ERTH2404
Lecture 3: Sedimentary Rocks

Photos: M.Lamontagne

Red Rock Canyon State Park, CA

Maurice Lamontagne

Reading assignment

- Please read Kehew’s book to complement the material presented in this lecture:

    Chap. 5;

Lecture content

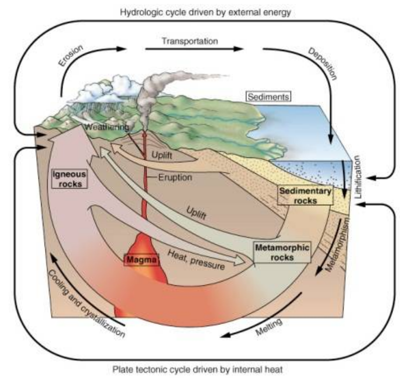
- Origin and classification of sedimentary rocks
  - Detrital sedimentary rocks
  - Chemical sedimentary rocks
- Sedimentary structures
- Sedimentary depositional environments
- Engineering considerations

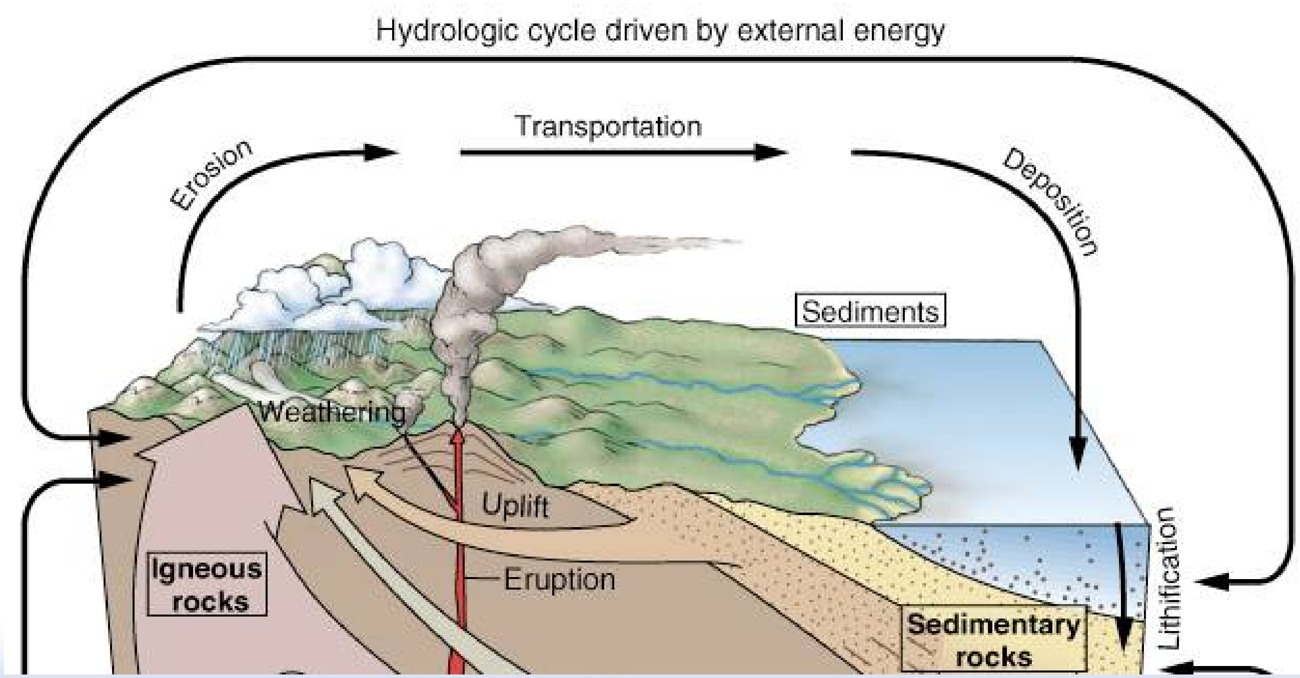
Sedimentary Rocks

- Significance
  - Sedimentary rocks make up 5% of crustal rocks
  - 75% of rock exposed
  - Important economically
    - Building material
    - Energy sources (coal, petroleum, natural gas)
    - Sources of iron, aluminum and manganese
  - Record Earth's past history and environments

Remember the rock cycle

What happens to rocks at the Earth's surface?





Remember the rock cycle

- Sedimentary rocks are formed from any type of pre-existing rocks by the processes of
  - Weathering
  - Erosion & Transportation
  - Deposition

- Common characteristic: BEDDING (layering)
- Sedimentary rocks reflects the environment of erosion (climate, ocean vs. land)

Classification of Sedimentary Rocks

- Two criteria:
  1. Process of formation: detrital or chemical
  2. Texture: grain size, shape, physical features

- **Detrital (clastic)**: formed by the erosion and deposition of rock fragments

- **Chemical**: formed by precipitation

Texture

- **Clastic rocks** are composed of aggregates of individual fragments:
  - **Clasts** (larger fragments) surrounded by a **matrix** (fine-grained sediments)
  - Commonly layered

- **Non-clastic rocks** are composed of a pattern of interlocking crystals
  - Similar to crystalline igneous rocks

Classification Table

Process of formation		Texture	
Detrital		Clastic	
Chemical	Inorganic		Non-clastic
	Biochemical		

Process of Formation

- Detrital Sedimentary Rocks
  - **Weathering**: breakdown of rocks into fragments
    - Physical (abrasion, freezing), chemical
  - **Erosion**: Detachment and transport of fragments by water, wind or gravity
  - **Deposition**: sediments deposited by natural process
  - **Lithification**: cementation and compaction

- Chemical Sedimentary Rocks
  - **Precipitation**: formation of a solid in a solution during a chemical reaction

Lithification

- **Lithification** (process in which sediments compact under pressure, expel connate fluids, and gradually become solid rock)

- Achieved in several ways
  1. Compaction: caused by weight of overlying material
     - Most basic lithification process
     - Mechanical reduction of void space in between particles
  2. Cementation: filling of void spaces by chemical precipitation
     - Generates cement that binds particles together
     - Two most common cements: quartz (SiO_2) and calcite ($CaCO_3$)

Lithification

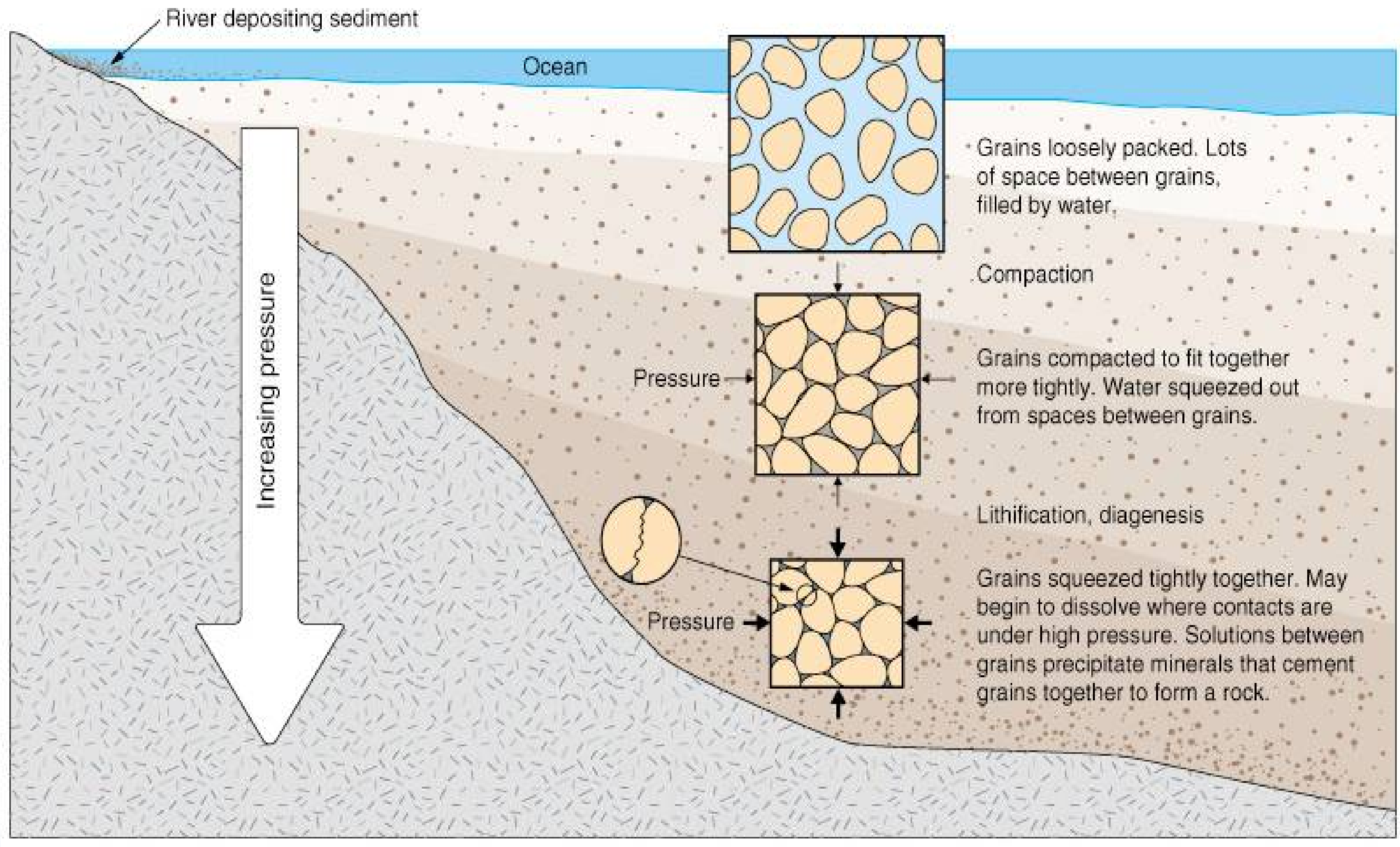
- Achieved in several ways

  3. Crystallization: additional growth of the original crystal within the void spaces
     - Without addition of new chemical substances

- Impact of lithification
  - Reduces the amount of void space between particles
  - Increase in density, decrease in porosity & permeability

- The degree of lithification influences the induration of sedimentary rocks

Lithification



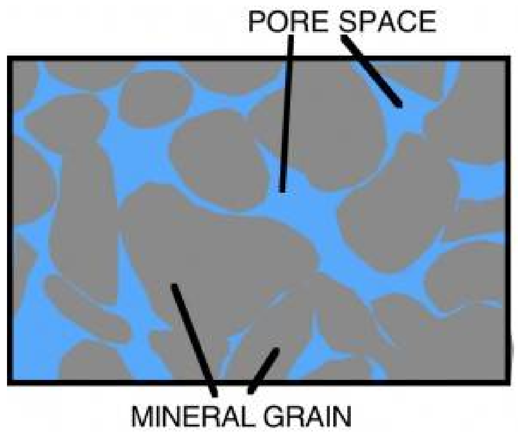
Porosity

- Total volume of Earth material: V_T
  Total volume of void space: V_v
  Total volume of particles: V_S

- **Porosity** [%] $\eta = V_v / V_T$

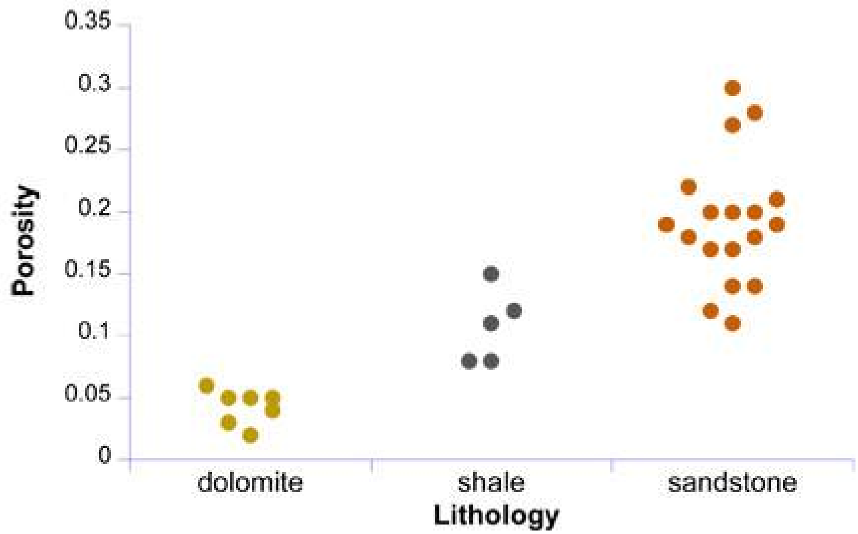
- **Void ratio** [%] $e = V_v / V_s$

- Note: porosity is not the same as permeability…

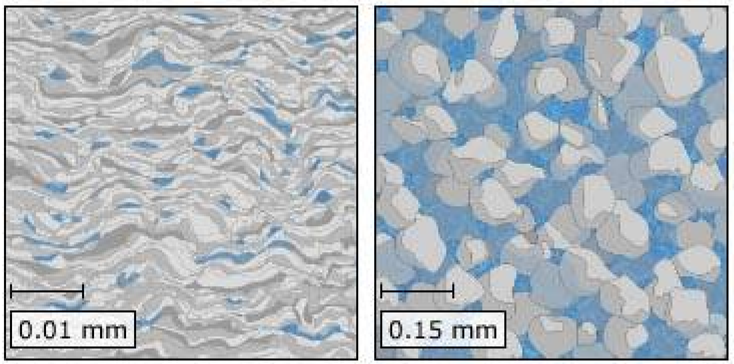


Source: Wisconsin Geological and Natural Survey

Some porosity values



Source: Wisconsin Geological and Natural Survey



Shale Sandstone

Permeability

- **Permeability**: general qualitative term describing the ability of a material to transmit fluids

- Permeability is a composite property of:
  - Material properties: size, shape and interconnectivity of the voids
  - Fluid properties: density, viscosity

- Permeability varies by several orders of magnitude in earth materials

Classification of detrital rocks

- Most common minerals are quartz, feldspar, clay minerals
- Detrital rocks are classified according to **particle/grain** size

Classification of detrital rocks

- Wentworth scale

Grain diameter [mm]	Size name
<1/256	clay
1/256 - 1/16	silt
1/16 - 2	sand
>2	gravel

Detrital rocks in the field

- http://www.glossary.oilfield.slb.com/Terms/u/udden-wentworth_scale.aspx
- Large blocks are found near the source whereas very fine grains end up in deep marine environments far from the source

Lake Powell, UT Photo: M.Lamontagne

Classification of detrital rocks:

Grain diameter [mm]	Size name	Detrital sedimentary rock
<1/256	clay	Mudstone
		Shale
1/256 - 1/16	silt	Siltstone
1/16 - 2	sand	Sandstone Arenite Wacke
>2	gravel	Conglomerate
		Breccia

Properties of detrital rocks

- **Grain size**: based on grain diameter
- **Roundness**: rounded vs. angular
- **Sorting**: distribution of grain sizes in sedimentary rock

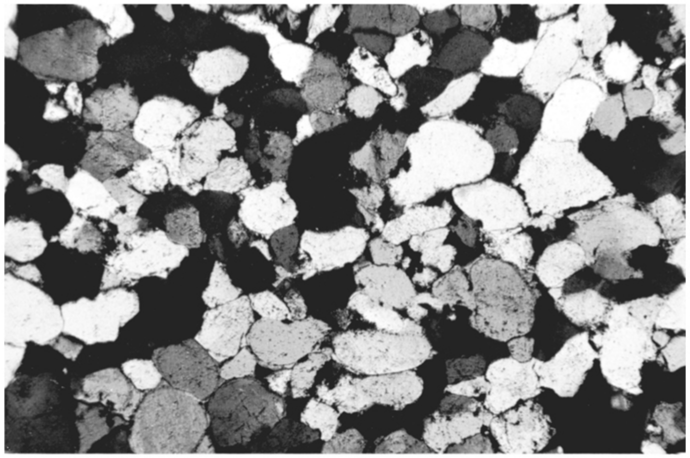
Grain size, Roundness, Sorting

- Grain size is related to the distance traveled from the sediment source
  - Due to abrasion
  - Mineral composition: how tough is a mineral?

