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SEDIMENTARY PETROLOGY (ii)

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References

- Boggs, S.Jr. (2009): Petrology of Sedimentary Rocks, 2 nd ed., Cambridge Univ. Press, 600p.
- Selley, R.C. (2000): Applied Sedimentology, 2 nd ed., Academic Press, 543p.

Sedimentary Petrology

Sedimentary Petrology: is that particular branch of study concerned especially with the **composition, characteristics, and origin of sediments and sedimentary rocks** (Boggs, 2009).

What are Sedimentary Rocks

- Sedimentary rocks are formed at **low temperatures and pressures** **at the surface of Earth** owing to deposition by **water, wind or ice**.
- Sedimentary rocks cover about 80% of the total land area of Earth.
- They make up **about 11%** of the volume of the Earth's crust (Ronov, 1983).
- They also cover most of the ocean's floor above a basement of volcanic rocks.

Source: Petrology of Sedimentary Rocks, by S. Boggs, Jr. (2009)

What are Sedimentary Rocks

- Sedimentary rocks are characterized by the presence of layers and by distinctive textures, structures, mineral composition and fossil content.
- They provide us available clues to evolution of Earth's landscapes and life forms through geologic time.
- In addition, many sedimentary rocks contain important economic products such as water, petroleum, natural gas, minerals, metallic ores, uranium, coal, iron, salts, etc...

Source: Petrology of Sedimentary Rocks, by S. Boggs, Jr. (2009)

What are Sedimentary Rocks

Sedimentary rocks are composed of either:

- ❖ **particles derived from pre-existing rocks (Terrigenous or Clastic sedimentary rocks)**

- ❖ **rocks precipitated from water by chemical or biochemical processes (Autochtonous Sed. rocks).**

Source: Petrology of Sedimentary Rocks, by S. Boggs, Jr. (2009)

Sedimentary Rocks

How do sedimentary rocks form?

- **Weathering & Erosion** (Mechanical breakdown, Chemical breakdown)
- **Transport** (Water, Air, Glaciers)
- **Deposition & Lithification**

  - Deposited in layers (strata)

  - Layers are progressively younger towards the top of a succession.
- **Terrestrial processes**
  – Rivers, Lakes, Deltas, Fans…
- **Precipitation**
  – Marine/ groundwater processes
  – Sea, Lakes, Cave systems…

Recognizing sedimentary rocks

- **Stratification visible** (Bedding – Lamination)
- **Fossils present**
- **Grains or pebbles visible**
- **Sedimentary minerals present**
- **Sedimentary structures visible on bedding planes**

Components of Sedimentary Rocks

Four Fundamental kinds of components:

- **Terrigenous siliciclastic particles:**
  (rock fragments - quartz - feldspars – micas -clay minerals & iron oxides).
- **Chemical/biochemical components:**
  (calcite – gypsum – apatite ***as well as*** calcareous and siliceous tests or shells of organisms)
- **Carbonaceous components :**
  (carbonized residues of terrestrial plants (Humic materials) and marine plants & animals, Petroleum bitumens)
- **Authigenic (secondary) components :**
  (quartz – feldspars – clay minerals – calcite – gypsum – barite - hematite)

Classification of Sedimentary Rocks

- **Terrigenous Rocks (Siliciclastic Rocks):**
  - Conglomerates, Sandstones, Mudrocks.
- **Marine Rocks (Biogenic, Biochemical Rocks):**
  - Limestones & Dolomites.
- **Others:**
  - Evaporites (chemical Rocks).
  - Siliceous rocks (Cherts) (chemical Rocks).
  - Ironstones (chemical Rocks).
  - Phosphates or Phosphorites.
  - Organics (Coals and Oil Shales).
  - Volcaniclastic Rocks (Pyroclastic Rocks).

Source: Petrology of Sedimentary Rocks, by S. Boggs, Jr. (2009)

Classification of Sedimentary Rocks

Composition		Group name	Particle size	Principal constituents	Main rock types
<~15% Carbonaceous residues	<50% Terrigenous siliciclastic grains	or siliciclastic rocks	>2 mm	Rock fragments	Conglomerates and breccias
			1/16–2 mm	Silicate minerals and rock fragments	Sandstones
			<1/16 mm	Silicate minerals	Shales (mudrocks)
	>50% Chemical/biochemical constituents	Chemical/biochemical rocks	Variable	Carbonate minerals, grains; skeletal fragments	Carbonate rocks (limestones and dolomites)
				Evaporite minerals (sulfates, chlorides)	Evaporites (rock salt, gypsum, anhydrite)
				Chalcedony, opal, siliceous skeletal remains	Siliceous rocks (cherts and related rocks)
				Ferruginous minerals	Ironstones and iron-formations
				Phosphate minerals	Phosphorites
>~15% Carbonaceous residues		Carbonaceous rocks	Variable	Siliciclastic or chemical–biochemical constituents: carbonaceous residues	Oil shales Impure coals
				Carbonaceous residues	Humic coals Cannel coals Solid hydrocarbons (bitumens)

Source: Petrology of Sedimentary Rocks, by S. Boggs, Jr. (2009)

Abundance of Sedimentary Rocks

Ronov (1983) suggest the followings:

- **Shales** makes up ~50% of Sed. Rocks on the continents
- **Sandstones & conglomerates** makes up ~24% of Sed. Rocks on the continents
- **Carbonates** makes up ~24% of Sed. Rocks on the continents
- **Evaporites** makes up ~1% of Sed. Rocks on the continents
- **Cherts** makes up ~1% of Sed. Rocks on the continents
- **Phosphorites and carbonaceous sedimentary rocks are quit small.**

Genetic Classification

Five main genetic classes of sediment can be recognized ***according to Hatch et al. (1971):***

chemical, organic, residual, terrigenous, and pyroclastic .

1) ***The chemical sediments:*** are those that form by direct precipitation in a subaqueous environment. ***Examples include evaporites such as gypsum and rock salt, as well as tufa and some lime muds.***

Genetic Classification

2) The organic sediments: are those composed of organic matter of both animal and vegetal origin.

Examples include *skeletal limestones and coal.*

3) The residual sediments: are those left in place after weathering.

Examples include the *laterites and bauxites.*

Genetic Classification

4) The terrigenous sediments: are those whose particles were originally derived from the earth, and include the ***mudrocks, siliciclastic sands, and conglomerates.***

4) Pyroclastic sediments: are the product of volcanic activity. ***Examples include ashes, tufs, volcaniclastic sands, and agglomerates.***

Genetic Classification

- These five main genetic classes of sedimentary rocks can be divided into ***two separate types:***
- ***The allochthonous and***
- ***the autochthonous deposits.***

Genetic Classification

- **The allochthonous sediments are:**

  those that are transported into the environment in which they are deposited.

- **They termed Extrabasinal Sediments**
- ***They include the terrigenous and pyroclastic classes, with rare reworked carbonates.***

Genetic Classification

- **The autochthonous sediments are:** ***those that form within the environment in which they are deposited.***
- **They termed Intrabasinal Sediments.**
- ***They include the chemical, organic, and residual classes.***

ALLOCHTHONOUS SEDIMENTS

(EXTRABASINAL SEDIMENTS)

ALLOCHTHONOUS SEDIMENTS

The allochthonous sediments are classified to four types :

- ***Terrigenous sediments:***
  - ***Mudrocks***
  - ***Siliciclastic sands***
  - ***Conglomerates.***
- ***Pyroclastic sediments*** *(ashes, tuffs, volcani-clastic sands & agglomerates).*

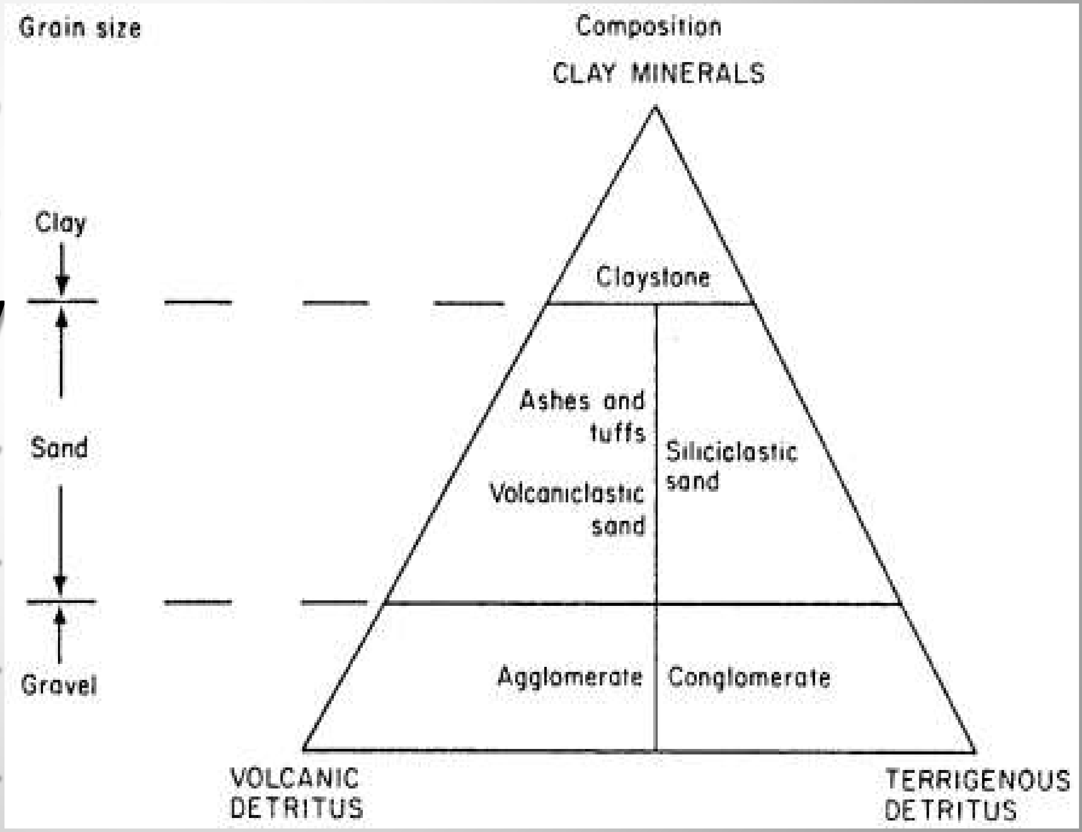
ALLOCHTHONOUS SEDIMENTS

Allochthonous Sediments are classified according to :

- *Grain Size*
- *Composition*

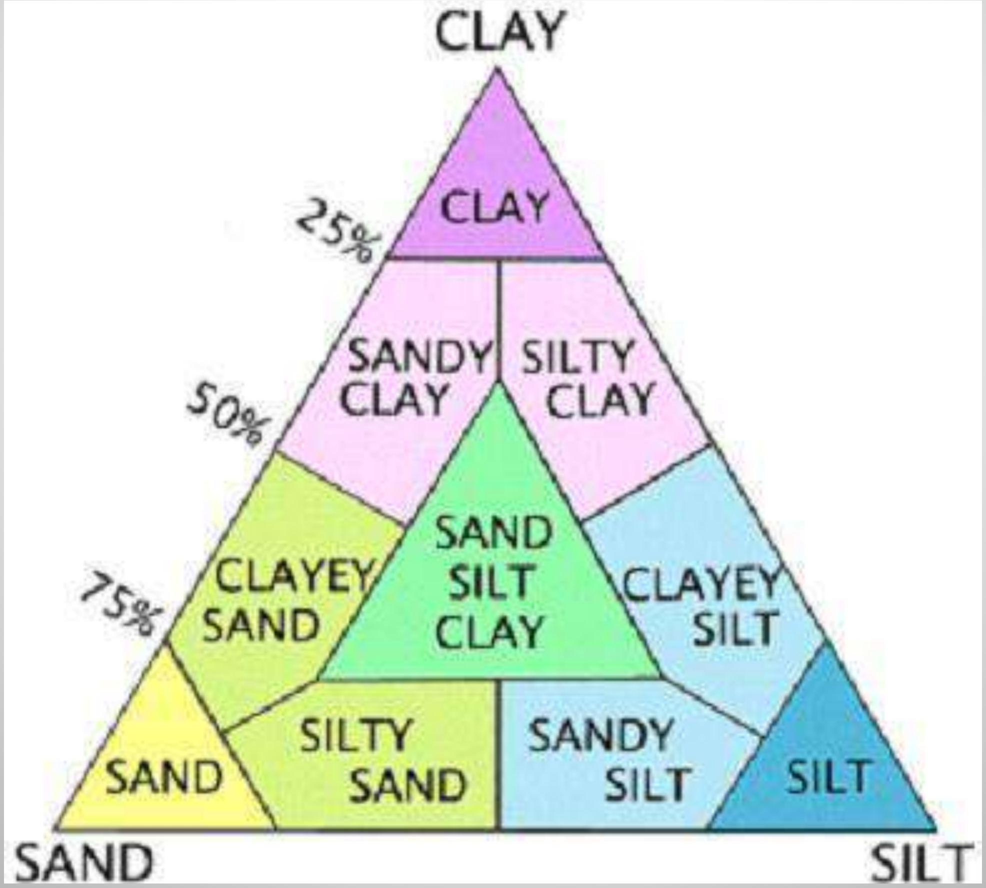
By using three end members;

- *Clay Minerals*
- *Volcanic Detritus*
- *Terrigenous Detritus*



Classification of unconsolidated sediments

on a basis of grain size (Shepard, 1954)




Siliciclastic
Sedimentary Rocks

Siliciclastic Sedimentary Rocks

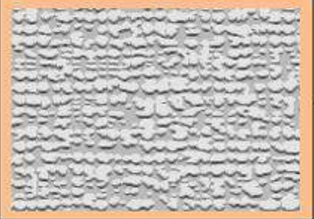
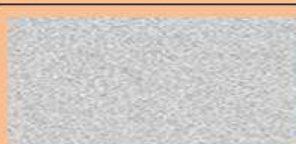
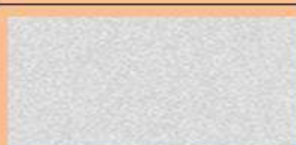
Siliciclastic (terrigenous) rocks are classified based on the grain size into three divisions:

1. ***Gravels & Conglomerates:*** *consist of clasts >2mm in diameter.*
2. ***Sand & Sandstones:*** *the particles range in diameter between 2mm and 63 μm.*
3. ***Muds & Mudstones (including clay and silt):*** *made up of particles < 63 μm.*

Wentworth scale of grain size classification

Millimeters (mm)		Micrometers (μm)	Phi (φ)	Wentworth size class		Rock type
	4096		-12.0			
				Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0			
				Cobble		
	64		-6.0			
				Pebble		
	4		-2.0			
				Granule		
	2.00		-1.0			
				Very coarse sand	Sand	Sandstone
	1.00		0.0			
				Coarse sand		
1/2	0.50	500	1.0			
				Medium sand		
1/4	0.25	250	2.0			
				Fine sand		
1/8	0.125	125	3.0			
				Very fine sand		
1/16	0.0625	63	4.0			
				Coarse silt	Silt	Siltstone
1/32	0.0310	31	5.0			
				Medium silt		
1/64	0.0156	15.6	6.0			
				Fine silt		
1/128	0.0078	7.8	7.0			
				Very fine silt		
1/256	0.0039	3.9	8.0			
	0.00006	0.06	14.0	Clay		Claystone

Clastic Sedimentary Rocks

Texture (grain size)		Sediment Name	Rock Name
Coarse (over 2 mm)		Gravel (rounded fragments)	Conglomerate
		Gravel (angular fragments)	Breccia
Medium (1/16 to 2 mm)		Sand	Sandstone
Fine (1/16 to 1/256 mm)		Mud	Siltstone
Very Fine (less than 1/256)		Mud	Shale

MUDROCKS

- ***The term "mud" in Recent deposits,*** refer to sediments that are **"wet clays"** with a certain amount of **silt** and **sand**.
- ***In lithified equivalents,*** are termed **"mudstones".**
- ***In Wentworth scale:***

Mud comprise: clay sediments (particles: < 0.004 mm)

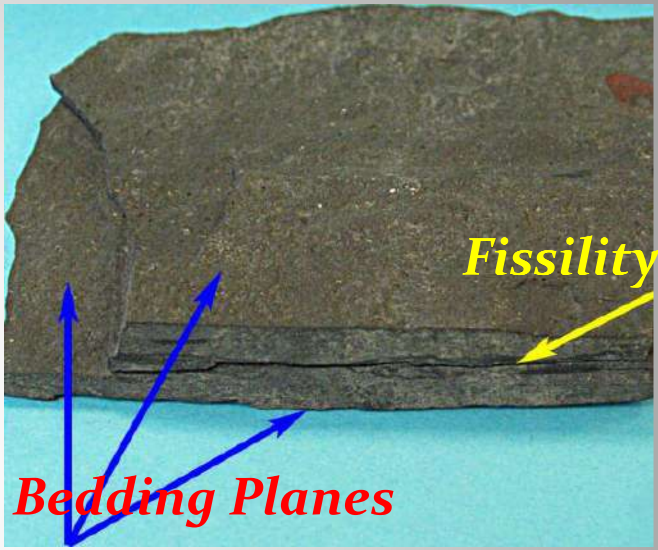
& Silt sediments (particles: 0.004 mm – 0.063 mm).

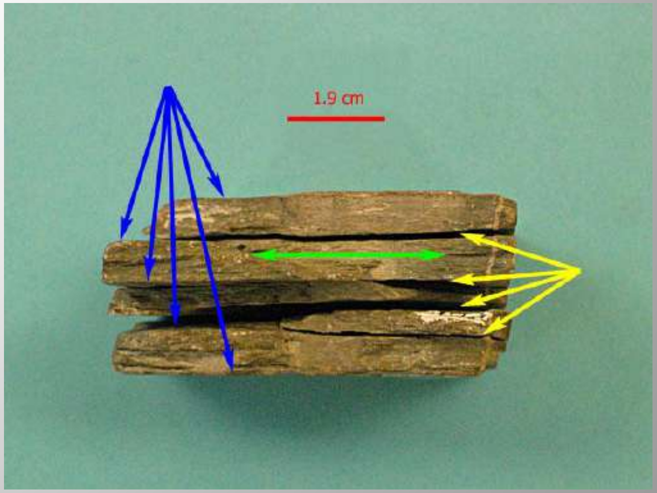
Their lithified equivalents are:

Claystones & siltstones.

MUDROCKS

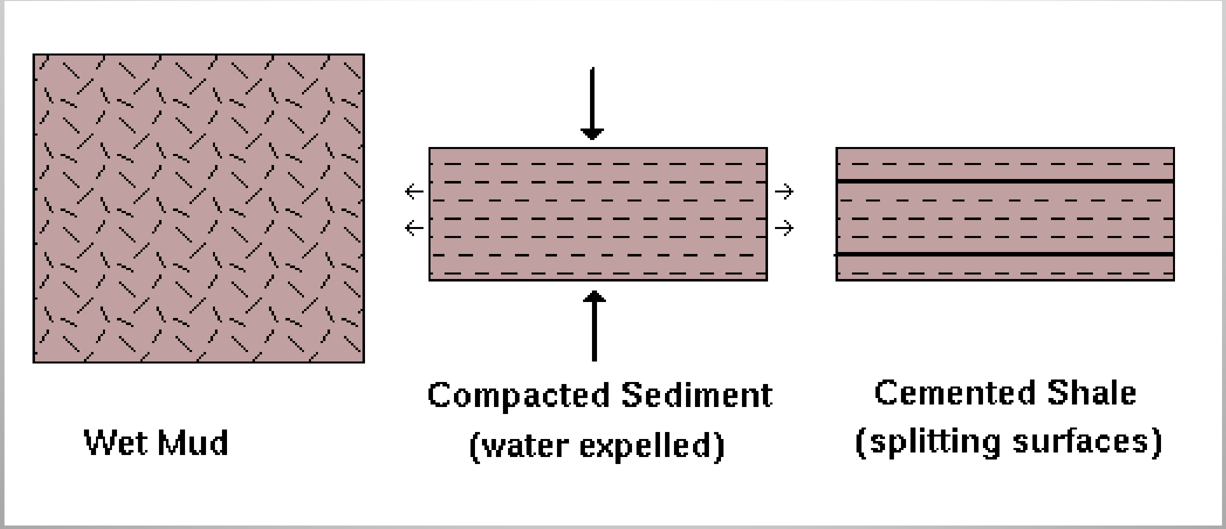
- Shale is another term applied to fine-grained sediments that have partings called ***fissility.***
- *This is due to traces of mica aligned on laminae at the time of deposition.*





MUDRÓCKS

- *Clays are deposited with a primary water-saturated porosity of* ***up to 80%.***
- *Most of this porosity is quickly lost, first by* ***dewatering*** *and later by* ***compaction****.*



Major constituents of mudrocks

Major constituents of mudrocks include:

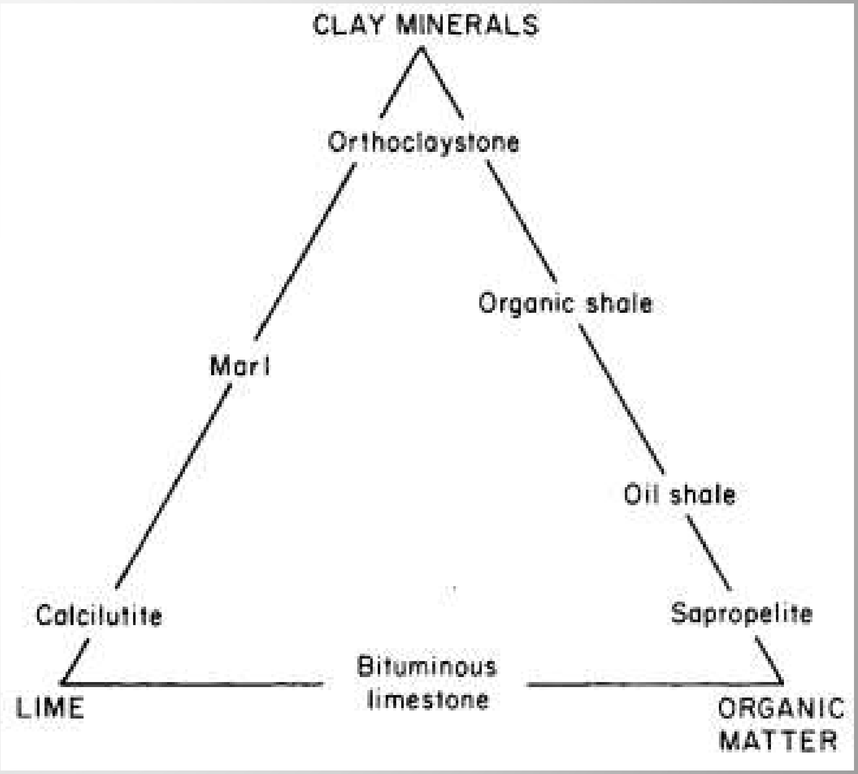
clay minerals, detrital grains, organic matter and carbonates.

- **Clay Minerals:** kaolin group, smectite group, illite group, chlorite & glauconite.
- **Detrital grains:** quartz, mica and heavy minerals.
- **Organic matter:** is chemically very complex & composed of kerogen, asphalt, crude oil and natural gas.

Nomenclature & composition of mudrocks

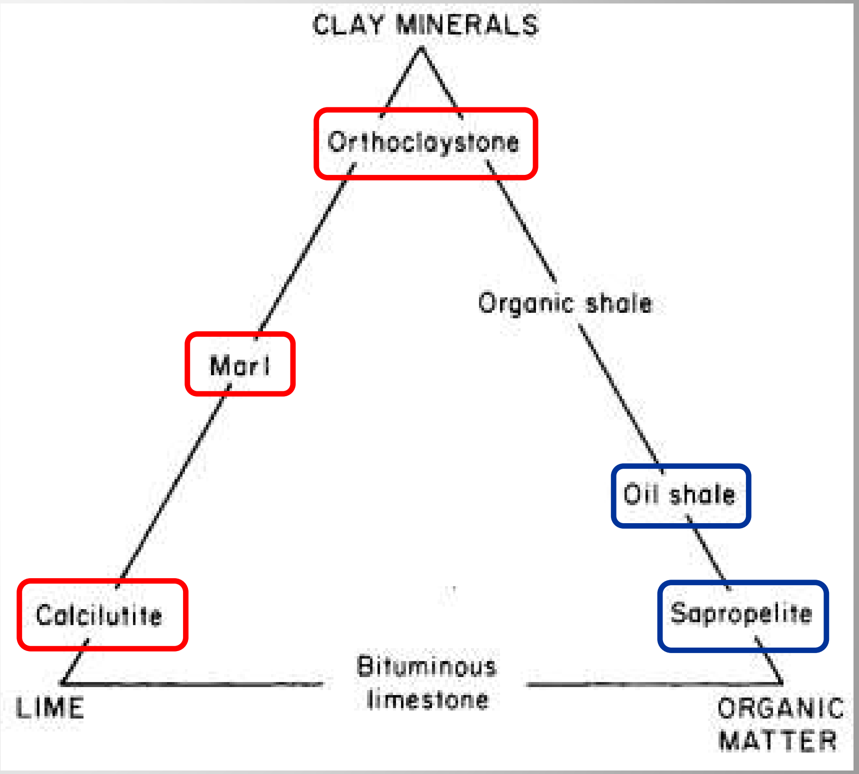
Mudrocks can be named with reference to an end-member triangle apices represent:

- *Organic Matter,*
- *Pure Lime (carbonates)*
- *Pure Clay Minerals.*



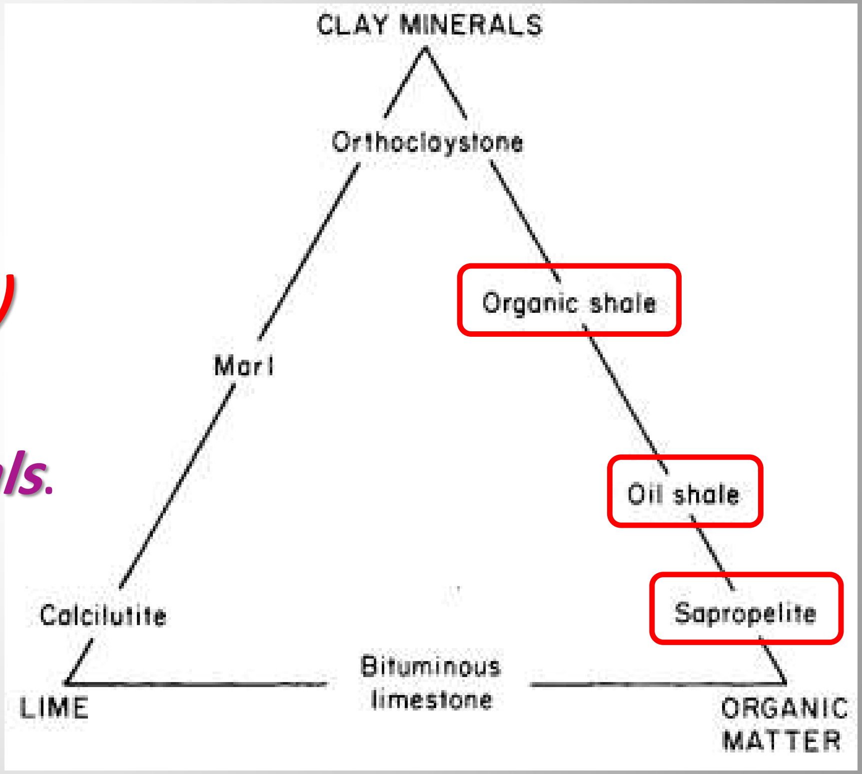
Nomenclature & composition of mudrocks

- Mudrocks composed largely of admixtures of clay minerals termed ***orthoclaystones***.
- With increasing lime content, claystones grade into ***marls*** and into ***micrites (calcilutites)*** which are pure lime mudrocks.



Nomenclature & composition of mudrocks

- Mudrocks with traces of organic matter are referred to as ***organic claystones (organic shales).***
- With increasing organic content, organic claystones ***(organic shales)*** grade into ***oil claystones (oil shales)*** and thence into the dominantly carbonaceous ***sapropelites and coals***.
- The organic-rich mudrocks are thought to be the ***source rocks*** from which liquid hydrocarbons are generated.



Nomenclature & composition of mudrocks

- Mudrock needs to contain over 1.5% organic carbon to be a significant source rock.
- The type of kerogen determine the type of hydro-carbon which may be generated:
  - Terrestrial humic kerogen tends to be gas prone.
  - Algal kerogen tends to be oil prone.
  - Mixed kerogen can generate both oil & gas.
- Temperature is also important for oil & gas generation;
  - Oil generation takes place between 60-120 °C.
  - Gas generation occurs between 120-220 °C.

ORGANIC MATTER

- **The organic matter in sediments is of four types:**

Kerogen, asphalt, crude oil & natural gas.

