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Long-term Study of Minerogenic Particle Optics in Cayuga Lake

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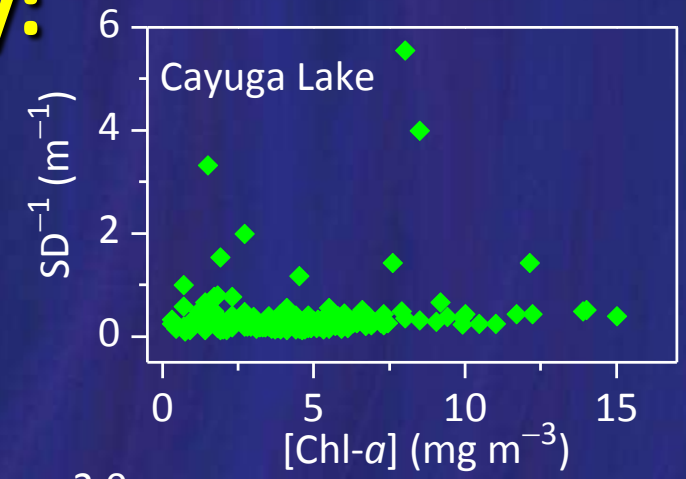
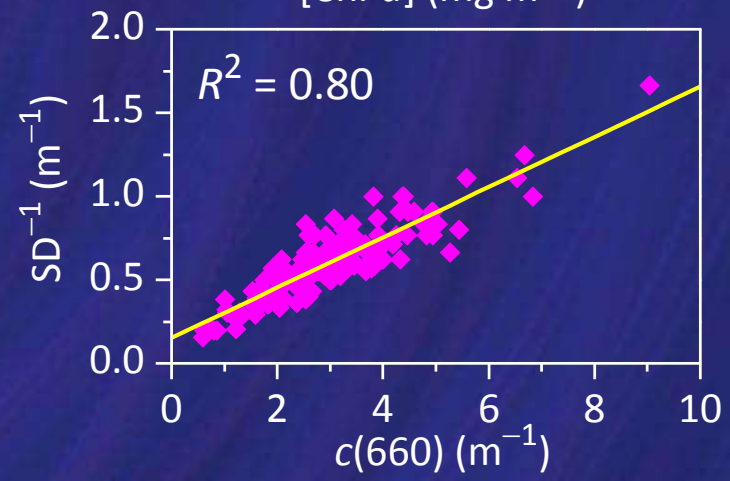
Light Scattering by Suspended Particles

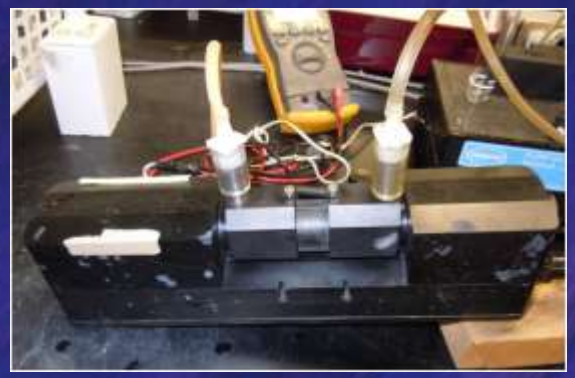
- reduces clarity, imparts cloudiness
  - often measured with a Secchi disk or turbidimeter
  - earlier efforts focused on nutrient (i.e., Phos.) control and organic particles
- inorganic (mineral) particles increasingly found to be important
  - scatter light more efficiently
  - different sources and management strategies
- need to resolve the contributions of these two particle populations

Particle Scattering and Clarity: Study Approach

- phytoplankton biomass ([Chl-*a*]) poor predictor of SD
- $SD^{-1} \propto$ particle scattering
  - widely documented (Davies-Colley et al. 2003)
  - Onondaga Lake example; $\propto c(660)$
- theoretical representation: scattering coefficient (b_p; m^{-1})
  - transmissometer, ac-s meter
  - *f* (composition, size distribution, number conc. of particles)
  - analytical support to provide particle optical attributes

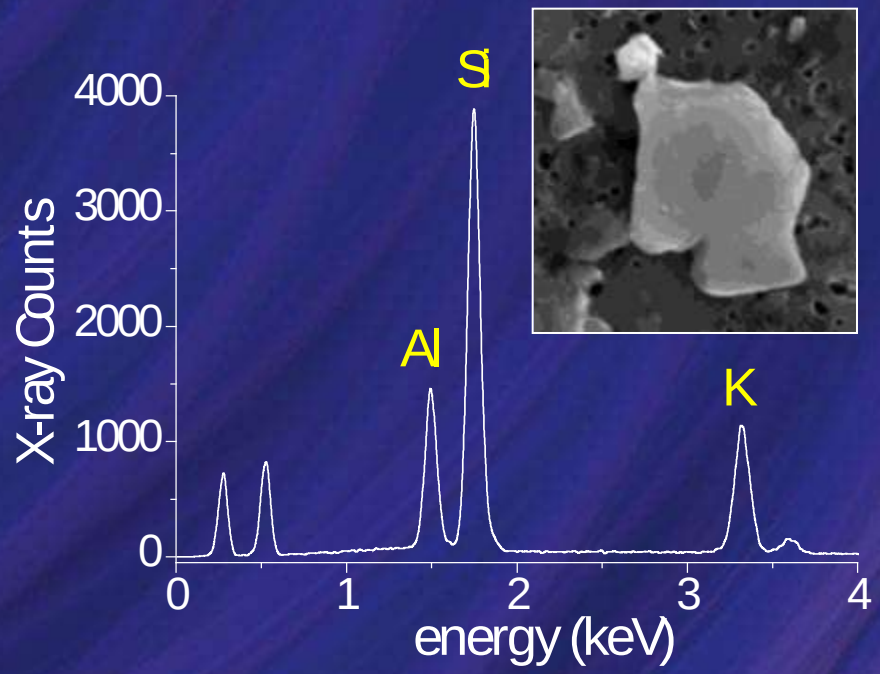






UFI's Contributions in Advancing Particle Optics Studies with SAX

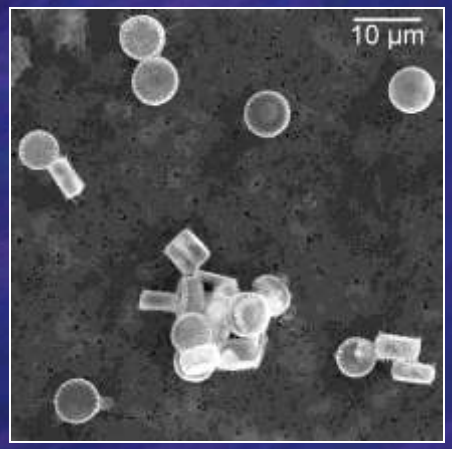
- Individual Particle Analysis by Scanning electron microscopy interfaced with Automated image and X-ray analyses (SAX)
- Detailed characterizations for individual mineral particles
  - morphology (size), composition (clay, calcite)
  - input for theoretical calculations
- Success documented in multiple publications

