Biological carbon pumping in ‘deep time’: The Force Awakens

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Outline

**solubility pump**
- out-gassing (70)
- $pCO_2$ (g)
- in-gassing (70)
- warm
- cold
- mixing
- deep-sea $CaCO_3$ burial (0.1)
- neritic $CaCO_3$ burial (~0.05)
- carbonate + silicate weathering (0.2)
- water-column dissolution (0.6)
- $CaCO_3 + CO_2(\text{aq}) + H_2O \rightarrow Ca^2+ + 2HCO_3^-$

**organic carbon pump**
- kerogen weathering (0.05)
- net $CO_2$ fixation (10.0)
- $C_{org}$ oxidation (9.9)
- $C_{org}$ oxidation (0.1)
- $pCO_2$ (g)

**carbonate pump**
- terrestrial DOC input
- UV creation/destruction
- RDOC [630 PgC]
- SLDOC [6]
- SRDOC [14]
- RDOC creation
- scavenging

**microbial carbon pump**
- $CaCO_3 + CO_2(\text{aq}) + H_2O \rightarrow Ca^2+ + 2HCO_3^-$
- calcification (1.1)
- $CaCO_3 + CO_2(\text{aq}) + H_2O \rightarrow Ca^2+ + 2HCO_3^-$
- seafloor dissolution (0.4)
- deep-sea $CaCO_3$ burial (0.1)
- neritic $CaCO_3$ burial (0.1)
Outline

**Carbonate Pump**
- Carbonate+silicate weathering (0.2)
- Water-column dissolution (0.6)
- Seafloor dissolution (0.4)
- Neritic CaCO₃ burial (0.1)
- Deep-sea CaCO₃ burial (0.1)

**Microbial Carbon Pump**
- Terrestrial DOC input
- UV creation/destroyment
- SRDOC [14]
- SLDOC [6]
- RDOC [630 PgC]
- RDOC creation
- Scavenging

**Organic Carbon Pump**
- Kerogen weathering (0.05)
- Net CO₂ fixation (10.0)
- C₉₉ oxidation (9.9)
- C₉₉ oxidation (0.1)

**Solubility Pump**
- Out-gassing (70)
- In-gassing (70)
- Warm pCO₂
- Cold pCO₂

**Outline**
- Biological export and remineralization
- Microbial carbon pump
- Carbonate pump
- Organic carbon pump
- Solubility pump

**Time Periods**
- Archean
- Paleoproterozoic
- Proterozoic
- Paleozoic
- Mesozoic
- Cenozoic

**Major Events**
- Calcification (1.1)
- Seafloor dissolution (0.4)
- Water-column dissolution (0.6)
- Carbonate+silicate weathering (0.2)
Outline

**carbonate pump**

- carbonate+silicate weathering (0.2)
- neritic CaCO$_3$ burial (0.1)
- water-column dissolution (0.6)
- seafloor dissolution (0.4)
- deep-sea CaCO$_3$ burial (0.1)

**organic carbon pump**

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**microbial carbon pump**

- terrestrial DOC input
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- SLDOC [6]
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- RDOC creation
- scavenging

**solubility pump**

- out-gassing (70)
- in-gassing (70)
- warm $p$CO$_2$
- cold $p$CO$_2$
- mixing

**biological export (f(...)), remineralization (f(...))

$pump = f(...)$
Outline

Phanerozoic

Cm

Proterozoic

Archean

Paleoproterozoic

Phanerozoic

Cenozoic

Mesozoic

Paleozoic

K

Pg

Ng

J

T

P

C

D

S

O

Cm

Neoprot.

Mesoprot.

Paleoproterozoic

Proterozoic

Archean

Lyons et al. [2014] (Nature 506)

Oxygenic photosynthesis

$\log[p_{O_2}(\text{atm})]$

$\log[p_{O_2}(\text{atm})]$

$10^0$

$10^{-2}$

$10^{-4}$

$10^0$

$10^{-2}$

$10^{-4}$

$10^{-6}$

$10^{-8}$

Age (Gyr ago)

$4.0$ $3.5$ $3.0$ $2.5$ $2.0$ $1.5$ $1.0$ $0.5$ $0.0$

-5

-4

-3

-2

-1

$O_{Lys}$ et al. [2014] (Nature 506)
Outline

Phanerozoic

Proterozoic

Archean

Paleoproterozoic

Phanerozoic

Cenozoic

Mesozoic

Paleozoic

Lyons et al. [2014] (Nature 506)
Origins ...
Solubility pump

- Out-gassing (70)
- In-gassing (70)

\[ p_{CO_2(g)} \]

Mixing

Up-welling

Down-welling

\[ p_{CO_2} \]

Carbonate+silicate weathering (0.2)

Neritic CaCO\(_3\) burial (0.2)

‘Abiotic’ precipitation rate:

\[ r = f \cdot (W-1)^n \]

where \( n \sim 1.5-2.0 \)

Burial ... but no ‘pump’
The Force awakens ... ???

