

Organic matter cycling

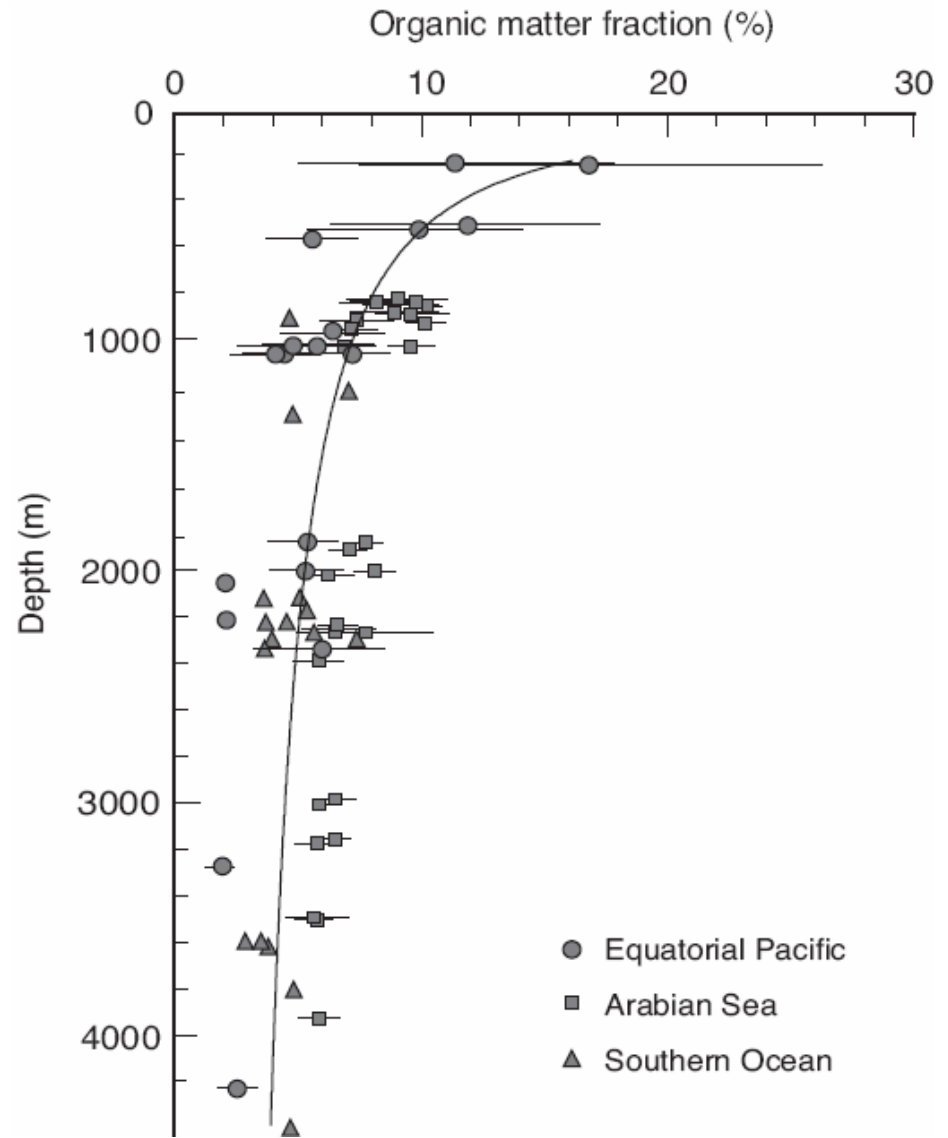
- we need to quantify and understand all terms in

$$\Gamma(POC) = SMS_{production}(POC) + SMS_{consumption}(POC) - w_{sink} \frac{dPOC}{dz}$$

$$\Gamma(DOC) = SMS_{production}(DOC) + SMS_{consumption}(DOC)$$

- we are particularly interested in carbon
- organic carbon forms 30-40% of POM close to the surface and decreases to ~ 10% at depth
- The overall concentration of POM decreases with depth (3-10mmol/m³ close to surface, to 3 mmol/m³ below 100m)

the rest of POM is made of biogenic CaCO_3 , silicate and other materials from dust and riverine input