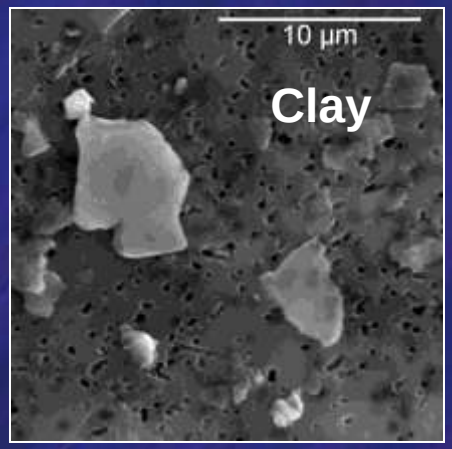


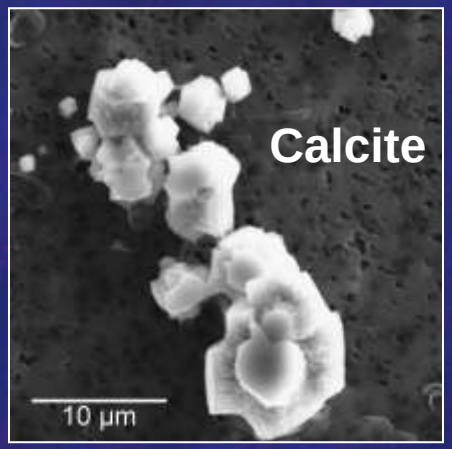
Partitioning b_p into Contributing Components

—two-component (organics and mineral) approach

$$b_p = b_o + b_m$$







phytoplankton

- empirical, bio-optical model $b_o = 0.34[\text{Chl-}a]^{0.77}$

mineral particles

- mechanistic, Mie theory
- based on results of SAX

Modeling Mineral Particle Scattering: SAX–Mie Approach

- single-particle optics to bulk properties

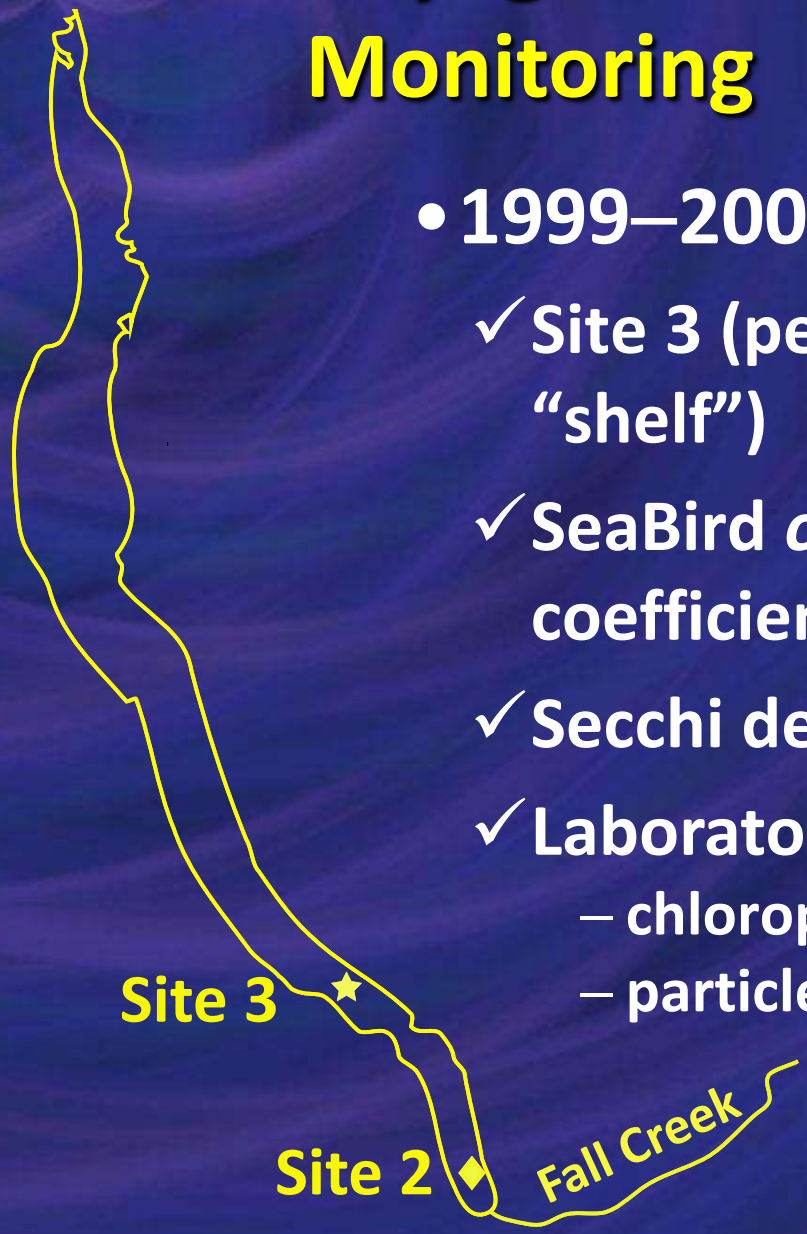
$$b_{\mathrm{m}} = \frac{1}{V}\sum_{i=1}^{N}\left(Q_{b,i} \times \mathrm{PA}_i\right)$$

- V: sampling volume
- N: num. of mineral particles in sampled volume
- $Q_{b,i}$: scattering efficiency factor
  - ☞ f (size, composition, λ); Mie
- PA_i : projected area of a particle ($\mathrm{PAV}_{\mathrm{m}}$—projected area conc.)

- Stramski et al. (2007) "… basic laboratory studies of particle types … with a detailed characterizations of particle populations with the use of … individual particle analysis, must be pressed further …"

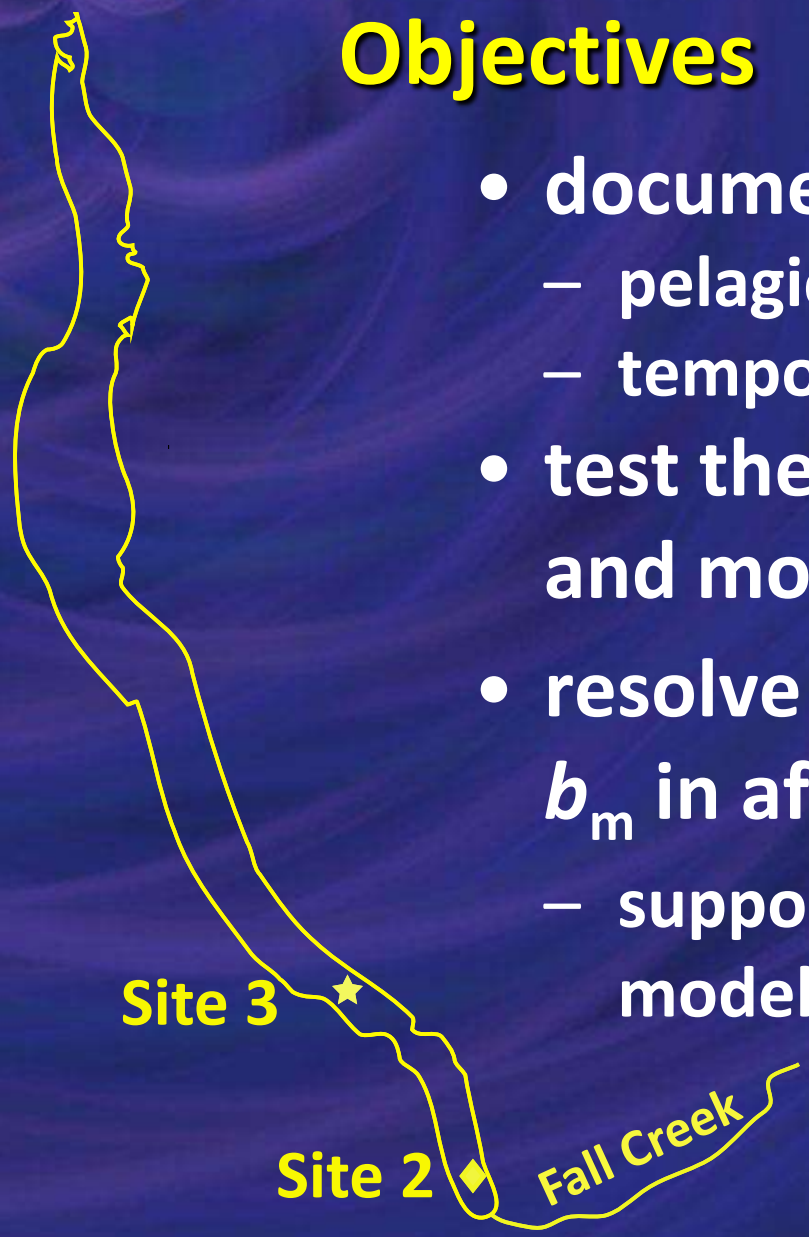
Cayuga Lake Particle Optics Study: Monitoring

