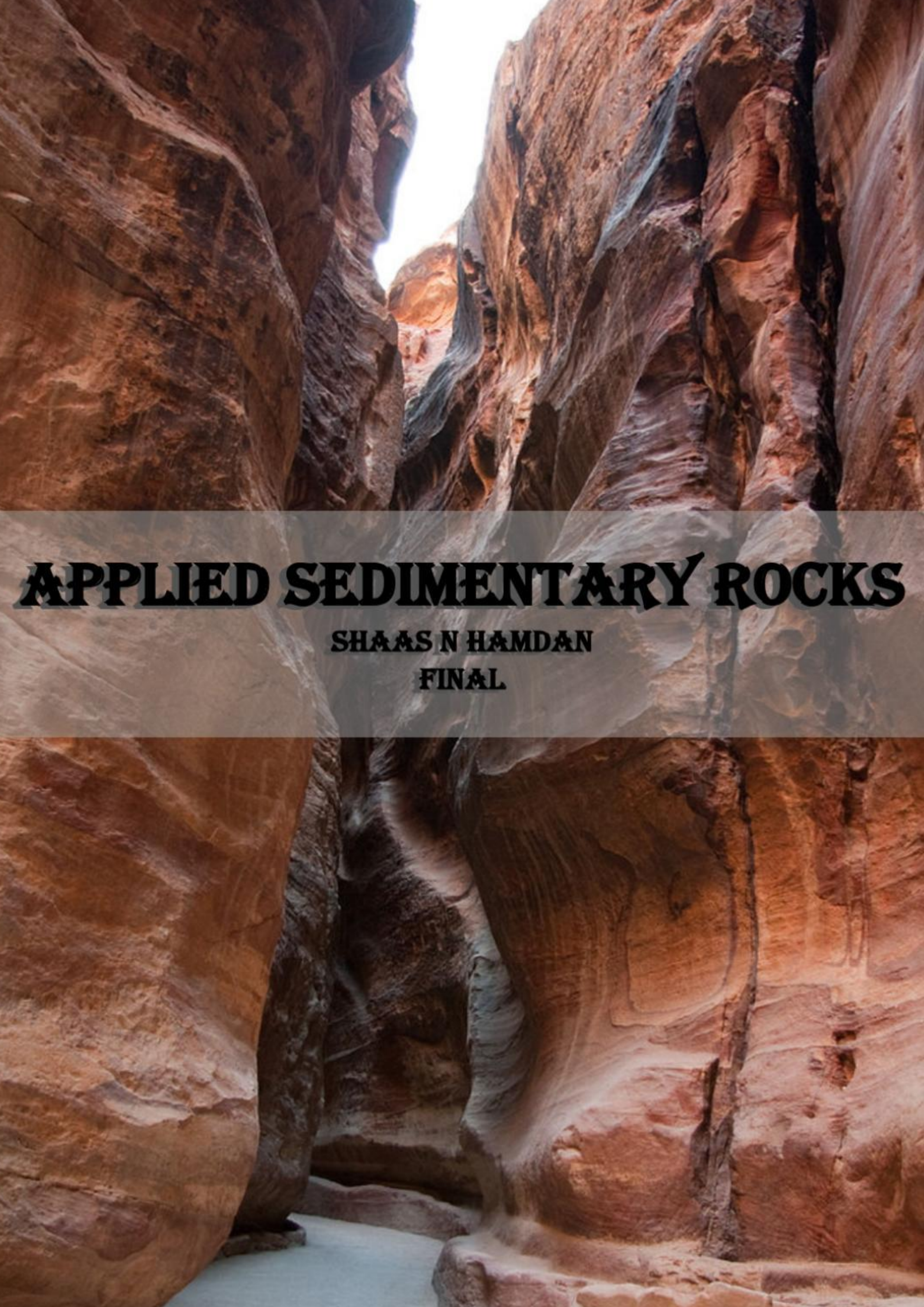


APPLIED SEDIMENTARY ROCKS

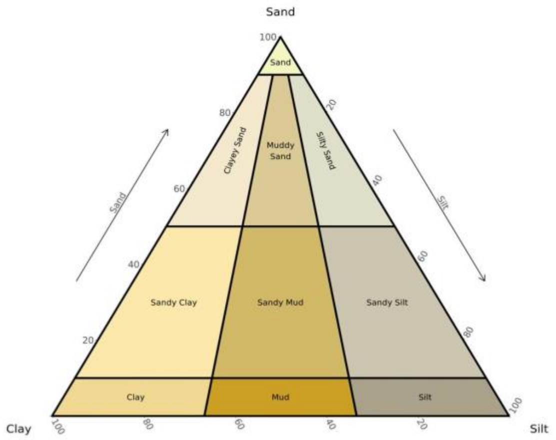
SHAAS N HAMDAN

FINAL

CLASTIC SEDIMENTARY ROCKS
MUDROCKS

- **Mudrocks**: most abundant type of sedimentary rocks 45-55%, consist clay minerals (<4µm), silt-grade quartz (4-62µm), & hydrous alumino-silicate “sheet structure”
  - **Mixture:** clay-grade to silt-grade material
  - Easily weathered so covered with vegetation & poorly exposed, deposited in all sedimentary environments (majority in floodplain, lake, deltas, distal areas of clastic shelves, basin, & sea floors)

Classification of Mudstones	
Mudstone	Indurated or lithified, blocky, & non-fissile mudrock
Claystone	Mudrock consists more clay-grade particles than silt
Siltstone	Mudrock consists more silt-grade particles than clay
Shale	Laminated & fissile mudrock
Argillite	More indurated or lithified mudrock
Calcareous	Marls
slate	Metamorphic mudrock with a cleavage



Mudrocks	Studied Using
Unconsolidated	sedimentation chamber or settling tube
Lithified	SEM

- In the filled, The terms mudstones, shales, claystones, & siltstones are referring to color, fissility, structures, mineral composition, organic materials & fossils content

Features used to description of mudrocks	
Colour	grey, green, red , brown, variegated, mottled
Fissility	Fissile, non-fissile, blocky, earthy flaggy. Papery
Sructure	Bedded,laminated,slumped,bioturbated,massive
Mineral	Quartzose, ilitic, kaolinitic, zeolitic, Micaceous, calcareous dolomitic, gypsiferous
Organic	Organic-rich, bituminous, carbonaceous
Fossils	Fossiliferous, foraminiferal , ostracod, Graptolitic

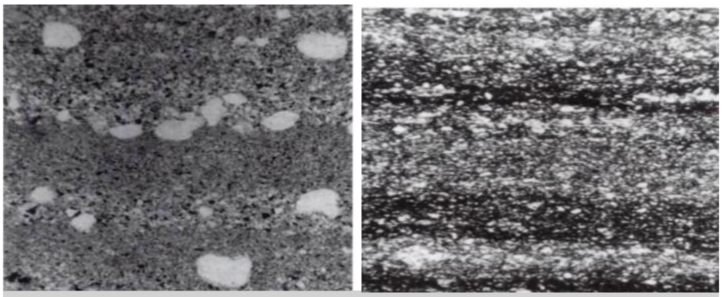
- **Fissility** is the ability of a rock to split into a thin sheets
  - Fissility of shale related to preferred orientation (alignment of clay by compaction, & lamination)
  - Absence of fissility (in mudrocks) explained by:
  1. **bioturbation**, & presence of **silt quartz or calcite**
  2. **flocculation** of clays during sedimentation that produce random fabric retained on compaction

TEXTURES & STRUCTURES

- The use of grain-size in interpretation of depositional environment is complicated because clay are deposited as floccules & aggregate, the feeding organisms generate pellets, & bioturbation disrupts mud textures
- **Preferred orientation** of clay minerals & mica flakes parallel to bedding plane, most **common texture**
  - Result of deposition of clay parallel to bedding plane
  - Disrupts by compaction & dewatering
- **Lamination**: produced by variation of grain size & chemical composition, most **common structure**

Laminae	Produced by
Size-graded	**Deposited from low-turbidity currents followed by deposition from suspension in short periods of time**
Size-graded	**Develop over longe periods of time, if there is a seasonal or annual fluctuation & biological activity**
Organic laminae	**Seasonal microbial blooms, & varved couplets of glacial lakes are taken to reflect the annual spring melting**
Cross-	**Current & Symmetrical wave-ripples in siltstones**

cross-lamination indicating a flow right to left & picked out by alternation of dark clay-rich & pale clay-poor laminae



Lamination: (left) rhythmites, graded silt passes upward to clay-grade material, (right) rhythmites consisting of alternations of silt-sized quartz & clay-organic matter resulting from seasonal deposition in non-glacial lake

- **Flaser & lenticular bedding (ripple-mud):** produced by deposition of mud-, fine-sand-, & silt-grade particles in tidal flats through fluctuating current regimes

- **Massive**: lack of any structures (structureless)

Lacking internal structures	Produced by deposition of mudrocks from high viscosity currents as mudflows & debris flows
Secondary structures	by Bioturbation, mass movement (sliding), soil processes (pedogenesis), dewatering, root growth

Shale characterized by fissility (left), Massive mud (right)

- **Grooves & Flutes structures:** erosional structures, cut in mud & preserved on soles of overlying sandstones
- **slump & rain-spot prints structures** desiccation cracks formed through subaerial exposure
- **Other structures:** Small-scale scour, & fill structures
- **Nodules (concretions):** regular to irregular, with spherical, ellipsoidal or flattened shape, composed of calcite, siderite, pyrite, chert, & calcium phosphate

Calcareous nodules in red mudrock

  - **Grow by** localized precipitation of cement from pore waters **during** diagenesis below sediment water interface, or deep in the sediment column
  - **Factors thet controlling nodule mineralogy & growth rates** composition, Eh, pH of waters
  - In some case nodules formed around a nucleus (e.g. fossil) as a result of local chemical conditions

Early diagenetic nodules	**Formed in** soft & uncompacted sediments **Characterized by** uncrushed fossils & folding of laminae (compaction after growth of nodule)
Late compaction	**Formed in** the host sediment during burial diagenesis **Characterized by** laminae pass unaffected via nodule
Nodules without nucleus	More common nodules, form along definite horizons or within particular beds, reflecting a level at which supersaturation of pore waters was achieved
Elongate	With preferred orientation (direction of pore water)

COLOR & COMPOSITION

- **The color depends on** rock mineralogy & geochemistry
- **Factors that controlling color of mudrocks**: organic content, pyrite & oxidation state of Fe

Color	Produced by	Environment
Grey & black	Organic matter & Pyrite	Marine & deltaic mudrocks
Red & purple	Hematite as grain coatings	After deposition, though an aeging of a hydrated Fe-oxide precursor
Red	Oxidizing nature	Flooding plain, Early diagenetic environment
Green	Ferrous Fe, illite & chlorite	In red mudrocks that subjected to reduction of hematite
Green spots	Fe reduction & organic matter	In some red mudrocks sites
olive & yellow	From mixing of color-producing components (mixing of green minerals & organic matter)	

- Precursor is detrital in origin, & in situ solution of metastable mafic mineral grains
- **Color mottling**: different shades of grey by bioturbation
  - **In yellows, reds, or browns mottles**
- **Pedogenic processes** resulting by moving water via soil & causes an irregular distribution of Fe-oxide, Fe-hydroxide, & carbonate, & the effect of roots
  - **Common in** lacustrine & floodplain muds & marls

MUDROCKS MINERALOGY

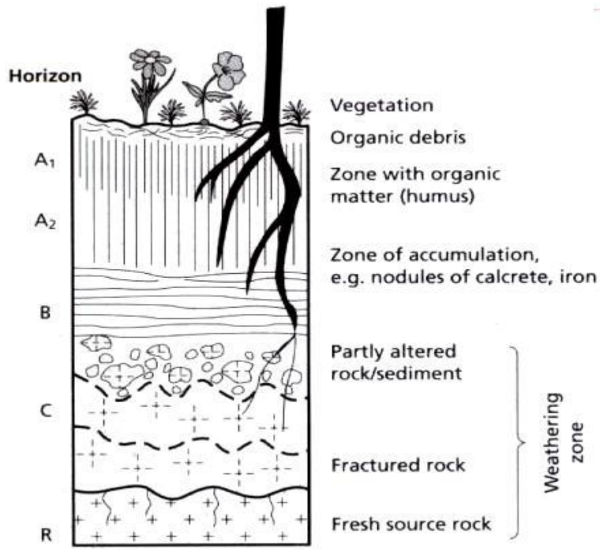
- **Clay minerals:** kandite group (kaolinite, dickite, & nacrite), smectite group (montmoroillonite, nantronite, saponite, & stevensite), Vermiculite, Illite (related to the muscovite), chlorite, Galuconite (related to illite & micas), Sepiolite, & palygorskite
- **Quartz:** silt-sized, or fine sand-sized quartz
- **Feldspars**: much less abundance than quartz, due to their lower chemical & mechanical stability, & lower permeability of mudstones than sandstones (feldspars are better preserved in sandstones)
- **Muscovite, Calcite, Dolomite, Siderite, Pyrite, glauconite, hematite, gypsum, anhydrite, & halite**
- **Organic matter** is common in mudrocks

CLAY-MINERAL FORMATION

- **Clay minerals in sedimentary rocks have 3 origins:** inheritance, neoformation, & transformation

Inherited	Detrital, transported & deposited away from source area, but stable in present location
Neoformed	Formed in situ by precipitation from solution or from amorphous silicate material
Transformed	Inherited, modified by ion exchange (ion in aqueous solution adsorbed & desorbed from clays)

- **3 major locations of clay-mineral formation:**
  1. weathering & soil environments
  2. depositional environments
  3. During diagenesis & low-grade metamorphism
- The major site is weathered & oil profiles developed on solid bedrock & unconsolidated sediment
- Soils develop via physio-chemical & biological processes (pedogenesis) & possess distinct horizons



- All clay mineral formed in horizon A by pedogenic, particularly chemical weathering of feldspar & mica

Illite	In soils by limited leaching in temperate
Chlorite	In acid soils by intermediate leaching in humid & arid
Kaolinite	Acid tropical soil, intensive leaching
Montmorillonite	Temperate soil by intermediate leaching with good drainage & neutral pH

- clay minerals, colloidal organic matter, & ions in solution, percolate downward from A to B ***eluviation***
- **eluviation or illuviation process**: downward percolated clay, Fe-oxides, & carbonates accumulate in B horizon
- The clay minerals formed in the soil profiles & in the weathering mantles on provenance region are now subject to erosion then transportation & deposition
- clay minerals may precipitate directly from water or pore water in surficial sediments, alteration of volcanic materials, or within siliciclastic sediments as cements
- The distribution of clay in modern sediments is mainly a reflection of climate & weathering of source rock area

Illite	In ocean muds of higher latitudes
Kaolinite	Low-latitude (river draining regions of tropical weathering)
Smectites	From volcanic material (mid-ocean ridge, volcanic islands)

DEPOSITIONAL ENVIRONMENT

Major groups of mudrocks in the geologic record	
Residual mudrocks	in situ through contemporaneous of weathering & soil formation on preexisting rock & sediments
Detrital	Formed by erosion, transportation,deposition
Volcaniclastic	in situ weathering & alteration of volcaniclats

RESIDUAL MUDROCKS & PALEOSOILS

- weathering mantle on bedrocks are quite rare
- Soils developed within sediments occur as old as the Precambrian, but much common as plants developed on land since the Silurian: calcretes & the seatearths

Types of paleosoils (Ancient Soils)	
Calcretes or caliches	Vary from scattered to densely packed nodules of $CaCO_3$ **Occur in:** • semi-arid climatic (**evaporation > precipitation**) • Many river floodplain of sediment & clay (smectite, sepiolite, playgorskite)
Seatearths or underclays	Are Clay soils, ommonly vertisols, massive with rootlets & siderite nodules, but commonly have polygonal & vertical crack systems **Occur in** • below coal seams • humid tropical climate with seasonal shrink-swell

DETRITAL MUDROCKS

- Majority of clay & silt-grade quartz in mudrocks are derived from erosion of continental rocks & soils
- Terrigenous clastic transported in suspension by water, with deposition in quiet, & low-energy environments
- Rivers transport vast quantities of silt & clay in suspension to be deposited in floodplains, lakes, deltaic, nearshore & offshore marine environments
- Wind can transport dust up to 1000's Km from source areas to the desert where loess (aeloian silt) deposited, dust can be carried by wind to the ocean where it's deposited as hemipelagic sediment
- Mud accumulated on continental shelves & solpes resedimented by storms or gravitational sliding & slumping (turbidity) to be deposited on deep ocean
- Alluvial & submarine fans, & glacial-regimes muds transported as viscous, laden, or water-poor flow (mudflows)

DETRITAL MUDROCKS: NON-MARINE MUDROCKS

- The mudrocks of river floodplains are best identified by association with fluvial sandstones, overbank deposits & represent upper parts of fining upward sequences
- Red-colored & contain calcareous pedogenic nodules if deposited under arid to semi-arid climate

Lacustrine (lake deposits)	Mudrocks vary considerably depending on the chemistry of lake water, organic productivity & climate **characterized by** millimetric-rhythmic laminations (by seasonal clastic influx, coupled with phytoplankton)
Glacial deposits	**Characterized by** varved rhythmic lamination with alternation of coarse & fine laminae

- **The coarse laminae** consisting of silt to fine sand-grade, deposited from low density suspension currents during spring melting
- **Fine laminae** consist of clay-material deposited from suspension during summer & winter

DETRITAL MUDROCKS : MARINE MUDROCKS

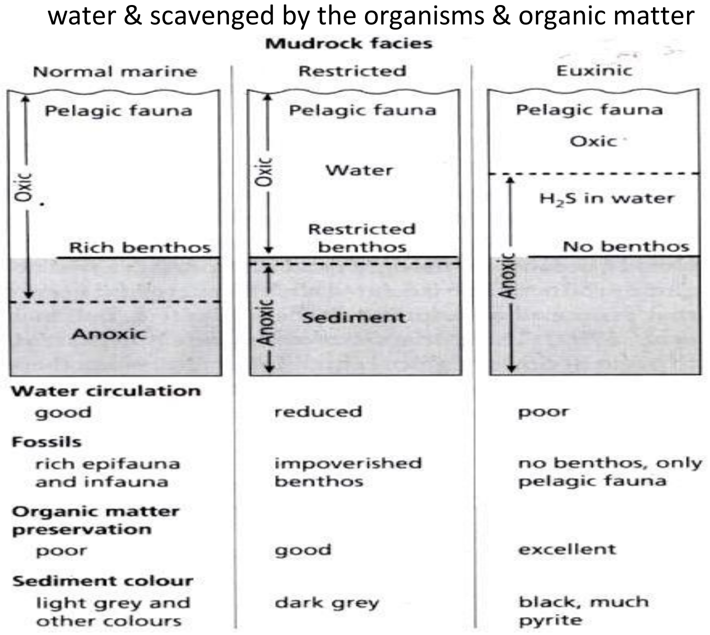
- In the marine, mudrocks are deposited in 5 location: muddy coastlines, nearshore & mid-shelf mud belt, open shelf mud blanket, basinal slope, & basin floor

Muddy coastline	Close to river bringing large quantities of suspended mud to sea include tidal flats, lagoons behind barrier islands, salt marches, & mangrove swamps, Off major deltas, marine shelves may be covered completely in mud to give a shelf mud blanket
Nearshore mud belt	5-20m depth, beyond foreshore-shoreface sand belt of coastlines. Mud is deposited out of suspension below fairweather wave-base
Open-shelf	Deposited below wave-base, various shades of grey & rich in fossils (epifaunal or infaunal with pelagic forms & Bioturbation) Thin sharp-based & graded beds of sandstone & limestone within the mudrocks may represent storm deposits (tempestites)
Deeper water (Hemi-pelagic)	From suspension, hemipelagites cover sea floor, outer continental shelves, on continental slopes & fast areas of ocean basin • characterized pelagic fauna (diatoms, foraminifera, Coccolithophoridae, graptolite), & commonly interbedded with siliciclastic & carbonate turbidites, Grade laterally or vertically into pelagic limestone, & at min. sedimentation • Modern hemipelagic accumulating below CCD cover abyssal plains of central pacific & occur in Atlantic & Indian Oceans, consist of detrital clay & silt, clay minerals, & zeolites derived from alteration of ash, radiolarian, diatom,&sponge spicule

- **Ancient mudrocks of shoreline are identified by:**
  1. **restricted fossil assemblages**: suggest brackish water or hypersaline conditions
  2. **the presence of rootlets:** indicate emergence
  3. **presence of mud cracks, rippled lenses sandstone**, & association with other channel
  4. **beach or barrier sandstone**
  5. dark grey color due to high **organic content**
- **epifaunal fossils:** living on the sediment surface
- **infaunal fossils:** living within the sediment
- **pelagic form:** free-swimming & free-floating species
- The deep-ocean floors are well oxygenated due to cold, dense oxygen-rich waters produced in Polar Regions, descend & flow above ocean bottom to lower latitudes

DETRITAL MUDROCKS : ORGANIC-RICH MUDROCKS

- **include** black shales, carbonaceous & bituminous
- contain 3-10% carbon, With an increasing organic content, & pass into oil shales, which yield oil on heating
- Organic matter is decomposed & destroyed at the sediment surface but if rate of organic productivity is high organic matter can be preserved
- The accumulation of organic matter is favored if the circulation of water is restricted to some extent so insufficient oxygen reaches the bottom sediments to decompose the organic material
- As a result of poor circulation & restriction, water body becomes stratified & sea or lake floor become oxygen deficient (dysaerobic) or totally anoxic
- **Dysaerobic conditions** occur in the sea floor within oxygen-minimum zone (100-1000 m)
- **Oxygen-minimum zone (100-1000m)**: low O_2 zone results from the bacterial decomposition of organic matter sinking from fertile, oxic, surface water, the major control on organic-carbon accumulation does appear to be the primary production rate
- Locations where this commonly takes place are lakes, fjords, silled basins (e.g. Black Sea), sediment-starved basin & deep ocean trenche(Cariaco trench)
- **In oxygen deficiency** on the sea floor, organic matter will be preserved, but the surface sediments still support a benthic epifauna, although of low diversity
- **In anoxic conditions** on the sea floor, there is much H_2S & benthic organisms are absent, This is the case with the Black Sea & Cariaco Trench at the present time
- **Mud in anoxic environment** contain only pelagic fossils
- Pyrite is common in marine & siderite in non-marine
- Organic-rich sediments contain high concentrations of trace elements (Cu, Pb, Zn, Mo, V, U, As) The trace elements are adsorbed onto the organic matter & to the clay minerals. the source of these elements is the sea water & scavenged by the organisms & organic matter