- only large, heavy particle sinks rapidly enough to get all the way to the abyss. Diameter $> 100\mu\text{m}$ ~ 1 particle in every 10^{10}
- using Stokes' law to estimate w_{sink}

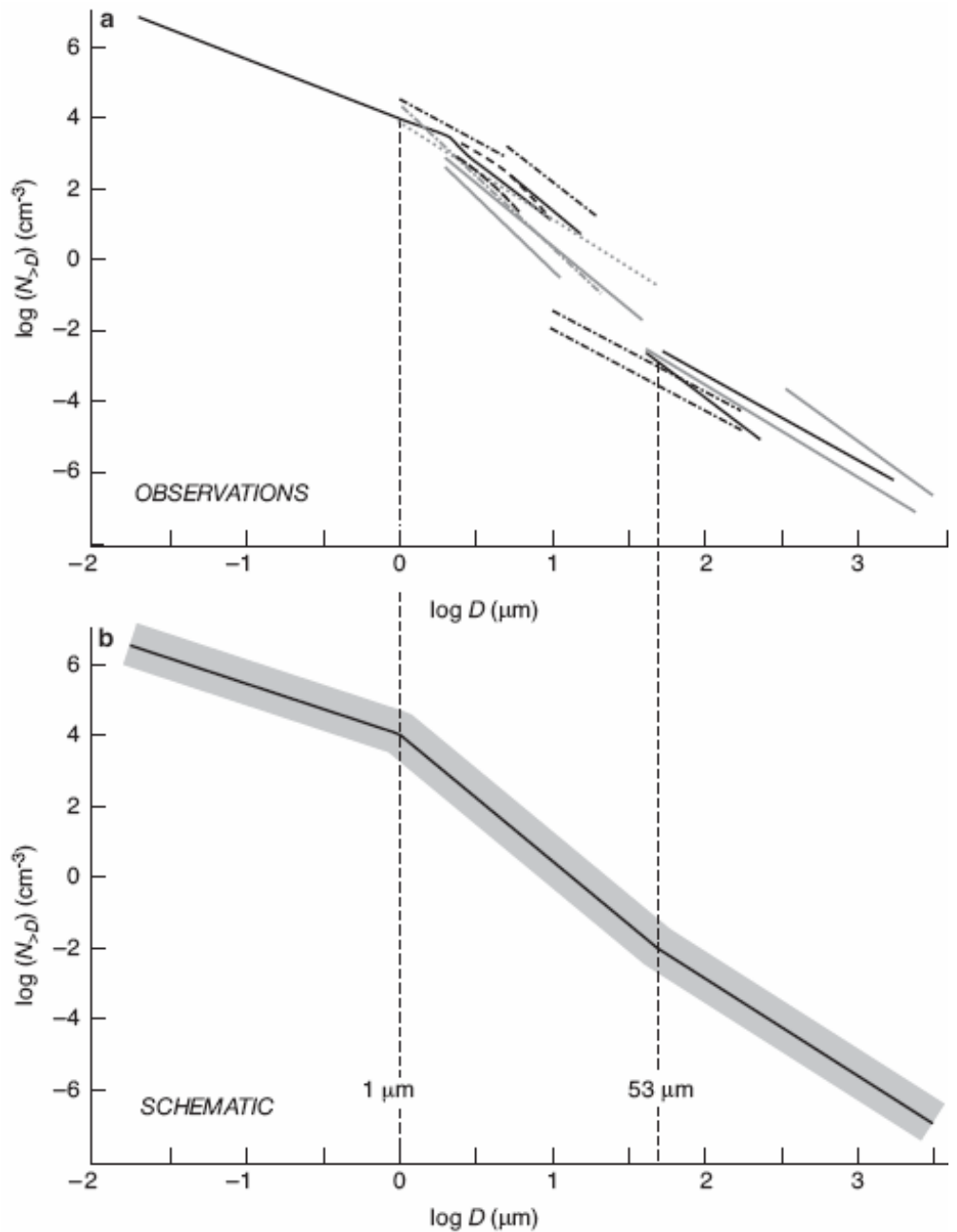
$$w_{\text{sink}} = \frac{2gr^2(\rho_{\text{particle}} - \rho_{\text{sea water}})}{9\mu}$$