- 1999–2006, Apr–Oct, biweekly
  - ✓ Site 3 (pelagic) & Site 2 (nearshore, "shelf")
  - ✓ SeaBird *c*(660): light-attenuation coefficient at 660 nm (to estimate b_p)
  - ✓ Secchi depth (SD)
  - ✓ Laboratory measurements
    - – chlorophyll-*a* concentration, [Chl-*a*]
    - – particle analysis by SAX



Cayuga Lake Particle Optics Study: Objectives

- document optical variability
  - pelagic vs. near-shore
  - tempo-spatial patterns of b_m
- test the credibility of b_m estimates and model closure ($b_p = b_m + b_o$)
- resolve the relative roles of b_o and b_m in affecting SD dynamics
  - supports Cayuga Lake TMDL modeling (submodel for SD)

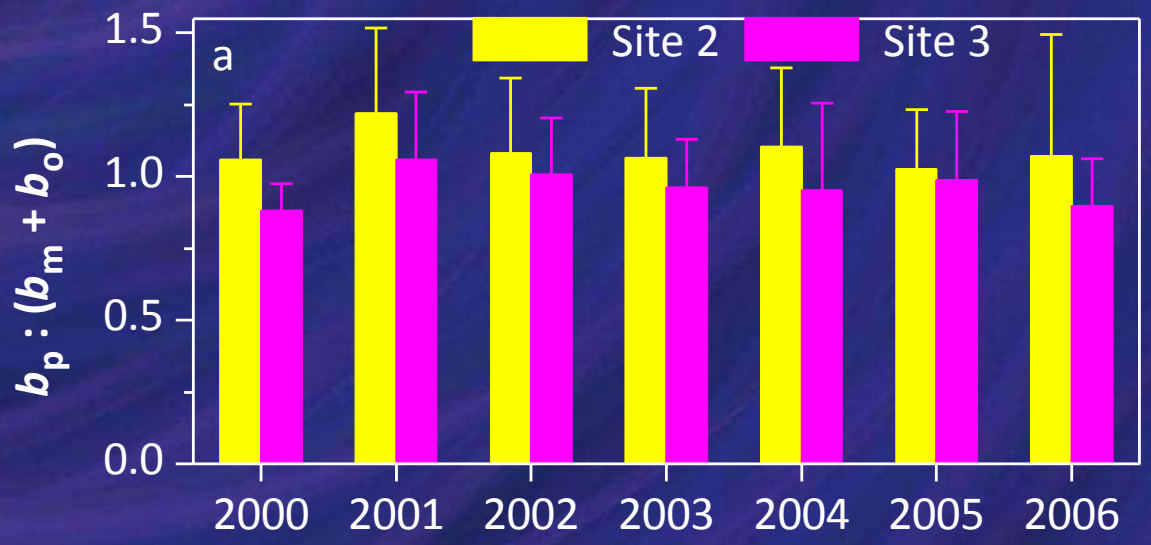


