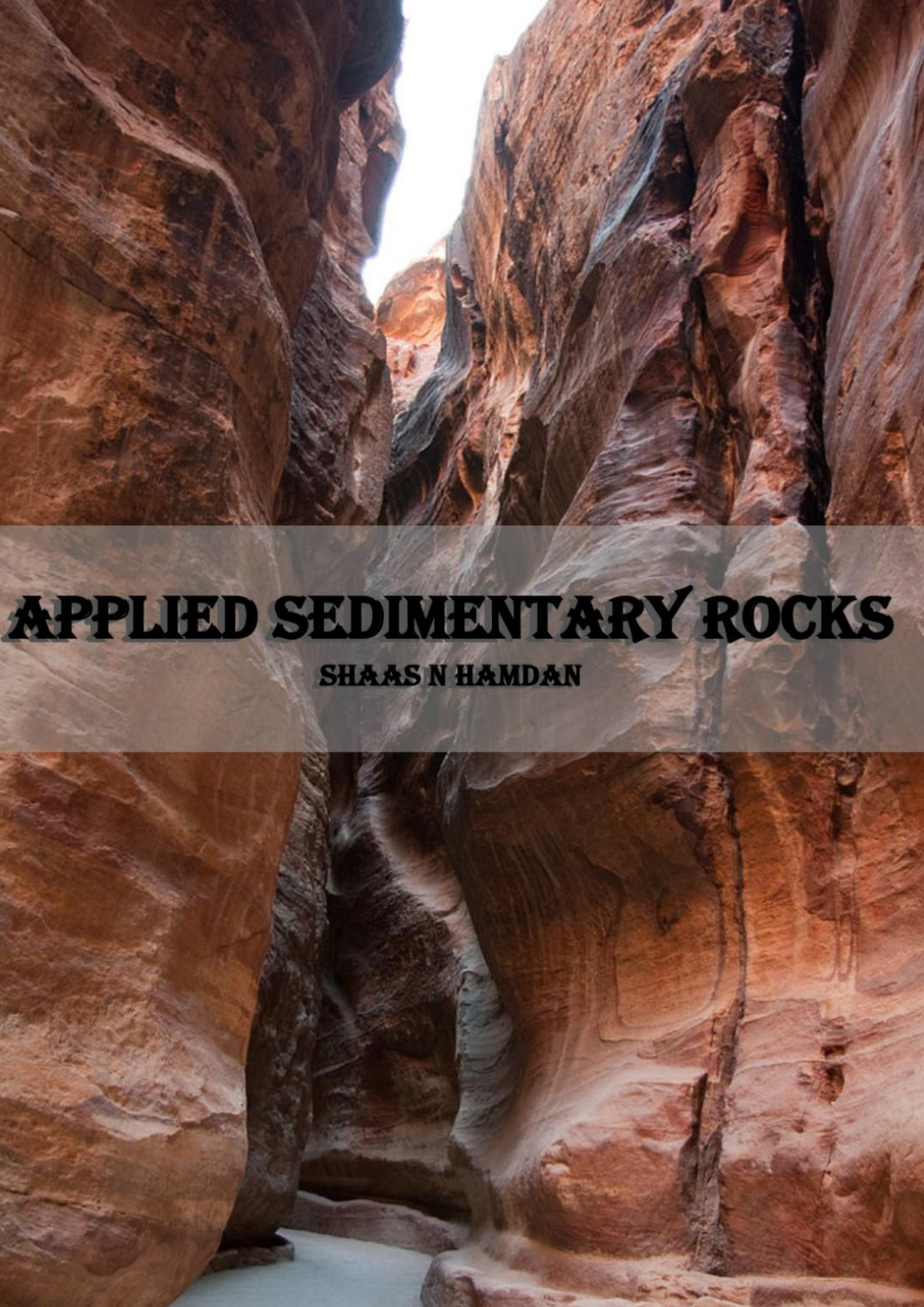


APPLIED SEDIMENTARY ROCKS

SHAAS N HAMDAN

TEXTURE & STRUCTURE OF CLASTIC ROCKS

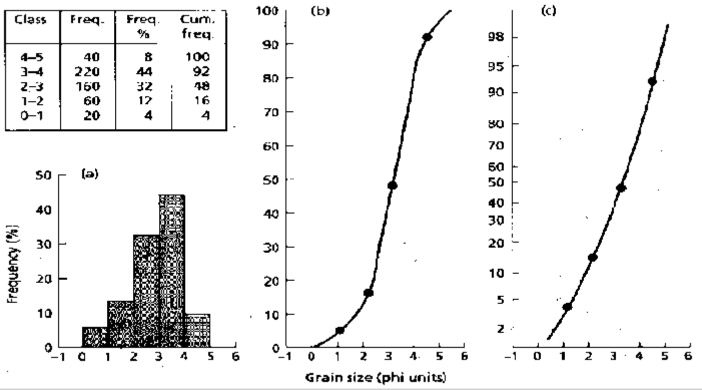
- **Sedimentation:** is accumulation of sediments, applied to settling of solid particle from a fluid
- **Sedimentology**: is the study of sedimentary deposits
- **Sedimentary petrology:** origin & formation of the rocks
- **Petrography:** is the science of description of the rocks
- **Sediment**: is a loose materials accumulated on surface
- **The sediment deposited or settled from**: solution (fluid), glacial, aeolian agencies, residual deposits, or by accumulation of organic debris (coal)
- **Lithification:** converted sediment into the sedimentary rock by compaction, cementation, & recrystallization
  - ➢ **Compaction:** due to increasing burial depth
  - ➢ **Cementation:** by precipitation of dissolved ions
- **Occurrence of a Sedimentary Rocks**
  - ➢ Most are occurs in low T-P, burt some formed at higher T (pyroclastic) & other at higher P (sea floor)
  - ➢ **Sedimentary & metasedimentary rock make** 5% of the lithosphere, but **they most abundant rocks on the surface** that cover 70% of Earth‘s surface (a thin veneer on surface 0-13 km thick, average 2.2km)
  - ➢ **3 types make >95% are** mudstone (shale), sandstone, & carbonates, **The remaining types** salt deposits, chert, coal, phosphates, & ironstones
- **Value**: Most of mineral product come from sed. deposit
  - ➢ ***Fuels (Valuable fluids):*** coal, gas, petroleum, & oil
  - ➢ ***Raw material:*** ceramics & Portland cement
  - ➢ ***non-metallic deposit***: building stones, molding sand
  - ➢ ***mineral fertilizers***: phosphates, potash salts
  - ➢ ***ore*** (Fe,Al,Cu,U,Mg,Mn) & ***brines*** (iodine, bromine)
  - ➢ ***gemstones***: gold, tin, tungsten, & platinum
- <u>Classification of Sedimentary Rocks</u>
  1. ***Siliciclastic (terrigenous, epiclastic)***: fragments of pre-existing rocks, which transported & deposited
  2. ***Limestone***: have biogenic, or biochemical origin altered to dolomite, phosphate, coal, oil shale, chert
  3. ***Evaporite & Ironstone***: chemically precipitation
  4. ***Volcaniclastic:*** by lava & volcanic fragments
  - ➢ Each group divided to smaller groups based on grain size & composition, many of them grade laterally or vertically to another through intermediate lithology
- **Siliciclastic:** breccia & conglomerate (rudaceous), sandstone (arenite), mudrock (lutites, argillaceous)
  - ➢ Composed of fragments (clasts, grains) formed by weathering, & transported by several ways
  - ➢ **Transportation way** effected 2 features (texture & structure) include rivers, tidal currents, turbidity currents, waves, winds, debris flows, or glaciers
- **Sedimentary texture:** small-scale features
  - ➢ **arise from:** size, shape, fabric, produced physically
  - ➢ **primary textural properties:** ***grain size*** & size parameters,***shape***(form,roundness,surface texture) & **fabric** (orientation & grain-to-grain relations)
  - ➢ **primary textur** controls other properties (e.g. density, porosity, & permeability)

