Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean

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Flux of material to the deep sea

→Dominated by particles settling at rates of several 100's $m.d^{-1}$

→ aggregation

Mineral ballast regulates the proportion of organic matter exported from the euphotic zone that reaches the deep sea?

By increasing sinking rates of particles (Ittekot et al., 1993)?

By protecting organic matter from biodegradation (Armstrong et al., 2001)?

If true → Transfer efficiency should increase with the flux of mineral ballast

Transfer efficiency = $^{z>2000m}(F_{Corg})$ / EP

$^{z>2000m}(F_{Corg})$ → measured with sediment traps

EP → from:

- satellite-derived ocean productivity model (Behrenfeld and Falkowski, 1997)
  (not in the Southern Ocean!!)

- f-ratio derived from a pelagic food web model (Laws et al., 2001)

- averaged over a 250 km x 250 km grid.

→ based on the "statistical funnel" through which particles sink before reaching the sediment trap (Siegel and Deuser, 1997).

Mean eddy kinetic energy ~10 $cm^2 s^{-2}$
Mean particle sinking rate ~200 m. d^{-1}

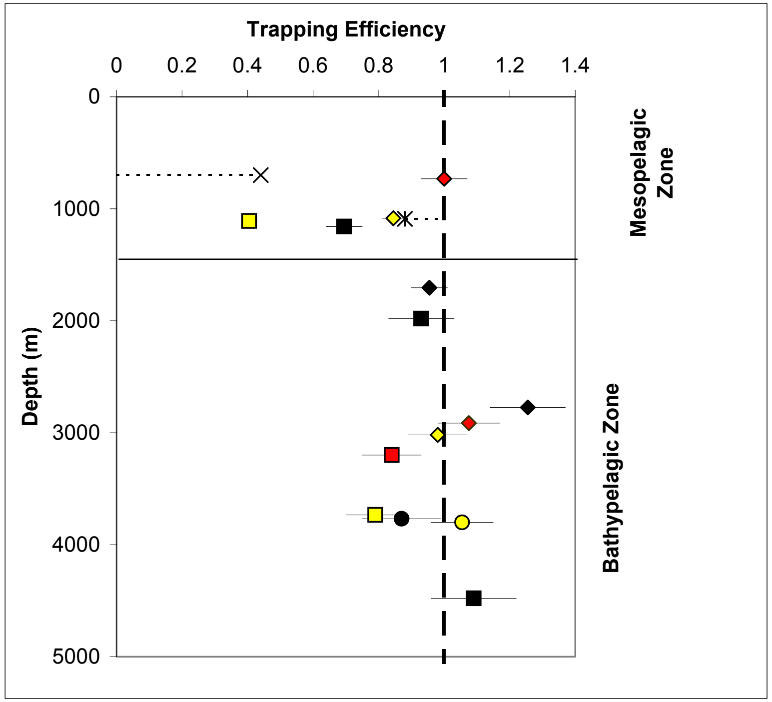
→ spatial averaging scale at the surface (L_x) for a trap deployed at 4000m depth is ~ 60 km (Siegel et al., 1990).

→ radius around the trap site from which 90% of the collected particles would originate is:

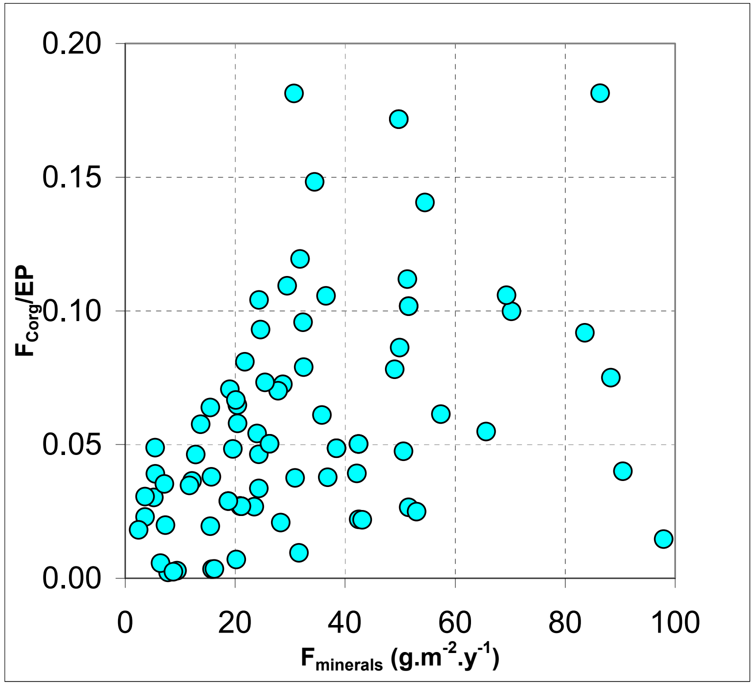
$\sqrt{-2\ln(0.1)}\, L_x = 125$ km

Why a 2000m cut-off?