DETRITAL MUDROCKS : LOESS & LOESSITE

- **Loess**: yellow-to-buff clastic deposit composed of silt-sized quartz grains, in the size 20-50 µm
- **Feature**: well-sorted silt, with angular grains
- Loess unstratified & unconsolidated, but it may contain shells of land snails & concretions formed around roots
- Deposited during the late Pleistocene, over vast areas
- Loess regarded primarily of aeolian (wind) deposit, but deposited modified by fluvial reworking & pedogenesis

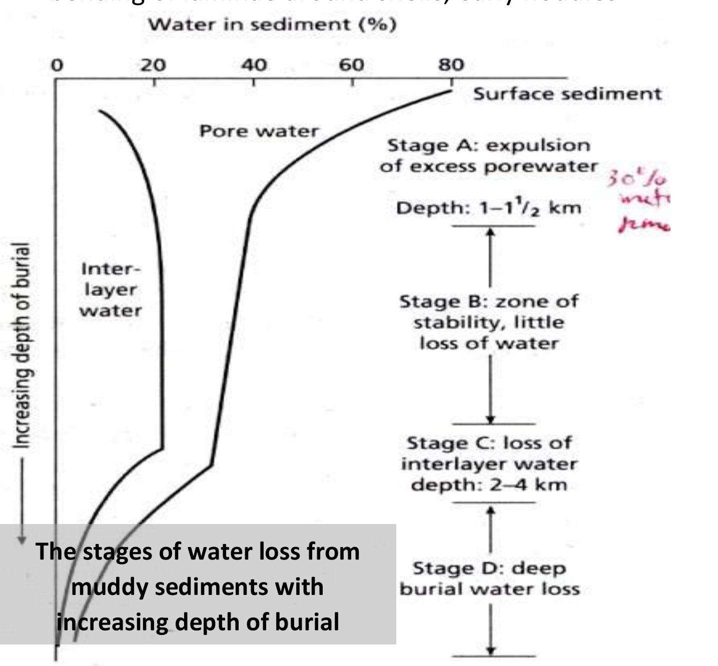
Loess of cold	Periglacial regimes derived from deflation of glacial-outwash plains (accounts for most of the late Pleistocene occurrences)
Other loess	From hot Arid, desert areas

MUDROCKS OF VOLCANICLASTIC ORIGIN

- **bentonites (or fuller's earth):** Mudrocks formed from alteration of volcaniclastic material
- if montmorillonite is present & tonstein if kaolinite is dominant, then Zeolites are also present
- Volcaniclastic deposit subaerial or subaqueous, but due to metastable nature of volcanic glass, devitrification takes place, clay minerals & zeolites form

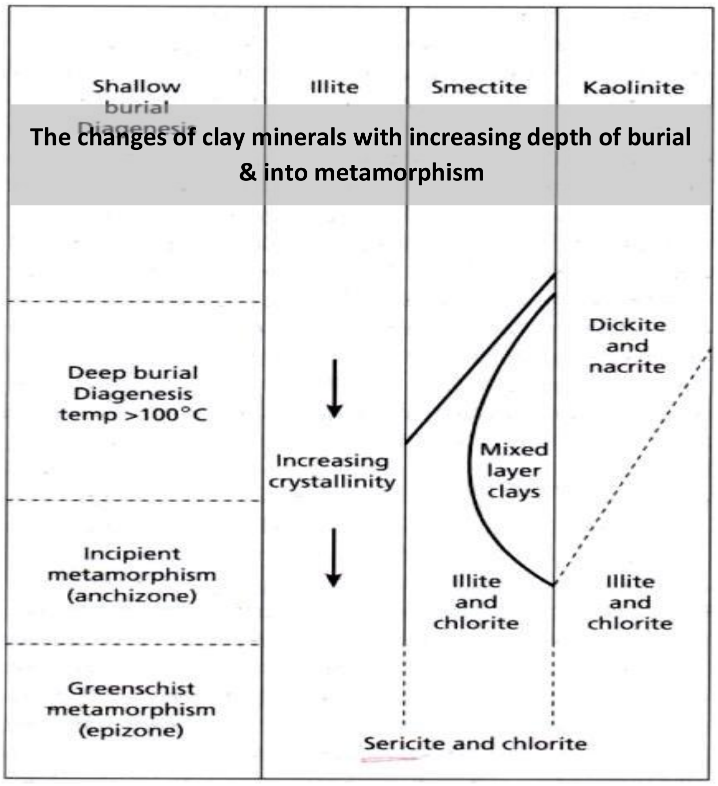
DIAGENESIS

- Clay modified & altered by diagenesis & metamorphism
- The main physical diagenetic affect mud is compaction
- Compaction in mudrocks expels water, reduces thickness of deposited sediment & reduces porosity
- Upon deposition, muds contain 70-90%volH_2O, which reduced to 30% at a burial depth of 100m
- Much of water isn't free pore but is contained in the lattice of the clay minerals & adsorbed onto the clays
- Further compaction (depth) causes further water loss
- At a burial depth (2-4 km) dehydration & change in clay mineralogy occurs, & Final compaction to give mudrock with only a few % water requires a longer period of overburden pressure with elevated temperature
- **Evidence of compaction**: shells, flattening of burrows, bending of laminae around shells, early nodules



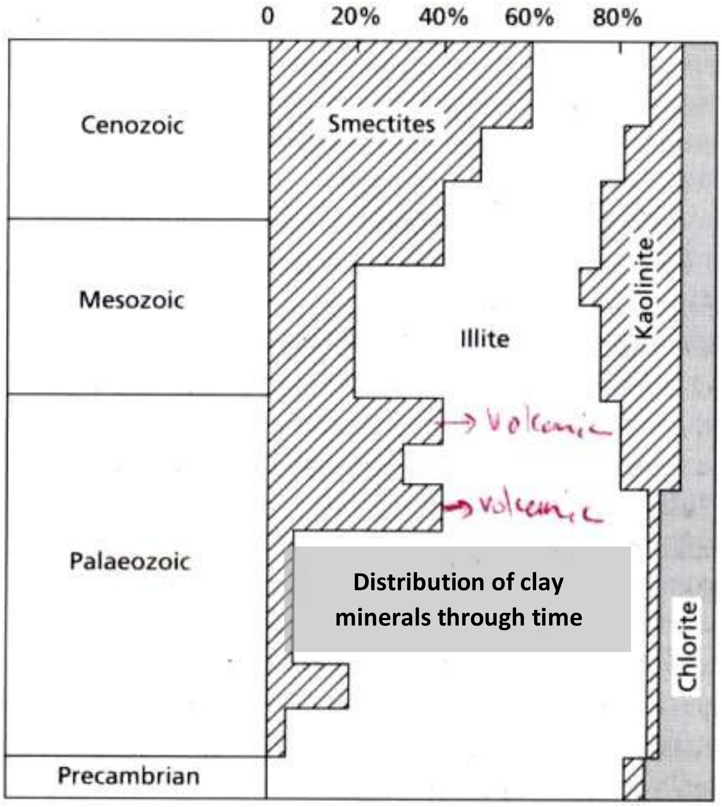
The stages of water loss from muddy sediments with increasing depth of burial

- **Chemical diagenesis:** change of chemistry & mineralogy of clay minerals, takes place through the rise of temperature accompanying increased burial depth
- The main change is the alteration of smectites to illite via mixed-layer clays of smectite-illite



The changes of clay minerals with increasing depth of burial & into metamorphism

- The alteration involves the incorporation of K^+ ions into the smectite structure & loss of interlayer water, This process is T-dependant, where the smectite starts to disappear at 70-95°C, corresponding to a burial depth of 3-3km under normal geothermal gradient (30°C/km)
- At higher T & depth, kaolinite replaced by illite &chlorite
- Mudrocks of the Upper Paleozoic, Mesozoic & Cenozoic contain a variety of clay minerals, whereas Lower Paleozoic & Precambrian dominated by illite & chlorite
- Similar to changes of clay by increasing depth, with greater ages more time allowed for diagenetic reactions
- irregular pattern of smectite behavior via time related to orogenic period, volcanism is more widespread, leading to the formation of much smectite
- Passing into the realm of incipient metamorphism (catagenesis or anchimetamorphism) clay minerals are further altered & replaced
- The phyllosilicate pyrophyllite (related to tlac) & laumontite (zeolite) may develop at the expense of clay
- Smectite, mixed-layers clays & kaolinite do not survive into metamorphism, illite & chlorite do
- With increasing degree of incipient & low grade metamorphism, the order or crystallinity of the illite lattice increases (measured from XRD)
- There are also changes in the chemical composition (increase in Al/(Fe+Mg) ratio) Illite replaced by sericite (fine crystalline muscovite), percentage of smectite-illite mixed layer decreases with increasing burial depth
- Studies of clay mineralogy, if combined with measurements of the rank of associated coal & vitrinite reflectance, can give an indication of the temperature to which the formation as a whole has been subjected



Distribution of clay minerals through time

CARBONATE SEDIMENTARY ROCKS
LIMESTONES & DOLOSTONES

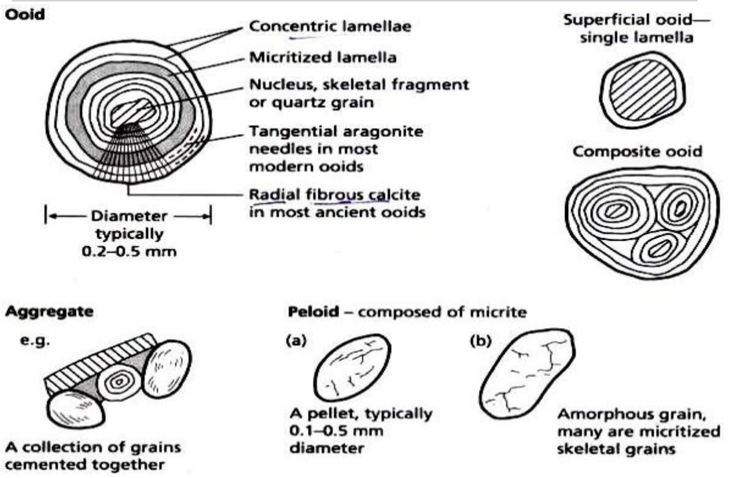
- **Carbonates deposited** biologically or biochemically deposition, & can be precipitated chemically
- Occur chemically from Precambrian (dominated by dolomites & may contain stromatolites). Now, develop anywhere because organisms with carbonate skeletons occur in all seas & oceans
- **Economic significance**:
  1. petroleum & gas reservoir, & groundwater aquifer
  2. major ingredients in manufactured cement
  3. epigenetic led & zink ore
- **carbonate deposition require (controlled by)**:
  1. **high T**: Warm water required for growth of carbonate skeletal organisms (e.g. coral reefs, & calcareous stromatolites)
  2. **Normal salinity (alkaline) water:** in shallow, & agitated photic zone (<10 m)
  3. **low siliciclastic input** (influx): carbonate organism cannot tolerate influx of many terrigenous mud, but a low siliciclastic influx required to deposition
- **Environments**:
  1. **Tropica to subtropical belt (30° N-S of the Equator)** because water in these regions are warm water
  2. **Pelagic environment:** calcareous oozes developed
  3. **In lakes & soils**
- **Photic Zone:** light penetrates depth in seas (100-200m)
- **Stromatolites:** sedimentary structure produced by microbes (cyanobacteria, or blue green algae)
- **Calcareous oozes:** skeleton of pelagic organisms (e.g. foraminifera, coccolith) which live in the photic zone, as death their skeletons fall down where a high rate of carbonate dissolution occurs (below CCD)
- To distinguish between the carbonate minerals:
  - **Staining**: alizarin Red S, K-ferricyanide pigments
  - **Cathodoluminescence(CL)**
  - **slabs** of limestone after being polished & then etched with **acid** (5% HCl)
  - Covered with **acetate peels** (to exhibit textures)

Staining products	Calcite	Dolomite
Nonferroan	Stains pink	Not stained
Ferroan	Stains blue to mauve	Turquoise-blue

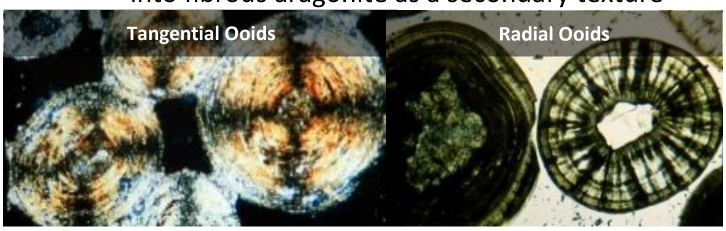
COMPONENTS OF A LIMESTONES

- **Type of components in a limestones**: carbonate grains (allochems), matrix (micrite), & cements (sparite)
- **Carbonate grains**: non-skeletal or skeletal garins
- **Non-Skeletal grains**: Ooids, Aggregates, Peloids, Pisoids
- **Skeletal Grains:** Mollusks, Brachiopod, Coral, Bryozoan, Echinodermata, Foraminifera, Microbe, Algae, Oncoid

NON-SKELETAL: OOIDS, AGGREGATES, PELOIDS, PISOIDS



- **Ooids**: spherical to subspherical, regular concentric lamellae around a nucleus (<2mm, normally 0.2-0.5mm)
  - **Nucleus** are carbonate or quartz grains
  - **Oolite**: Sediment composed of ooids
  - **Ooids form in** agitated water where they are movement as sand waves, dunes, & ripples by tidal currents, storm currents, & wave currents
  - **Recent marine ooids**: aragonite & high-Mg calcite
  - The characteristic microstructure of ooids:
    1. **Tangential orientation**: 2μm, acicular needles (yield pseudo-uniaxial), found in recent marine
    2. **Radial orientation needles**: radiating of bladed into fibrous aragonite as a secondary texture

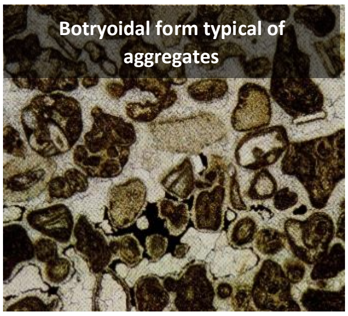


- **Pisoid:** regular, well-defined concentric layering (same as ooids but larger & inorganic)
  - **Pisoliths**: sediments that forms from pisoids

- **Peloids**: spherical, ellipsoidal or angular, composed of microcrystalline carbonate (micrite), lack of internal structure (0.1 to > 0.5mm)

Faecal pellets	(biogenic, or biochemical) regular, rich in organic materials
Micritization	by microbes, irregular more than faecal pellet(form micrite)

- **Aggregates:** are irregular carbonate particles
  - ➢ **cemented by** micrite or organic materials
  - ➢ Forms **Grapestones**
  - ➢ **Formed** beneath a surfacial of microbial mat in subtidal area



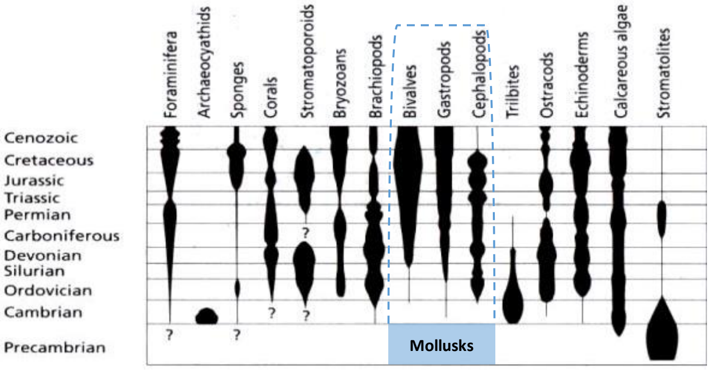
- **Intraclasts**: fragment of lithified or partly lithified sediments, formed inside depositional environments
  - ➢ **Micritic flake or chip**: intraclasts derived from desiccation of tidal flat muds or disruption by storm of partially lithified or cemented subtidal lime mud

Large grain with brachiopod nucleus, surrounded by a coating of micrite, The coating is external to the shell & has a sharp contact (not formed by micritization), The brachiopod shells incorporated in a fine-grained sediment which later eroded & reworked in the basin of sedimentation in order to produced the intraclasts

- The Term ***coated grains*** is used to indicate ooids, pisoids, & oncoids (**grains with a microbial coating**)

SKELETAL COMPONENTS

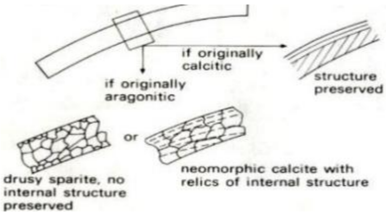
- organisms that secretes carbonates of their hard parts



MOLLUSCS (MOLLUSKS) : Bivalve, Gastropod, Cephalopod

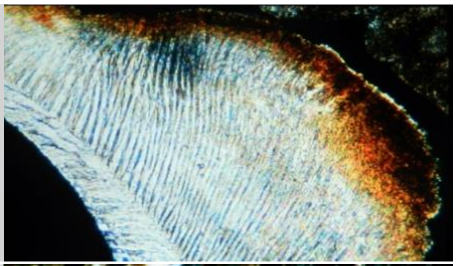
- **Molluscs**: occur in limestones from the Early Paleozoic
- **Bivalves** (**pelycepods**): Composed of aragonite, & some such as the oysters high Mg-clacitic
  - ➢ aragonite dissolved during diagenesis & leave mold which filled with calcite cement (drusy calcite), so the clear coarse ***sparite*** or ***neomorphic calcite*** are formed

Preservation of original structures	
Origin	Preservation of Structure
Calcite	Preserved
Aragonite	Not preserved

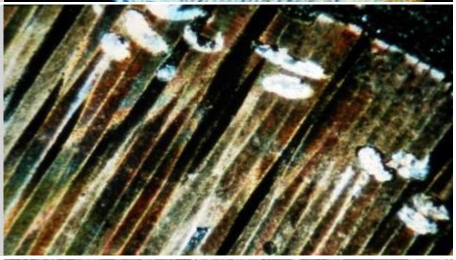


  - ➢ The aragonite can be replace by calcite (***calcitized***), so faint relics of internal structure (growth lines) can be preserved

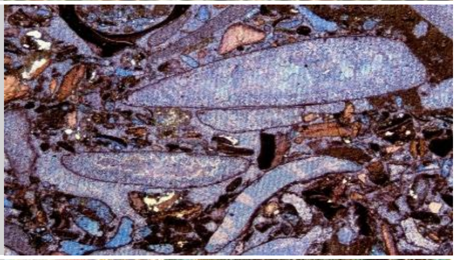
Crossed-lamellar one of the major types of ***aragonitic textures in mollusks***, from a Holocene ***gastropod***. The narrow bands of alternating light & dark extinction which wedge out along axis



An inoceramus shell with very distinctive prismatic structure Break up into individual prisms which constitute important fraction of some sediments. boring in hell wall

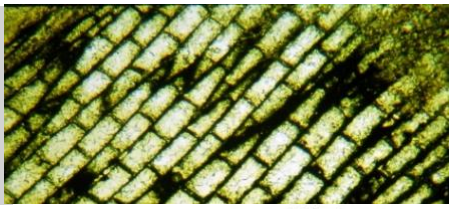


The importance of micrite is in preserving of fragments Original aragonitic molluscan shell are dissolved & mould outlined by a thin micrite envelope, which filled by Fe-drusy sparry calcite

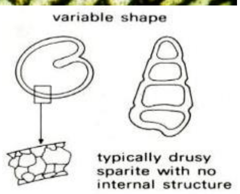


Calcitization of the shells of bivlaves The shells consist of a blue-ferroan calcite sparry mosaic, but there are lines of inclusions cutting across crystal boundaries & indicating the original foliated structure of the shell

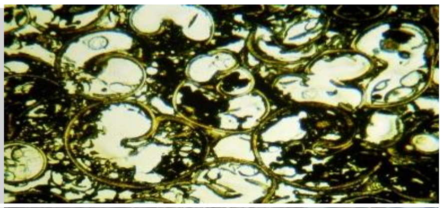
The well preserved cellular prismatic outer layer of the shell. These rudists are the major contributors to Cretaceous reefs & bioherms



- **Gastropods**: aragonite with cross-lamellar structure, similar internal microstructure to bivalves
  - ➢ **Shape of fragments**: helical, globular, or conical



Sorted gastropod limestone with fresh water gastropod. The variety of shapes produced by different angles of section

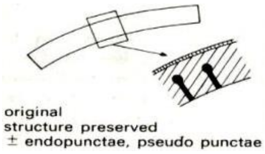


Longitudinal high-spiral gastropod Aragonite converted to calcite with loss of internal detail, yet internal & external outline are faithfully preserved by micrite

- **Cephalopods**: originally aragonite & found in limestone as sparite with little or no internal structure, including nautiloids & ammonoids
  - ➢ **Nautiloid & ammonoid shape**: large in size, characterized by presence of septa

BRACHIOPODS

- **Brachiopods**: similar to bivalves but composed of low-Mg calcite, so that the internal structure is well preserved



- brachiopod modified by punctae & pseudopunctae

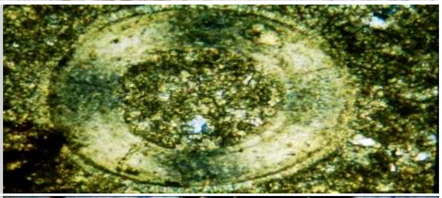
Punctate (Endopunctate)	Fine tubes, perpendicular to shell perforate inner layer & filled with sparite or micrite
Pseudopunctate	prominent rod-like prisms within the shell