GRAIN SIZE

- **Grade scales:** The basic descriptive element
- **Udden-Wentworth scale** based on constant ratio of successive boundaries
  - ➢ Φ-scale make calculation easier: $\mathbf{\Phi=-\log_2{}^{[X]}}$
  - ➢ The size decreases with increasing +ve Φ

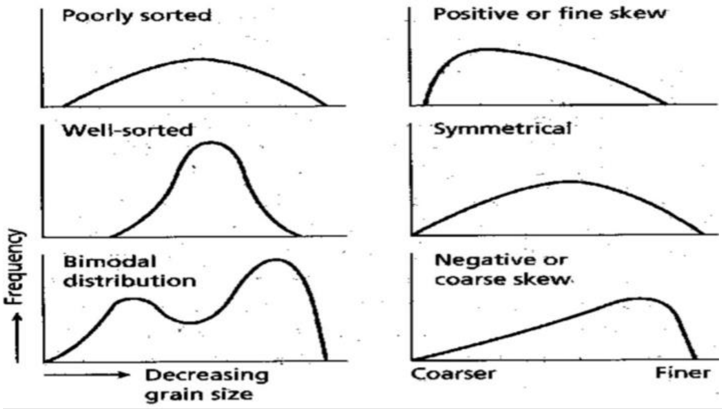
Length (mm)	Φ		Class	Sediment/ rock name
			block	mega-conglomerate
4096	-12	vc	boulder	gravel conglomerate
2048	-11	c		
1024	-10	m		
512	-9	f		
256	-8	c	cobble	
128	-7	f		
64	-6	vc	pebble	
32	-5	c		
16	-4	m		
8	-3	f		
4	-2		granule	
2	-1	vc	sand	sand sandstone
1	0	c		
0.50	1	m		
0.25	2	f		
0.125	3	vf		
0.063	4	c	silt	silt siltstone
0.031	5	m		
0.015	6	f		
0.008	7	vf		
0.004	8		clay	clay claystone

Particle Size	Measured Techniques
Large particle (pebble-boulder)	**Measured manually with a tape or caliper**
Unconsolated (Granule – Silt)	**by sieving technique using vertically mounted sieves**
Well-cemented (sand-silt)	**Using thinsections, eyepiece graticule, & point counter**
Small particles (Silt – Clay)	**By measuring settling velocity via column of water**



Graphic presentation of grain-size data of 500g sandstone

- histogram (a): grain size decrease away from origin
- cumulative frequency (b): % of grains coarser than a value
- probability scale (c): From the cumulative frequency



Smoothed frequency distribution curves showing types of sorting & skewness

- **Median**: size at 50%, is not useful as the mean
- **Mean**: average grain size at 16th, 50th, & 84th %
- **Mode**: mid point of the most abundant class
- Most sediments are ***unimodal*** (one size dominates) but bimodal & polymodal aren't uncommon
- **Sorting**: measure of standard deviation (grain-size distribution), gives indication of the effectiveness of the depositional medium in separating of grains

Grain size [Φ]	Terms for sorting
<0.35	Very well sorted
0.35 – 0.50	Well sorted
0.50 – 0.71	Moderately well sorted
0.71 – 1.00	Moderately sorted
1.00 – 2.00	Poorly sorted
>2.00	Very poorly sorted

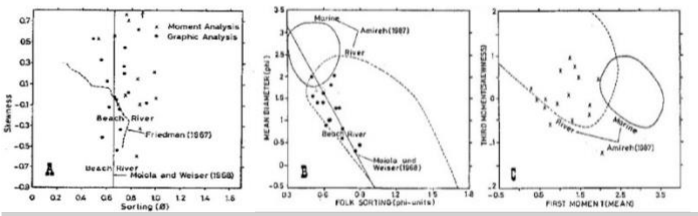
- **Factors that determine Sorting**:
  1. ***Depositional mechanism:*** reworked by wind or water & rate of deposition

Sorted	deserts, beaches, & shallow shelf seas
Poorly	Quickly deposite: storm bed & mudflow (viscous)

  2. ***Grains***: sand more sorted (easily transported)
  3. ***Distance of transport***: sorting improves along the transport path e.g. desert (size decrease downwind)
- **Skewness**: measure symmetry of distribution & best seen from the smoothed frequency curve
  - ***-ve skewed***: If distribution has a coarse 'tail' (there is an excess of coarse grain), ***+ve skewed:*** a fine 'tail'

Sk	Terms for skewness
<-0.3	Strongly coarse-skewed
-0.10 – -0.30	Coarse-skewed
+0.10 – -0.10	Near-symmetrical
+0.30 – +0.10	Fine-skewed
>+0.30	Strongly fine-skewed

- skewness is a reflection of depositional process:
  1. **Beach sands**: -ve skewed, finer component are carried off by the persistent wave action
  2. **river sands:** +ve, finer trapped between large grains
- **The moment method**: obtain the grain size parameters by direct calculations using computer without graphic
- **Interpretation & Uses of Grain Size Analyses:**
  1. Determine different environment & process
  2. Distinguish the sediments of modern deposit
  3. Infer direction of sediment dispersal (decreasing away from the source), this down-current occur in fluvial, deltaic, & in turbidites in deep sea basins
- **Scatter diagrams (bivariate discriminant plot):** to distinguish between beach, river, & dune sand

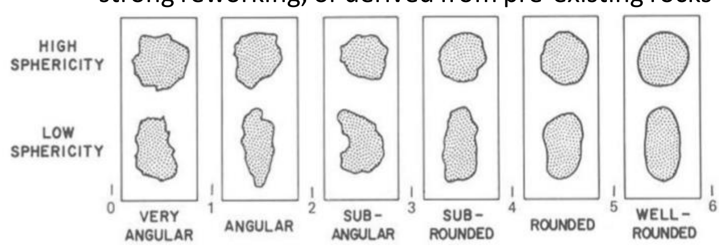


A: sorting Vs skewness, B: sorting Vs diameter
C: 1st moment (mean) Vs 3rd (skewness)
This fig. used to distinguish river & beach depositional env.

- Grain sizes aren't used to interpret environments but coupled with structures due to 2 problems:
  1. **Inheritance of sand**: Some sands are derived from adjacent or pre-existing environment
  2. **Origin of clay:** infiltrated to depositional site, break-down product mudstone, or a diagenetic precipitate

GRAIN MORPHOLOGY

- **There are 3 aspects of morphology**:
  1. **Shape**: sphere, rod, disc, or blade
  2. **Sphericity**: grain approache a sphere shape
  3. **Roundness**: curvature of corners of a grain
- **Roundness**: depend on weathering, abrasion, & trans-portation, significant for environmental interpretations
  - **Rounding particles:** long transportation distance, strong reworking, or derived from pre-existing rocks



Beach sands	Rounded: strong reworking by waves
Glacial sand	Angular: Lack of reworking
River sands	Wide range: depend on distance of transportation & # of deposition cycles

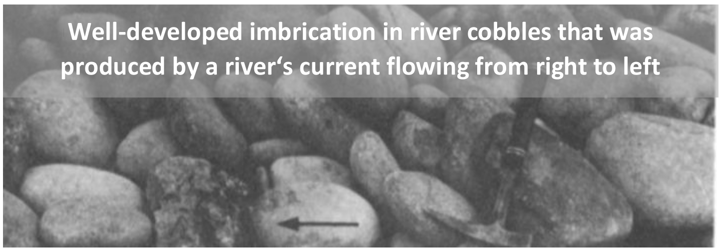
- **Grain Surface Texture:** distinct appearance of the surface of grains, including size, shape & field, used to infer depositional process & environments

Environment	Surface Texture
Glacial	Parallel to semi-parallel striation & conchoidal
Wind	Smooth surface (polished) in aeolian sand
Beache, rivers	V-shaped or crescentic impact marks

- **Fabric:** grain orientation & contacts (grain aggregates), Produced by interaction of wind, water, or ice (medium)

