Making Sediments: Biogenic Production, Carbonate Saturation and Sediment Distributions

OCN 623 – Chemical Oceanography

Reading: Libes, Chapters 15 and 16
Outline

I. Deep sea sedimentation
   • Detrital sediments
   • Authigenic sediments
   • Biogenic sediments

II. Controls on type of sediment accumulation
   • Physical effects
   • Chemical effects
I. Deep Sea Sedimentation

Major Sediment Types:

- Detrital
- Authigenic
- Biogenic
1. Detrital Sediments

• Most voluminous component
• From chemical or mechanical weathering of continental material
• Typically occur as aluminosilicates
• Transported by rivers, wind, volcanoes,
• Accumulate most rapidly near continental margins
• Deep-sea detrital sediment is predominantly red clay
Red Clay...

- **Red clay** (brown clay or pelagic clay) consists of very fine, weathered particles of (mostly) wind-blown terrigenous clays and extraterrestrial dust.
  - Accounts for 38% of deep-sea sediments

- Clay composition is climate-controlled, consisting mainly of **kaolinite** in the tropics and subtropics and **chlorite** in the polar and subpolar regions
## Table 2-1. Mineralogy of alumino-silicate detritus transported from the continents into the sea via rivers and air.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>SiO₂</td>
</tr>
<tr>
<td>Orthoclase</td>
<td>KAlSi₃O₈</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>xNaAlSi₃O₈ + (1-x)CaAl₂Si₂O₈</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>Al₂Si₂O₅(OH)₄</td>
</tr>
<tr>
<td>Illite</td>
<td>KAl₃Si₃O₁₀(OH)₂</td>
</tr>
<tr>
<td>Smectite</td>
<td>Al₂Si₄O₁₀(OH)₂ • xH₂O</td>
</tr>
<tr>
<td>Chlorite</td>
<td>(Mg,Fe,Al)₆(Al,Si)₄O₁₀(OH)₈</td>
</tr>
<tr>
<td>Vermiculite</td>
<td>Mg₃Si₄O₁₀(OH)₂ • xH₂O</td>
</tr>
</tbody>
</table>
Volcanic ash, tephra

**20 cm**

**2 mm**

**800 km**
Sediment Deposition Rates

- ≤ 1 cm/1000 yr (red clay)
- 1–5 cm/1000 yr (ooze)
- ≥ 5 cm/1000 yr (terrigenous deposits)
- No data or no sediment cover

(b) SEDIMENTATION RATES
2. Authigenic Sediments

- Formed by crystallization within sediment or water column (latter referred to as *hydrogenous*)

- Fe-Mn oxides are the most important

- Make up small fraction of total sediment

- Form through reduction of metals in sediment column coupled with upward diffusion to oxic waters where they precipitate

- Also produced by hydrothermal activity
Major Authigenic Sediments

- **Ferromanganese nodules**
  - Deep-sea deposits
  - Concentric layers of metallic compounds
  - Precipitated by a combination of bacteria, foraminifera, and inorganic chemical reactions

- **Phosphorites**
  - Continental shelf P-rich deposit
    - *Apatite* = $\text{Ca}_5(\text{PO}_4)_3(\text{OH,F,Cl})$
  - Formed where upwelling of nutrient-rich water generates high biological productivity
  - Results from high sediment concentrations of P-rich organic debris
Review of reverse weathering

Chemical balance between the atmosphere, the continents and the oceans was hypothesized in the 1950's by Lars Gunnar Sillén of the Royal Institute of Technology in Stockholm and worked out in detail by Frederick T. Mackenzie and Robert M. Garrels of Northwestern University. In the atmosphere (a) carbon dioxide is dissolved in water vapor as carbonic acid. The water rains or snows on the continents (b), where hydrogen ions from the acid solution leach cations (positive ions) such as calcium, magnesium, sodium and potassium out of the continental rocks. Rivers carry the results of the continental weathering to the oceans (c). In the oceans, which are poor in hydrogen ions, the reactions reverse, creating sedimentary rock rich in cations and restoring carbon dioxide to the atmosphere.