Small brachiopods with the large pedicle valve & smaller brachial valve

A brachiopod fragment with outer prismatic layer preserved (is impunctate having no punctae)

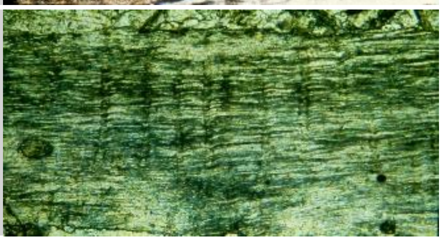
Broken brachiopod with 2 valves, & micrite envelope Fibrous structure & the fine tubes at right angles to the wall (endopunctae) sparis blue stained due to high Fe

Brachiopod spine Fibrous structure yielding pseudo-uniaxial cross, central canal, & outer wall



punctate brachiopod clearly defined pores (punctae) completely penetrate shell, filled with micrite (micrite-coated echinoderm & bryozoan fragments)

pseudopunctate brachiopod parallel fibrous wall structure with small plications that run vertically via shell. These are the true pseudopunctae that do not represent actual openings or pores in the shell

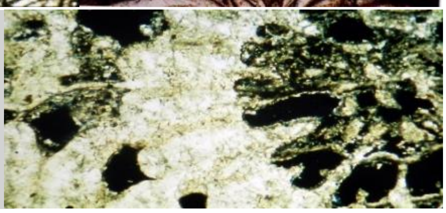


CORALS

- **Corals:** reef-forming at present time, identified based on internal feature such as septa & other internal plates
- ***Rugose & Tabulate corals***: calcite (well preserved)
- ***Scleractnian corals***: aragonite (poorly preserved)

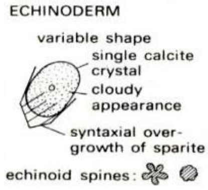
Rugose coral (Lithostrotion)

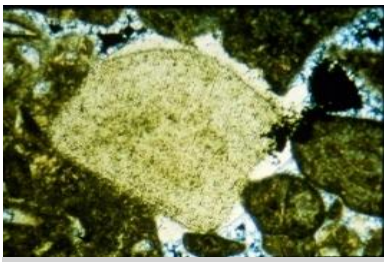
Scleractinian coral original septa (central dark line) & partial filling of living chambers, Considerable recrystallization has occurred



ECHINODERMATA (ECHINODERMS): Echinoids & crinoids

- **Echinoderms** skeletons are calcite, & modern forms have high-Mg content
- asily identified because:
  1. each grain composed of a large calcite crystal (unit extinction)
  2. Have syntaxial overgrowth of sparite cement
  3. The fragments has dusty or cloudy appearance
  4. Show porous structure filled with micrite or sparite

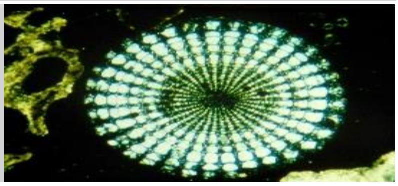




Large echinoid fragment single-crystal extinction & uniform granular microstructure (small pores filled with dirt), Early calcite overgrowth in optical continuity with grain, & later silica cement

Large crinoid ossicle single crystal extinction, Circular shape & central canal (common)

Echinoderm spine show single-crystal structure & very characteristic lacy pattern

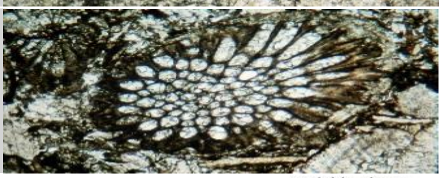


BRYOZOAN (ZOOECIA)

Broyozoa encrusting 2 brachiopod spines (circular), concentrically-laminated grains Thick calcite wall of the bryozoan & the pores (***zoooecia***) of different sizes filled with calcite cement

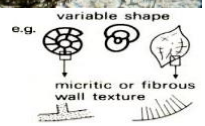
A large bryozoan frond with regular circular to elongate holes (zooecia) & fibrous wall structure

A large bryozoan frond showing typical shape & structure

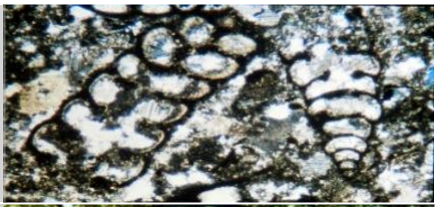


FORAMINIFERA

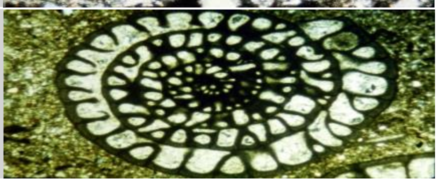
- **Foraminifera**: Composed of low-Mg calcite or high-Mg calcite



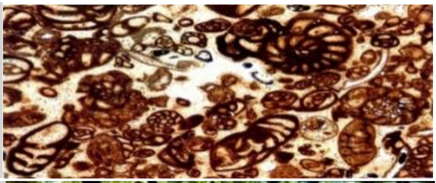
Sections through uniserial & biserial foraminifera Micritized wall structures & chamber shapes



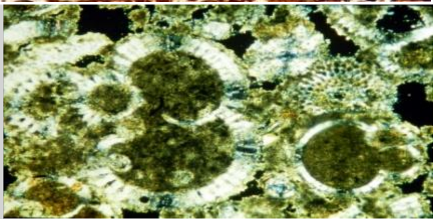
Fusulinid Foraminifera Chamber shapes & radial wall structure



A limestone composed largely of miliolid Foraminifera



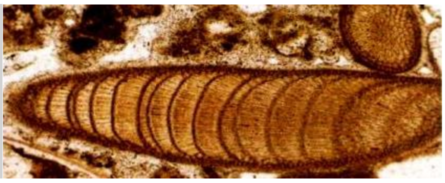
planktonic Foraminifera well-preserved porous radial wall structure & micrite filling of chambers



ALGAE & MICROBES

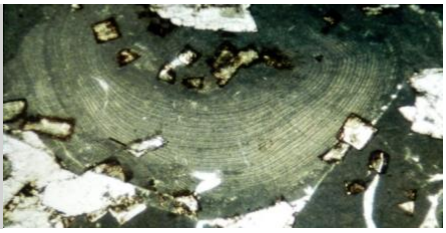
- Algae & microbes make a major contribution to limestone by providing skeletal carbonate particles, trapping grains to form laminated sediment, & attacking particles & substrates via boring activities
- **Groups of algae**: red algae (Rhodophyta), green algae (Chlorophyta), yellow-green algae (Chrysophyta), & blue- green algae (cyanobacteria)
- **Rhodophyta (red):** Calcareous (cryptocrystalline calcite)

Calcareous red algae, Lithothamnion in longitudinal section (showing seasonal growth zones)



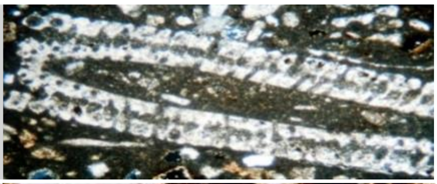
Very well-preserved red alga, possibly Lithophyllum. The cellular structure, branching form, & good preservation characterizes this type

Large red algal with typical laminated & cellular structures. Cut by rhombs of dolomite (often selectively because of original high Mg content)



- **Chlorophyta (green algae):** Dasyclad, segments are cemented by sparite at grain contacts (***meniscus cement***) by meteoric waters
  - ➢ **Groups**: Codiaceae, Dasycladaceae, & Characeae

Large green-algal (Dasycladacean) with oblique cut through central cavity & radiating porous tubes



Dasyclad algae

A sediment made up largely of segments of the codiacean algae Halimeda. The rock is highly porous & thus impregnated (the brownish gray background)

- **Yellow-green algae (Chrysophyta, Coccoliths)**
  - ➢ ***Coccolithophorids***: planktonic algae, have low-Mg calcite skeleton with spherical coccosphere (10-100µm), numerous calcareous plate (coccolith)
  - ➢ Very important due to production of calcareous ooze in the deep oceans (<CCD)

SEM view of coccolith ooze Sediment is composed almost entirely of coccolith plates and fragments of planktonic foraminifera

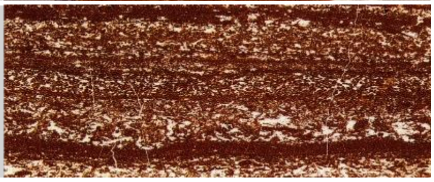
- **Micrite envelop:** dark micrite layers around grains formed by ***endolithic bacteria*** that filled pore space with micrite, degradation of this process produce a totally micritized grains (peloid devoid of skeletal)

Micrite envelops: Developed on brachiopod shells (the foliated structure) & echinoderm fragments (the speckled plates)

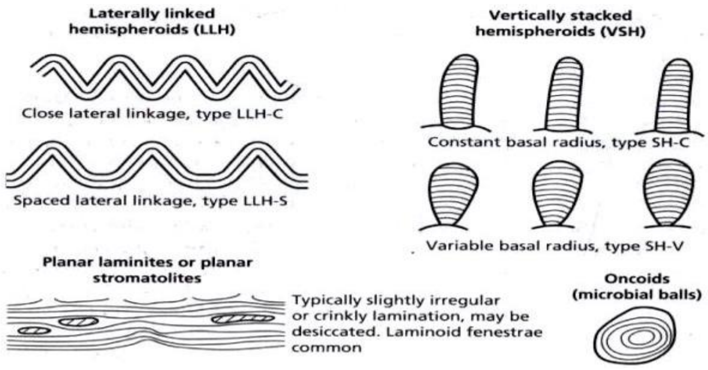
- **Stromatolite:** by microbial or algal mats (cyanobacteria)

Stromatolite Layering is irregular & picked out by color differences, & laminae may form flat or crinkly structure, or build up into columns or domes

Stromatolite appearing The laminations consist of alternating thin micriteic layers & layers containing a mixture of micrite & sparite



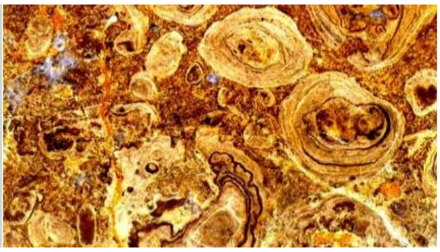
- ➢ Irregualr micrite area coating of filaments decayed, having a mold (filled with sparite cement)
- ➢ organic mats occur on sediment surfaces & form planar sheets, columns, & domes



- ➢ Cyanobacteria have filaments enable it to trapping & binding with sediments which may be preserved
- ➢ The lamination in modern intertidal mats consists of couplets of dark organic rich layers with light
- ➢ **The alternating laminae reflect** growth of mats followed by sedimentation, then trapping & binding of the sediment particles into the mat, as microbial filaments grow to form a new layer

- **Microbialites**: laminated structure formed by mats
- **Oncoids:** microbial-structure formed by cyanobacteria, have balls or nodules shape with internal concentric lamination, which may be asymmetric, composed of micrite or more clotted

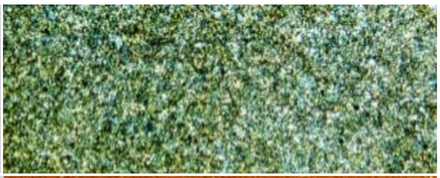
Polished rock surface showing oncoids
The bluish areas are sparry calcite



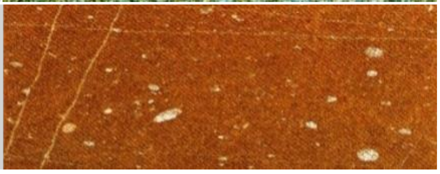
MATRIX (LIME-MUD & MICRITE)

- **Micrite**: microcrystalline calcite (<4μm) exists as matrix

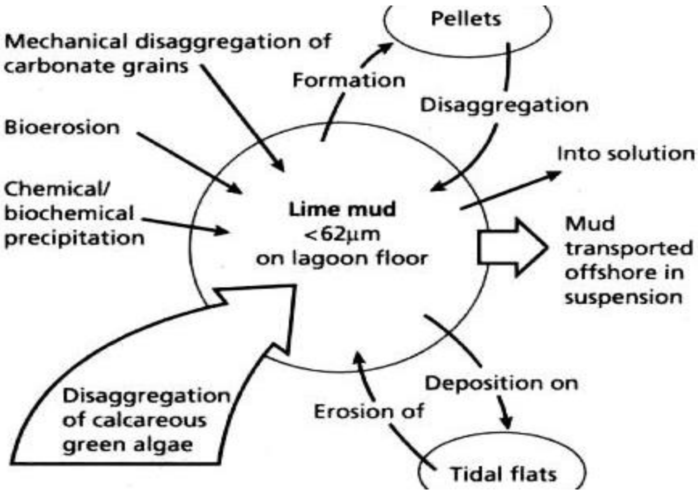
Micrite (rather lithified carbonate mud)



Micrite with < 10% allochems (forminifera & radiolaria)

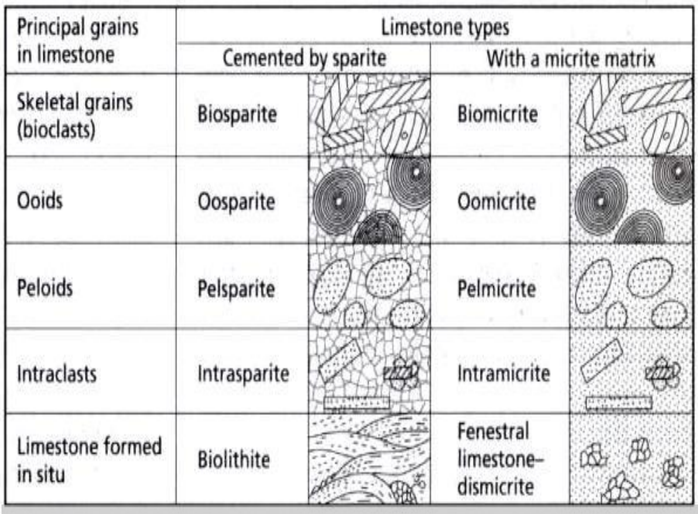


- **Carbonate mud environments**:
  1. Tidal flats & shallow lagoons to the deep-sea floor
  2. Subtidal areas of seas (aragonite needles & laths)
  3. The shallow subtidal zone are carbonate factory
  4. Deep-oceanic floor (oozes with chiefly of coccoliths, or larger foraminiferal & pteropod)
- Micrites are susceptible to **<u>diagenitic alteration</u>** & replaced by coarser microspar (5-154μm)
- **Lime mud formed by the following process:**
  1. **<u>Biogenic deposition</u>** 20% of total sediments
  2. **<u>Inorganic precipitation</u>** by occasional evaporation "whiting", a sudden milkiness of sea resulting from suspended aragonite needles
  3. **<u>Disaggregation</u>** of green algae in lagoons (source of mud in tidal flats)
  4. **<u>Bioerosion</u>**: organisms attack carbonate grains & substrates (e.g. boring sponges & microbes)
  5. **<u>Mechanical breakdown</u>** of skeletal: wave & current



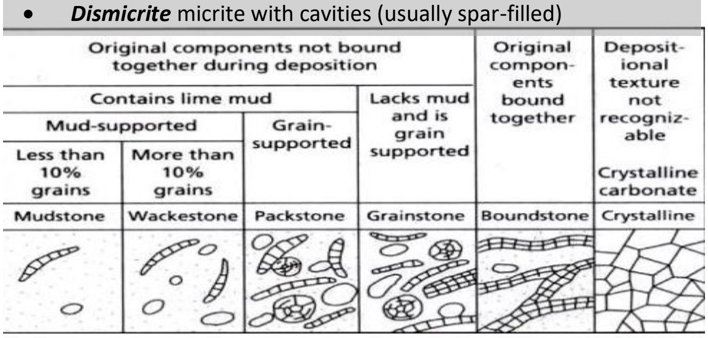
LIMESTONE CLASSIFICATION

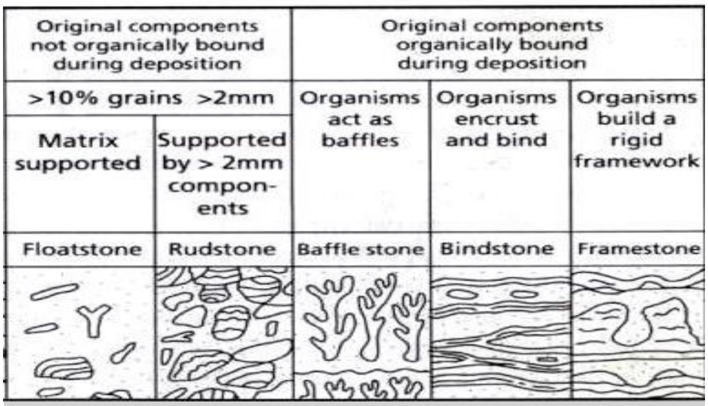
- **Simple classification**: based on grain size to *calcirudite* (>2mm), *calcarenite* (2mm-63μm), & *calclutite* (<63μm)
- **Folk's classification**: based on *grains* (allochems), *micrite* (matrix), & *cement* (usually sparite)
- **Dunham classification**: based on texture into *grainstone* (without matrix = bio- or Oo-sparite), packstone (grains in contact with matrix = biomicrite), *wackestone* (grains are coarse, & floating in matrix = biomicrite), & *mudstone* (just a few grains)



Folk's classification of limestone

- Terms can be combined if there are 2 type of grains (e.g. biopelmicrite, intrabiosparite…), or modified to gives an indication of coarse grain size (e.g. oosparrudite)
- ***Biolithite*** formed in situ (e.g.reef-rock, stromatolite)
- ***Dismicrite*** micrite with cavities (usually spar-filled)





Dunham's classification

Other terms: (after Embry & Klovan)

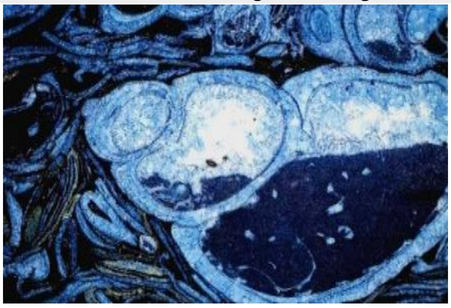
1. ***Skeletal grainstone, peloidal mudstone, or echinoidal rudstone***: give composition information
2. ***Floatstone & rudstone:*** to Indicate coarse grain size
3. ***Baffelstone, bindstone, & framestone***: the type of organic binding in boundstone

LIMESTONE STRUCTURES

Bedding plane	***Formed by change in sedimentation condition reflected in grain size, composition, & lithology***
Hardground surface	***Type of bedding planes, horizons of synsedimentary cementation taking place at or below sediment surface*** • encrusted by sessile benthic organisms (e.g. corals, bivalves "oysters", foraminifers, & bored) • hardground surfaces may become mineralized & impregnated by Fe-Mn oxide, P, & glauconite
Tepee	***disruption bedding to "pseudoanticlines" & in plan view tepee crests form polygonal pattern*** • **Formed on** intertidal to supratidal flats, distinctive structure of peritidal limestone • **Result by** cementation & expansion of sediments
Palaeo-karstic surfaces	***Bedding discontinuity, irregular & pot-hold surface*** • **produced by** dissolution of emergent carbonate by contact with meteoric water
Karst	Dissolution features • **Result by** by chemical weathering in humid regions
Current & wave structures	***Wave & current ripple, cross-lamination, scour, channel, hummocky cross-stratification, sole, turbidity*** • **Used in** environmental interpretation & facies analysis, giving information on depositional process, paleocurrents, depth, & water turbulence

CAVITY STRUCTURES	
Geopetal	partly filled with sediments that washed into occupy lower part of the cavity, with the space above occupied by a later sparite cement, indicator to sparite at the top
Fenestral (birdseyes)	Small cavities, in peloidal mud-stone of intertidal to supratidal areas, spar-filled or sediment-filled • **Irregular** ascribed to gas entrapment &desiccation so characteristic intertidal facies indicators • **Laminoid:** In laminated sediment from decay of organic matter, desiccation & parting of laminae • **Tubular fenestrae**: formed by burrowing organisms & plant roots
Stromatactis	Irregular cavities, with unsupported roof & flat floor • **cement**: fibrous calcite, followed by drusy sparite • **formed by:** organic or inorganic internal sediment • **Organic:** Recrystallization of bacterial colonies, algal, cyanobacteria, uncemented sponge decay • **Inorganic origin:** collapse, dewatering, & dissolution of sediments during burial diagenesis

Geopetal structure within a gastropod



DIAGENESIS PROCESS

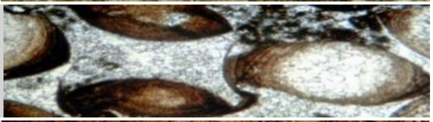
Diagenesis Process	
Cementation	***Precipitation*** of $CaCO_3$ in pore-spaces
Compaction	during burial diagenesis, & resulting in ***closed packing of grains, fracture, & internal dissolution*** Leads to stylolite & dissolution seams
Dissolution	passage of ***pore fluids*** which under-saturated with carbonate, tack place in near-surface marine, meteoric diagenetic, sea floor, &during deep burial
Micritization	By Microbes
Neomorphism	***Change in mineralogy, transformation between one mineral & polymorph***
Dolomitization	Replacement of aragonite or calcite (i.e. limestones) into dolomite (i.e. dolostones)

COMPACTION

Mechanical compaction	After deposition, leads to closer packing of grains, & rotation of elongate grain parallel to bedding plane
Chemical compaction	By increase solubility at grain contacts & sediment interface under applied stress by increase overburden • **Texture**: Fitted Fabric, Stylolite, P-solution seams • **Stylolites:** through-going sutured surfaces that cut grain, cement & matrix indiscriminately

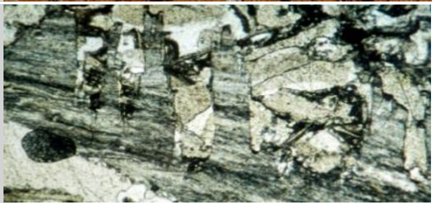
Machanical Compaction
Highly compacted bioclastic sediment, consisting of 2-valved ostracods & single ostracod (aligned parallel to the bedding & some show folding & fracturing)