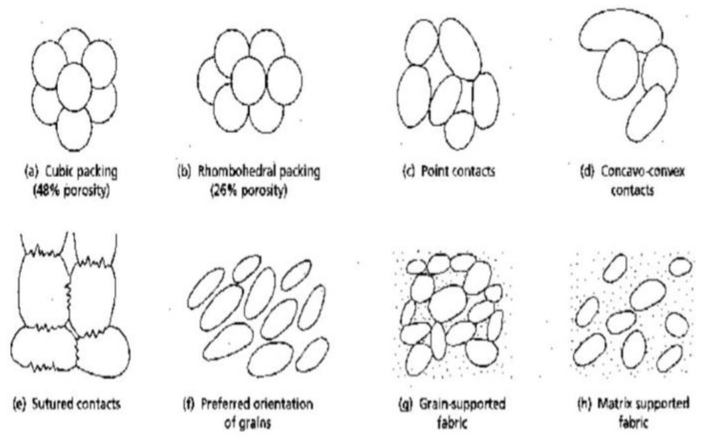
Orientation	Produced by
Preferred	In a platy or elongated (rod) particles
Normal-to-current	Rolling of pebbles
Parallel-to-current	Sliding motion
Imbrication (More important)	Oblate grains aligned overlapping each other, & dipping in upstream direction

  - ➢ Pebbles with long axes in **fluvial** environment oriented parallel- or normal-to-current direction



Well-developed imbrication in river cobbles that was produced by a river‘s current flowing from right to left

Contacts	Produced by
Point contact	Touch of grains, produced grain-supporte
Sutured contact	Mutual penetration
Concavo-convex	One grain penetrates another



Grain fabric in sediments: a, b (packing), c, d, e (contacts), g, h (grain-matrix relationships)

  - ➢ If there is a lot of matrix, grains not contact & float in the matrix produced matrix-supported fabric

- **The fabric has significance in interpreting the depositional process of conglomerate**

Environment	Matrix	Environments
Debris flow, glacial tills,tillites	A lot of matrix	Pebbles floating in matrix
River, stream flood, & beach	Little matrix	Pebbles are in contact

- **Grain packing**: spacing or density of grains as a function of size, shape, & degree of compaction
  - ➢ Affects density, porosity, & permeability

Packing	Porosity	Produced by
Loosest	48%	cubic arrangement
Tightest	26%	Rhombohedral arrangement

- **Textural maturity:** affects porosity & permeability (increase with increasing maturity)

Maturity	Matrix	Sorting	Rounding
Immature	Much	Poorly sorted	Angular
Mature	Little	Moderat to good	Sub-rounded
Supermature	No	Very good sorting	Well-rounded

Maturity	Depositional process
Immature	Little current activity, Glacial, & fluvial
Mature	Persistent currents or wind activity
Supermature	Beach, desert, & shallow marine

STRUCTURES

- **Structures**: large-scale (cutcrop), classified into 4 groups based on genesis (origin) or description
- **used to determine the following (Applications)**:
  1. **Depositional environments**: depositional process, burial depth, current, & wind strength
  2. **Paleocurrent & Paleogeography**
  3. way of **rock succession in complex folding**

Classification	Environment
Depositional	Bedding, Lamination, Graded, Massive, Ripples, Syneresis, Mudcracks, dunes, Hummocky, draas, aeolian, rain spot
Erosional	Flute marks, Groove marks, & Channels
Postdeposition	slump, load cast, ball, pillow, overturned, convolute,seismite
Biogenic	resting,crawling, grazing, feeding, dwelling, burrows, borings

AQUEOUS FLOW

- **Aqueous flow Include** river, tidal, & storm current
- Produce a wide range of sedimentary structures
- **Turbidity currents & debris flow arise when** sediment moved downslope under gravity

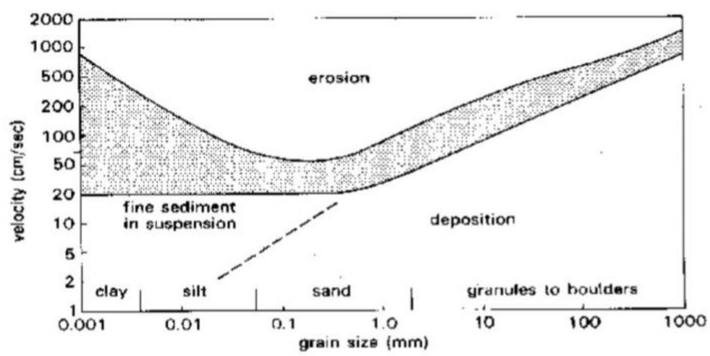
Sediment	Transported by	Transported as
Fine	Water, air	Suspension, bed load
Coarse	saltation, rolling, sliding	bed load

  - ➢ sediments kept in suspension by fluid turbulence

- **Bed shear stress (mean flow velocity)**: average force/ area for flow on the sediment surface (strength of flow)

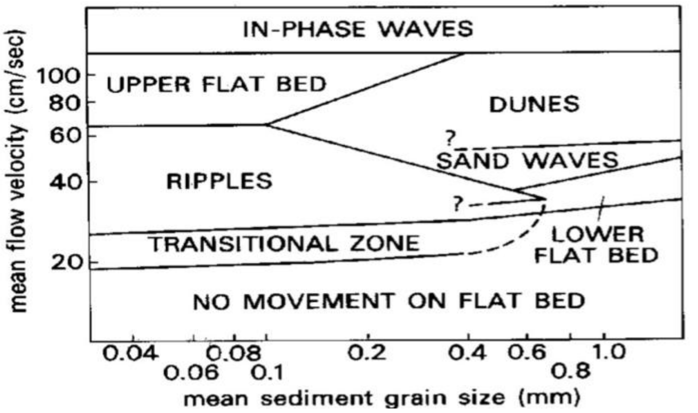
Types of aqueous flow	
Laminar	smoothly with little diffusion-exchange
Turbulent	Higher velocity, with much diffusion, components & water moves as packets

- Fine sand are more easily eroded, finer sediments are held in suspension until flow velocity is minimal
- The higher erosion velocities required for silt & clay are a reflection of cohesive force between particles



Hjulstrom‘s diagram: relationship between grain size & current velocity (the critical erosion velocity)
Sediment may continue to be transported after current velocity has fallen below level at which initially eroded

- The nature of sediment surface & its structure (***bed forms)*** dependent on the flow conditions
  - Flow condition of ripple & dune: lower flow regime, upper flow regime, & upper plane bed



0.1–0.03	Increasing flow strength → flat bed with no sediment movement gives way to ripples & then to upper flat bed
0.1 – 0.6	The sequence is no movement: ripples, dunes, & then upper flat bed
> 0.6	Sequence is no movement: lower flat bed, upper flat bed, & then dunes

- At higher flow strength sinusoidal undulation again develop on the sandy bed (antidunes), which are in phase with stationary water-surface
- **Characteristic feature of the upper flat bed**
  1. primary current lineation, & a few grains high
  2. low flow-parallel ridges, & streaks on surface

DEPOSITIONAL STRUCTURES

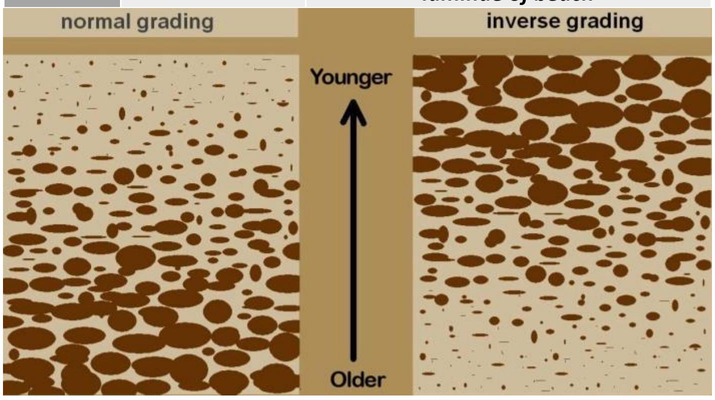
Bedding & Lamination Structures

- **basic character of sedimentary rocks, bed is strata with thickness >1cm, & lamina is finer strata**