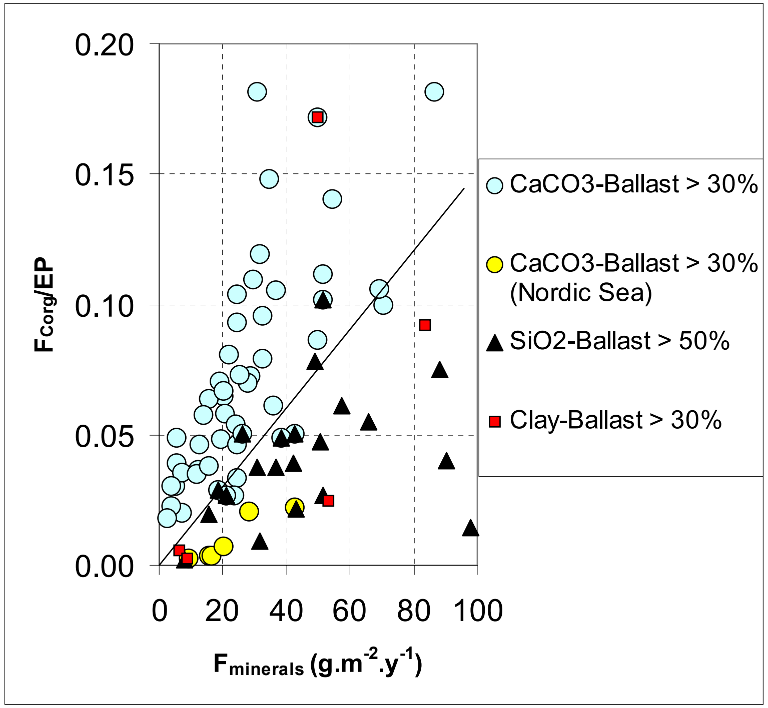
From mass balance of ^{230}Th and ^{231}Pa, sediment traps:
- Capture effectively the settling flux in the bathypelagic zone.
- Are more erratic and tend to undertrap in the mesopelagic zone



→ Shallow traps could add noise to the flux data, which could obscure statistical relationships between measured fluxes and other parameters.



$F_{minerals}$ = total flux - 1.87 x F_{Corg}



-->supports the view that the flux of minerals must be an important factor in establishing the transfer efficiency of organic carbon to the deep sea.
-->indicates that the nature of the minerals is equally important:
denser carbonates are more efficient than biogenic silica. The effect of lithogenic particles is less clear-cut, largely because they never are the dominant constituents of particles settling in the open ocean.

[Nordic Seas]??

Simplest empirical relationship predicting F_{Corg} to depths > 2000m from satellite-derived EP?

Within the range of $F_{minerals}$ measured over most of the ocean

→ F_{Corg}/EP appears to be:
- Broadly proportional to the flux of minerals
- Dependent on the type of minerals

We first assume that:

- F_{Corg}/EP at Z>2000m is linearly related to $F_{minerals}$
- Ballasting "capacity" of settling material depends on the relative proportion of opal, carbonate and lithics

$$F_{Corg}/EP = [(k_1^{ball}CaCO_3 + k_2^{ball}Opal + k_3^{ball}Lithog)\ F_{ballast}] + [k_4\ Z^{-1}]$$

→ We have 64 sites with:

- Independent estimates of F_{Corg} (from sediment traps deployed at depth > 2000m)
- EP (Behrenfeld and Falkowski, 1997; Laws et al., 2000)
- Direct measurements of carbonate, silica and lithogenic material

➔ 64 equations and 4 unknowns
➔ Fitted by multiple linear regression

Difference in biodegradability of organic matter exported from different planktonic ecosystems?

Warm, oligotrophic, carbonate-dominated systems

Less seasonal
Lower f-ratios.

→ Organic matter exported from the euphotic zone:
- has been **more thoroughly processed** by more complex food webs and effective microbial loops
- is more refractory

➔ Less remineralization in intermediate waters
➔ Higher transfer efficiency to the deep sea.

Colder, diatom-dominated regions

More seasonal
Blooms are more prominent
Higher f-ratios

→ Organic matter exported from the euphotic zone:
- has been **less thoroughly processed** by the food web
- is more labile

➔ More efficient remineralization in intermediate waters
➔ Lower transfer efficiency to the deep sea.

→ Add simple linear term to explore the importance of **seasonality** (ΔPP) in controlling transfer efficiency

$$\mathbf{F_{Corg}/EP} = \mathbf{[(k_1^{ball}CaCO_3 + k_2^{ball}Opal + k_3^{ball}Lithog)\ F_{ballast}] + [k_4\ Z^{-1}] + [k_5\ \Delta PP]}$$

ΔPP = difference between maximum and minimum seasonal production

Seasonal net primary production

January – March / April – June
July – September / October – December
($gC.m^{-2}.season^{-1}$)

taken from Behrenfeld and Falkowski productivity map

What does

$$\mathbf{F_{Corg}/EP = [3.64\ 10^{-3}\ F_{CaCO3}] + [68.4\ \ Z^{-1}] - [0.337\ 10^{-3}\ \Delta PP] - 0.002}$$

mean?