Performance of the Two-component Model

- compare ($b_m + b_o$) to bulk measured b_p

$$b_p : (b_m + b_o)$$

$$n = 199, \text{ mean} = 1.03, \text{ median} = 1.04$$



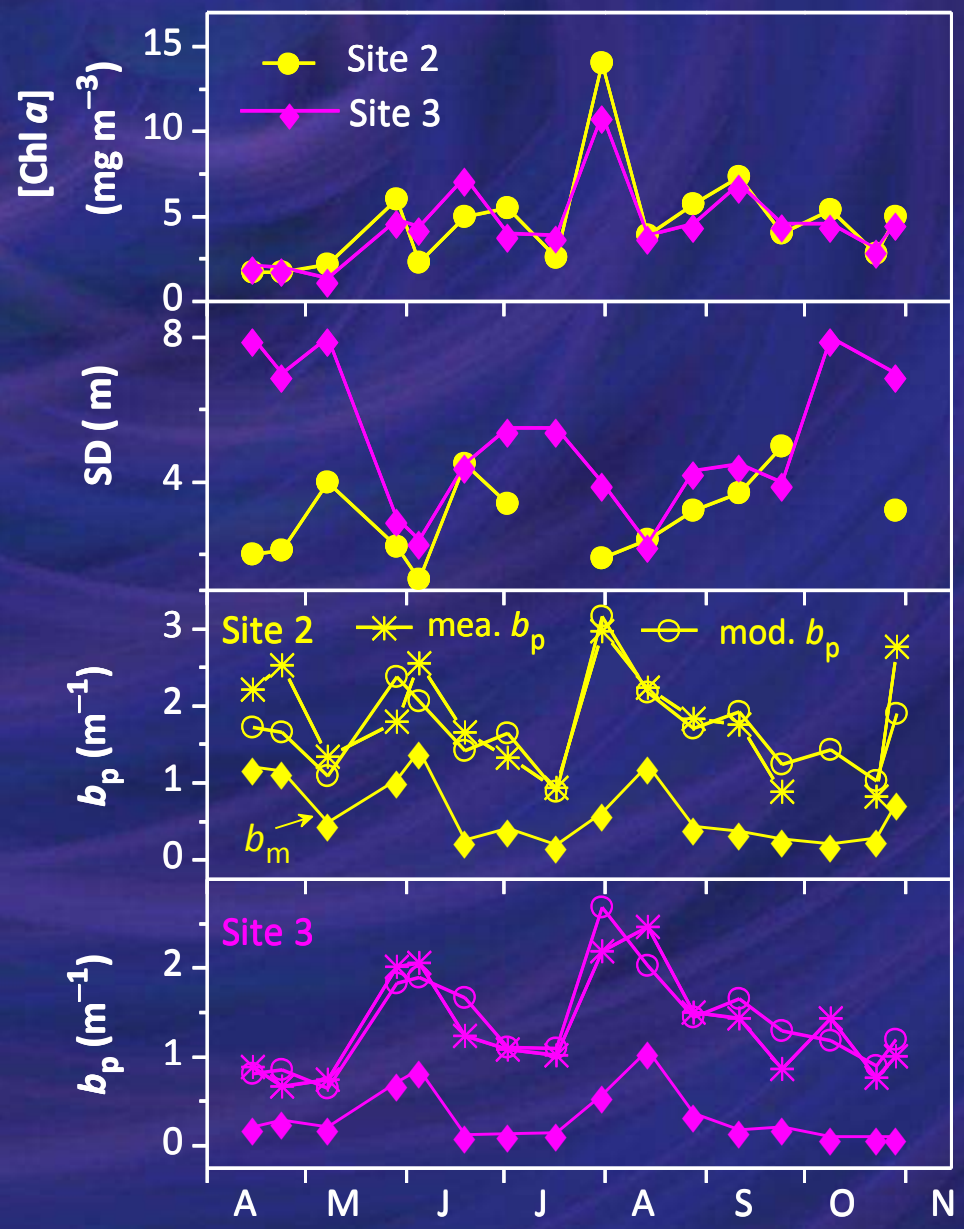
average by site

- Site 2: 1.09
- Site 3: 0.97

✓ level of model closure generally satisfactory

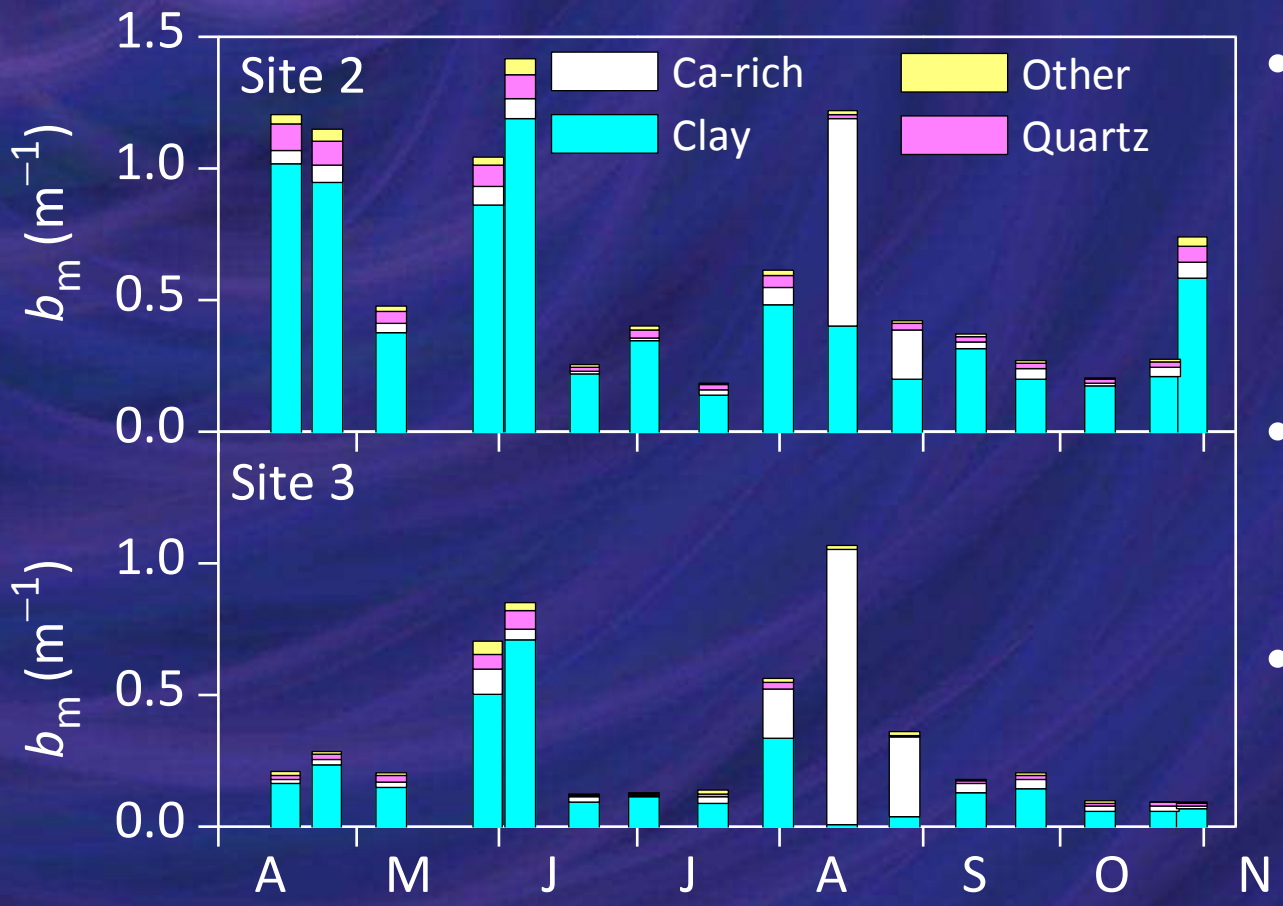
✓ provides support for b_p components and SD analyses

Detailed Temporal Dynamics (Year 2003)



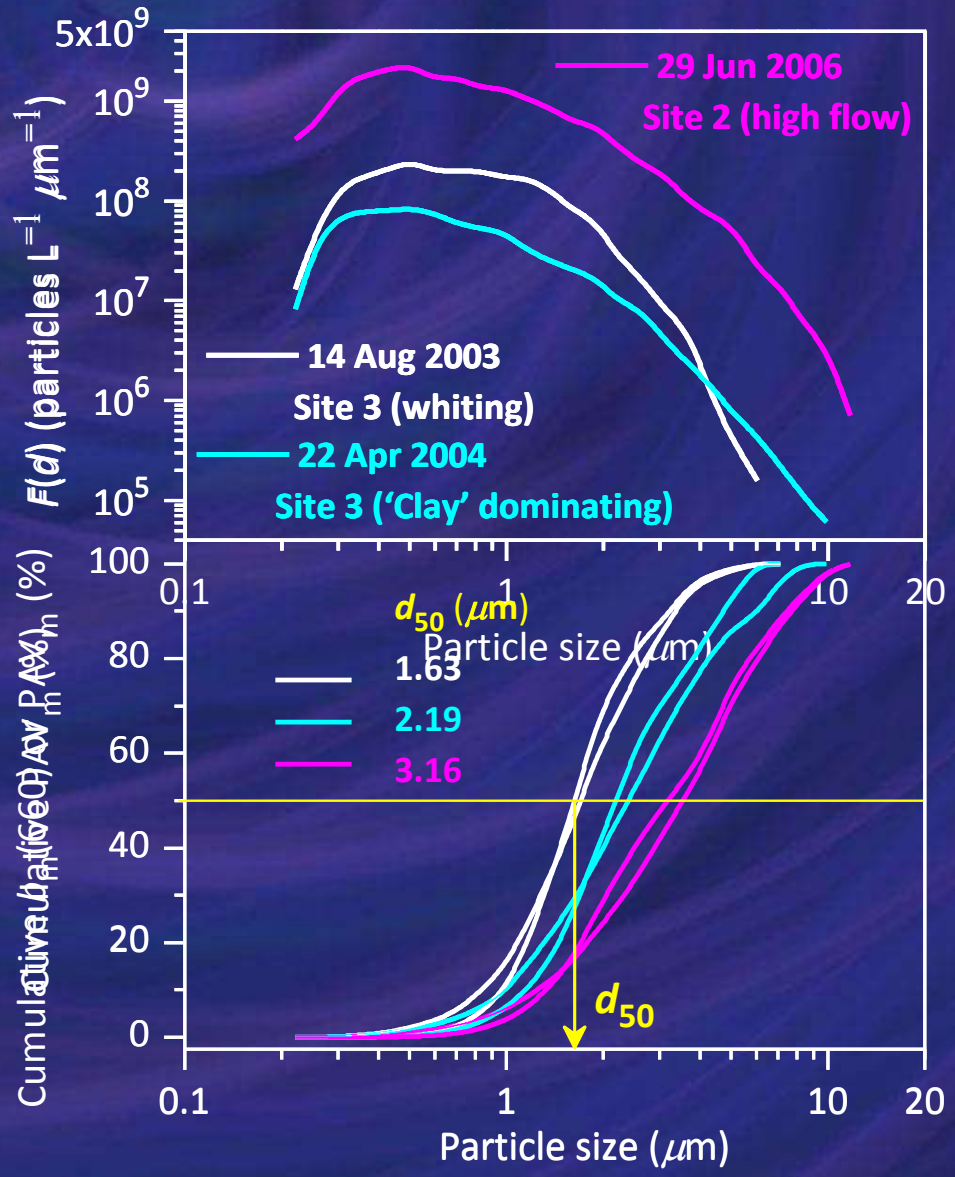
- spatial differences not significant
- higher clarity at Site 3 (paired observations)
- b_p patterns roughly inverse of those of SD
- two-component model performed well
- b_m dynamics driving b_p

