Rock types: Metamorphic
• Rocks that have been subjected to enough heat and pressure to change the crystal structure but not enough to melt the minerals

- Classified by texture
  1. Granular
     - Quartz > quartzite
     - Calcite > marble

- Foliated
  - Layered or banded due to heat and direct pressure

  Phyllite
  Gneiss
  Slate
  Schist
Rock types: Metamorphic processes
• Hydrothermal metamorphism
  - low T, low P
  - associated with water near igneous intrusions
  - examples: pegmatite, serpentinite, soapstone

http://csmres.jmu.edu/geollab/fichter/IgnRx/Introigrx.html

Rock types: Metamorphic processes
• Contact metamorphism
  - high T, low P
  - associated with igneous intrusions
  - examples: hornfels, marble, quartzite

http://csmres.jmu.edu/geollab/fichter/IgnRx/Introigrx.html

Rock types: Metamorphic processes
• Regional (Barrobian) metamorphism
  - Low-high T, intermediate P
  - associated with orogenic events (mountain building)
  - examples: slate, phyllite, schist, gneiss

http://csmres.jmu.edu/geollab/fichter/IgnRx/Introigrx.html
Rock types: Metamorphic processes

- **Blueschist**
  - high T, low P
  - associated with subduction zones
  - examples: blue color from mineral glauophane

- **Eclogite**
  - moderate T, very high P
  - metamorphism occurs in the mantle (rarely outcrops)

Ore deposits and Ore Minerals
Metals

“Stone Age”
• 20,000 years ago
• Use of native elements: gold, silver, copper

“Copper Age”
• 5,000 years ago
• Separating copper, tin, lead, zinc from sulfides/oxides

“Bronze Age”
• 4,000 years ago
• Alloys of copper and tin

“Iron Age”
• 1,000 years ago

Technological progression based on our ability to isolate metals!

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Ore Minerals

Every American Born Will Need...

3.5 million pounds of minerals, metals, and fuels in a lifetime

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Ore Minerals

<table>
<thead>
<tr>
<th>Element</th>
<th>Crustal Abundance (%)</th>
<th>Concentration Factor (enrichment)</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>8.0</td>
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</tr>
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**Ore Deposit:** Where minerals are concentrated 10-1000 times to the degree that they can be extracted profitably.

### Ore Deposits

- **Hydrothermal**
- **Igneous**
- **Sedimentary**
- **Metamorphic**
Ore Deposits: Hydrothermal

Hydrothermal activity near volcanically active terrains
- majority of ore deposits
- hot seawater or groundwater leaches minerals from permeable rocks
- minerals precipitate into cracks from metal-rich solutions
- range of temperatures, depths and pressures
- examples: iron, zinc, copper, chromite, lead, mercury, arsenic, gold, silver, bismuth, antimony

1. Hydrothermal Ore/Vein Deposits
- minerals dissolved in hot water that comes from or contacts a cooling magma body are deposited as they flow into cool cracks in the surrounding rock

2. Hydrothermal disseminated deposits
- mineralized fluid from cooling pluton invades and saturates permeable rock surrounding pluton
3. Pegmatite/Porphyry deposits
- coarse grained intrusive igneous bodies due to preferential settling of denser ore-rich minerals in a magma chamber
- copper, molybdenum, silver, gold, lead, zinc, tungsten

Ore Deposits: Hydrothermal

300 million years ago Appalachians were pushed up when N America collided with Europe
- heated water leached lead and zinc into groundwater
- minerals deposited within carbonate rocks

http://www.ksu.edu/Publications/pic17/pic17_1.html
Ore Deposits: Hydrothermal

4. Volcanogenic
- mineral-rich fluids vented to surface by volcanic activity black smoker

http://www.divediscover.whoi.edu/vents/vent-chemistry.html#

Ore Deposits: Igneous

1. Crystal fractionation
- Early crystallized minerals sink
- Can form cumulate layers of minerals with repeated magma injections
- “Layered igneous intrusion” or complex

http://web.uct.ac.za/depts/geolsci/dlr/301s/bushveld%20field%20photos.html

Ore Deposits: Igneous

1. Crystal fractionation
- Bushveld Igneous Complex, South Africa
- 2 Byr old volcanic formation
- Platinum group metals, iron, tin, chromium, titanium

http://www.divediscover.whoi.edu/vents/vent-chemistry.html#
Ore Deposits: Igneous

2. Magmatic immiscibility
   - Separation of metal sulfide or metal oxide magma
   - Copper, iron, nickel sulfides in ultramafic magmas

Ore Deposits: Igneous

3. Komatiites (no longer forming)
   - Ultramafic volcanic rocks erupted into ocean basins
   - 2.8 billion years ago
   - Earth no longer hot enough to melt shallow komatiites
   - Nickel and magnesium
   - S. Africa, Australia, Canada

Ore Deposits: Sedimentary

1. Chemical precipitate
   - Mild hydrothermal events (<250°C) near igneous intrusions
   - Water travels through sedimentary rocks and creates a band of metals

   Banded Iron Formation
   - formed 3.8-1.7 Byr ago
   - oxygen producing bacteria helped precipitate iron from seawater into iron oxides

   Hematite (Fe₂O₃)
   Jasper (SiO₂)
2. Deep ocean (or lake) precipitate
   - "Manganese" nodules 4,000-6,000 m deep
   - Contain manganese, iron, nickel, copper, cobalt
   - Growth of 1 cm per 1 million years

3. Placer or alluvial deposits
   - Ore minerals accumulate in river gravel
   - Mechanically segregated (typically dense) ore minerals
   - Examples: gold, magnetite, chromite, tin, platinum

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[Diagram showing ore deposits]

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[Table showing age of rock deposits]

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[External image links]
Biogeochemical Cycles

- Stock (Reservoir weight)
- Fluxes (Flow rate in weight per unit time)
- Residence time = stock in reservoir / flux
  - in atmosphere
  - in soils/rocks
  - in water

Environmental Consequences

- Groundwater and surface water contamination
- Collapse of unfilled tunnels
- Destruction of landscape
- Smelting pollution: heat separates metal from slag
  - Air emissions
    - Sulfur dioxide in acid rain
    - Copper and selenium particulates
    - Mercury, cadmium and arsenic particulates
  - Wastewater
- Energy intensive

Clean Air Act, 1970
Clean Water Act, 1972
Federal emission standards
Environmental Consequences

- Question: Does one risk a pristine resource even if assorted groups and models (all of which have proven imperfect in the past) suggest that the risk is minimal?
- Conflict: If one doesn't accept mines, where will the resources that we demand to maintain our standard of living come from?

Mineral exploration

- Exploration: success rate of 1%
  - Field mapping
  - Geochemical sampling
  - Geophysical surveys
  - Data compilation
  - Drill testing
  - up to $100 million, 10 years
- Feasibility studies
  - Further drill tests to determine economic viability...
  - Size? Tonnage? Price? Demand?
  - Grade? (Concentration of mineral opposed to gangue)
  - Cut-off grade? (Minimum concentration to make a profit)
  - Cost of cleanup?
  - Surrounding flora, fauna, air and water quality?

Mineral exploration

- Mine development
  - Establish infrastructure: site clearing, roads, power, mill, disposal areas, mine buildings, shaft sinking or pit design
- Mineral extraction
  - Ore goes to the mill
  - Waste to tailings disposal
Mineral exploration

- Mineral processing: milling
  - Crushing and further separation of ore from gangue
  - Concentrated ore to the smelter
  - Waste to tailings disposal
- Smelting
  - Extract metals from concentrate
- Marketing
- Closure and clean-up