Machanical Compaction
Strongly deformed ooids due to compaction



Chemical Compaction
Limestone that has undergone grains P-solution leading to fine saw-tooth appearance characteristic of styloiltes

An extreme case of stylolitization
Large brachiopod shell & numerous echinoderm fragments have mutually dissolved & interpenetrated each other



NEOMORPHISM

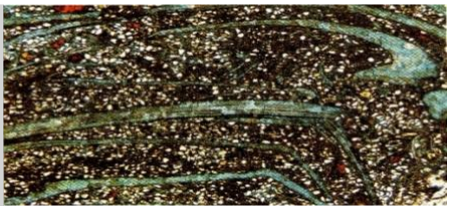
Replacement	**Microspar-pseudospar formation**: From micrite
Recrystallization	coarsening of micrite
Aggrading neomorphism	fine-micritic matrix (<4μm) replaced by microspar (4-10μm) & pseudospar (10-50μm)
Calcitization	Replacement of aragonite or high Mg-calcite into low Mg-calcite (Degrading results in finer mosaic)
Silicification	Replacement of calcite or dolomite by silica (Sponge, diatoms, & radiolarians are the main sources of silica required for silicification)

limestone with fine pseudospar matrix

microspar limestone

- **Neomorphic recognized by**: Irregular or Gradational or curved intercrystalline boundaries, irregular crystal-size distribution, skeletal grains floating in coarse spar

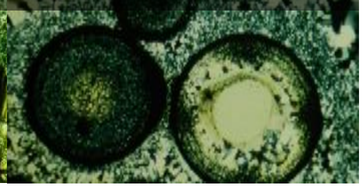
Neomorphism of the parts of the bivlaves shells
consist of a blue-ferroan sparite mosaic & lines of inclusions cutting across boundaries indicating original foliated structure



- **Diagenetic silica**: euhedral-,micro-,mega-,chalcedonic-Qz

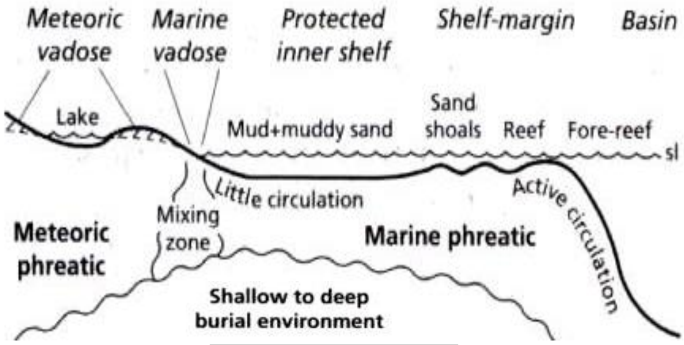
Chalcedonic quartz infilling of a calcareous sponge

Complete silica replacement of carbonate (oolitic) sediment



DIAGENESIS ENVIRONMENTS

Near-Marine	Diagenesis takes place on & below sea-floor in shallow water, deep water, & in the intertidal to supratidal zone
Meteoric diagenesis	affect a sediment soon after deposited in shoreline progradation or sea level fall, or operate after burial
Burial depth	at a depth below the sediment surface 10's – 100's m (near metamorphism), below the zone affected by surface processes

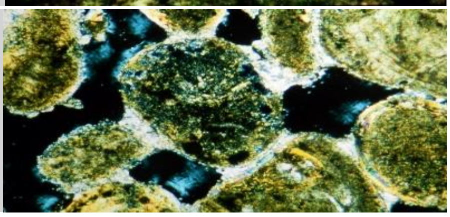


MARINE DIAGENESIS

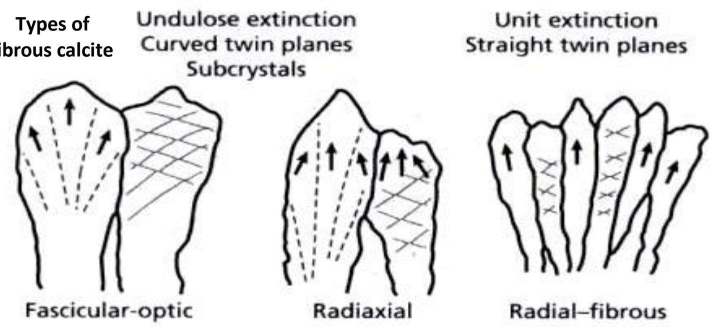
MARINE DIAGENESIS IN RECENT CARBONATE SEDIMENTS	
Beachrocks	Cements produced in intertidal zone, composed of calcareous sediment & may have siliciclastic component
Isopachous	Equal thickness, indicating marine phreatic (below water table) precipitation where pores water-filled
Asymmetric cement fringes	Meniscus or vadose cements, formed in marine vadose, Thicker on underside of grains, & concentrated at grain contacts, have fibrous shape, recorded from beachrock
MARINE DIAGENESIS IN ANCIENT LIMESTONES	
Marine calcite cement	1st generation cement, form isopachous fringes around grains, cut by borings or skeletal debris, crystals are non-ferroan & non-luminescent, succeeded by clear spar
Ancient cement	Marine calcite, Fibrous, with elongate crystals oriented normal to substrate, with cloudy or dusty appearance

Beachrocks
uniform isopachous fringe of fibrous aragonite-needle holding together oolitic

Meniscus calcite cement (vadose cement)
Cement found grain contacts (presumably where water meniscus water films were trapped), no complete cavity linings

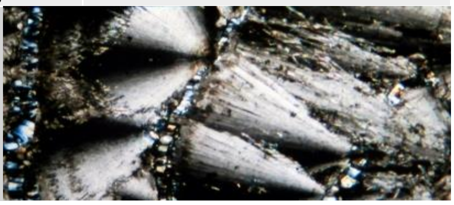


Types of fibrous calcite



Extention	Twin planes	Types
Undulose	Curved	Fascucular-optic, Radiaxial
Non-undulose	Straight	Radial fibrous

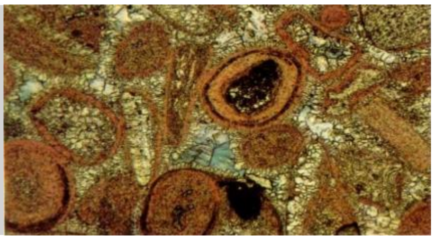
Coarse fibrous calcite crystals showing radially oriented fan-shaped clusters interspersed with thin rinds of gypsum



METEORIC DIAGENESIS

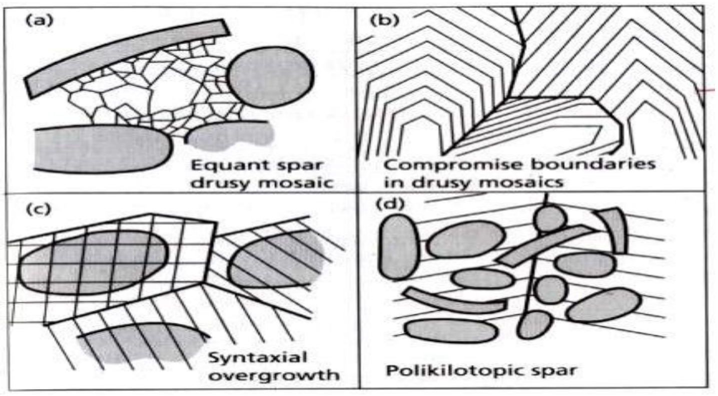
- **processes**: dissolution, cementation, soil formation
- The position of groundwater table is important, Vadose zone above is distinguished from phreatic zone below
- In **phreatic zone** (below water table) all pores are filled with water, low-Mg calcite is precipitated on the surface of grains as in isopachous fringe (uniform thickness)

2 cement generation:
a rim of crystals of equal thickness (isopachous) with radial fibrous fabric
a pore fill of equant sparite blue stained & thus ferroan calcite precipitated from meteoric water



CALCITE SPAR (SPARITE)

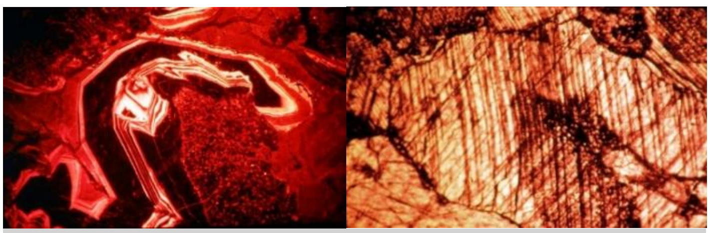
- **Sparite (calcite spar)** clear, equant, occupies pore space
- **Location:** between grains & skeletons, or within cavities
- **Characterized by:** clear, inclusions, pf planar boundaries
- **Precipitated after** the fibrous calcite (marine cement) so fibrous called A & spar called B



Types of calcite spar cement	
Drusy (common)	characterized by an increasing crystal size away from the substrate towards the cavity center
Growth zones	straight crystal boundaries (compromise boundaries) between adjacent crystals
Syntaxial overgrowths	in optical continuity with a host grain, twin planes from cement to grain
Poikilotopic	large crystals enveloping several grains

Large echinoderm fragment show characteristic unit extinction & uniform granular microstructure & early calcite overgrowth in optical continuity with grain, & later silica cement

- Calcite spar crystals are delicately zoned as a result of subtle variation in Fe-Mn contents. This zonation revealed by observing cathodoluminescence view



A transmitted light photomicrograph (left) illustrating a cement zone in crinoidal limestone constituted only of one generation of overgrowth. Right is a photomicrograph show five generations of cementation.

DEPOSITIONAL ENVIRONMENTS

- **The major depositional environments of carbonate limestone is a shallow marine Environments**

NON-MARINES CARBONATE SEDIMENTS

- **Lacustrine limestones:** chemically presentated in lacks, arranged similar to their marine equivalents
  - ➢ Stromatolite (reefs) & ooid shoals occur in agitated shallow waters, & lime muds shoreward on litoral flats in protected bays & in central deep lakes

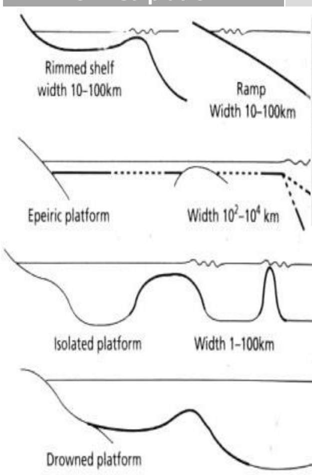
Lake-deposited carbonates	
Inorganic precipitates	Forms lime mud, Ooids, & besides mud • produced by: **evaporation** aided by CO_2 loss due to photosynthesis, **changes in P-T**, **mixing** of fresh stream (spring water with saline lake water)
Carbonate sediments (organic)	Form stromatolites, & Oncoids • Produced by activities of algae, cyanobacteria, microbes, & phytoplankton blooms
Skeletal sands	Contain fragments of calcareous algae, such as Chara, bivalves, & gastropods

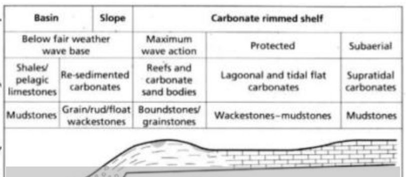
- **Calcrete or caliche:** pedogenic carbonate (soil-related)
  - ➢ Calcareous soils formed in river floodplains, aeolian, lacustrine, colluvial, & marine (subaerially exposed)
- **Textures of Calcrete or Cliche**:
  1. Nodules or massive, laminated & pisolitic layers
  2. **Alveolar**: spar-filled small tubes formerly occupied by rooltlets, characterized by delicate micritic "septa", formed by calcification of fungal filaments
  3. **Rhizocretion**: rootlet encrustations
  4. Coating & pisoids (by calcification of fungal-cluster)

MARINE CARBONATES & CARBONATE PLATFORMS

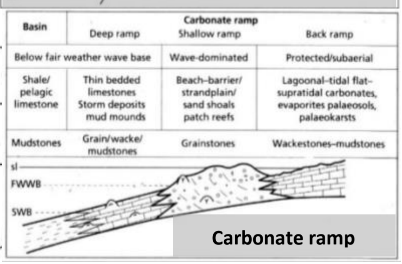
- Shallow marine carbonate are deposited in platforms
- **Carbonate platforms**: located in passive continental margins, intracratonic basins, & failed rifts

Types of platform, each with a particular facies & facies associations	
Rimmed shelf	**10 – 100 km**
Carbonate ramps	**10 - 100km**
Epeiric platform	**100 – 10000 km**
Isolated platform	**1 – 100 km**
Drowned platform	





Rimmed shelf: Facies, limestone types



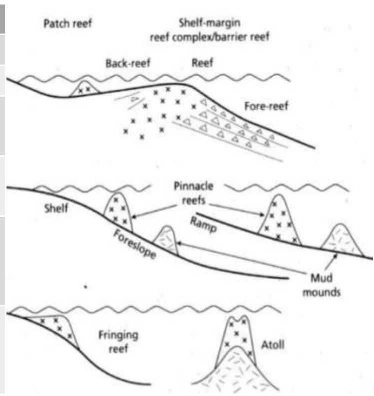
Carbonate ramp

- **Rimmed shelf**: shallow-water platform with a distinct braek-of-slope into deep water
- **Carbonate ramps:** gently sloping with high-energy, inner ramp shoreline passing offshore, deeper-water outer ramp, affected periodically by storms

REEFS & CARBONATE BUILD UPS

- **Carbonate build ups:** are locally formed limestone bodies that had original topographic relief.
- **Reefs**: restricted to carbonate build up that possesses wave-resistant framework by organisms

Types of reefs	
Patch	Small & circular
Pinnacle	Conical
Barrier	separated from coast by a lagoon
Fringing	Attached to coast & atoll, enclosing lagoon
Bioherm	Local in organic growth situ with or without framework
Biostrom	Laterally extensive in situ growth may contain framework



- Different organisms involved in construction of reefs:
  1. **Corals & coralline algae:** builders reef
  2. **Different invertebrate groups (cyanobacteria & microbes):** Stromatolites bioherms or biostromes (Precam – Cam), stromatoporoids (Ordo – Devo), rugose corals (Silu – Carboni), scleractinian corals (Tri-Rec), sponges (Tri-Jur), rudistid bivalves (Creta)

Roles of organisms in reefs	
Framework builder	Provide skeletal framework
Frame-binders & encrusters	Consolidate the framework (e.g. calcareous algae & bryozoans)
Reef-users	e.g predatory fish, & echinoderms
Factors controlling the present of coral reefs	
Water T	Optimum growth occurs around 25°C
Water depth	Most takes place within 10m
Salinity	Corals cannot tolerate great fluctuation
Turbidity & wave action	Intensive wave action & absence of terrigenous silt & clay

PELAGIC LIMESTONES

- **Accumulate in** the absence of terrigenous clays, if water depth is too great for benthic organisms to flourish (50-100m) to a depth of CCD
- **Bellow CCD** carbonates are dissolved due to low T which increases CO_2, so water becomes undersaturated with respect to aragonite & calcite
- **CCD varies in tropical water**

Depths	Accumulation of
4500 – 5000m	Calcite
2500 - 3000m	Aragonite
Ocean floor	Calcareous oozes
Below CCD	Siliceous oozes & red clays

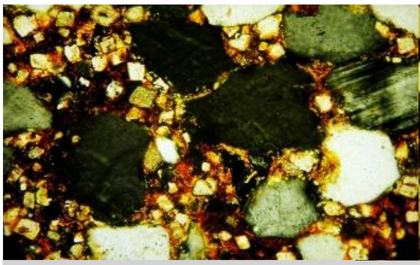
- **Modern pelagic carbonates sediments are composed of** pteropods (aragonitic), coccoliths & foraminifers
- **Besides pelagic fauna & limestones characterized by**:
  1. **condensed nature**
  2. **evidence for synsedimentary cementation**: in the form of hardgrounds, lithoclasts, sheet cracks, & Neptunian dikes
  3. **nodular-like appearance**
  4. **presence of frromagnesian nodules & crusts**

DOLOMITE & DOLOMITIZATION

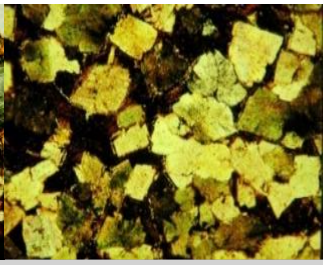
- **Dolomite $CaMg(CO_3)_2$**: rhomohedral, with equal Ca^{2+} & Mg^{2+} arranged in separate sheets with planes of CO_3^{2+}
- The well-ordered nature of the lattice is responsible for reflections XRD not present in calcite, & modern dolomites have a lower degree of ordering

Protodolomite	Dolomite with Ca:Mg = 50:50
Ferroan dolomite	Dolomite with few mol%$FeCO_3$
ankerite	$CaMg_{0.5}Fe_{0.5}(CO_3)_2$

- **Pencontemporaneous dolomitization**: replacement of calcite by dolomite & precipitation of dolomite cement
  - During early diagenesis & after deposition
  - After cementation (long time after deposition)
- **Primary dolomite:** directly precipitated from sea or lake
- the majority of dolomites formed by dolomitization



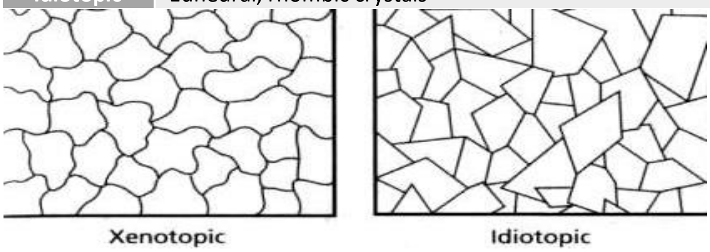
Dolomite rhombs replacing a micritic matrix between framework Qz & Fs



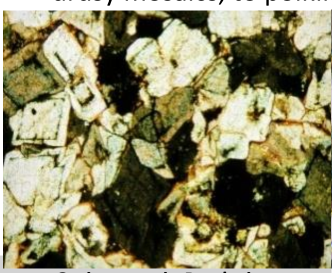
Dolomite rock (dolostone) consisting entirely of rhombs

- Dolomite is used to indicate mineral & rock type
- The term ***dolostone*** used for the dolomite rocks & described in terms of Dunham's or Folk's classification, preceded by the word dolomitic or prefixed by dolo-
  - ***dolorudite***, ***dolarenite***, ***dolosparite***, & ***dolomicrit***
- dolomitization not totally destroyed original structures

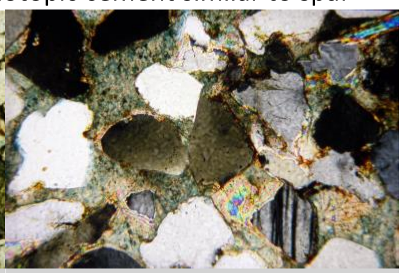
Dolomite Textures	
Xenotopic	Anhedral, & curved to serrated, with irregular boundary
Idiotopic	Euhedral, rhombic crystals



- Dolomite are ***zoned***, the inner part is more cloudy (from fluid inclusions or calcite relics) & the outer part is clear
- **Dolomite cements:** opposed to replacement, in primary & secondary cavities in many limestones, dolomites, & sandstones, vary from cavity lining of clear rhombs to drusy mosaics, to poikilotopic cement similar to spar



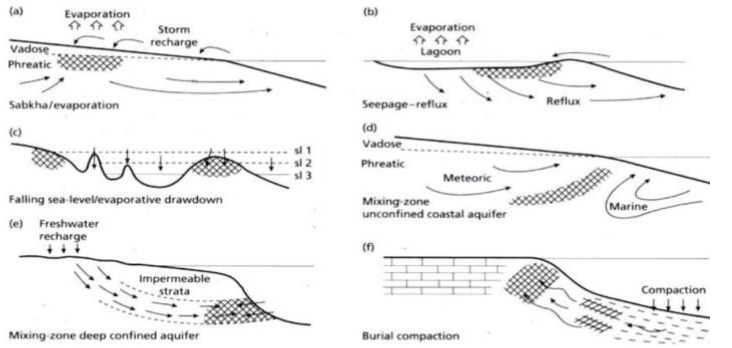
Grain-to-grain P-solution
Before the pores were filled by a cement, stress was concentrated at points contacts



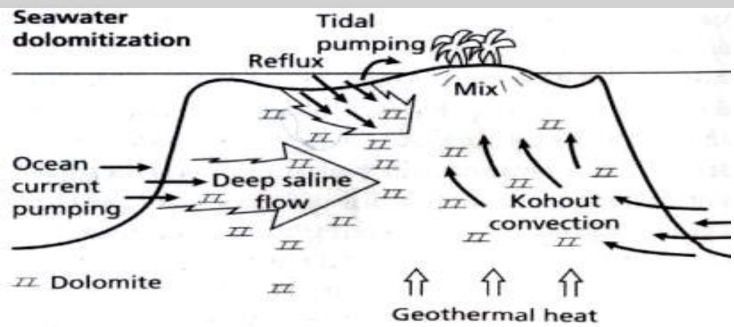
Poikilotopic dolomite engulfing several Qz & Fs (The dolomite is stained turquoise blue due to high Fe-content)

ORIGIN OF DOLOMITE & DOLOMITIZATION MODELS

- Sea water is super saturated with respect to dolomite, but the highly ordered structure of dolomite prevents precipitation. Instead, aragonite & high-Mg calcite, with their simpler structure are precipitated
- The source of Mg ions is the major concern
- **Dedolomitization arise from** contact meteoric water

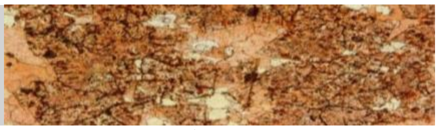


Models of dolomitization: mechanisms for moving dolomitizing fluids



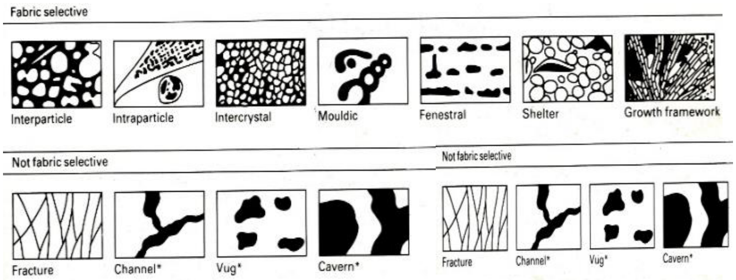
- **The dedolomite recognized by:** noting dolomite crystal (rhombohedral), occupied by calcite (pseudomorph), & fabrics calcite inclusions