μ = dynamic viscosity

μ depends on the internal friction of the fluid

- ρ for organic matter is similar to water, but calcium carbonate, opal, lithogenic material from rivers and dust have densities twice or larger than water
- w_{sink} for any of such particles assuming a diameter of $100\mu\text{m}$ is $\sim 12\text{m/day}$ for organic material, 600m/day for particle made of lithogenic material or calcium carbonate, 400m/day for opal (\sim order a week for the last three to reach the bottom at $\sim 4000\text{m}$)
- small or light particles are too slow and remineralization/dissolution processes are faster and take place before the particle reaches the bottom
- from observations: lower mean sinking velocity close to the surface and increasing values with depth (vertical mixing? ambient population?)

frequency spectra of particles in POM as function of their diameter

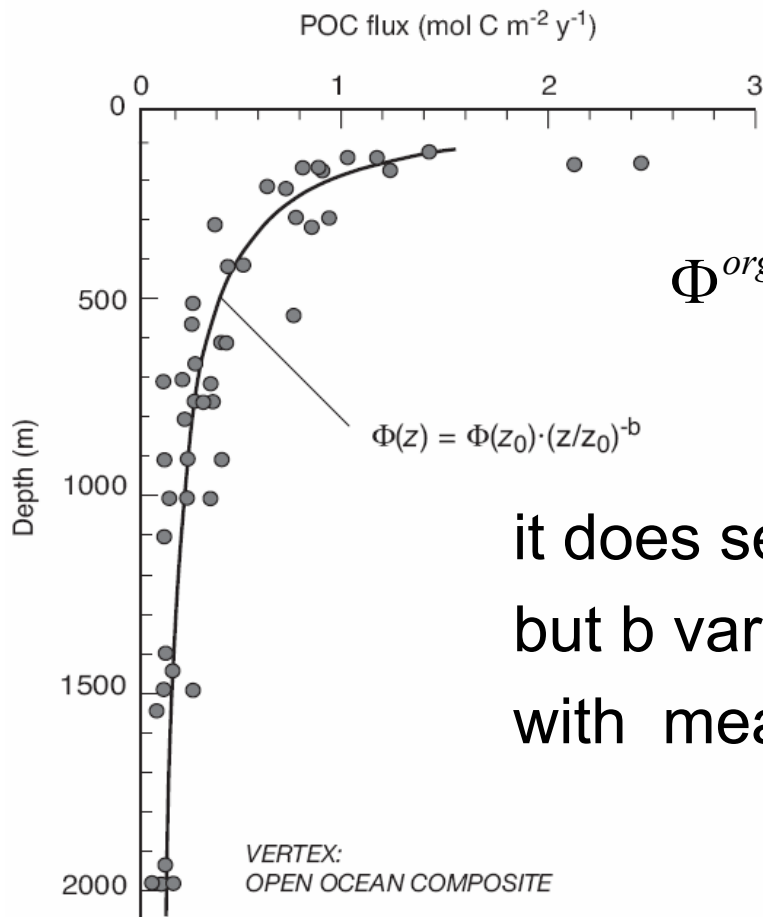


particle flux

- measured with traps. Conical first, then cylindrical (better). A lot of problems (very small size particles can escape for example). Poisoned so that remineralization does not occur but also the poison can bias measures
- Thorium-234 technique: the absorption of Thorium-234 into particles during their sinking cause a thorium deficit proportional to the amount of particles. However: extensive sampling temporally and spatially. Not used a lot and mainly close to surface