- ***Kerogen:*** *is a dark greyish-black amorphous solid , present in varying amounts in mudrocks,* ***when pure it is coal.***
- *The exact molecular structure of kerogen is not well known.*
- *It includes hydrocarbon compounds which are insoluble in normal petroleum solvents.*
- ***Kerogen*** *is the major consituent of the organic-rich mudrocks.*

ORGANIC MATTER

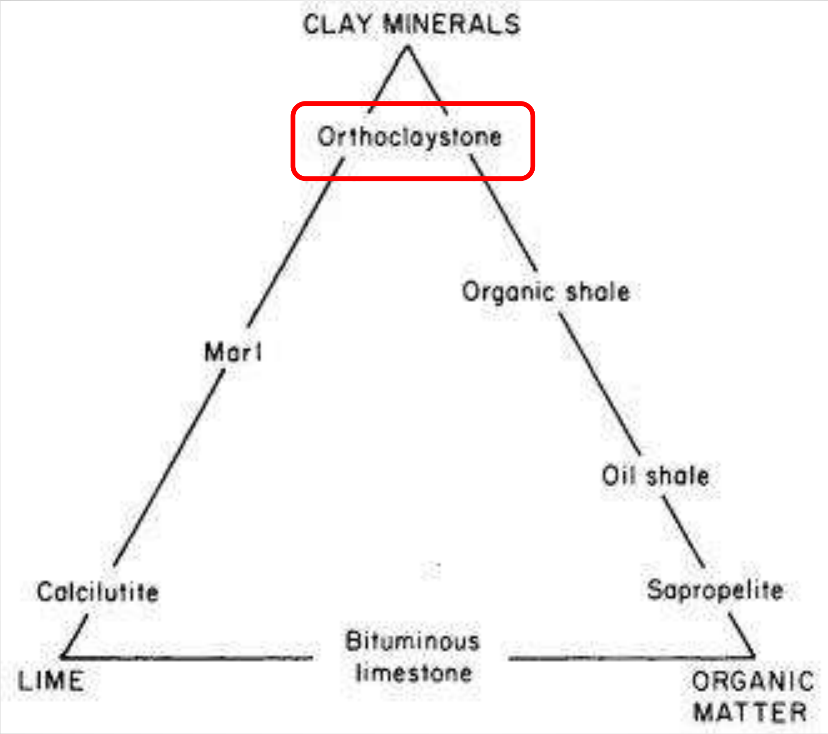
- ***Asphalt or bitumen,*** is similar to kerogen, but it is soluble in normal petroleum solvent.
- ***Asphalt*** *occurs both in infilling sediment pores and fractures.*
- ***Crude Oil*** *comprises hydrocarbons which are liquid at normal temperatures and pressure.*
- ***Crude Oils*** *are generally consist of varying proportions of four main groups,* ***The paraffins, aromatics, naphthenes, and asphalts.***
- ***Crude Oil*** *occurs in pore spaces of many rocks in favourable circumstances.*

ORGANIC MATTER

Table 8.2
Properties and composition of the main groups of organic hydrocarbons

		Average composition (% weight)		
Organic matter	Properties	C	H_2	$S + N + O_2$, etc.
Kerogen	Solid at surface temperatures and pressures. Insoluble in normal petroleum solvents	75	10	15
Asphalt	Solid or plastic at surface temperatures and pressures. Soluble in normal petroleum solvents	83	10	7
Crude oil	Liquid at surface temperatures and pressures	85	13	2
Natural gas	Gaseous at surface temperatures and pressures	70	20	10

ORTHOCLAYSTONES

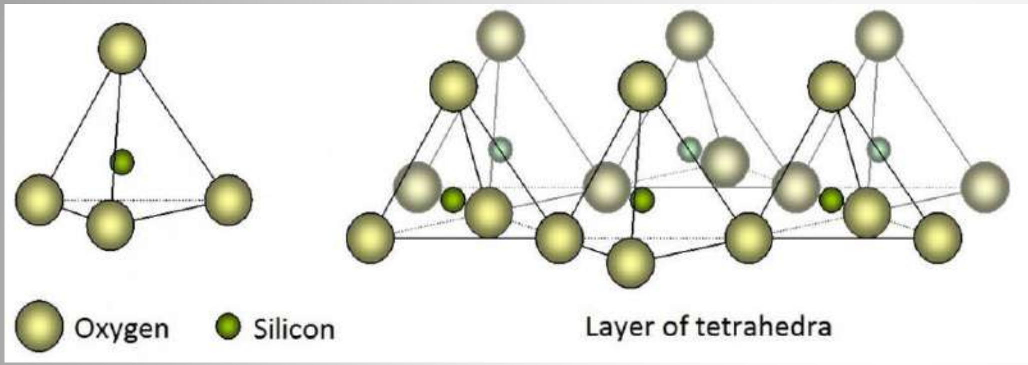


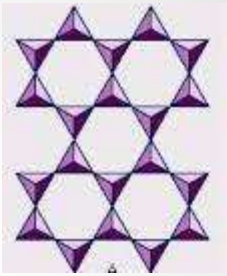
ORTHOCLAYSTONES

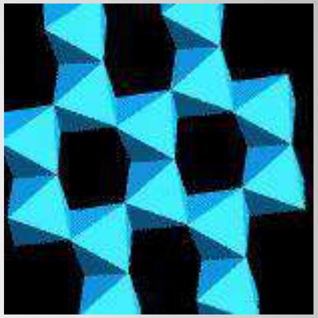
- The orthoclaystones composed ***mainly of the clay minerals groups.***
- There are five principal groups of clay minerals: ***illites, smectites (montmorillonites), kaolins, Chlorites and glauconite.***
- ***The last two differ from the other clay minerals in mode of formation, but show similarities in composition & atomic structure.***
- **All five mineral groups are *hydrous alumino-silicates.***
- ***All clay minerals are crystalline except glauconite is amorphous.***

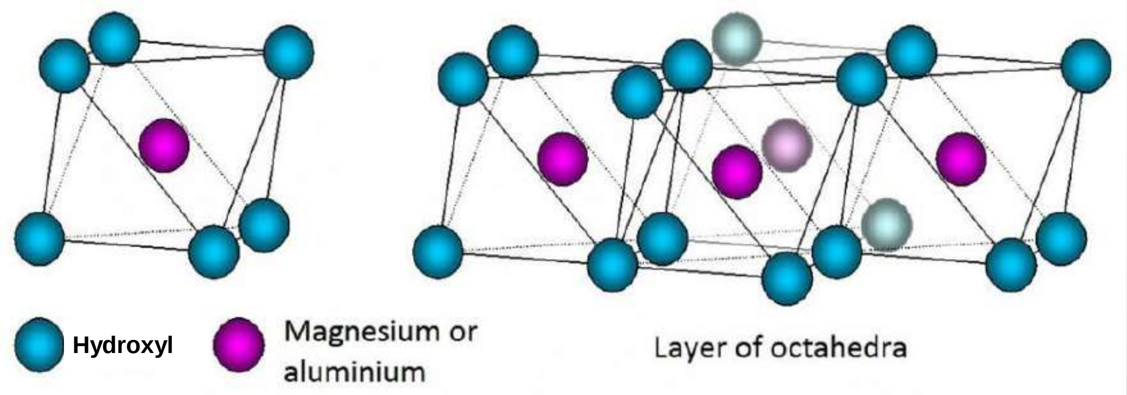
CLAY MINERALS

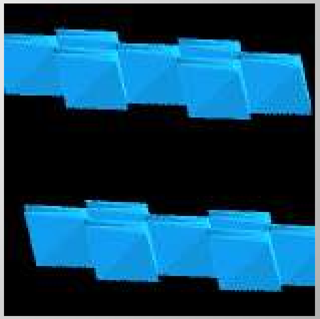
- ***The clays are composed of different arrangement of tetrahedra and octahedra layers.***



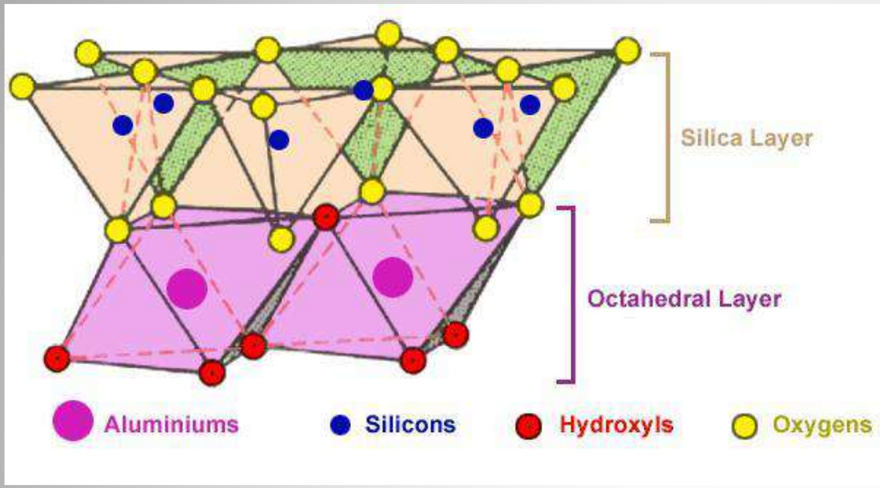


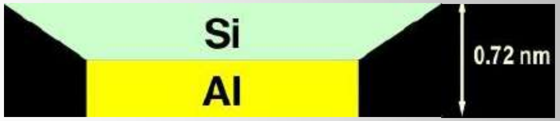


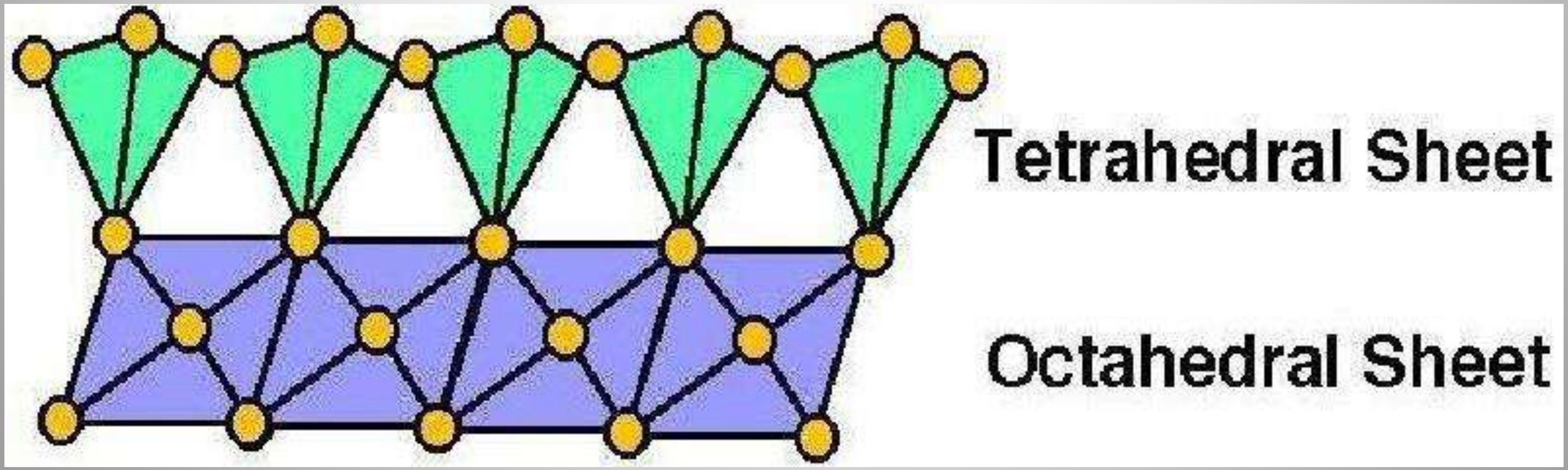




Linkage of Terahedra & Octahedra

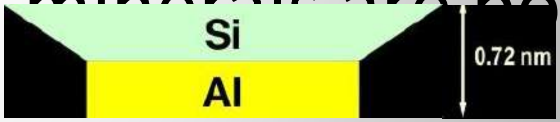


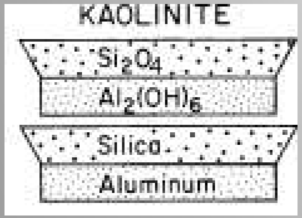


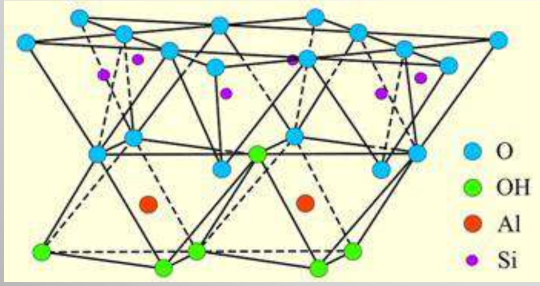


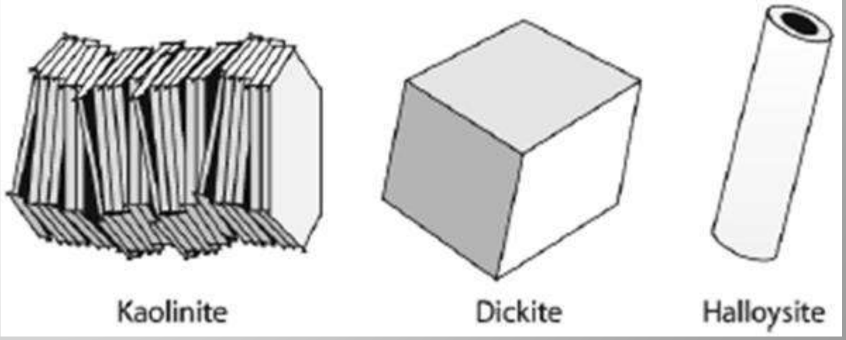
Kaolin group
(1:1 Structure)

- The kaolin group of clay minerals includes ***kaolinite, dickite, nacrite, halloysite and allophane.***
- The differences between these minerals are both ***chemical & structural***.



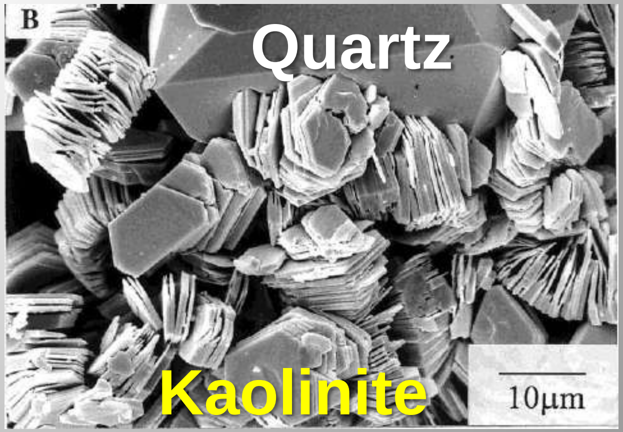






Kaolin group *(1:1 Structure)*

- ***Kaolinite*** is the simplest clay mineral in structure and the purest in composition **[$Al_2Si_2O_5(OH)_4$].**
- It is formed from feldspars by ***hydrothermal alteration & superficial weathering.***
- ***Kaolinite*** is the common detrital clay mineral in sediments derived from ***granitic and gneissose sources.***
- ***Kaolinite*** is an important authigenic cement in some sandstones.



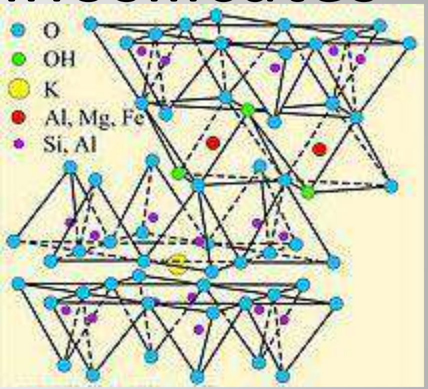
Kaolin group (1:1 Structure)

- In certain circumstances kaolin sedimentation is sufficiently abundant to form ***a pure kaolin claystone.***
- The rock type is variously termed ***pipe clay, china clay & fire clay.***
- ***Tonstein*** is another distinctive rock type, composed largely of kaolinite.
- ***Kaolinite is extensively used in ceramic, paper-making and pharmaceutical industries.***
- ***Pure kaolinite rocks are non-marine in origin because kaolinite quickly transforms to more complex clays in the presence of sea water.***

ILLITE GROUP

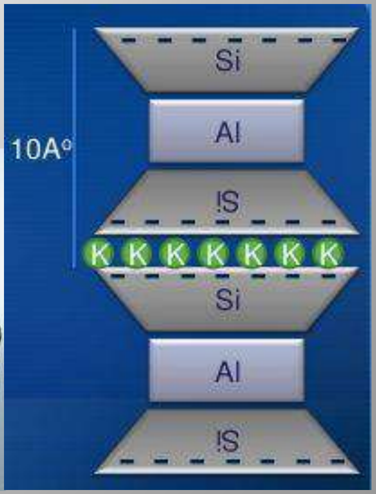
(2:1 Structure)

- The illite clays, sometimes termed the ***hydromicas.***
- They composed of three-layer aluminosilicates with up to 8% K_2O .



$[K_{0.8-0.9}(Al,Fe,Mg)_2(Si,Al)_4O_{10}(OH)_2]$

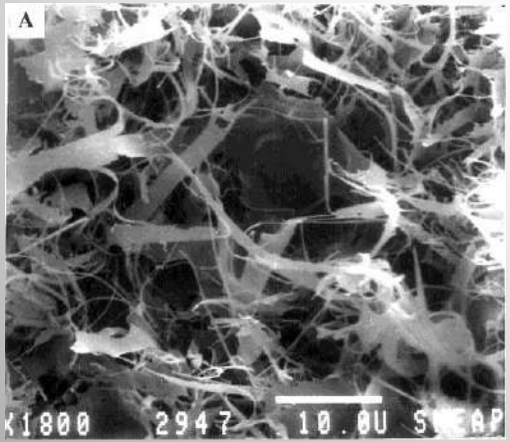
- ***Potassium*** may either be present due to incomplete degradation of K-feldspar to kaolinite, or to diagenesis of kaolinite Within marine environment.

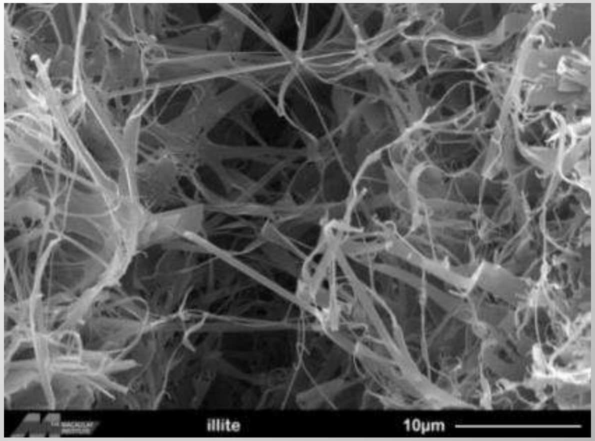


ILLITE GROUP

(2:1 Structure)

- Illite is less obvious than kaolinite because it is seldom present in crystals.
- **Under SEM,** illite crystals are smaller and less well developed than those of kaolinite.





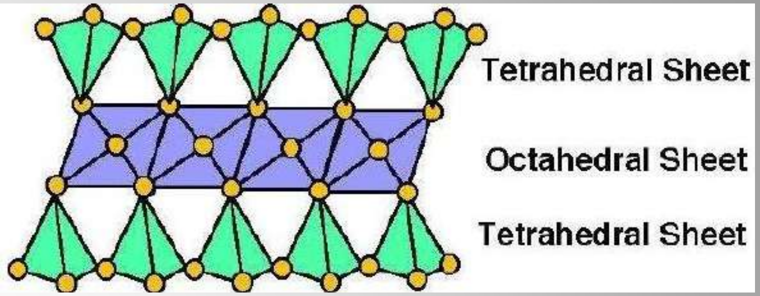
SMECTITE GROUP

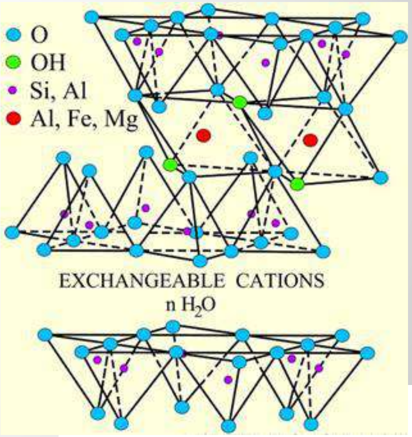
(2:1 Structure)

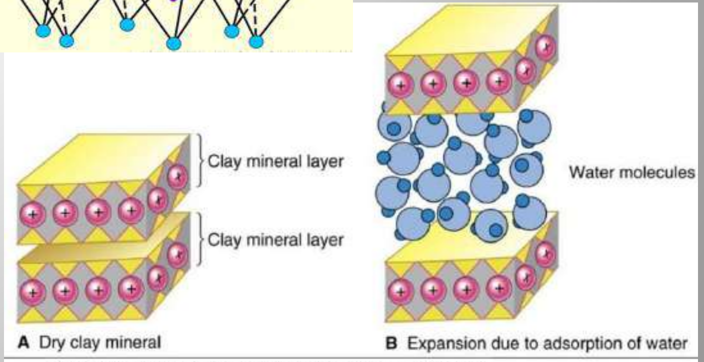
- These are three-layer types which have unusual property of ***expanding & contracting*** to absorb or lose water.

- ***Montmorillonite*** is the chief example of smectite group.

- ***Mont.*** Can contain up to 20% water as well as Ca & Mg ions.





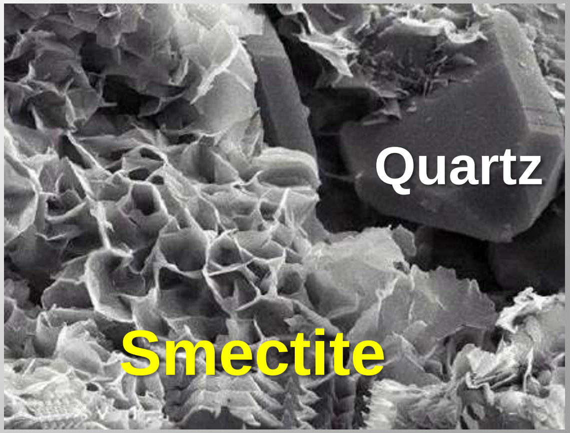


Plummer et al., Physical Geology 9th edition, McGraw Hill Inc, Box 02.04.f1

SMECTITE GROUP

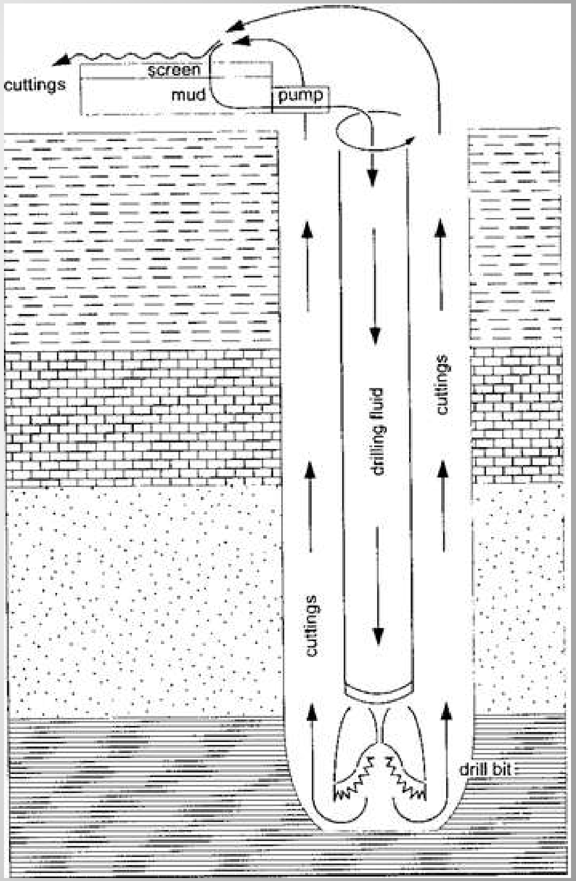
(2:1 Structure)

- Mudrocks composed largely of smectite clays termed ***Bentonites.***
- ***Bentonites*** are formed by the alteration of volcanic ash in situ.
- This may occur in both marine & continental environments.
- They composed of fragments of detrital glass, with microscopic grains of quartz, mica, feldspars & heavy minerals.



Bentonites

- ***Bentonites*** are a major constiuent of circulating mud systems used in rotary drilling.
- ***Conversely, montmorillonite*** is an unfortunate clay mineral as a matrix in an oil reservoir.
- During production, water entering the reservoir may cause the clay matrix to expand and thus destroy permeability.

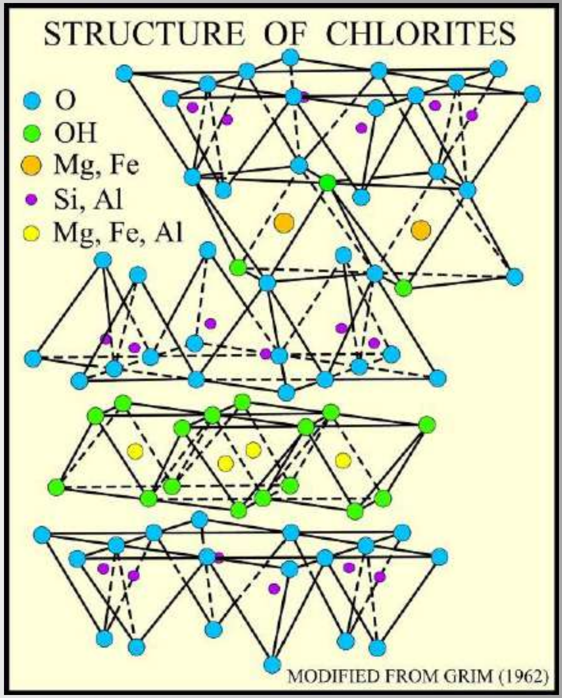


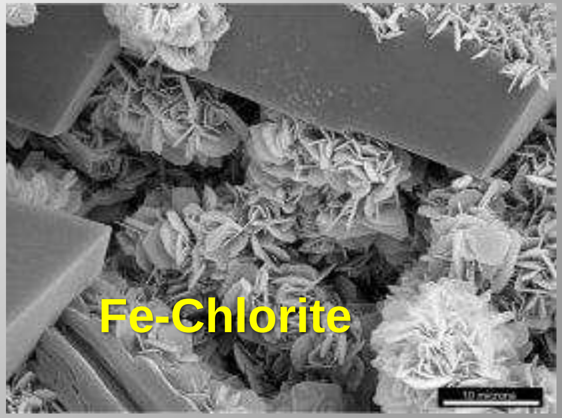
CHLORITES (2:1:1 STRUCTURE)

- The chlorites are mixed-layer lattice clays with up to 9% FeO and 30% MgO.
- The overall chemical composition of Chlorite minerals is:

$$(Mg,Fe,Al)_6\,(Si,Al)_4O_{10}(OH)_8$$

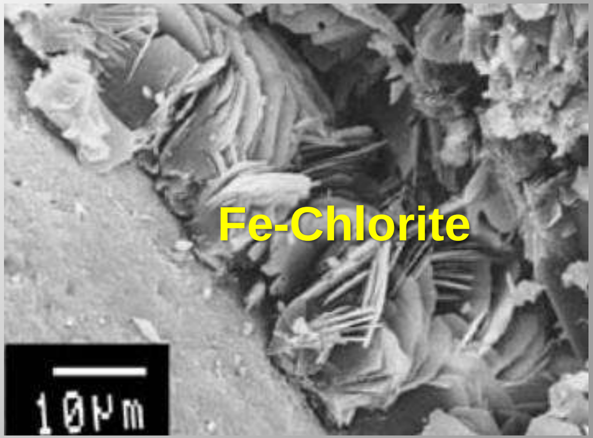
- The common chlorite minerals are: **Clinochlore** (Mg-rich chlorite), **Chamosite** (Fe-rich chlorite).





CHLORITES (2:1:1 STRUCTURE)

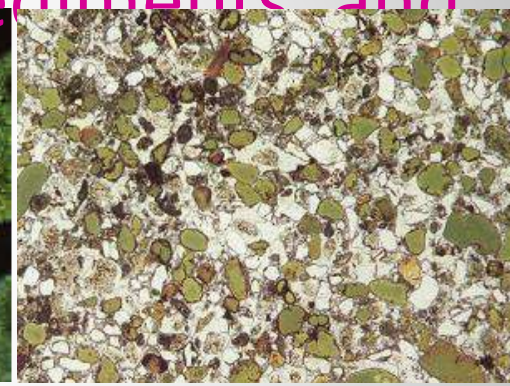
- *Chlorites have quite a variable chemical compositions due to a lot of the **Al** is normally replaced by **Mg** and **Fe** .*
- *Other metals including **Zn**, **Mn** and **Ni** can also replace **Al** .*
- *Chlorites occur as an alteration product of micas.*
- *Chlorite is a common accessory detrital mineral in immature sands and mudrocks.*
- *It is characteristic constituent of the microcrystalline matrix of greywackes.*



GLAUCONITE (2:1 Structure)

- *The term **glauconite** is used in two ways:*
- It is applied to pretty, rounded green grains commonly seen in marine sediments, and





- The term is applied to a particular mineral.
- Analyses of glauconites show them to contain a mixture of clays whose lattices are in various

GLAUCONITE

- Glauconite proper is a three-layer clay mineral containing ***Mg, Fe & K***.
- The chemical composition: $(K,Na)(Fe,Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$
- It occurs in dark green amorphous grains seldom larger than fine-sand grade.
- **It is found in mudrocks & sandstones.**

GLAUCONITE (2:1 STRUCTURE)

- Geochemical evidence suggests that glauconite formation occurs in seawater at low temperatures ***in an environment which is neither strongly oxidizing nor reducing.***

- Optimum depth for glauconite genesis appears to be between 50 and 1000 m below sea level.

- **Glauconite is abundant only in sea-floor areas that are isolated from large supplies of land-derived sediment.**

Glauconite forms by three principal processes:

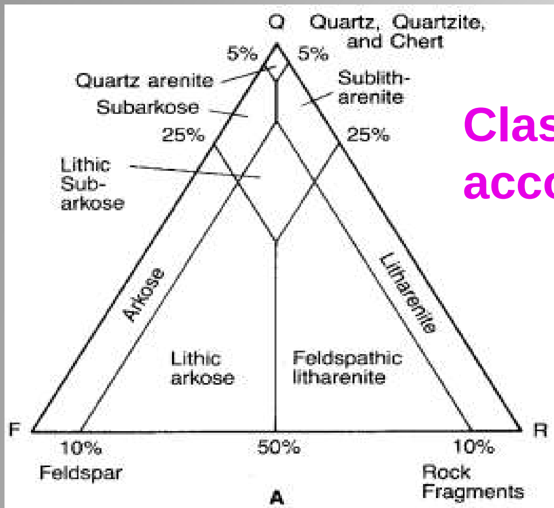
1. Replacement of the fecal pellets of bottom-dwelling organisms and by infilling foraminiferal tests & larger shells.;
2. Modification of particles of illitic and biotitic clays by seawater;
3. Direct precipitation from seawater.


SANDSTONES

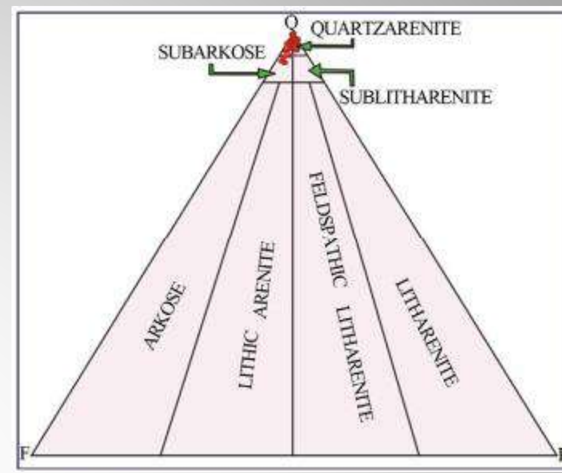
INTRODUCTION

- **About 30% of the land's sedimentary cover is made of *terrigenous sand and sandstone.***
- **Sandstones make up nearly *one-quarter* of the sedimentary rocks in the geologic record.**
- **They form under a wide range of depositional conditions in a variety of depositional environments.**
- **Because they are often *highly porous*, sandstones are frequently *major aquifers and petroleum reservoirs.***
- **They are more uniform in stratigraphy and petrophysical character than carbonate rocks.**

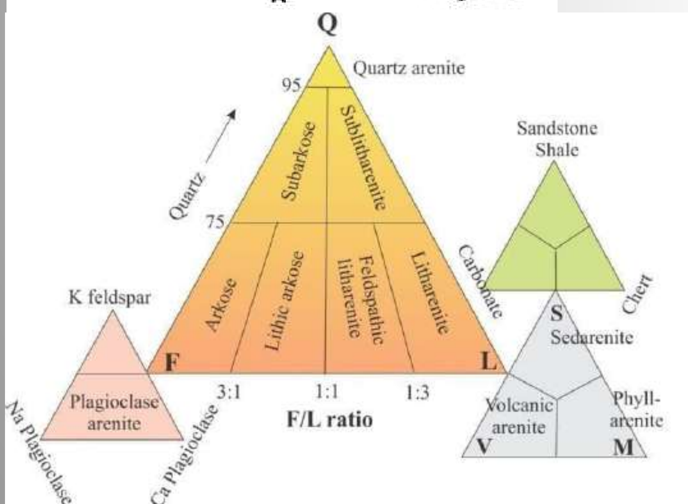
Nomenclature and Classification of Sandstones

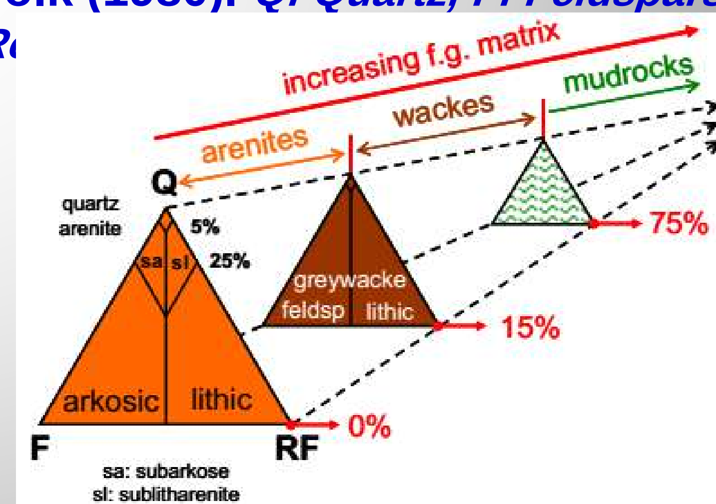


Classification of sandstones according to McBride (1963)



Classification of sandstones according to
Folk (1980). *Q: Quartz, F: Feldspars, R: R*





Classification of sandstones according to
Folk (1968). *Q: Quartz, F: Feldspars, L:*

Classification of sandstones after Pettijohn *et al*. (1987).