Silica + degraded aluminous clays + iron oxide + organic carbon + soluble cations + bicarbonate

↓

New clay material + Carbon dioxide + water
3. Biogenic Sediments

- Produced from hard parts of plankton (plant/animal) in surface ocean
- Soft tissue residues are rarely important, yet a good correlation exists between sediment accumulation rate and sediment OC %

Figure 2-1. Organic carbon content of marine sediments as a function of bulk sediment accumulation rate. Results summarized by Ross Heath and his colleagues (531).
Biogenic oozes are fine-grained sediments -- at least 30% is shells of micro-organisms

Classified by their composition:

A. Calcareous oozes consist of the CaCO$_3$ shells of:
   - Foraminifera (animals, protozoa)
   - Pteropods (planktonic gastropods)
   - Coccoliths (algae)
   - Ostraracods (planktonic crustaceans)

- Pteropod shells are made of aragonite (more soluble), others are made of calcite
- Calcareous oozes account for about 48% of deep-sea sediment
B. *Siliceous oozes* consist of the shells of:

- **Radiolarians** (protozoa)
- **Diatoms** (algae)

- Diatoms are common in cold water (Antarctica)
- Radiolaria are common near the equator
- Siliceous oozes account for about 14% of deep-sea sediment
- Distribution of *opal* ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) in deep-sea sediments is closely related to pattern of productivity in overlying water...
Primary Organisms Contributing to Deep-Sea Biogenic Sediments

A. CALCAREOUS

1. Forams
   a. Protozoans (Class Sarcodina)
   b. Both planktonic and benthonic forms
   c. Planktonic
      1. Calcite
      2. Generally 50–400 microns; up to 1 mm
      3. Generally 0–200 m depth (photic zone) because most have zooxanthellae
      4. Evolved in Jurassic; presently 30 species
      5. Nonmotile
      6. Distribution limited by food; sensitive markers of water mass
   d. Benthonic
      1. Calcite; a few aragonite, Mg–calcite, siliceous, and agglutinated forms
      2. 20–300 microns; up to 16 mm
      3. All depths; important only in nearshore
      4. Evolved in Cambrian
      5. Live at or near the sediment surface; both mobile and sessile forms
      6. Good indicators of bottom water characteristics (temperature, etc.) so depth zonations are important
   e. Important in paleoceanography
      1. High diversity
      2. Present in all marine environments (marginal basins, deep sea, surface ocean, all latitudes)
2. Pteropods
   a. Gastropods
   b. Planktonic
   c. Aragonite (CaCO$_3$ - more soluble than calcite)
   d. Generally $0.3-10$ mm
   e. Generally upper few 100 m
   f. Evolved in Eocene, but most important in Quaternary so of limited
      biostratigraphic use
   g. Mobile (have gastropod foot) so can select environment
   h. Distinct water mass preferences - tropics and subtropics
   i. Pteropod oozes found only in semi-isolated marginal seas because of
      limited preservation of aragonitic test

3. Nannofossils
   a. Coccolithophorida
      1. Single-celled algae
      2. Mostly planktonic
      3. Calcite surface cells (coccoliths) surround body (coccosphere)
      4. Cocospheres - 2-50 microns; rare in sediments; contain 10-150
         coccoliths
      5. Coccoliths - $<1-10$ microns; usually disc-shaped; important in
         sediments
      6. Limited to photic zone
      7. Evolved in early Jurassic; especially important in Cretaceous
      8. T range: 0-34 C; S range: 15-40 % ; a few fresh water varieties
      9. Very important in sediments
   b. Discoasters
      1. Star-shaped; calcite
      2. 6-25 microns
      3. Warm surface waters
      4. Late Paleocene to Plio/Pleistocene boundary; now extinct
Biogenic Sediment Sources

What’s this?
Where might it have been deposited?
Biogenic Sediment Sources

The Black Sea
Numbers in circles for Leg #1
Numbers in squares for Leg #2
4. Ostracods
   a. Crustaceans
   b. Mostly benthonic (planktonic are chitinous, not preserved)
   c. Bivalve carapace of chitinous-rich calcite
   d. 0.5–2 mm
   e. All depths
   f. Plentiful since Ordovician
   g. Wide salinity tolerance as a group; sensitive to water mass so good tracers for bottom waters
   h. Volumetrically unimportant