	Close to Source	Far from Source
Grain Size	Larger	Smaller
Roundness	Angular	Rounded
Sorting	Poorly sorted	Better sorted

Sediment Maturity

- **Mature** vs. **Immature**
- Mature: well sorted, fine-grained (sand or smaller), rounded, mostly quartz grains
- Immature: poorly sorted, coarse-grained, angular, very little proportion of quartz



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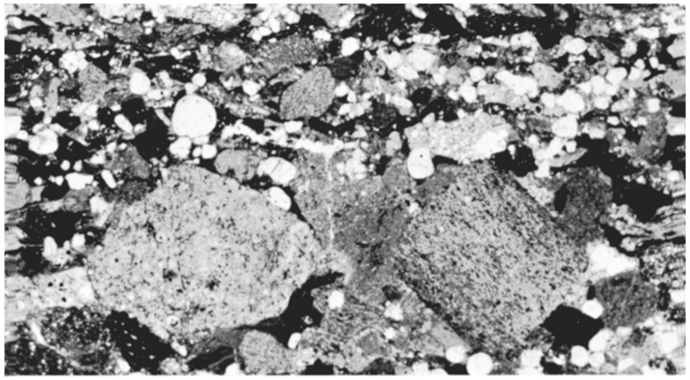

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Common detrital rocks

- Uniform grain size
  - **Shale**: composed of mud
  - **Siltstone:** composed of silt
  - **Sandstone**: composed of sand (gritty)
    - Arenite (<15% matrix) (from latin: arena: sand)
    - Wacke (>15% matrix)

Common detrital rocks: Shale

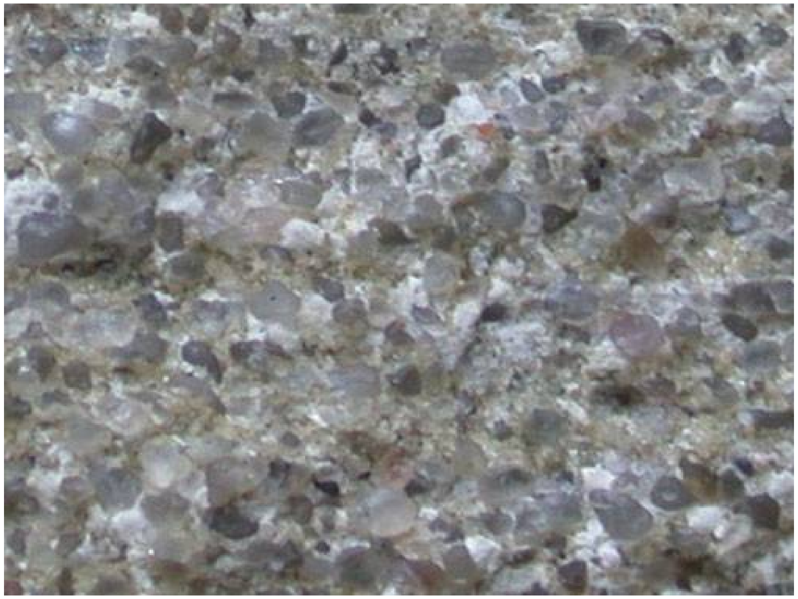
- Most common sedimentary rock (50% of all sed. rocks)
- Formed by the compaction and/or cementation of clay minerals
- Particles (<1/256 mm) deposited in thin layers (laminellae)
- Shale splits into thin layers (fissility)
- Usually parallel to depositional layering
- Shale weathers readily
- Found in gentle slopes
- Important source of hydrocarbons (shale gas, shale oil)

Common detrital rocks: Sandstone

- Sandstone is formed in a variety of environments
- Texture can be used to interpret the rock's history
- Quartz (SiO_2) is the prominent mineral
- More durable than shale
- Found in steeper slopes

Common detrital rocks: Sandstone

- Quartz Sandstone:
  - All sand-sized, all rounded, well sorted, 99% quartz
  - monomineralic rock



Lake Powell, UT Photo: M.Lamontagne

Bryce Canyon, UT Photo: M.Lamontagne

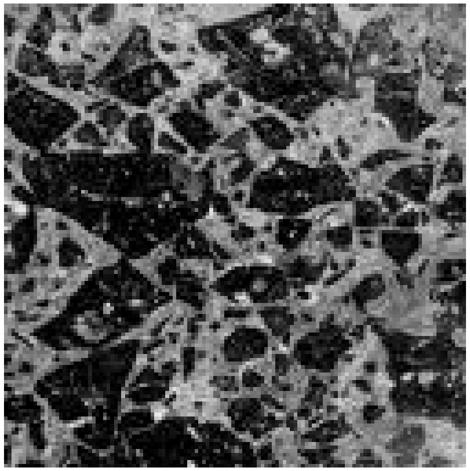
- Arches NP, UT Photo: M.Lamontagne

- Arches NP, UT Photo: M.Lamontagne

Common detrital rocks

- Wide range of grain size > 2 mm
  - **Breccia**: composed of angular gravel
    - Deposited closer to source
  - **Conglomerate**: composited of rounded gravel
    - Transported further from source

conglomerate



breccia

USGS

Chemical sedimentary rocks

- We now discuss <u>chemical</u> sedimentary rocks

Great Salt Lake, UT Photo: M.Lamontagne

Chemical sedimentary rocks

- Material precipitated from water
  - Inorganic: minerals crystallize from supersaturated water
  - Biochemical/Organic: organisms extract compounds from seawater to form shell; when dies, sinks to bottom of ocean
    - Biochemical sediment

Inorganic Precipitation

- Water supersaturated in certain elements
  - Often because of evaporation

- Precipitated crystals sink to bottom

- Ca, CO_3 → limestone ($CaCO_3$)
- Ca, Mg, CO_3 → dolostone ($CaMg(CO_3)_2$)
- SiO_2 → chert
- Na, K, Cl → rock salt (NaCl, KCl)
- Ca, SO_4 → gypsum ($CaSO_4 . 2H_2O$)

Inorganic Precipitation

- SiO_2 based
  - Chert, opal ($+H_2O$): microcrystalline
  - Geode: mineral deposits in cavities in rocks

Chert

Geode

Biochemical/Organic Precipitation

- Organisms extract minerals from seawater and build shells
- Shells sink when organisms die

- Reef, benthic and some planktonic organisms extract Ca and CO_2 → limestone ($CaCO_3$)

- Other planktonic organisms extract SiO_2 → chert

Limestone

- Most common chemical sedimentary rock (10% of all sedimentary rocks)
    - Composed mainly of mineral calcite ($CaCO_3$)
    - Produced by **biochemical** and **inorganic** precipitation

- Marine biochemical origin most common
    - Coral reefs (important petroleum reservoir rock)
    - Coquina (broken shells)
    - Chalk (shells of microscopic organisms)

Generalized bedrock geology,
Ottawa-Hull, Ontario and Quebec; Harrison, J E; MacDonald, G.
Geological Survey of Canada, "A" Series Map 1508A, 1979, 1 sheet,
https://doi.org/10.4095/109223

- The map can be downloaded at:

- https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/downloade.web&search1=R=109223

Limestones in the Ottawa-Gatineau Region

Photo: GeoheritageOttawa

- Photo: NRCan

Organic limestone

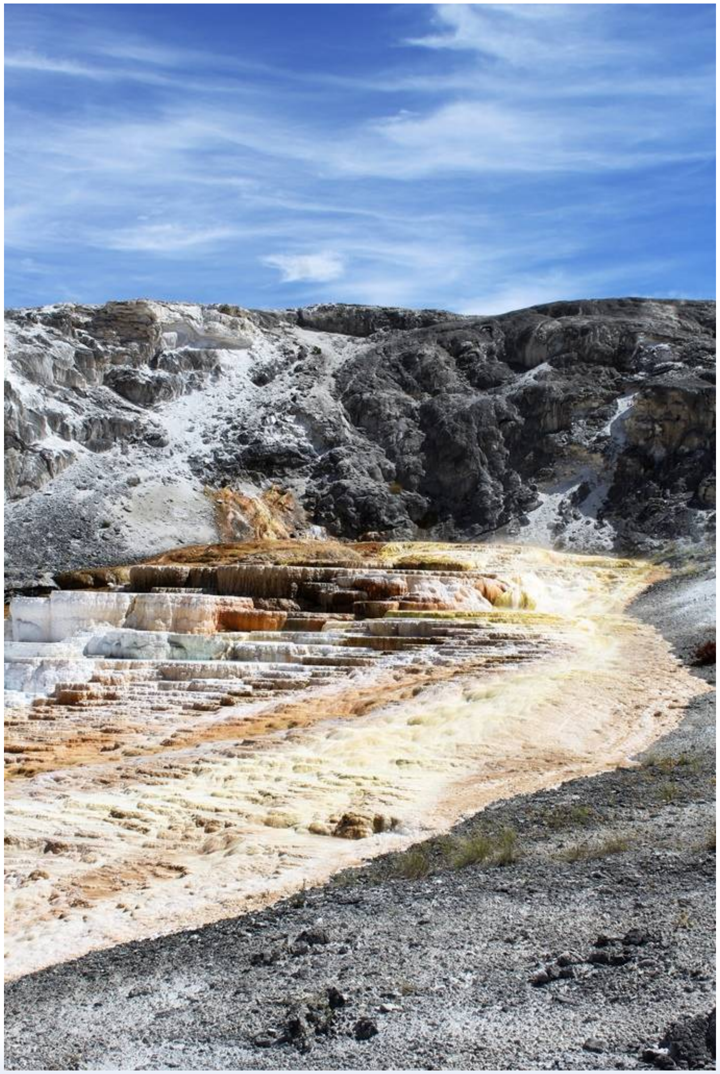
- Coquina: composed of poorly cemented shells

Scale in mm

Inorganic limestone

- Travertine (limestone): stalactites, stalagmites, hot springs

Inorganic limestone



- Travertine deposits: Hot springs (Yellowstone)

Photo: M. Lamontagne

Inorganic Precipitation

- Evaporites
  - Precipitation due to evaporation of shallow lakes, inland seas
  - Minerals precipitate in order of increasing solubility:

1. Ca + SO_4 --> gypsum ($CaSO_4 \cdot H_2O$)
2. Na + Cl --> halite (NaCl)
3. K + Cl --> sylvite (KCl)

Salt flats

- Playa (ephemeral) lake: a waterbody existing for a short period following precipitation or snowmelt
- In a desert environment where rain dissolves elements from rocks, washes down into valleys ephemeral lakes
- Salt flat: water evaporates leaving behind salts

Credit: Eos, AGU

Salt flats

- Bonneville Salt Flats (Utah)

Sedimentary structures

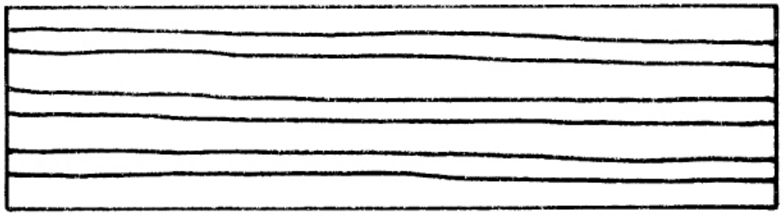
- Sediments deposited in layers: beds, **strata**
- Each layer unique, records conditions under which particles, minerals deposited
- **Bedding plane:** surface that separates each successive layer
- Conditions recorded in **sedimentary structures** within layers
- **Folding**: strata deformed and curved

Sedimentary structures: Bedding

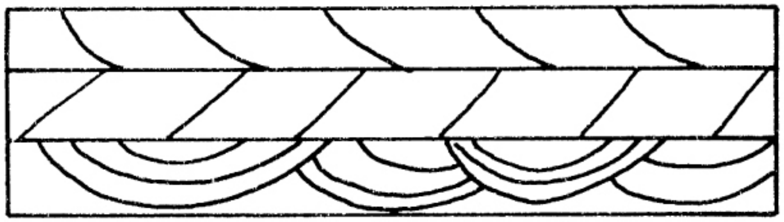
- **Parallel bedding**: quiet deposition of particles falling to the bottom of a water column by gravity
- **Cross bedding**: deposition under alternating wind or water current direction
- **Graded bedding**:
  - Coarse particles at the bottom, changing to finer particles at the top
  - Deposition of material moving rapidly downslope

Sedimentary structures: Bedding

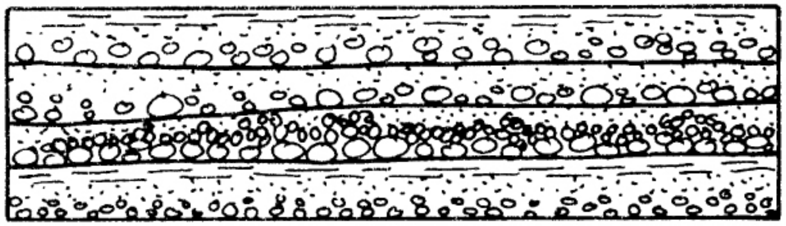
- **Parallel bedding**



- **Cross bedding**

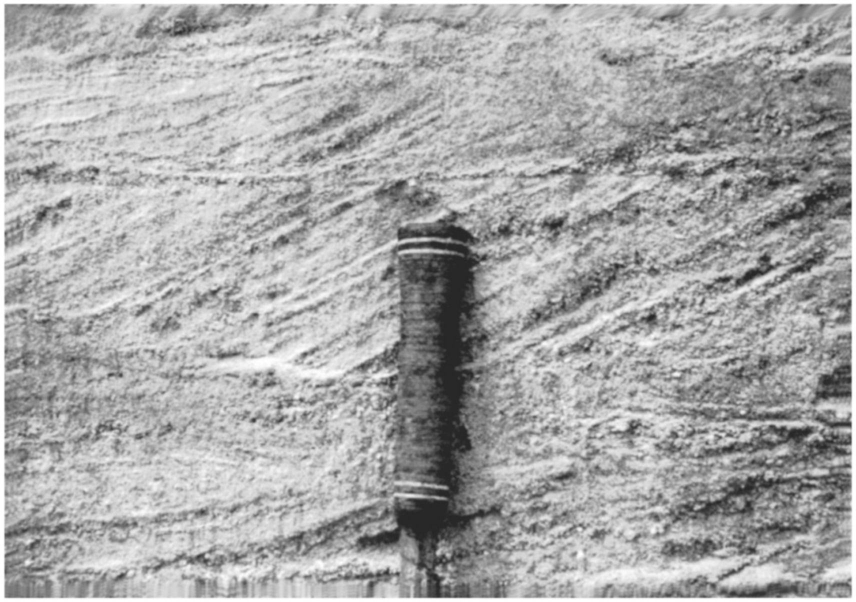


- **Graded bedding**



Sedimentary structures: Cross-bedding

- Sand dunes, some river deposits
- Records alternating wind or current direction