Nomenclature and Classification of Sandstones

- One of the most fruitful concepts on which sandstone nomenclature is based on the ***idea of maturity (maturation).***
- ***The maturation of a sand takes place in two ways:***

It matures ***chemically,*** and

it matures ***physically.***

Nomenclature and Classification of Sandstones

Chemical Maturity (Mineralogical M.):

- **Sediments form from the weathering of mineralogically complex source rocks.**
- **Throughout weathering and transportation relatively *unstable minerals* are destroyed and *chemically stable minerals* thus increase proportionally.**

Nomenclature and Classification of Sandstones

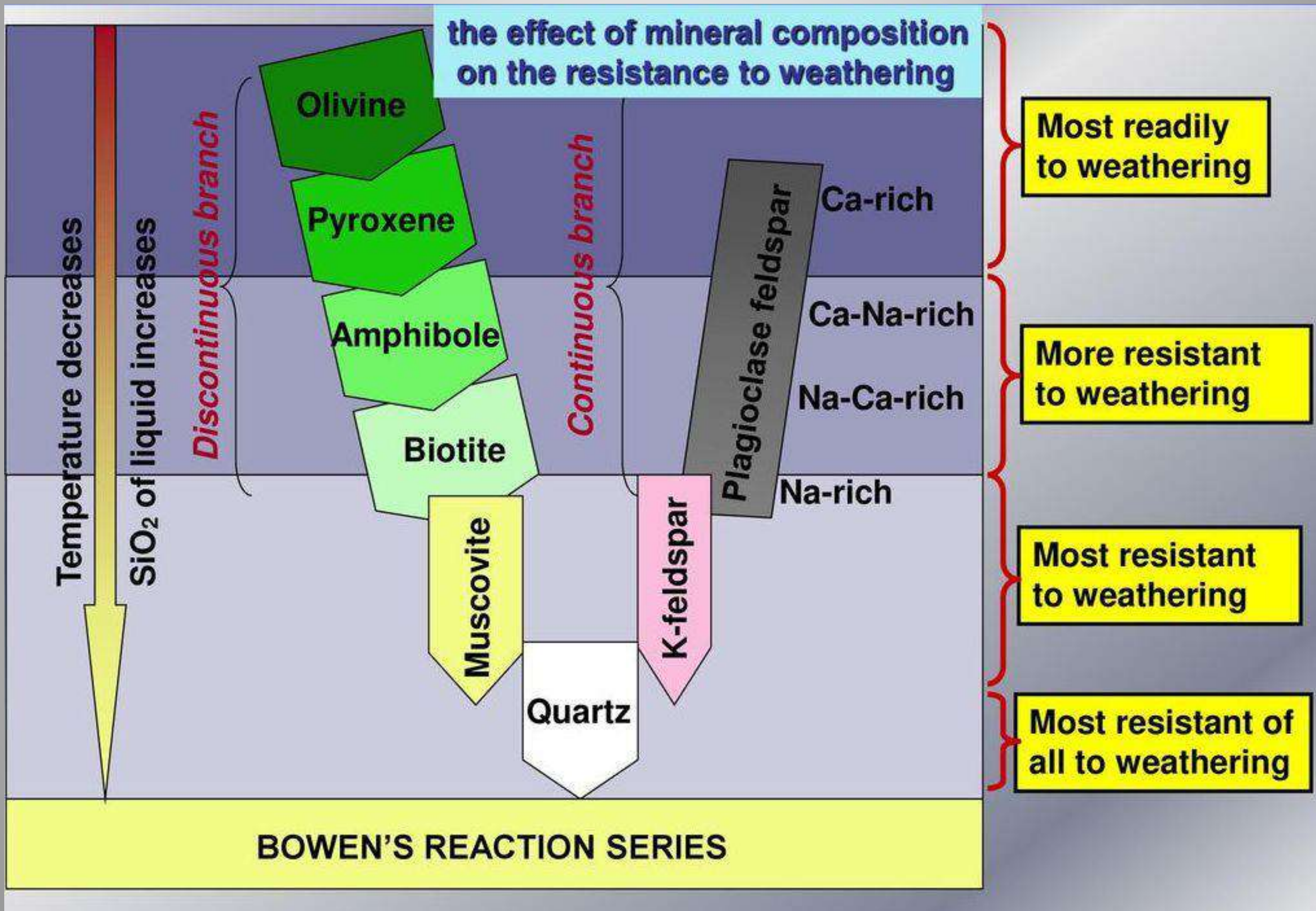
- ***Quartz*** **is the most abundant stable mineral &** ***feldspar*** **is a common example of an unstable mineral.**
- **An index of the chemical maturity of a rock might be:** ***the ratio of quartz to feldspar.***
- As sediments are reworked through **two or more cycles of sediment,** they thus ***tend to be mature to pure quartz sands.***

Intensity of weathering

Table Minerals Remaining in Clastic Sediments Derived from an Average Granite Outcrop Under Varying Intensities of Weathering

INTENSITY OF WEATHERING		
Low	**Medium**	**High**
Quartz	Quartz	Quartz
Feldspar	Feldspar	Clay minerals
Mica	Mica	
Pyroxene	Clay minerals	
Amphibole		

Resistance of Minerals to Weathering



Chemical Stability of Minerals during Weathering

Stability of minerals	Rate of weathering
MOST STABLE	**Slowest**
Iron oxide (hematite)	↓
Aluminum hydroxides (gibbsite)	
Quartz	
Clay minerals	
Muscovite mica	
Potassium feldspar	
Biotite	
Albite (Na-rich feldspar)	
Amphiboles	
Pyroxene	
Anorthite (Ca-rich feldspar)	
Olivine	
Calcite	
Halite	
LEAST STABLE	**Fastest**

Nomenclature and Classification of Sandstones

Physical Maturity (Textural M.):

- Physical maturity describes **the textural changes that a sediment undergoes from the time it is weathered until it is deposited.**

- **These changes involve both:**

  an increase in the degree of sorting **&**

  a decrease in matrix content.

- **Thus an index of the degree of physical maturation might be:**

  the ratio of grains to matrix.

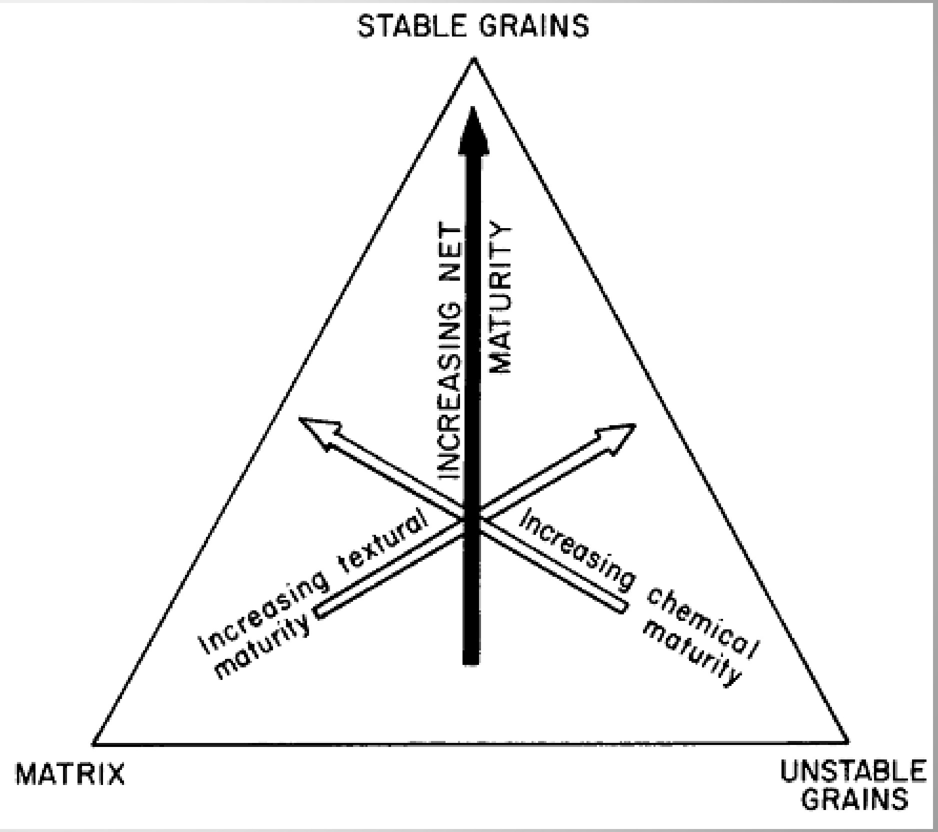
- ***Total clay content*** is a useful index of textural maturation.

Nomenclature and Classification of Sandstones

- **Both physical and chemical maturation** ***occur during the history of a sand population, but they are not closely related*** (Johnson and Basu, 1993).
- ***Thus a chemically mature sand may be physically immature and vice versa !!!!***

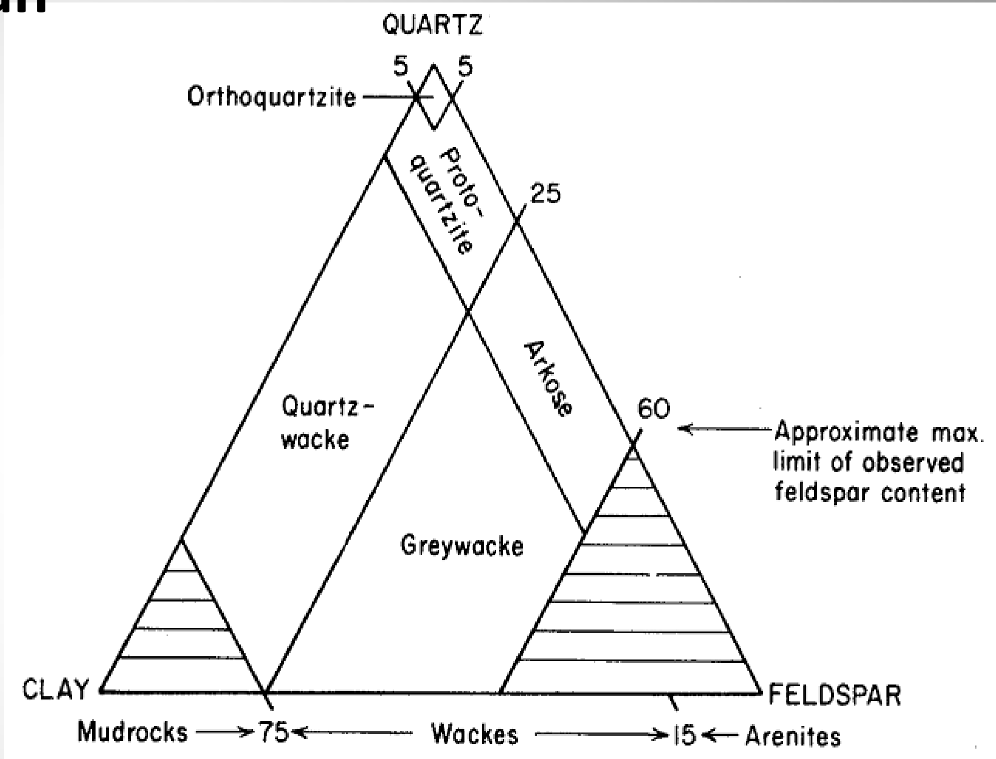
Nomenclature and Classification of Sandstones

it would appear that the most appropriate ***triangular classification*** to adopt would have ***stable grains at one apex, matrix at the second*** and ***unstable grains at the third.***



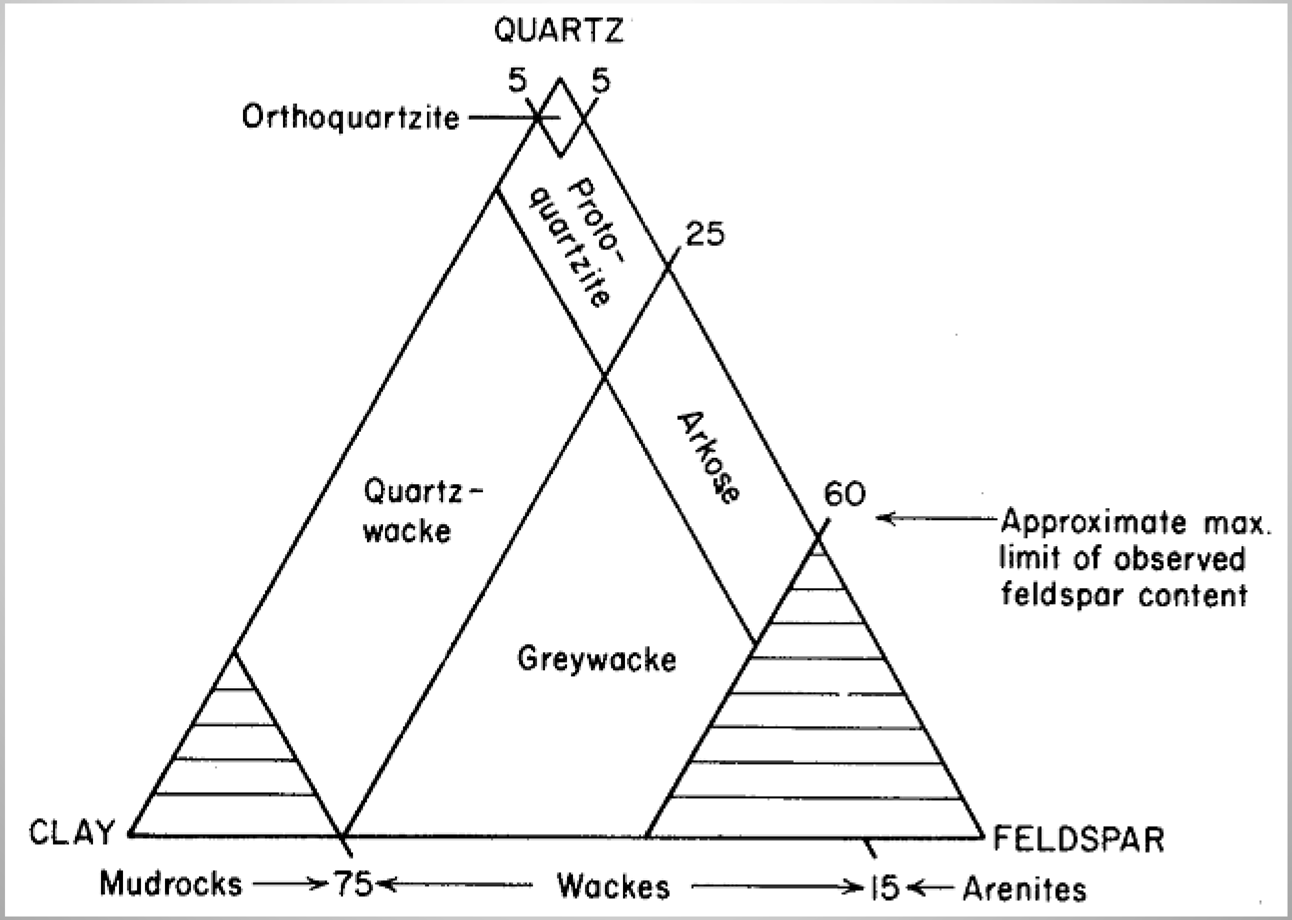
Nomenclature and Classification of Sandstones

- These concepts of maturity can be used as a basis for S.st. nomenclature.
- ***The total amount of clay*** in a sand is **the best indicator of matrix content.**
- ***Feldspar*** is a common abundant unstable mineral (index of chemical immaturity).
- ***Quartz*** is the index mineral for the apex of chemical stability.

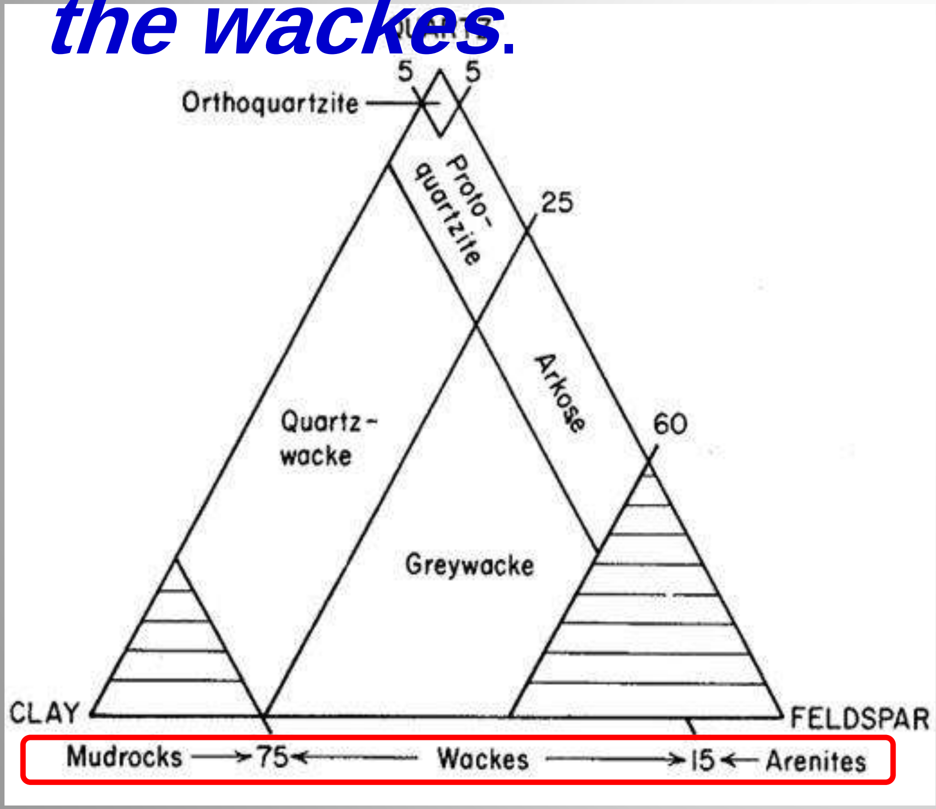


Nomenclature and Classification of Sandstones

- Using ***quartz, feldspar, and clay*** as end-members, a sand classification scheme can be drawn up as shown.



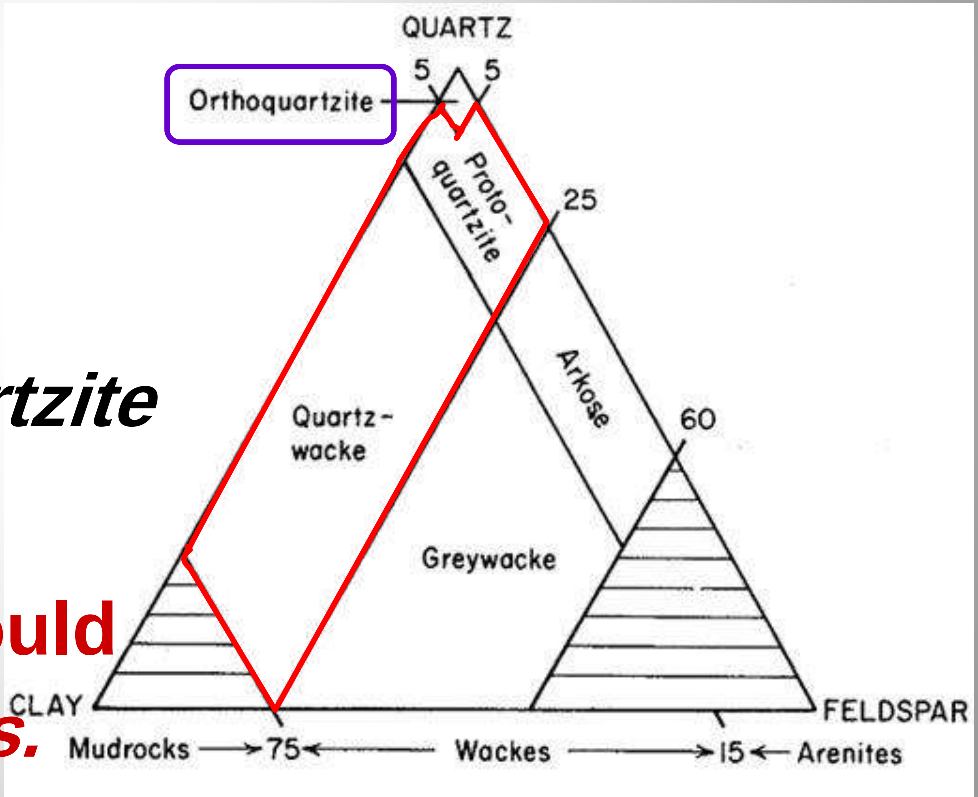
sands may be divided into **two broad textural types**, ***the arenites*** and ***the wackes***.



- ***Arenites,*** **with a matrix content of < 15%, are *texturally mature.***
- ***Wackes*, with a matrix content of 15 -75%, are *texturally immature.***
- ***Rocks* with >75 % matrix *are not sandstones* but *mudrocks*.**

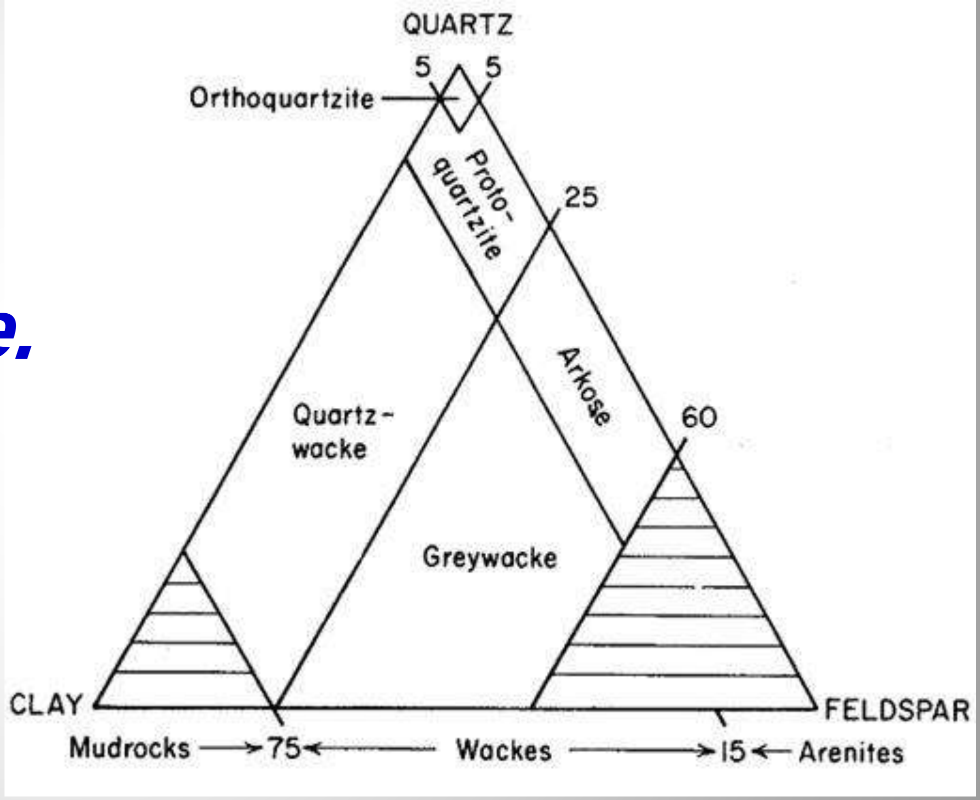
Nomenclature and Classification of Sandstones

- ***Similarly,*** **sands can be divided into *chemically mature arenites* & *chemically mature wackes*.**
- **Both have *< 25 % of feldspar.* These two sandstones are: *protoquartzite & quartz-wacke.***
- **The mature arenites should be called *quartz-arenites.***
- **Space is found in the quartz apex for *orthoquartzite sands,***



Nomenclature and Classification of Sandstones

- Sands with **>25 % feldspar** are ***chemically immature.***
- They are divided into: ***arkoses*** **for the arenites &** ***greywackes*** **for the wackes.**



Nomenclature and Classification of Sandstones

- It is convenient to divide the Sandstones into ***three groups :***

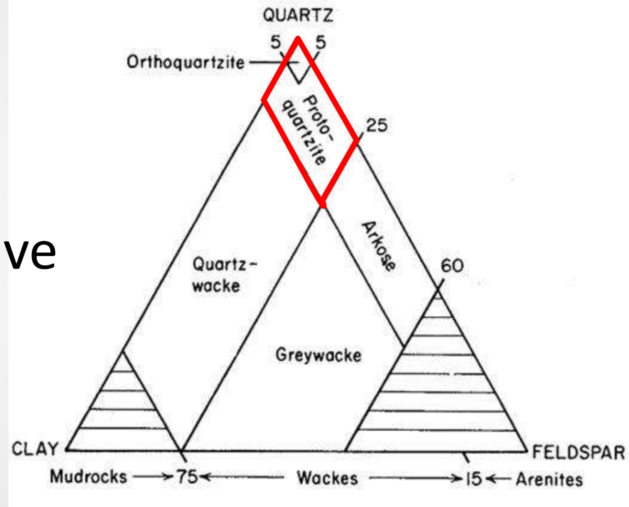
- ***The quartzites:*** (including both protoquartzites & orthoquartzites).
- ***The arkoses***
- ***The wackes:*** (including both quartz-wacke & greywacke).

QUARTZITE

(Orthoquartzites & Protoquartzites)

Quartzites
(Characteristic Features)

- ***Sands that are mature in texture and mineralogy*** are broadly referable to as the ***quartzites*** or ***quartz-arenites.***
- Among sedimentary petrographers, a quartzite generally refers to a ***quartz-rich sand*** irrespective of its degree of lithification.
- **Quartzites have < 25 % feldspar & < 15 % matrix.**



- **Quartzites are generally divisible into *protoquartzites***

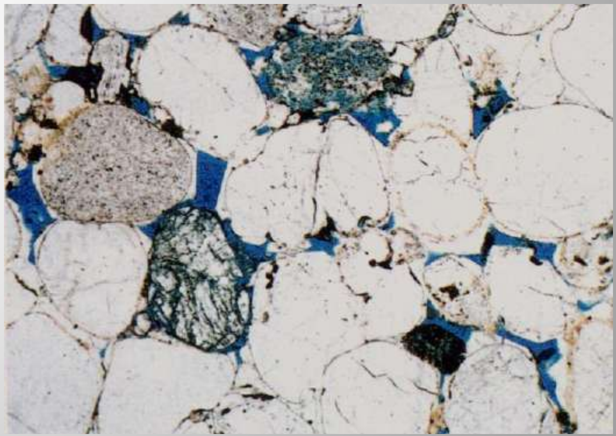
  which contain some feldspars (< 25%) and matrix (< 15%),

  & *orthoquartzites,* which are almost pure silica.

Quartzites

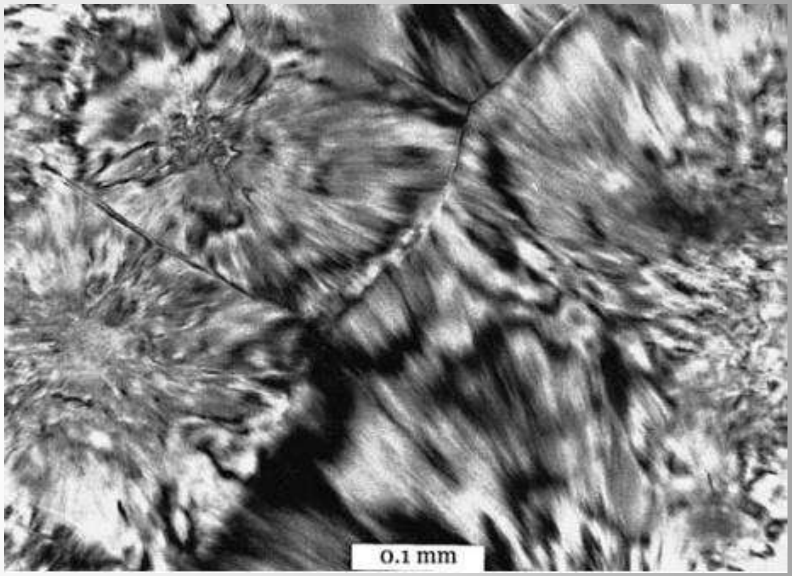
(Characteristic Features)

- The quartzites are, therefore, sands that are chemically …………….. and physically ……………..!!!!!
- ***Typical quartzites* are white, pale gray, or pink in color.**
- They range from unconsolidated to splintery in their degree of lithification.
- Grain size is variable, but sorting is ***generally good*** and individual grains are normally ***well rounded***.



Mineralogical composition of Quartzites

- The main detrital grains are ***quartz*** (derived from igneous and metamorphic rocks), and ***cherts*** (made of quartz, chalcedony, or crystobalite) reworked from sediments.



Fibrous to feathery texture of chalcedony. Unknown formation. Crossed nicols (From Boggs, 2009).

Mineralogical composition of Quartzites

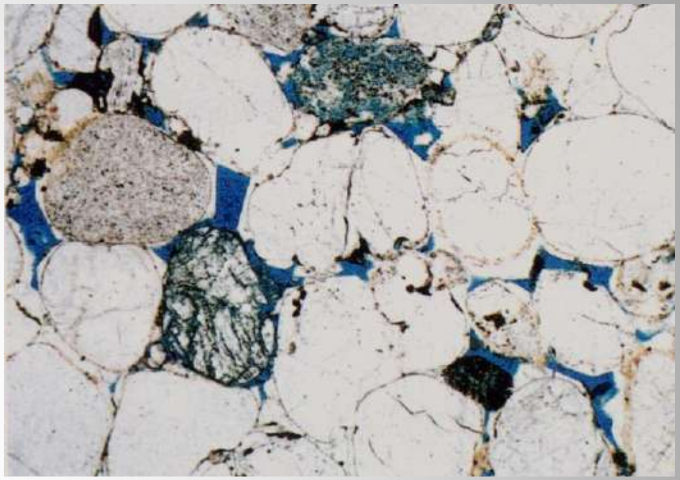
- **Rare** ***feldspar.***
- ***Mica*** grains may be present.
- ***Heavy minerals*** are generally the stable residue such as ***zircon, tourmaline, apatite, and garnet.***
- Intraformational autochthonous detrital grains are common in quartzites, such as ***glauconite, phosphate pellets, and skeletal debris.***

Quartzites
(Cementation)

- Quartzites possess high porosities and permeabilities at the time of their deposition.

  Why?