B. SILICEOUS

1. Radiolaria
   a. Protozoans
   b. All planktonic; marine
   c. 3 major groups
      1. Acantharia - SrSO₄ tests
      2. Tripylea - siliceous/organic tests
      3. Polycystina - opaline silica tests (SiO₂·4H₂O); important in sediments; 2 morphologies: spherical (Spumellaria) and cap or helmet shaped (Nassellaria)
   d. 50–400 microns
   e. Generally near surface (50–200 m), although some as deep as 2000 m
   f. Evolved in Cambrian
   g. Most diverse of marine microfossils
   h. High densities in upwelling regions
2. Diatoms
   a. Solitary or colonial algae
   b. Both planktonic and benthonic forms
   c. Highly diverse - marine, fresh water, and wet soil environments
   d. Opaline silica
   e. 2 microns to 2 mm, mostly 10 -100 microns
   f. Limited to photic zone
   g. Naked forms (no test) evolved in Jurassic; centric forms (mostly planktonic) evolved in Cretaceous; pennate forms (mostly benthonic) evolved in late Paleocene
   h. Especially important in sediments under regions of high productivity and at high latitudes
   i. 70-90 % of suspended opaline silica is in diatoms

3. Silicoflagellates
   a. Single celled algae/protozoa (characteristics of both)
   b. Planktonic
   c. Internal skeleton of hollow tubes of opaline silica - not well preserved
   d. 10-100 microns
   e. Photic zone; mobile (have flagellum)
   f. Evolved in mid-Cretaceous
   g. Slow evolution so not useful biostratigraphically
The Paradoxes of Biogenic Sediments

- Opal ($\text{SiO}_2$) and calcite ($\text{CaCO}_3$) generated by organisms in the sea account for ~50% of sediment accumulation on seafloor
- Geographic distribution of sediment is not uniform
- Some areas of nearly pure opal, some of nearly pure carbonates…
- Other areas nearly devoid of biogenic sediment…

WHY?
II. Controls on Type of Sediment

If influx of terrigenous sediment is low and the water is warm, carbonate sediments will dominate.

If influx of terrigenous sediment is low and the water is cold, siliceous sediments can dominate.

The distribution of sediments in the deep ocean varies greatly, but is strongly controlled by corrosion of carbonates in deep waters.
Seawater Si Removal by Phytoplankton

Dominated by Upwelling Regions:

Fig. 2. Regional variation in the rate of extraction of dissolved silicon (g SiO$_2$ m$^{-2}$ year$^{-1}$) by phytoplankton in near-surface waters. Modified from Lisitzin et al. (1967).
Distribution of Opal in Marine Sediments
Production is 200 g/m²/yr

River input is 4 x 10^{14} g/yr

Flux into sediment is 1 g/m²/yr to balance river input

99.5% of production is dissolved
Distribution of Carbonates in Marine Sediments

- Calcite production is widespread and relatively uniform in surface waters
- Si is not needed for growth of calcareous organisms
- Yet large areas of world do not have calcareous seds
- Calcite-rich zones are found on ridge crests and other topographic highs
Controls on Biogenic Sediment Distribution

• Production rates (siliceous and carbonaceous)

• Preservation during transport and deposition
  – Settling velocity
  – Sedimentation rate
  – Solubility

• Dilution by non-biogenic material
Settling Velocities of Biogenic Particles

Settling velocity is proportional to size:

\[ \text{Sinking rate} = \text{Us} = \alpha B r^2 \text{ (cm sec}^{-1}) \]

- \( R \) is linear dimension, (radius)
- \( \alpha \) is shape factor
- \( B \) depends on fluid composition