Thickness	Classification
< 1cm	**Lamina (thin<3mm, thick:3-10mm)**
1cm - 3cm	**Very thin bed**
3cm - 10cm	**Thin bed**
10cm - 30cm	**Medium bed**
30cm - 100cm	**Thick bed**
> 100cm	**Very thick bed**

- **Bed**: tabular or lenticular layer formed under constant condition, has charateristic lithology (texture, structure)
  - clearly distinguish from another layers
  - deposited above previous one by change the rate of sedimentation, degree of composition, & grain size
  - **Bedding plane**: is the upper & lower surfaces of bed, represent period of non-deposition, or changes in depositional or erosional conditions
- **Laminae** produced by:
  1. less severe, or short lived fluctuations
  2. Changing in depositional conditions (cause variation in grain size, clay, organic matter, & microfossil)
  3. Alternating layers of finer & coarser grained sediments (the most common kind)
  4. silt & clay deposition from suspension in lakes, deltas, tidal flats, subtidal shelf, & deep sea
  5. chemical precipitation (subaqueous evaporite)
  6. phytoplankton blooms (organic rich layers)
  7. Formation of parallel laminae in sand-sediment deposited by swash & backwash on beaches
  8. alternations of laminae of sand, silt, or mud (rythmites) generated by reversal tidal currents
- **Graded bed**: has distinct vertical gradation in grain sizes

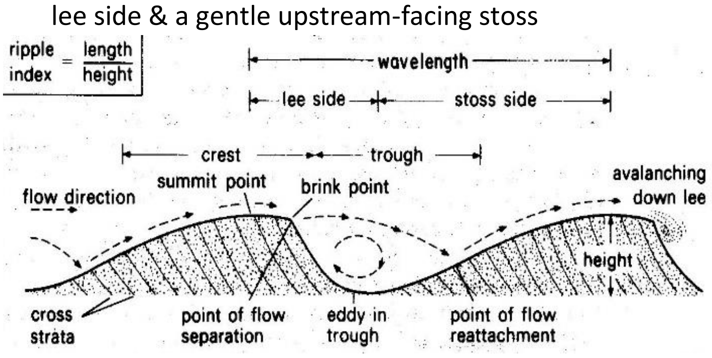
Types	Gradation	Produced by
Normal	coarse particles at the base to finer at the top	**change rate of settling particles** of different size from suspension during the ***waning stage of turbidity current***
Reverse (Inverse) rare	Coarse particles at the top to finer particles at the base	**Segregation** of fine-sized heavy mineral, coarser grained light mineral, & certain deepwater sediments In some ***volcaniclastic deposits, & In laminae of beach***

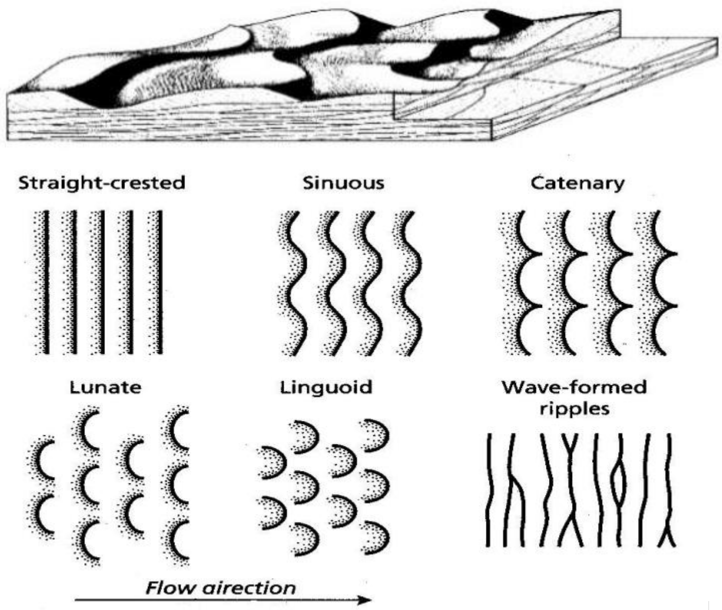


- **Massive bedding**: structureless, produced by
  1. Destroying original structure by **Bioturbation, Dewatering, Recrystallization, & Replacement**
  2. **Grain flow**: rapid deposition a dumping of sediment
  3. **Other re-sedimentation** process
  - Some rock appear massive (structurless), but X-ray techniques show that this is not the case

Current-Ripples, & Dunes structures

- **Ripples & Dunes**: is a downstream-migrating bedforms produced by unidirectional aqueous flow
- Ripple & dune migrate downstream via erosion of sediment from stoss slope & transport to the crest from the sediments avalanche down the lee slope
- **Current ripples**: small-scale bedform (λ= cm - cm's)
- **bedforms common in:** rivers, estuaries, tidal flats, delta, shoreline, shallow marine shelves, sea floor
- Ripples described by **ripple index** (λ/height)
- For current ripple RI=8-12, The larger bedforms **subaqueous dunes** with 1m & height 10cm
- In Profile: asymmetric with steeper, downstream-facing lee side & a gentle upstream-facing stoss





Ripple terminology for the shape of crests of ripples & dunes shape described as 2D if crests are straight, or 3D if sinuous, catenary, lunate or linguoid (Other terms for large-scale bedforms: megaripple, sandwave, bar, & ***dunes***)

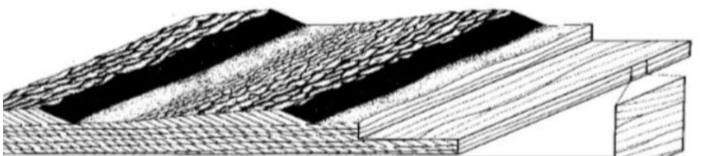
Cross-Stratification & Cross-Bedding Structures

- **Stratification**: one of the most common structures in sandstones, produced by migration of bedforms
- **Cross-strata**: is a foresets, represent the former position of the ripple & dune lee face (Downstream migration of ripples & dunes under conditions of net sedimentation)

Types of cross-bedding	
Types	Produced by
Herringbone	reverse tidal current in tidal region (affected by high & low tides)
Planar & trough	straight crested, & linguoid ripple (set height < a few cm's)
Climbing-ripple	Rapid sedimentation, as ripples build up as well as forward, so a ripple 'climbs' up the stoss side of the one downstream

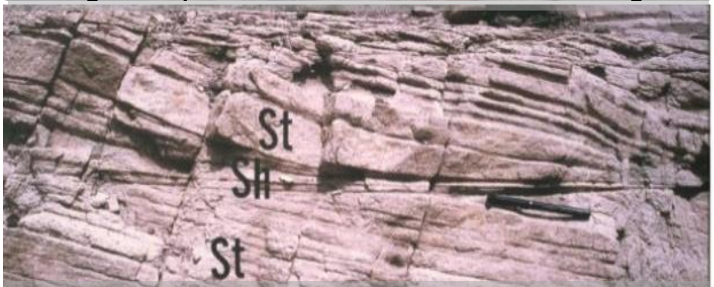
Types of cross-stratification (cross-bedding)		
Type	Produced by	Dimensions
Planar	**Downstream migration of straight -crested**	**Dimensional bedforms**
Trough	**Downstream migration of curved-crested**	**3D bedforms, (lunate, sinuous dune)**

- **Set** individual bed of cross-strata (deci-m – m's)
- **Coset**: a group of similar sets
- **Planar cross-bedding:** foresets (sloping beds) dip at angle ≥ 30°, have angular or tangential basal contact with the horizontal & Forms tabular sets, scoop-(tangential bases), & wedge-shaped sets (rare)
- Large scale cross-bedding deposited in braided river & alluvial fans by downstream gravel bars



Planar tabular cross-bedding

Large-scale planar cross-stratification. Flow left → right



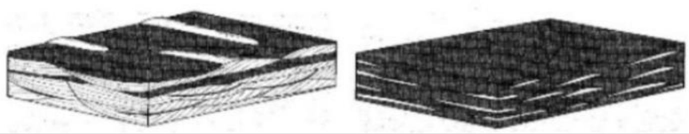
Trough cross-bedding (St) with planar bedding (Sh), Trend of current is almost perpendicular to the photo