Detailed Temporal Dynamics (Year 2003) —b_m composition



- higher levels at Site 2 than at Site 3 (mean 0.6 vs. 0.3 m^{-1})
  - 'Clay' peaks reflected runoff events
- clay minerals dominating (>65% on average)
- summer whiting ($CaCO_3$↓), especially at Site 3

Particle Size Distribution (PSD)
—Size Dependency of Scattering

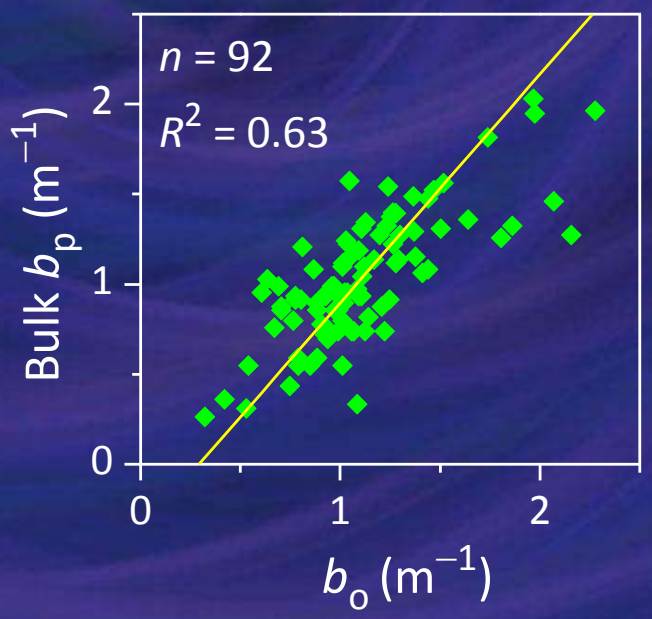


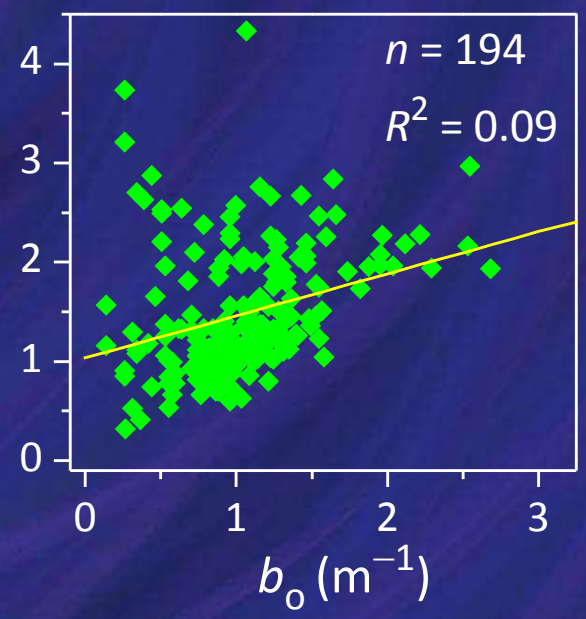
- distinctive curvature
- higher conc. of particles during runoff event(s)
- plateau feature for whiting event sample

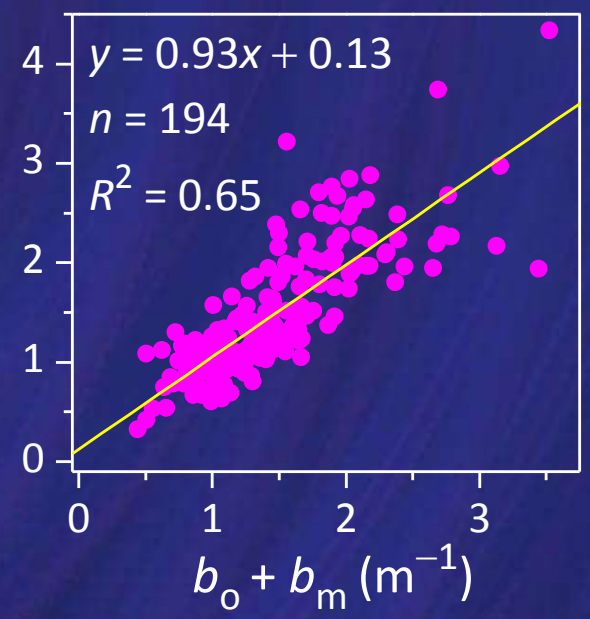
- resolve particle size class contributions to PAV_m (1–10 μm)
- $b_m \propto PAV_m$
  - median size of scattering, d_{50}