Sedimentary structures: Ripples

- **Ripple marks**
  - Small scale back-and-forth motion of waves
  - Occur on beaches and streams

Sedimentary structures: Mud cracks

- Muddy sediment dries and shrinks
  - cracks fill with different sediment (desert, dry lakes)

Fossils

Photo: M. Lamontagne
Museum of Natural Sciences, Beijing

- Remains of plants or organisms
- shells, bones, petrified wood, imprints of plants
- **index fossils**: indicator of relative time

Sedimentary environments

- Features of sedimentary rocks reflect their depositional environments

- Important factors:
  - Transporting agent (water, wind, ice)
  - Flow characteristics
  - Characteristics of body of water
    - Size, shape, depth, circulation of water
  - Presence of life
  - Nature of sediments being deposited

Sedimentary environments

- Types of sedimentary environments

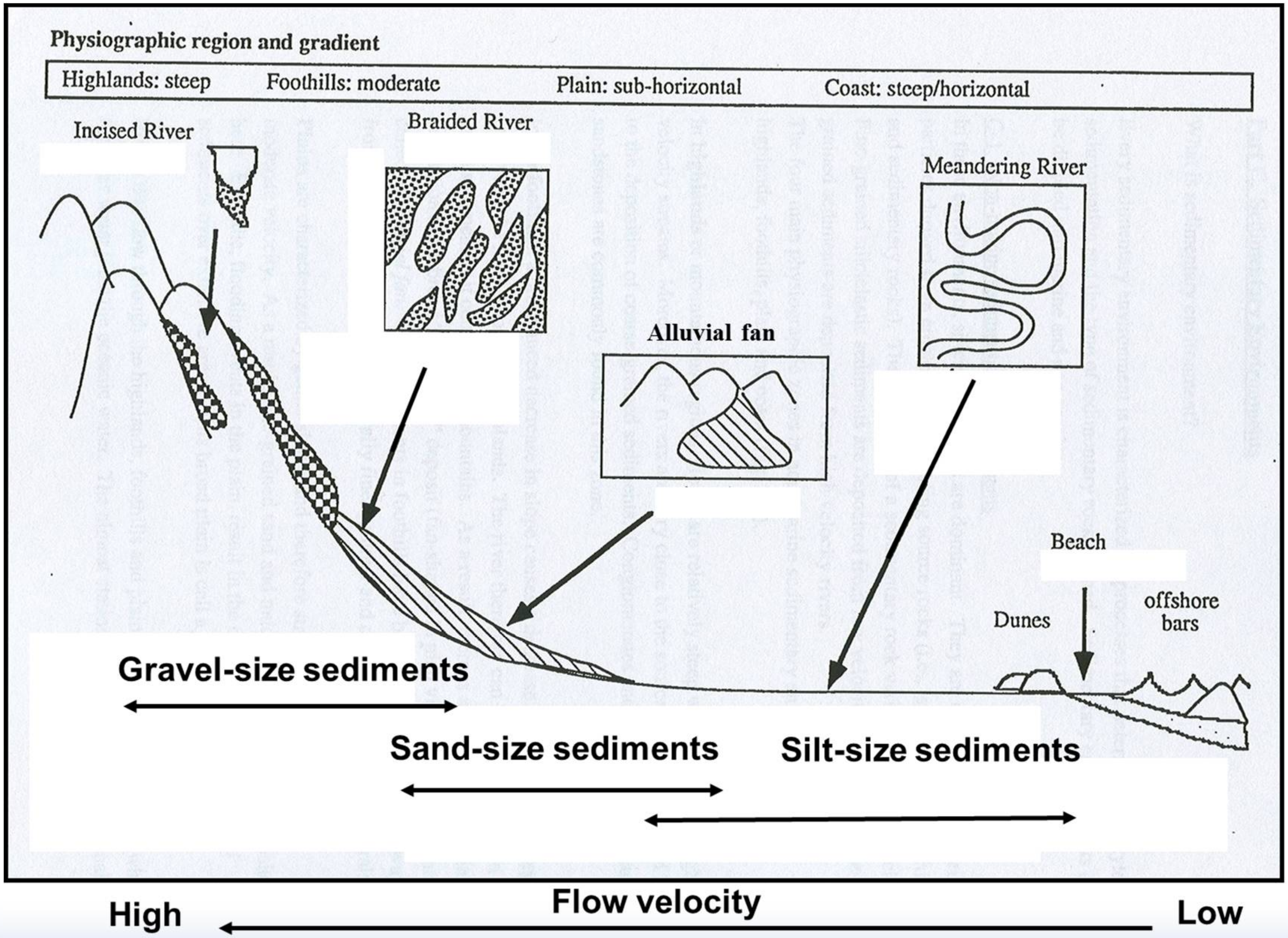
1. Continental

2. Marine
   - Shallow (continental shelf; depth ≤ 200 m)
   - Deep (seaward of continental shelf)

Continental environments

- Dominated by erosion and deposition associated with water, ice and wind
- Detrital sedimentary rocks dominant
- Grain size varies with flow velocity
  - Coarse-grained sediments deposited by fast-flowing rivers
  - Fine-grained sediments deposited by slow-flowing rivers

Continental environments



Great Sand Dune NP, CO

Photo: M. Lamontagne

Marine environments

- Shallow
  - Detrital sedimentary rocks
    - Near shore:
      - Low-energy environment
        (e.g. protected lagoon): silt-size sediments
      - High-energy environment
        (e.g. exposed beach): sand-size sediments
      -
    - Shelf: wide range of sediment sizes
    - Slope: frequent mass movements, graded bedding

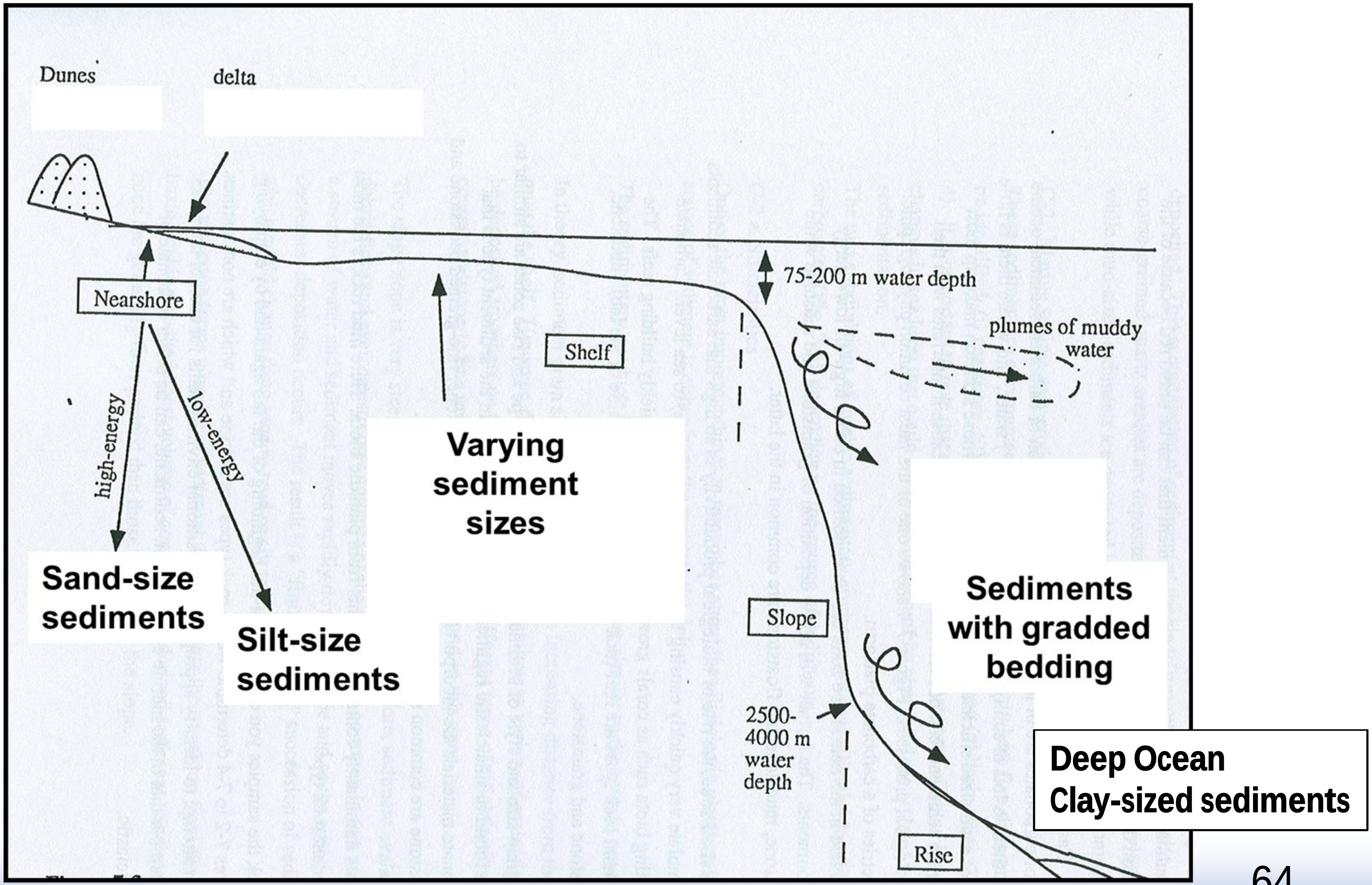
Marine environments

- Shallow
  - Biochemical sedimentary rocks
    - Conditions for accumulation of biochemical sedimentary rocks
      - Sunlight
      - Oxygen
      - Warm water (T>20°C)
      - Little silt- and clay-size sediments

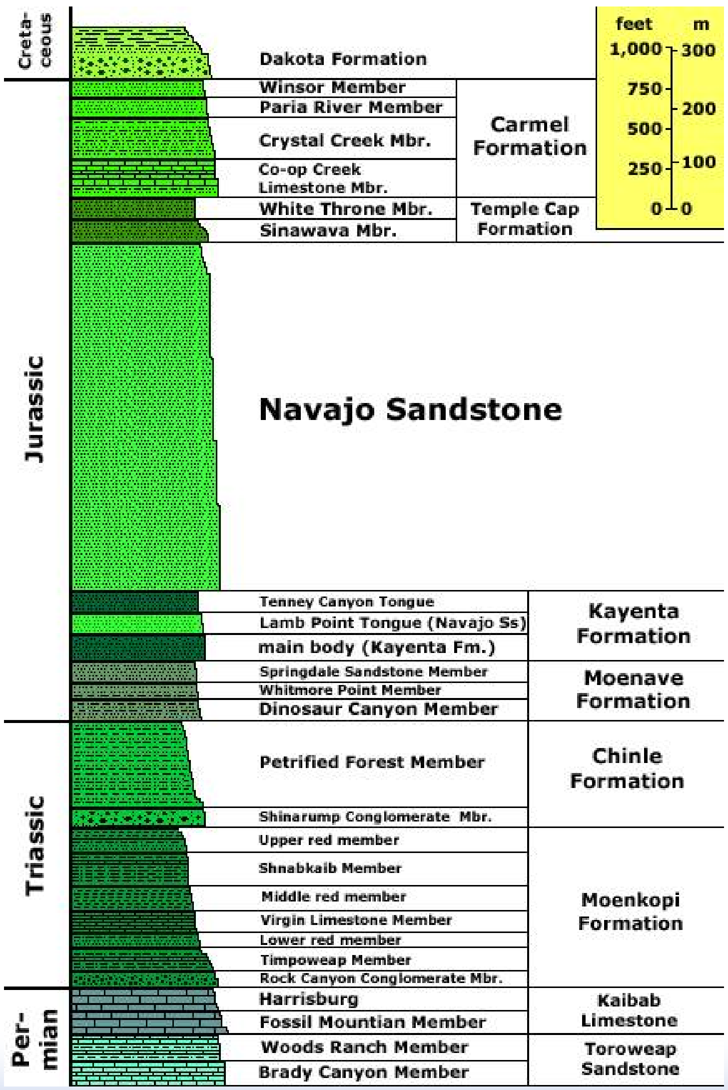
Marine environments

- Deep ocean
  - Clay-size sediments
  - Quiet environment
    - Conducive to the formation of shale
  - No biochemical sedimentary rocks
    - Reefs cannot develop