Martin et al. 1987 model

- empirical fit to average trap measurements of POC in the N. Pacific



$$\Phi^{org}(z) = \Phi^{org}(z_o) \left(\frac{z}{z_o} \right)^{-b} \quad z_o = 100m$$

it does seem to work quite well,
but b varies a lot from region to region
with mean of 0.82

the role of ballast

- carbon fluxes tend to cluster. Trying to explain this it has been found that downward fluxes of OM can be separated in two classes: quantitatively associated with ballast minerals and possibly protected by remineralization and unprotected or unassociated (Armstrong et al., 2002)
- In simple words, OM sinking in association with a ballast sinks faster and has less time to remineralize
- different types of ballast (CaCO_3 , opal, lithogenic material) have different associated fractions which may explain the variability seen in space and sometime in time (seasonality) in POC sinking

particle remineralization

- the vertical flux of POC is equal to the sinking of POC and at the steady state this is equal to the remineralization term

$$\frac{d\Phi^{org}(z)}{dz} = SMS_{consumption}(POC) = -w_{sink} \frac{dPOC}{dz}$$

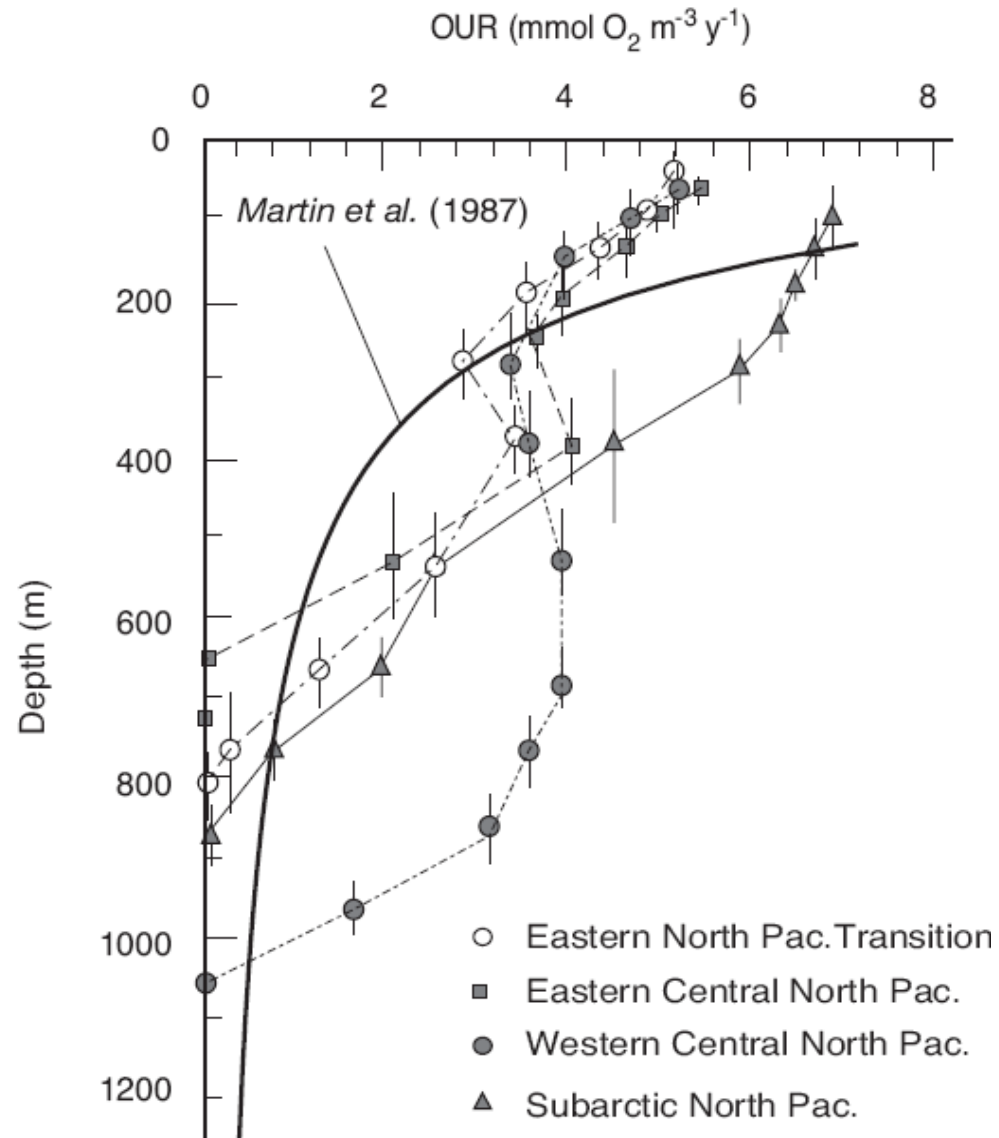
assuming a linear remineralization reaction

$$SMS_{consumption}(POC) = -k_{remin} POC$$

and a constant sinking velocity \Rightarrow

$$\Phi^{org}(z) = \Phi^{org}(z_o) \exp\left(-\frac{k_{remin}}{w_{sink}}(z - z_o)\right)$$