<table>
<thead>
<tr>
<th>Typical settling rates of empty shells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ranked from slow to fast. All figures are approximations. Within each group rates vary within a factor of at least 2 or 3, depending on the thickness of the shell and the morphology.*</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Size</th>
<th>m day(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coccolithophores</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solitary</td>
<td>\sim 10 \mu m</td>
<td>0.3–13</td>
</tr>
<tr>
<td>Aggregate</td>
<td>up to 1 mm</td>
<td>10–6000</td>
</tr>
<tr>
<td>Diatoms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skeletonema</td>
<td>\sim 20 \mu m</td>
<td>\sim 1 (max. 7)</td>
</tr>
<tr>
<td>Coscinodiscus</td>
<td>70 \mu m</td>
<td>15</td>
</tr>
<tr>
<td>Ditylum</td>
<td>60 \mu m</td>
<td>7</td>
</tr>
<tr>
<td>Ethmodiscus</td>
<td>1 mm</td>
<td>500</td>
</tr>
<tr>
<td>Radiolarians</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Various Forms</td>
<td>30–60 \mu m</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>60–120 \mu m</td>
<td>100–200</td>
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<tr>
<td></td>
<td>240 \mu m</td>
<td>500</td>
</tr>
<tr>
<td>Foraminifera</td>
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<tr>
<td>Various Forms</td>
<td>62–125 \mu m</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td>125–177 \mu m</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>177–250 \mu m</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>&gt; 250 \mu m</td>
<td>2000</td>
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<tr>
<td>Pteropods</td>
<td>mm range</td>
<td>1000–2000</td>
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<tr>
<td>Faecal Pellets</td>
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<tr>
<td>Euphausid</td>
<td>n.d.</td>
<td>100–1000</td>
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<tr>
<td>Unspecified</td>
<td>120 × 50 to 200 × 100 \mu m</td>
<td>100–300</td>
</tr>
<tr>
<td>Copepod</td>
<td>100 × 45 to 200 × 45 \mu m</td>
<td>100–200</td>
</tr>
</tbody>
</table>
Effect of Settling Rate on Preservation

• The range of settling velocities observed for biogenic particles in the ocean is very large.

• This has a significant effect on the degree of particle dissolution.

• The longer particles spend in the water column, the more they can “react” with seawater.

• Opal (amorphous silica) and calcite, however, display VERY different dissolution behavior in the oceans...
Corrosion Zones for Biogenic Particles

- Silica dissolves more in warmer, higher pH surface water.
- Calcite dissolves in colder, higher $\Sigma CO_2$ (more acidic) deep water.

Fig. 29.17. Corrosion zones for siliceous and calcareous particles, based on field experiments in the North Pacific near 19° N, 169° W (Berger, 1967, 1968b). Boundaries have been drawn at depth of maximum rate change, they are not the same as facies boundaries in the ocean.

Berger, 1976
Calcite Compensation Depth

- Lysocline is point where dissolution increases markedly.
- CCD is point where rate of calcite supply is matched by rate of dissolution.
Calcite Dissolution

- Remineralization of organic matter in the water column produces CO$_2$ that reacts with CO$_3^{2-}$

  \[
  \text{CH}_2\text{O} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}
  \]

  \[
  \text{CO}_2 + \text{CO}_3^{2-} + \text{H}_2\text{O} \rightarrow 2\text{HCO}_3^-
  \]

- Higher $\Sigma\text{CO}_2$ at depth
- Lower CO$_3^{2-}$ at depth

- In the deep ocean, the decrease in [CO$_3^{2-}$] from this reaction has a marked effect on CaCO$_3$ solubility
Two endmembers:
- Cold surface seawater
- Pacific Deep Water

Alkalinity increase due to release of Ca$^{2+}$

$$\text{CO}_2^{(aq)} + \text{CaCO}_3^{(s)} + \text{H}_2\text{O}^{(l)} = \text{Ca}^{2+}_{(aq)} + 2\text{HCO}_3^{-}_{(aq)}$$

As a water mass ages, its bicarbonate concentration increases & its carbonate ion concentration decreases because of continuing generation of CO$_2$. 
Saturation State of SW

• The saturation state of SW with respect to calcite (and aragonite, Mg-rich calcite, etc.) determines whether these phases will dissolve or not