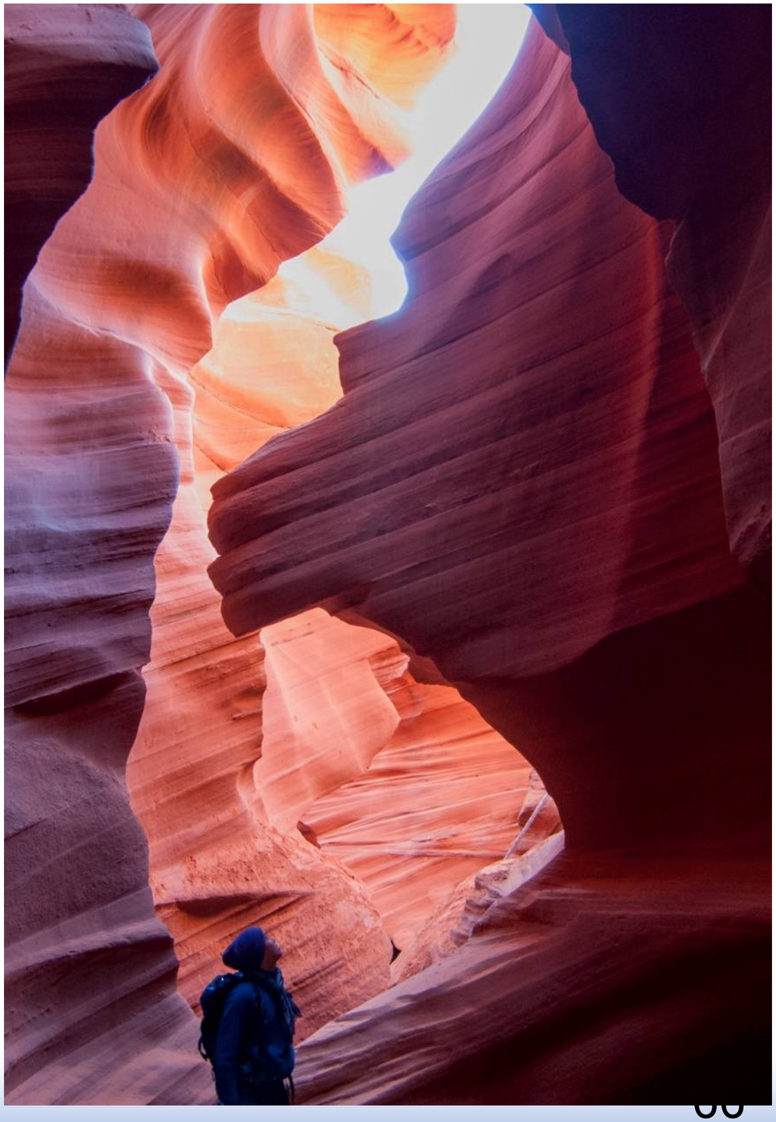
Marine environments



Zion National Park: Navajo Sandstone



Navajo Sandstone: Antelope Canyon



Dinosaur Provincial Park, Alberta

- World Heritage Site since 1979
- Mesozoic era (Cretaceous (≈ 75 Ma))
- Warm inland sea at the base of Cordillera
  - Subtropical climate
  - Lush vegetation in coastal plain
  - Rivers carried organic-rich sediments into sea
- Layer-cake sedimentary deposits
  - Mostly shale, sandstone and mudstone
  - Rich deposit of dinosaur fossils

Dinosaur Provincial Park, Alberta

- Valleys carved by water from melting glaciers at the end of the last glaciation (≈13,000 years ago)

Dinosaur Provincial Park, Alberta

- Formation

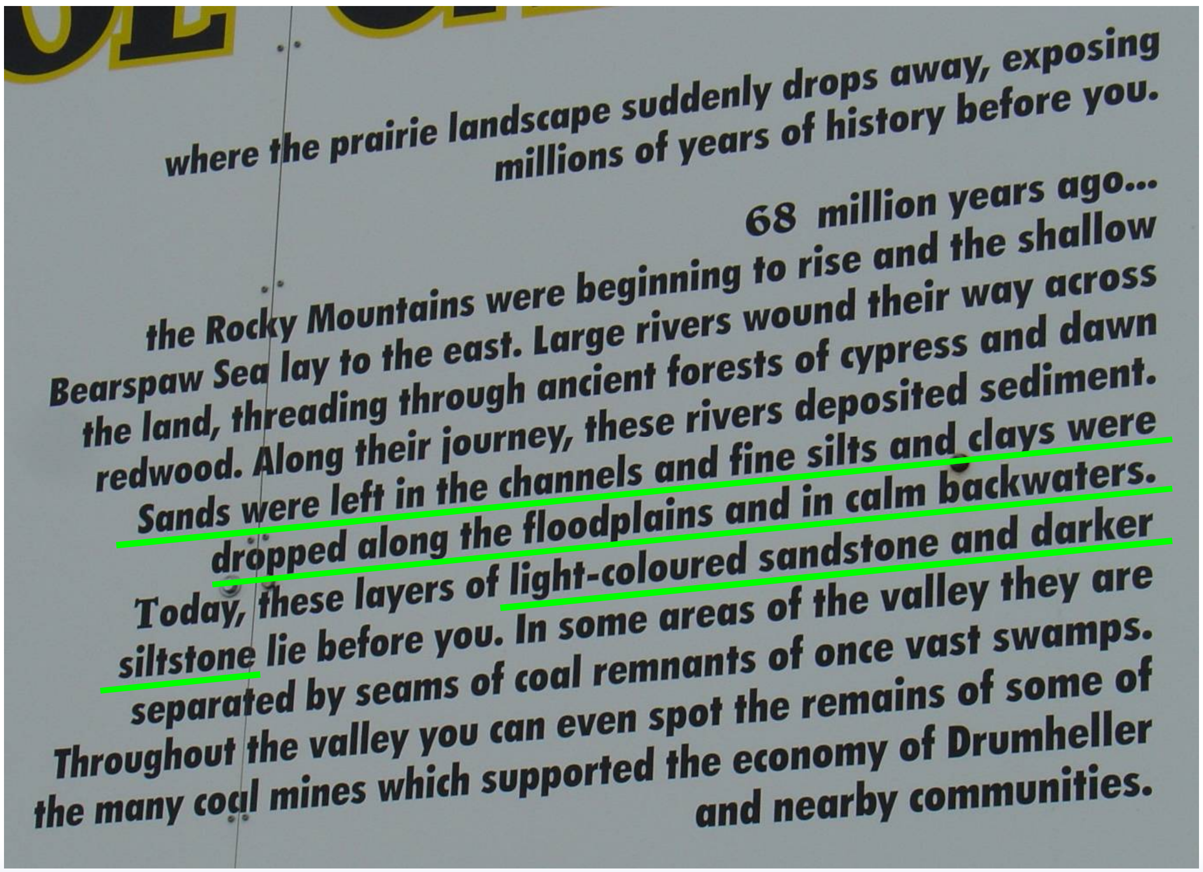


Photo: C. Samson, Carleton U.

Engineering considerations

- Water infiltrates porous/permeable rocks
- Cracks open after several freeze/thaw cycles

Engineering considerations: Detrital

- Variability
  - Vertical and horizontal gradation into other sedimentary rocks
  - Variations within each strata
    - Knowledge of depositional environments may allow for prediction of rock type and properties
    - Quarries, exploration areas, oil and gas exploration

Engineering considerations: Detrital

- Bedding causes extremes in directional properties
  - **Anisotropy**: characteristic of a property having a different value when measured in different directions
    - Strength, permeability, seismic velocity
- Bedding planes are zones of weakness
  - Exploit them in quarrying

Engineering considerations: Detrital

- Engineering properties influenced by geological events occurring long after sediment deposition
  - Lithification affects strength
  - Strength influenced by type and amount of cement
  - Quartz (SiO_2) cement stronger than calcite ($CaCO_3$) cement
  - Conglomerates often weak due to poor cementing between clasts and matrix

Engineering considerations: Chemical

- Carbonate rocks: limestone and dolostone
- PROS
  - Best sedimentary aggregates
  - Excellent source of building rock
  - Carved limestone blocks used as foundation in older Ottawa neighborhoods
- CONS
  - Thin bedded limestones separated by layers of clay or shale may serve as sliding planes
  - May dissolve and form a system of subterranean galleries (karst terrain)

Next: Metamorphic Rocks

ERTH2404
Metamorphic Rocks

Gneisses

Maurice Lamontagne

Reading assignment

- Please read Kehew's book to complement the material presented in this lecture:

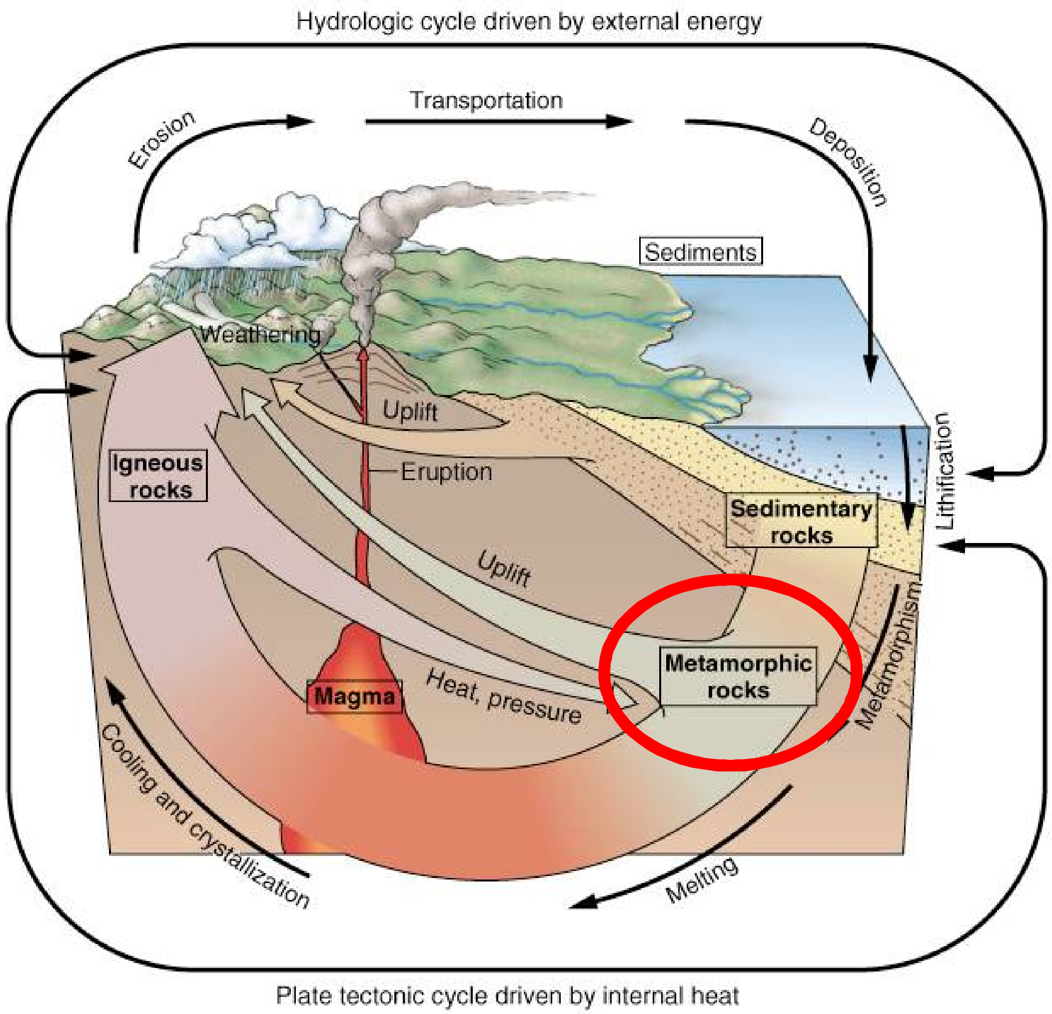
  Chap. 6;

Lecture objectives

- To learn the different types of metamorphism
- To understand the relationship between metamorphic rocks and other rock types
- To be able to characterize and identify metamorphic rocks
- To be aware of how the characteristics of metamorphic rocks might impact engineering work

Remember the rock cycle

- Metamorphic rocks are formed from any type of pre-existing rock



Metamorphism

- **Metamorphism**: transformation of one rock into another through the action of
  - Heat
  - Pressure
  - Chemically active fluids (metamorphic agents)

- Rocks retain their solid form
  - But they can flow in a plastic-manner (i.e very slow deformation)

Metamorphism

- Metamorphism may cause many changes to rock
  - Formation of larger or smaller grains
  - Reorientation of mineral grains
  - Texture such as banded appearance, sheen
  - Increase in density
  - Transformation of existing minerals into minerals stable in the new T-P conditions

Metamorphism

- Metamorphism occurs in the Earth's crust over 100s of Ma
  - In the core of mountain belts
  - At depth within stable continental interiors (shields)
  - Often in association with igneous intrusions

- Metamorphic rocks can become exposed at the surface when overlying rocks have been removed by erosion or when tectonic movements bring them closer to the surface
  - Exposed outcrops are commonly of Precambrian age due to the long time needed for erosion to occur

Metamorphism

- **Metamorphic grade**
  - Certain minerals and textures are diagnostic of the degree of metamorphism experienced by rocks

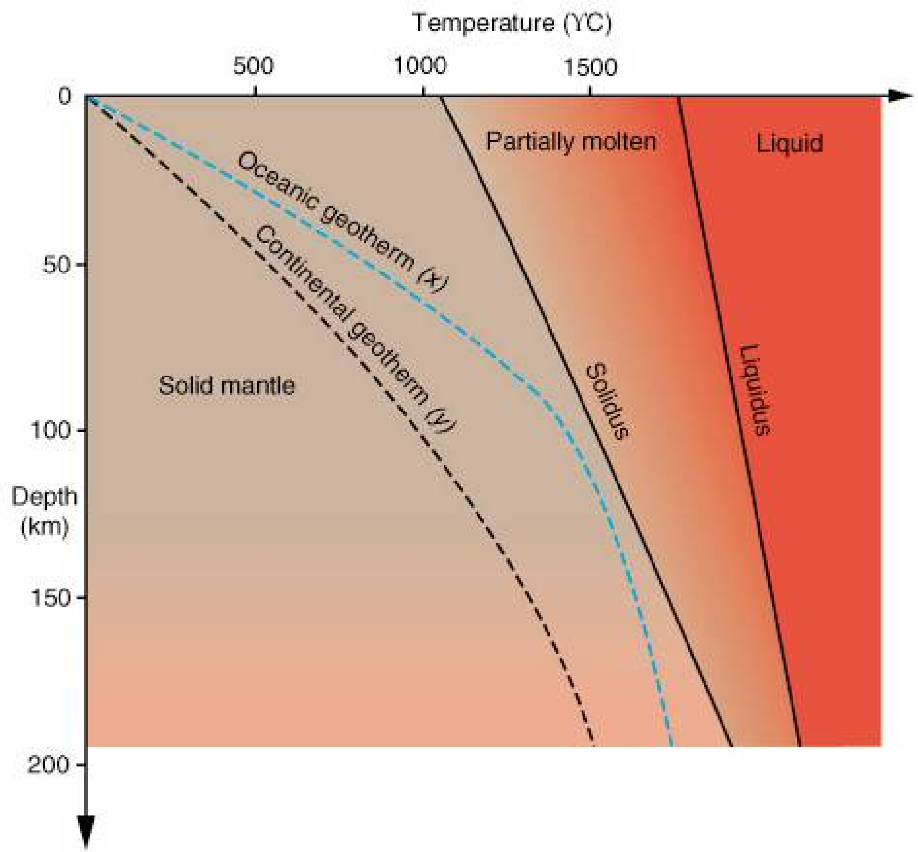
Low-grade	Mineralogy and texture changes	High-grade
Low T Low P	→	High T High P

Metamorphism: Temperature

- Most important factor for metamorphism
- Drives chemical changes
  - Recrystallization of existing minerals into new minerals

  Impacts:
  - Texture, crystal structure, crystal size
- Two sources:
  - Magma intrusion
  - Geothermal gradient (increase of T with depth)

