Twilight zone 100-1000m Rapid drop off of POC and PON with depth

- Active bacteria and zooplankton communities
- Bacterial; see rise in Arches at depth
- Zooplankton vertical migrations
- nycthemeral (daily) or onthogenic (seasonal)
- daily migrate up at night (feeding) - (net downward vertical flux)

Figure 1.

- Separation of organic material into POC vs. DOC; Operational depending on filter size (0.4μm); 30-50% may be colloidal.
- 0.45μm Glass fiber filter GF/F
- colloidal ~ 10,000 daltons → diameter of 0.4μm
- POM filtering and then elemental analyzer, beam attenuation transmissometer
- DOM more difficult - because of salt and recalcitrant DOM
- As move down water column, can identify less and less of DOM as specific compounds
- UV-oxidation, high temperature oxidation
- DOM “suspended”; POM “sinks”
- DOM pool, large ~ 700 Pg C
- POM pool drops off sharply with depth
- Only a few Pg C
- POM sinking / Particulate matter (POM, CaCO3, SiO2, dust)
- biological production, aeolian deposition, riverine inputs, shelf/slope resuspension
• 3 – 10µm/kg in upper 100 meters - drop off sharply with depth

Figure 2.

• Particle size spectrum - mechanisms exchanging particles between size clusters

Stokes’ Law for small particles-gravitational force balanced by molecular viscous drag. For spherical particles:

\[
\frac{w_{sink}}{cm/s} = 2gr^2\frac{\rho_{part} - \rho_{sw}}{9\mu}
\]

Where:

- \( r^2 \) = radius [m]
- \( \rho \) = density [kg m\(^{-3}\)]
- \( \mu \) = viscosity dynamic \( \left[ \frac{N \cdot s}{m^2} \right] \)

McCave (1975)

Stokes Law for large particles (> 100µm)—gravitational force balanced by turbulent wake drag. For spherical particles:

\[
\frac{w_{sink}}{cm/s} = \left(\frac{16gr(\rho_{part} - \rho_{sw})}{3\rho_{sw}}\right)^{\frac{1}{2}}
\]

• Verticle sinking flux driven by large, rare particles
• ballast materials important
Rough Scaling

\[
\begin{align*}
\rho_{sw} & \sim 1027 \text{ kg/m}^3 \\
\rho_{org} & \sim 1060 \text{ kg/m}^3 \\
\rho_{CaCO_3} & \sim 2700 \text{ kg/m}^3 \\
\rho_{lithographic} & \sim 2700 \text{ kg/m}^3 \\
\rho_{opal} & \sim 2100 \text{ kg/m}^3 \\
\mu & \sim 1.25 \times 10^{-3} \text{ N} \cdot \text{s} \cdot \text{m}^{-2}
\end{align*}
\]

so

- 50μm organic particles → 12 m/day, \( \sim \) 1 year for 4000 meters
- \( \text{CaCO}_3 \) → 400 m/day, \( \sim \) 1 week for 4000 meters

- surface area \( r^2 \)
- volume \( r^3 \)

Figure 3.

Vertical Mass Flux

Deep moored sediment traps

- All the issues of traps
- Hydrodynamics - less turbulent at depth (sometimes)
- Swimmers - reduced biomass
- Attach current meters to traps
- Rotating cups (time-series) 6-12 month deployment
- 500 m, 1500 m, 2500 m, 4000 m
- Mass flux - org, \( \text{CaCO}_3 \), Silica, lithogenic
- Particle Velocities; lagged peak correlations
• Wide statistical cone - sinking particles “sink” at very oblique angles
• Say 100 m/day; horizontal currents of mesoscale eddies O(10 cm/s)

Figure 4.

• nepheloid layers, turbulent resuspension
• High eddy/kinetic energy (storms, DWBC)

Figure 5.

Rapid loss of organic matter with depth

![Graph showing rapid loss of organic matter with depth](image)

Martin et al. (1987) synthesis of VERTEX data

\[
\text{Flux}(z) = \text{Flux}(z_0) \left( \frac{z}{z_0} \right)^{-b}
\]

- \(z_0 = 100\) m
- \(b = 0.858\) (Berelson, 2001) 0.82 ± 0.16

Figure 6.

• mechanism: large sinking → small suspended (repackaging)
• Zooplankton consumption (filter feeders) or processing into small particles
- Attached bacteria - extracellular enzymes - thought small
- Mechanical/turbulent disruption
- Bacterial respiration (thymidine incorporation, ETS), grazing rates, ree respiration rates large
- Mass imbalance
- Rapid fall off with depth, artifact → fluxes because simple sampling of biomass (Michaels and Silver)
- Hydrothermal particles/plumes
- Iron sulfides, manganese oxides, MnO₂ “downstream” of ridges.
- Ballast - organic matter synergy
- Organic matter makes small inorganic particles bind together to create larger aggregate with larger sinking speed - e.g. how do small CaCO₃ liths reach the sea floor
- ballast added to ↑ sinking speed (Armstrong et al. 2002)
- deep water sinking particles tend to approach ~ constant POC/ballast

**Two Exponential Model**

![Diagram showing Two Exponential Model](image)

- Associated but not protected/bound
- Silica near surface
- CaCO₃ at depth density, distribution of CaCO₃ prod. transfer efficiency

Figure 7.

