2$

Dissolved oxygen ($\mu$mol kg$^{-1}$)

Dissolved $\text{H}_2\text{S}$ (mmol kg$^{-1}$)

Period Era Eon

<table>
<thead>
<tr>
<th>Ng</th>
<th>Pg</th>
<th>K</th>
<th>J</th>
<th>T</th>
<th>P</th>
<th>C</th>
<th>D</th>
<th>O</th>
<th>Cm</th>
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</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td></td>
<td>Mesozoic</td>
<td></td>
<td></td>
<td>Paleozoic</td>
<td>Phanerozoic</td>
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<tr>
<td>Neoproterozoic</td>
<td></td>
<td>Mesoproterozoic</td>
<td></td>
<td></td>
<td>Paleoproterozoic</td>
<td>Proterozoic</td>
<td>Archean</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time (Ma)

Modern Pacific (zonal mean)
Evolution of the Biological Pump

Major changes in plankton assemblage:
- Coccolithophorids
- Diatoms
- Radiolarians
- Foraminifera

Martin [1995]

Period:
- Ng
- Pg
- K
- J
- T
- P
- C
- D
- O
- Cm

Era:
- Cenozoic
- Mesozoic
- Phanerozoic
- Paleozoic
- Proterozoic
- Neoproterozoic
- Mesoproterozoic
- Paleoproterozoic
- Archean

Time (Ma)
Evolution of the Biological Pump

Reconstructed pCO₂

Occurrence of ice ages (relative intensity)

Major changes in plankton assemblage

Martin [1995]

Crowell [1999]

Period Era Eon

Cenozoic Mesozoic Paleozoic Phanerozoic

Neoproterozoic Mesoproterozoic Paleoproterozoic Proterozoic Archean

Time (Ma)

0 100 200 300 400 500 1000 1500 2000 2500 3000 3500

pCO₂ (ppm)

0 1000 2000 3000 4000 5000 6000 7000

Evolution of plankton assemblage over time, with changes in CO₂ levels and ice ages.

Foraminifera

Coccolithophorids

Dinoflagellates

Acrifarchs

Radiolaria

Diatoms

Martin [1995]

Crowell [1999]

Royer et al. [2004]

Reconstructed pCO₂

Period

Era

Eon

Ng Pg K J T P C D O Cm

Neoproterozoic Mesoproterozoic Paleoproterozoic Proterozoic Archean

Time (Ma)

0 100 200 300 400 500 1000 1500 2000 2500 3000 3500

Evolution of plankton assemblage over time, with changes in CO₂ levels and ice ages.

Foraminifera

Coccolithophorids

Dinoflagellates

Acrifarchs

Radiolaria

Diatoms

Martin [1995]

Crowell [1999]

Royer et al. [2004]
The processes that govern the partitioning of carbon (and alkalinity) between the surface ocean (and hence atmosphere) and ocean interior, are traditionally described in terms of three conceptual 'pumps':

(1) the 'solubility' pump
(2) the 'organic matter' (or 'soft tissue') pump, and
(3) the 'carbonate' (or 'counter') pump.

This conceptual framework has more recently extended by a fourth component:
(4) the microbial carbon pump.
(1) The solubility pump

- Mixing
- Up-welling
- Down-welling
- Surface ocean
- Deep ocean
(1) The solubility pump

![Diagram showing oceanic mixing and air-sea O\textsubscript{2} exchange.]

- **Modern Atlantic (zonal mean)**
- **Modern Pacific (zonal mean)**

- Dissolved oxygen (µmol kg\(^{-1}\))
- Depth (km)

- **Air-sea O\textsubscript{2} exchange**
- Mixing
- Upwelling
- Downwelling
(1) The solubility pump

![Diagram showing solubility pump and air-sea \( \delta^{13}C \) fractionation](image)
(2) The organic matter (soft-tissue) pump

The strength of the biological pump is dictated by biological export production and all the processes (e.g., nutrient availability) that govern that.
The efficiency of the biological pump is dictated by the depth at which organic matter is remineralized and carbon (and nutrients) released into the water column together with the large-scale circulation of the ocean which sets the rate and location of carbon (and nutrient) return to the surface.
(2) The organic matter (soft-tissue) pump

- Modern Atlantic (zonal mean)
- Modern Pacific (zonal mean)

Dissolved oxygen (µmol kg\(^{-1}\))

Depth (km)

- CO\(_2\) fixation
- C\(_{org}\) oxidation
- C\(_{org}\) oxidation

Surface ocean

Deep ocean
(2) The organic matter (soft-tissue) pump

The diagram shows the distribution of $\delta^{13}C_{\text{DIC}}$ (%) with depth in the modern Atlantic and Pacific Oceans. The areas labeled 'Modern Atlantic (zonal mean)' and 'Modern Pacific (zonal mean)' indicate the average conditions in these regions.