- we are ~ back to Martin et al.



what is found in particle traps?

- fecal pellets
- marine snow (macroscopic aggregates of detritus, mucus-feeding structures from zooplankton, mucus excreted by phytoplankton, mixed of almost anything that can be generated by biological processes)
- radiolarians, foraminifera
- we don't have a good mechanistic understanding of what is going on. From the consumption budgets of bacteria and zooplankton we are left with the following problem: both of them alone seem to consume all DOC available. Bacteria may use somehow POC, but it must be broken down and degraded to DOC and measurements does not show substantial POC degradation at depth

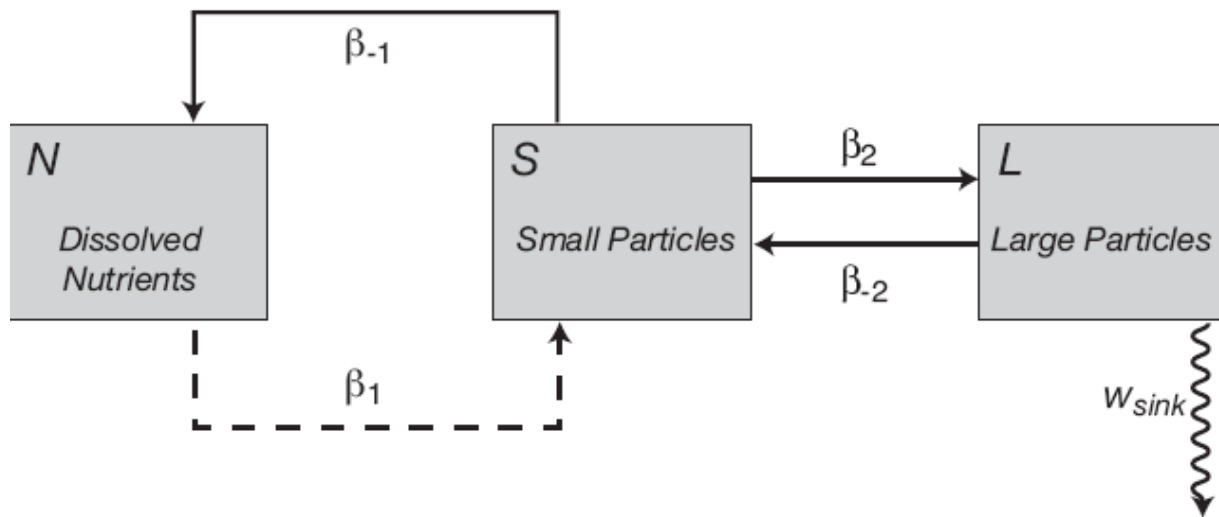
Models of particle interactions

- 2 classes min (sinking and nonsinking)
- biological breakdown of particles has to be taken into account
- models usually assume that large particles are broken down in small particles before they can be remineralized