Relative Importance of b_o vs. b_m in Regulating Bulk b_p

- [Chl-*a*] only
- [Chl-*a*] & b_m





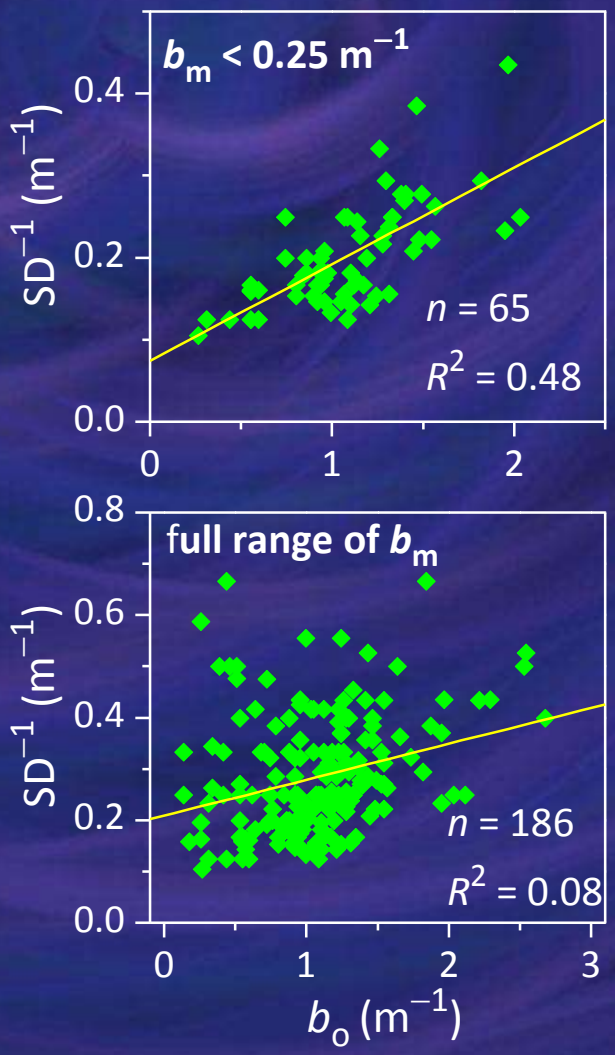


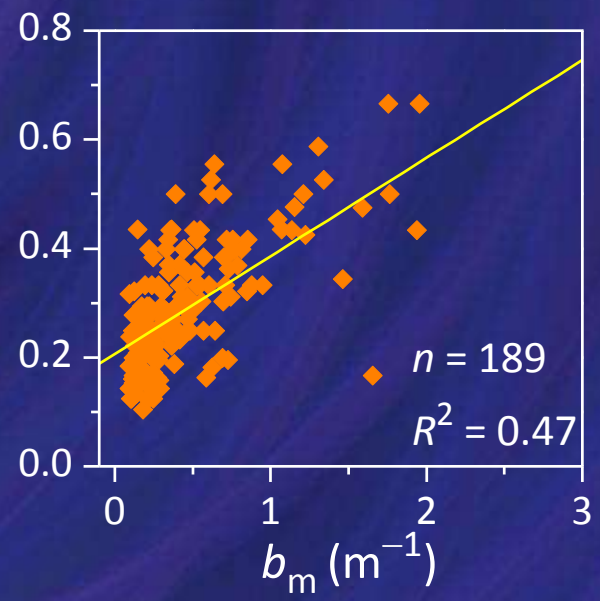
✓ b_o important when b_p and b_m levels were low

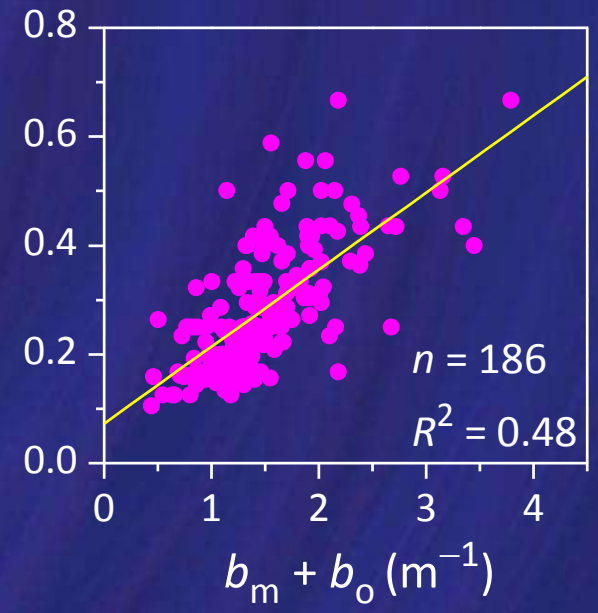
× not so much for full range of b_p

☺ good closure with overall b_p

What Regulated Secchi Depth Dynamics?







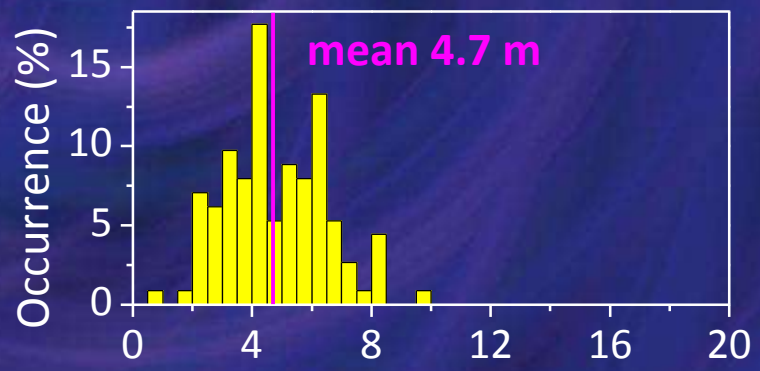
- b_o a predictor of SD only when b_m levels low