Key processes highlighted include:
- CO$_2$ fixation
- C$_{\text{org}}$ oxidation
- Surface ocean
- Deep ocean
(3) The carbonate pump

\[
\text{Ca}^{2+} + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 + \text{CO}_{2\text{aq}} + \text{H}_2\text{O}
\]
(4) The microbial (dissolved organic) carbon pump

Hansell [2012]
Evolution of the Biological Pump: The ‘stagnant’ ocean(?)
The ‘stagnant’ ocean(?)

End Cretaceous (@180°W)

Modern (@180°W)
The ‘stagnant’ ocean(?)

Modern (@180°W)

End Cretaceous (@180°W)
The ‘stagnant’ ocean (?)
The ‘stagnant’ ocean(?)

* see: Eleanor John’s talk after lunch *

+ T-dependent POC remineralization

<table>
<thead>
<tr>
<th>Depth (km)</th>
<th>Dissolved oxygen (μmol kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

Modern (@180°W)

End Cretaceous (@180°W)
Evolution of the Biological Pump:

Pelagic biomineralizers and the ‘ballast hypothesis’

Major changes in plankton assembled

Eon
Archean
Proterozoic
Paleoproterozoic
Mesoproterozoic
Neoproterozoic
Phanerozoic
Cm

Period
Cenozoic
Paleozoic
Mesozoic
Phanerozoic

Time (Ma)
0 100 200 300 400 500 1000 1500 2000 2500 3000 3500

Foraminifera
Dinoflagellates
Acrifarchs
Radiolaria
Coccolithophorids
Diatoms
Acritarchs

Martin [1995]
Pelagic biomineralizers and the ‘ballast hypothesis’

Wilson et al. [2012]
Pelagic biomineralizers and the ‘ballast hypothesis’

Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for CaCO₃.

Wilson et al. [2012]
Evolution of the Biological Pump: A DOC-dominated carbon cycle?
A DOC-dominated carbon cycle?

Contours of carbon release vs. source isotopic signature for a global -4‰ carbon isotopic excursion. Contours differ according to the initial mean global $\delta^{13}C$. 

Ridgwell and Arndt [submitted]
A DOC-dominated carbon cycle?

In the Rothman et al. [2003] model, the RDOC reservoir is assumed to have been at least 10 times the size of the inorganic (ocean DIC + atmospheric pCO$_2$) reservoir. For a modern DIC + pCO$_2$ reservoir of 39,000 PgC, this means 390,000 PgC of DOC – more than 500 times larger than modern). For a higher late Precambrian DIC reservoir, the minimum DOC reservoir becomes $1.6 \times 10^6$ PgC, equivalent to a concentration of over 1000 mgC per L of seawater and becoming the third most dominant dissolved species in the ocean after Cl$^-$. 

Ridgwell and Arndt [submitted]
A DOC-dominated carbon cycle?

In the Eocene hyperthermal RDOC hypothesis, difficulties include envisioning a sufficiently stratified deep ocean (even when ignoring the lack of any evidence for widespread anoxia) that could partition RDOC away from the upper ocean and destruction by oxidation/photo-dedegregation.
One possibility might be a biotic change that resulted in a drastic reduction in RDOC production. Notably: the (modern) decay time of RDOC – ca. 10 kyr – is consistent with the time-scale of PETM onset.
Evolution of the Biological Pump: Beginnings
Marine planktonic cyanobacteria and Molybdenum record

Sahoo et al. (2012); Sanchez-Baracaldo et al. submitted
Biological pump during the boring billion?

Minimal N supply to the open ocean
Minimal open ocean primary production

Transitional interval
Origin of eumetazoa
Origin of pelagic eumetazoa

Taxonomic longevity (~Stability)
(pre-metazoan)
Microbial world

Increase fossil diversity
750 Ma

Planktonic N Fixers
Syn/Pro

Morphological disparity /Biomass

Cambrian explosion

MESOPROTEROZOIC
NEOPROTEROZOIC
PHANEROZOIC

1600 1000 630 530 0 Ma

Butterfield (2011)
Evolution of the Biological Pump: Summary (of sorts)
Thanks to:

Jamie Wilson & Steve Barker [Cardiff]
Patricia Sanchez-Baracaldo [Bristol]
Eleanor John, Paul Pearson [Cardiff]