- Cementation is generally by ***calcite*** or ***secondary silica.***
- But where cement is absent, ***quartzites make the best aquifers and hydrocarbon reservoirs of all the sandstone types.***

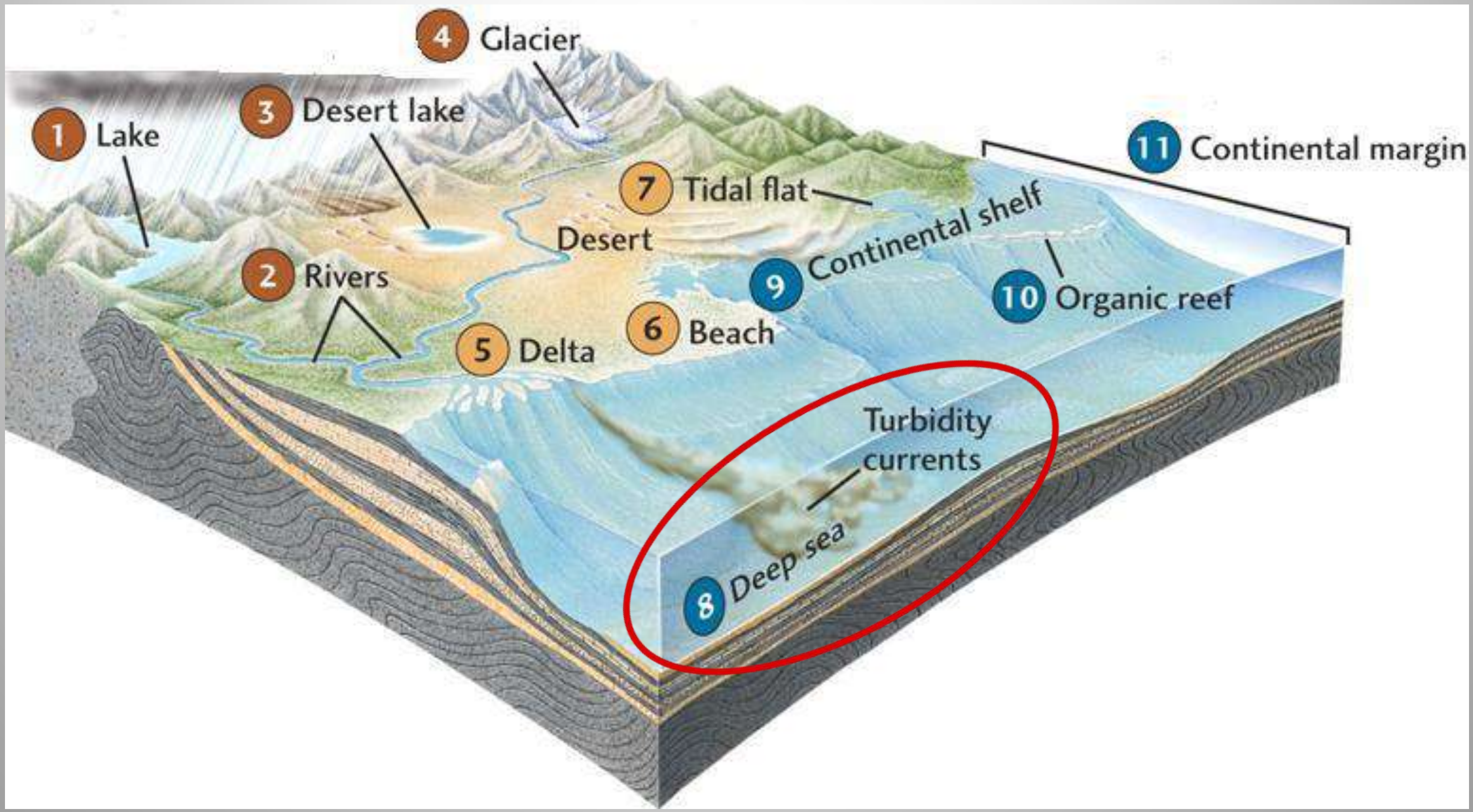


Origin of Quartzites

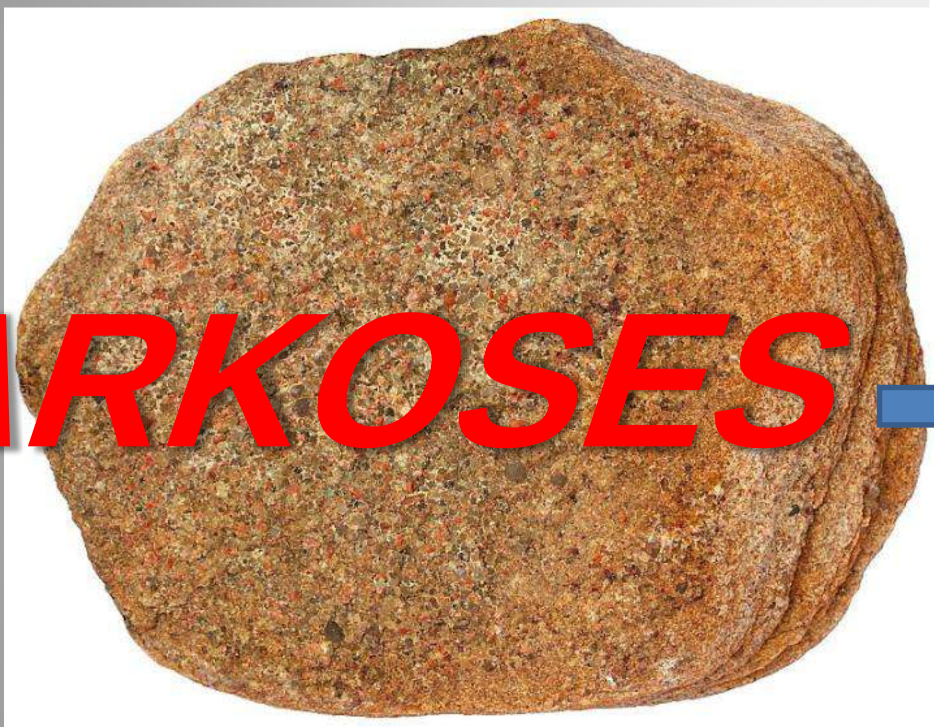
- **It is probable that most, if not all, quartzites are *polycyclic in origin.***
- **i.e.,** they have been through **more than one cycle of weathering, erosion, transportation, and deposition** to achieve the necessary maturity to qualify.
- **The majority of quartzites were deposited in marine sand-shoal environments.**

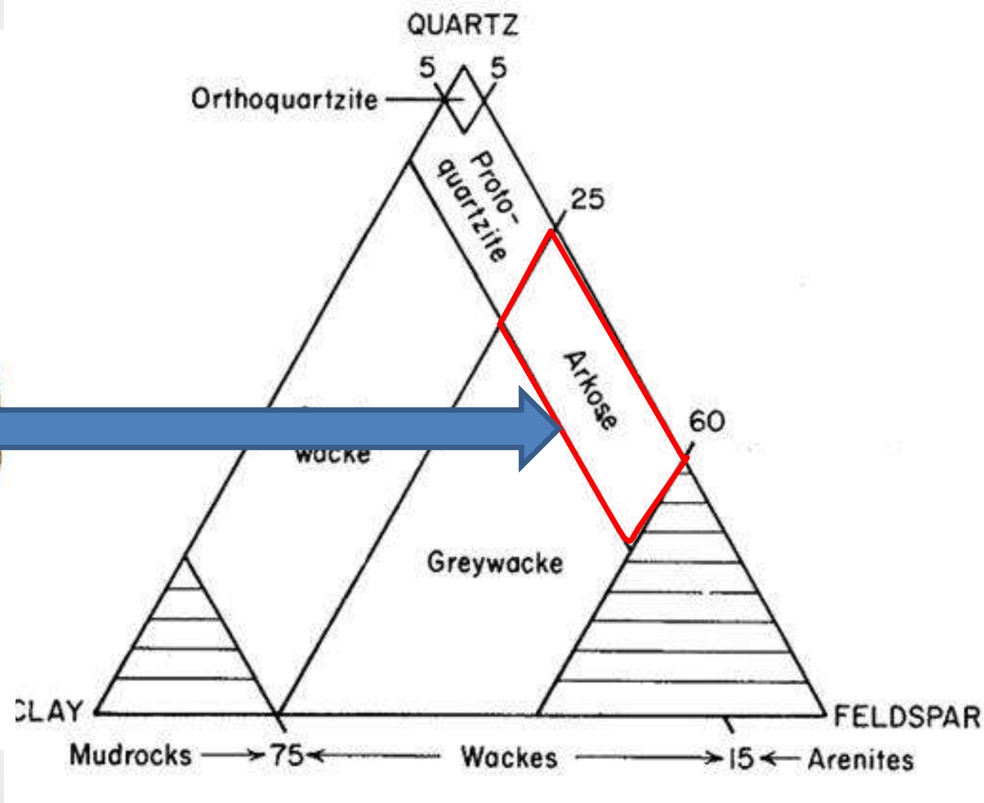
Origin of Quartzites

- They also occur in many other environments, including **modern deep-sea sands (Hubert, 1964) and ancient turbidites (Sturt, 1961).**



RKOSES



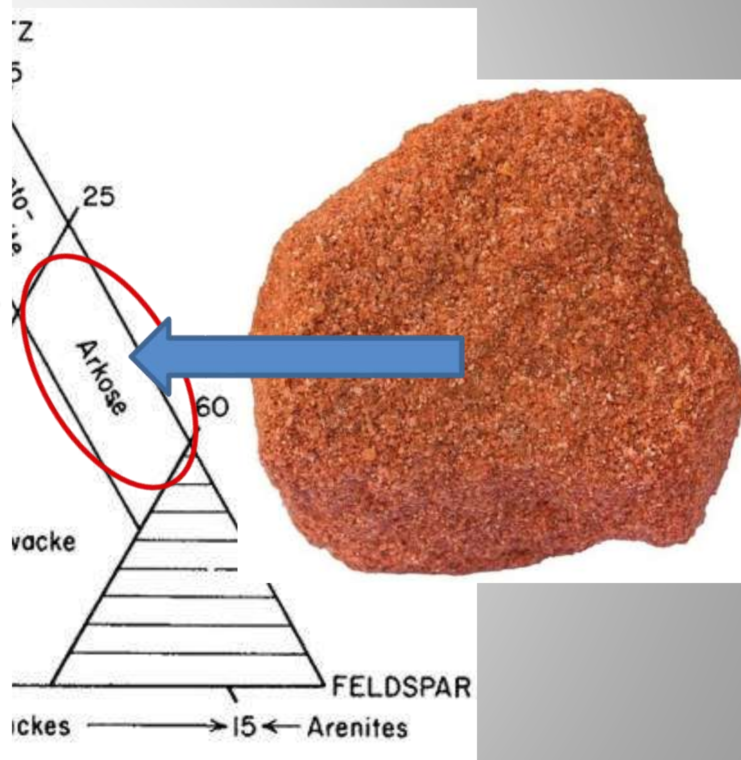

QUARTZ
5
5
Orthoquartzite
Proto-quartzite
25
Arkose
60
wacke
Greywacke
CLAY
FELDSPAR
Mudrocks → 75 ← Wackes → 15 ← Arenites

ARKOSES
(Definition)

- The term arkose was first proposed by ***Brogniart (1826)*** for a coarse sand ***composed of quartz and substantial quantities of feldspar*** from the Auvergne in France.
- Arkoses are the product of the incomplete degradation of ***acid igneous & metamorphic rocks*** ***such as granites and gneisses.***
- Arkose often forms in place on granites forming a transitional weathering zone, termed ***"granite wash".***

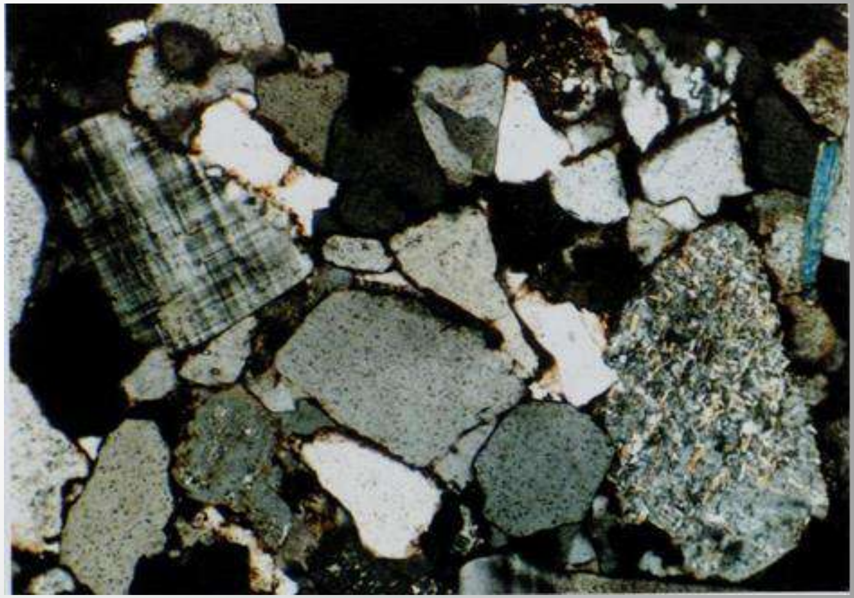
Characteristic Features of Arkoses

- The arkoses are sands which are relatively ***mature in texture*** **(i.e. < 15 % clay matrix)** & are ***immature in mineralogy*** **(> 25 % feldspar)**.
- ***Colour:*** The typical arkose is a ***pink*** ***or red, less commonly it is gray.***
- ***Pink coloration: is due to the feldspars.***
- ***The red color: owe to absorption of red ferric oxide into the clay matrix.***



Characteristic Features of Arkoses

- ***Arkoses*** show a ***wide range of grain sizes*** **&** ***are often poorly sorted.***
- The grains of arkoses are typically ***angular to sub-rounded.***

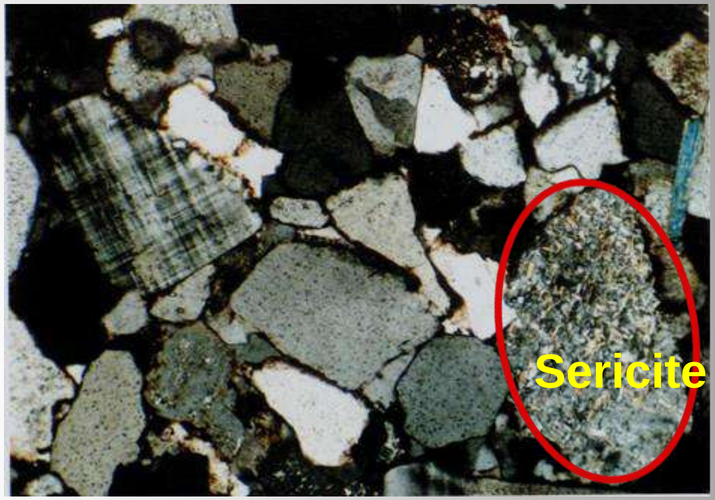


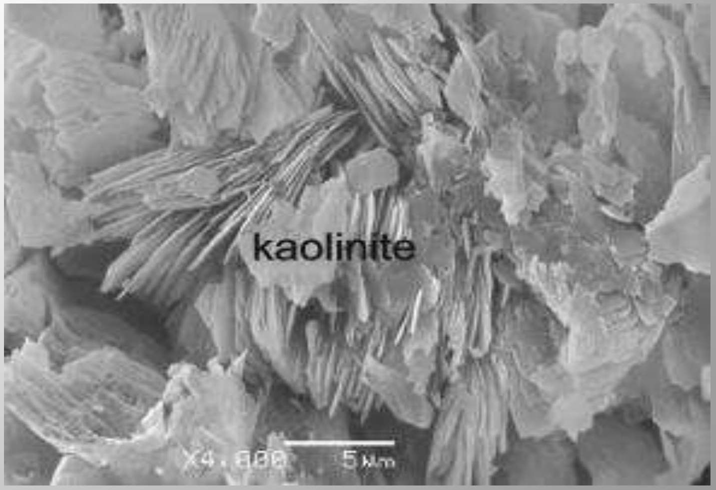
Characteristic Features of Arkoses

- **There is a significant amount of clay matrix.**
- **For this reason arkoses seldom stay unconsolidated for long time.**
- In extreme cases ***porosity*** **can be completely obliterated** by a ***silica*** **or** ***carbonate*** **cement.**

Mineralogy of Arkoses

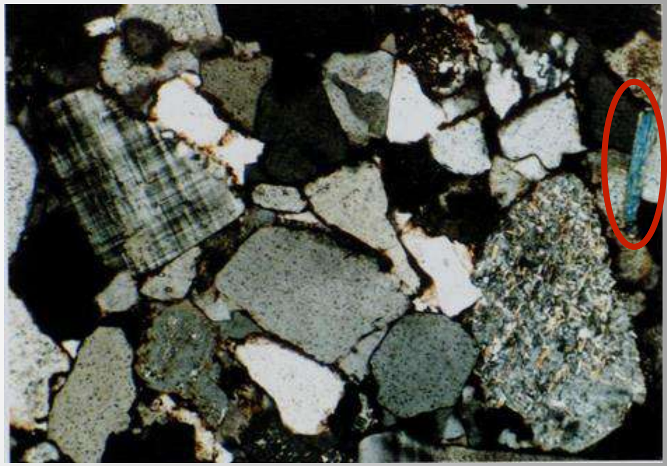
- ***The feldspars*** in arkose are of various types, depending on the nature of the source rock, but ***microcline & albite more abundant than the less stable calcic feldspars***.
- Alteration of the feldspars to ***sericite & kaolinite*** is a common feature.





Mineralogy of Arkoses

- ***Micas*** are a common accessory minerals.
- Arkoses often contain a ***diverse suite of heavy minerals.***
- ***These*** may give some ***indication of the source terrain***, whether it was ***igneous*** or ***metamorphic***.
- ***Opaque iron ores*** are found in addition to the stable suite of ***zircon***, ***apatite***, ***garnet*** & ***tourmaline***, as well as many other heavy minerals.



Depositional Environments of Arkoses

- Most arkoses seem to occur in alluvium adjacent to granitoid basement.
- Because such sediments are deposited in an **oxidizing alluvial fan environment,** many arkoses are termed the ***"red beds"*** facies assemblage.

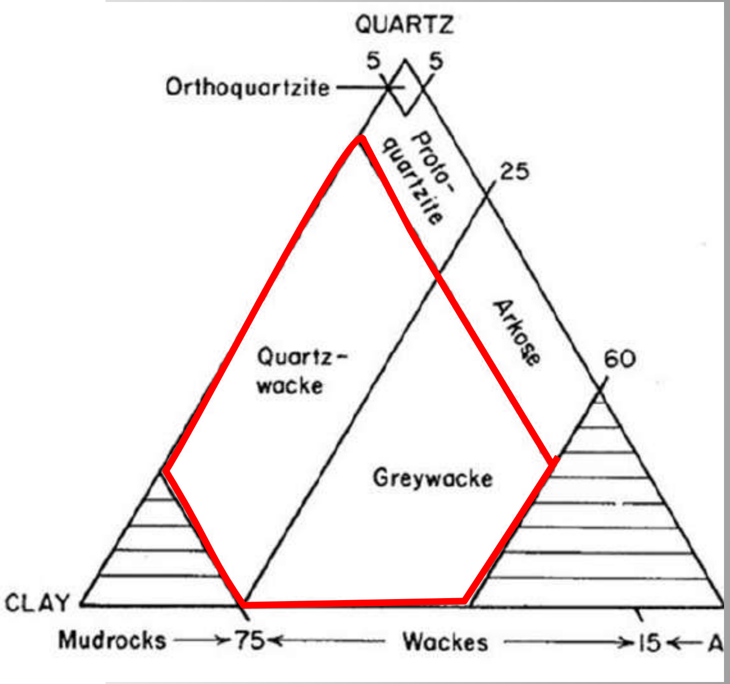
Depositional Environments of Arkoses

- Though probably the bulk of arkoses occur in ***fluvial environments,*** they are also found elsewhere.
- Arkoses mixed with ***coralgal debris*** **occur on modern beaches of the fault-bounded Red Sea.**


WACKES

Characteristic Features of Wackes

- The wackes are **texturally** ***immature sands with more than 15 % matrix.***
- **Chemically mature wackes,** with less than 25 % feldspar, ***are termed "quartz-wackes".***
- **Chemically immature wackes** with more than 25 % feldspar, ***are "greywackes".***
- The name ***"greywacke"*** comes from the German "grauewacke," which **was applied to the Paleozoic sandstones of the Harz Mountain.**

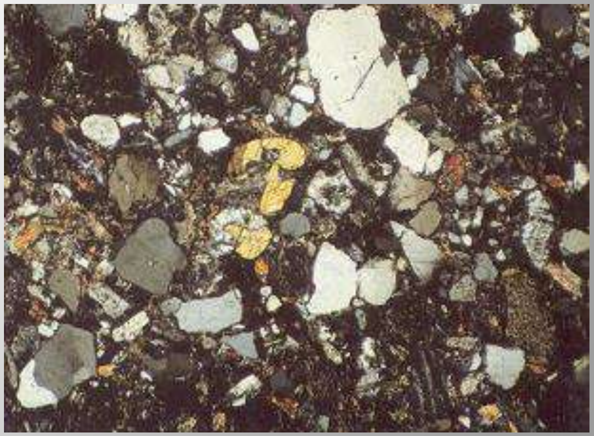


Characteristic Features of Wackes

- The **greywackes** are hard, dark gray-green rocks that break with a hackly fracture.
- ***Greywackes*** are very poorly sorted with particles ranging from ***very coarse sand grains down into clay-grade matrix.***
- They have been described as ***microconglomerates.***
- Grains are commonly ***angular*** and of ***poor sphericity.***

Mineralogical composition of Wackes

- ***Quartz*** is the most abundant detrital mineral.
- ***Feldspar*** is present, but so also are mafic grains such as ***horneblende*** & occasionally, ***pyroxenes.***
- Some of the larger grains are ***lithic rock fragments.***
- These may have been derived from volcanics or older metasediments such as quartzite or slate.



Mineralogical composition of Wackes

- ***Micas*** are abundant and include both ***muscovite & biotite***, as well as microcrystalline diagenetic ***chlorite & sericite.***
- A diverse suite of ***unstable heavy minerals*** is also typical.
- All of the detrital grains are set in the **abundant matrix**.

- This is a microcrystalline paste of clay minerals, chlorite, sericite, quartz, carbonate (often siderite), pyrite, and occasionally carbonaceous matter.

Mineralogical composition of Wackes

- The **quartz-wackes** differ from the **typical greywackes** in that they lack the diverse suite of unstable detrital minerals.
- In hand specimen **quartz-wackes** and **greywackes** are hard to distinguish.
- The poor sorting of these sandstones presupposes that the matrix may be largely syndepositional.

Origin of Wackes

- The typical wackes are largely Pre-Cambrian and Paleozoic in age. This suggests that time, ***deep burial***, and/or ***high geothermal gradients*** are needed to generate greywackes.
- The greywackes are commonly found in pre-Mesozoic flysch facies. These typically occur in ***subductive troughs.***
- From petrology and regional setting, it is noted that **greywackes are often derived from the rising island arcs of volcanic origin.** Hence the unstable suite of mafic minerals and the relatively high percentage of iron and magnesia in greywackes.

Origin of Wackes

- **Quartz-wackes** are more usually ***derived from preexisting sediments.*** Sands contribute the quartz, shales produce the clay, and the lithic fraction comes from the indurated equivalents of both.
- **Continental quartz-wackes** are often **red-brown in color** due to impregnation of the clay matrix by red ferric oxide.
- **With increasing transportation,** the quartz-wackes lose some of their clay content and assume a rock type often termed ***subgreywacke.***
- **This is found in both fluvial and deltaic deposits.**

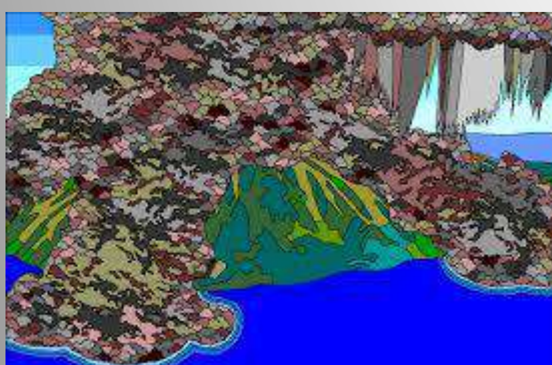
RUDACEOUS ROCKS

موضوع يكلف به مجموعة من الطلاب بالبحث فى مكتبة الكلية وشبكة المعلومات الدولية (الإنترنت) ثم عرضه ومناقشته أثناء المحاضرة



VOLCANICLASTIC ROCKS

(PYROCLASTIC ROCKS)



Volcaniclastic sediments

Volcaniclastic sediments are classified into two types according to mode of formation :

1. ***Erosional volcaniclastic sediments:*** *are produced by normal subaerial or subaqueous processes acting on eruptive rocks.*
2. ***Pyroclastic sediments:*** *ejected into atmosphere during volcanic eruptions.*

➢ *Pyroclasts include:*

- ***Bombs*** *that fall close to the vent (larger than 64 mm in diameter).*
- ***Sands*** *which fall around the vent for a distance of kilometers,*
- ***Dust*** *which may carried into the upper atmosphere & transported around the world.*

VOLCANICLASTIC ROCKS

- ***Volcaniclastic sediments can be classified into three groups according to their particle size:***

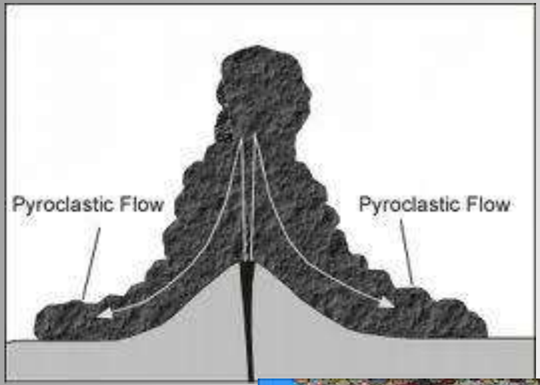
1. ***Agglomerates:*** *are the counterpart to conglomerates.*
2. ***Sand-grade volcaniclastic sediments.***
3. ***Fine-grained volcanic ash.***

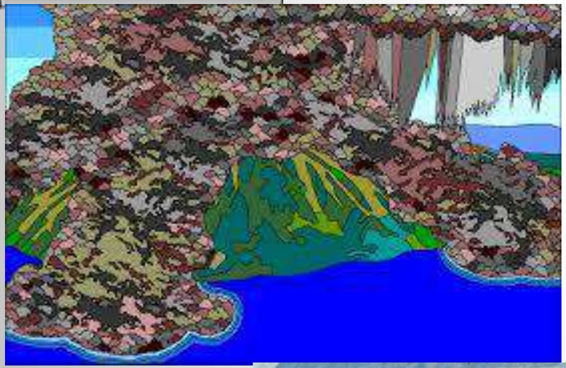
Agglomerates

- ***Agglomerates:*** *are the counterpart to conglomerates.*



Agglomerates





- ***Agglomerates*** are formed by explosive eruptions & by scree movement of volcanic detritus within a caldera & on the flanks of volcanoes.

Sand-grade Volcaniclastics

- ***Volcaniclastic sands** are generally referred to as **"tuffs" or "ashes".***
- ***They may be subaerial or subaqueous.***
- ***Volcaniclastic sands** are composed of crystals, glass & rock fragments.*
- ***The crystals:** are of minerals associated with the eruption, such as olivine & quartz.*
- ***Glass:** occurs as globules & angular irregularly shaped shards.*
- ***Rock fragments**: are composite grains of volcanic minerals and glass.*

Sand-grade Volcaniclastics

- ***Volcaniclastic sands*** *are generally poorly sorted.*
- ***Eolian volcaniclastic sands*** *are an exception to this rule.*



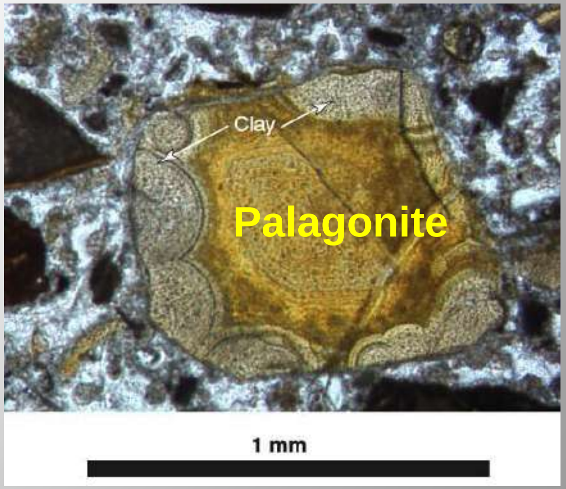
Sand-grade Volcaniclastics

- *Volcaniclastic sands may have good primary porosity & permeability, especially if deposited on beaches or dunes.*
- *They lose porosity on burial very quickly, because of their unstable mineralogy.*
- *During shallow burial they undergo hydration & carbonation leading to the formation of authigenic carbonate, clay, laumontite & other zeolites.*
- *Further burial results in dehydration of clays, albitization of feldspars & development of additional zeolites.*

VOLCANIC ASH

VOLCANIC ASH

- Fine-grained volcanic ash tends to undergo intensive post-depositional alteration giving rise to the ***bentonites.***
- ***Palagonite:*** *is a mineraloid produced by the alteration of basalt glass.*
- Traces of volcanic ash are a common component of modern pelagic sediments.



Volcaniclastic rocks

- *Volcaniclastic rocks are generally poor quality aquifers or petroleum reservoirs.*
- *They are of interest in mineral exploration.*
- *They appear to be the primary source of some metalliferous deposits.*

AUTOCHTHONOUS SEDIMENTS

AUTOCHTHONOUS SEDIMENTS

(INTRODUCTION)

- The second great group of sedimentary rocks is variously referred to as the ***chemical group*** or ***autochthonous sediments group***.
- The chemical rocks are sometimes divided into

✓ **Organic group (e.g. Carbonate skeletal sands)** &

✓ **Inorganic group (evaporites)**.

Major Types of Chemical Rocks

Carbonates	Limestone & Dolomite (Dolostone)
Evaporites	Anhydrite/Gypsum Halite/Rock salt Potash salts, etc.
Siliceous rocks	Chert, Radiolarite, Novaculite
Carbonaceous rocks	Humic group - Coal series Sapropelitic group- Oil shales & Cannel coals
Sedimentary ironstones	Goethite, Hematite & chamosite
Phosphates	Collophane, Dahllite, Francolite & Fluorapatite.

AUTOCHTHONOUS SEDIMENTS
(INTRODUCTION)

- This group consists of rocks **that form within a depositional basin.**
- **Not all chemical sediments are syndepositional.**
- Diagenetic processes are important in the genesis of some evaporites, dolomites, cherts, ironstones, and phosphates.

AUTOCHTHONOUS SEDIMENTS

(Mode of formation)

1. **The carbonate rocks form by:**
   - ***organic processes,***
   - ***Direct inorganic precipitation*** **&**
   - ***Diagenesis.***
2. **Evaporites form by:**
   - ***Inorganic crystallization &***
   - ***Diagenesis.***
3. **The sedimentary ironstones also form as:**
   - ***Precipitates &***
   - ***Diagenesis.***

AUTOCHTHONOUS SEDIMENTS
(Mode of formation)

4. **Phosphates form largely during early diagenesis in sediment, beneath the sediment/water interface.**

5. **Coal is formed entirely by biochemical processes.**

6. **Hydrous silica (opal), occurs in Tertiary rocks, but appears to dehydrate on burial to silica.**

CARBONATE ROCKS

CARBONATES
(INTRODUCTION)

- Carbonates are important aquifers and hydrocarbon reservoirs ***because of the high porosity which they sometimes contain.***
- Carbonate rocks are ***intrabasinal in origin.***
- They are deposited at or close to their point of origin.
- Most carbonate rocks are ***organic in origin.***
- They are easily weathered and ***their weathering products are transported as solutes.***
- They contain a wide spectrum of particle sizes, ranging from whole shells to lime mud of diverse origin.