Metamorphism: Temperature



Geothermal gradient

Metamorphism: Pressure

- Approximate increase of 1 kbar per depth of 4.4 km
- **Confining pressure**: pressure applied in all directions
  - Causes decrease in rock size and an increase in density
  - Does not fold or deform rock
- **Differential stress**: pressure applied from specific directions
  - In ductile regime, can deform rocks
  - Associated with mountain building and faulting

Metamorphism: Fluids

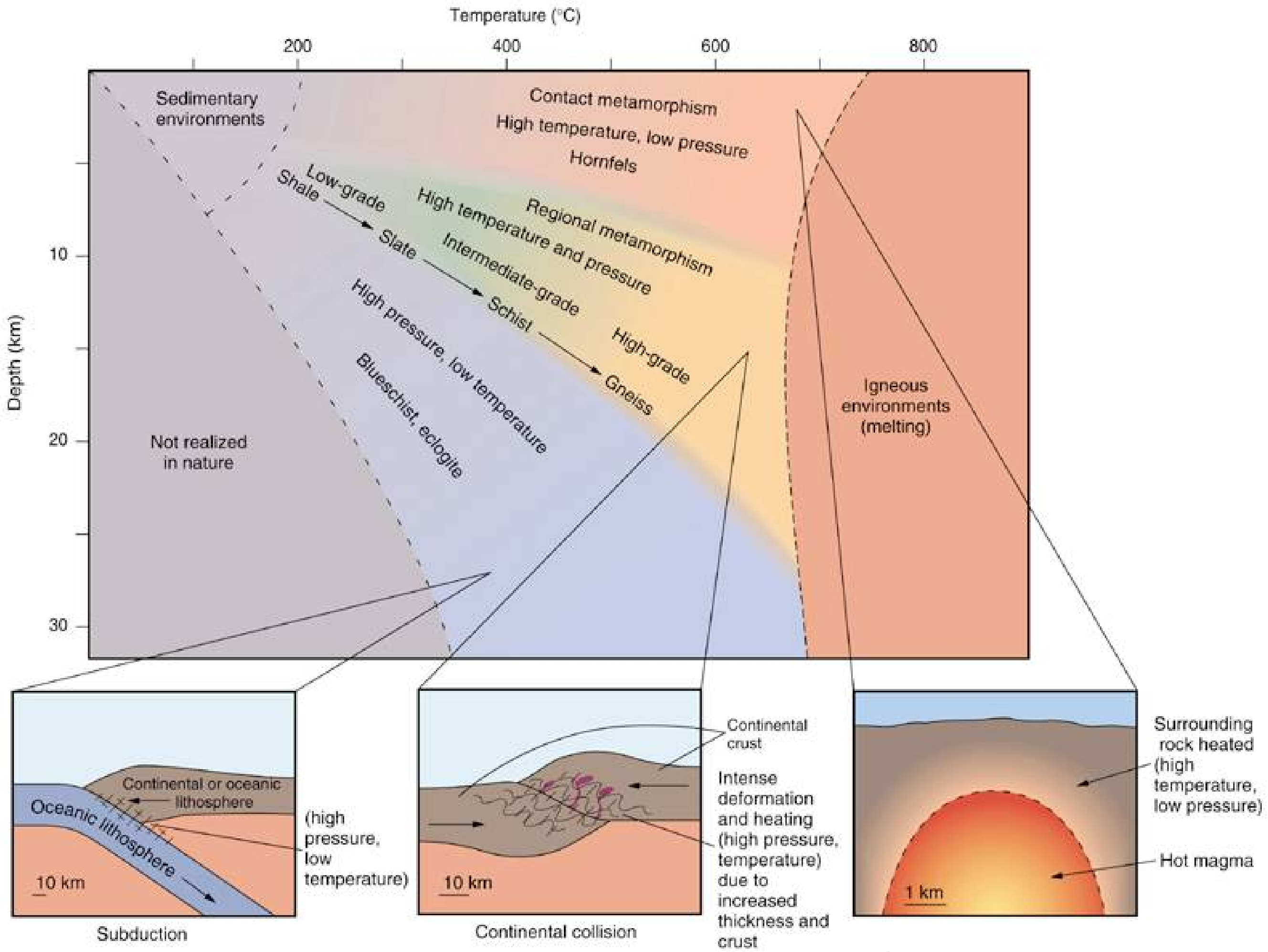
- Water acts as catalyst during metamorphism
  - Conduit for ion exchange in the growth of crystals
- Sources of fluid:
  - From pore fluids of sedimentary rocks
  - From cooling of plutons
  - Dehydration by heat of minerals (clay, micas)
- Aid in recrystallization of existed minerals

Types Metamorphism

Scale	Type of metamorphism	Metamorphic agents	Change in chemical composition
Regional	Regional Sedimentary rocks only: Burial	Heat and P	No
Local	Contact	Heat	
	Dynamic	P	
	Impact	P	
	Hydrothermal	Fluids	Yes

- Regional: large scale, plate tectonics
- Local: smaller scale, faults, igneous bodies

Types Metamorphism



Regional (High P, Low T)

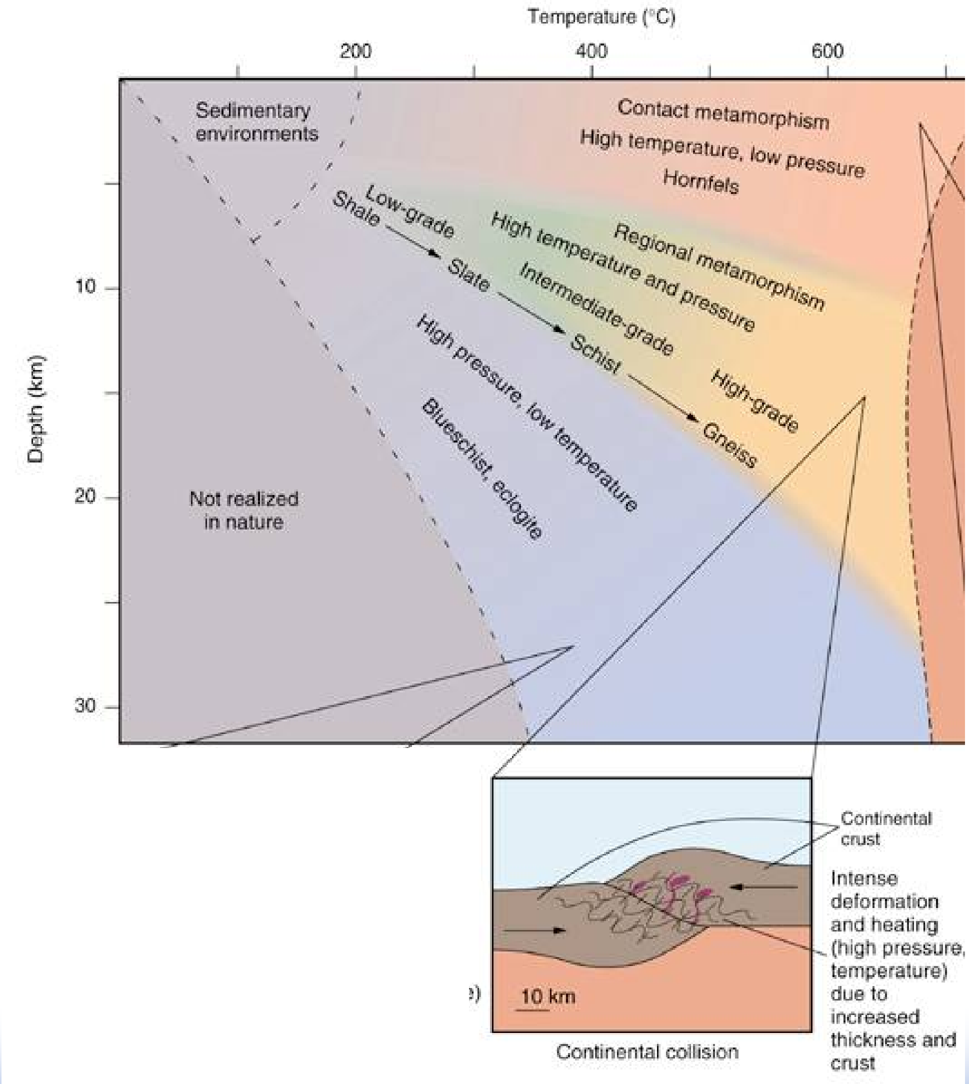
Regional (High P, High T)

Contact (Low P, High T)

Regional Metamorphism

- Continental crust exposed to extreme T and P at convergent plate boundaries
  - Enormous thickness of rocks involved (9-12 km)
  - Greatest quantity of metamorphic rocks produced

Regional Metamorphism

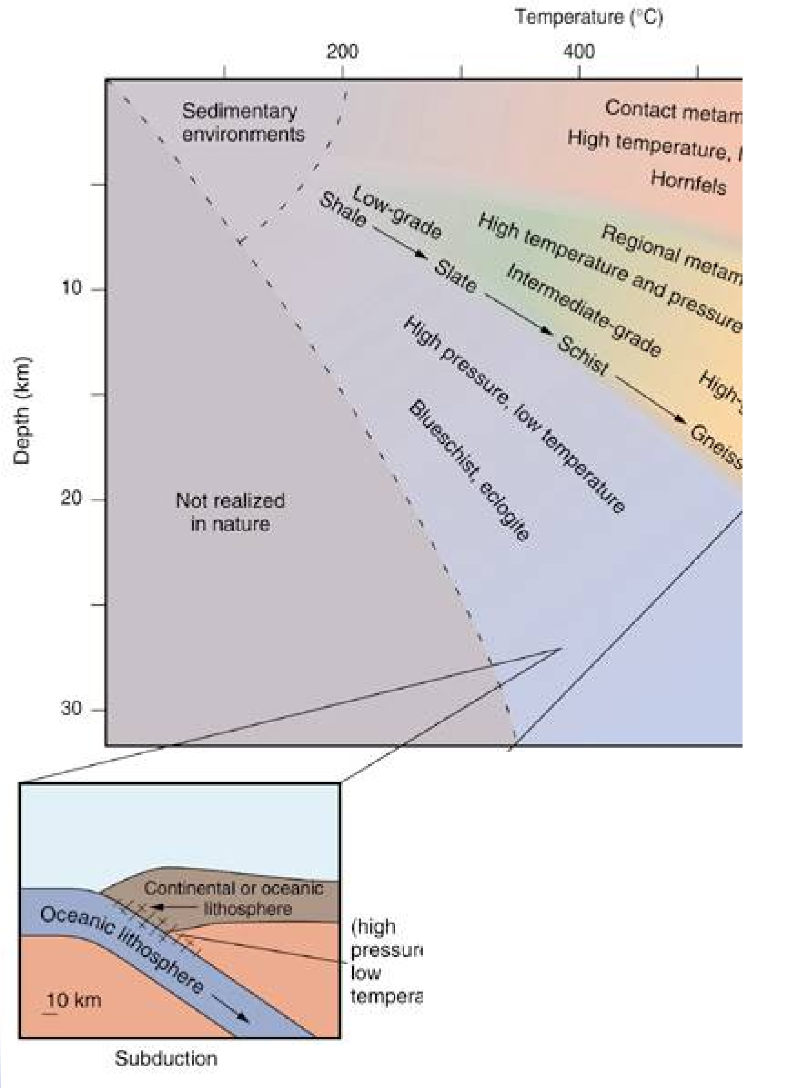


- Crustal thickening, continental collision
- Leads to foliation, alignment of minerals

Regional Metamorphism

- Low Grade: rock harder, more compact (interlocking crystals), minor increase in grain size
- Medium Grade: grain size increases, new mica crystals form
- High grade: grains recrystallize with preferred orientation (foliation)

Regional Metamorphism

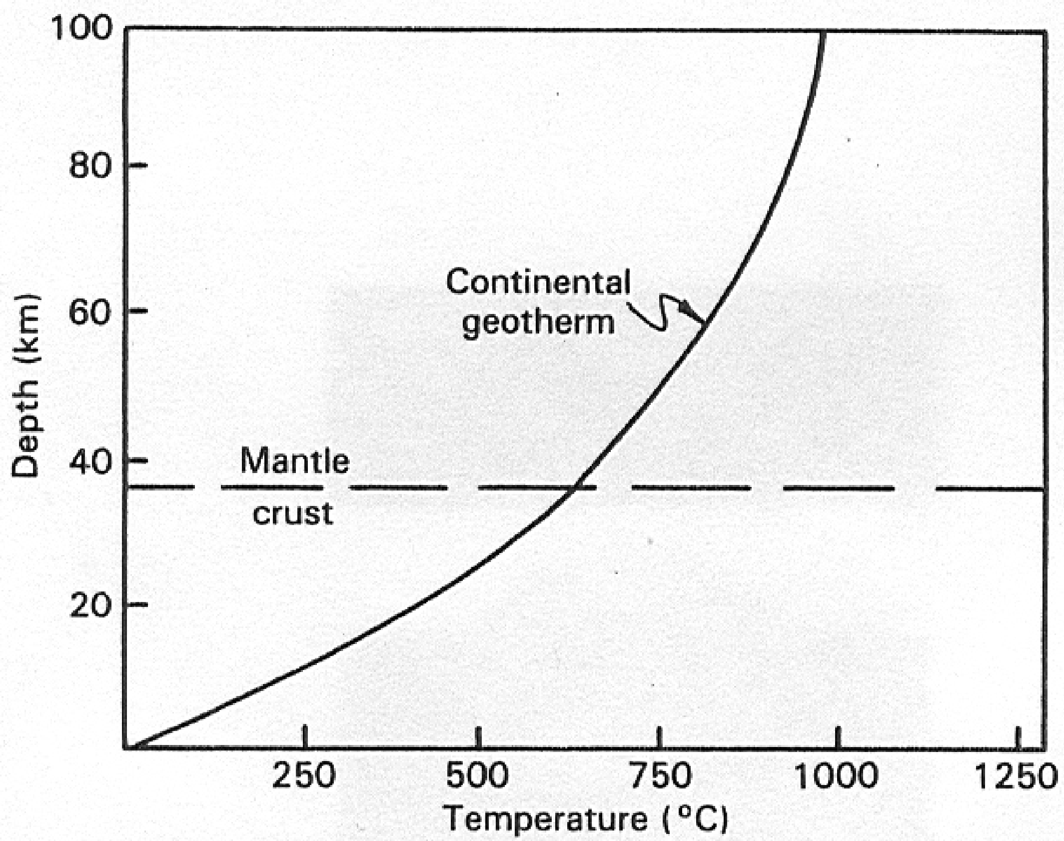


- At subduction zones of the lithospheric plate
  - Low T, High P
- Cold, slow to heat by conduction, but plunges quickly to great depth
- Sediments, basalts form high-P minerals

Burial Metamorphism

- Subset of regional metamorphism
  - Associated with thick sedimentary strata
- Metamorphism due to burial beneath other rocks
  - Certain mineral become unstable due to increased T and P, and change to new minerals
  - Required depth for metamorphism varies from one location to another depending on the **geothermal gradient**
- Bedding and other sedimentary structures preserved
- Clay becomes mica when buried several km's deep