✓ b_m more important in regulating SD

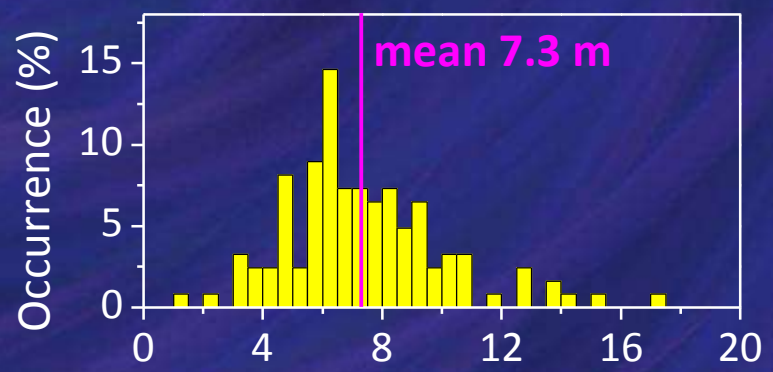
✓ limited benefit in adding b_o

Scenario Analyses for Secchi Dynamics

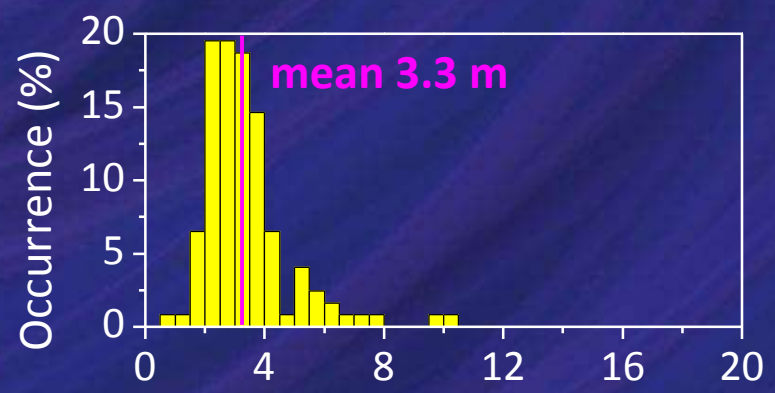
$SD^{-1} = 0.16 \times b_p + 0.004$



- Site 3 long-term observations; *n* = 113



- if [Chl-*a*] decreases by half



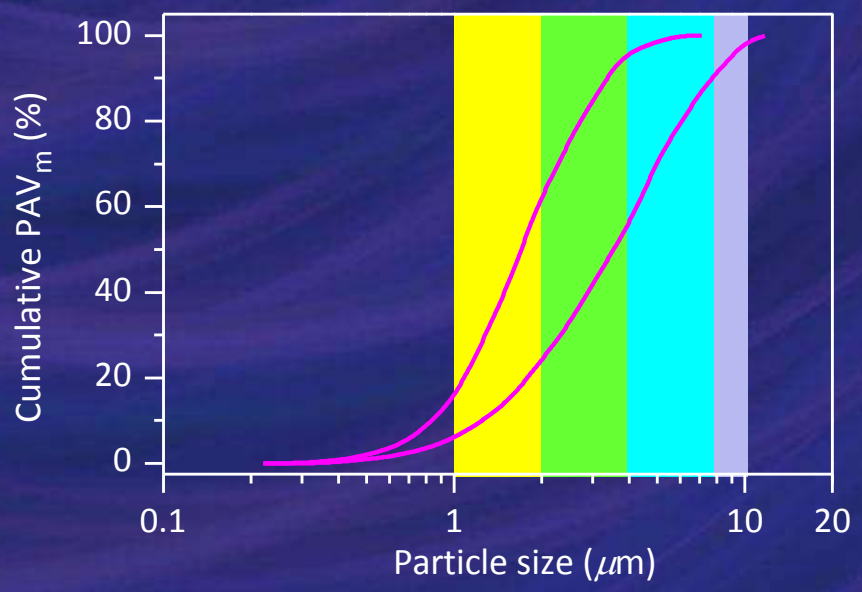
- if [Chl-*a*] doubles

Long-term Particle Optics Study Summary

- the most comprehensive test of SAX–Mie and two-component modeling approaches
  - reasonable degree of optical closure
  - detailed particle dynamics (conc., composition, size)
- clarity (Secchi depth) regulated by particle scattering (b_p)
  - scattering by algal particles (b_o) poor predictor of SD
  - mineral particle scattering (b_m) more important to SD dynamics
- b_p–SD relationship provides insights and expectations for management strategies
  - nutrient vs. erosion control
  - cost vs. effect

Implications for TMDL Modeling

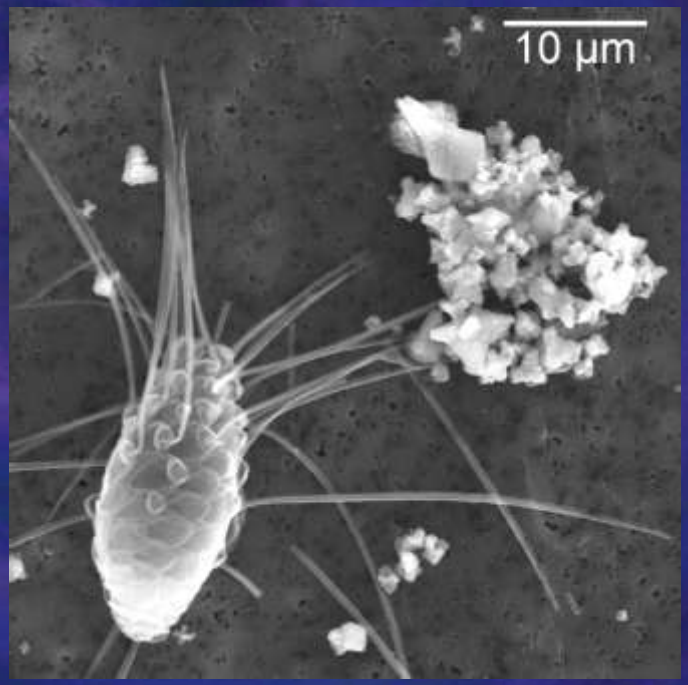
- need to resolve contributions of phytoplankton and mineorgenic particles to scattering and SD
- particle size and composition classes of PAV_m may be appropriate state variables

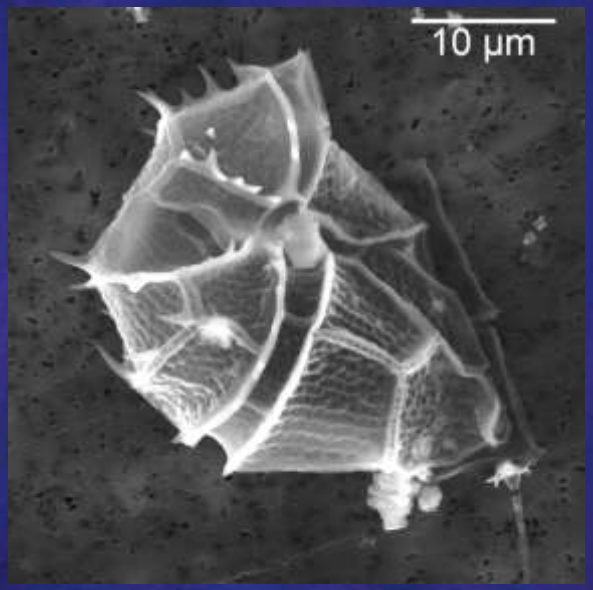


- contribution of particles in 1–2 μm size range to PAV_m (b_m)
  ~ 40% @ low flow conditions
  ~ 15% @ high flow conditions

Acknowledgments

- ☺ UFI's field crew, including B. Wagner, A. Prestigiacomo, A. Effler, and M. Spada, collected water samples and conducted field measurements.
- ☺ UFI's laboratory staff members, including G. Kehoe, measured chlorophyll-*a* concentrations.
- ☺ D. Matthews organized SeaBird and Secchi depth data.