Evolutionary innovations & plankton assemblage

Cyanobacteria

Period
Era
Eon

Time (Ma)

origin of photosystems I and II

Archean
The Force awakens ...

Blank and Sánchez-Baracaldo [2010] (Geobiology)

Salinity
- freshwater
- brackish
- marine
- hypersaline

Period
Era
Eon

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

Time (Ma)

Acaryochloris marina MBIC11017
Synechococcus sp. IR11
Synechococcus sp. PCC6312
Synechococcus sp. PCC6716
Thermosynechococcus elongatus BP1
Anabaena variabilis ATCC25943
Nostoc sp. PCC7120
Nodularia PCC73104
Nodularia spumigena CCY9414
Nostoc punctiforme PCC73102
Chlorogloeopsis PCC6912
Fischbeckia muscosa
Chroococcidiopsis thermalis PCC7203
Chroococcidiopsis sp. PCC7451
Arthrospira platensis PCC7345
Lyngbya sp. PCC7419
Trichodesmium erythraeum IMS101
Oscillatoria sp. PCC7112
Crocophora watsonii WH8501
Cyanothecae sp. CCY0110
Gloeotheca KO1000
Cyanothecae sp. PCC5801
Cyanothecae sp. PCC7418
Pleurocapsa PCC7119
Xenococcus sp. PCC7307
Stainier cyanospirae PCC7437
Oscillatoria rosea IAM M-220
Synechococcus sp. PCC7002
Synechococcus sp. PCC8806
Leptolyngbya nodulosa UTEX2910
Oscillatoria neglecta IAM M-62
Leptolyngbya PCC7104
Phormidium sp. MBIC1025
Spirulina taxinimia
Leptolyngbya sp. MIES
Leptolyngbya PCC7375
LPP cyanobacterium

Phormidium princeps ANT P.2.6
Synechococcus sp. PCC7335
Pleocystis F3
Cyanobium gracile PCC6307
Synechococcus sp. PCC7918
Cyanobium PCC7009
Synechococcus sp. NAN
Synechococcus sp. PCC600
Cyanobium sp. PCC7001
Prochlorococcus marinus str. MIT9211
Prochlorococcus marinus str. CCMP1375
Prochlorococcus marinus str. MIT19312
Prochlorococcus marinus str. CCMP1986
Prochlorococcus marinus str. MITL2A
Prochlorococcus marinus str. MIT9313
Synechococcus sp. CC9311
Synechococcus sp. WH8020
Synechococcus sp. WH7803
Synechococcus sp. WH7806
Synechococcus sp. WH8015
Synechococcus sp. RS9917
Synechococcus sp. CS0605
Synechococcus sp. WH8102
Nannochloropsis oithonoides NIES-40
Microcystis elobens NIES-43
Synechococcus elongatus PCC6301
Synechococcus sp. JA-2-3D(12-13)
Synechococcus sp. JA-3-3Ab
Gloeobacter violaceus PCC7421
**solubility pump**

- Out-gassing (70)
- In-gassing (70)
- Warm $pCO_2(g)$
- Cold $pCO_2$
- Mixing
- Up-welling
- Down-welling

**microbial carbon pump**

- Carbonate+silicate weathering (0.2)
- Neritic $CaCO_3$ burial (~0.05)
- Kerogen weathering (0.05)
- DOC leak ???

**Period**

- Paleoarchean
- Paleoproterozoic
- Proterozoic

**Time (Ma)**

- 0 to 3500
The Force awakens ...

Evolutionary innovations & plankton assemblage

- **Eukaryotes [Knoll, 2014]**
- **Cyanobacteria (planktonic) [Sánchez-Baracaldo, 2015]**
- **Cyanobacteria (benthic) [Sánchez-Baracaldo, 2015]**
solubility pump

out-gassing (70) \[ pCO_2 \] (g) \[ warm \]\[ pCO_2 \] \[ cold \] in-gassing (70)

mixing

up-welling

donw-welling

carbonate+silicate weathering (0.2)

neritic \[ \text{CaCO}_3 \] burial (0.2)

kerogen weathering (0.05)

neritic \[ \text{CaCO}_3 \] burial (~0.05)

microbial carbon pump

terrestrial DOC input

UV creation/destruction

SLDOC

SRDOC

RDOC

Period
Era
Eon

Mesoproterozoic
Paleoproterozoic
Proterozoic
Archean

Time (Ma)

0 500 1000 1500 2000 2500 3000 3500
Ridgwell and Arndt [2014]
When RDOM ruled the World(?)