CARBONATES

(INTRODUCTION)

- Carbonate sediments are deposited with a high primary porosity.
- The carbonate minerals are ***chemically unstable.***
- The combination of high primary porosity and permeability, coupled with chemical instability, **is responsible for the complicated diagenesis of carbonate rocks.**

CARBONATE MINERALS

- ***Calcium carbonate (CaCO3)*** is the dominant constituent of modern carbonates and ancient limestones.
- It occurs as two minerals, **aragonite** and **calcite.**
- ***Aragonite*** crystallizes in the **orthorhombic crystal System,**
- **Calcite crystallizes in the rhombohedral class (Trigonal system).**

CARBONATE MINERALS

- ***Calcite is the more stable variety, while aragonite is unstable.***
- A distinction is made between **high- and low-magnesium calcite,** with the boundary being set at **10 mol%.**
- Ancient limestones are composed largely of ***low-magnesium calcite,*** while modern carbonate sediments are made mainly of ***aragonite & high-magnesian calcite.***
- **Skeletal aragonite & calcite** also contain minor amounts of **strontium, iron, and other trace elements.**

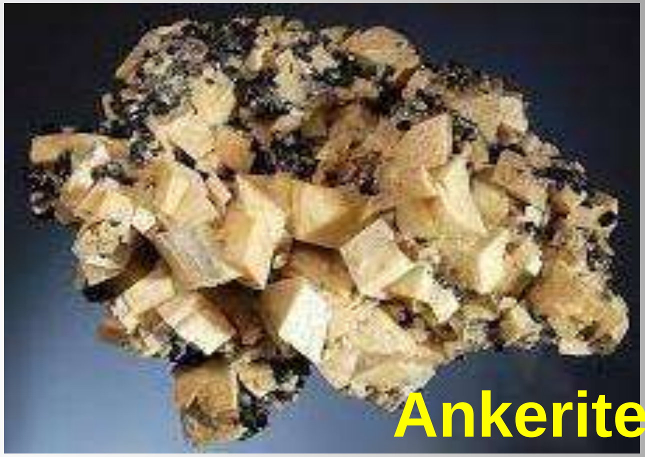
CARBONATE MINERALS

- ***Dolomite*** is another important carbonate mineral, giving its name also to the rock.
- ***Dolomite*** is calcium magnesium carbonate [CaMg(CO3)2].

- ***Dolomite*** does not occur as a biogenic skeletal mineral.
- ***Dolomite*** is generally found either ***crystalline***, as an obvious secondary replacement of other carbonates, **or rarely** as a primary or penecontemporaneous replacement mineral in cryptocrystalline form.

CARBONATE MINERALS

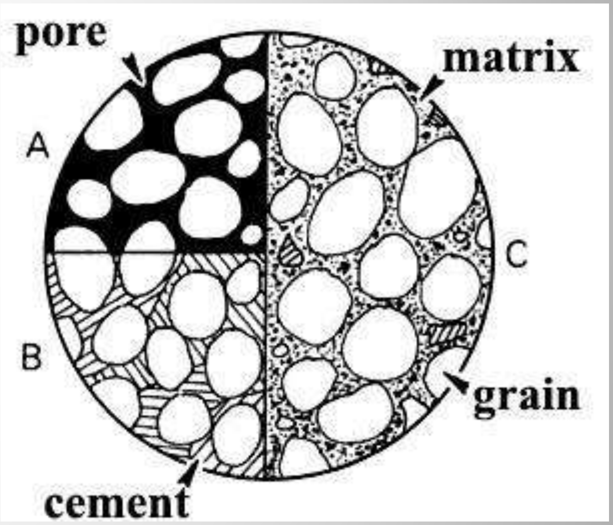
- ***Isomorphous substitution*** of some magnesium for iron is found in the mineral termed ***ferroan dolomite*** ***or*** ***ankerite*** ***[Ca(Mg,Fe)(CO3)2]***
- ***Siderite (FeCO3)*** is one of the rarer carbonate minerals.
- ***It occurs,*** as a primary precipitate, **in ooliths.**



MAIN COMPONENTS OF CARBONATE ROCKS

- **Carbonate rocks have four main components: *grains, matrix, cement, & pores.***

- The grains of carbonate rocks, commonly ***mono-minerallic***, are texturally diverse and polygenetic.



MAIN COMPONENTS OF CARBONATE ROCKS

Main Components of Carbonate Rock

I. Grains	(a) Detrital grains	Lithoclasts; Intraclasts
	(b) Skeletal grains	
	(c) Peloids (including fecal pellets)	
	(d) Lumps	Composite grains; Algal lumps
	(e) Coated grains	Ooliths; Pisoliths; Algally encrusted grains
II. Matrix	Micrite; Clay	
III. Cement	Sparite	
IV. Pores		

GRAINS

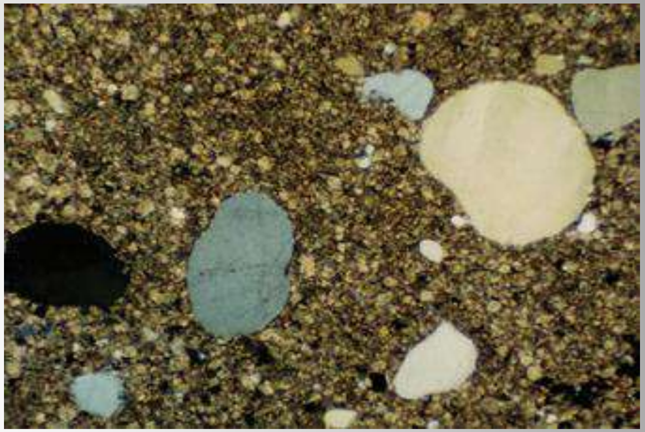
- ***Grains*** are the particles that support the framework of a sediment.
- They are generally of ***sand grade or larger.***
- **carbonate grains** are of many types as listed in the following table:

GRAINS *(LITHOCLASTS)*

The detrital grains are of two types,
Lithoclasts & intraclasts.

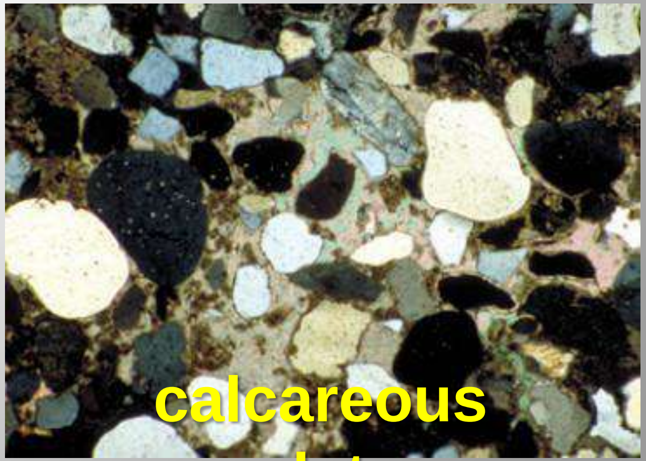
1) ***Lithoclasts (Rock fragments)***:

These are grains of ***non-carbonate material*** which originated **outside** the depositional basin.



Well-rounded detrital quartz sand grains are scattered throughout dolomitized carbonate mudstone.

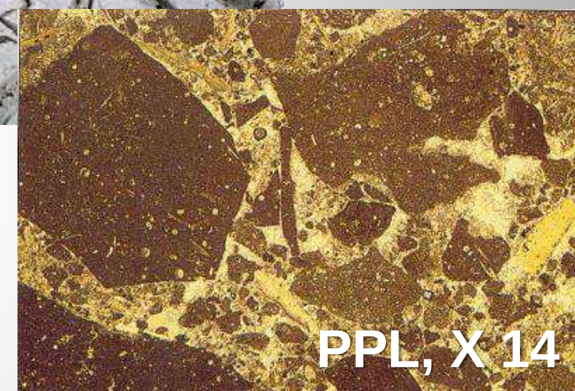
- **Quartz grains** are a typical example of lithoclasts and, as they increase in abundance, **limestones grade into *sandy limestones* & thence to *calcareous sandstones*.**



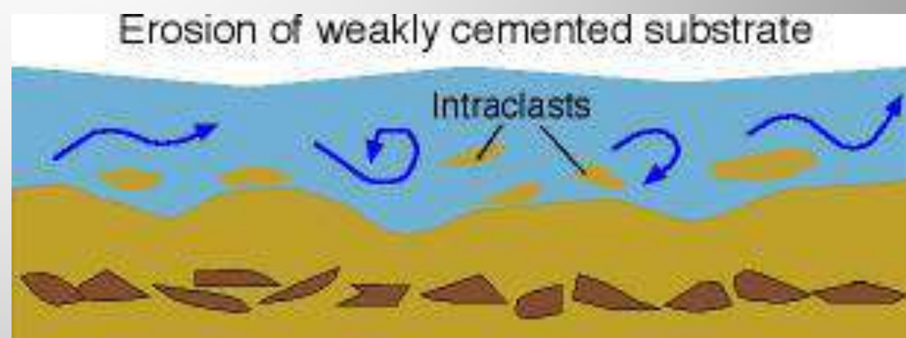
GRAINS

(INTRACLASTS)

2) **Intraclasts:** These are fragments of reworked carbonate rock which originated within the depositional basin.



Early cementation followed by penecontemporaneous erosion **is responsible for the generation of intraclasts.**

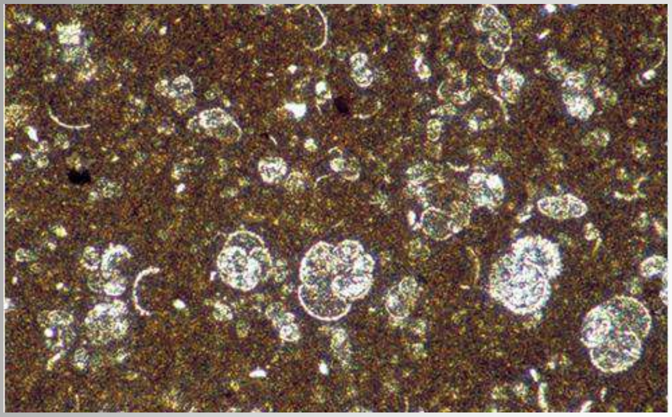


GRAINS

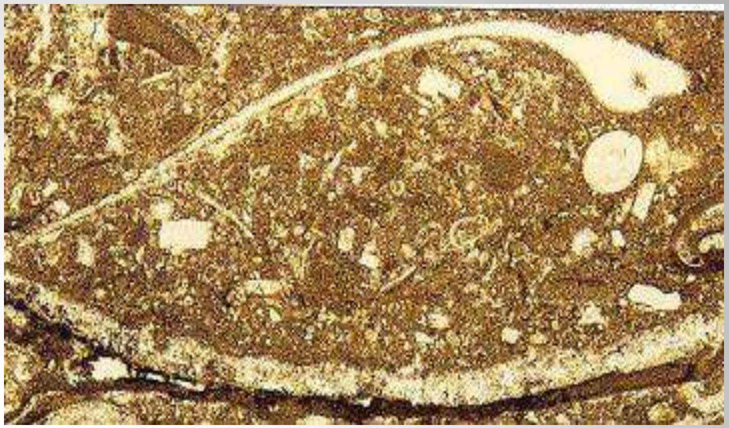
(BIOCLASTS)

- ***Skeletal detritus*** are the most important of all grain types.
- **They are termed *bioclasts*.**
- They are composed of ***aragonite or calcite*** with varying amounts of trace elements.
- The crystal habit of skeletal matter is varied, ranging from ***acicular aragonite crystals of lamellibranch shells to single calcite crystals of echinoid plates.***
- The size of skeletal particles is very variable, ranging from the largest shell to individual microscopic crystals.

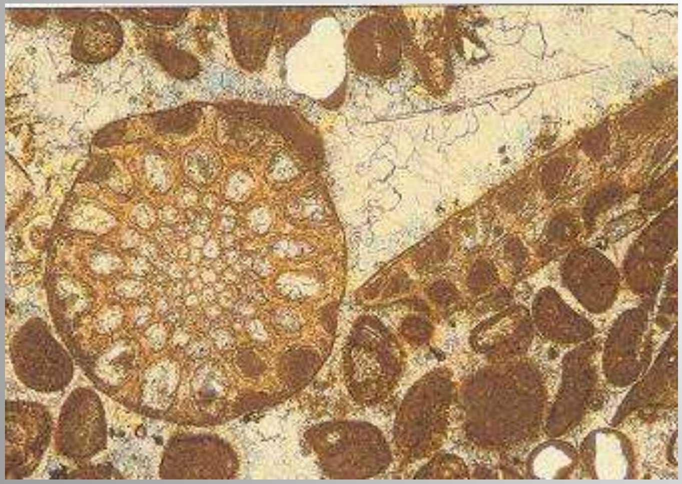
Skeletal Grains in Carbonate Rocks



Planktonic Foraminifera, PPL



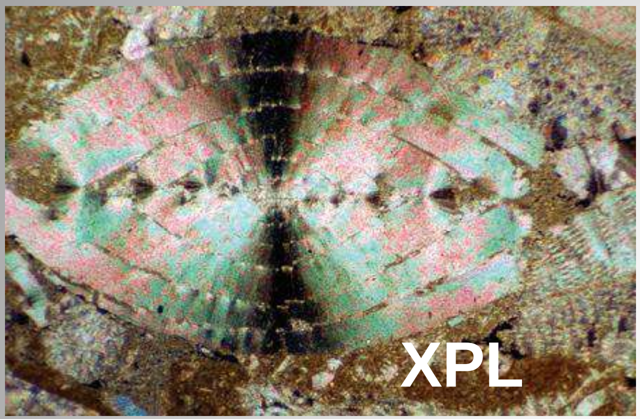
Bivalve, PPL, X25



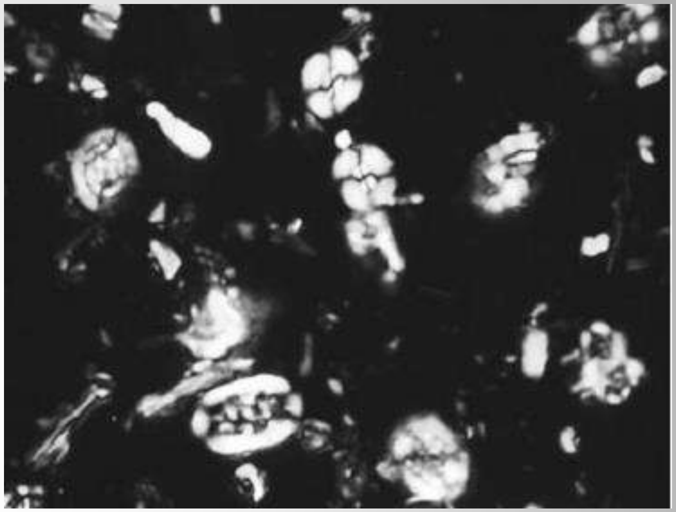
Bryozoan colony, PPL, X36

Echinoid spine, PPL, X50

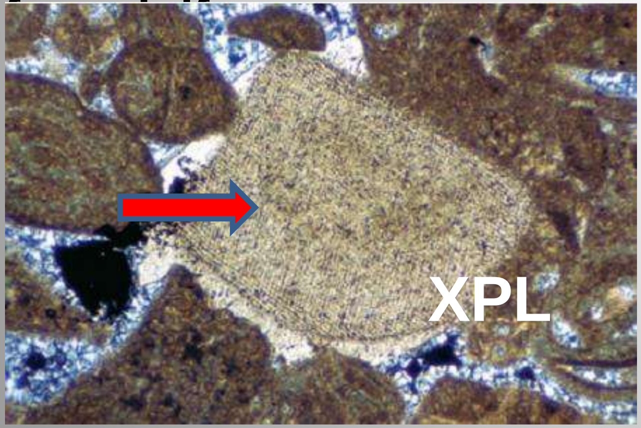
Skeletal Grains in Carbonate Rocks



A longitudinal axial section of
a single nummulite



A high-magnification view shows the distinctive oval outlines of minute coccoliths.



An echinoderm fragment with characteristic single-crystal and uniform “honeycomb” microtexture (small pores filled with micrite).

Table: Shows the mineralogy of the major groups of carbonate-secreting organisms,after Scholle (1978).

Mineralogy of Skeletal Organisms

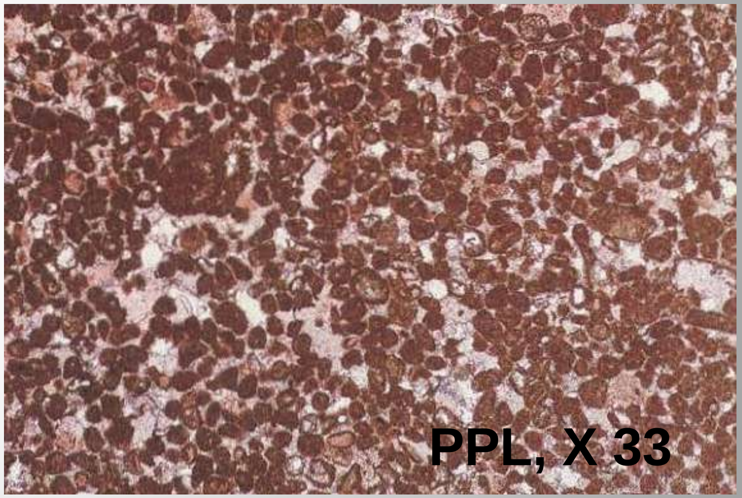
Taxon	Aragonite	Calcite %Mg (0 5 10 15 20 30 35)	Both Aragonite & Calcite
Calcareous Algae:			
Red	R	●——●	
Green	●		
Coccoliths		●	
Foraminifera:			
Benthic	R	●——●- - -●	
Planktonic		●–●	
Sponges:	R	●–●	
Coelenterates:			
Stromatoporoids	●	● ?	
Milleporoids	●		
Rugose		●?	
Tabulate		●?	
Scleractinian	●		
Alcyonarian	R	●—●	
Bryozoans:	R	●—●	R
Brachiopods:		●–●	
Molluscs:			
Chitons	●		
Bivalves	●	●–●	●
Gastropods	●	●–●	●
Pteropods	●		
Cephalopods	●		
Belemnoids & Aptychi		●	
Serpulids:	●	●—●	●
Arthropods:			
Decapods		●–●	
Ostracodes		●–●	
Barnacles		●–●	
Trilobites		●	
Echinoderms:		●——●	

● Common R Rare

GRAINS

(PELOIDS)

- **Peloids are a third major grain type.**
- These were first defined as structure-less cryptocrystalline carbonate grains of some 20-60/µm in diameter (McKee and Gutschick, 1969).
- **Peloids form in many different ways:**
  - ➢ ***Pellets*** are peloids of fecal origin, excreted by marine invertebrates.

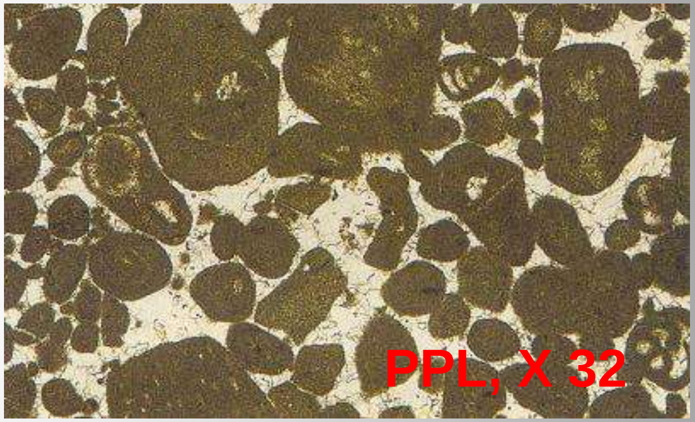


PPL, X 33

GRAINS
(PELOIDS)

- ***Pelletoids*** are peloids formed by the micritization of skeletal grains through the action of endolithic algae.

- ***Peloidal deposits*** are especially characteristic of lagoons and other sheltered shallow inner-shelf environments.



NOMENCLATURE AND CLASSIFICATION OF CARBONATES

NOMENCLATURE AND CLASSIFICATION OF CARBONATES

- So many parameters can be used to define carbonate rock types.
- These include ***chemical composition, grain size, particle type, type and amount of porosity, degree of crystallinity, quantity of mud,*** *and so on*.
- **Folk (1962) & Dunham (1962) proposed a series of terms and groupings which are widely used today.**

Folk's CLASSIFICATION (1962)

- Folk's classification is applicable to thin-section analysis.
- It is not an easy classification to use in the field.
- Folk (1962) divided limestones ***into four main classes as follows:***
- ***The first two classes*** include rocks composed largely of carbonate grains (allochems); these are termed the "***allochemical limestones***".
  - One class is dominated by ***sparite cement.***
  - The other is dominated by ***micrite matrix.***

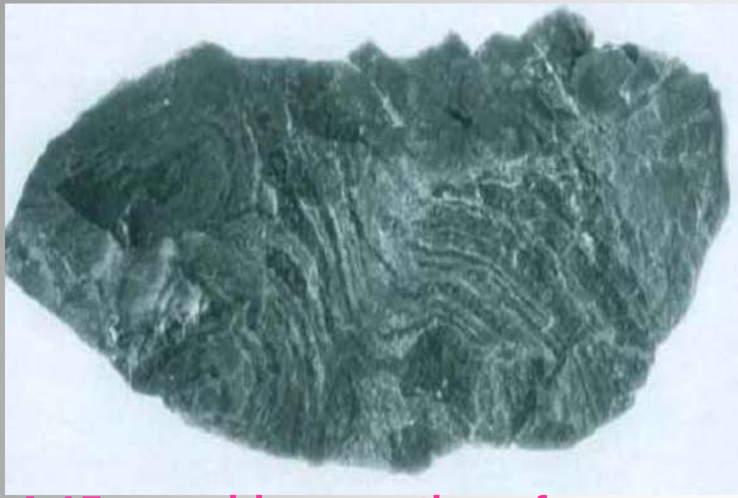
Folk's CLASSIFICATION (1962)

- **The third class** is for rocks ***lacking grains***, termed the ***"orthochemical limestones"***.
  - This group includes ***micrite lime mud carbonates***.

- **The fourth group** is for rocks made of in-place (in situ) skeletal fabrics.

This group, the autochthonous reef rocks, includes *"coral biolithite"* & *"algal stromatolites"*.

Folk's CLASSIFICATION (1962)

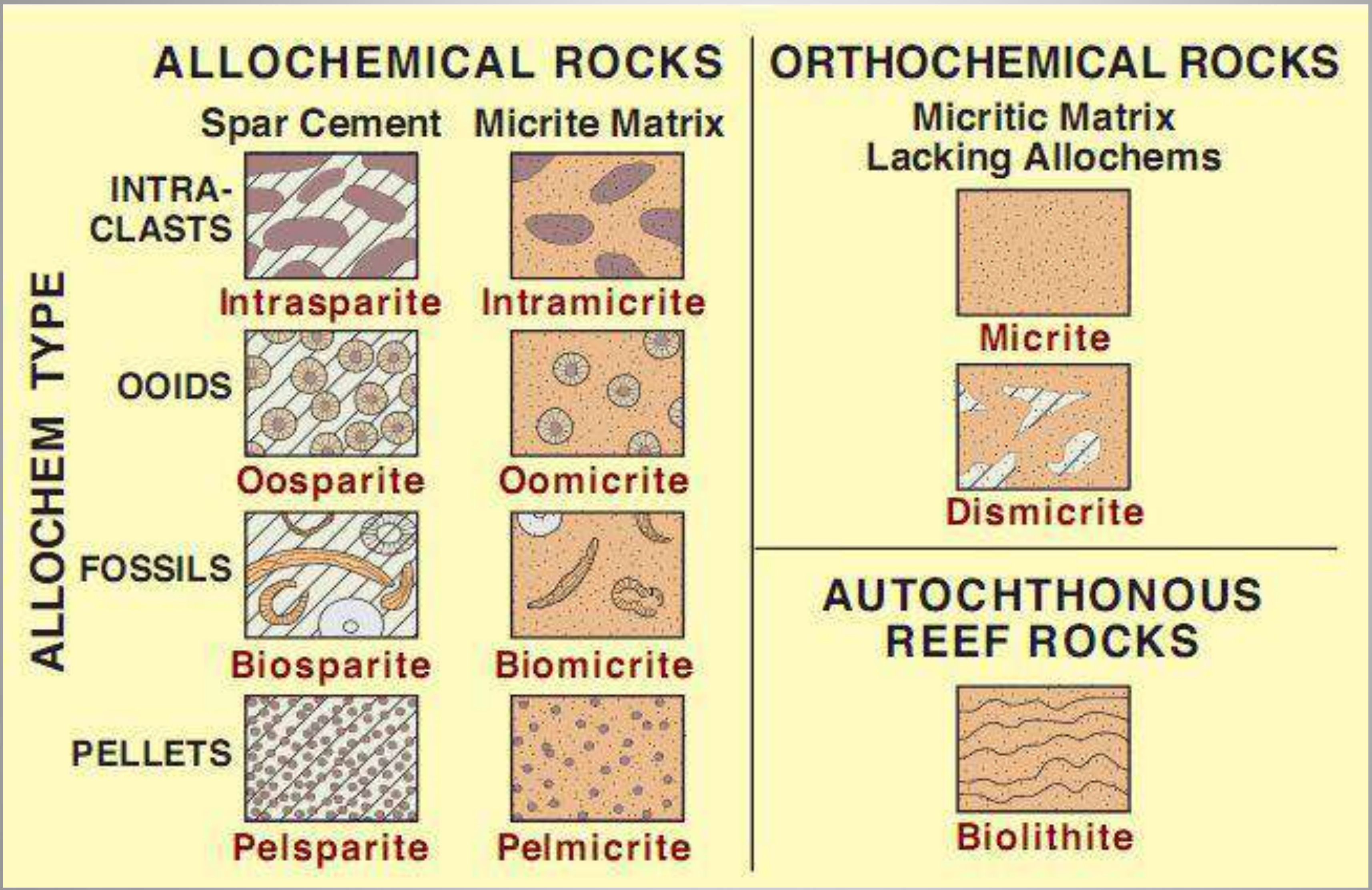


A 15-cm-wide v. section of laminated algal stromatolite

Polished hand specimen of stromatolite Magnification, x1.8

Stained thin section of stromatolite, PPL, x 9

Folk's CLASSIFICATION (1962)



Folk's CLASSIFICATION (1962)

- Folk proposed a ***"bipartite nomenclature"*** for the allochemical rocks (the first two classes).
  - The first (prefix) defined the ***grain type*** &
  - The second (suffix) denoted whether ***sparite* or *micrite*** predominated.

For example: "oosparite" ??

& "pelmicrite" ??

Folk’s CLASSIFICATION (1962)

- ***Where more than one allochem type was present***, two should be used, with ***the major one first,*** as in ***"bioöosparite “.***

- When both ***micrite & sparite*** are present, they could both be compounded with **the dominant constituent first**: as in

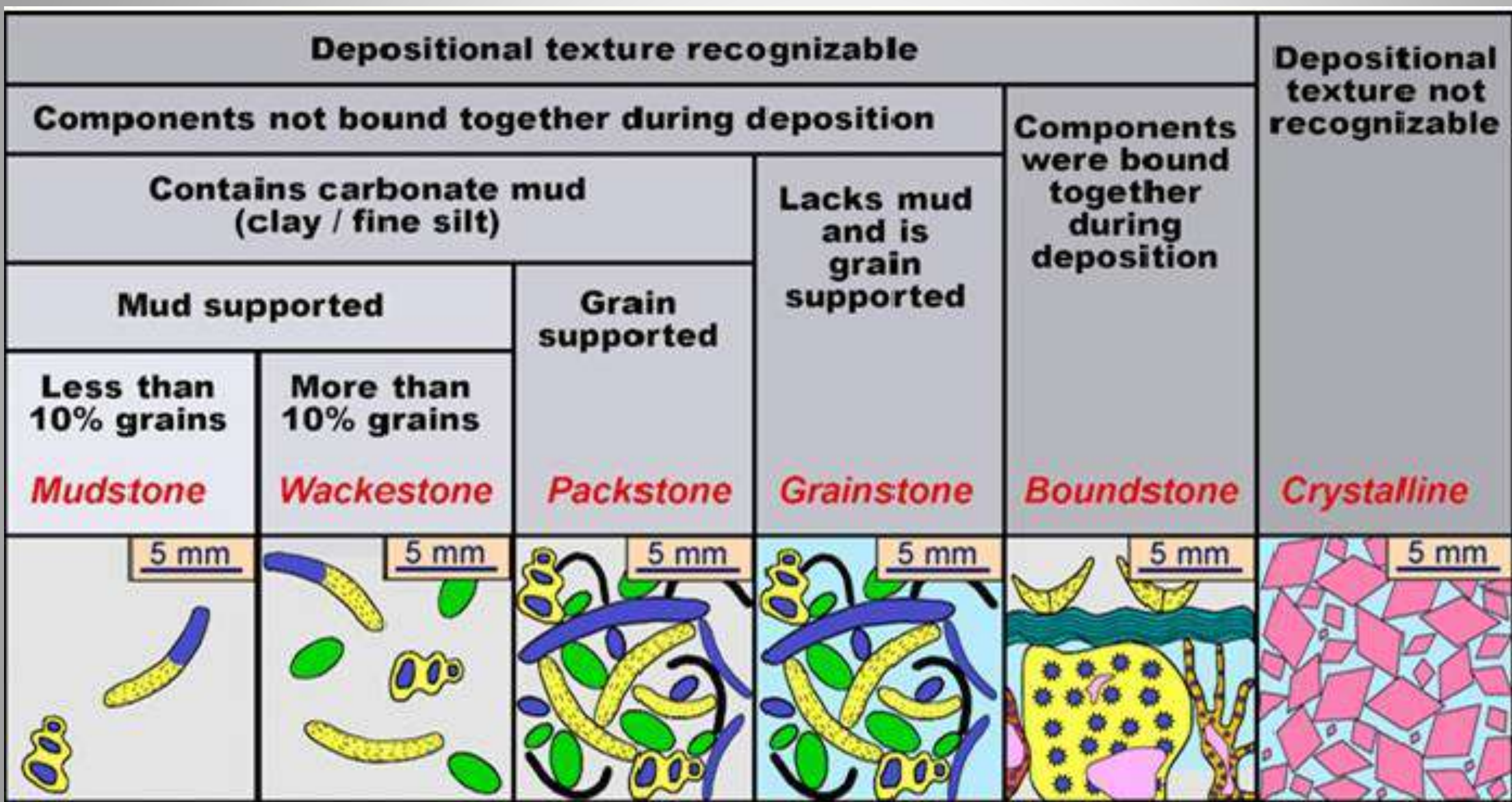
DUNHAM's CLASSIFICATION (1962)

- ***Dunham (1962)*** focused upon depositional limestone textures rather than upon the identity of specific kinds of carbonate grains.