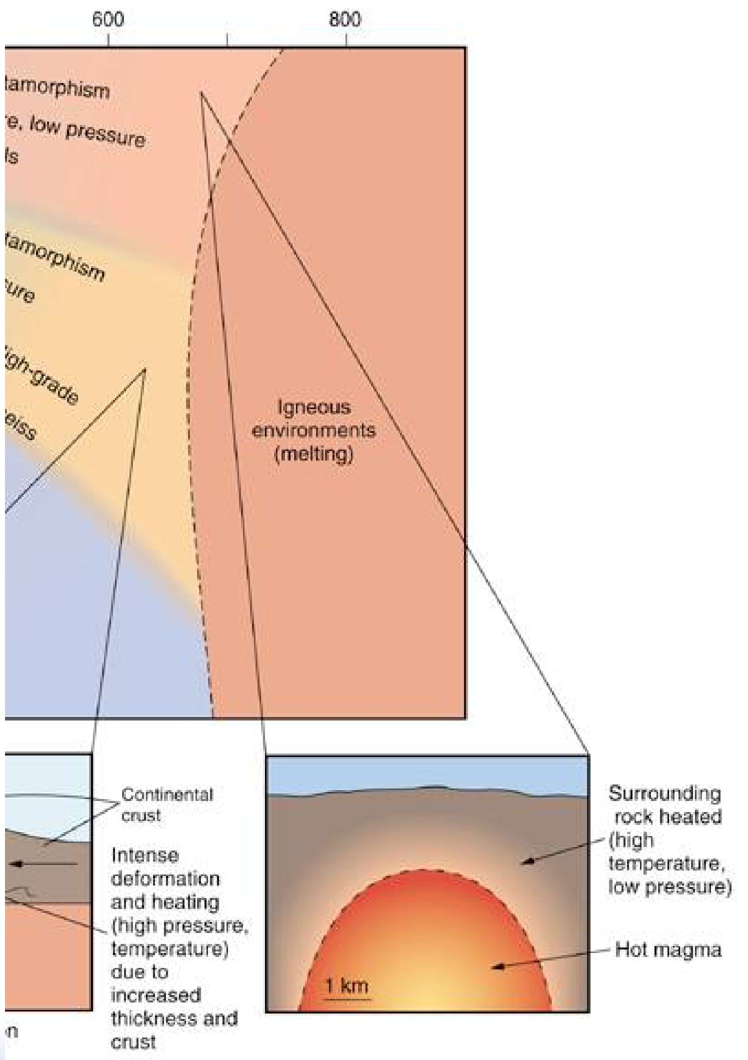
Continental geotherm



Ref.: Kehew, A.E. 1995. Geology for Engineers & Environmental Scientists. 2nd Edition. Fig. 5.2. Shown with permission.

Contact Metamorphism (Local)

- Magma intrudes a host rock leading to an increase in temperature
  - Increase in temperature leads to re-crystallization
- **Aureole**: zone of alteration, forms in the rock surrounding the igneous intrusion



Local Metamorphism: Contact

- **Aureole**
  - Extent depends on the size of the intrusion and the host rock
    - Sills, dikes → cm–m wide aureole
    - Batholiths → km wide aureole

- Typically fine-grained, dense and tough
  - No directional alignment of minerals because pressure is not a major factor

Dynamic Metamorphism (Local)

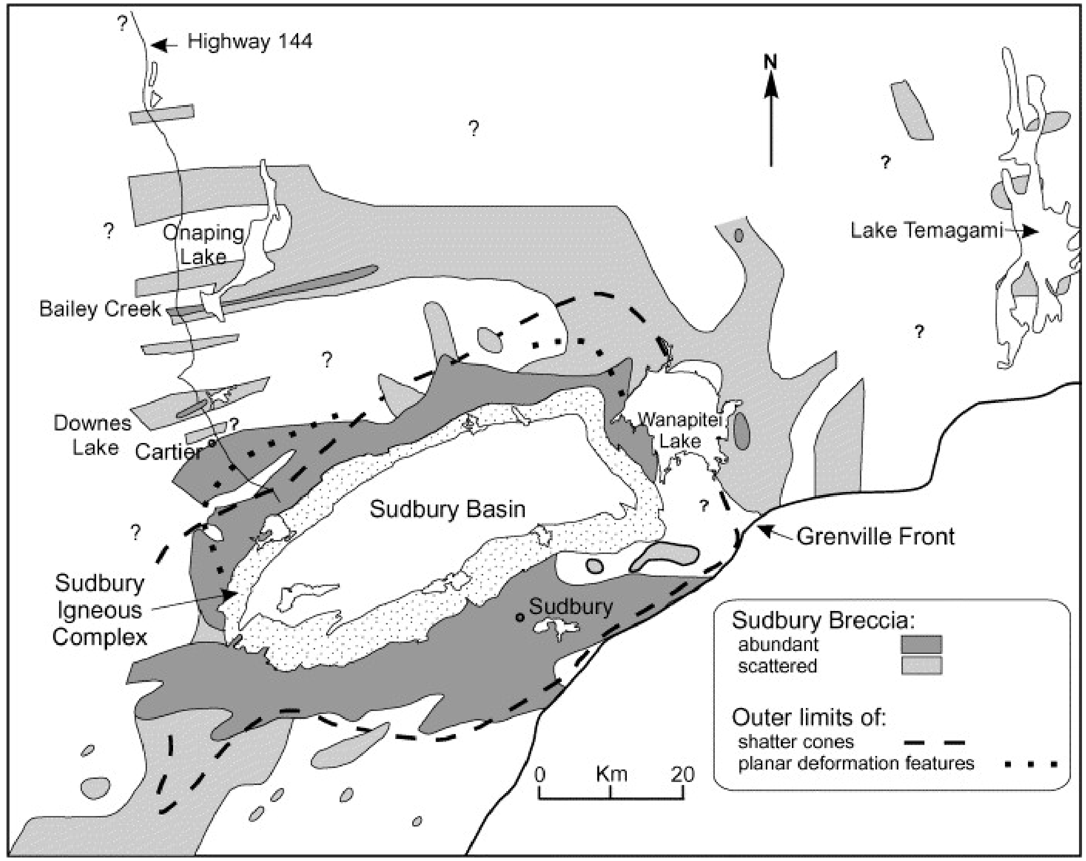
- Dynamic metamorphism is associated with localized events along fault zones
  - Rocks are broken and pulverized as rock blocks along fault zone grind past each other
  - **Fault breccia**: loose rock consisting of broken and crushed rock fragments
- Pressure is the only metamorphic agent

Impact Metamorphism (Local)

- Occurs when large space bodies strike the Earth's surface
  - Creates shattered and melted rocks adjacent to the impact crater
  - Shatter cone: a conical fragment of host rock that is formed from the high pressure of meteorite impact and has striations radiating from the apex
    - 2-30 GPa of pressure required

Blast shatter cone

Photo: W. Carter, Carleton U.

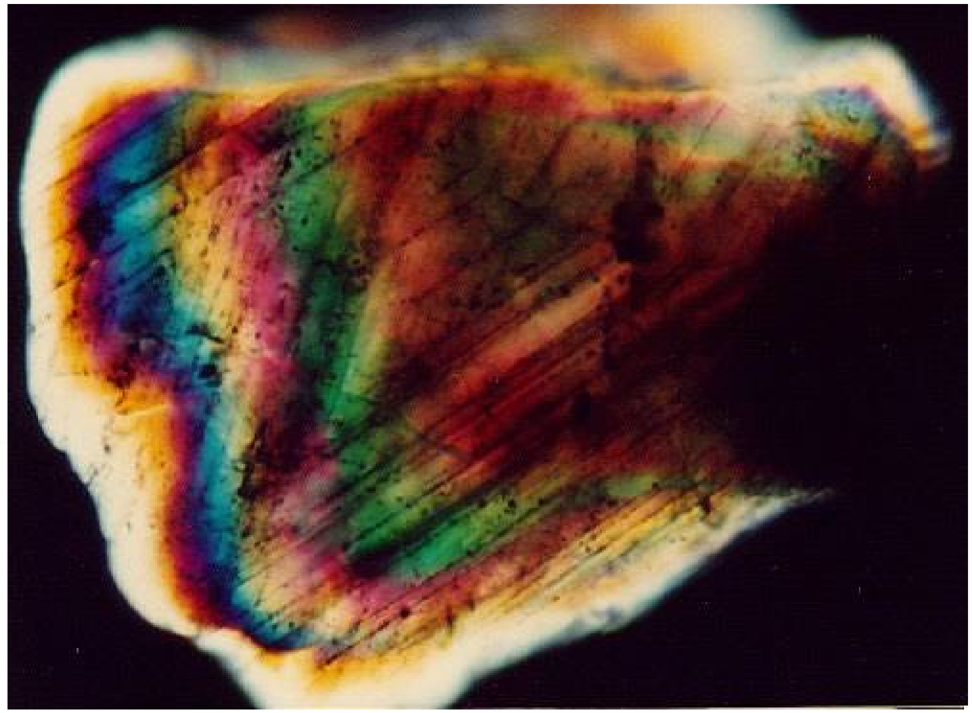


Rousell et al. 2003

http://dx.doi.org/10.1016/S0012-8252(02)00091-0

Shocked quartz

Chicxulub crater, Mexico
dia > 180km



Dislocation of crystal orientations due to shock wave (~5–8 Gpa)

Hydrothermal Metamorphism (Local)

- A form of **metasomatism**: change in the composition of a rock or mineral by the addition or replacement of chemicals
  - Chemical alteration caused by hot, ion-rich fluids (**hydrothermal solutions**) that circulate through cracks
  - Hydrothermal solutions are expelled from cooling plutons
  - Invade country rock

Local Metamorphism: Hydrothermal

- Add ions to rock to form new minerals
- May generate metallic ore deposits
    - Copper, gold, molybdenum, tin, iron

- Example:
    - Hydrothermal metamorphism is widespread along mid-ocean ridges
    - Fe-Mg rich minerals metamorphose into talc, serpentine

Classification

- Key terms, textures, characteristics, naming convention

Protolith

- **Protolith**: original rock from which a given metamorphic rock was formed
  - Most metamorphic rocks have the same overall chemical composition as their protolith
  - Original mineral makeup determines, to large extent, the degree of which each metamorphic agent will cause change

- Example: quartz sandstone is the protolith of quartzite

Protolith

- Different metamorphic minerals can be produced from the same original rock under different temperature and pressure conditions

- Example: shale → slate → schist → gneiss

Metamorphic textures

- Three metamorphic textures:
  - Foliated textures
    - Pressure is the key metamorphic agent
    - Mostly associated with regional metamorphism
  - Non-foliated texture
    - Temperature is the key metamorphic agent
    - Mostly associated with contact metamorphism
  - Porphyroblastic texture
    - Large crystals growing in a finer matrix
    - Example: garnet

Foliation

- **Foliation**: parallel orientation of mineral grains within a metamorphic rock
  - Foliation give metamorphic rocks a banded appearance
  - Watch out! Foliation resembles the bedding of sedimentary rocks
  - .. The two are produced by different mechanisms

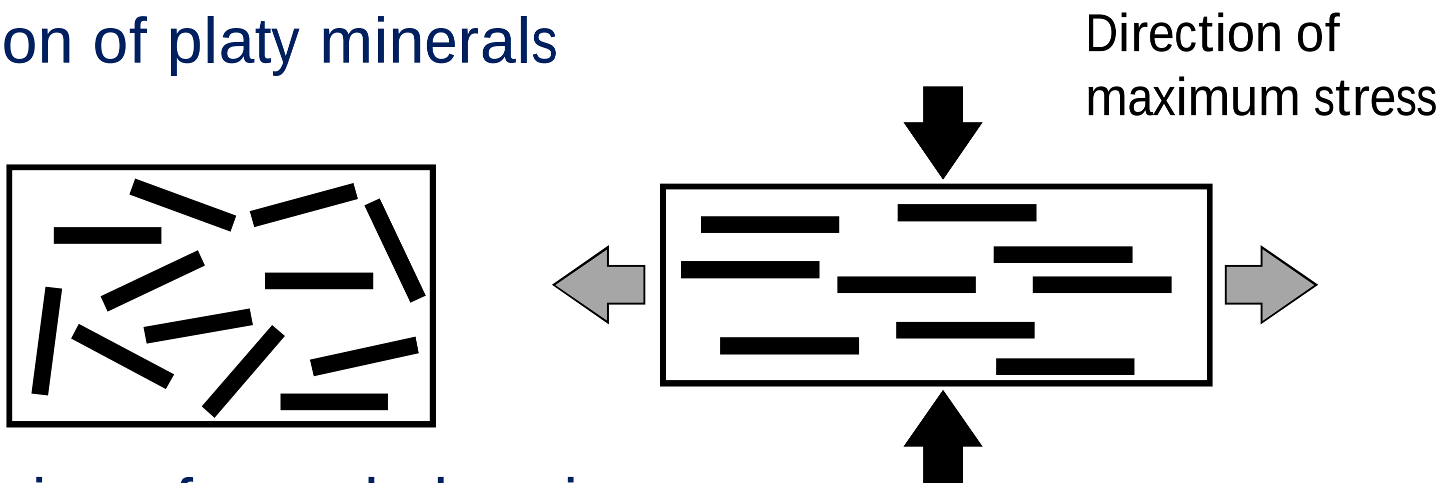
Foliation

- Foliation can develop in different ways:
  1. Rotation of platy minerals under pressure
  2. Recrystallization of minerals under pressure
  3. Flattening of rounded grains in the direction of maximum stress

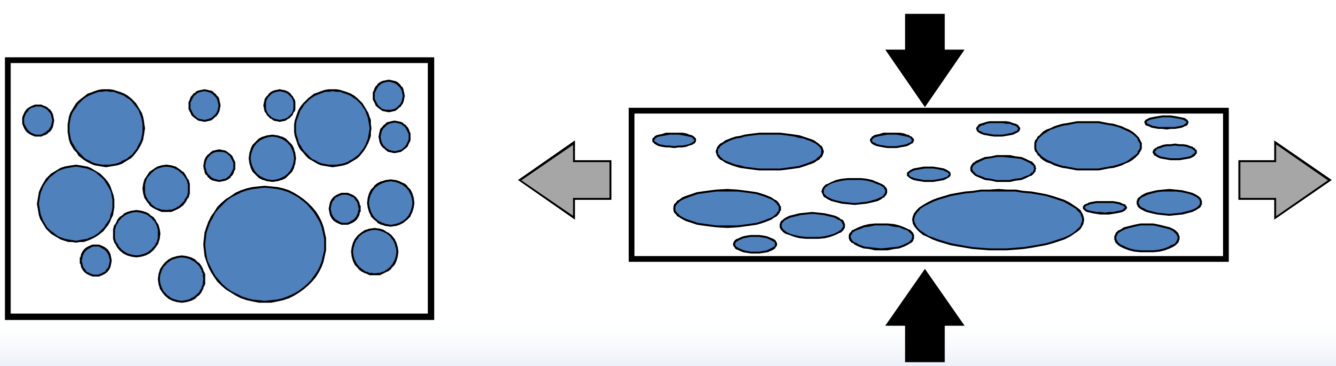
- New mineral orientation is perpendicular to the direction of maximum stress

