Introduction

- Carbonates cover 7% land surface
- Economic Importance
  - Greater than 50% oil and gas reservoirs worldwide are contained in carbonate rocks
  - 70% giant oil fields in Cretaceous rudistid reefs (Middle East)
  - In Western Canada, carbonate-hosted petroleum deposits are primarily found in Devonian reefs
  - Carbonate deposits host Mississippi Valley type (Pb-Zn) ore deposits
  - Major economic importance as industrial "mineral" (agriculture stone, cement)
- Most carbon on earth is stored in carbonate sediments, therefore plays a major role in the global carbon cycle
Carbonate Mineralogy

- Carbonate minerals include calcite, magnesite, dolomite, siderite, ankerite, and others
- Modern carbonate sediments consist primarily of aragonite, but include some calcite and dolomite

Calcite can contain several percent Mg
- Low-magnesian calcite ("calcite") < 4% MgCO₃
- High-magnesian calcite > 4% MgCO₃
- Dolomite – CaMg(CO₃)₂ – different crystal structure than high-magnesian calcite

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
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<tbody>
<tr>
<td>Calcite</td>
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<tr>
<td>Siderite</td>
<td>FeCO₃</td>
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<tr>
<td>Rhombohedral</td>
<td>MnCO₃</td>
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<tr>
<td>Aragonite</td>
<td>CaMg(CO₃)₂</td>
</tr>
<tr>
<td>Ankerite</td>
<td>CaMg(Fe₂)(CO₃)₂</td>
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<tr>
<td>Witherite</td>
<td>BaCO₃</td>
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<td>Strontianite</td>
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Carbonate Mineralogy Table

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<tr>
<th>Calcite Group (Hexagonal)</th>
<th>Dolomite Group (Hexagonal)</th>
<th>Aragonite Group (Orthorhombic)</th>
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Carbonate Mineralogy
- Modern oceans favour precipitation of aragonite or high-mag calcite
- Early Palaeozoic and middle-late Cenozoic favoured precipitation of (low-mag) calcite, because of lower Mg/Ca ratios at those times

Carbonate Reactions
\[ \text{H}_2\text{O} + \text{CO}_2 + \text{CaCO}_3 \leftrightarrow \text{Ca}^{2+} + 2\text{HCO}_3^- \]
- Carbon dioxide dissolved in water produces carbonic acid, which in turn dissolves calcium carbonate (either aragonite or calcite)
- However, when bicarbonate and calcium are in sufficient supply, calcium carbonate can precipitate
  \[ \text{CO}_2 + \text{H}_2\text{O} \leftrightarrow \text{H}_2\text{CO}_3 \text{ (carbonic acid)} \]
  \[ \text{H}_2\text{CO}_3 \leftrightarrow \text{H}^+ + \text{HCO}_3^- \text{ (bicarbonate ion)} \]
  \[ \text{HCO}_3^- \leftrightarrow \text{H}^+ + \text{CO}_3^{2-} \text{ (carbonate ion)} \]

Carbonates and Biology
- Extraction of Ca\textsuperscript{2+} and HCO\textsubscript{3}\textsuperscript{-} from seawater to precipitate skeletal carbonate (grains)
- Photosynthesis removes CO\textsubscript{2} from water and increases pH, which in turn promotes calcium carbonate precipitation
- Decay of soft tissues can increase alkalinity, increasing pH and promoting carbonate precipitation
- Feeding/sediment ingestion reshapes sediment, generating pellets
- Bacterial activity catalyzes calcium carbonate precipitation
Formation of Carbonate Sediments

- Environment must be “just right”
  - Depth, temperature, salinity, clastic influx, nutrients, etc.
  - "Goldilocks window" (Goldhammer et al. 1990)
- Generally marine environments
- Most carbonate sediments are produced biologically or by biochemical mediation

Figure 6. A sketch depicting the environmental window in which modern coral-reef reefs grow best. Numbers for temperature and salinity define the growth limits of corals. Boxes enclose optimum values.