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 [2014]
When RDOM ruled the World(?)

Terrestrial DOC input (?)

UV creation/destruction

SLDOC [6]

SRDOC [14]

RDOC [630 PgC]

RDOC [??? PgC]

deep ocean

surface ocean

DOC creation

scavenging
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 1.6×10$^6$ PgC, equivalent to concentration of a little over 1000 mgC per L of seawater and becoming the third most dominant dissolved species in the ocean after Cl.)
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 pCO₂) reservoir. For a modern DIC + pCO₂ reservoir of 39,000 PgC, this mean 390,000 PgC of DOC – more than 500 times larger than modern).

(For a higher late Precambrian DIC reservoir, the minimum DOC reservoir becomes 1.6×10⁶ PgC, equivalent to concentration of a little over 1000 mgC per L of seawater and becoming the third most dominant dissolved species in the ocean after Cl⁻.)
When RDOM ruled the World(?)

Lyons et al. [2014] (Nature 506)

Oxygenic photosynthesis

microbial carbon pump

UV creation/destruction

CO₂ fixation

C₆ oxidation

H₂S deep ocean

H₂S surface ocean
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.
The Force awakens ... for sure this time ... ???

Evolutionary innovations & plankton assemblage

Animals! (metzoans)
Eukaryotes [Knoll, 2014]
Cyanobacteria (planktonic) [Sánchez-Baracaldo, 2015]
Cyanobacteria (benthic) [Sánchez-Baracaldo, 2015]

Lyons et al. [2014] (Nature 506)
The Force awakens ... for sure this time ... ???

Low fixed N supply to the open ocean
Low open ocean primary production

Transitional interval

High diversity of N fixers
High primary production

Nodes of planktonic cyanobacteria
first occurrence (dashed circle)
and divergence (full circle)

Cyanobacterium UCYN-A
Cyanothece & Crocosphaera

Prochlorococcus

Marine Synechococcus

Trichodesmium

Sanchez-Baracaldo et al. [2014]

Paleoproterozoic  Mesoproterozoic  T  Cryogenian  E
Neoproterozoic  
Proterozoic  Phanerozoic

Age (Ma)

Mo/TOC (ppm wt-1)

N-fixers

I

IIa

IIb

III

Glacial events
The Force awakens!

Major changes in plankton assemblage

- Foraminifera
- Acritarchs
- Foraminifera
- Radiolarians
- CoccolithophorIDS
- Dinoflagellates

Periods:
- Neoproterozoic
- Mesoproterozoic
- Paleoproterozoic
- Proterozoic
- Paleozoic
- Mesozoic
- Cenozoic

Eons:
- Archean
- Proterozoic
- Phanerozoic

Time (Ma):
- 0
- 500
- 1000
- 1500
- 2000
- 2500
- 3000
- 3500
The Force awakens!

% occurrence of carbonate in ophiolite suites

Major changes in plankton assemblaged

Foraminifera

Boss and Wilkinson [1991]

% occurrence of carbonate in ophiolite suites

Diatoms

Era

Mesozoic

Paleozoic

Cenozoic

Phanerozoic

Period

Paleoproterozoic

Neoproterozoic

Proterozoic

Archean

Time (Ma)

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

Martin [1995]

Dinoflagellates

Acritarchs

Coccolithophorids

Radiolaria

Foraminifera

Phanerozoic

Cm

K

Pg

Ng

J

T

P

C

D

S

O

Neoproterozoic

Mesoproterozoic

Paleoproterozoic

Proterozoic

Archean

The Force awakens!
Compilation of sediment trap observations:
depths $\geq 2000$ m (to exclude hydrodynamically distorted
fluxes and relationships) and differentiated by basin:
cyan == Atl, yellow == Ind, green == Pac, magenta == SO.

[Wilson et al., 2012; GBC 26, doi:10.1029/2012GB004398]
Spatial distribution of carrying capacity (ballasting) coefficients calculated using geographically weighted regression analysis for CaCO$_3$. 

Wilson et al. [2012]
*When* did the Force awaken (modern biological pump form)?

- (1) Foraminifera
- (2) Coccolithophorids
- (3) Dinoflagellates
  - Bacteria
  - Algae
  - Plants
  - Animals
*When* did the Force awaken (modern biological pump form)?