- He placed, like Folk the ***in-place reef rocks*** in a separate class, termed them ***boundstones.***

- Dunham divided the rest of the carbonates into ***four groups*** according to whether their

DUNHAM's CLASSIFICATION
Of carbonates (1962)



DUNHAM's CLASSIFICATION
Of carbonates (1962)

- ***Grainstones*** are grain-supported sands with no micrite matrix.
- ***Packstones*** are grain-supported sands with minor amounts of matrix.
- ***Wackestones*** are mud-supported rocks with dispersed number of grains.
- ***Mudstones*** are carbonate muds.

DUNHAM's CLASSIFICATION Of carbonates (1962)

- The nomenclature is simple & identification can be made with only a hand lens.

- Furthermore, this nomenclature, by drawing attention to ***fabric and matrix content***, gives an index of the depositional energy.

  - ***Thus the mud-supported limestones*** may indicate deposition in a low-energy environment.

  - ***By contrast, the matrix-free grain-supported rocks*** suggest deposition in high-energy environment in which no mud could come to rest.

DUNHAM's CLASSIFICATION Of carbonates (1962)

- The textural maturity of carbonate sediments may be considered is analogous to the maturity of terrigenous sands.

  - ***A mature carbonate sediment*** is one that is composed exclusively of one grain type.
  - ***The different carbonate grains*** result from different processes operating in different environments.
  - Thus a carbonate rock composed of a ***single grain type*** indicates genesis from a ***single process.***
  - Carbonate rock composed of ***two grain types*** reflects genesis from ***two processes***, and so forth (Smosna, 1987).

DUNHAM's CLASSIFICATION
Of carbonates (1962)

- The grain size, sorting, and matrix content can be used with reservations ***as indicators of hydro-dynamic environment in carbonate rocks.***

- **The origin of micrite is polygenetic.**
  - ✓ Micrite may develop by ***bioturbation, algal micritization, cementation* & *by infiltration due to high permeability.***

FOLK's & DUNHAM's CLASSIFICATION
Of carbonates

- Finally, the classifications and nomenclature of carbonates proposed by ***Folk and Dunham*** are extremely useful and, used in conjunction, encompass most varieties of limestones with flexibility and finesse.

Nomenclature and classification of limestones according to schemes of Dunham (1962), and Folk (1962).

	GRAIN TYPES			
MUDSTONE < 10% grains	Lime mud, micrite, calcilutite, chalk			
	PELLETS	SHELL DEBRIS	OOLITHS	INTRACLASTS
WACKESTONE > 10% grains, mud supported	 Pelmicrite	Biomicrite	Oomicrite	Intramicrite
PACKSTONE > 5% mud, grain supported	Pelmicsparite	 Biomicsparite	Oomicsparite	Intramicsparite
GRAINSTONE < 5% mud	Pelsparite	Biosparite	 Oosparite	Intrasparite
BOUNDSTONE original components bound together	Reef rock, biolithite			

CLASSIFICATION Of carbonates

- Sadly neither of both schemes embrace the most important aspect of carbonates for many geologists, ***namely, their reservoir characteristics, in terms of porosity and permeability.***

- ***Archie (1952)*** classified carbonate reservoirs **based on the concept that *pore-size distribution controls permeability and petroleum saturation,***
and that *pore-size distribution is related to the fabric of the rock.*

CLASSIFICATION Of carbonates (Lucia, 1995 & 1999)

- ***Lucia (1995 & 1999)*** developed scheme classifies carbonates (limestones & dolomites) **into three petrophysical classes** ***according to their pore-type:***

Class (1): Interparticle (intergranular) vugs,

Class (2): Separated (isolated) vugs,

Class (3): Communicating (connected) vugs.

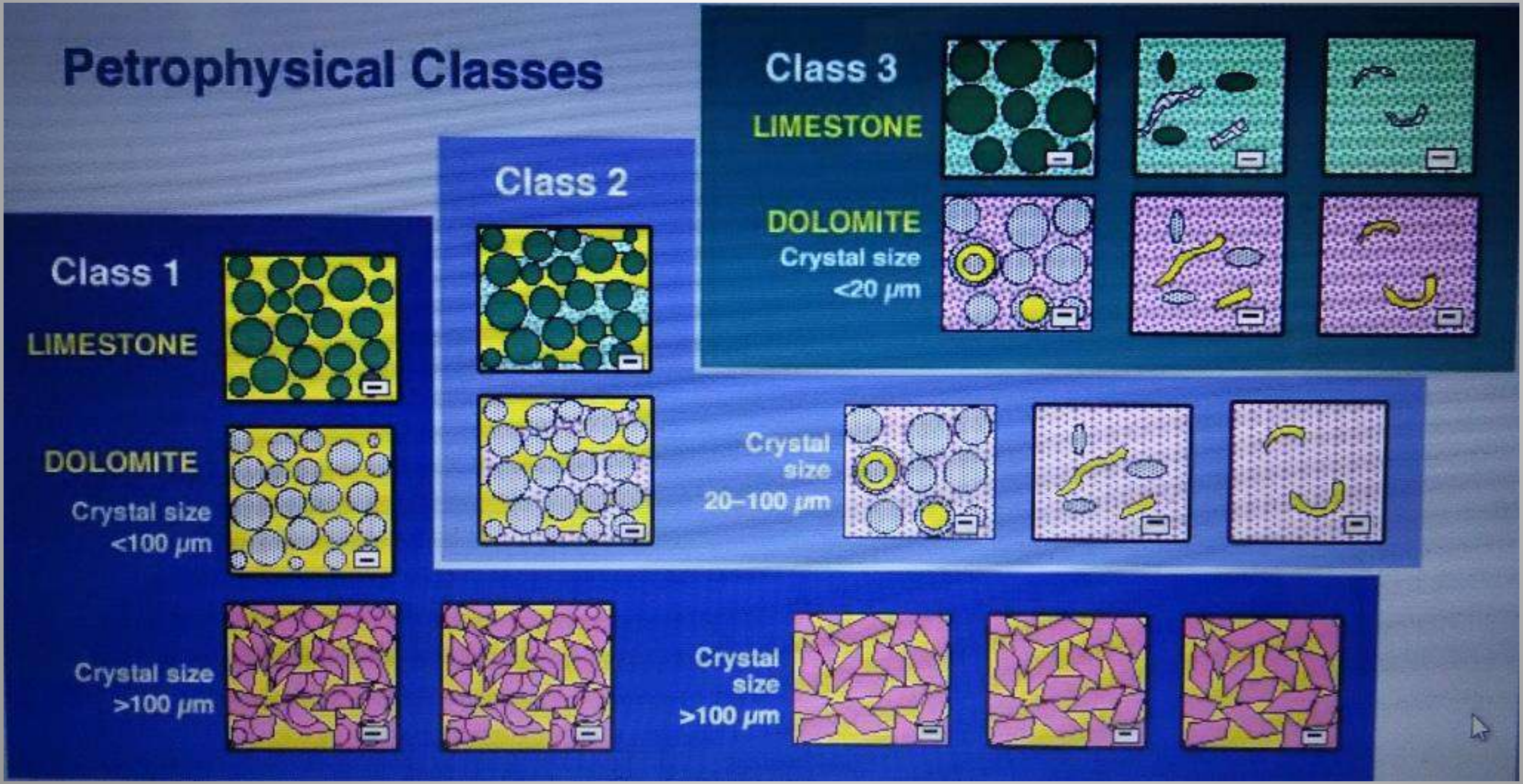
- These three petrophysical classes may then be subdivided acording to Dunham's terminology of ***grainstone, packstone, wackestone & mudstone.***

- **In general Lucia's classification follows the Dunham carbonate classification, except that the packstone fabric group has been divided into *grain-dominated and mud-dominated classes.***

CLASSIFICATION Of carbonates (Lucia, 1995 & 1999)

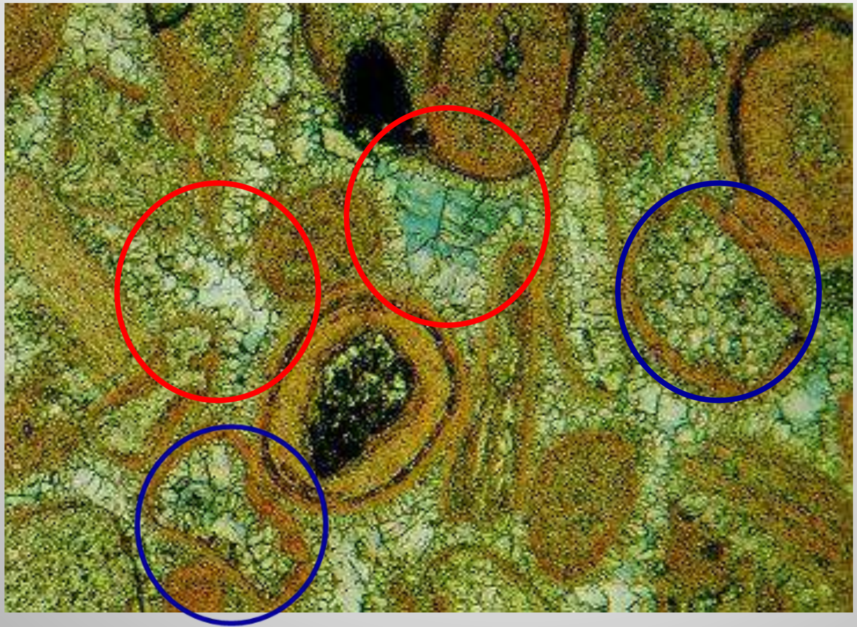
Grain dominated fabric
Grainstone   Packstone

Mud dominated fabric
Packstone/Wackstone/Mudstone



DIAGENESIS OF CARBONATES

- ***Crystallization:*** means the infilling of ***primary inter- and intraparticle porosity*** by the drusy growth of sparite out from the pore walls.
  - This naturally results in a **decrease in porosity.**



Stained thin section, PPL, X 122

DIAGENESIS OF CARBONATES

- ***Neomorphism***: is the term applied to describe the recrystallization or replacement of a mineral (Folk,1965).

➢ Neomorphism can lead to **both increasing**, **or unaltered porosities.**

1) Recrystallization defined as ***neomorphism*** in which the mineralogy is unchanged, does not significantly alter the amount or type of

DIAGENESIS OF CARBONATES

2) *polymorphic transformations,* in which one mineral replaces another, **can have large effects on rock porosity.**

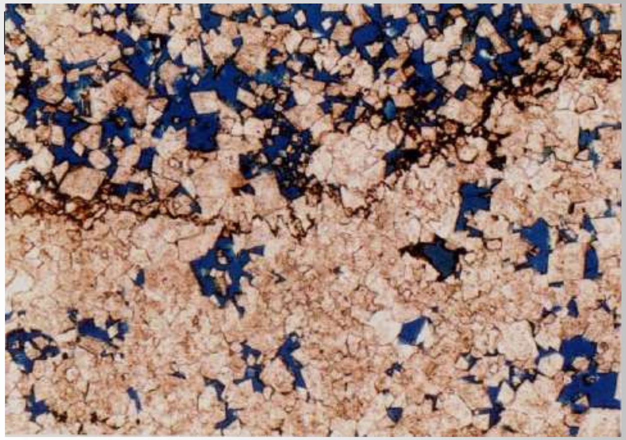
i. One of the earliest diagenetic changes is the *transformation of aragonite to calcite.*

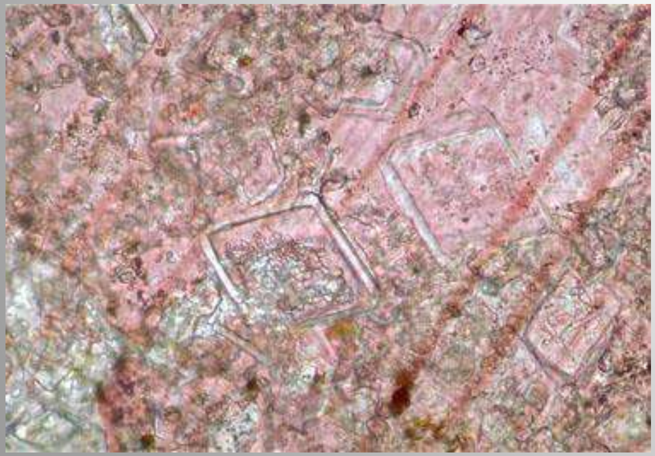
- This results in ***an increase*** in total rock volume ***of 8%,***
- ***i.e. decrease in rock porosity of 8%.***

ii. The replacement of ***calcite by dolomite (dolomitization)*** can cause an overall ***contraction of the rock by as much as 13%*** (Chilingar and Terry, 1964) , ***i.e. increase in rock porosity of 13%.***

DIAGENESIS OF CARBONATES

- ***The intercrystalline porosity*** caused this replacement that makes secondary dolomites such attractive reservoir rocks.

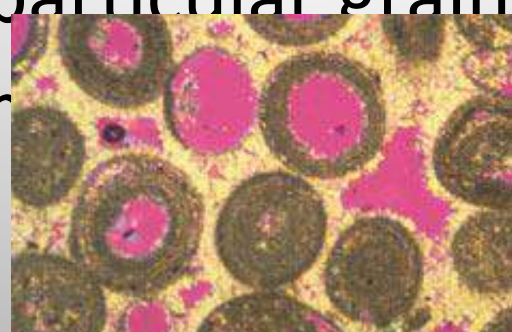


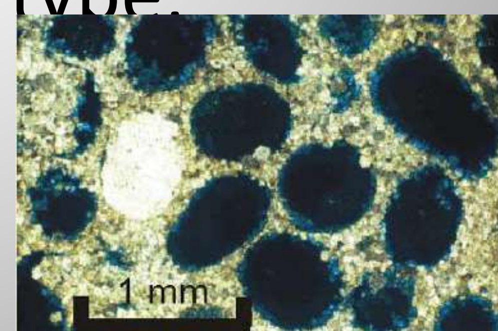


- ***Conversely,*** a decrease in porosity is caused by the ***transformation of dolomite to calcite***; ***(dedolomitization or calcitization)*** as it is called (Shearman et al., 1961).

DIAGENESIS OF CARBONATES

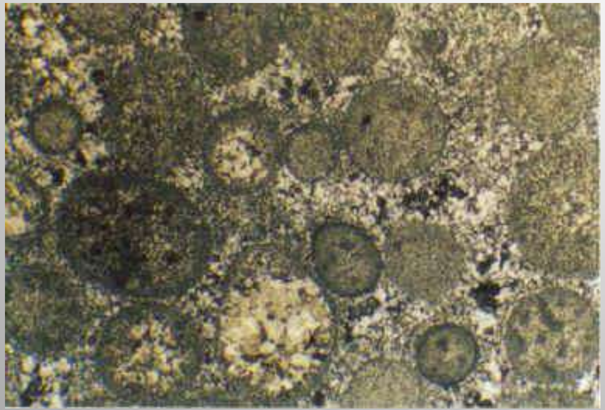
- ***Leaching:*** is an important process giving rise to secondary porosity.
- ***Solution porosity:*** may be due to the selective solution of matrix, cement, or specific grain types.
- ***Vuggy porosity:*** results from the solution of pores whose boundaries cross-cut the fabric.
- ***Moldic porosity:*** describes the selective solution of one particular grain type.
- for examp r porosity.





DIAGENESIS OF CARBONATES

- ***Silicification:*** is another characteristic diagenetic process in carbonate rocks.
- The silicification of lime muds is not of petrophysical significance.
- In calcarenites and reef rocks, silicification can be an important destroyer of primary porosity when it develops as a chalcedonic cement.




EVAPORITES

INTRODUCTION

- The evaporites form by the evaporation of salt-rich fluids.
- Evaporites can form in both **marine and nonmarine environments.**
- Owing to differences in the dissolved mineral composition of the feed waters, **different suites of minerals tend to form in the two environments.**
- The evaporites include some common minerals ***(Eight minerals as mention in the following table)***, but the total number of evaporite minerals ***is vast***.
- **Approximately 80 minerals in total** have been reported from evaporite deposits ***(Stewart, 1963)***.

COMMON EVAPORITE MINERALS

Some of the More Common Evaporite Minerals

Name	Composition	
Anhydrite	$CaSO_4$	Sulfates
Gypsum	$CaSO_4 \cdot 2H_2O$	
Polyhalite	$CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$	
Epsomite	$MgSO_4 \cdot nH_2O$	
Halite	$NaCl$	Chlorides
Sylvite	KCl	
Carnallite	$KMgCl_3 \cdot 6H_2O$	
Bischofite	$MgCl_2 \cdot 6H_2O$	

Major Evaporite Minerals (cited from Boggs, 2009)

Mineral	Formula	Mineral	Formula
Anhydrite	$CaSO_4$	Leonhardtite	$MgSO_4 \cdot 4H_2O$
Antarcticite	$CaCl_2 \cdot 6H_2O$	Leonite	$MgSO_4 \cdot K_2SO_4 \cdot 4H_2O$
Aphthitalite (glaserite)	$K_2SO_4 \cdot (Na,K)SO_4$	Loewite	$2MgSO_4 \cdot 2Na_2SO_4 \cdot 5H_2O$
Aragonite **	$CaCO_3$	Mg-calcite**	$(Mg_xCa_{1-x})CO_3$
Bassanite	$CaSO_4 \cdot 1/2H_2O$	Magnesite**	$MgCO_3$
Bischofite	$MgCl_2 \cdot 6H_2O$	Meyerhoffite	$Ca_2B_5O_{11} \cdot 7H_2O$
Bloedite (astrakanite)	$Na_2SO_4 \cdot MgSO_4 \cdot 4H_2O$	Mirabilite	$Na_2SO_4 \cdot 10H_2O$
Borax (tincal)	$Na_2B_4O_7 \cdot 10H_2O$	Nahcolite	$NaHCO_3$
Boracite	$Mg_3B_7O_{13} \cdot Cl$	Natron	$Na_2CO_3 \cdot 10H_2O$
Burkeite	$Na_2CO_3 \cdot 2Na_2SO_4$	Nitratite (soda nitre)	$NaNO_3$
Calcite**	$CaCO_3$	Nitre (salt petre)	KNO_3
Carnallite	$MgCl_2 \cdot KCl \cdot 6H_2O$	Pentahydrite	$MgSO_4 \cdot 5H_2O$
Colemanite	$Ca_2B_5O_{11} \cdot 5H_2O$	Pirssonite	$CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$
Darapskite	$NaSO_4 \cdot NaNO_3 \cdot H_2O$	Polyhalite	$2CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot H_2O$
Dolomite**	$Ca_{(1+x)}Mg_{(1-x)}(CO_3)_2$	Proberite	$NaCaB_5O_9 \cdot 5H_2O$
Epsomite	$MgSO_4 \cdot 7H_2O$	Priceite (pandermite)	$CaB_4O_{10} \cdot 7H_2O$
Ferronatrite	$3NaSO_4 \cdot Fe_2(SO_4)_3 \cdot 6H_2O$	Rinneite	$FeCl_2 \cdot NaCl \cdot 3KCl$
Gaylussite	$CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$	Sanderite	$MgSO_4 \cdot 2H_2O$
Glauberite	$CaSO_4 \cdot Na_2SO_4$	Schoenite (picromerite)	$MgSO_4 \cdot K_2SO_4 \cdot 6H_2O$
Gypsum	$CaSO_4 \cdot 2H_2O$	Shortite	$2CaCO_3 \cdot Na_2CO_3$
Halite	$NaCl$	Sylvite	KCl
Hanksite	$9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$	Syngenite	$CaSO_4 \cdot K_2SO_4 \cdot H_2O$
Hexahydrite	$MgSO_4 \cdot 6H_2O$	Tachyhydrite	$CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$
Howlite	$H_5Ca_2SiB_5O_{14}$	Thenardite	Na_2SO_4
Ikaite**	$CaCO_3 \cdot 6H_2O$	Thermonatrite	$NaCO_3 \cdot H_2O$
Inyoite	$Ca_2B_6O_{11} \cdot 13H_2O$	Tincalconite	$Na_2B_4O_7 \cdot 5H_2O$
Kainite	$4MgSO_4 \cdot 4KCl \cdot 11H_2O$	Trona	$NaHCO_3 \cdot Na_2CO_3 \cdot 2H_2O$
Kernite	$Na_2B_4O_7 \cdot 4H_2O$	Tychite	$2MgCO_3 \cdot 2NaCO_3 \cdot Na_2SO_4$
Kieserite	$MgSO_4 \cdot H_2O$	Ulexite	$NaCaB_5O_9 \cdot 5H_2O$
Langbeinite	$2MgSO_4 \cdot K_2SO_4$	Van'thoffite	$MgSO_4 \cdot 3Na_2SO_4$

GENESIS OF EVAPORITES

- **Previously,** it was widely accepted that evaporites formed largely by the ***precipitation or crystallization*** **of salts** ***at the sediment : water interface*** (e.g., Borchert and Muir, 1964).
- **It is now** largely accepted that the genesis of evaporites ***by diagenesis is the rule*** (Kirkland and Evans, 1973; Kendall, 1984; Sonnenfeld, 1984).

GENESIS OF EVAPORITES

- It appears most probable that evaporites form from saline-rich fluids **(brines)**.
- ***Brines*** may be generated by ***concentration of seawater, by evaporation or freezing, or as residual connate fluids in the subsurface.***
- **Secondary brines** can form where meteoric groundwater passes through and dissolves previously formed evaporites.
- **Normal ocean water contains 3.45 % by weight of *dissolved substances.***
- **99.9% of the dissolved material comprises *nine ions*.**
- ***These ions are: Sodium, Magnesium, Calcium, Potassium, Strontium, Chloride, Sulphate, Bicarbonate and Bromine.***

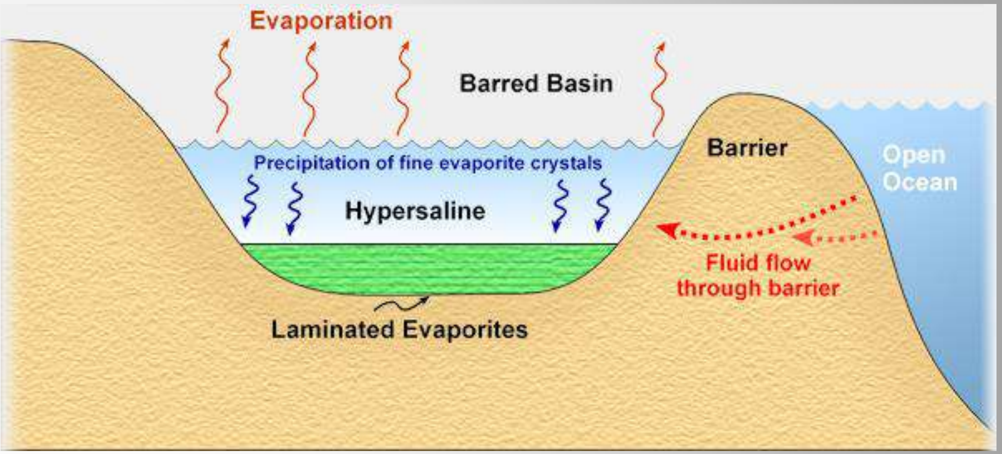
GENESIS OF EVAPORITES

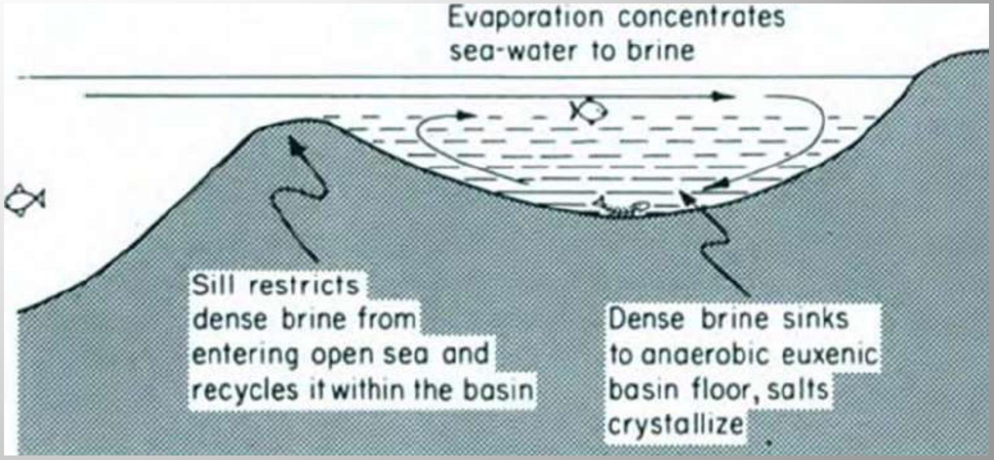
- Some of the earliest works on the genesis of evaporites was to study salts formed from the evaporation of seawater (Usiglio, 1849; Van't Hoff and Weigert, 1901).
- **These studies demonstrated two main facts; that**

1. Inconceivable quantities of seawater were necessary to form observed volumes of evaporites in a closed system.
2. The observed percentages of salts in an evaporite assemblage differ somewhat from those produced by the evaporation of seawater.

GENESIS OF EVAPORITES

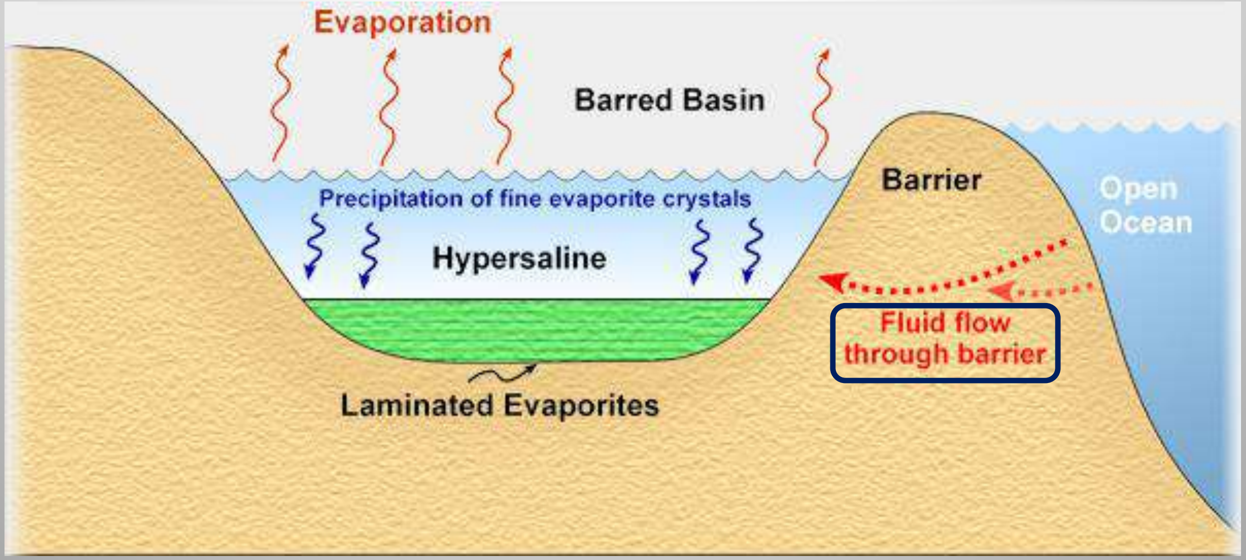
- The explanation that evaporite formation characteristically occur in basins that had restricted access to the sea (silled basin).





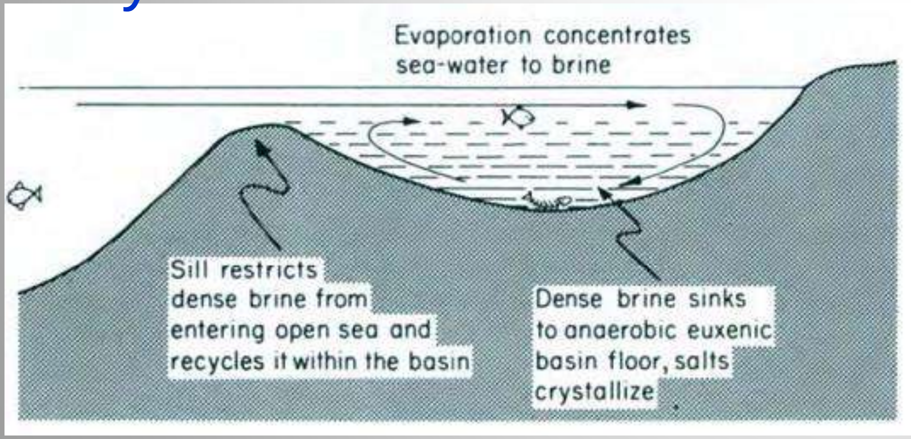
GENESIS OF EVAPORITES

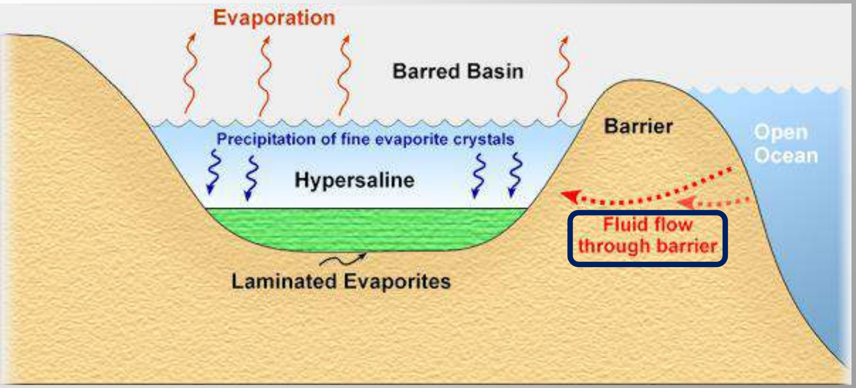
- In a restricted basin the seawater flow from the open ocean into the basin by underground seepage.
- Here excessive evaporation concentrates the seawater.
- The incipient brine sinks to the basin floor because of its higher density.



GENESIS OF EVAPORITES

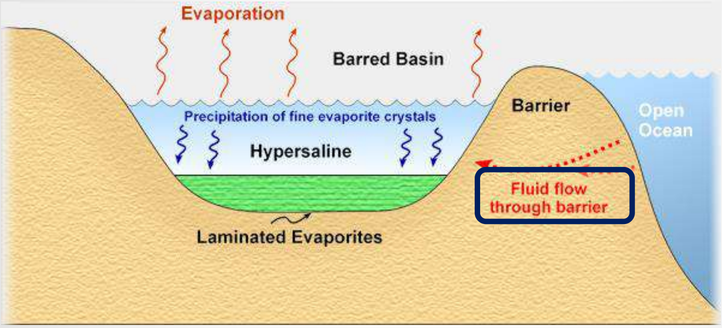
- The sill prevents drainage of the brine out to the open sea.
- Continuous recycling of the brine increases concentration to the point at which evaporites begin to crystallize on the basin floor.





GENESIS OF EVAPORITES

- This process would be aided by the fluctuating sea level, which allows repeated influxes of water over the sill,
- followed by a drop in water level so as to completely restrict the body of brine.



- This is the classic ***"evaporating dish mechanism"*** for evaporite genesis (Sloss, 1969).
- **Supporting evidence** for this mechanism includes the fact that evaporites tend to be zonally arranged within a basin, **with salts requiring higher salinity for their formation occurring toward the depocenter.**

GENESIS OF EVAPORITES

- Similarly, evaporite minerals tend to be cyclically arranged in the same motif (as shown below).
- This cyclicity is classically demonstrated in the ***Zechstein evaporites of the North Sea basin*** and also found in most other examples.