- Marine snow, aggregates
  - Biological structures, mucus, feeding structures (appendicularians)
  - Biological aggregation, spontaneous formation DOM → colloids, microaggregation
  - Diatom flocculation

Constraining particle interactions - U-Th isotopes
a simple model of particle interactions
- Two size classes sinking/suspended
- biological mediation
• $^{234}$U preferentially released from rocks during weathering because of $\alpha$ recoil
• Th is very particle reactive

Figure 8.

$$k_{scav} = \lambda_{230} \cdot \frac{A_{U234} - A_{Th230}}{A_{Th230}}$$ (3)

$$\tau_{scav} = \frac{1}{\lambda_{230}} \cdot \frac{A_{U234} - A_{Th230}}{A_{Th230}} = \frac{1}{9.22 \times 10^{-6}} \cdot \frac{10^{-3}}{2.7 - 10^{-3}} \approx 40 \text{ years}$$ (5)

Irreversible Scavenging

At steady state:

$$A_{U234} = k_1 Th_d + \lambda Th_d$$

$$k_1 Th_d = \lambda Th_p + \frac{[sTh_p(z_2) - sTh_p(z_1)]}{\Delta z}$$

$$= \lambda Th_p + s \left( \frac{\partial Th_p}{\partial z} \right)$$

Figure 9.
for $^{230}\text{Th}$, $k_1 \gg \lambda$

$Th_d = \frac{A_{U_{234}}}{k_1 + \lambda} \approx \frac{A_{U_{234}}}{k_1}$

Plug back into $Th_p$:

$A_{U_{234}} \approx \lambda Th_p + s \left( \frac{\partial Th_p}{\partial z} \right)$

Assume $A_{U_{234}} \gg A_{Th_{230,p}}$:

$A_{U_{234}} \approx s \left( \frac{\partial Th_p}{\partial z} \right)$

$\Rightarrow Th_p = \frac{A_{U_{234}}}{s} \cdot z$  \hspace{1cm} (6)

What you often measure is $s \cdot Th_p$, or flux

**Reversible Scavenging**

$$A_{U_{234}} + K_{-1} Th_p = k_1 Th_d + \lambda Th_d$$

$$Th_d = \frac{(A_{U_{234}} + k_{-1} Th_p)}{(k_1 + \lambda)}$$

$$k_1 Th_d = (\lambda + k_{-1}) Th_p + s \left( \frac{\partial Th_p}{\partial z} \right)$$

$$Th_p = \frac{k_1 A_{U_{234}}}{[k_{-1} + k_1 + \lambda] \lambda} \left( 1 - \exp \left( \frac{\lambda (k_{-1} + k_1 + \lambda)}{s(k_1 + \lambda)} z \right) \right)$$  \hspace{1cm} (7)

$k_1$ and $k_{-1} \gg \lambda$

$Th_d \approx \frac{(A_{U_{234}} + k_{-1} Th_p)}{k_1}$  \hspace{1cm} (8)

give slope to $^{230}Th_d$
\[ s \left( \frac{\partial T h_p}{\partial z} \right) = A_{U_{234}} \]

\[ \implies T h_p = \frac{A_{U_{234}}}{s} z \]

(9)

About 20% of Th is adsorbed onto particles.

\[ \tau_{\text{particles}} = \frac{\tau_{T h}}{1 - \frac{T h_p}{T h_p + T h_d}} \]

From this, find

\[ \tau_{T h} \approx 40 \text{ years} \]

\[ \tau_{\text{particles}} \approx 8 \text{ years} \]

- For 4,000 m \( \implies s \sim 500 \text{ m/yr} \)
- Metals “see” small, mostly suspended particles
- Traps “see” large, rapidly sinking particles

**One More Level of Sophistication**

Size classes, particle formation/creation, adsorption/desorption

![Diagram](image-url)

Figure 12.

- Sediment Trap Calibration

\[ \text{Flux} = s \cdot T h_p \approx A_{U_{234}} \cdot z \]

look for excess/deficit

- \(^{230}\text{Th}\) versus \(^{231}\text{Pa}\), Th is more particle reactive

\(^{231}\text{Pa}\) comes from \(^{235}\text{U}\) and has \(\tau_{1/2}\) of 32,000 years

*Constant Production ratio = 0.093*
To find production (in terms of activities) NOT reach secular eq.

\[ \lambda_{Th} A_{U_{234}} = 2.5 \times 10^{-5} \text{dpm/l/yr} \]
\[ \lambda_{Pa} A_{U_{234}} = 2.3 \times 10^{-6} \text{dpm/l/yr} \]

\[ Th \sim 40 \text{ year scavenging} \]
\[ Pa \sim 100 - 200 \text{ year scavenging} \]

–trapping efficiency Bacon et al. 1985

–boundary scavenging

With two isotopes can separate effects of vertical transport vs. lateral

Deep trapping efficiency below 1500 m: 98\% ± 14\%

Figure 13.