Tidal Current Structures

- **Tidal flat environment** characterized by deposition of mud during slack-water periods, & sand during higher energy periods of the high & low tides

Cross-bedding	Occur in sands, sandstones, gravel, & conglomerate
Herringbone cross-strata	Produced by reverse tidal current (one tidal current are dominant & unidirectional formed, Then other current direction dominant in the opposite direction were deposited above the lower set)
Flaser bedding	Thin streaks of mud between sets of cross-laminations (Mud is concentrated in the ripple troughs but may also cover the crests)
Lenticular bedding	Isolated ripples, seen in cross section as lenses of cross-laminated sand, within mud or mudstone

Herringbone cross-stratification



Flaser bedding (left) & lenticular bedding (right)

Wave-formed Ripples & Cross-Lamination

- **Wave-ripples**: characterized by symmetrical profile & straight crest, common in shallow marine, intertidal, deltaic, & estuarine sandstone

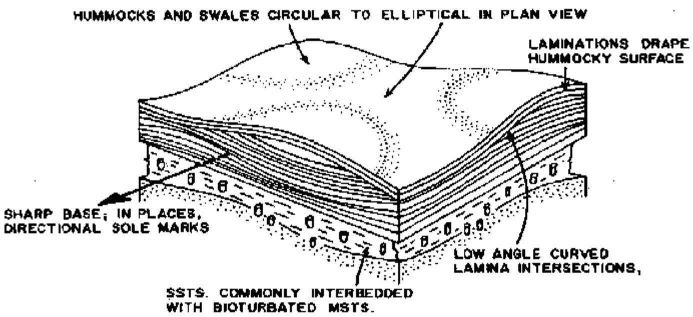
Wave-formed ripples; ripple profiles are symmetrical & crest are straight & bifurcating (at mid-upper part), trend of waves from upper right -> lower left

- The crests are pointed compared with more rounded troughs, & RI (6-10) lower than that of current (8-20)
- **In tidal:** Wave-ripple double crested, ladder-backed, or of the interference crest due to high complicated
  - ➢ ripples are more complicated due to change in water depth, & the direction of wind & runoff

Interference ripples formed with burrows

Hummocky cross-stratification

- **Hummocky cross-stratification**: Is an undulating sets of cross-lamiae (concave up: swale, convex up hummock)
- Occurs in fine sandstone to coarse siltstone that contains mica & fine carbonaceous plant debris
- occurs in sets (15-20cm) with wavy erosional bases, rippled, bioturbated top,in shallow marine environment
- **Formed by large storm** waves which erodes the seabed to low hummock-swale (lack of significant orientations) & mantled by sandy laminae (swept over hummocks)
- The cross-laminae are gently curved, low angle (<15°) & intersect each other at a low angle



Hummocky-strata (above), & swaley-strata (below)

Wind-formed Structures

- Sands transported by saltation, surface creep, & suspension (for fine sediments)

Wind-ripples	Straight-crested asymmetrical forms with some crest bifurcation & has a larger RI (more than current & wave) λ & height depend on grain size & wind strength
Dune	Is the most important ***aeolian bedform*** • λ 10's – 100's m & height of several meters • Type: ***Bracha*** (lunate), ***Seif*** (elongate ridge) • Less common type: parabolic, star, transverse
Draa's	Similar as dune but larger (λ = Km's, h = 10's m)
Aeolian cross-bedding	Same as subaqueous dune but with steeper dip angle (pf = 25-35°), & thicker than subaqueous dune (1-30m) • Sand is moved up wind-facing slope & on the top of the lee surface from they avalanches down at an angle 35°

Mud-cracks structures

- indicate subaerial exposure if formed via desiccation, found in fine-grained sediment

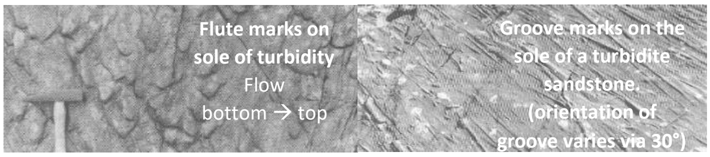
Desiccation	Polygonal, common on tidal flat & reworking them leads to generation of intraclasts
Shrinkag	Develop subaqueously because of syneresis produces due to slight changes in water chemistry
Syneresis	Is a contraction of the sediment through loss of water, Common in lacustrine environment
Rain spots	In mudrocks of continental & shoreline

EROSIONAL STRUCTURES

- Formed through erosion by aqueous & sediment-laden currents before deposition of the overlying bed, by objects in transport striking the sediment surface

Flute-marks & Groove-marks structures

- **Flute marks:** spatulate or heel-shaped, consisting of rounded or bulbou upstream end, which flares downstream & merges into bedding plane
- **Groove-marks:** Linear ridges on the sole of sand beds



	Flute Marks	Groove Marks
Formed by	The infilling of a groove cut into the underlying mud bed, & Formed from tool (fossil, mud clast) carried by a current, gouging the groove into the underlying mud bed, & The tool found at end of the groove	Localized erosion of sand-laden currents, passing over a cohesive mud & as current velocity decreases sand infills flute
Occur in	Singly or groups on one surface, all parallel or deviating in orientation	groups, all with a similar orientation & size
Common on	soles of turbidite beds, floodplain, river, shallow marine (storm surge)	Sole of turbidites
Uses	Palaeocurrent indicator	Flow direction indicator

Channels & scours

- Found in sediments of almost all environments
- Channel are on the scale of meters (or km's) & scours are smaller, occurring within or on the bases of beds
- They can be recognized by cutting of bedding planes & lamination in underlying sediments

Scour	Local, oval to elongate with smooth to irregular, concave-up shape, with slightly coarser sediment, represent short-lived erosion events
Channel	More organized & were often the pathways for sediment & water for considerable time

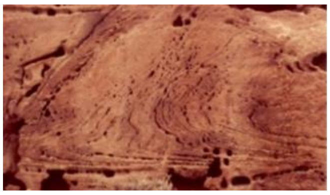
- The larger channels are palaeogeographic indicator
- Channel Infilled with coarse sediments, thin lag deposit of pebbles & intraformational clasts at the base

- **Environment**: alluvial fan, braided rivers, meandering rivers, glacial, deltaic, slope, submarine fan

POST-DEPOSITIONAL STRUCTURES

- Formed after deposition & before complete lithification
- **Slump:** produce by slumping of sediments deposited on slight to significant slopes, initiated via earthquake
  - Downslope movement take place on large or small scale, involving individual bed or thick packet strata
  - Crumbling & folding of such beds common & wholesale brecciation can result
- **Convolute bedding:** in cross- & planar-laminated strata & consists of regular to irregular folds & contortions
  - It is only uppermost part of the bed & convolution planed off, indicating their syn-sedimentary origin
  - **Origin**: liquefaction, shearing of sediment surface by currents, & dewatering (from the sudden loss of pore-water causing sediment to lose its strength)
  - Common in turbidite beds, but it also occurs in fluvial, tidal flat, & other sediments

- **Overturned cross-bedding**: turning over of the upper parts of forests in the downstream direction
  - The cause of cross-bedding overturning is frictional drag are passage of sand-saturated water current over the surface of non-indurate cross-bedded



- **Load casts**: common sole marks, as bulbous, downward directed protuberances of a sands bed into underlying sediment, normally mud
  - Show variation in shape & size, common structure is the squeezing of mud (flame)
  - Formed by vertical density contrast between the overlying more dense sand & the underlying less dense mud, so sand sinks to mud

- **Ball & pillow**: related to load casts, where sand bed lying within mudstone has broken up into pillow-shaped, partly connected or free floating, & formed by earthquakes shock

- **water escape structures**: soft-sediments deformation structures result from dewatering due to liquefaction by particles shaken loose each other through some applied stress which associated with an earthquakes
  - Include disruption & contortion of bedding, & sandstone dykes cutting across primary structures, & if reaching the surface forming a sand volcano
- **Seismites**: structures deformed by seismic events

