# The Fate of Particulate Organic Material in the Oceans

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## Outline

- Why is remineralization in the oceans important?
- Processes affecting remineralization
  - Particle type & properties, concentration, settling speed,
     biology
- Representing remineralization in models

# Why?

- Flux
  - Crucial role in biogeochemical cycles in the ocean.

### Olimate

• Sinking particles can sequester carbon in the deep

### Trace Metals

• Particles provide surfaces for trace-metal sorption

### Deep Water Ecology

• Sinking particles provide food for deep water organisms

## Processes affecting particles



Burd & Jackson, Ann. Rev. Mar. Sci., 1:65–90, 2009

### eWOCE

Nitrate [µmol/kg]







# Feeding the Deep Ocean?



## Carbon sequestration



Kwon et al., *Nature Geosci.*, 2:630–635, 2009

## What are marine particles?



Alice Alldredge



Debbie Steinberg



**Richard Lampitt** 



Alice Alldredge

## Nanoparticles



Verdugo, Ann. Rev. Mar. Sci., 4:375–400,2012

## **Capturing Particles**





Stemmann et al., ICES J. Mar. Sci., 65:433-442, 2008

## Particulate Flux

### Particulate flux = Concentration × Settling Velocity



54:639–658, 2007

# Particle type: fluffy aggregates



Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011



Fig. 2. Size characteristics of marine snow. A. Aggregate volume as a function of diameter (regression coefficient, rc, = 0.97; P < 0.001). B. Aggregate dry weight as a function of diameter (rc = 0.71; P < 0.001). C. Aggregate porosity as a function of diameter: O-diatom floos: -all other marine snow regardless of origin (rc = 0.79; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.79; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.71; P < 0.001). D. Aggregate excess density as a function of diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001) is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001) is the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001) is the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001). So that the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.001 is the second diameter (rc = 0.19, P < 0.00

snow in situ as a function of various particle characteristics. Mean settling rate was  $74\pm39$  m d<sup>-1</sup>. Sinking speed increased exponentially with particle diameter (Fig. 3A). Settling velocities increased with the increasing ratio of volume to projected area, as predicted by settling theory (Fig. 3B).

Settling rate in situ increased exponentially with aggregate dry weight (Fig. 3C). We compared the size-specific settling rates of marine snow determined in the laboratory with rates for similarly sized and shaped aggregates determined in situ with dry weight as an accurate measure of aggregate size. Despite minimal handling of particles, settling velocities measured in the laboratory were consistently higher, by up to four times, than those of similarly sized aggregates measured in situ (Fig. 3C). No significant statistical correlation could be found between sinking rate and dry weight of aggregates studied in the laboratory.

Although settling theory predicts that the sinking rate of an object settling in a fluid is a function of the excess density of the object, our data did not yield a significant relationship between excess aggregate density, as calculated by our methods, and sinking rate (Fig. 3D).

We measured or derived all of the dimensional terms in the force balance Eq. 1 for a settling object. Thus, we can directly calculate the drag coefficient,  $C_D$ , for each sinking aggregate. Calculations of  $C_D$  for our nonspherical aggregates can provide insight into the effects of shape and other variables that potentially alter the settling behavior of marine snow relative to sinking spheres.

# Particle type: fecal aggregates



Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011

# Particle type: cylindrical pellet



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# Particle type: ovoid pellet



Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011



Alldredge, Deep-Sea Res. 1, 45:529–541, 1998

# Particle type: phyto cells



Ebersbach et al., Deep-Sea Res. II, 58:2260-2276, 2011

### 140 m 290 m



Ebersbach et al., *Deep-Sea Res. II*, 58:2260–2276, 2011



Smayda, Limnol. Oceanogr. 14:621–625, 1969



Fowler & Small, *Limnol. Oceanogr.*, 17:293– 296, 1972

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Picheral et al., *Limnol. Oceanogr. Methods*, 8:462–473, 2010

## Particle Size Spectra



Jackson et al., Deep-Sea Res. 1997

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## Particle Size Spectra



Jackson et al., Deep-Sea Res. 1997

## Variations in spectral slope



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# **Settling Velocity**



Stemmann et al., 2004



Peterson et al., Limnol. Oceanogr. Methods, 3:520–532, 2005





### Non-calcifying

Calcifying

(A)

2.5



Engel et al., *Deep-Sea Res. II*, 56:1396–1407, 2009

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Engel et al., *Deep-Sea Res. II*, 56:1396–1407, 2009