Foliation

- Rotation of platy minerals



- Flattening of rounded grains



Foliation

- Different expressions of foliation
  - Parallel alignment
  - Compositional banding
  - Zones of weakness where rocks can easily split into thin sheets

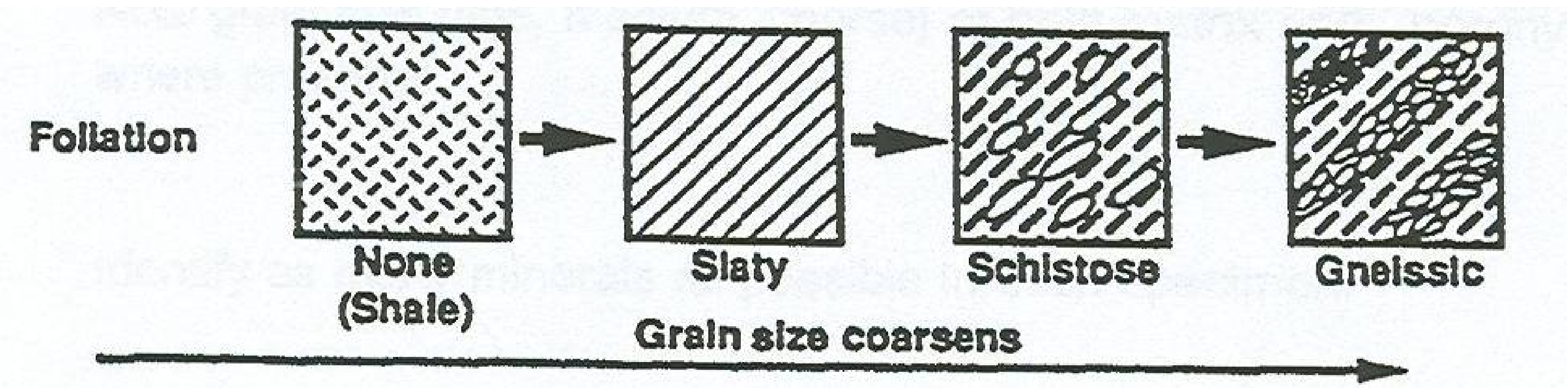
Foliated textures

- **Slaty cleavage**
  - Closely spaced planar surfaces along which rocks split
- **Schistose**
  - Platy mineral grains grow larger when rock is subjected to higher T and pressure
  - Rock exhibit a “scaly” appearance
  - Platy minerals visible to unaided eye

Foliated textures

- **Gneissic texture**
  - During higher grades of metamorphism, ion migration results in segregation of minerals
  - Distinct banded appearance due to segregation of dark and light silicate minerals

Foliated textures



Increasing Metamorphic grade

Non-Foliated textures

- Develop in environments where deformation is minimal
  - Mostly associated with contact metamorphism
- Develop from rocks composed primarily of one mineral, exhibiting equi-dimensional crystals
- Examples:
  - Limestone → marble
  - Quartz sandstone → quartzite

Porphyroblasts

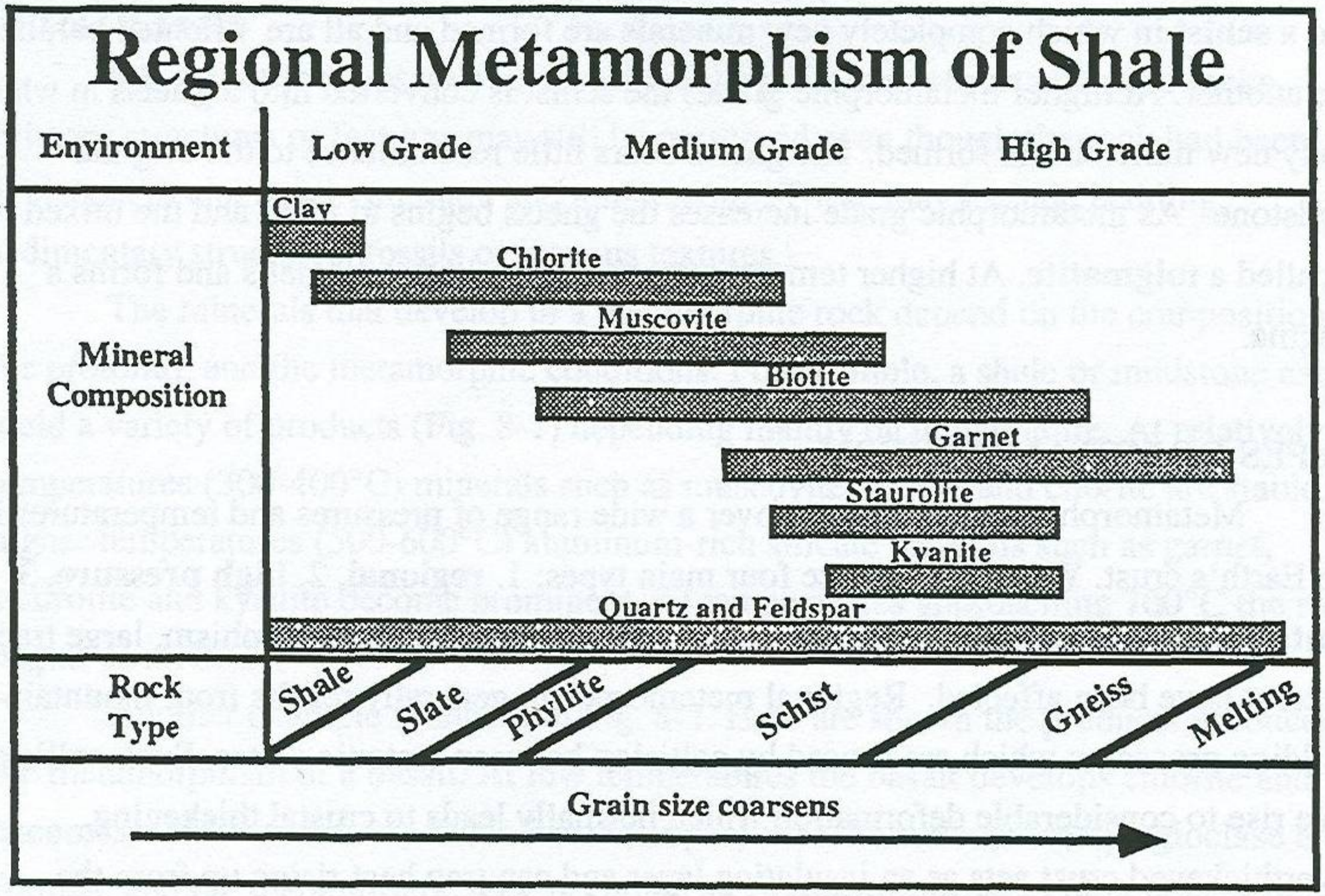
- Large mineral grains/crystals (porphyroblasts) surrounded by a fine-grained matrix of other minerals
- Grows within the solid state
- Examples: garnet, staurolite, andalusite

Porphyroblasts

Classification

- Metamorphic rocks are classified according to:
  - Texture
  - Protolith

Metamorphism of Shale

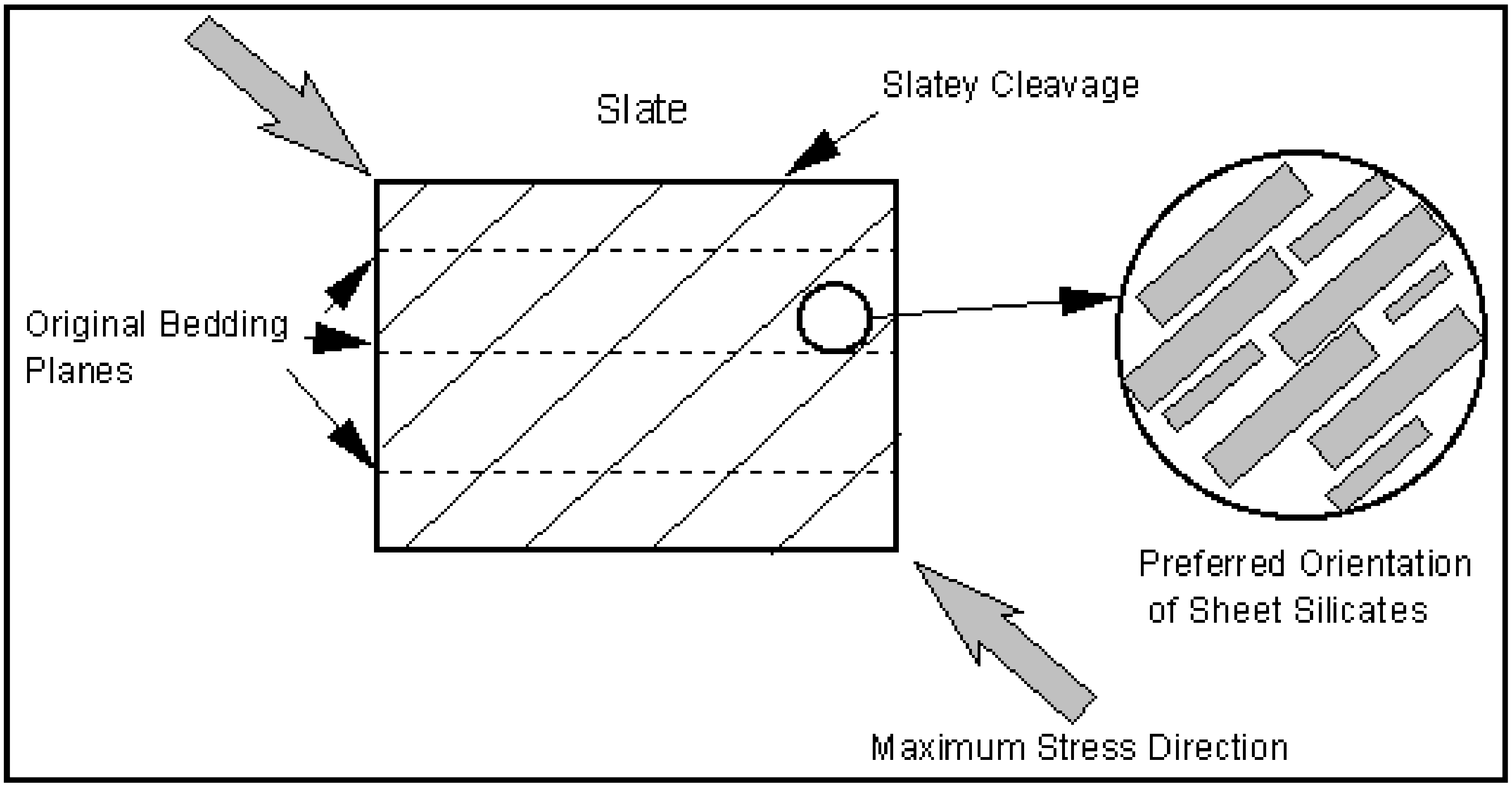


Ref.: ERTH2404 Lab manual

Slate

- Generated from low-grade metamorphism of shale
  - Very fine grained (minute mica flakes)
  - Color depends on mineral constituent
    - Black: organic material
    - Red: iron oxide
    - Green: chlorite minerals
- Excellent cleavage
  - Tiles
- Original bedding may or not be preserved
  - Slaty cleavage may develop at an angle to original bedding

Slate



Source: Earth Science Australia
(http://earthsci.org)

Slate

Shale

Slaty cleavage

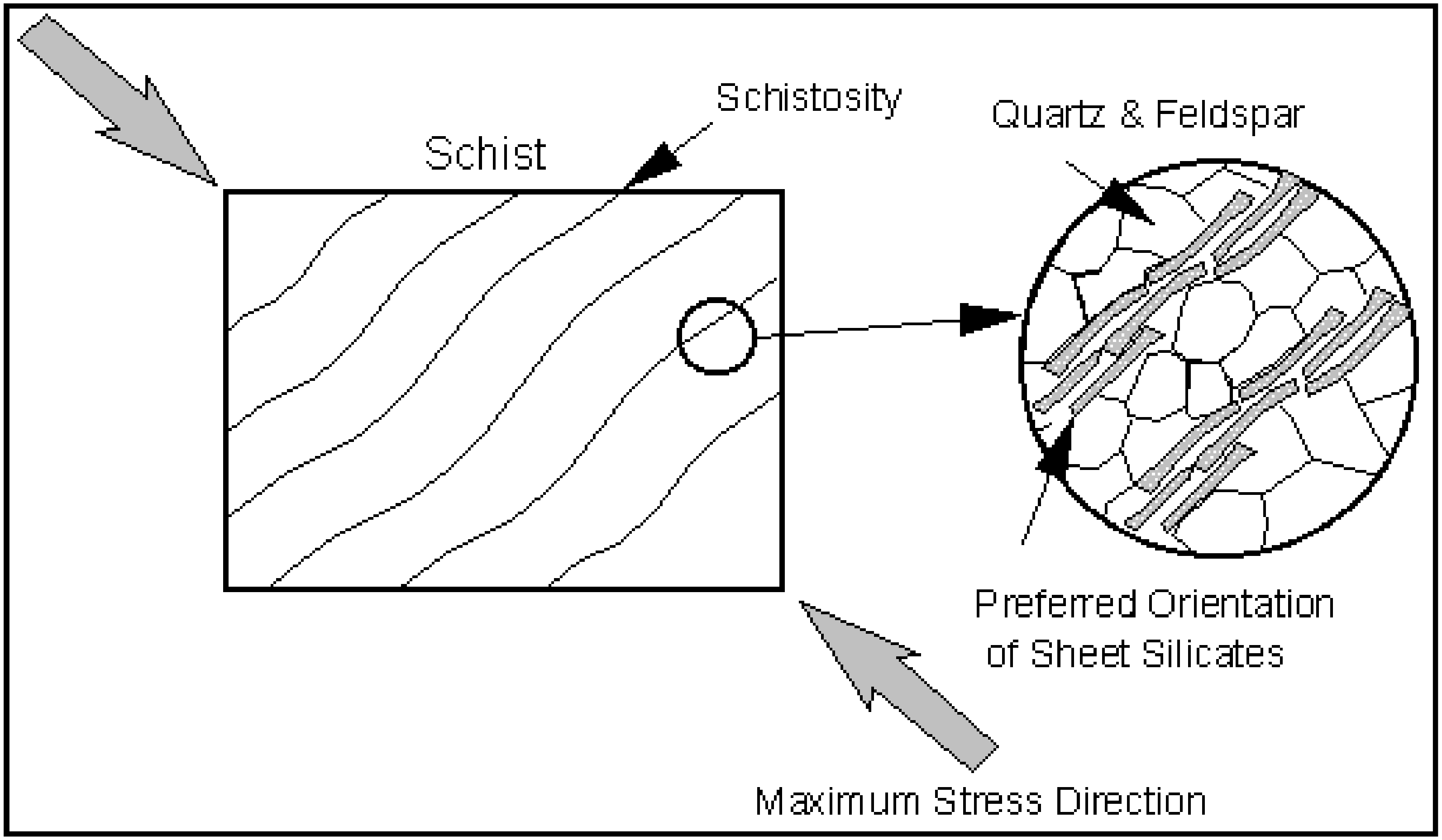
Phyllite

- Lies between slate and schist
  - Characteristic rock “sheen”