BIOGENIC STRUCTURES

- produced by activities of organisms from vague bioturbation (by burrowing) to trace fossils (ichno-)
- Structura produced by trace fossils are distinctive features that attributed to a particular organism
- **Resting trace**: by vagile epibenthic (moving on surface)
- **Crawling traces**: by mobile animal (trilobite - dinosaur)
  - Trails & trackways of moving animals
  - the trilobite foraging trail, is common on the surface or sole of Lower Paleozoic
- **Grazing trace:** by mobile, deposit feeding epibenthic that feed at/near sediment surface
  - Consist of curved, coiled, & radiating furrow
  - formed by the organisms systematically ingesting the sediment for food
- **Dwelling burrows**: by sessile & semisessile endobenthic animals (suspension feeders, predators & scavengers)
  - The burrows vertical tubes (eg. ***Skolithos***) These trace common in the intertidal zone
- **Feeding traces**: intrastratal type, formed below the sediment surface, & endobenthic deposit feeders
  - living within a burrow system
  - network of filled burrows (branching or not)
- **Borings**: trace fossils found in limestone that differ from burrows by being made into a hard substrate, such as a hardground surface or a pebble or carbonate skeleton

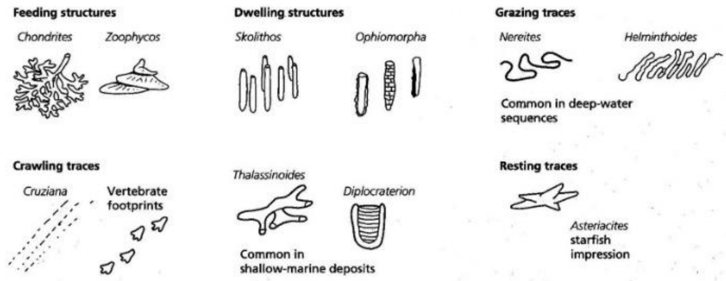


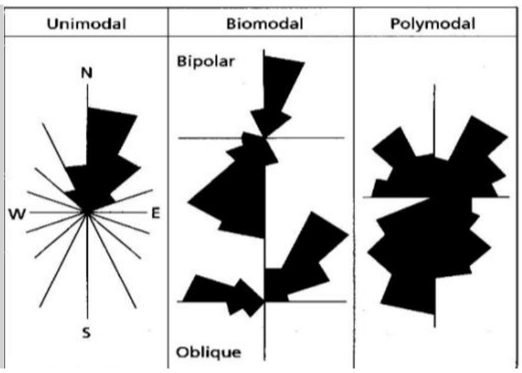
Fig. 1.33: Illustrations of the common types of trace fossils.

PALAEOCURRENT ANALYSIS

- erosional & depositional structures used to determine the paleocurrent which used to determine palageography, sand-body geometry, & provenance

Vectorial structures	Flow direction indicator
Cross bedding	**Pebbles, & Fossils**
asymmetric ripples	**symmetric ripples**
Flute marks	**Groove marks**
imbrications	**preferred orientation**

usually presented as rose diagrams
The 4 common palaeocurrent patterns are:
Unimodal
Bipolar
Oblique
Polymodal



CLASTIC SEDIMENTARY ROCKS SANDSTONE & CONGLOMERATE

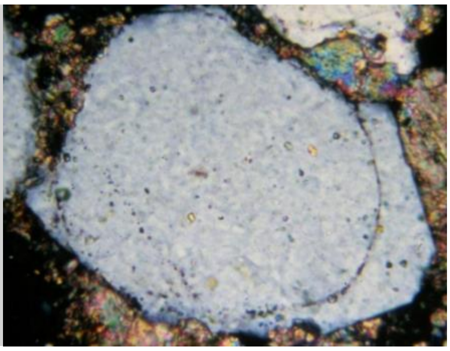
SANDSTONE COMPOSITION

- The clastic texture of detrital (clastic) sedimentary rocks (conglomerates & sandstones) consists of:
  1. **Framework components**: clasts, grains, or particles which constitute the skeleton of the rock, include quartz, feldspar, & rock fragments
  2. **Matrix**: consists of grains < silt (<0.63mm) located between the clasts
  3. **Cement**: filling remaining pore spaces between the grains & matrix

Quartz [Qz, SiO_2]

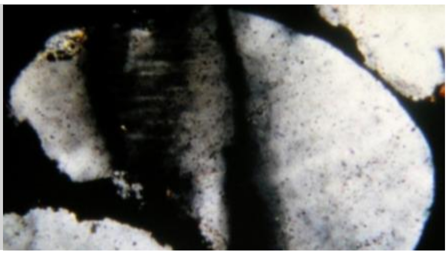
- The most common detrital mineral in all sandstones
- No sandstone without Qz, because Qz most stable silicate light mineral under sedimentary conditions
- 3 varieties of quartz are found in clastic rocks:
  1. **Non-undulose monocrystalline Qz**: each grain is single crystal, with straight or unit extinction

Non-undulose monocrystalline Qz overgrowth separated from the detrital core by presence of the dust line, crossed polarized light



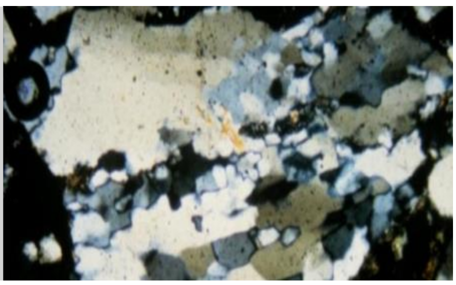
  2. **Undulose monocrystalline Qz:** each grain consists of single crystal, having wavy or undulose extinction

Undulose monocrystalline quartz, crossed polarized light



  3. **Polycrystalline quartz**: each grain consists of ≥ 2 crystals (The contact straight, sutured, or irregular)

Polycrystalline quartz, crossed polarized light

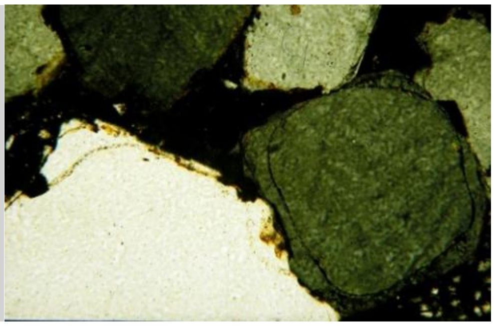


- Qz grains characterized by presence of some inclusions such as needles of sillaminite, vacuoles of fluids or minute crystals (tourmaline, mica or rutile)
- Qz are derived from plutonic granitoid rocks, acid gneisses, schist, in some cases pre-existing sandstones

Properties of Qz that can be employed to infer its source rock	
Sources	**Quartz properties**
Volcanic rock	Non-undulose Monocrystalline Qz no inclusions & euhedral crystals
Hydrothermal vein	Have fluid-filled vacuoles
Metamorphic rocks	Polycrystalline, Elongate,with sutured contacts, & sillaminite inclusions
Plutonic rocks	Undulose extinction (due to the strain in the crystal lattice)
Sandstone	Non-undulose monocrystaline Qz

- Non-undulose monocrystalline Qz is the most common in sandstones than other varieties due to its higher resistance to weathering, transportation, & diagenesis
- Recycled Qz recognized by the presence of overqrowth, that in some cases followed by a second overgrowth

2 quartz grain exhibiting 2 stages of quartz overgrowth XPL



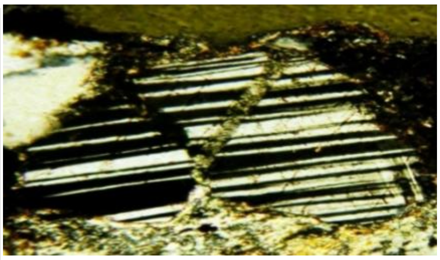
Feldspars [Fs, $(Na,K)AlSi_3O_8$, $CaAl_2Si_2O_8$]