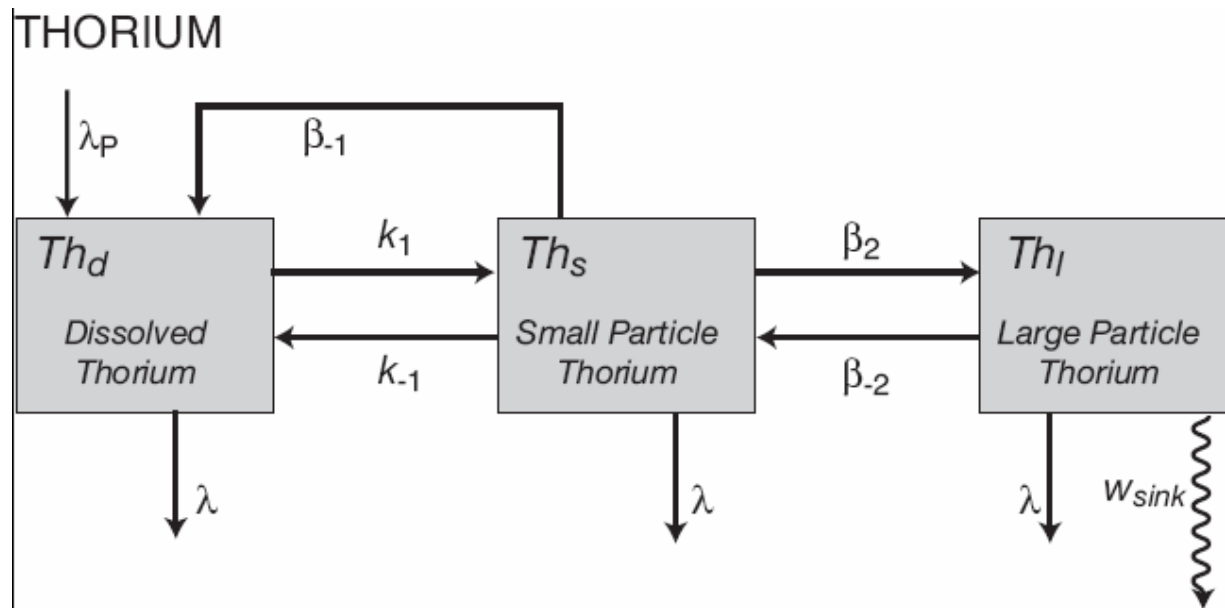
$$\Gamma(L) = \beta_2 [S] - \beta_{-2} [L] - w_{\text{sink}} \frac{d[L]}{dz}$$