Schist

- Generated from intermediate-grade metamorphism of shale
  - Often related to mountain building
- Medium to coarse grained rock readily split into thin scales
  - Platy mica minerals dominate
  - Often contains accessory minerals unique to metamorphic rocks (e.g. garnet)
- Term “schist” describes the texture
  - To indicate composition, mineral names are used (e.g. mica schist)

Schist



Source: Earth Science Australia
(http://earthsci.org)

Schist

- Naming convention applies porphyroblast(s) first
  - If there are more than one, name most abundant first

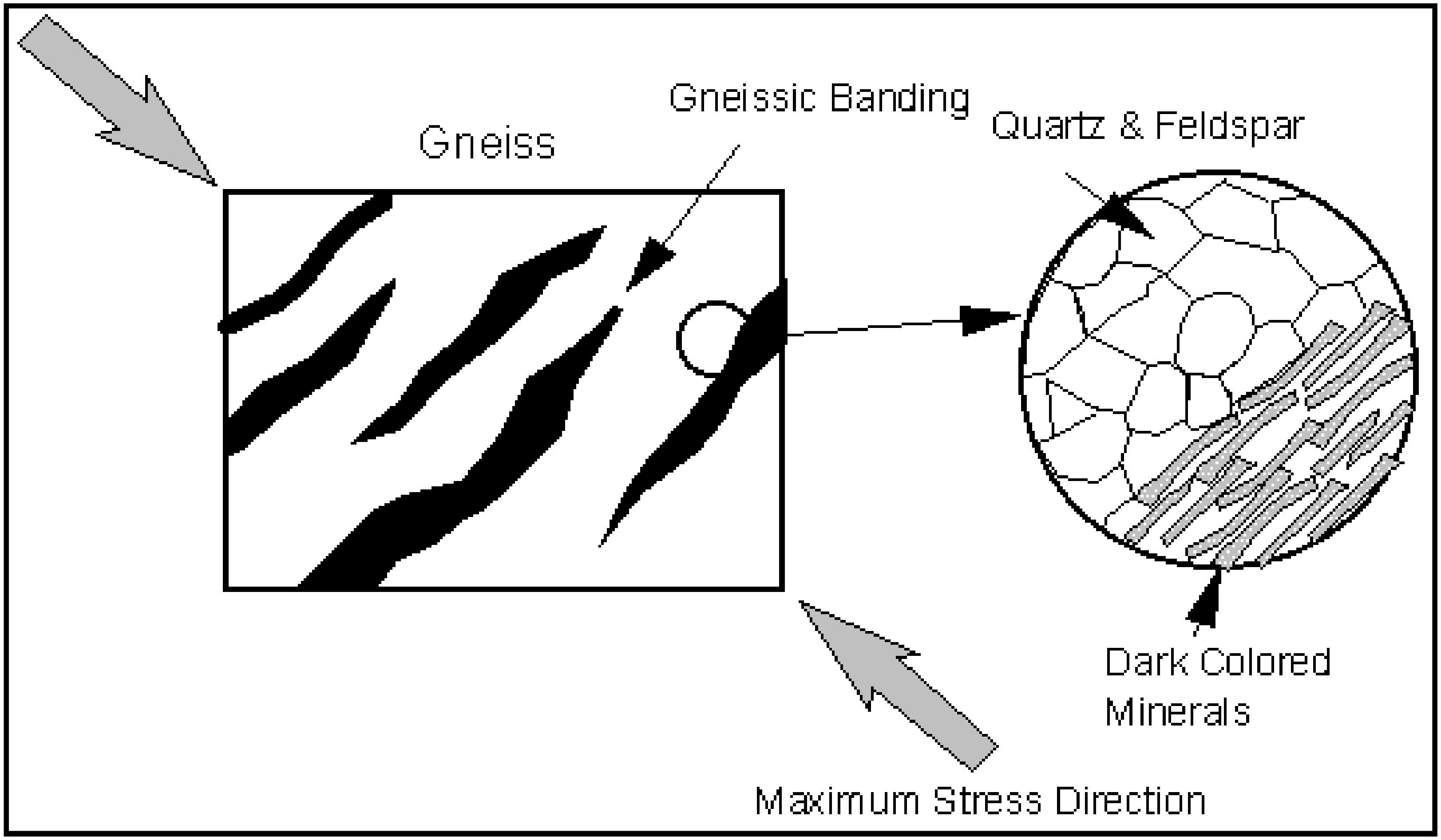
Garnet schist

Muscovite schist

Gneiss

- Generated from high grade metamorphism of shale or granite
- Medium to coarse grained rock with elongated granular minerals (quartz, feldspar, hornblende) and a lesser amount of platy minerals (mica)
- Banded appearance
- Break in irregular fashion

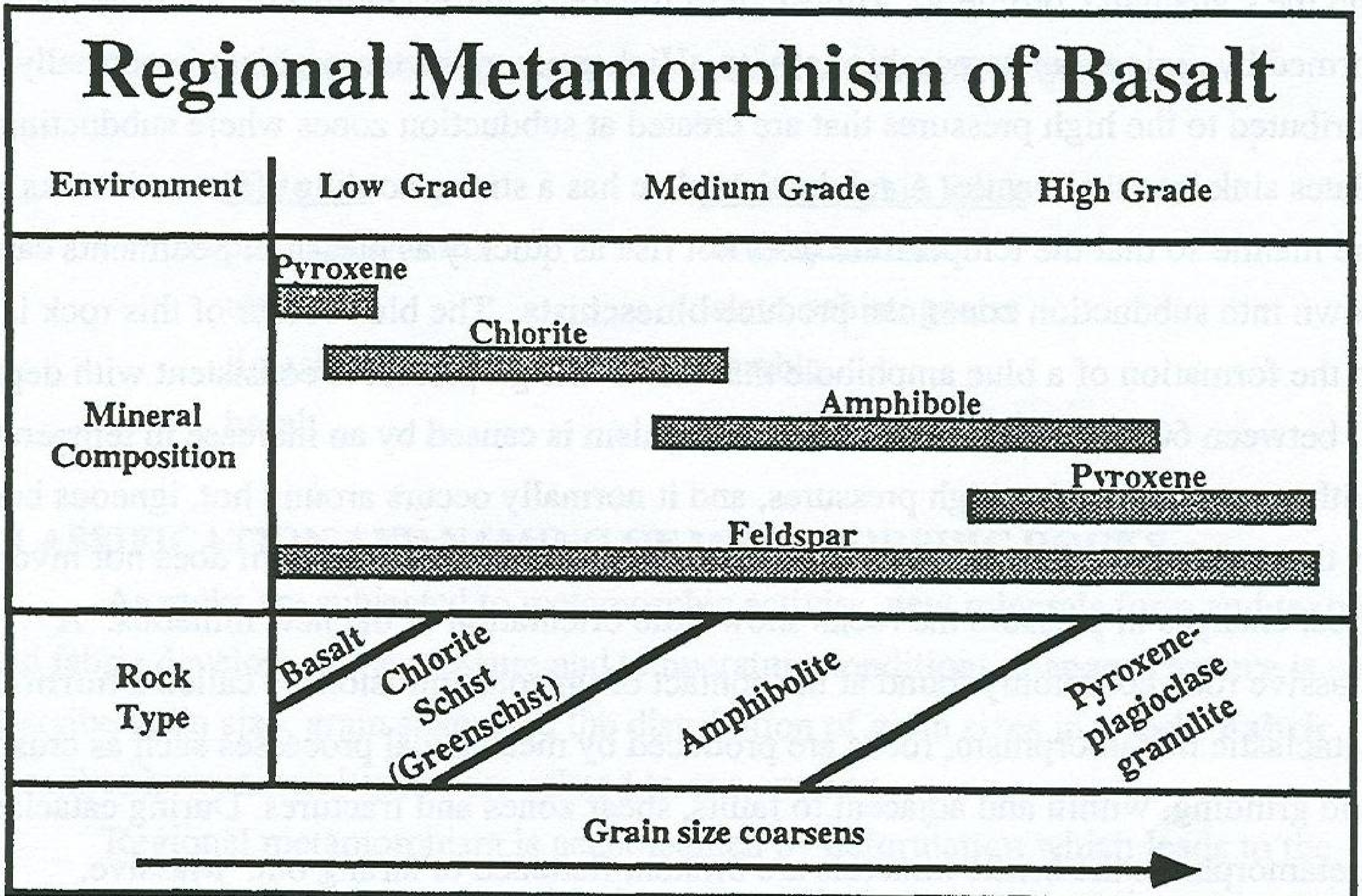
Gneiss



Source: Earth Science Australia
(http://earthsci.org)

Gneiss

Acasta Gneiss of the Slave Province of the Shield (4.03 Ga old)



Ref.: ERTH2404 Lab manual

Marble

- Common non-folitated metamorphic rock
- Protolith is limestone or dolostone
- Composed essentially of calcite or dolomite
- Decorative stone

Quartzite

- Common non-folitated metamorphic rock
- Protolith is quartz sandstone
  - Quartz grains are fused together
- Very hard rock
  - Rock splits through quartz grains, not in between original grains

Engineering considerations

- Non-foliated metamorphic rocks have similar properties as intrusive igneous rocks
  - Great strength

Engineering considerations

- Foliated metamorphic rocks are susceptible to failure along specific planes
  - Orientation of foliation planes is a critical factor in slope stability
  - Avoid transferring load (from bridges, dams, building foundations) onto foliated rock mass in a direction parallel to the foliation

Engineering considerations

- Landslides associated with schist
  - Generally controlled by orientation of schistosity
  - Presence of slick minerals (e.g. talc, clay, graphite) may increase sliding potential

Failure of St. Francis Dam, CA

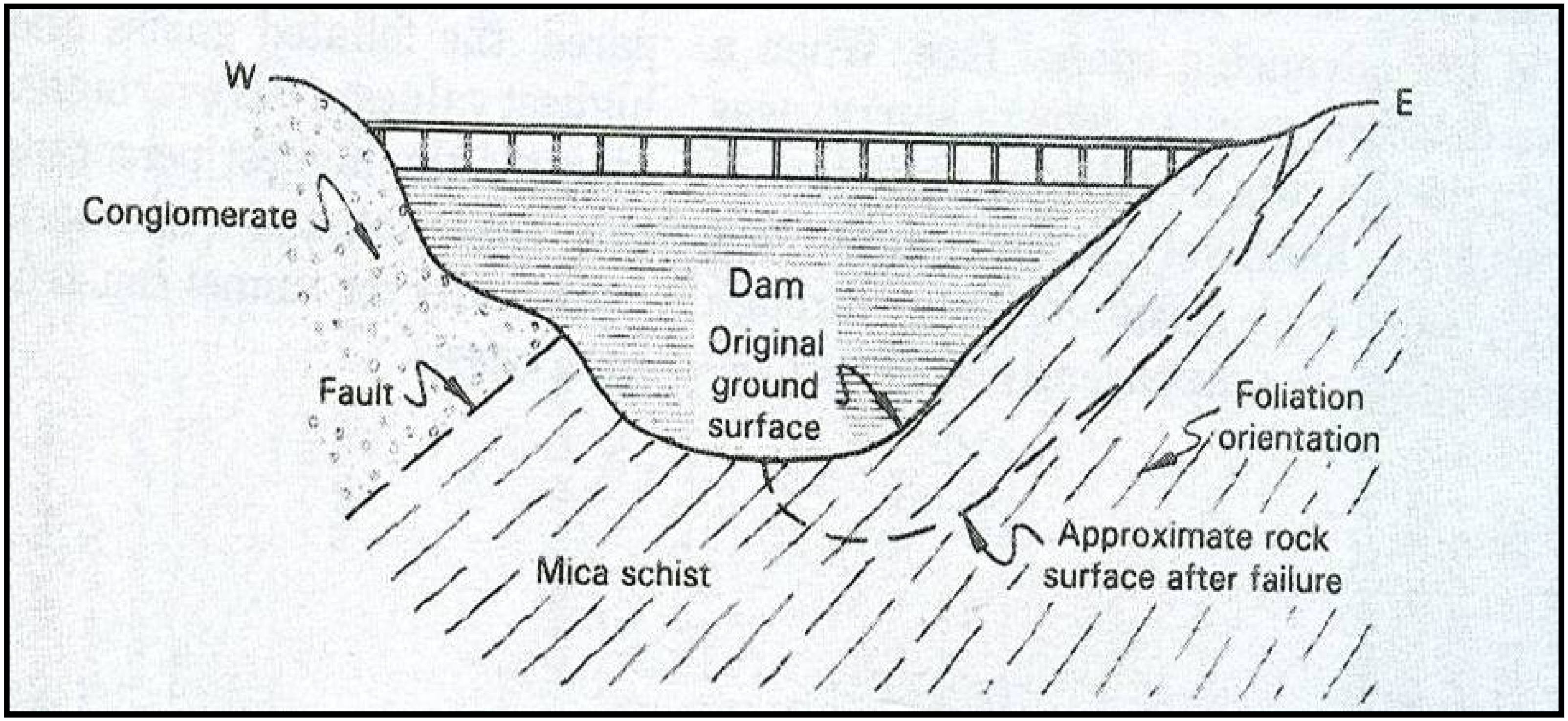
- https://www.youtube.com/watch?v=_6AvEZO34xI

- Built in 1926 to regulate the Los Angeles Aqueduct
- 12 March 1928, the dam suffered from catastrophic failure
  - Releasing 45 Billion liters
  - > 600 estimated deaths from the resultant flood

Failure of St. Francis Dam, CA

- Geological context
  - Poorly consolidated conglomerate of gravels, sands and muds held together by clay and cemented by gypsum
  - Schist with steeply dipping foliation planes
  - Load of the dam parallel to foliation

Failure of St. Francis Dam, CA



Ref.: Kehew, A.E. 1995. Geology for Engineers & Environmental Scientists. 2nd Edition. Fig. 5.16. Shown with permission.

Failure of St. Francis Dam, CA

- Water seeping from reservoir weakened rocks beneath the dam
  - Fault zone acts as a conduit for water
  - Degradation of weak bounds between mica grains along foliation planes in the schist
  - Water dissolved gypsum cement in the conglomerate

Next: Plate Tectonics!!