**Diagram:***

- **Atmospheric pCO₂ (ppm):**
  - From 0 to 7000 ppm, showing fluctuations over time.

- **Occurrence of ice ages (relative intensity):**
  - Graph showing periods of high and low intensity.

- **Periods and Eras:**
  - Archean
  - Proterozoic
  - Paleozoic
  - Mesozoic
  - Cenozoic

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**Textual Information:**

- **Martin [1995]:**
  - Events such as Diatoms, Coccolithophorids, Foraminifera.

- **Crowell [1999]:**
  - Occurrence of ice ages.

- **Royer et al. [2004]:**
  - Atmospheric pCO₂ data.

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**Legend:**

- **Cm**: Cenozoic
- **Pg**: Paleozoic
- **K**: Mesozoic
- **T**: Proterozoic
- **D**: Paleoproterozoic
- **S**: Neoproterozoic
- **Archean**

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**Questions:**

1. What is the significance of the Foraminifera data in relation to the ice ages?
2. How does the atmospheric pCO₂ data correlate with the ice age occurrences?
3. What is the timeline for the emergence of the Force (modern biological pump form)?

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**Notes:**

- Coccolithophorids, Radiolaria, Dinoflagellates, Diatoms, Acritarchs.
Paleo Perspectives – Extreme climate states
(warm == stratified) && (stratified == anoxic) == .true.

???

(‘stratified’ || ‘sluggish’ || ‘stagnant’ )
Paleo Perspectives – Extreme climate states

x1 CO₂ pre-industrial reference simulation

x4 CO₂ Maastrichtian reference simulation
Paleo Perspectives – Testing the ‘metabolic’ hypothesis

(for water column POC remineralization)

John et al. [2014] (PPP 413)

early Eocene Tanzania

yellow == foraminiferal $\delta^{13}$C
$\delta^{18}$O has been converted into paleo temperature and then to habitat depth using a coupled GCM
red = binned data

Paleo Perspectives

Phanerozoic
- Cenozoic
- Mesozoic
- Paleozoic

Eon
- Phanerozoic
- Eon
- Paleozoic
- Mesozoic
- Cenozoic
- Period
- P, T, J, K, Pg, Ng

Time (Ma)
- 0
- 100
- 200
- 300
- 400
- 500

$\delta^{13}$C$_{DIC}$ (‰)
- -1.0
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

Paleo Perspectives – Testing the ‘metabolic’ hypothesis

Yellow == foraminiferal $\delta^{13}$C
$\delta^{18}$O has been converted into paleo temperature and then to habitat depth using a coupled GCM.
Red = binned data
Paleo Perspectives – Testing the ‘metabolic’ hypothesis

modern observations

yellow == observed $\delta^{13}$C$_{DIC}$
blue == model $\delta^{13}$C$_{DIC}$ (year 1994)
Paleo Perspectives – Testing the ‘metabolic’ hypothesis

- Modern observations
- Early Eocene Tanzania

Ocean depth (km)

δ^{13}C_{DIC} (‰)

blue == model δ^{13}C_{DIC} (Eocene config) using a Q_{10} remineralization formulation
Paleo Perspectives – ‘Hiccups’

(temporary disruption or removal of one or more processes)

Ridgwell et al. [in prep]
Summary and Perspectives

**Solubility Pump**
- Out-gassing (70)
- Warm
- $pCO_2(g)$
- In-gassing (70)
- Cold
- $pCO_2$

**Organic Carbon Pump**
- Kerogen weathering (0.05)
- Net CO$_2$ fixation (10.0)

**Carbonate Pump**
- Carbonate+silicate weathering (0.2)
- Water-column dissolution (0.6)
- Sea-floor dissolution (0.4)
- Deep-sea CaCO$_3$ burial (0.1)

**Microbial Carbon Pump**
- Terrestrial DOC input
- UV creation/destruction
- SLDOC [6]
- SRDOC [14]
- RDOC [630 PgC]
- SRDOC creation
- Scavenging

**Chemical Reactions**
- $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$
- $Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O$
- Calcification (1.1)
- Seafloor dissolution (0.4)
- Water-column dissolution (0.6)
- Deep-sea CaCO$_3$ burial (0.1)

**Geological Periods**
- Neoprot.
- Mesoprot.
- Paleoproterozoic
- Proterozoic
- Archean

**Geological Time**
- Phanerozoic
- Cenozoic
- Mesozoic
- Paleozoic
- Neoproterozoic
- Paleoproterozoic
- Archean
- Proterozoic
- Neoproterozoic
- Paleoproterozoic
- Archean
- Proterozoic
- Neoproterozoic
- Paleoproterozoic
- Archean