$$\Gamma(S) = -\beta_2 [S] + \beta_{-2} [L] - \beta_{-1} [S]$$

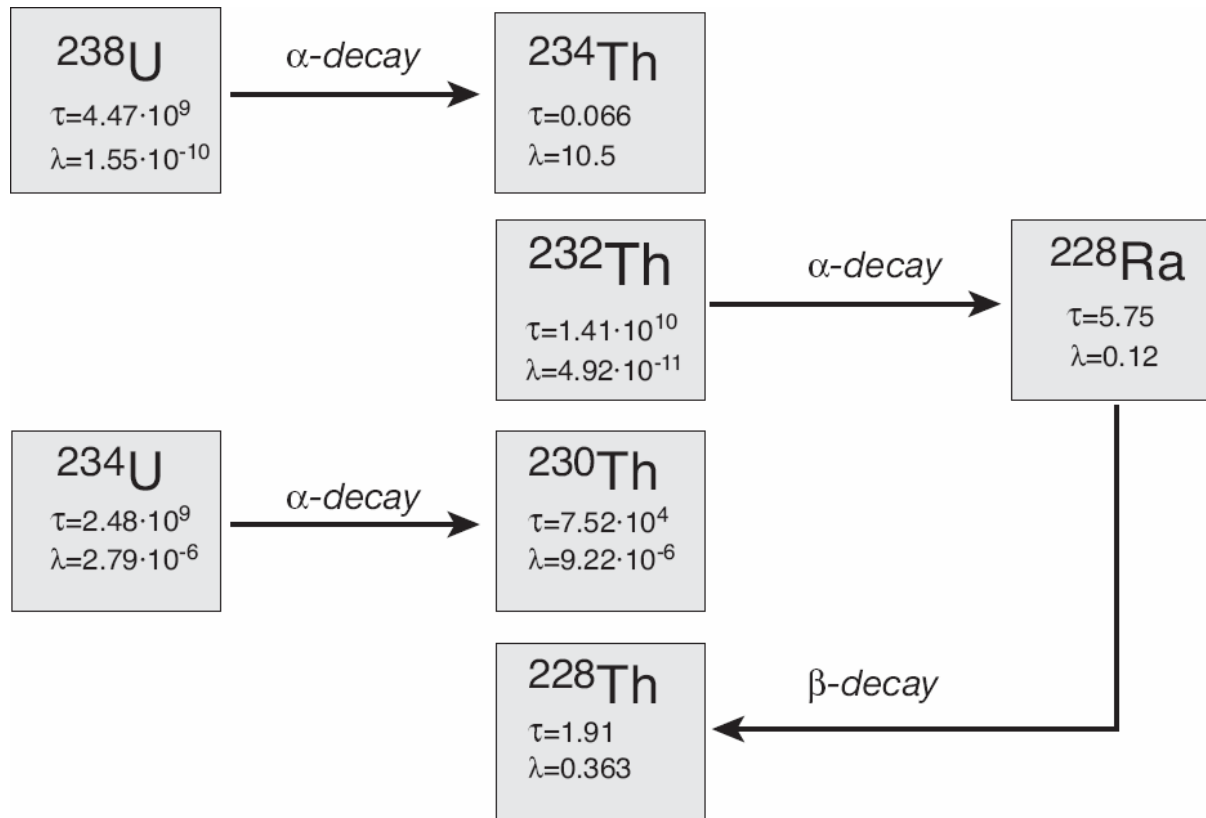
BIOGENIC PARTICLES



- alternatively a model based on thorium-234 has been developed, where the thorium absorption onto particles is followed in time as the particles agglomerate and are broken down