Dedolomite with spar rhombs outlined by Fe-oxide & inclusion indicative of former dolomite rhombs



POROSITY

- Carbonate sediments porosity of after deposition is very high (80% in lime mud, 50% in sand)
- **Forms by** dissolution, dolomitization,tectonic fracturing
- **Reduced by** cementation, compaction, & P-solution
- Porosity in limestones could be either primary (depositional) or secondary (diagenetic or tectonic)
- secondary porosity created by carbonate dissolution are very important in hydrocarbon reservoirs



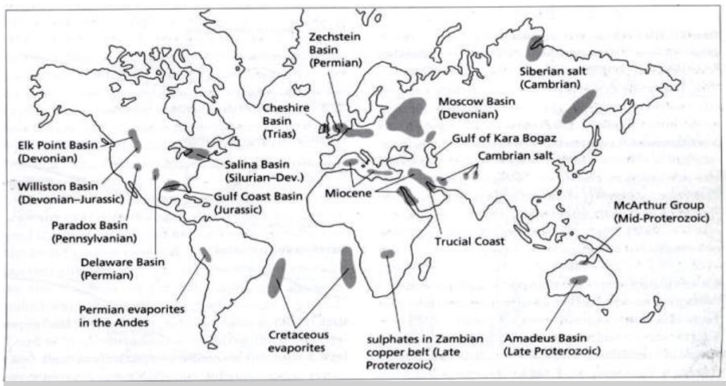
Primary porosity	Secondary porosity
Framework: formed by rigid carbonate skeletons (reefs, algae)	**mould, vug, cavern** by dissolution (meteoric, basinal, connate water)
Interparticle in carbonate sands	**Intecrystalline:** by dolomitization
Fenestrae (birdseyes) in muds	**Fracture:** by tectonic P, via collapse, & brecciation of limestones

EVAPORATES SEDIMENTARY ROCKS

- **Evaporites**: chemically precipitated sediments, precipitated from water following evaporative
- **Evaporite series:** calcite or dolomite, Halite, Gypsum or Anhydrite, & Finally Na- or Mg-source

Marine evaporate minerals	Non-marine evaporate minerals
Sylvite KCl	Gypsum, Anhydrite, Halite
Halite NaCl	Epsomite $MgSO_4.7H_2O$
Carnallite $KMgCl_36H_2O$	Trona $Na_2CO_3.NaHCO_3.2H_2O$
Kainite $KMgClSO_4.3H_2O$	Mirabilite $Na_2SO_4.10H_2O$
Anhydrite $CaSO_4$	Thenardite $NaSO_4$
Gypsum $CaSO_4.2H_2O$	Bloedite $Na_2SO_4.MgSO_4.4H_2O$
Polyhalite $K_2MgCa_2(SO_4)_4.2H_2O$	Gaylussite $Na_2CO_3.CaCO_3.5H_2O$
Kieserite $MgSO_4.H_2O$	Glauberite $CaSO_4.Na_2SO_4$

- Non-marine environment: lacks, soil, weathering Profile
- Evaporites are of great economic significance & have many uses & applications
  1. Act as **cap rocks** to carbonate reservoir rocks
  2. **Affect structural traps** through salt diapirism
  3. **Paleogeographic indicators**: arid regions, low latitudes, low relative humidity, high T, & areas where evaporation exceeds precipitation



location & age of major evaporite deposits & the location of the Trucial Coast, Arabian Gulf, where sabkha sulphates are forming today

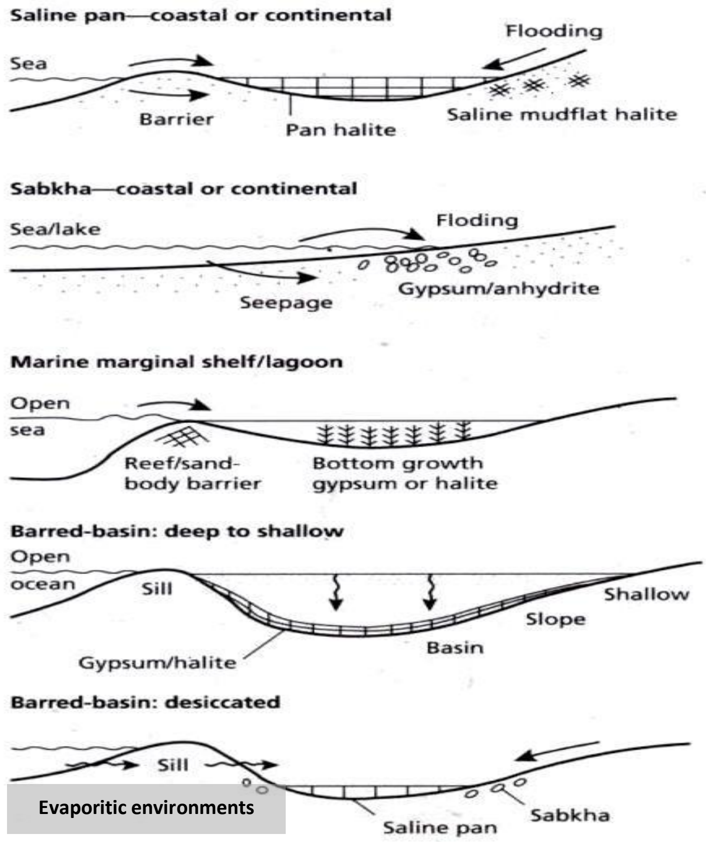
- At present time, evaporites are formed but not to the same extent as in some intervals of the past

deposited	Evaporation of seawater (reduces vol%)
Halite	9.5%
Gypsum	19%
Mg & K minerals	Complete dryness (100%)

DEPOSITIONAL ENVIRONMENTS

- Thick evaporite successions (reaching > 1000m), fill many ***large intracratonic sedimentary basins***
- Other evaporite formations grade with ***non-evaporitic sediments*** (limestone, marl) occur on stable platforms, shelves, subsiding basins, intracratonic rifts as dead sea salts, & Tertiary evaporites on either side of the Red Sea
- In marine environment, a barrier (reefs, sands, & silts) is required to allow the water to evaporate to high salinities, but water should be added to the brine body periodically from sea to replace the evaporated water

Principal modes of evaporite deposition	
Subaqueous precipitation	From shallow- to deep-water on a small (lake or lagoon) or large (intracratonic or rift basin) scale
Subaerial	In sediment(sabkha) or shallow desiccated saline pans

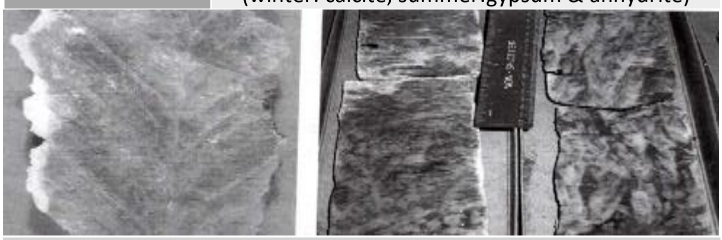


Evaporitic environments

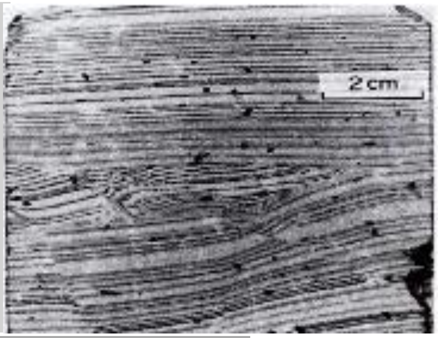
SUBAQUEOUSLY EVAPORITES

- Simple evaporate-dish process, with evaporates mineral
- In the past, evaporites precipitated subaqueous in shelf lagoons behind sand barriers, & barred-basin floors
- **Subaqueous gypsum** precipitated on lagoons, lakes, & shallow shelve floor (characterized by selenitic gypsum)
- **Textures**:
  1. the water-air interface, also nucleating on the sediment surface (**bottom growth**)
  2. ***selenitic*** gypsum growing vertically like grass, or single prismatic, or twinned swallow-tail
  3. **bedding feature (lamination)**: thin sulphate laminae, with laminae of another composition
  4. **palmate shapes** in anhydrite after selenitic gypsum

Lamination are characterized by	
Lateral continuity	Depend on the size of basins
Varved (organic)	season change lead to precipitation of 2 laminae (winter: calcite, summer:gypsum & anhydrite)



Bottom-growth gypsum: Twinned selenitic gypsum (left), palmate shapes in anhydrite after selenitic gypsum (right)

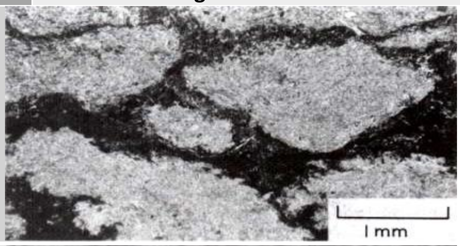


Laminated anhydrite Laminae of microcrystalline anhydrite alternate with organic-rich laminae. The synsedimentary faults & discontinuities that indicate downslope mass movement of sediments

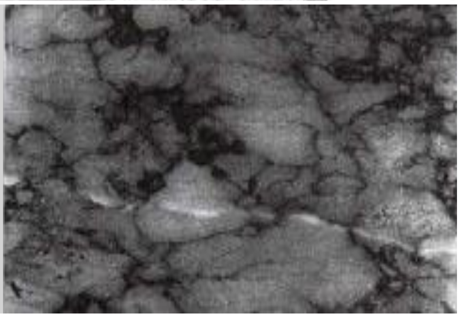
SUBAERIAL PRECIPITATION

- **Subaerial precipitation** of gypsum-anhydrite forms now within sediments of intertidal to supratidal flats (***sabkhas***) along Trucial Coast of the Arabian Gulf

Environments	
Vadose & phreatic zone	**From sediment pore water**
Oases	**Is the continental or inland sabkhas**
Other environments: Salt lakes & dry rivers in desert	
Textures	
Discoidal, rosette, selenite, & twinned	**(<1mm - >25 cm) in tidal gypsum of the coastal or inland sabkhas**
Chicken-wire	**Closely packed anhydrite nodules within host sediment restricted to thin stringers**
Enterolithic	**Nodules connected to each other forming irregular contorted beds**
Flood recharge	**Pore water in sediments comes from surface flooding of seawater**



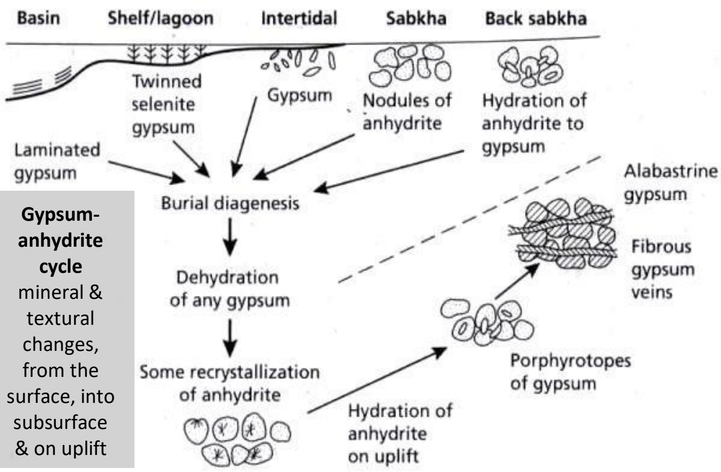
Nodules of aphanitic anhydrite, partly retaining shape of original gypsum crystals. Dolomitic host sediment between nodules



Chicken-wire anhydrite showing closely packed nodules of anhydrite with thin stringers of sediment

GYPSUM & ANHYDRITE

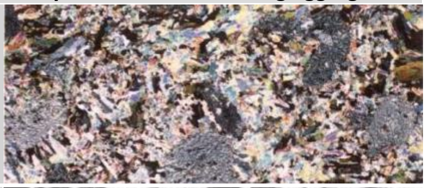
- **Carbonate dolomitization associated with gypsum precipitation**, due to increased in Ca/Mg ratio
- **If the host sediment is cohesive** the shape of original gypsum retained or pseudomorphosed by the anhydrite
- **The formation of anhydrite requires:** arid climate, high mean temperature (>22°), seasonal temperature (>35°)
  - **If the climate is less arid** primary nodules of gypsum crystals are formed within the sediment
- **Gypsum-anhydrite cycle**: in burial of gypsum & anhydrite to depths > Hundreds of meters, water gets out from gypsum converting it to anhydrite so in ancient rocks only anhydrite is occurring
  - If these rock subjected to uplift,anhydrite converted to gypsum upon contact with fresh meteoric waters



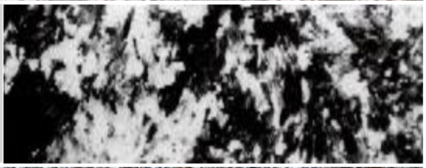
Gypsum-anhydrite cycle mineral & textural changes, from the surface, into subsurface & on uplift

Varieties of secondary gypsum	
Porphyrotope	**Large crystals, several mm's, 1st order IC**
Alabastrine	**small to large, poor interlocking,irregular extinction**
Fibrous (Satin Spar)	**Vertical fibers, parallel to subparallel to bedding planes, have displacive relationship (mm's – cm's)**
Primary textures of anhydrite (2nd order IC)	
Aphanitic	**Fine equant mosaic**
Laths	**Fleted & parallel to subparallel**
Recrystallization of mosaics & laths anhydrite produce	
Mosaic	**Coarse granular mosaic**
Fibrous	**Large fibrous crystals, & fibro-radiating aggregates**

Anhydrite & gypsum small crystals & laths of anhydrite (2nd IC) replaced by large porphyrotopic gypsum crystals (1st IC)



Alabastrine gypsum, formed by replacement of anhydrite



gypsum (a network of irregular crystals, & fibers or satin spar) & dolomite (fine-grained & opaque)

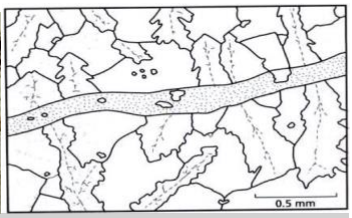
Sedimentary rock composed entirely of anhydrite laths with a radiating habit (2nd-order IC)

HALITE

- **Optically**: isotropic (cubic), strong cleavage & fracture planes, & possesses fluid inclusions

Textures	
Bedded	**Formed in** deep water (below water base) **Result from** color variation by clay content
laminated	**Formed in** deep water (below water base) **Result from** alternation of halite beds with anhydrite laminae (e.g. Permian Zechstein)
Chevron	**Formed in** saline pans & saline lake **Result from** precipitation of halite as a crust that break into polygons & tepees. Then the spaces & vugs filled with halite cement
Clear halite	**Formed in** saline pans & saline lakes

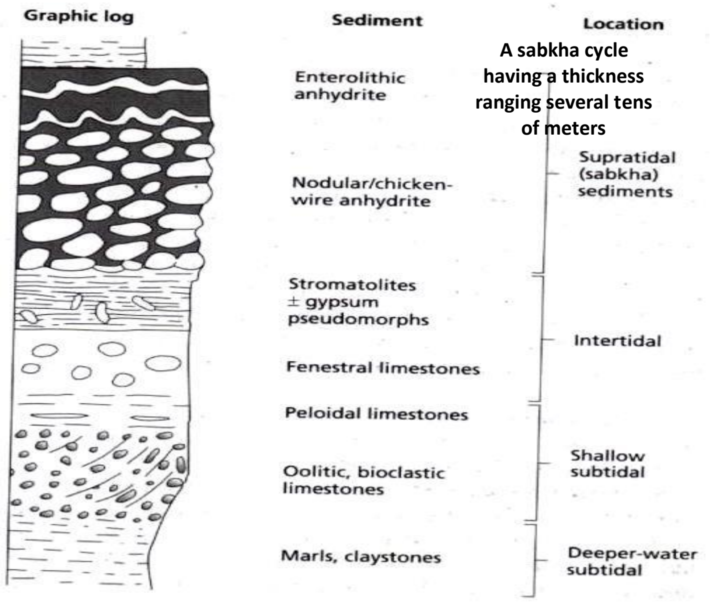
Halite & sylvite
Halite shows slight zoning, sylvite is reddish-brown in color owing to the presence of slight amounts of hematite. Minerals have perfect cleavage &are isotropic

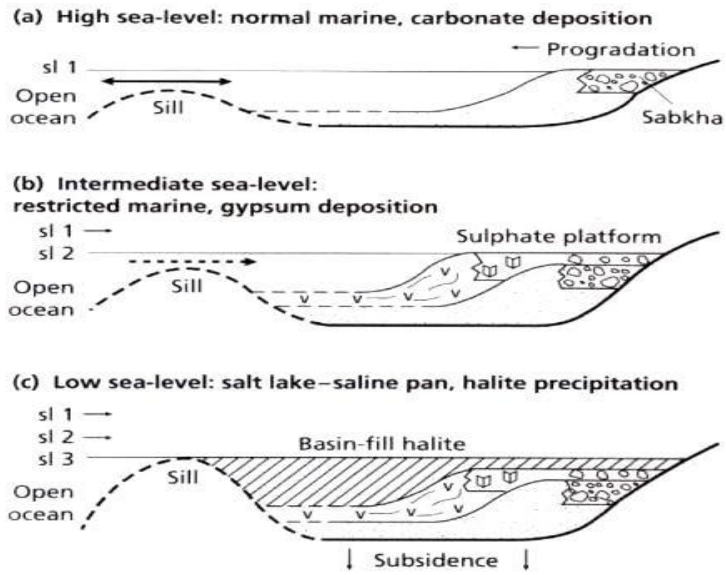


Sketch of chevron & clear halite with an anhydrite layer, plane polarized light

EVAPORITE SEQUENCES

- **The typical facies of ancient sabkha evaporites**: are nodules such as chicken-wire & enterolithic anhydrite
- **Feature of sabkha evaporite**: shallow-water & intertidal sedimentary structures & associated with carbonates
- **Sabkha cycle:** formed by progrades of sabkha seaward over the intertidal sediments as a result of deposition
- **Evaporite deposits are commonly cyclic, such as:**
  - ➢ Consist thin gypsum-anhydrite bed with little halite, alternating with limestone & marl
  - ➢ gypsum-anhydrite passing up to soluble halite, with thin beds of highly soluble bittern salts (K & Mg)





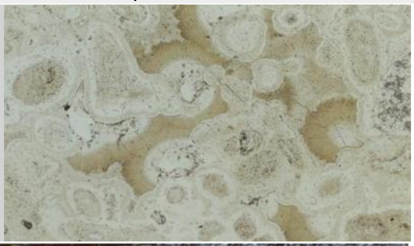
Model for evaporite deposition in an intracartonic basin, where eustatic changes are a major control

CHERTS & SILICEOUS SEDIMENTS

- **Chert**: fine-grained siliceous sediments, dense, hard, with conchoidal fracture, have inorganic, biochemical, biogenic, volcanic, or hydrothermal origin

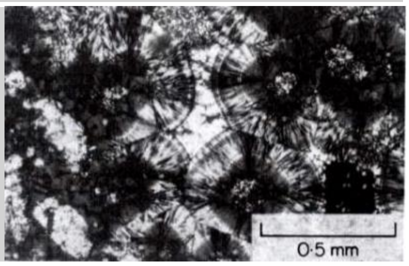
Flint	**Bedded & chert nodules, in Cretaceous chalks**
Jasper	**Red chert with fine disseminated hematite**
Porcelanite	**texture & fracture similar to unglazed porcelain & used for claystone, composed of opal-CT**
Cherts in the stratigraphic record are divided into	
Bedded cherts	**Origin:** Volcanic, biogenic (radiolarian, diatom) **primary marine accumulation**
Nodular cherts	**Origin:** diagenetic, deposited in lakes or form soils (silecretes), **occurs within limestones, mudstones, & evaporites**
Types of Quartz in Bedded & nodular cherts	
Micro-	Equant quartz crystals (a few microns)
Mega- (drusy)	Larger (500µm) with unit extinction, good shape & termination, occurs as filling pore spaces with increasing size from walls of pores to center
Chalcedonic	(10's–100's)µm, Fibrous, radiating, wedge-shape, mammillated, spherulitic structure

Microquartz, chalcedonic, & megaquartz (PPL)
The brown & pore-filling is chalcedonic, light brown or colorless is microquartz & megaquartz



microqrtz in circular to elliptical areas consisting of very fine quartz crystals (pin-point extinction) that replace original calcite. Megaquartz coarse equant quartz (with inclusions of high birefrengent calcite) indicating replacement origin of megaquartz to calcite grains. The chalcedonic Qz occurs filling spaces between replaced calcite grains in form of radial fibrous crystals

Chalcedonic quartz in spherulitic growth structure (XPL)



BEDDED CHERTS

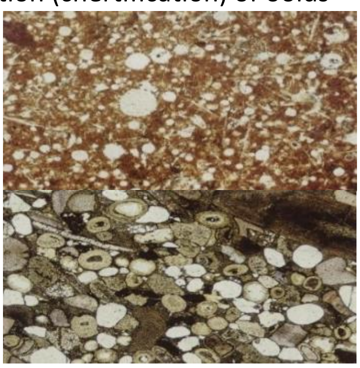
- accumulation in marine, have organic or volcanic origin
- **common in:** Precambrian banded iron-formations (Fe-formations) were no siliceous organism
  - **siliceous organism:** source of silica in volcanic materials & hydrothermal fluids
  - the sea water during the early Precambrian had higher concentration of silica than Phanerozoic & lower pH to promote primary silica precipitation