- More abundant than quartz in granitoid & gneissos source rocks, & less common in sandstones
- The reason for lower concentration than quartz:
  1. **lower chemical stability** against chemical weathering, particularly hydrolysis & leaching
  2. **lower resistance against mechanical abrasion** due to well-developed cleavage
- Types of Feldspar grains in sandstones:
  1. **K-Fs:** orthoclase, microcline, & rarely sanidine

Orthoclase with overgrowth The overgrowth lacks weathering or alteration products

2. **Plagioclase**: less common than K-Fs due to its lower stability against weathering, & less abundance in continental basement rocks (granites & gneisses) that are the provenance of many sandstones

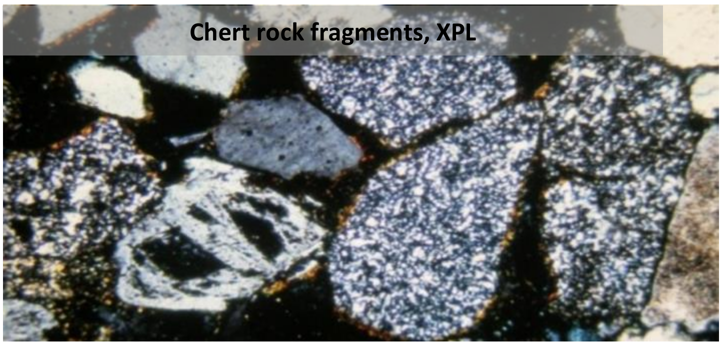
Plagioclase grain characterized by multiple twining, XPL



- **Feldspar grains Vs quartz grains in thin sections**
  1. **Twining**: Cross-hatch twining of microcline, & Carlsbad twining of orthoclase
  2. **Cleavage**: characterized Fs particularly when it is associated with chemical alteration products (clay minerals & sericite) along cleavage planes
  3. **Appearance**: chemical weathering of Fs imparts a turbid color, cloudy, or dusty appearance, whereas Qz are clear lacking this appearance
- The majority of Fs in rock are of first cycle origin due to mechanical indurability during transportation, & chemical instability, they are destroyed via recycling
- Conditions for existence of feldspar are arid climate, since humid climate promotes chemical weathering
- high rate of erosion associated with the high relief in tectonic active areas that enables feldspar to escape even intensive chemical weathering in humid region

Rock Fragments [lithic fragments]

- more abundant in conglomerate than in sandstones
- if source are coarse crystalline granite or gneiss, sand sized fragments will be composed of one crystal of an individual mineral, so only fine-grained or fine crystalline volcanic, metamorphic & sedimentary rocks supply sandstone with fragment
  1. **Fine-grained sedimentary**: commonly mudstone, shale, sometimes silt- or limestone, siliceous (chert)



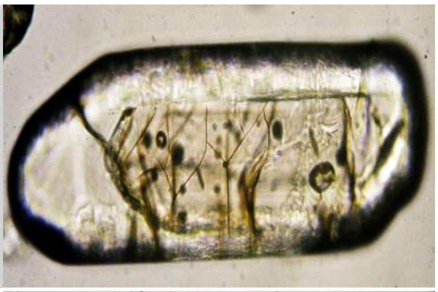
Chert rock fragments, XPL

  2. **Fine-grained metamorphic rocks**: slate, phyllite, pelite & mice schist
  3. **Volcanic rocks**: rhyolite, andesite, & basalt
- Rock fragments are very useful in studies of provenance of sandstone & important to study rock fragments of similar size, since their percentage increases with increasing grain size
- Many fragments are unstable (labile grains) such as mudstone or slate, become indistiguishible from the primary mud matrix by diagenitic compaction, or altered or replaced by chlorite or zeolite

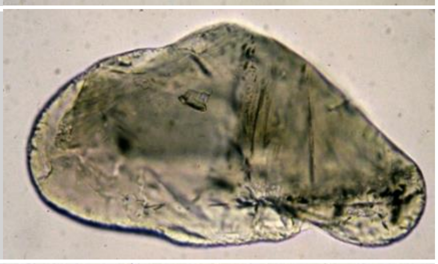
Other Components

- **carbonate fragments:** shell, ooid, peloid, intraclasts
- **Galuconite & phosphatic grains**
- **Detrital micas**: biotite, muscovite, & rarely chlorite
  - ➢ Occur in sandstone in form of flakes arranged parallel to bedding plane due to sheet structure
  - ➢ Derived from plutonic granitoid, schist, & phyllite
  - ➢ muscovite is more common in sandstones than biotite which unstable against chemical weathering
  - ➢ The biotite mainly altered Fe-iron oxide, chlorite, or clay mineral (illite or kaolinite)
- **Heavy minerals (HM):** accessory minerals present in sandstone with a concentration < 1%
  - ➢ Specific gravity > 2.9, for Qz & Fs ≈ 2.6
  - ➢ Types of heavy minerals:
  1. **Transparent:** silicates (zircon, tourmaline, & rutile), present in every sandstone, since they stable to ultrastable against chemical weathering & abrasion
  2. **Opaque**: are oxide & less significant in provenance determination than transparent heavy minerals

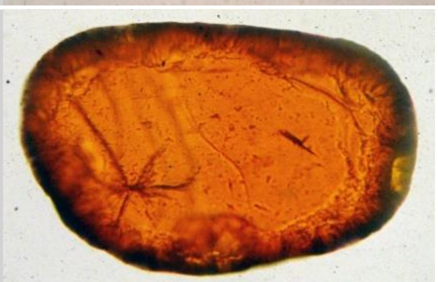
Zircon: very high relief, high IC, inclusions, the borders of the grain are heavily abraded (XPL)



Tourmaline: strong relief, high order IC, & strong pleochroism (XPL)



Rutile: red, very strong relief & IC, masked by the original color of the mineral (PPL)



  - ➢ **Metastable** heavy minerals are ***apatite, garnet, epidote, sillimanite, & staurolite***
  - ➢ **Unstable** (least stable) heavy minerals **olivine, pyroxene, hornblende, & biotite**
  - ➢ HM are obtained from sandstone by separation using heavy liquid such tetrambromoethane or bromoform which having a specific gravity of 2.9

- ➢ HM useful in determination of provenance, climate, weathering, distance of transport, depositional environment , & burial depth during diagenesis

Characteristic **HM** of different source rocks **(provenance)**	
Source rock	Characteristic HM
Acid (felsic) ign.	Apatite, Biotite, Hornblende, Magnetite, & Zircon
Basic(Mafic) ign	Augite, Hypersthene, illmenite, & Rutile
Pegmatite ign.	Fluorite, Garnet, & Tourmaline
High-grade met.	Epidote, Garnet, Kyanite, Sillimanite, & Staurolite
Low-grade met.	Biotite, & Tourmaline
Sedimentary	Reworked Tourmaline & Zircon (rounded)

Factor that influencing framework component

- Composition of grains in sandstone & cong. depends on:
  1. **Provenance (source rock)**: provided mineral grains through mechanical weathering
  2. **Tectonic setting**: determines the type of relief dominating the provenance

Activity	Relief	Note
High	High	Such as orogenic terranes
Low	Low	Low rate of epeirogenic uplift

  3. **Climate & type of weathering**

Climate	Weathering
Humid hot	Promotes chemical weathering
Dry, arid to semiarid, cold or hot	**Reduces:** leaching & chemical weathering **Facilitates**: disintegration & physical weathering

  4. **Transpiration**: influence mechanical abrasion (river, stream, glacier, wind, tidal currents have roles on dissolution or preservation of detrital minerals)
  5. **Deposition env**: Preservation of unstable minerals

Environment	Preservation
Fluvial, braided, meandering	Lower
Milder marine	Higher

  6. **Diagenesis**: physical & chemical processes affected sediments from sedimentation to metamorphism. (the most effective diagenitic **intrastratal solution**, where specific types of HM dissolved by action of pore fluids at great depth 2000m)