where the decay constant λ are given by

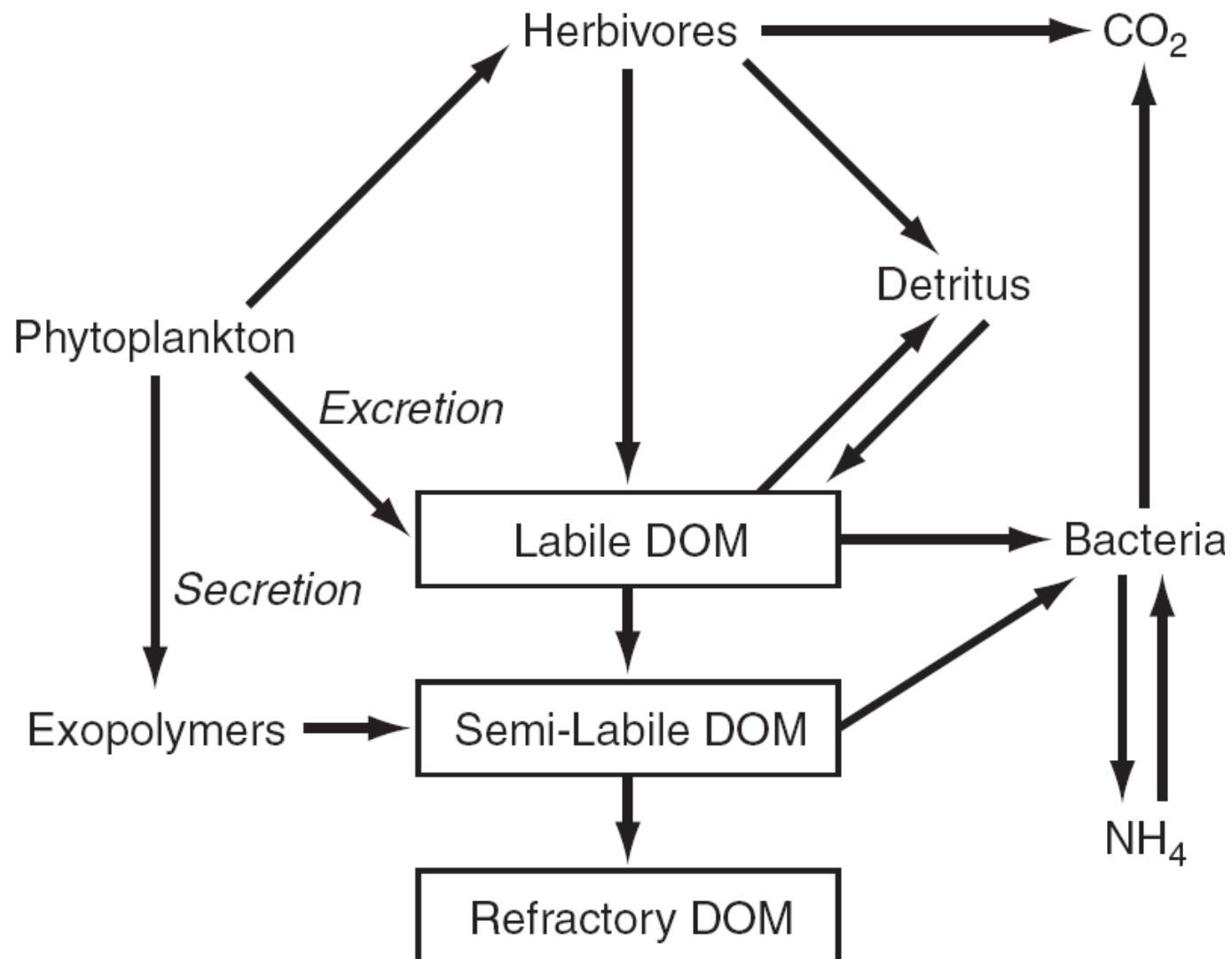


DOC

- $DOM = DOC + DON + DOP$ we know little of DON and DOP. DOC has been studied in more details but still speculative interpretations
- TOC and DOC concentrations have been determined by oxidation to CO_2 and measuring the evolved gas
- higher surface concentrations ($\sim 70 \text{ mmol m}^{-3}$ at low latitudes and $40\text{-}50 \text{ mmol m}^{-3}$ at high latitudes) dropping to $30\text{-}40 \text{ mmol m}^{-3}$ at depth
- contribution of POC to TOC is very small ($1\text{-}10 \text{ mmol m}^{-3}$ at most at the surface and 3 mmol m^{-3} at depth). Exception in the eutrophic coastal region (up to 20 mmol m^{-3})

- DOC is made of three pools: refractory, i.e. with very slow biological degradation and several thousand years life time; highly labile, whose biological degradation is very fast (few hours to days); semilabile, in between, with lifetime long enough to be transported around but subject to bacterial breakdown
- the lifetime of DOC can be measured by radiocarbon (Druffel and her group) → ~ 4000 years in the Atlantic to ~ 6000 years in the Pacific
- 80% of refractory DOC is turned unchanged each time the deep water is replaced by surface. 20% is removed over each turnover
- almost all DOC entering the deep ocean comes from the North Atlantic

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- most likely the DOC is present in a continuous spectrum between labile and refractory, with a semilabile component with residence time between a season and a year or so which is particularly abundant and important in the main thermocline
 - 5 different mechanisms for DOM formation:
 1. excretion and secretion from phyto
 2. spontaneous autolysis and cell lysis of phyto from viral attacks
 3. sloppy feeding by zoo
 4. bacterial transformation and release
 5. degradation of fecal material and detritus
 - Very poor understanding of the various contributions





Models

ingredients:

1. ocean circulation
2. gas exchange
3. biology at the surface
4. transport and remineralization of POM
5. transport and remineralization of DOM
6. info on the stoichiometric ratios to 'connect' and constrain all cycles

It's just too complicated. Box Models are the feasible alternative when going global

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- major challenges:
 - parameterizations for mesoscale variations are not perfect and global models cannot be run at high resolution for thousands of year (this much is required to reach a steady state for ocean circulation and to analyze the impact of the turnover of water masses by MOC)
 - No existing parameterizations for the marine ecosystem (!!)
 - one-class models are 'too simple' but multi-class models have a lot of unconstrained parameters
 - at global scale box-models provide useful information but very strong assumptions (e.g. export is directly proportional to light and nutrient concentrations; regionally is worth to use 'realistic' general circulation models)

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- sensitivity studies, i.e. how to determine parameters you don't know: run the model to equilibrium with different sets/combinations of parameters and validate the solutions with observations. If obs are scarce you are in trouble.
 - There are optimization numerical tools: i.e. you can do the work above in automatic mode. The complex numerical code searches for the combination of parameters that provides best agreement with the obs