Organism that produce Chert: opaline silica, & up to 10% water	
Radiolarians	Marine zooplankton, disc-shaped, elongate or spherical test with spine, &surface ornamentation
Diatoms	Marine & non-marine phytoplanktons, have disc-shaped, elongate or spherical test with spine, & surface ornamentation
Siliceous sponges	Marine & non-marine, have similar size & Y-shape, giving circular & elongate sections in thin sections

- **Environments:**
  - **Siliceous oozes:** Radiolarian & diatom accumulating in abyssal plains where depths exceed CCD (4500m)
  - shallower depths than CCD where surface water is fertile & there is a paucity of calcareous plankton & terrigenous detrital material
  - **Ancient bedded cherts** occur in mountainous belts, & deep-water basins (rhythmic bedding)
  - **Deposited by turbidity** currents derived from some topographic high, & slided downslope as turbidity
  - **Volcanic:** deposited within or above billow lavas, igneous sedimentary assemblage (ophiolite suite), or devitrification of volcanic ash or biogenic silica
- **Diatomites:** Siliceous sediments rich in diatoms, such as the diatomite of the Azraq lake in Jordan
- The depth at which silica dissolves rapidly is the ***opal compensational depth (OCD)***, around 6000m

Structure	
Rhythmic bedding	**several cm's, with mm-thick beds & partings of shale**
Massive	**No internal sedimentary structure**
Cross-lamination	**Small scales, Parallel**
Other structures: Graded bedding, & basal scour	

- **May be consist of:**
  1. poorly preserved radiolarian test with microquartz-&megaquartz-filled moulds in matrix of microqurtaz
  2. Fine clastic & carbonate sediment may be present, produced by Silicification (chertification) of ooids



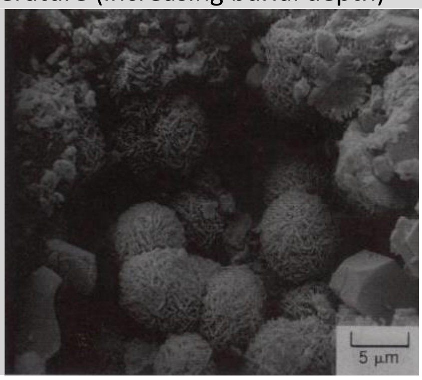
THE ORIGIN OF CHERTS

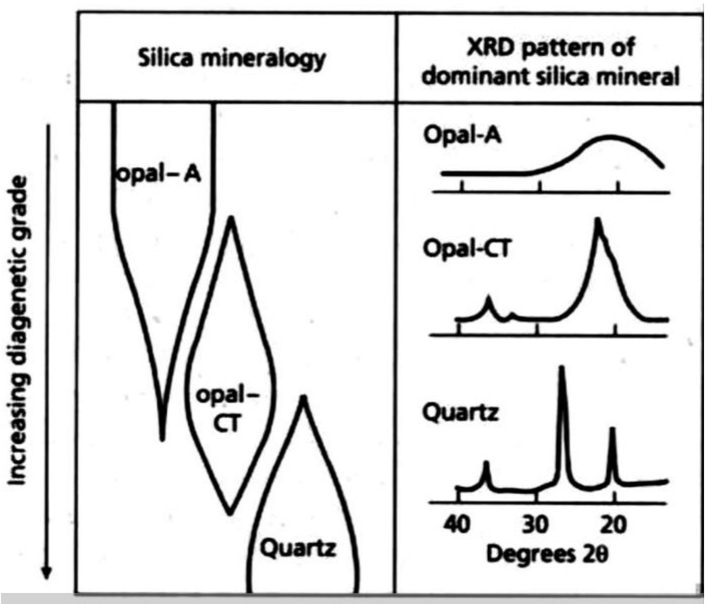
2 alternative views for formation of chert
Entirely biogenic: unrelated to any igneous activity
Submarine volcanism: inorganic precipitation of silica by: 1. **Directly,** subaqueous magma & hydrothermal fluids 2. **Indirectly,** plankton blooms by submarine volcanism **This view is rejected for Phanerozoic, but not for Precambrian because radiolarian cherts are only biogenic**

- **Seafloor volcanic activities**: restricted to oceanic ridges & hot spots, not give rise to regionally extensive cherts

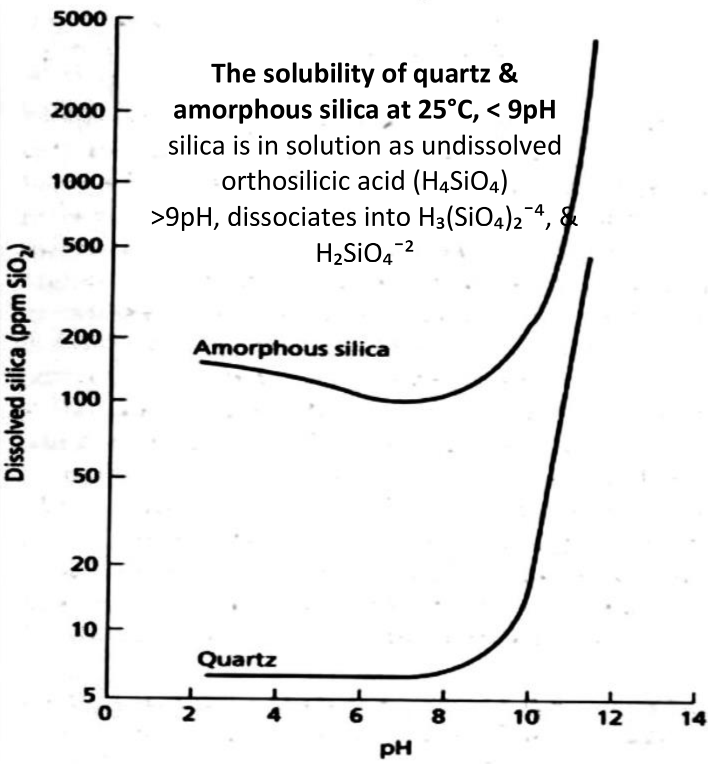
Opal-A	***Is a biogenic amorphous opal*** • **Found in** siliceous oozes • **Maturation**: formation of chert from opal-A • **The maturation leads to a decrease in porosity:** diatomites porosities 50-90%, porcelanites (metastable precursor to chert) < 30%, & cherts < 10% • If metastable opal-A dissolves, the solution become saturated with respect to CT & Qz
Opal-CT	***Crystalline, produced by first diagenetic stage*** • Called ***disordered cristobalite***, ***alpha-cristobalite or lussatite*** because consists of an interlayering of cristobalite & tridymite • **Disordered nature of Opal-CT results from** 1. the small crystal size 2. incorporation of cations to crystal lattice • Produced ***lepispheres (microspherules 5-10μm)*** when replace radiolarian & diatom & precipitated as bladed crystals lining cavities • Recrystallization of opal-CT obliterates structure of many diatom & radiolarian tests
Quartz	• Further diagenesis of opal-CT converted it into quartz chert (with equant mosaic of microquartz & chalcedonic quartz) • **Factors to form chert from biogenic opal-A** 1. **solubility differences:** Biogenic silica solubility 120-140, cristobalite 25-30, & quartz 6-10 ppm in pH of marine 2. **chemical conditions** • **Precipitation of opal-CT as Qz result from:** 1. **High internal structured nature of Quartz:** require slow precipitation from less concentrated solutions 2. **Temperature**: rate of transformation of opal-CT into Qz increase with increasing temperature (increasing burial depth)

Lepispheres of opal-CT growing in voids in silicified chalk (630m below sea floor)
Prismatic crystals are clinoptilolite (zeolite) SEM

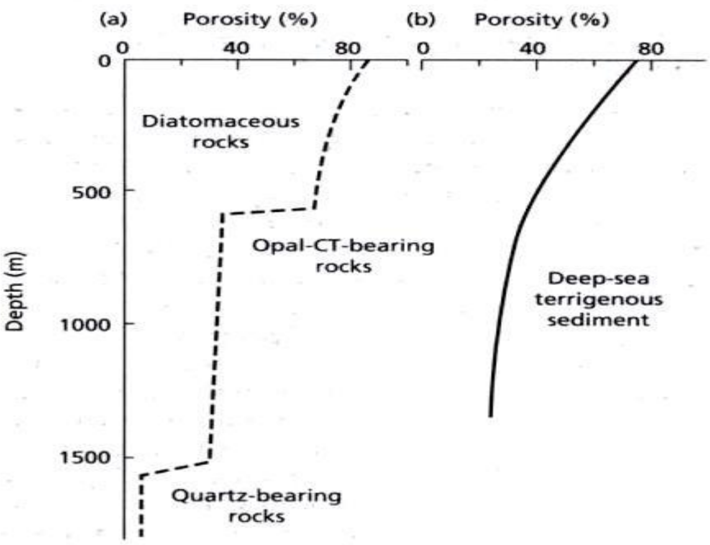




Schematic changes in silica mineralogy with increasing diagenesis, & XRD patterns for opal-A, opal-CT, & quartz showing increasing crystallinity



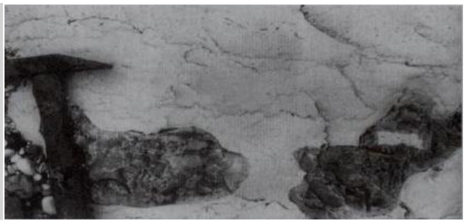
The solubility of quartz & amorphous silica at 25°C, < 9pH
silica is in solution as undissolved orthosilicic acid (H_4SiO_4)
>9pH, dissociates into $H_3(SiO_4)_2^{-4}$, & $H_2SiO_4^{-2}$



NODUALR CHERTS

- **Nodular chert crystals:** Small to large, subspherical to irregular, concentrated along bedding planes; may be coalesce to form near continuous layers where they resemble bedded cherts, **occur within** carbonate host
- **common in** shelf & pelagic limestones, & many have developed in burrow fills & nucleated around fossils

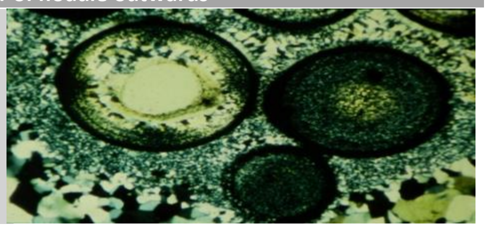
Chert nodules (flint) in Cretaceous chalk, Sutured stylolites present in the chalk



- **Origin**: *there is evidence* that they originate through replacement by diagenetic (not directly precipitation)
  - **The diagenetic processes involved in chert-nodule formation are** similar to operating in bedded chert
  - **microquartz formed by replacement of carbonates**
  - **dominantly pore filling: megaquartz & chalcedonic**

Biogenic silica disseminated & re-precipitated as opal-CT at nodule growth points then Opal-CT (lepispheres) fill pore spaces
Carbonates & matrix replacement by opal-CT
Maturation of opal-CT converted it into microquartz & chalcedonic quartz from the center of nodule outwards

Silicified oolite
Ooids replaced by microquartz & are enclosed in microquartz & megaquartz mosaic



NON-MARINE CHERTS

- **May be biogenic or inorganic siliceous sediments, formed in lakes, ephemeral water bodies, & in soils**
- **Inorganic non marine cherts** forms in great fluctuations
- **Diatoms** occur in great abundances in lakes

pH	Solubility of quartz
9	Quartz starts to dissolve
9 <	Solubility increases: Lake becomes supersaturated with respect to amorphous silica due to photosynthesis
9 >	Silica precipitated as a gel of cristobalite, due to evaporation of lack water (convert to chert by maturation)

- **Silica precipitated from hot springs by**:
  1. **evaporation & rapid cooling of spring water** to form sinter
  2. **Silicification (chertification) of microbes** (impregnation of tissues)
- **Chert precipitated in some soils, if silcrete is deposited**
- **Silcretes**: form under arid or semi-arid climate, where ground waters are alkaline with pH > 9
  - can form in humid areas
  - **Consists of** microquartz cement between sand grains, & microquartz mosaic where they have formed within fine-grained sediments
  - **Megaquartz, chalcedonic** may be occur within vugs (small canals & tubes from decay of rootlets)

IRONSTONES

- It forms ironstones & Fe-formations, if iron > 15%
- **The behavior of Fe & Fe-minerals precipitation are controlled by** the chemistry of the surface & diagenetic environments because the iron has a variations in its state (ferrous Fe^{2+} & ferric Fe^{3+})

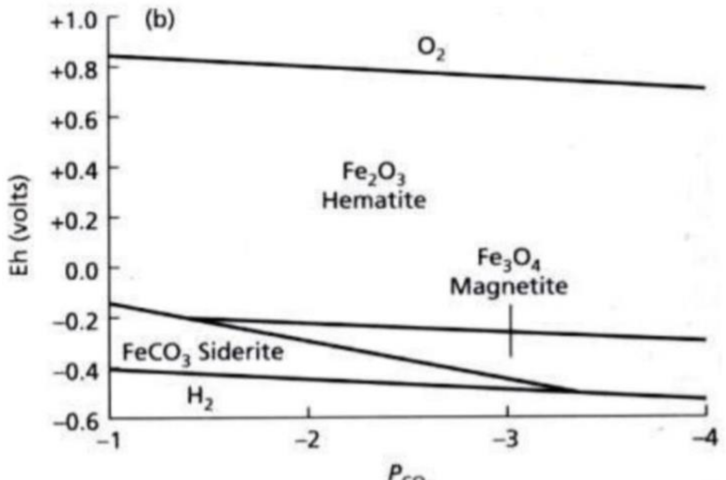
Common Fe minerals in sedimentary rocks	
Oxides	Hematite Fe_2O_3, Magnetite Fe_3O_4 Geothite FeO(OH), Limonite $FeO(OH).nH_2O$
Carbonates	Siderite $FeCO_3$
Silicates	Berthierine $(Fe_4Al_2)(Al_2Si_2)O_{10}(OH)_8$ Chamosite $(Fe_5Al)(Si_3Al)O_{10}(OH)_8$ Greenlite $Fe_6Si_4O_{10}(OH)_8$ Glauconite $KMg(FeAl)(SiO_3)_6.3H_2O$
Sulphides	Pyrite FeS_2, Marcasite FeS_2

- **Environments of Fe-deposit:**
  1. majority formed in **marine environment**
  2. **large intracratonic basins**: Precambrian, BIF
  3. In **localized small areas:** Phanerozoic, mainly oolitic
- **Banded iron formations (BIF)**: thick units of various Fe minerals (ironstone) interbedded with chert

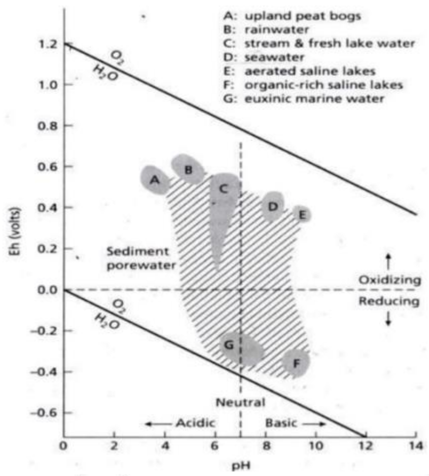
Sources of Fe for formation of ironstone	
Continental weathering	In humid tropical climate releases Fe from mafic minerals • **Produce** Fe-charged ground water, Fe-rich lateritic soils • **transported to the sea by** rivers after erosion of soils
Volcanic	Can supply considerable amounts of Fe, in Precambrian • **Includes** volcanic & hydrothermal activities

- **Iron is used to explained continental weathering & volcanic-hydrothermal activity:** Precambrian atmosphere have more CO_2 & less O_2 in order to allow leaching & transportation of Fe more efficiently
- **Iron can be transported by 3 mechanisms:**
  1. **River in colloidal Fe of ferric hydroxide** stabilized in the presence of organic matter
  2. **adsorption & chelation** to organic matter
  3. **clay minerals** as part of the clay structure, or as oxide films on the surface of clays
- When clays & organic matter deposited, Fe released into pore water of sediments if Eh-pH appropriate, & then re-precipitated to form iron minerals
- $[Fe]_{river\ \&\ ground\ water}$ <1ppm, $[Fe]_{seawater}$ 0.003ppm, Ph-Eh make Fe stable as insoluble ferric hydroxide, not ferrous
- **Ironstone formation favored at environments with:**
  1. low rates of sedimentation
  2. Presence of siliciclastic & carbonates materials

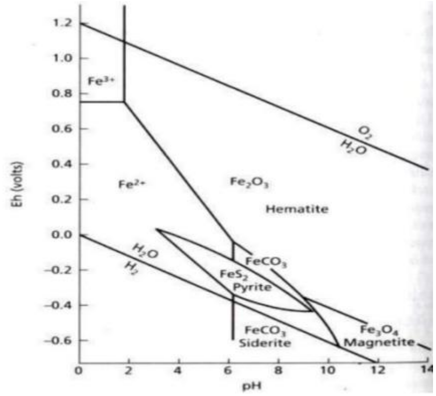
Factors control the precipitation of iron minerals	
Eh-pH	• Fe^{3+} present in highly insoluble FeO(OH) • Fe^{2+} is present in solution as ions
CO_2 Activity	Effective partial pressure of CO_2
S activity	-log of sulphur ions (pS^{2-})



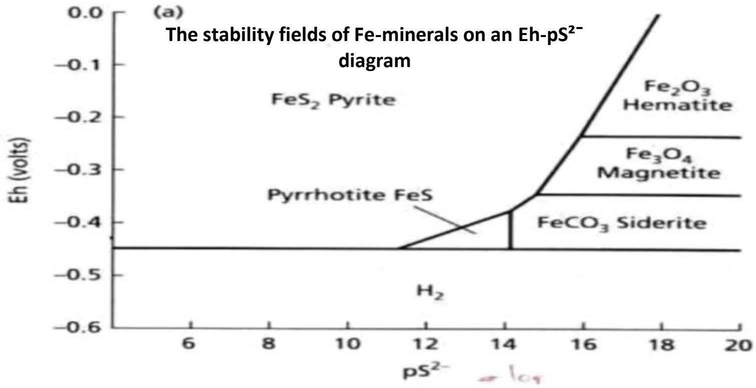
stability fields of Fe-minerals on Eh-P_{CO_2}



Eh-pH diagram: the fields of some waters
Redox potentials of natural solutions are limited by reactions involving water (depend on pH) The upper limit of Eh is determined by the oxidation of water to O & the lower the reduction of water to H. The pH is a measure of the acidity or alkalinity of the solution



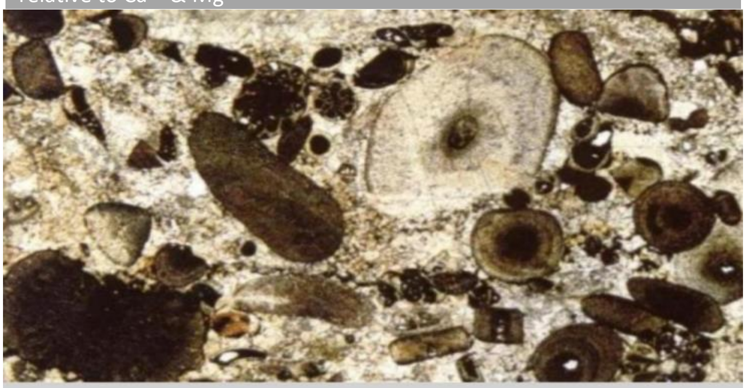
Eh-pH diagram showing the stability fields of ferrous & ferric iron minerals
Fe^{3+} stable under more oxidizing & alkaline conditions, & Fe^{2+} stable under more reducing & acidic conditions



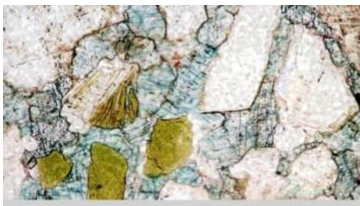
The stability fields of Fe-minerals on an Eh-pS^{2-} diagram

Iron minerals	
Hematite Fe_2O_3 (opaque, crypto-crystalline (or coarse), red, & translucent)	• ***Most stable Fe-mineral under oxidizing conditions*** • **Formation**: 1. **Dehydration process (diagenetically)** by hydrated ferric iron oxide similar to goethite 2. **Present as cement in sands** • **In Precambrian**: thin bed & laminae, alternating with chert, massive, peloidal, & oolitic form • **In Phanerozoic**: ironstones occurs as ooids, impregnations, & replacement of fossils

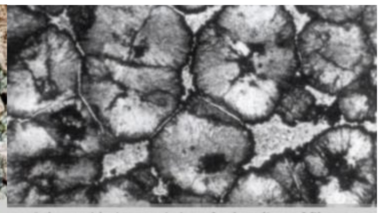
Magnetite Fe_3O_4	***stable under low [S], carbonate, -Eh, & nature pH, Such conditions are rare, so magnetite is not common*** • **Reducing conditions developed by** bacterial decomposition of organic matter • Have Fe^{2+} in the pore waters, liberated by bacterial reduction of Fe on clay & organic matter in sediment • **Formation**: 1. precipitated within sediment (not at sediment surface) during early diagenesis 2. **abundant in Precambrian BIF** (interlaminated with chert) & **rare in Phanerozoic ironstones** 3. occurs as **small replacement crystals** or **granules** within oolitic ironstones
Pyrite FeS_2 (black & finely crystalline)	Authigenic mineral of organic-rich marine muds, form by anoxic (free O) S-diagenetic, Precipitation require S • **S come from** bacterial reduction of dissolved S, which produces H_2S that reacts with Fe^{2+} in solution • **Formation**: 1. Dissolved [S] are low in fresh water so pyrite is ***not common in non-marine sediments*** 2. Occur as **minor mineral in organic-sediments** 3. **Environments:** estuarine & tidal flat 4. occur as **disseminated grains & crystals (cubic)** 5. may **replace skeletal fragments** • **framboids**: Aggregates of spherical pyrite
Siderite $FeCO_3$	**Under high carbonate & low SO_4^{2-} activities** • **Formation**: 1. Precipitate if all SO_4^{2-} is reduced, so more ***common in non-marine sediments*** 2. **Common in anoxic non-sulphidic methane-rich diagenetic environment** 3. Major constituent of Precam. & Phanero. 4. **cement of berthierine-chamosite oolites** 5. can **replace ooids & skeletal grains** • **Sphaerosiderite**:fibrous spherical siderite aggregate
Goethite FeO(OH)	**absent from Precambrian, abundant in Phanerozoic** • form ooids & pisoids in lateritic soils of tropical areas
Limonite (amorphous)	**poorly defined hydrated form of Fe-oxide** • **containing** goethite & other materials such as clays • **Produced by** subaerial weathering of Fe-oxide
Iron silicate minerals	
Berthierine-chamosite	• Forms as ooids in Phanerozoic ironstones, within a cement of siderite or calcite
Galuconite	**K-Fe aluminosilicate with high Fe^{3+}/Fe^{2+}, occurs as a light to dark green pellets & aggregates (1mm)** • **Occurs in** many sandstone & greensand • It is of great significance to Bir Fa'as Formation of Jordan, it's employed via K/Ar radiometric dating to constrain the Aptian Age of this formation
Greenalite	**Hydrous ferrous silicate interbedded with chert** • **Occur as** beds & lenses in Precambrian Fe-deposits • rounded to subangular pellet,little internal structure
Ankerite & ferroan calcite or dolomite formed if there is insufficient Fe^{2+} relative to Ca^{2+} & Mg^{2+}	