# Zooplankton



## Vertical Migration



Steinberg et al., *Deep-Sea Res. II*, 55:1615–1635, 2008

## **Microbial Processes**



#### COG FUNCTIONAL CATEGORIES

- C: Energy production and conversion
- **D:** Cell cycle control, cell division, chromosome partitioning
- E: Amino acid transport and metabolism
- F: Nucleotide transport and metabolism
- G: Carbohydrate transport and metabolism
- H: Coenzyme transport and metabolism
- I: Lipid transport and metabolism
- J: Translation, ribosomal structure and biogenesis
- K: Transcription
- L: Replication, recombination and repair
- M: Cell wall/membrane/envelope biogenesis
- N: Cell motility
- **O:** Posttranslational modification, protein turnover, chaperones
- P: Inorganic ion transport and metabolism
- **Q:** Secondary metabolites biosynthesis, transport and catabolism
- R: General function prediction only
- S: Function unknown
- T: Signal transduction mechanisms
- U: Intracellular trafficking, secretion, and vesicular transport
- V: Defense mechanisms

Ivars-Martinez et al., ISME Journal, 2:1194-1212, 2008

## **Degradation Rates**



Iversen & Ploug, Biogeosciences, 10:4073–4085,2013

> C specific degradation rate = 0.03 ± 0.01

C specific degradation rate =  $0.12 \pm 0.03$ 

## **Empirical Models**



 $F(z) = F_{100} \left(\frac{z}{100}\right)^{t}$ 

### $b = -0.973 \rightarrow -0.319$

b = -0.858



Burd and Passow (unpubublished)



2 size classes, prescribed settling, high grazing

**Ballast Model** 



Gehlen et al., Biogeosciences, 2006

2 size classes, no aggregation, prescribed settling

### Simple Spectral Model



Primeau, Deep-Sea Res. 1, 53:1335-1343, 2006



Filter feeder scaling factor = 0.307 m<sup>-3</sup> Particle breaker scaling factor = 0.14 m<sup>-3</sup> Passive flux feeder scaling factor = 0.063 m<sup>-3</sup> Mesozooplankton scaling factor = 250 m<sup>-3</sup>



Stemmann et al., Deep-Sea Res. I, 51:885–908



Clegg & Whitfield, Deep-Sea Res. I, 37:91–120, 1991



Marchal & Lam, Geochim. Cosmochim. Acta, 90:126–148, 2012

## **Two Size-Classes**



$$\frac{dP_{S}}{dt} = \mu P_{S} - \tilde{\beta} P_{S} - \frac{\nu_{S}}{z} P_{S}$$
$$\frac{dP_{L}}{dt} = \tilde{\beta} P_{S} - \frac{\nu_{L}}{z} P_{L}$$

## **Coagulation Equation**

$$\frac{\mathrm{d}n(\mathrm{m},\mathrm{t})}{\mathrm{d}\mathrm{t}} = \frac{\alpha}{2} \int_0^{\mathrm{m}} \beta(\mathrm{m}_j, \,\mathrm{m} - \mathrm{m}_j) n(\mathrm{m} - \mathrm{m}_j, \,\mathrm{t}) n(\mathrm{m}_j, \,\mathrm{t}) \,\mathrm{d}\mathrm{m}_j$$
$$- \alpha n(\mathrm{m}, \,\mathrm{t}) \int_0^{\infty} \beta(\mathrm{m}, \,\mathrm{m}_j) n(\mathrm{m}_j, \,\mathrm{t}) \,\mathrm{d}\mathrm{m}_j$$
$$- n(\mathrm{m}, \mathrm{t}) \frac{w_s(\mathrm{m})}{z} + I(\mathrm{m}, \mathrm{t})$$



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## **Two Size-Classes**



$$\frac{\mathrm{d}\mathsf{P}_{\mathrm{S}}}{\mathrm{d}t} = \mu\mathsf{P}_{\mathrm{S}} - \beta_{1}\mathsf{P}_{\mathrm{S}}^{2} - \beta_{2}\mathsf{P}_{\mathrm{S}}\mathsf{P}_{\mathrm{L}} - \frac{\nu_{\mathrm{S}}}{z}\mathsf{P}_{\mathrm{S}}$$
$$\frac{\mathrm{d}\mathsf{P}_{\mathrm{L}}}{\mathrm{d}t} = \beta_{1}\mathsf{P}_{\mathrm{S}}^{2} + \beta_{2}\mathsf{P}_{\mathrm{S}}\mathsf{P}_{\mathrm{L}} - \frac{\nu_{\mathrm{L}}}{z}\mathsf{P}_{\mathrm{L}}$$



Two size classes, second order aggregation, large/small particle interactions

# Full aggregation model

Burd, J. Geophys, Res., 2013



Burd & Jackson, Env. Sci. Technol., 36:323-327, 2002

## Future Work

- Size resolved aggregation and flux models
  - Underway
- Better understanding of settling velocities
- Better understanding of biological processes
  - Particle repackaging, microbial processes



- What determines particle sinking velocities?
- Details matter!
- Are there simple relationships between degradation and physical parameters?
- How best to incorporate remineralization into models?