Economic Significance of Evaporites

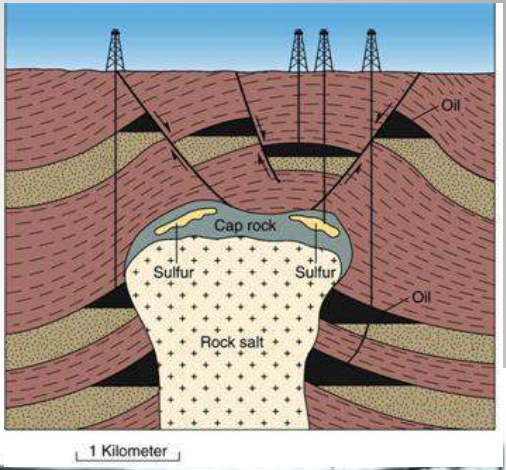
- ***Evaporite minerals are of great economic importance for three reasons,***
    1. They are an economic material in their own right.
    2. They are closely related to the genesis and entrapment of hydrocarbons, and
    3. There is a strong presumption that evaporite associated brines play an important role in the genesis of certain metallic ores (Melvin, 1991).

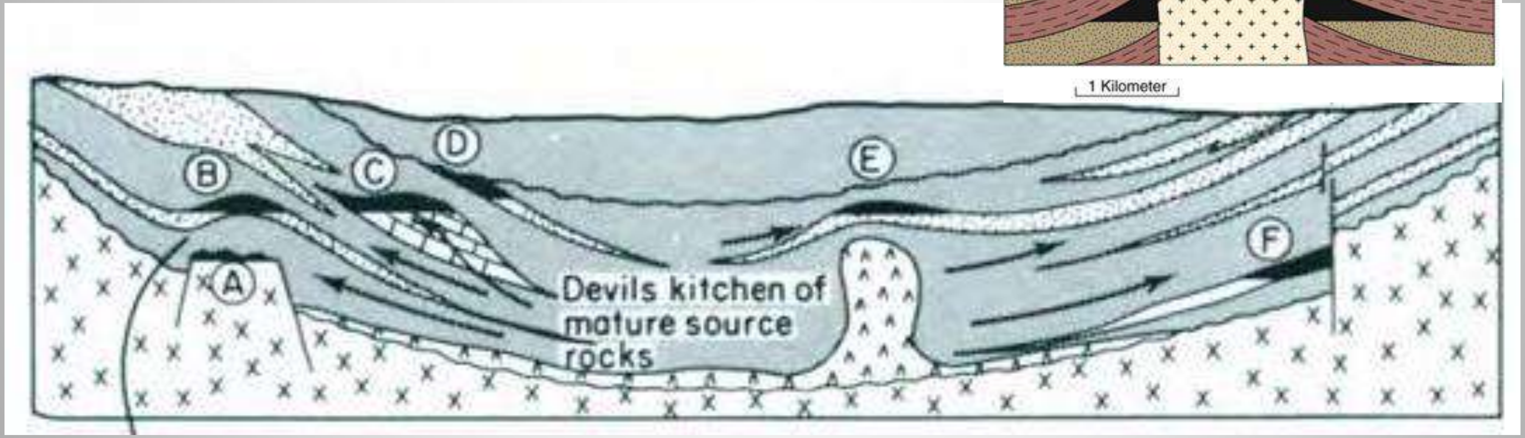
Economic Significance of Evaporites

- Evaporites are a natural resource of great importance, that ***supply a large proportion of the world's requirements for the rare earth elements.***
- Evaporites are of importance in the search ***for oil and natural gas*** ***for three reasons:*** source, structure and seal (Buzzalini et al., 1969).
- The crests of salt domes ***develop a diagenetic cap rock of limestone, dolomite, anhydrite, gypsum, native sulfur, and diverse sulfide minerals (Kyle and Posey, 1991).***

Economic Significance of Evaporites

- ***Salt domes*** host a series of potential hydrocarbon traps, both domal anticlines above the cap rock and faulted flank traps.





Various types of trap are shown as follows: (A) Weathered basement on fault block, (B) anticlinal trap, (C) limestone reef, (D) truncation trap, (E) closure over salt dome, (F) trap due to sealing fault.

Economic Significance of Evaporites

Finally, evaporites are significant because they provide an ideal reservoir seal, combining a maximum of plasticity with a minimum of permeability.

PHOSPHATES

INTRODUCTION

- Phosphorus is an essential element ***of all living matter, both plant and animal.***
- Phosphate minerals are extensively used ***as agricultural fertilizers.***
- Some phosphates occur in igneous rocks as apatite.
- **The majority of economic phosphates are in sedimentary rocks.**
- **Phosphorus-rich sedimentary rocks are called by a variety of names: *phosphate rock, phosphates, phosphatites, and phosphorites.***

MINERALOGY OF PHOSPHATES

- Typical phosphate minerals are admixtures of the **phosphate radical (PO_4)** ***with calcium, water, and traces of fluoride and uranium.***
- Sedimentary phosphates are composed of phosphate minerals, ***all of which are varieties of apatite.***
- **The principal varieties are:**
  - **Fluorapatite [$Ca_5(PO_4)_3F$],**
  - **Chlorapatite [$Ca_5(PO_4)_3Cl$], and**
  - **hydroxyapatite [$Ca_5(PO_4)_3OH$].**

MINERALOGY OF PHOSPHATES

- Most sedimentary phosphates are ***carbonate fluorapatites*** in which up to ***10 % carbonate ions*** can be substituted for phosphate ions to yield the general formula [$Ca_{10}(PO_4, CO_3)_6F_{2-3}$]
- These carbonate fluorapatites are commonly called ***francolite.***
- ***Francolite*** is not a formal mineral name; some workers prefer to use the name ***carbonate-fluorapatite (CAF) instead.***
- Although ***more than 300 phosphate minerals*** are known, ***francolite*** is virtually the only phosphate mineral that ***occurs in unweathered marine phosphorites.***

MINERALOGY OF PHOSPHATES

- The term ***collophane*** is often used for sedimentary apatites for which the exact chemical composition has not been determined.
- Phosphorites commonly also contain some ***detrital quartz*** ***and authigenic chert***.
- Both ***calcite and dolomite*** may occur in phosphorites, and dolomite may be particularly abundant.
- ***Glauconite, illite, montmorillonite and zeolites*** may also be present in some deposits.
- ***Organic matter*** is a characteristic constituent of many phosphorites (Nathan, 1984).

OCCURRENCE OF PHOSPHATES

- Most phosphate deposits occur in marine sedimentary sequences.
- They have been reported in rocks of all ages and on all continents.
- Phosphates occur in sedimentary rocks as matrix and as nodules, ooliths, pellets and phosphatized shells, bones, teeth, and coprolites.
- They also occur as ***a replacement of limestones*** (Bentor, 1980).

MODE OF FORMATION OF PHOSPHATES

- Seawater is generally saturated with ***phosphate ions,*** ranging from ***0 to 3 ppm PO_4 in deep cold water*** to about ***0.01 ppm in warm surface water.***
- The solubility of phosphate decreases with increasing temperature and increasing pH.
- These changes occur, and phosphates thus tend to be precipitated, ***where deep cold oceanic water wells up into shallower warmer waters.***

MODE OF FORMATION OF PHOSPHATES

- The most significant locus at the present time appears to be ***along the western coasts of South America and Africa.***
- Phosphate removed from the seawater by organisms returns again when they die, and settles on the sea bed within miscellaneous organic matter.
- Phosphates become concentrated during early compaction of the mud.

MODE OF FORMATION OF PHOSPHATES

- Constant agitation winnows out the lighter material to leave denser incipient phosphate mud pellets.
- These continue to become enriched with phosphate, as do ***bones, teeth, and shell debris.***
- In this manner, bedded phosphate rock (phosphorite) is formed.
- The optimum depth for phosphate formation ***ranges from 30 to 200m.***

MODE OF FORMATION OF PHOSPHATES

- **Eight factors favor phosphate formation (Brown, 1994):**
  1. A broad shallow shelf,
  2. An adjacent major ocean,
  3. A low latitude (<40°)
  4. High organic productivity,
  5. Shallow marine sedimentation,
  6. Minimal terrigenous input,
  7. A marine transgression, and
  8. A suitable environmental trap, such as a bay, estuary or carbonate bank.

STRATIGRAPHIC CHARACTERISTICS OF PHOSPHORITES

- In ancient phosphorite deposits, phosphate-rich layers typically occur interbedded with carbonate rocks, mudrocks, or chert.
- A characteristic feature of many major phosphorite accumulations is the triple association of phosphate, chert, and sediments containing abundant organic carbon.

PETROGRAPHIC CLASSIFICATION OF PHOSPHORITES

- Phosphorites have textures that resemble those in limestones. Thus, they may contain ooids, peloids, fossils (bioclasts), and clasts.
- These grains are composed of apatite.
- Some phosphorites lack distinctive granular textures and are composed of fine, micrite-like, textureless collophane.
- Cook (1976) refers to this kind of phosphorite as ***phospholutite.***

PETROGRAPHIC CLASSIFICATION OF PHOSPHORITES

- Most grains in phosphorites are sand size; however, particles >2 mm may occur.
- These large grains are commonly referred to as ***nodules*** and can range in size from 2 mm to several tens of centimeters.
- No scheme for naming and classifying of phosphorites on the basis of texture appears to be in wide use at this time (Boggs, 2009).

PETROGRAPHIC CLASSIFICATION OF PHOSPHORITES

- Because phosphorites have textures similar to those in limestones (e.g. peloidal, oolitic, fossiliferous), some geologists have suggested using modified limestone classifications to distinguish different kinds of phosphorites.
- ***Slansky (1986)*** used a classification system based on Folk's (1962) limestone classification.

PETROGRAPHIC CLASSIFICATION OF PHOSPHORITES

- ***Cook and Shergold (1986) and Trappe (2001)*** suggested adopting Dunham's (1962) carbonate classification.
- Use of these modified carbonate classification schemes yields names such as ***wackestone phosphorite (Cook and Shergold)*** ***and phosclast wackestone (Trappe).***

KINDS OF PHOSPHATE DEPOSITS

- Phosphorite deposits can be divided into ***five principal groups*** on the basis of bedding characteristics and the principal types of phosphate materials that make up the deposits as follows:

1. ***Bedded phosphorites:*** form distinct beds of variable thickness, commonly *interbedded with carbonaceous mudrocks, cherts, and carbonate rocks.*

➢ The phosphorite occurs as peloids, ooids, pisoids, phosphatized fossils and skeletal fragments, and cements.

KINDS OF PHOSPHATE DEPOSITS

2. ***Bioclastic phosphorites:*** are a special type of bedded phosphate deposit composed largely of vertebrate skeletal fragments such as fish bones, shark teeth, fish scales, coprolites, etc.

3. ***Nodular phosphates:*** are spherical to irregular-shaped nodules ranging in size from a few centimeters to a meter or more.
   - Phosphatic grains, pellets, shark teeth, and other fossils may occur within the nodules.

KINDS OF PHOSPHATE DEPOSITS

4. ***Pebble-bed phosphorites:*** are composed of phosphatic nodules, phosphatized limestone fragments, or phosphatic fossils that have been mechanically concentrated by reworking of earlier-formed phosphate deposits.

5. ***Guano deposits:*** are composed of the excrement of birds that has been leached to form an insoluble residue of calcium phosphate.

SILICEOUS ROCKS

موضوع يكلف به مجموعة من الطلاب بالبحث فى مكتبة الكلية وشبكة المعلومات الدولية (الإنترنت) ثم عرضه ومناقشته أثناء المحاضرة

COAL

موضوع يكلف به مجموعة من الطلاب بالبحث فى مكتبة الكلية وشبكة المعلومات الدولية (الإنترنت) ثم عرضه ومناقشته أثناء المحاضرة

Practical course-Sedimentary rock (ii).

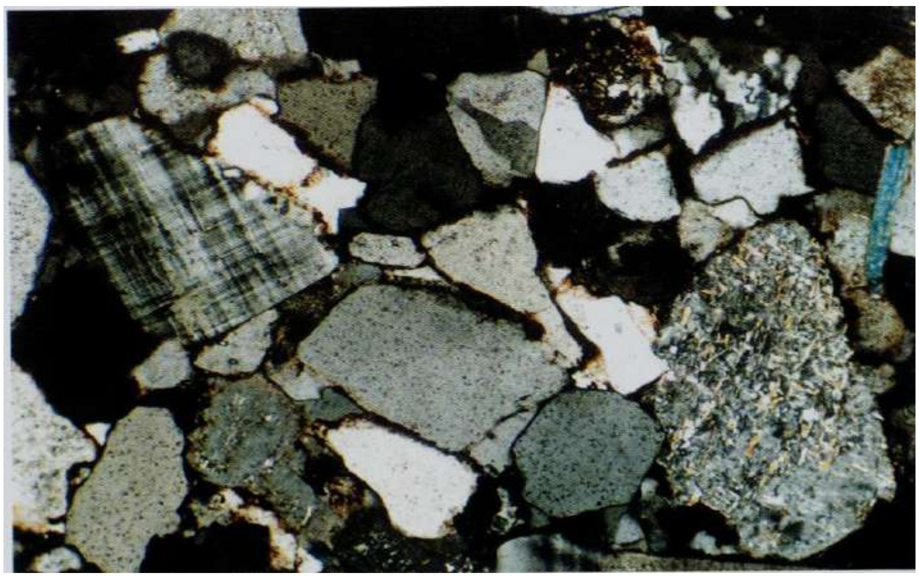
Section No	Contents
1	• Handspecimens description.
2	• Coarse grains clastic sediments(Conglomerate& Breccia).
3	• Medium grains clastics sediments (sandstone)
4	• Medium grains clastics sediments (sandstone
5	• Fine grains clastic sediments(siltstone, clay or mudstone).
6	• Carbonate rocks (limestone).
7	• Carbonate rocks (Dolomite).
8	• Phosphates.
9	• Phosphates.
10	• Evaporites (Gypsum &Rock salts).
11	• Silicious rocks(iron bearing sediments)
12	• Revision

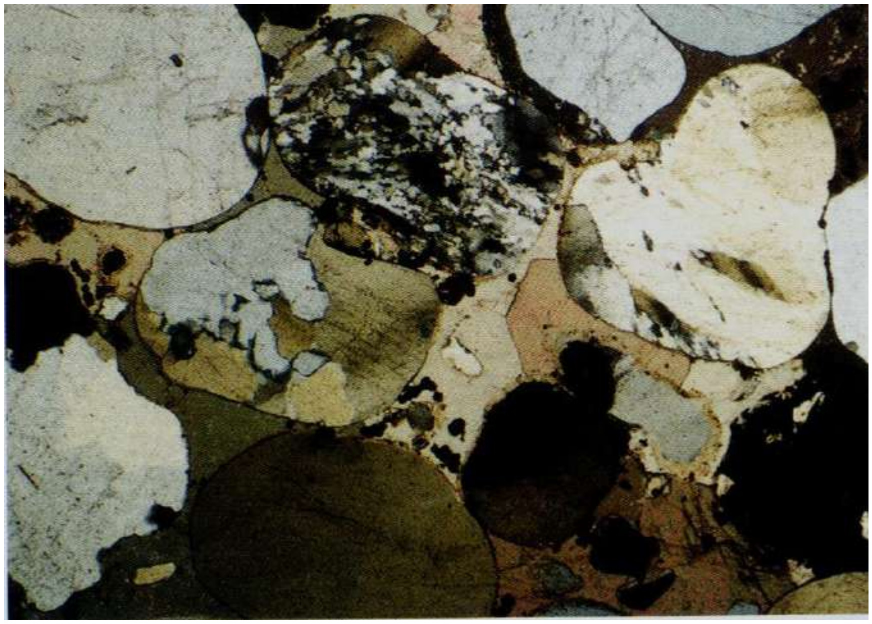
Week (1-3)

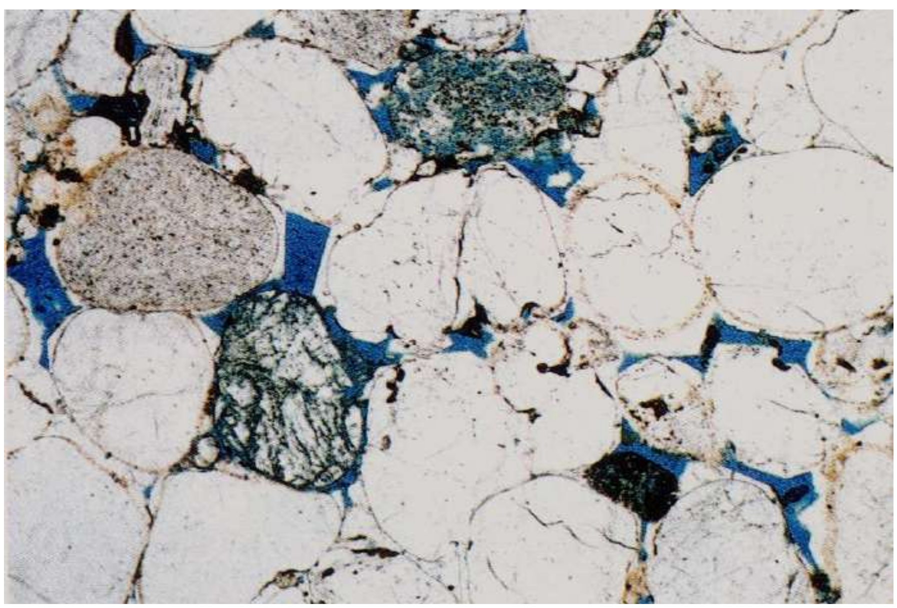
Item of description:

- Grain size
- Grain shape
- Sorting
- Matrix/cement
- Origin
- Name

Sandstone



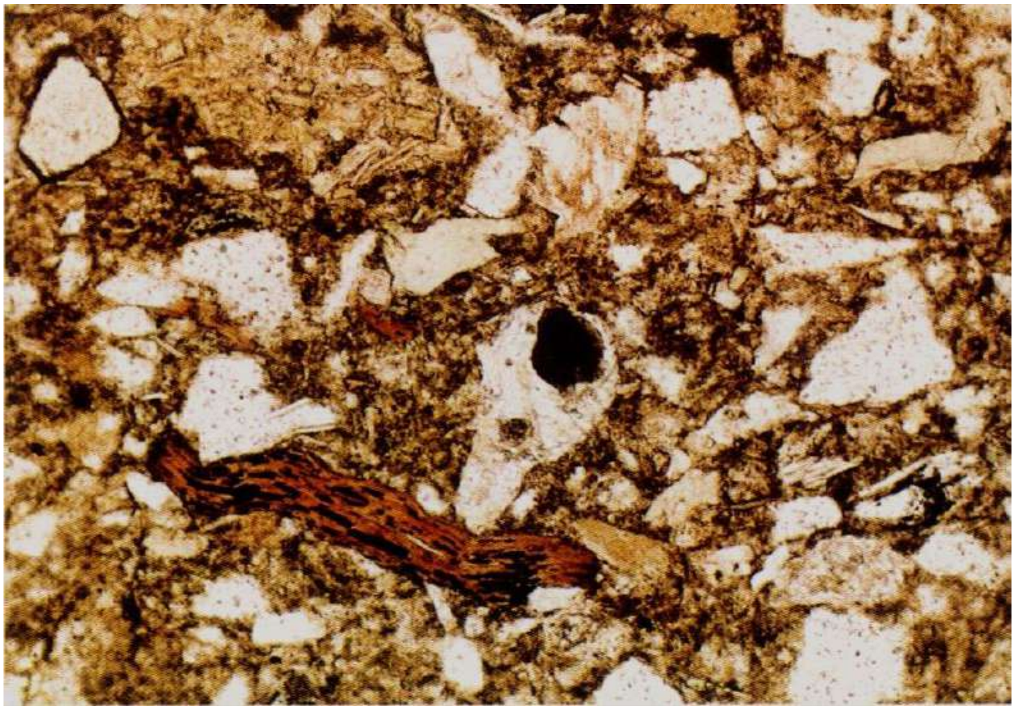




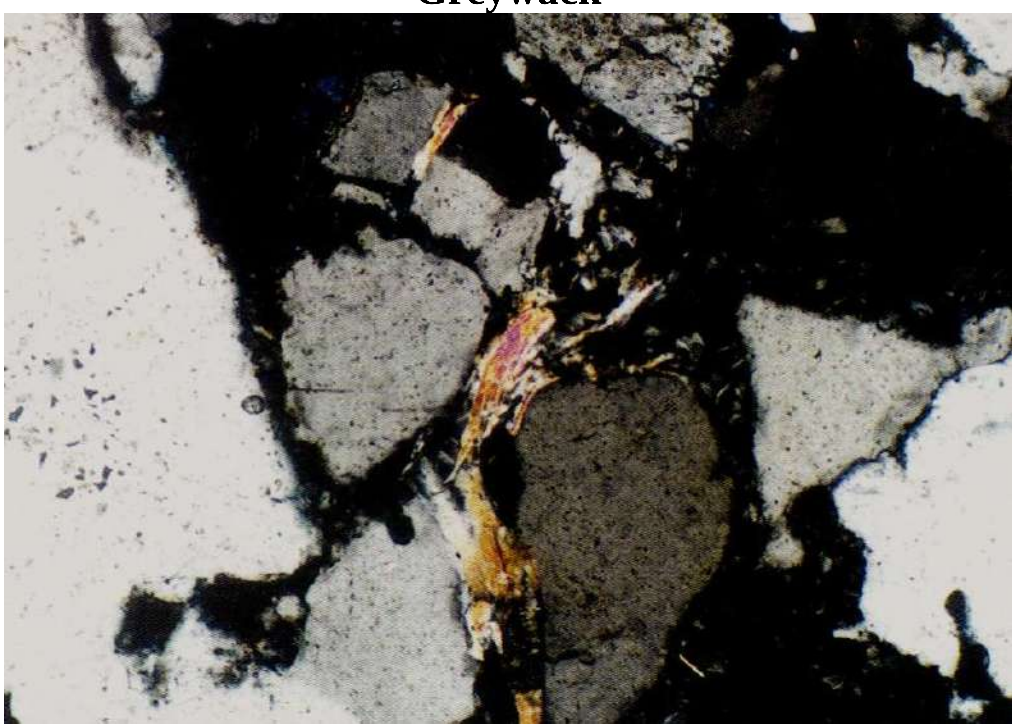
Quartz arenite.

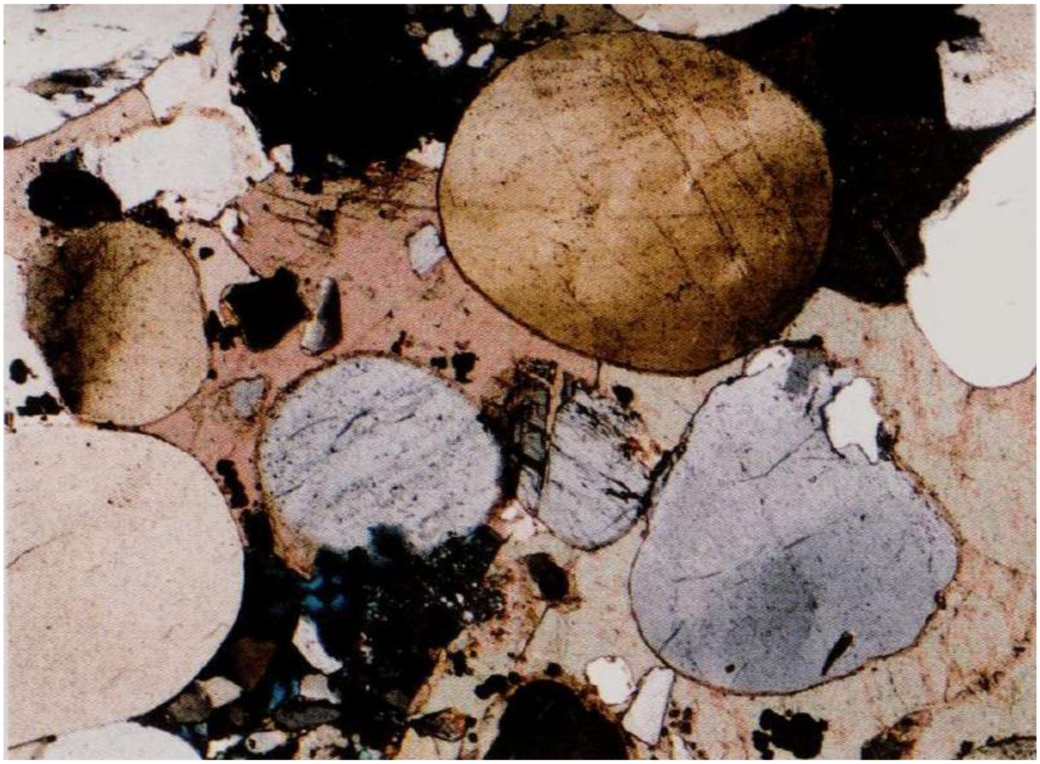
Quartz arenite

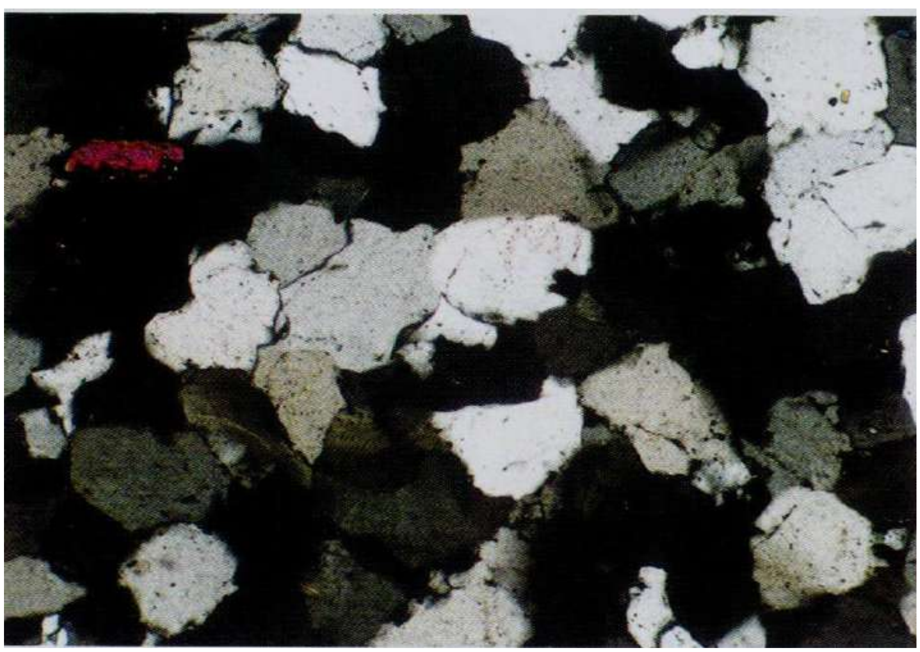
Week (4):



Greywack



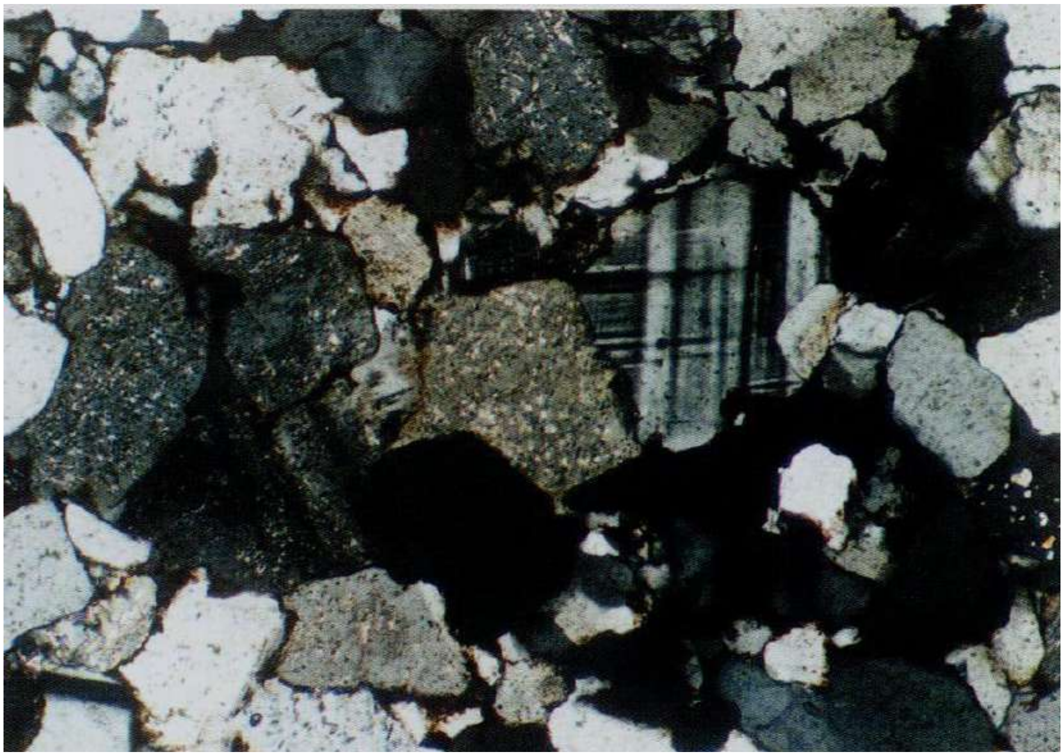


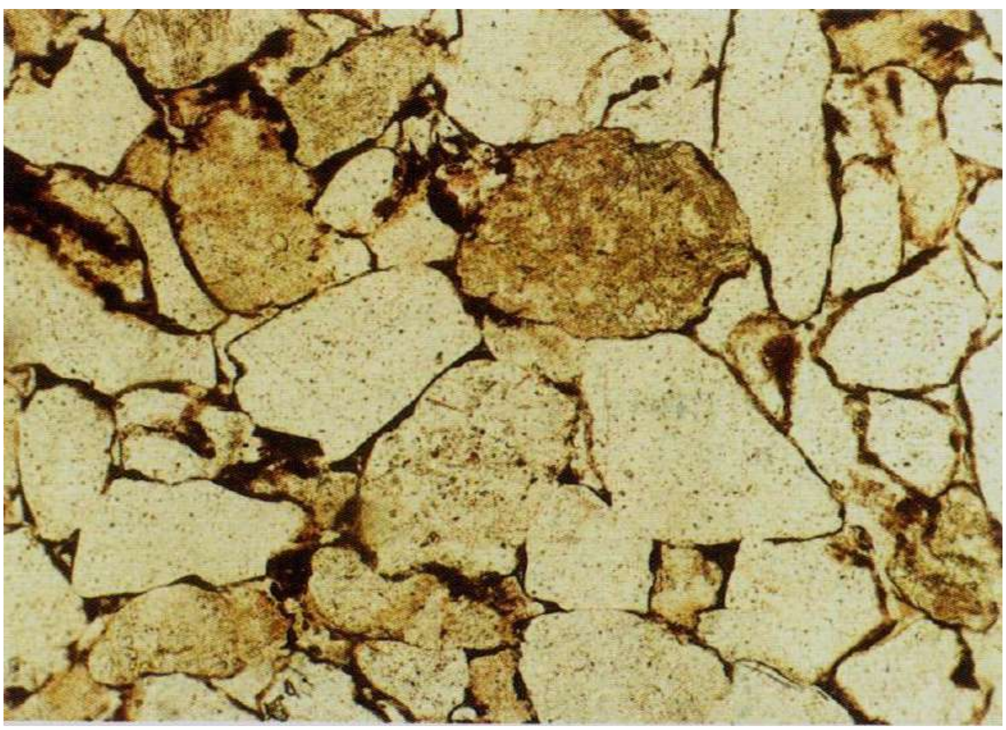


Quart arenite

Week (5):

litharenite

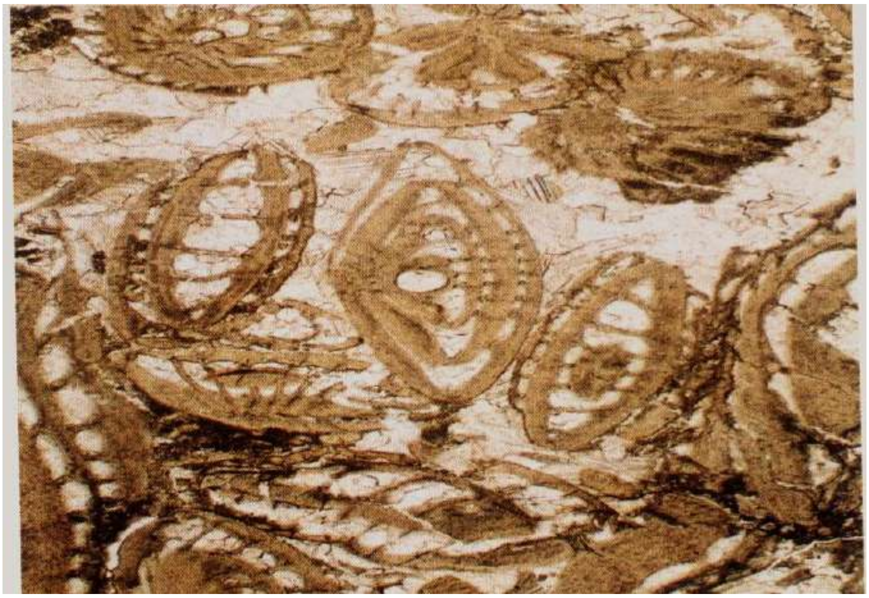




Arcose

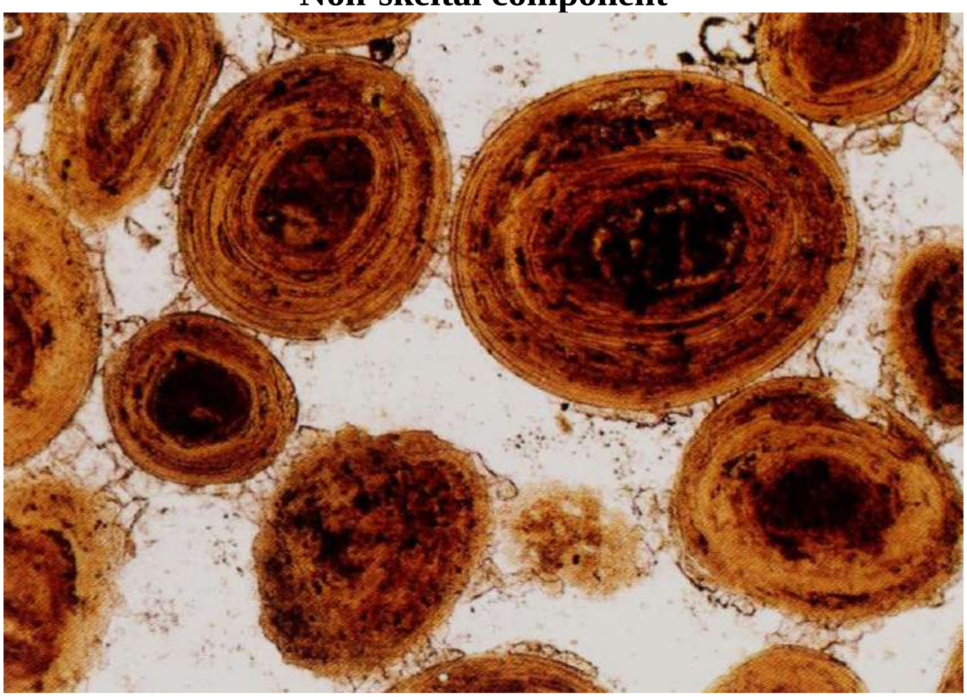
Lithicarenite.