Hematite replacing crinoidal fragments & carbonate ooids in Jurassic sediment (PPL)



Glauconite (four green grains) PPL: Galuconite characterized by green color, microcrystalline nature

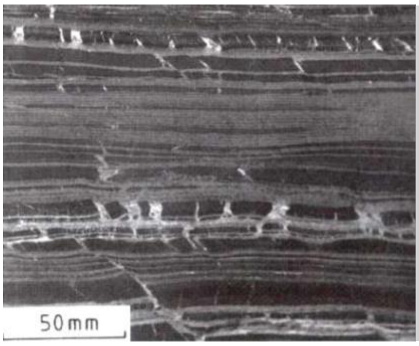


Sphaerosiderite consisting of spherulites of fibrous siderite (PPL)

PRECAMBRIAN BIF

Banded iron formations (BIF) in Canada	
Algoma-deposits	Lenticular, thin, narrow across strike, closely associated with volcanic rock & graywacke (Archaean 2500-3000Ma)
Superior deposits	Thicker, more regionally extensive, deposited on stable shelves & broad basin (middle Proterozoic 1900-2500Ma)

- **Facies of BIF**: oxide (hematite, magnetite), silicate (greenalite), carbonate (siderite), sulphide (pyrite)
- **BIF characterized by bedding structure**: alternating beds or laminae or bands of ironstone (hematite, magnetite, siderite, greenalite) interbedded with chert
- The lamination indicates seasonal changes
- Bands traced > 30,000km². & indicate Fe facies were deposited in deep-water basins, shelves, & in lagoons



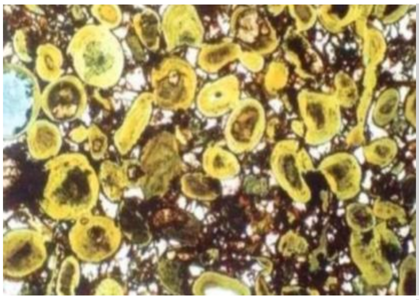
A polished hand-specimen of (BIF) fine lamination of light colored hematitic chert laminae alternating with darker hematite laminae

Source of Fe in BIF deposition	
Volcanic	**Associated with contemporaneous volcanic rocks** For Archaean Algoma-type deposits
Hydrothermal vents	**On the sea floor,** The rare earth elements (REE) & Nd isotopes data suggest a hydrothermal source for BIF
weathering	**Deep weathering of continental rocks** For Proterozoic Superior-type deposits

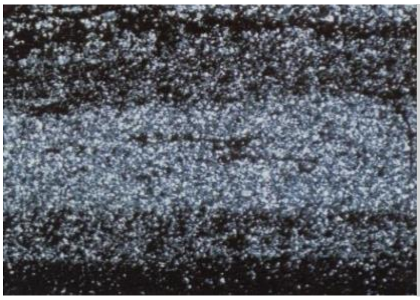
- in Precambrian atmosphere had higher CO_2 & little or no O_2, & partial Pressure of CO_2 lowering pH of surface waters → led to greater **leaching & transportation of Fe**
  - Water with a low pH is a major reservoir of Fe^{2+}

PHANEROZOIC IRONSTONE

- Vary in grade, lithology, & Fe minerals types
- **The Most important Phanerozoic ironstone: oolitic**
  - **In the Paleozoic:** hematite-chamosite
  - **In the Mesozoic:** goethite-berthierine
  - **Ordovician-Jurassic:** interval of global high sea level & warm humid climate which facilitated intensive chemical weathering that produce iron minerals
  - **Sea level changes** are important in controlling the amount of Fe that supplied to marine environment by reworking terrestrial weathering products
  - Hematitic-Oolitic limestones occur in the Bir Fa'as Formation in Jordan
- **Less significant Phanerozoic ironstone are sideritc mudstones, & sulphidic ironstone**



Berthierine-chamosite ooids (PPL) with some shape distortion, in a siderite cement partly altered to goethite (brown)



Berthierine-chamosite ooids (PPL): distorted shapes & elephantine features in calcite cement

RECENT IRON-DEPOSITS

- **Fe-ores:** are hard oolitic-concretionary to earthy-soft
  - **forming** in swamps & lakes of the mid to high latitude (N-America, Europe, & Asia)
  - **Consist of** goethite, siderite, & vivianite
- Ferromanganese nodules, crusts, & metalliferous occur on sea floor (Atlantic, Pacific, & Indian)
- **Nodules of Mn & Fe (Ferromanganese)**
  - **Mn-oxides constitute a few percent (up to 40%)**
  - **vary considerably in chemistry & mineralogy:** Both Mn-rich-Fe-poor & Fe-rich-Mn-poor varieties occur, rich in metals: Co, Ni, Cu, Cr, V

	NSS*	DSSA*	SN*	AN*	ARN*
Fe	4.8300	5.4700	15.810	17.270	19.150
Mn	0.0850	0.3980	14.620	16.780	15.510
Cu	0.0048	0.0115	0.0580	00.370	00.080
Co	0.0013	0.0039	1.1500	00.256	00.400
Ni	0.0055	0.0079	0.3510	00.540	00.310

Average concentration of (Fe, Mn, Cu, Co, & Ni)% in shallow, & deep water sediments, & ferromanganese nodules from 3 settings
NSS: Near-Shore Sediment, DSSA: Deep-Sea Sediment Atlantic, SN: Seamount Nodules, AN: Abyssal Nodules, ARN: Active-Ridge Nodules

  - According to concentration of base metals, submarine mining of deposits considered a viability
  - The minerals constituting the nodules are X-ray amorphous, & todorokite
  - The majority of ferromanganese nodules form at slow rates of around 1mm/Ma
- **Todorokite**: Mn-oxide occurs with hydrated goethite
- **Environments of Mn & Fe Nodules (Ferromanganese)**
  1. **In low sedimentation areas**: in strong bottom currents, at depths of several Km's
  2. **In oceanic settings:** on the flanks of active mid ocean ridges, seamounts, & abyssal plains
  3. **In some cases nodules are present in areas far away from volcanism:** so some sort of direct or indirect precipitation from sea water is needed
  4. **attributed to hydrothermal-volcanic activities** & associated with mid-oceanic ridge volcanism

PHOSPHATES

- **Metalliferous sediments** occur in the vicinity of oceanic active spreading ridges at top of ocean floor basalts
  - **rich in** Fe, Mn, Cu, Pb, Zn, Ni, Co, Cr & V
- **The fluids causing metal enrichment are derive from** mantle magmatic sources or the interaction of basalt
- **Phosphate deposits (phosphorites)** contain a few % of Ca-phosphate (apatite, bones, or coprolites)
  - Are important as natural resources
- **Phosphorus fertilizers** used in chemical industry
  - contain high amounts of useful elements (U, F, V)
- **Phosphorus:** present in living matter, & essential for life
  - a minor portion of plant & animal soft parts
  - major of vertebrate skeleton (bone,teeth,hard part)
- **Apatite $Ca_5(PO_4)_3(F,Cl,OH)$**: most common phosphate
  - **Fluorapatite $Ca_5(PO_4)_3F$**: In igneous rocks
  - in sedimentary replaced by carbonate or sulphate
  - Ca may be replaced by Na^+, Mg^{2+}, Sr^{3+}, U^{4+}, & REE^{3+}
  - Fluorine replaced by hydroxyl (OH) or chlorine (Cl)

Apatite minerals (identified by XRD & chemical analysis)	
Francolite	Anisotropic, > 1% F & large amount of carbonate
Dahllite	Anisotropic, Carbonate hydroxyl with < 1%F
Collophane	Isotropic, cryptocrystalline, compositional variable

- **Forms of sedimentary phosphates:** _Nodular & bedded_, _Bioclastic & pebble-bed_, _Oceanic-island (guano)_

NODULAR & BEDDED PHOSPHORITES

RECENT & SUB-RECENT OCCURRENCES & SEQUENCES

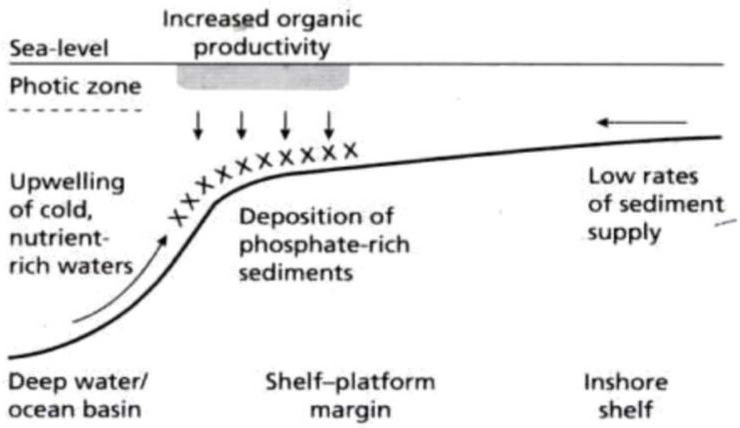
- **Phosphate nodule & crust**: Slabs or spherical with irregular masses, Contain pellets, coated grains (ooids), vertebrate skeletal debris (fish), & coprolite associated
  - occur at 60-300m depth, & cm - >1m in diameter
  - **Internal structures:** homogeneous to concentrically laminated & conglomeratic nodules

Origin of phosphorites	
Marine	Is a primary nutrient so control of organic productivity **deposits on** sea-floor & **recorded on** continental shelf & slopes (40°NS of the Equator) such as W-coasts of N-America or S-America, shelves of NW-Africa, & Japan
Seawater	**Occur as** dissolved orthophosphate Contained in or adsorbed to organic detritus
Ocean	Organic productivity utilizes dissolved orthophosphate through phytoplankton growth in photic zone

- **Upwelling current:** cold waters containing nutrients rises towards surface, lead to high organic productivity & high phytoplankton growth in surface waters
  - **results in** organic-rich sediments (phosphate-enriched) & oxygen-deficient water over sea floor
  - Is a feature of mid-latitude continental margins, controlled by predominant high-P atm systems

- ➢ There are 5 major zones of coastal upwelling, located on the western side of the landmass
- **The dissolved orthophosphate** is concentrated into the sediment through upwelling mechanism
- **Mass mortalities of fish** take place in areas of upwelling, via poisoning by phytoplankton blooms, organic matter, phosphorus & skeletal phosphate (bones) materials
- **Roles of phytoplankton**: transporting phosphate from upwelling current & near-surface waters to the sea floor
- **Roles of Microorganism (bacteria & fungi) & microbes:** important in the process of concentrating phosphate
- **sea floor phosphorite** deposited within the ***Oxygen-minimum zone*** (a few 100's m depths)
  - ➢ Oxygen-depleted waters permit the deposition of organic matter,PO_4^{2-} released by bacteria reduction
- **Phospho-genesis require** Low sedimentation rates
  - ➢ **Reflected in**: organic-rich mudrocks, cherts, pelagic limestones, hardgrounds, & glauconites

Formation of phosphorites	
Replacement &impregnation	Preset data indecate that phosphate not precipitated directly from seawater but formed by Replacement
Bacterial decay	Liberate phosphate that precipitate in the pellets & coprolites, & replaces siliceous, calcareous skeleton, & lime mud, giving rise to nodular phosphorites
Reworking	Ocean current & severe storms remove the fine unphosphatized sediment from seafloor in stages of induration & phosphate impregnation



Model for formation of marine phosphorites

ANCIENT PHOSPHORITES OCCURRENCES & SEQUENCES

Environments	
Outer shelf	At times of sea-level rise (short transgression), with sediment starvation in deeper water
Shallow & fertile shelf sea	Promote phytoplankton blooms, which led to poorly oxygenated sea floor where organic materials & phosphates accumulate
Warm climate	**Indicate** the increase in phosphorus flux by increased chemical weathering on the land, **leads to** prevalence of O-depleted waters due to reduced Oxygen-solubility

- Phosphate deposits related to upwelling & high organic productivity are known from Precambrian
- There are a number of phosphogenic episodes of global extent (Precambrian-Cambrian, Permian, Cretaceous - Triassic, & Miocene-Paleocene)
- Extensive & valuable phosphate deposits occur in Creta-Ter of N-Africa & Middle East (Morocco, Iraq, & Turkey)

These bioclastic & pelleted phosphorites accumulated on continental margin along S-Tethys Seaway

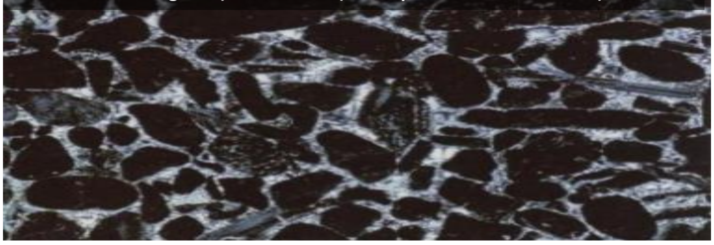
BIOCLASTIC & PEBBLE-BED

- **Vertebrate skeletal fragments concentrated to form:**
  1. bone beds, with fish scales
  2. coprolites (spherical to elongate faecal pellets)
- **Phosphatic concentrated by:**
  1. currents & wave-reworking of sediments
  2. winnowing of finer material
- **coarse phosphatic grains** are left over lag deposits, in:
  1. **transgressive & regressive shelves**
  2. **shore zones, fluvial, & intertidal currents**
  3. associated with **upwelling deposits**
- **skeletal phosphate Optically:** yellow-brown, regular canals (canaliculi) & growth line microstructure
  - ➢ **Bone phosphate:** isotropic, or anisotropic with weak, irregular, patchy, or undulose extinction

(PPL) coprolites (elongate, oval shape, brown color) & bone fragments (gray or colorless), Cement between grains is quartz

- **Coprolites**: homogeneous or concentric laminations
  - ➢ **contain** broken shell fragments & silt quartz, depending on what organism had eaten
  - ➢ **Isotropic** because composed of collophane

(XPL) coprolites (isotropic, totally extinction), bone (anisotropic, weak birefringence), Qz cement (microquartz with 1st order IC)



- **During diagenesis**: bioclastic phosphorite bones further enriched in phosphate via cementation by collophane & formation of phosphate nodules by nucleation
  - ➢ Diagenetic phosphate precipitated in limestone, mudrocks, & sandstones in the form of nodules
  - ➢ Cements or replace calcareous grains

OCEAN-ISLAND (GUANO)

- Mainly excrements of birds, & less commonly excrements of bats, form thick phosphate deposits (***guano***) which has an economic significance
- Thick accumulations of guano are found on small islands in the E-Pacific, & along coast of S-America
- downward percolation of solution from leaching guano may be cause phosphatization of underlying carbonate sediments on some islands (***<u>ocean-island phosphorites</u>***)

COAL, OIL SHALE, & PETROLEUM

- **Organic matter found in most sedimentary rocks**: in sandstone 0.05%, limestone 0.3%, & mudrocks 2%
- **Organic matter originated through** photosynthesis, as plants manufacture carbohydrates from CO_2 & water using sunlight(energy) & chlorophyll(catalyst)
- Organic matter may be buried with sediments to be broken down (decomposed) in presence of oxygen into CO_2 & water (the reverse of photosynthesis)
- If there is a deficiency in O, organic decomposition is incomplete & quite stable organic compounds can be developed & preserved in the rock record
- The preservation of organic matter takes place in anoxic (reducing) environments (e.g.stagnant lakes, stratified marine basins, swamps, & bogs or mires)
- In reducing condition, anaerobic decomposition produce hydrocarbons & complex organic compound during diagenesis & metamorphism
- The organic–rich sediments & sedimentary rocks (organic deposits) include oil shales, peat, lignite, brown coal, hard coal, oil & natural gas derived from some of these organic-rich deposits
- All of organic–rich deposits can be termed fossil fuels that have immense significance to humans

Types of Modern organic deposits	
Humus	Is fresh, decaying organic matter occurring in the upper part of soil profiles, Decay products are humic acids that help in leaching rock fragments & clays is oxidized with time, & not preserved in sediments
Peat (mires)	dense mass of plant remains, accumulate in water logged, boggy swamps, & marshy regions, anaerobic prevent the complete breakdown of organic matter Peat forms at all latitudes, in equatorial regions, in tropical rainforests & mangrove swamps
Sapropel	accumulates subaqueously (below water) in shallow to deep marine basins, lagoons, & lakes, derived from phytoplankton, which live in the upper photic zone Fine–grained terrigenous clastic sediment can be deposited with the sapropelic organic matter

- ➢ Most coals come from peat derived from trees & leaves via compaction & alteration, so tens of m of peat required to form one meter of coal
- ➢ Anaerobic conditions required for preservation unless very high rate of sedimentation, restricted water circulation, water stratification

- **Ancient organic deposits**
  1. **Phytoclast**: plant fragment (wood, leaf, cuticle)
  2. **Bitumen**: liquid or solid hydrocarbon, soluble in organic solvent (acetone, carbon-tetrachloride)
  3. **Asphalt**: solid or semi-solid bitumen
  4. **Kerogen**: organic matter insoluble in organic solvents, it is a geopolymer consisting of long-chain hydrocarbons of high molecular weight.
  5. **Petroleum**: crude oils, chiefly short & long chain hydrocarbons, & gases, mainly methane, which migrated into porous rocks from source rocks

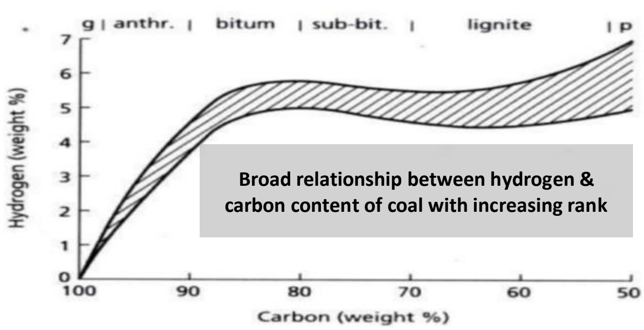
FORMATION & RANK OF COAL

- Most coal are humic,formed in situ by accumulation of woody plant (peat) in forest swamps
- Humic coals series: peat → brown coal (lignite) → bituminous coals → anthracite
- ***Coalification:*** changes from plant to coal, controlled by burial T (carbonification,organic metamorphism)
- Various microbiological, physical, & chemical processes take place during coalification, all contributing towards the rank of coal
- **Rank of coal:** measure of degree of coalification or level of organic metamorphism
- The initial stages of coalification take place during peat formation, the processes are mainly microbial, with little alteration of the original plant material
- In soft brown coal (lignite) many plant fragments are readily seen, with their original cell structure
- ***Gelification*** process during the formation of sub-bitumenous cause homogenization & compaction of plant cell walls, leads to the formation of ***vitrinite*** (one of the main constituents of bituminous coal)
- With increasing rank the carbon content increases & the volatile content decreases (Tab. 5.1, Fig. 5.1)

Rank stage	CDF%	V%	C[KJ/g]	VRO
Peat	< 50	> 50	———	——
Lingnite	60	50	15 - 26	0.3
Subbitumineous	75	45	25 - 30	0.5
Bitumineous	85	35	31 - 35	1.0
Semi-Anthracite	87	25	30 - 34	1.5
Anthracite	90	10	30 - 33	2.5
Graphite	> 95	< 5	———	——

The rank stages of coal with values of various parameters used to estimate rank

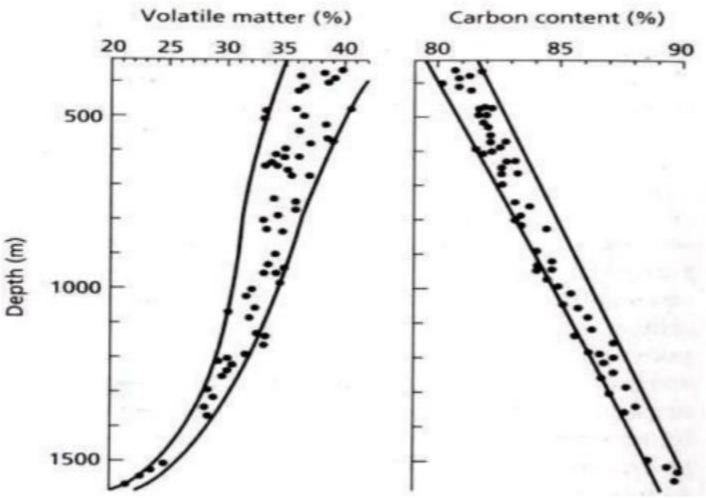
CDF: C-dry ash free, V: volatile, C: Clalory, VRO: vitrinite reflectance in oil



Broad relationship between hydrogen & carbon content of coal with increasing rank

- The volatiles include combustible gases (e.g. H_2, CO_2 & CH_4) & condensable substances (mainly water)
- **Low-rank**: volatile-rich, burn easily with smoky flame, **high-rank**: volatile poor, more difficult to ignite, but burn with a smokeless flame