Global Distribution of Reefs

Boggs 2001
Carbonates and Salinity

Minerology of Skeletal Organisms

Formation of Carbonate Sediments

- Four types of carbonate particles:
  - Precipitates – direct or biologically mediated precipitation (e.g., ooids)
  - Bioclasts – shells, tests, spicules etc. of invertebrates, microbes and algae
  - Peloids – microcrystalline carbonate, generally agglutinated feces or diagenetically altered grains
  - Lithoclasts – fragments of consolidated or lithified sediment
Sediment Production

Formation of Carbonate Sediments
- Controls on distribution of carbonates:
  - Environmental tolerances of skeleton producing organisms
  - Concentration of necessary components (Ca$^{2+}$, CO$_3^{-2}$)
  - Dilution of sediment production by siliciclastics
    - Abundant mud can shut down carbonate-secreting organisms (e.g., filter feeders)

Formation of Carbonate Sediments
- Sediment composition is fundamental in characterizing the depositional environment
- Grain size not necessarily a function of hydraulic regime
  - Commonly is, but some carbonates behave like clastic sediments (e.g., grainstones, carbonate turbidites)
- Platforms, banks formed in situ self-generating and self-sustaining
- Temporal and spatial style of accumulation depends upon nature of the sediments themselves
Marine Environments

Calcareous Algae
Formation of Carbonate Sediments

- Carbonate rocks contain many of the same types of sedimentary structures present in siliciclastic rocks
  - E.g., cross-bedding, cross-lamination, parallel lamination, trace fossils, etc.
- Other structures include stromatolites, teepee structures, etc.

Dunes of oolithically coated peloids

Cross-bedded Pleistocene grainstones
Petrology of Carbonate Rocks

- Grains (Skeletal)
- Mud (Micrite)
- Cement

Calcite is present in at least three textural forms in a limestone:
- Carbonate grains
- Carbonate mud
- Sparry calcite

Carbonate grains – aggregate particles or grains that may have undergone mechanical transport before deposition:
- "Allochems"
- Silt size or larger
- Skeletal particles, ooids, etc.
Petrology of Carbonate Rocks

- Carbonate mud (Microcrystalline calcite)
  - Modern environments – generally needle-shaped aragonite crystals
  - Ancient limestones have similar-size particles made of calcite
  - May also include some siliciclastic grains (clays, quartz, etc.)
  - "Micrite"

Petrology of Carbonate Rocks

- Sparry Calcite
  - Relatively large crystals of calcite, generally 0.02 -> 0.1 mm
  - White in hand specimen or in plane-polarized light
  - Product of diagenesis
    - Pore-filling cement
    - Replacement

Petrology of Carbonate Rocks

- Mineralogy plays a small role in classification -> most carbonates are monomineralic
  - Mineralogy used to distinguish dolomite (dolostone) from limestone or carbonates from non-carbonates
Petrology of Carbonate Rocks

- When studying carbonate rocks, we first distinguish them on the basis of chemical composition, then focus on texture
- Different from siliciclastic sedimentary rocks

Sedimentary Rocks

- Clastic
- Chemical/Biochemical

Particle Size

Composition

Particle Size (Carbonates)

Petrology of Carbonate Rocks

- Dunham (1962; and modifications by Embry and Klovan, 1972)
- Based on depositional texture:
  - Grain packing and relative abundance of allochems to micrite
  - Depositional binding of grains

Carbonate Classification

“Modified Dunham”
Petrology of Carbonate Rocks

- Folk (1959, 1962)
- Based on relative abundance of allochems, micrite, sparry calcite cement

Carbonate Classification (Folk)

Coral Boundstone or Framestone
Dolomite/dolostone
- Composed of > 50% of the mineral dolomite
- Abundant from Precambrian to Holocene
- Some are obviously diagenetically altered limestones (see "Diagenesis")
- Origin of fine-grained dolostones remains elusive – "dolomite problem"

Several models for early-formed dolomite
- Hypersaline model (sabkhas, etc.)
- Mixing-zone model
- Seawater model
Diagenesis

- After deposition, carbonate sediments are subjected to a variety of diagenetic processes
  - Changes in porosity, mineralogy, chemistry
  - Carbonate minerals more susceptible to dissolution, recrystallization, replacement than most siliciclastic minerals

Diagenesis

- Carbonate minerals may experience pervasive alteration of mineralogy
  - E.g., aragonite $\rightarrow$ calcite, dolomitization
  - These changes can alter or destroy original depositional textures
  - Porosity may be reduced or enhanced

Carbonate Cements

![Image of Carbonate Cements](image_url)
### Summary

- Calcite, aragonite and dolomite are most common carbonate minerals
- Environmental conditions need to be “just right” for deposition of carbonate sediments
  - Salinity, temperature, water depth, etc.
  - Most carbonate sediments produced biologically or by biochemical mediation

### Summary

- Limestones consist primarily of grains (allochems), micrite and sparry calcite
- Four types of carbonate grains: lithoclasts, skeletal particles, precipitates, peloids
- Modified Dunham classification uses (primarily) relative proportion of grains and micrite

### Summary

- Dolostone (“dolomite rock”) consists of >50% dolomite
  - Different origins possible
- Diagenesis can dramatically affect mineralogy, porosity, texture of carbonate rocks