Week (6)

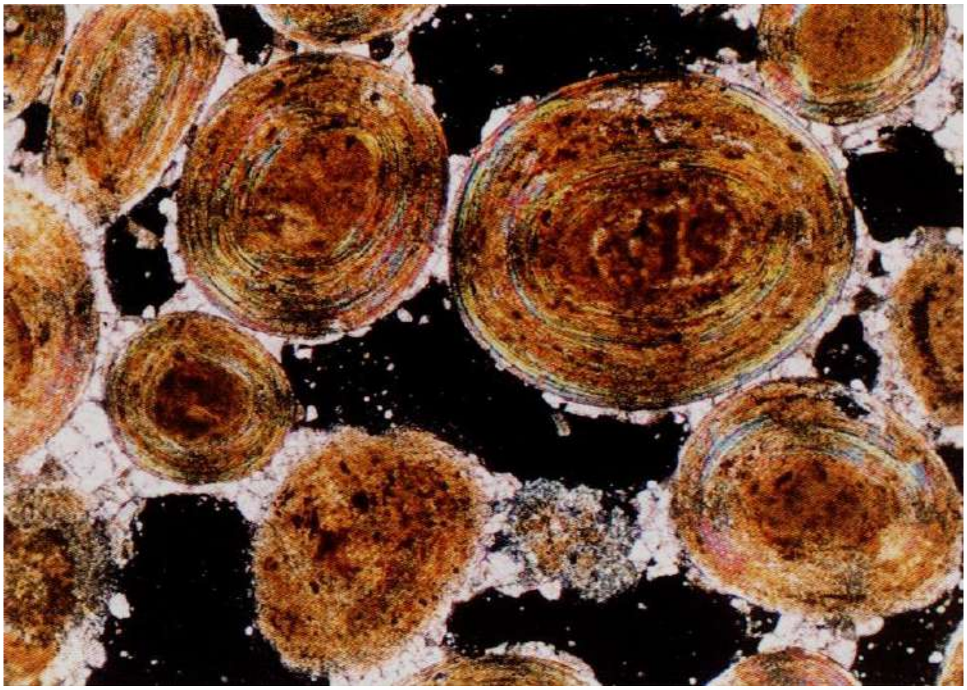


Nummulitic limestone

Non-skeltal component



Ooids



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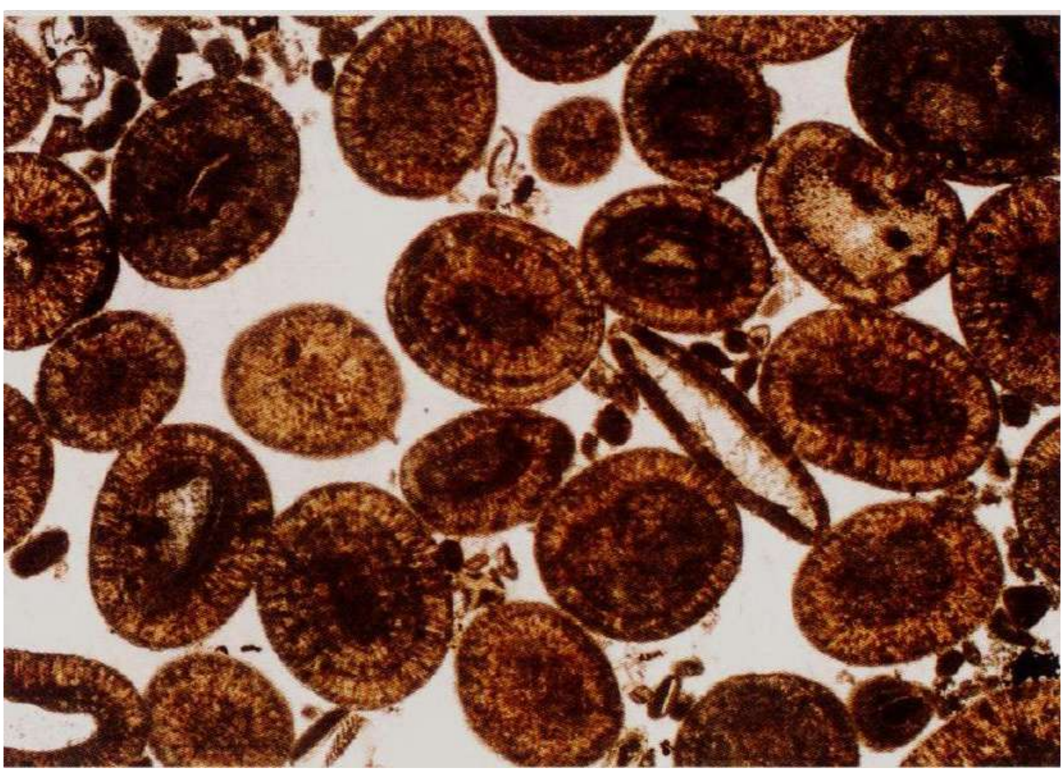
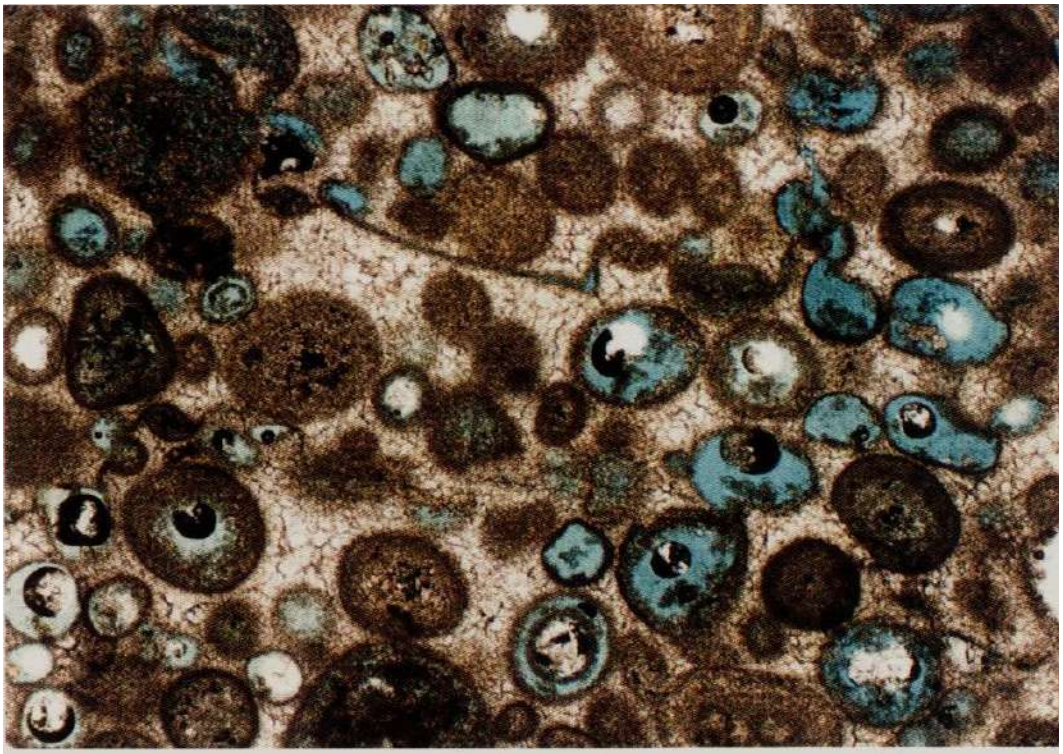
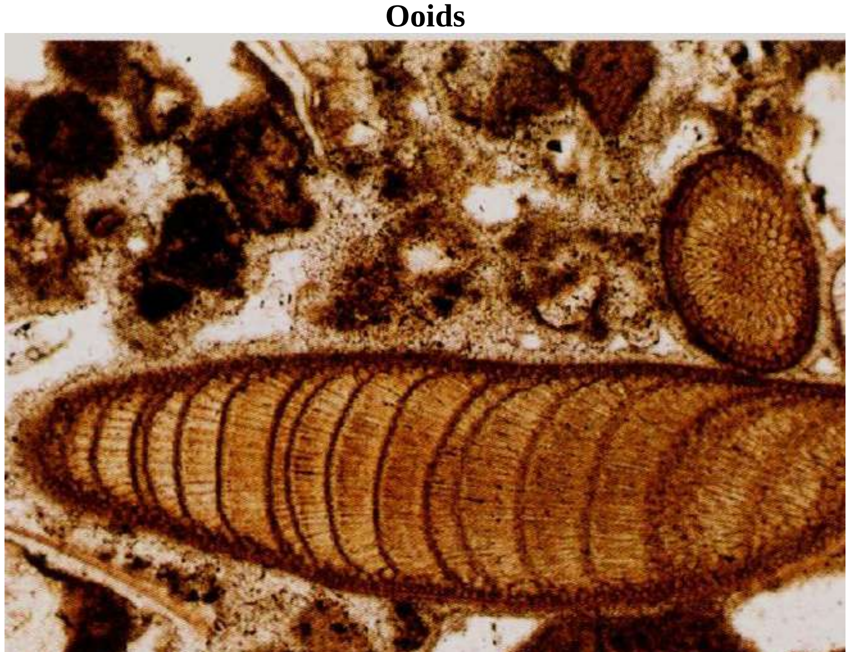


Ooids

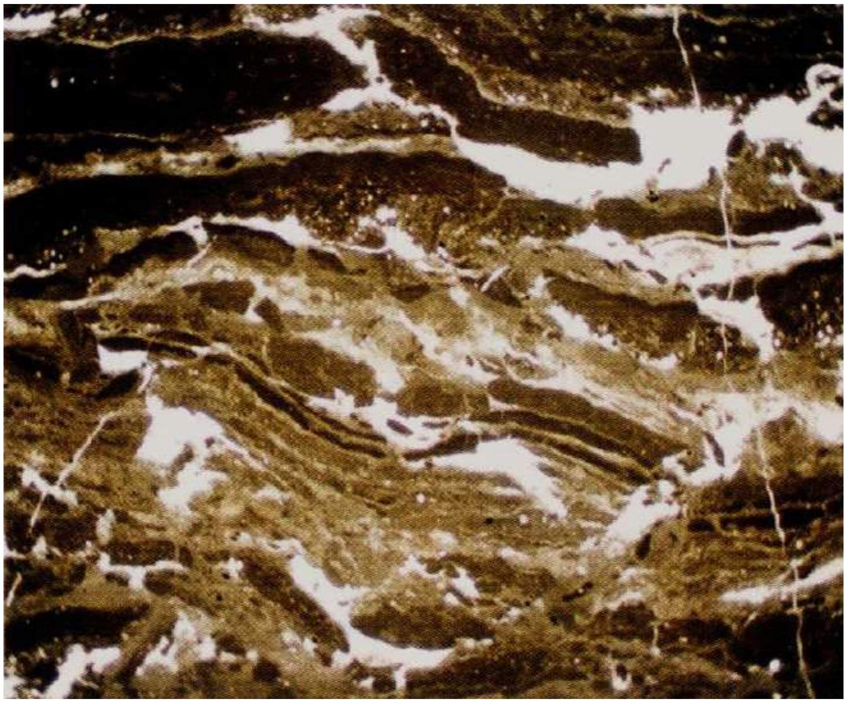


Ooids



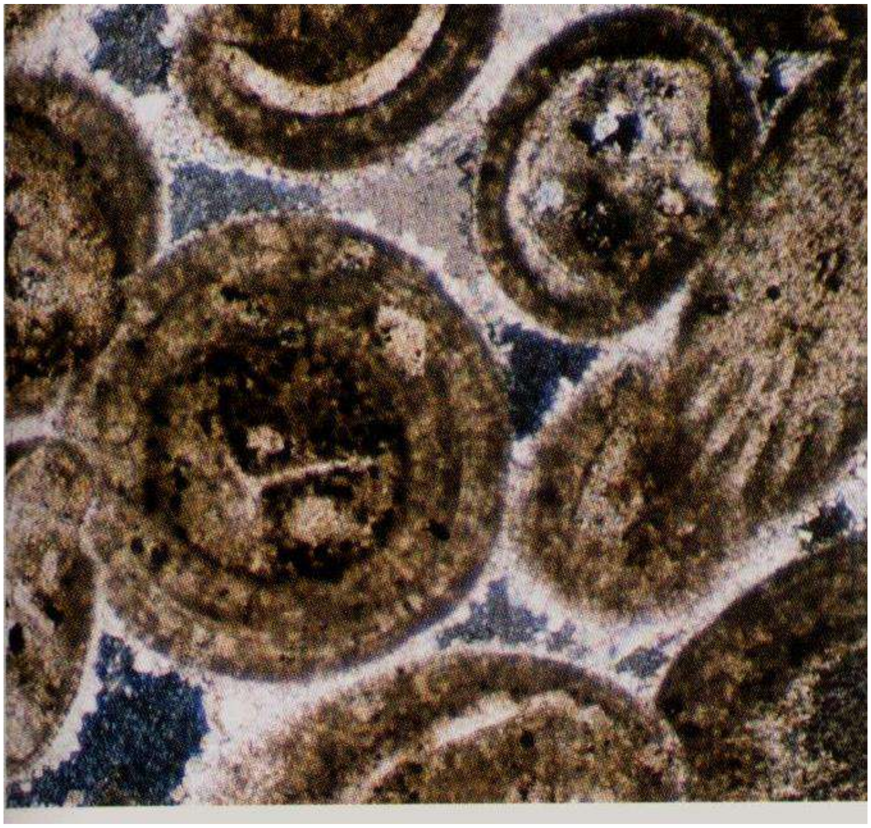
Week (7):

Carbonate rock

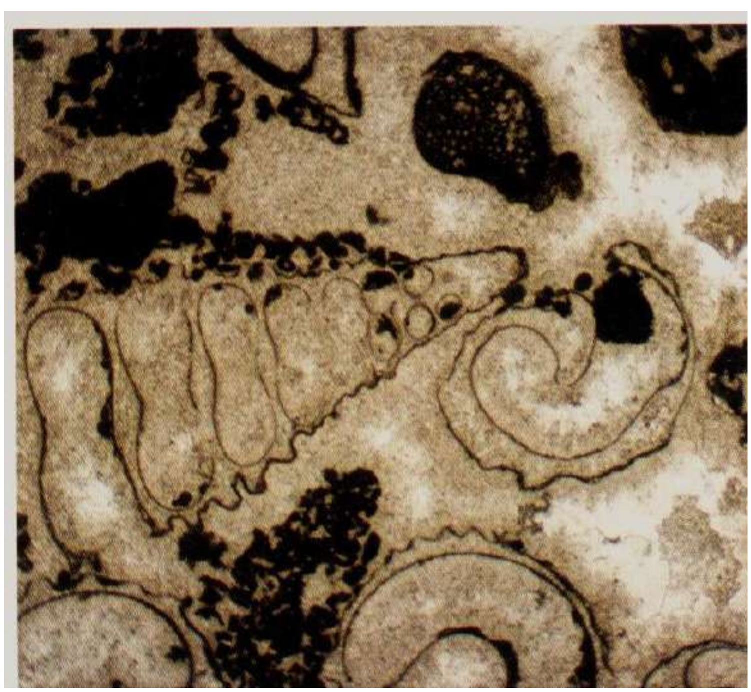


Carbonate rocks

Carbonate rich skeltal



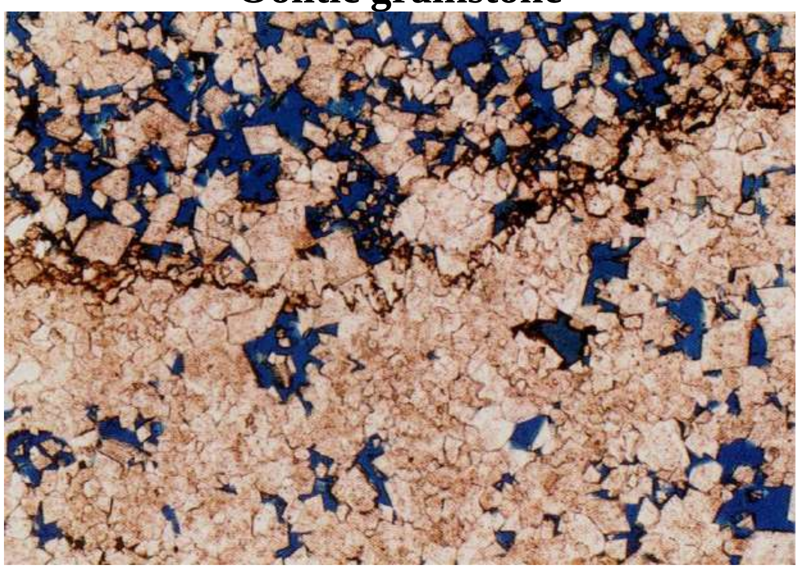
Calcareous cemented skeltal grains



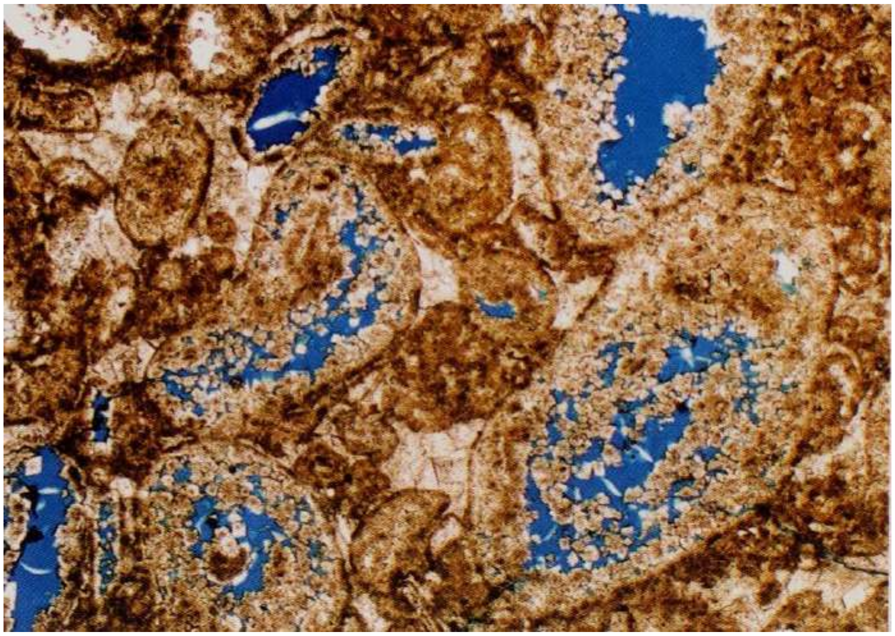
Week (8):

Limestone rich Gastropods

Oolitic grainstone

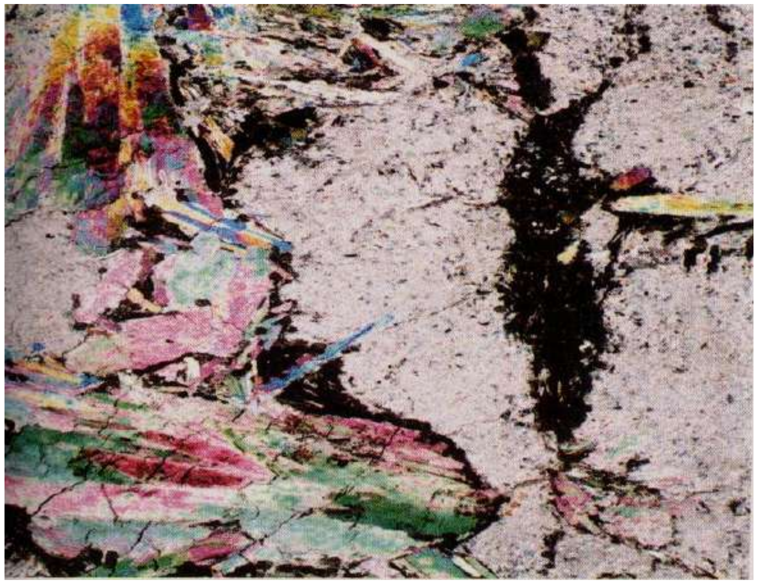


Dolomite

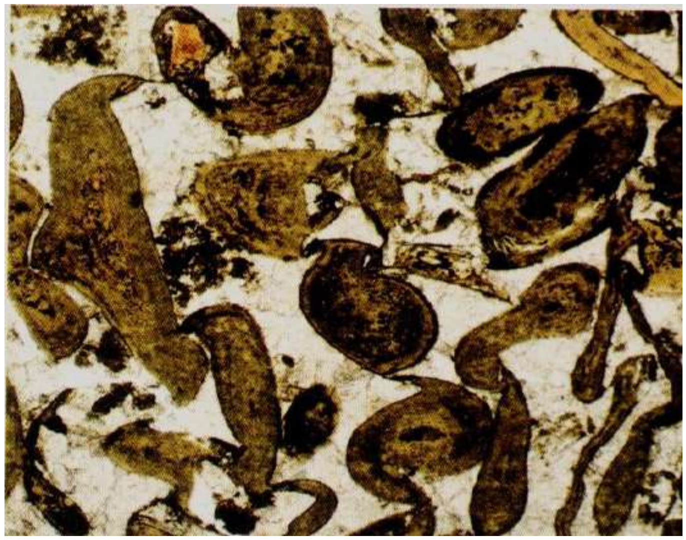


Dolomitized grainstone

Week (9):

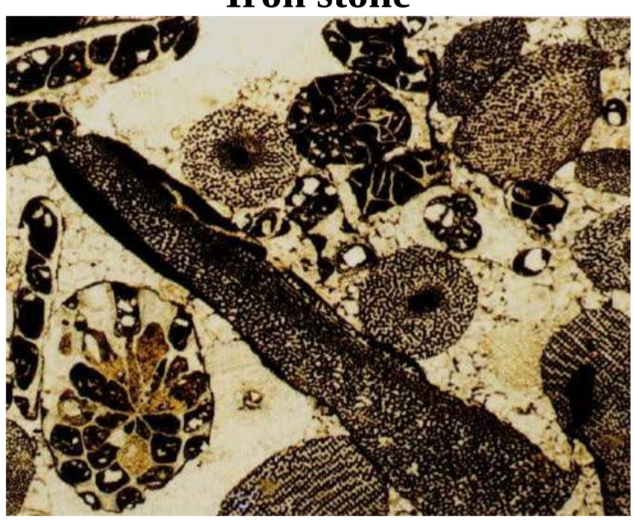


Anhydrite

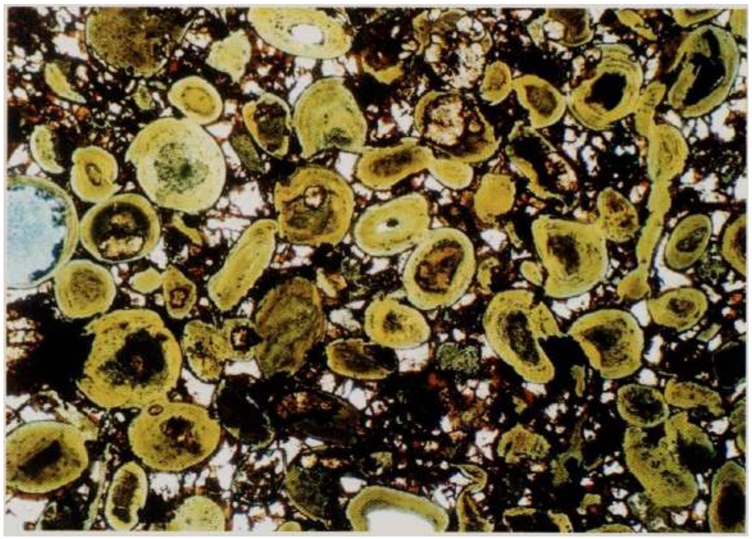


Grainstone

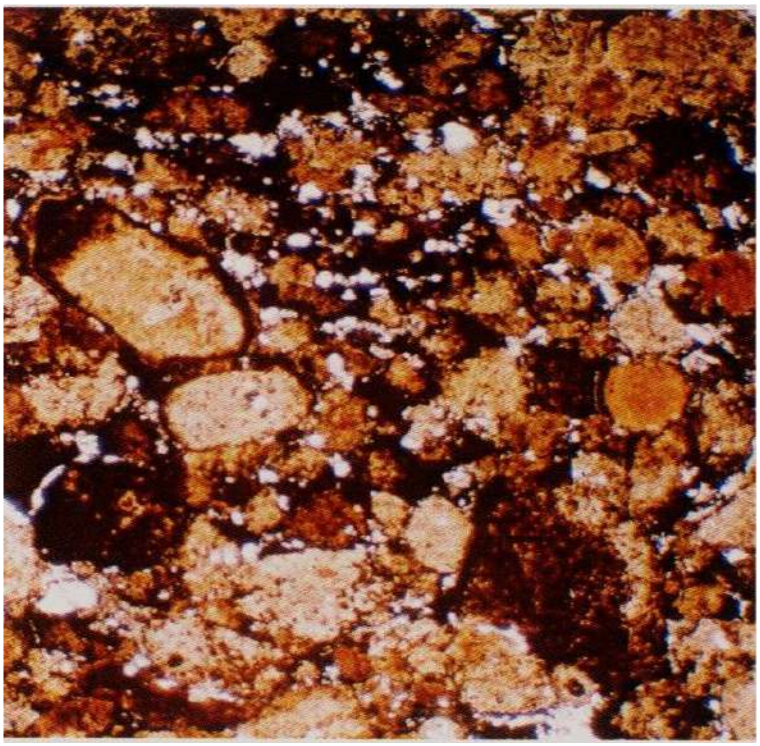
Iron stone



Week (10):



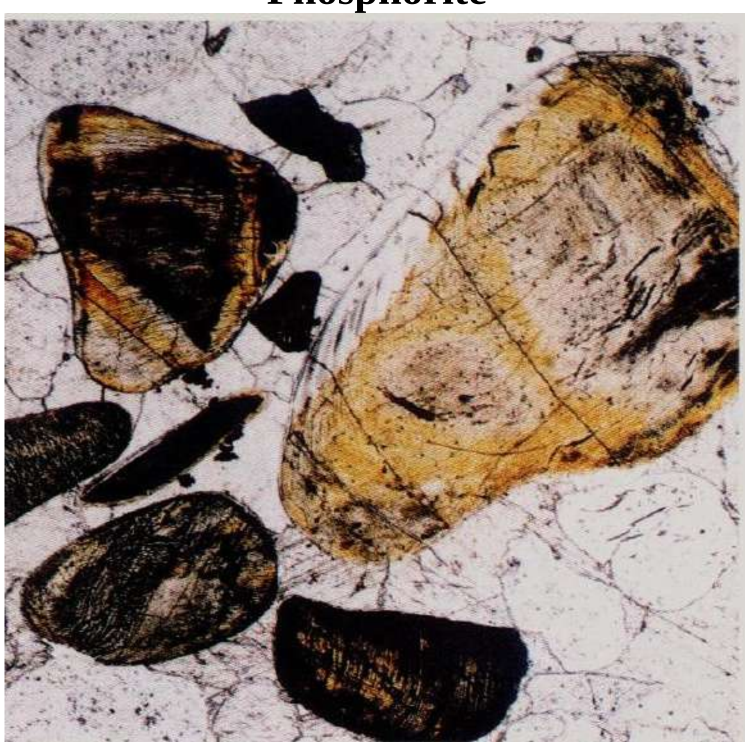
Bertheriene-chamosite



Phosphorite

Week (11):

Phosphorite



Phosphorite