- **Coke**: is the carbonized residue remaining after removing the volatiles
- **Humic coals classification** (according to rank): peat, lignite (soft brown), sub-bituminous (hard brown), bituminous (hard), semi-anthracite, anthracite, & graphite (metamorphism coal)
- **Rank measured by**: amount of C, H, O, volatiles, & moisture, the colorific value (heat produced by burning), & the reflectance of vitrinite
- **Rank depends on** depth of burial that determines T, & length of time that the coal has been subjected to (rank increases with depth)
- At the same depths older coals have a higher rank



COAL PETROLOGY

- Coal consists of organic & inorganic constituents

Organic constituents

- In the study of coal petrology a polished surface of the coal sample is prepared to be studied by the reflected-light microscope, with oil immersion objectives for increased contrast
- **Maceral**: is the microscopic constituents of coal, analogous to the minerals of rocks

Group	Macral	Origin
Vitrinite	Collinite, telinite	Wood
Inretinite	Fusinite, Semifusinite	Woody tissues
	Sclerotinite	Fungi
	Micrite	Polymerized resin
Liptinite	Sporinite	Spores
	Cutinite	Cuticle
	Resinite	Resin
	Alginite	Alge

Minerals in macral types

- **Vitrinite:** derived from wood fragments accumulated in stagnant, anaerobic water, & were soon buried
- **Inertinite**: that derived from wood tissues have preserved cell structures
- With increasing rank, the whole coal becomes homogeneous & the macerals lose their identities
- The 4 common microlithotype forming microscopic bands & layers in hard coal & composed of various macerals: vitrite, fusite, clarite, & durite

Lithotype	Microlithotype	Marcerals in lithotype
Vitrain	Vitrinite	Vitrinites
Fusain	Fusite	Intertinites, Fusinite
Durain	Durite	Liptinite + inertinite
Clarain	Clarite	Vitrinite + Liptinite

The lithotypes & microlithotypes of coal, with the principal macerals forming the microlithotypes

Inorganic constituents

- Quartz, clay, & heavy minerals are the main sedimentary inorganic constituents of coal
- Kaolinite is the main clay mineral as many coals formed in tropical swamps, where this clay mineral is dominant in these regions.
- with burial kaolinite is converted into illite, so in higher rank coals illite is more abundant
- Early diagenetic nodules found in coals composed of siderite, ankerite, dolomite, calcite, & pyrite
- Pyrite is common in coals, derived from the activities of sulphate-reducing bacteria

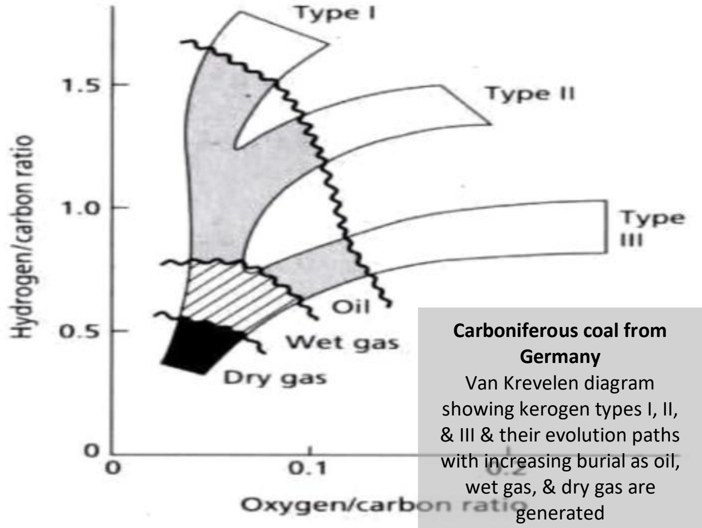
Occurrence of coal

- In the geologic record, coals formed in:
  1. humid climatic areas from the Devonian, when plants evolved & proliferated
  2. Formed in deltaic environments as thin (< 3 m)
  3. Formed in continental basins around lake, & in rift basins as very thick seams (100's of m)

OIL SHALES

- **Oil shales**: group of rocks contain organic material insoluble in organic solvents & extracted by heating (distillation), organic matter is kerogen or bitumen
- The quantity of oil that extracted ranges 4 - 50%wt of the rock (yielding 50 - 700 L of oil / ton)
- Oil shales contain a substantial amount of inorganic material consisting of Qz silt & clay minerals, Some organic-rich siltstones & mudstones, some organic-rich limestones (such as Jordanian oil shales → bituminous limestones)
- Much of the organic matter in oil shales is finely disseminated, so altered that the organisms from which it formed cannot be identified
- In many oil shales the remains of algae & algal spores are common so the organic matter assumed to be of algal origin
- Fine-grained higher plant debris & megaspores also may be an important constituent
- Anaerobic conditions required to prevent oxidation of organic matter & reduce bacterial degradation, unless the rate of organic productivity is very high, when accumulation take place in oxidizing env.
- Many oil shales formed in stratified water bodies where oxygenated surface waters permitted plankton growth, & anoxic bottom waters allowed the preservation of the organic matter

- The kerogen in oil shales is mainly type I: high H:C & low O:C ratio derived from algal lipid matter (fats & fatty acids) rather than carbohydrate, lignin, & waxe



Carboniferous coal from Germany
Van Krevelen diagram showing kerogen types I, II, & III & their evolution paths with increasing burial as oil, wet gas, & dry gas are generated

- Kerogen type III formed from vascular plant debris
- Certain metals (V, Ni, U, M) enriched in oil shales
- Oil shales deposited in lacustrine environments (e.g. Eocene Green River Formation of USA), or in marine environment (e.g. Jordanian oil shale)

FORMATION OF KEROGEN

- Kerogen is a very complex geopolymer of high Mw formed from the diagenesis of organic matter
- **Major groups of organic compounds in living organisms**: carbohydrates, lignin, protein, & lipids

	C	H	S	N	O
Carbohydrate	44	06	0.0	0.0	40
Lignin	63	05	0.1	0.3	32
Proteins	53	07	1.0	17	22
Lipids	76	12	0.0	0.0	12
Petroleum	85	13	1.0	0.5	0.5
Kerogen	79	06	5.0	2.0	8.0

Average composition of organic compounds in organic matter compared with typical petroleum & kerogen

- the composition of lipids is closest to kerogen
- **In oxidizing**: aerobic bacterial activity & oxidation breakdown organic matter into CO_2, NH_3, & H_2O
- **In reducing env:** anaerobic bacteria decompose organic matter (carbohydrates, via fermentation) to new & residual organic compounds, CH_4, & CO_2
- The material left by microbial-bacterial activity recombines by polycondensation & polymerization to form organic compounds (fulvic & humic acids)
- During shallow burial, depths of tens to hundreds of meters, and over several millions of years, these organic compounds are converted to insoluble humin. Further burial, with decreasing O:C & N:C ratios, leads to the formation of kerogen
- The composition is variable, but kerogen of Eocene Green River Formation is $C_{215}H_{330}O_{12}N_5S$
- With further burial, but still in the realm of catagenesis, composition of kerogen is modified through decrease in the O:C & H:C ratios as oil & gas are generated
- **Kerogen in polished section**: structurless, occurring in bands & stringers parallel to stratification
- **Immature (shallow-burial) kerogen**: yellow-amber color, but with increased burial & evolution (maturation). It takes on a brown & then black color

PETROLEUM

- The generation of petroleum is one of the stages in the alteration of organic matter buried in sediments
- Formed by increasing burial & T (part of process of organic matter diagenesis & metamorphism)
- Consists of crude oil & gas
  - **Crude oils**: C (85wt%) + H (13wt%), in the ratio of 1.85 H-atoms to 1 C-atom
  - Minor elements, S, N, & O in < 3% in most oils
  - phosphorus & vanadium may be present
- **sulphurous oils (sour oils)** have > 7% S, & are distinguished from low-sulphur sweet oils
- Hydrogen is a much lighter element than the others, so that the specific gravity of oil indicate H content
- A higher H content gives a lower specific gravity (Ex. 14%H oil has G = 0.86, & 12% H has a G = 0.95)
- Petroleum is composed of a great number & variety of simple & complex hydrocarbon compounds, from CH_4 (Mw = 16) to the asphaltene (Mw in thousands)
- common hydrocarbon compounds in petroleum belong to the alkane-paraffin (C_nH_{2n+2}), naphthene-cycloalkane (C_nN_{2n}), & arene-aromatic (C_nH_{2n-6})
- Compounds with S, N, & O: the thiols, thiophenes, pyridines, quinolines, carboxylic acids & phenols
- Natural gas occurs as a cap to oil reservoirs, in solution in oil (released when P decreases) and as a reservoir fluid alone
- Dry gas consisting of CH_4 &ethane CH_6 distinguished from wetgas with >50%propaneC_3H_8 & butaneC_4H_{10}
- Wet gas is closely associated with oil, & dry gas is more associated with coal deposits & derived from deeply buried source rocks
- H_2S, CO_2, & N_2 may form a significant component of natural gas, & He is also present
- Water occurs in most oilfields & is typically a brine, much more saline than seawater
- Now about one-third of the world's oil comes from the Middle East: Saudi Arabia, Iran, Iraq & the UAE
- There are major oilfield "giants" in the USA, Canada, Russia, Venezuela, Nigeria, Libya, Mexico, Western Europe, N-Sea & Indonesia

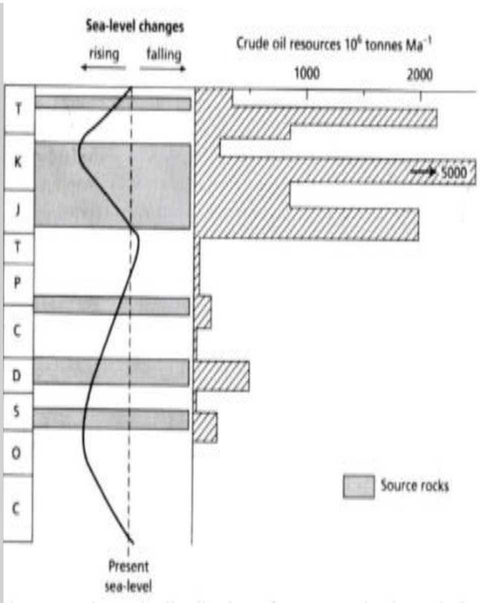
Formation of petroleum

- Derived from source rocks & migrates into reservoir rocks, which are sandstones & limestones
- The porosity & permeability of reservoir rocks are obviously very important, impervious seal required to prevent upward escape of petroleum from the reservoir

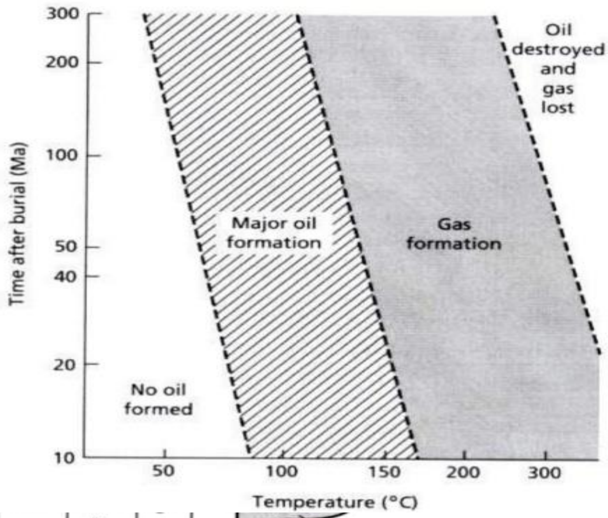
& common cap rocks in oilfields are mudrocks & evaporites

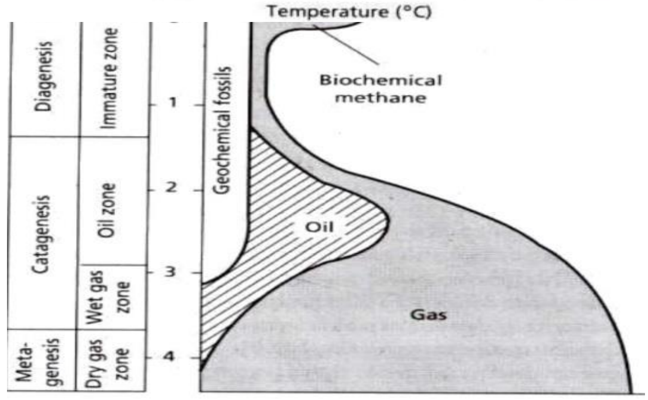
- To contain the petroleum some form of trap is necessary, Many traps are structural, involving folds (domes & anticlines), faults, & salt diapirs, & others are depositional, arising from the geometry of the reservoir sandstone body or limestone mass & its overlying cap rock
- Petroleum is derived from maturation of organic matter deposited in fine-grained marine sediments
- Organic-rich sediments deposited in anoxic silled basins, on shelf margins in association with upwelling, & on the sea floor at times of oceanic anoxic events
- Many marine hydrocarbon source rocks formed at times of high organic productivity of marine plankton, coinciding with transgressive events & high-stands of sea level
- Diagenesis of the organic matter begins very early at shallow burial depths, & substantial amounts of methane produced through bacterial fermentation. This marsh gas normally escapes to the atmosphere, but it might be trapped
- Burial diagenesis of deposited organic matter leads to the formation of kerogen
- Burial to T 50-80°C causes thermocatalytic reactions in the kerogen, in types I & II, cycloalkanes, & alkanes are generated, two of the main constituents of crude oil, When this process takes place, the source rock is said to be mature.
- With increasing T, oil is generated until a maximum is reached, & quantity decreases & an increasing amount of gas is formed

Schematic distribution of source rocks through time, relative to the first order global sea-level curve & crude oil reservoirs through time



- The principal phase of oil generation takes place at T = 70-100°C (depths of 2-3.5km, oil window). The gas produced is wet initially, but above 150°C only methane (dry gas) is generated
- Time also is a factor in source-rock maturation, higher T (greater burial depths) are required for oil generation from younger rocks, compared with older rocks which can reach maturity at lower T





- Some organic compounds in organic matter, the porphyrins are resistant to diagenetic alteration & found in hydrocarbon source rocks & crud oils
- These geochemical fossils or biomarkers very useful in correlating an oil with its source rock, At higher T, the biomarkers break down so they can give also an indication of the maturity of the source rock
- In the search for petroleum, use can be made of the color of pollens and spores (palynomorphs) in the source rock to see if the stage of petroleum generation has been reached
- With rising T & higher level of organic metamorphism, palynomorphs change color from yellow to brown when crude oil is evolved, & to black when dry gas is generated
- Indication of burial T also obtained from the vitrinite reflectance of phytoclasts & the color of conodonts
- Other tests for source-rock maturity determination of H:C & O:C ratios, UV fluorescence, & pyrolysis

Vitrinite reflectance	Spore color	Hydrocarbon generation		
	Yellow			
0.5	Orange	——		
		Oil	——	
1.0	Brown	Window	Wet	——
1.5		——	Gas	Dry
2.0	Black		——	Gas
5.0				——

TEST BANK

1. Solid hydrocarbons that are soluble in organic solvents

A. Bitumen
B. Phytoclast
C. Kerogen
D. Petroleum
E. Asphalt

2. Banding in femicrete exhibits following features except

A. It could be lenticular
B. consists of strikingly red & gray bands in outcrop
C. partly by absence of burrowing in Precambrian
D. an original depositional structure
E. formed after uplift of the Fe-rich succession

3. Francolite

A. has < 1% F
B. is not crystalline
C. has > 1% fluorine & appreciable carbonate
D. is the same as collophane

4. Hemipelagic mudrocks exhibit following features except

A. Covered the sea floor on the deep outer parts of continental shelves, continental slopes & vast areas
B. characterized by pelagic fauna such as diatoms, planktonic foraminifera, & Coccolithophoridae
C. Grey color, although red , brown , green or black
D. accumulate now above CCD, red & brown colors
E. They are commonly interbedded with siliciclastic & carbonate turbidites

5. About phosphate, following statements are true , except

A. can be represented by: $Ca_{10}(PO_4, CO_3)_6F_{2-3}$
B. It is fluorapatite
C. It can be called carbonate hydroxyl fluorapatite
D. It contains no fluorine in all cases

6. About clay minerals origin, the wrong statements is

A. Neoformed clay minerals are the clay minerals that formed in situ by precipitation from solution
B. Transformed clay are inherited clay minerals that modified by ion exchange or cation arrangement
C. Degraded clay minerals are formed by cementation in deep buried sediments
D. Inherited clay are detrital clay, formed in another area, transported, & deposited away from source

7. false statement about Palaeokarstic surface in limestone

A. contain preserved soil as discontinuous clay seam or bed immediately above the dissolution surface
B. were formed after emergence of carbonate sediments followed by dissolution through contact with meteoric water
C. are a type of bedding discontinuity peculiar to some limestones
D. formed now at ocean sediment-water interface

8. Subaqueous precipitation of evaporites:

A. basically a simple "evaporating-dish process"
B. takes place in supratidal environment
C. takes place within sediment (sabkha)
D. gives rise to chicken wire texture
E. Formed quartz

9. Phosphorites

A. used to produce fertilizers
B. only in Upper Cretaceous in stratigraphic record
C. are not present in Jordan
D. phosphate deposit containing any amount of PO_4

10. Evaporites include the following minerals, except:

A. Sylvite
B. Kainite
C. Tremolite
D. Halite
E. Anhydrite

11. Bedded cherts

A. Black colored variety called novaculite
B. always show regular flat bedding
C. devoid of ripple marks & cross-bedding in all case
D. are produced by replacement of carbonate grains
E. May associated with limestone & phosphorites

12. Phosphorites

A. consist only of detrital apatite
B. contain at least 50% P_2O_5
C. are restricted in age to the Permian
D. cryptocrystalline to X-ray amorphous collophane
E. Not found in Jordan

13. Mudrocks formed from the alteration of volcaniclastic

A. may contain zeolite minerals
B. known as tenstein it montmorillonite is dominant
C. subjected to vitrification (forms macroquartz)
D. Is fuller's earth if vermiculite main clay present
E. Is bentonites if illite is main clay mineral present

14. Peloids

A. are very poorly sorted
B. devoid of any internal structure
C. are composted of coarse crystalline carbonate
D. have multiple internal concentric layers
E. are sub-spherical or ellipsoidal angular grains

15. Chert

A. consists only of mega or coarse crystalline quartz
B. cannot be formed by replacement of limestone
C. Could occur in a bedded form
D. is found only in Upper Cretaceous strata
E. always black due to content of organic matter

16. Dolomite

A. associated with supratidal deposit in arid climate
B. stains red through staining with Alizarin red S
C. has the formula $CaMgCO_3$
D. formed by direct precipitation from sea water
E. is a mineral not a rock

17. Loess is

A. usually stratified & consolidated

B. yellow-to-buff clastic deposit composed silt-Qz

C. characterized by distinctive poor-sorting silt-sand

D. Always devoid of shells of land snails & concretions formed around roots

E. primarily of a fluvial origin

18. Regarding the silica that formed the chert nodules, the following statements are true, except

A. It was precipitated originally as opal & subsequently crystallized to chert

B. originated by dissolution of associated limestone

C. Came from dissolved tests of siliceous organisms

D. It migrated along surfaces of greater permeability

E. have crossed bedding plane & filled burrows

19. Aragonite shells

A. a are characterized by concavo-convex outline

B. exhibit microstructure in Paleozoic limestone

C. are very stable during chemical weathering

D. are very stable during diagenesis

E. commonly dissolve in diagenesis to form molds that may or may not be refilled with cement

20. phosphates occur in the following forms, except

A. Metamorphic apatite deposits

B. Bioclastic & pebble-bed phosphorites

C. Nodular & bedded phosphorites

D. Oceanic island phosphorites

E. guano phosphorites

21. Regarding the phosphorites, which of following is true

A. distributed equally in the stratigraphic record

B. Phosphatization of lime is among the processes involved in formation of the phosphorites

C. Most phosphorites deposited in deep marine

D. Invertebrates are the only organisms involved in the formation of phosphorites

E. Upwelling currents required for deposition of phosphorites are occurring on the eastern margin of continents in tropical or subtropical latitudes

22. Hematite

A. need high organic content to formed & preserved

B. stable under moderate-high reducing conditions

C. forms diagenetically from a hydrated ferric oxide precursor by ageing process involving dehydration

D. occurs only as a cement of sandstone

23. Gypsum crystals that precipitated on floor of a lagoons, lakes, & shallow shelves around evaporite basins in form of the following , except

A. enterolithic texture

B. selenitic gypsum crystals

C. single prismatic crystals

D. growing vertical crystals like grass

E. twinned (swallow-tail) crystals

24. Organisms in reets are the following types, except

A. reef-users as calcareous algae

B. crawlers as Trilobite

C. framework builders as corals now

D. frame-binders & encrusters as sponges & predatory fish

25. Bedded iron-rich deposits

A. encountered in Precambrian & Phanerozoic

B. include the Phanerozoic banded iron formations

C. include the Precambrian ooidal ironstones

D. consist only of ferrous-containing minerals

E. are defined as those that contain at least 5٪Fe

26. Wet gas

A. is closely associated with coal deposits

B. consists mainly of methane & ethane

C. contains > 50% propane & butane

D. does not contain any quantity of H_2S, CO_2 & N_2

27. Regarding guano, the following statements true except

A. Guano consists of birds and bats excrements

B. Forms now on some oceanic islands in E-Pacific

C. Form phosphate deposit of economic significance

D. leached to give downward percolating solutions cause phosphatization of underlying carbonates

28. The least common Fe-oxide in sedimentary rocks is

A. Goethite

B. Hematite

C. Siderite

D. Magnetite

E. Pyrite

29. Mudrocks

A. the least abundant type of sedimentary rocks (5-15 % of the sedimentary sequences)

B. can be deposited only in river's floodplains

C. are very well exposed

D. Composed mainly of clay minerals & silt-grade Qz

E. are restricted to the Mesozoic Erathem

30. Micrite originates

A. by direct precipitation of calcite filling pore spaces between carbonate grains

B. by recrystallization of microsparite into micrite

C. by direct precipitation from sea water under-saturated with respect to calcium carbonate

D. by organisms that have hard parts consisting of tiny aragonite needles such as diatoms

E. By disintegration of calcareous green algae