• Define the saturation state of SW with respect to calcite (CaCO₃) as:

\[
\Omega = \frac{(\{\text{Ca}^{2+}\} \{\text{CO}_3^{2-}\})_{\text{Seawater}}}{(\{\text{Ca}^{2+}\} \{\text{CO}_3^{2-}\})_{\text{Calcite–saturated seawater}}}
\]

Assumes \{CaCO₃\} = 1

The denominator is also known as \(K_{sp}\), the “solubility product”

• Depth at which \(\Omega = 1\) is called the saturation horizon
Solubility of Mixed Carbonates

A variety of mixed carbonates, $\text{Ca}_{(1-x)}\text{Mg}_x\text{CO}_3$:

- $x = 0$: Calcite or aragonite
- $x < 0.04$: Low Mg-calcite
- $0.04 < x < 0.20$: High Mg-calcite
- $x = 0.5$: Dolomite
- $x = 1$: Magnesite

$\text{CaCO}_3 \rightarrow \text{Ca}^{2+} + \text{CO}_3^{2-}$

$K = \{\text{Ca}^{2+}\} \{\text{CO}_3^{2-}\} / 1$

Higher $K$ means $\text{CaCO}_3$ dissolves with higher activities of $\text{Ca}^{2+}$ and $\text{CO}_3^{2-}$.

$\therefore$ $\text{CaCO}_3$ is more soluble

Solubility of Mg-calcite increases with increased Mg content
• The upper ocean is supersaturated wrt both calcite and aragonite
• Aragonite is more soluble than calcite in SW
• Saturation horizon is deeper in Atlantic than in Pacific
To recap some definitions

- **Saturation Horizon** is where $\Omega = 1$

- **Lysocline** is where dissolution effects first appear in carbonate grains
  - Since degree of saturation decreases with depth, dissolution rates should increase with depth… (*Libes has this wrong*)

- **Carbonate Compensation Depth (CCD)** is where the depositional rate of carbonate is equal to the dissolution rate (i.e., no net accumulation)

- The lysocline occurs above the CCD, but is at or below the saturation horizon because of
  - Kinetic effects
  - Protection by organic matter on particulates
  - Inhibitory effect of dissolved species like phosphate which have mid-depth maxima
• No calcite should persist below ~4500 m in Atlantic and ~3500 m in Pacific

• No aragonite should persist in either ocean below ~1000 m

• However, carbonate sediments occur well below these depths (i.e., the CCD is deeper than the saturation horizon) --- WHY?
Carbonate Sediments are Generally Controlled by Sediment Depth

Below the CCD, cold water holds more CO₂, which results in more carbonic acid, which dissolves CaCO₃ faster.
Kinetic Considerations

• CaCO$_3$ should not be preserved in sediments below the saturation horizon

• Yet, calcareous shells do persist… Why?

• Main factor: slow dissolution rates relative to rates of sinking (in water) and burial (in sediment)

• Likelihood of dissolution of a shell depends on factors that control sinking rate and dissolution

• Both influenced by the size, density and shape of a shell

• Dissolution is also controlled by organic coatings and effects of trace ions on shell surfaces
What Controls the Distribution of Various Kinds of Seafloor Sediments?

The answer is "the 3 D's":

1) **Delivery**: Without delivery of sediments into the ocean, they will of course never be found there.

2) **Dilution**: Many different types of sediment particles reach the seafloor. If too much of one type reaches a given place, or the rate of dilution is very high, the other types will become unimportant.

3) **Destruction**: Certain chemical, physical, and biological processes destroy sedimentary particles, removing them from the seafloor sediment.
Distribution Summary of the Principal Types of Sediment on the Seafloor

Thick terrigenous layers in aprons around continents;
Biogenic in equatorial band & along western continental boundaries…WHY?
Authigenic and eolian sediments across vast areas of deep ocean floor covered by sediments of ~100s meters
Volcanic tephra within 1000km of islands arcs and volcanic belts
Thin sediment at active spreading centers

Davis & Gorsline, 1976
In-class exercise:

What is the dominant sediment type for:

A
B
C
D
E

Note: ‘core depth’ does not equal ‘water depth’.