→ just a statistical relationship

→ not an explicit proof that F_{Corg} to the deep sea is directly and linearly controlled by carb. flux and seasonality as defined here

→ provides clues for possible underpinning mechanisms

65% of ΔT_{eff} is due to ΔF_{carb}

→ Suggests that ballasting effect of dense carbonates (2.7) may be important for increasing the sinking rates of settling particles.

→ But, biogenic opal and lithogenic materials are also denser than organic matter, and yet these minerals do not have "ballasting" capacities

➔ density cannot be the only factor coming into play

Is there a "packaging" factor that correlates with carbonate fluxes?

Particles sinking from carbonate-dominated ecosystem with complex food webs would be more tightly packaged in fecal pellets, while particles sinking from opal-dominated systems would be looser, less hydrodynamic aggregates made largely of senescent diatoms.

➔ Both higher biodegradability and loose packaging may be promoted by the highly seasonal nature of primary production at high latitudes, explaining the low transfer efficiency in these regions.

That must be directly tested by:

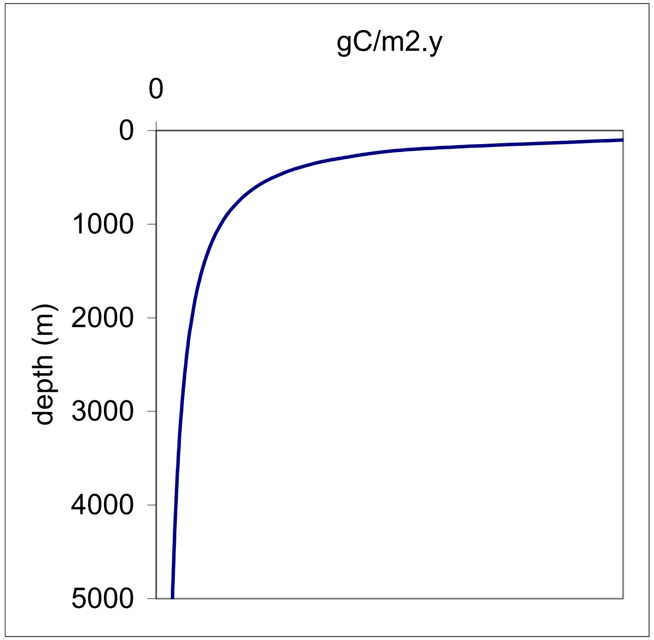
- Contrasting mean sinking rates and morphology of particles sinking in the mesopelagic zone of different oceanic regions (carb. vs opal dominated regions, high vs low latitude; mesotr. vs oligotr.)

- Developing means of assessing the "biodegradability" of sinking organic matter.

Martin et al (1987) equation

$$F_{Corg} = F_{100} \left({}^{Z}/_{100}\right)^{-0.858}$$

- Short-term deployments (6 – 34 days)
- Upper 2000 m only
- Limited geographic area



➔ **Globally applicable???**

In high latitude regions dominated by opal

→ ThE is high

→ Suggests that diatoms and seasonality promote export of organic matter from surface waters.

In low latitude oligotrophic carbonate-dominated ecosystems

→ ThE is low (most of the primary production is recycled through the microbial loop)

..but biogenic opal is much less efficient at transferring organic carbon to deeper water than carbonate.

→ Higher fraction of the organic carbon produced in diatom-dominated regions is exported

→ More efficiently remineralized within the mesopelagic zone

→ Smaller fraction of organic matter produced in calcite-dominated systems is exported

→ Larger fraction of the exported organic carbon is transferred to the deep-sea for long-term removal.

Conclusions

Multiple linear regressions between satellite-derived EP and settling fluxes measured with deep (>2000m) traps at 64 sites reveal that transfer efficiency of organic carbon is directly and strongly related to the flux of calcium carbonate and inversely related to seasonality.

→ Suggest importance of ballasting effect by carbonate, and possibly a "packaging" factor statistically related to carbonate production

→ Negative correlation with seasonality is interpreted as reflecting the effect of the biodegradability of the exported organic matter.

➔ resulting algorithm

= globally applicable

= explains > 80% of the variability in the transfer efficiency

→ Suggest that the exponent in Martin's equation must be adjusted systematically between oceanic regions.

- high seasonality; low carbonate fluxes → $b < -1$
- high to low seasonality; high carbonate fluxes → $b > -0.8$
- Meso- and oligotrophic regions→ $-1.0 > b > -0.8$

➔ In high latitude productive regions: larger proportion of export production is remineralized in the mesopelagic zone

➔ Low latitude productive regions are the most efficient open ocean sites at transferring organic carbon to the bathypelagic zone.

Caveat:

- Mesopelagic fluxes are still poorly constrained