10 µm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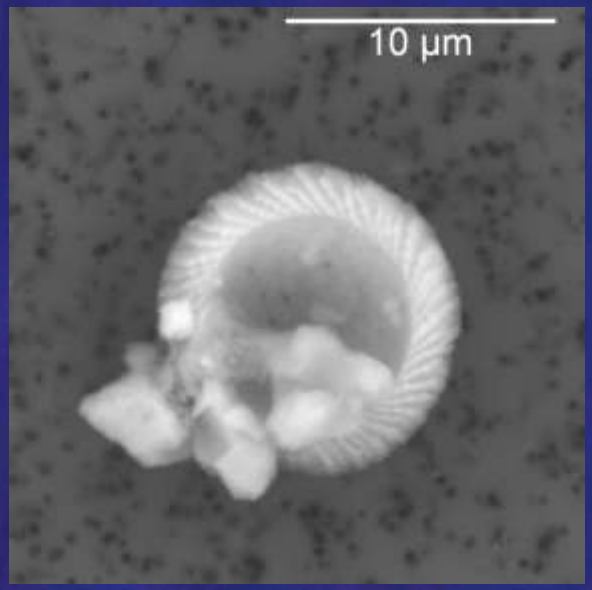
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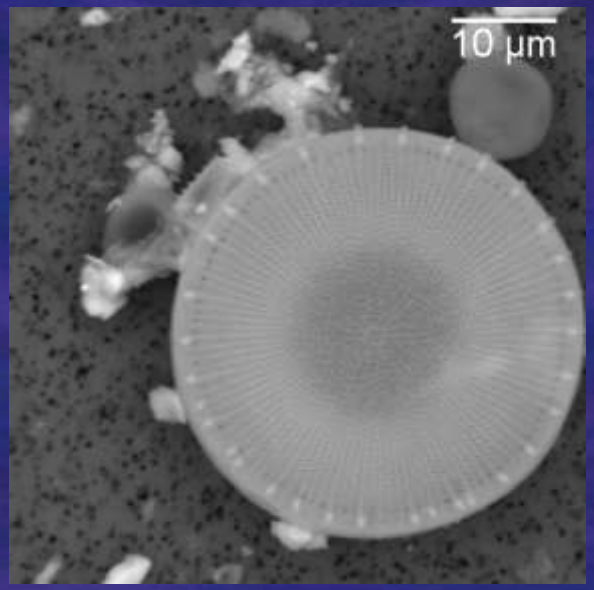
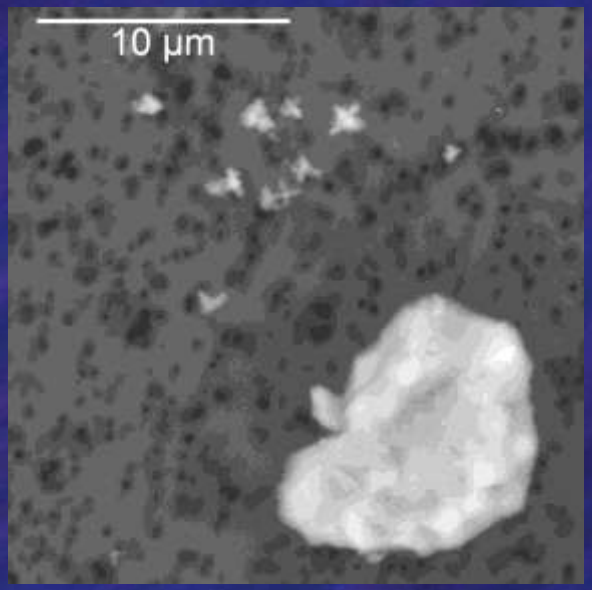
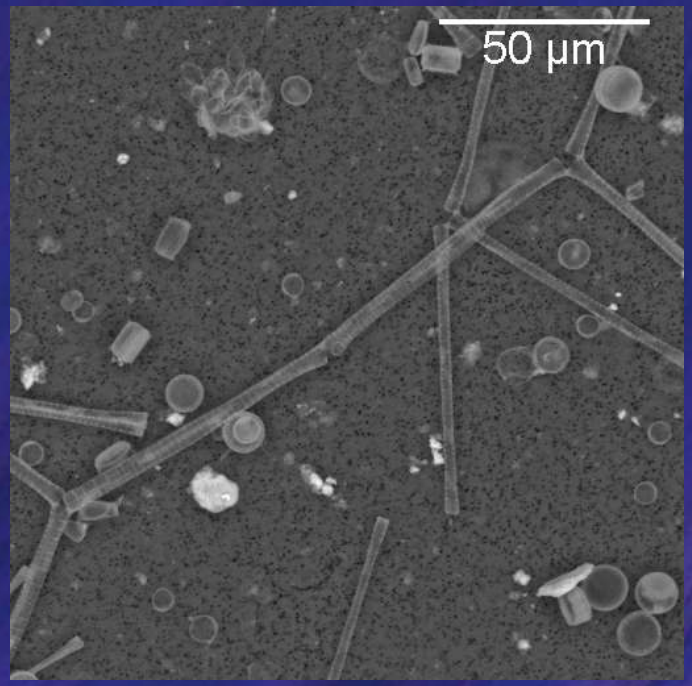
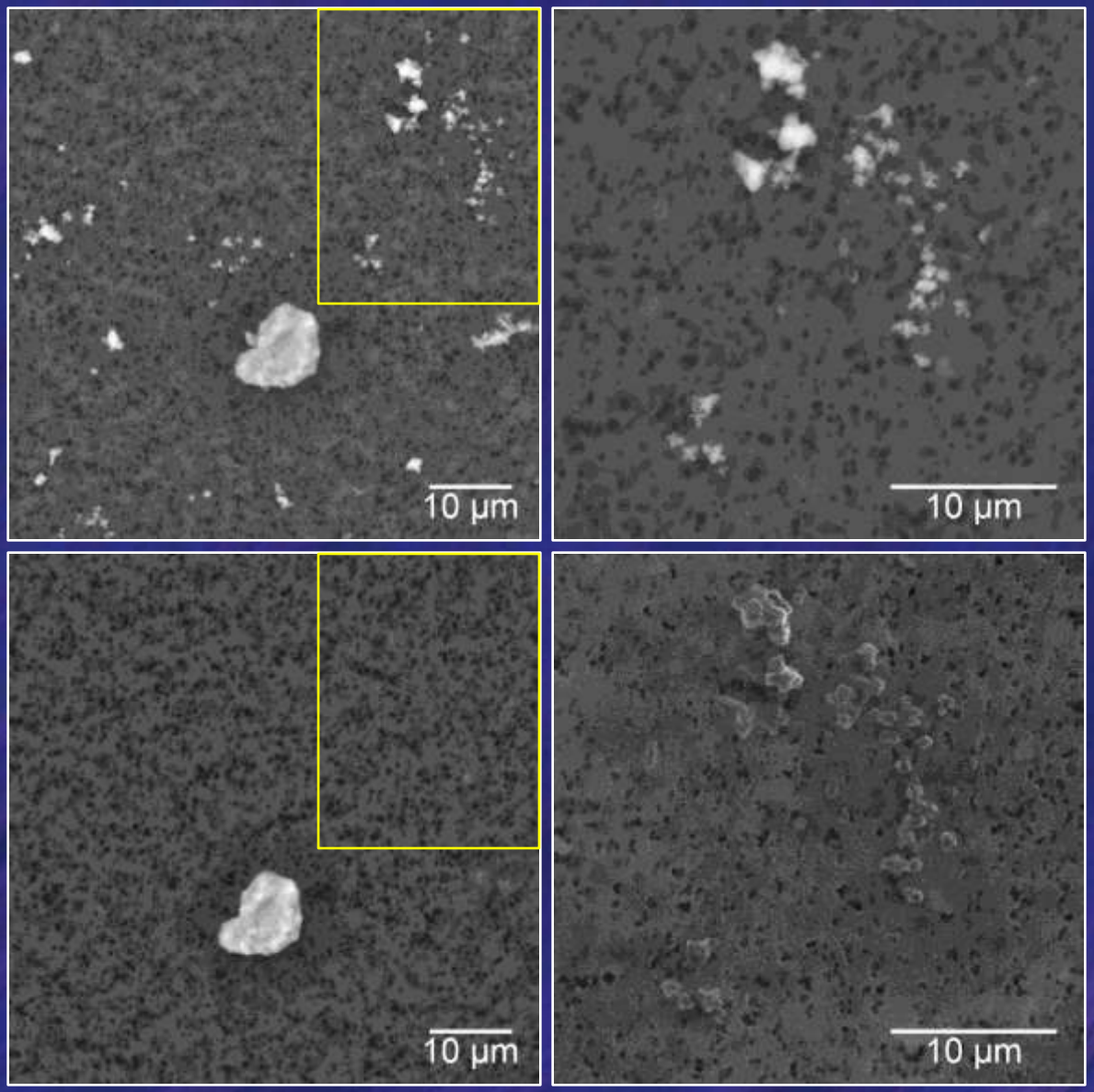

10 µm


10 µm


50 µm

Calcite Nuclei: Differential IPA