- **The Saleb Sandstone Formation** (early Cam age, conformably by Cam. Umm Ishrin formation)
  - ➢ Qz, K-Fs, apatite, & trace (plagioclase, mica, zircon, tourmaline, & rutile)→***granitic, granitoidal source***
  - ➢ Poly- or mono-crystalline Qz, mica & undulose Qz → ***metamorphic (mica-schist, metasediments) source***
  - ➢ All these rocks crop out in the crystalline basement of Wadi Araba & S-Jordan (part of Arabian-Nubian)
  - ➢ Sedimentological investigation of conglomerate to coarse sandstone formation indicates alluvial fan to braided river with a northward dispersal direction, proving S-located Arabian-Nubian Shield
  - ➢ Apatite, illitic matrix, & Fs is due to rapid sedimentation & short distance of transport
  - ➢ Cong. indicate high rate of erosion that associated with strong relief (result of rapid uplift & intense faulting during molasses of Pan African Orogeny)
  - ➢ Concerning the role of climate, it is agreed that the Cam over the globe was warm, & the same should be in the source area, & probably humid
  - ➢ In humid climate, Fs & apatite not destroyed, due to rapid deposition in adjacent depositional env., & preserved during diagenesis from intrastratal solution by the preservation role of the illitic matrix
- **The Cambrian Umm Ishrin Sandstone Formation** is a fluvial one consisting of mature quartz arenite
  - ➢ Unstable Fs are absent & HM suite is restricted only to ultrastable zircon, tourmaline & rutile
  - ➢ High content of 3 varieties Qz & the ultrastabel heavies → plutonic or metamorphic provenance
  - ➢ There is no reason to consider different source rock than that for the underlying formation
- **The absence of Feldspar, mica, & apatite explanation in the Middle East** (Through Late Cam): source area was stable due to no epeirogenic movement, which lead to low relief & erosion rate, Under warm humid climate
- **The Chemical Weathering are intensive under the following conditions:**
  1. **A low relief** of a tectonically stable source area which is **related to low rate of erosion**
  2. **long distance of transport** by low-braided rivers
  3. **A low rate of deposition** in fluvial environment which is associated with **low rate of subsidence**
  4. **Slight acidic conditions**: prevailing in weathering site, the transport way, & depositional environment (indicated from the presence of kaolinite)
  - ➢ Such vigorous chemical weathering conditions are sufficient to dissolve all Feldspar & unstable HM
- **Maturity**: content of chemically stable light & HM

Maturity	Consists of
Supermature	Quartz, & ultrastable HM (zircon, tourmaline & rutile)
Mature	Quartz, slight amounts of feldspar or rock fragments, & metastabe HM (apatite, garnet) & 3 ultrastable HM
Immature	Quartz, considerable amount of Feldspar, labile fragments, & some of unstable HM (hornblende, & pyroxene)

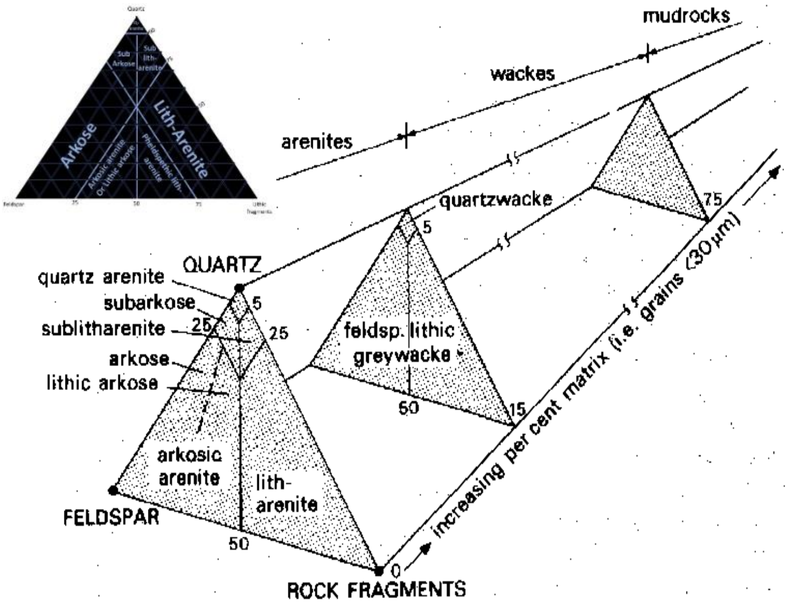
  - ➢ **supermature & mature sandstones environment**
  1. Multiple cycling of sediments (1st-cycle sediments)
  2. intensive chemical weathering
  3. humid climate in stable area
  4. long distance of transportation
  5. deposited in energetic environment which led to a strong reworking

Detrital matrix & Cements

- **Matrix**: finer grained detrital minerals, between the framework component of sandstone, & conglomerate
  - ➢ The grain size of matrix: clay size in sandstones (<20 µm) & the silt size in conglomerates (<63 microns)
  - ➢ Matrix consist of the same minerals as framework, & the dominant mineral are clay minerals
- **Cements (authigenic, or neoformed minerals)** chemically precipitated minerals filled pore spaces between framework grains & matrix during diagenesis

CLASSIFICATIONS

- Sandstone composition obtained by 300-500 count of the framework, matrix, & cement using point counter
  1. Matrix%: < 15% → arenite, 15 - 75% → wacky
  2. Quartz, feldspar, & fragments recalculated to 100%



Example sandstone has 7%matrix, 10%Fe-oxide cement, 60%Quartz, 15%Feldspar, & 8%fragments

72%Qz, 18%Fs, 10%fragment → ***suabarkose***

Matrix < 15% → ***suabarkose-arenite sandstone***

If Fe-oxide hematite→***hematitic subarkosic arenite***

Conglomerate classification

Based on	Classification of conglomerate & breccia
Roundness	**Sub- to well- rounded** conglomerates
	Angular breccia
Origin	**Extraformational**: composed of clasts by source away from depositional site
	Intraformational: composed of clasts from within the basin of deposition
Composition	**Monomictic:** single type of clasts
	Polymictic: two or more clast types
Sediment fabric	**Orthoconglomerate:** clast-supported
	Paraconglomerate (diamictite) supported

Monomictic Umm Ghaddah Conglomerate, consisting totally of rhyolitic rock fragments

Polymictic Conglomerate (pink granitic, red rhyolitic, & basaltic black) well-rounded rock fragments

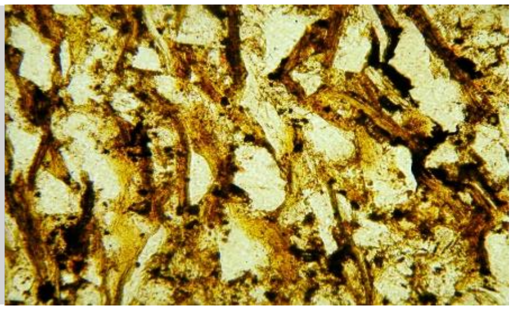
DIAGENESIS

- **Diagenesis**: all physical & chemical processes that affect the sediments from sedimentation until the on set of low grade metamorphism
- **Authigenesis**: precipitation of minerals within the pore spaces, **Cementation**: precipitation of new minerals within the pore spaces of sediment in a large quantity
- **Recrystallization**: crystal fabric change of a mineral of sediment without changing its mineralogy

Physical diagenesis

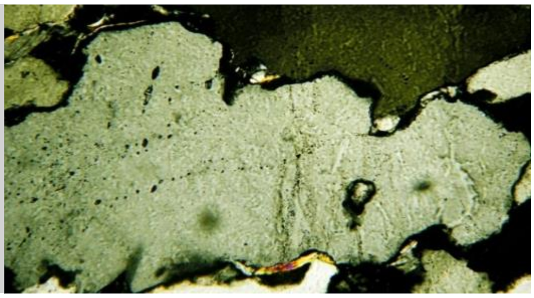
- Results from the weight of overlying sediments & starts by mechanical compaction followed by pressure solution due to increasing of burial depth
- ***At a low overburden (early stage of compaction)***, sediments compacted by dewatering & decreasing porosity, long axis or maximum surface-area of elongate (plate) grains (mica flake) orientated parallel to bedding planes, Point contacts between grains are still visible

Orientation of long surface area of biotite flakes grains parallel to bedding planes



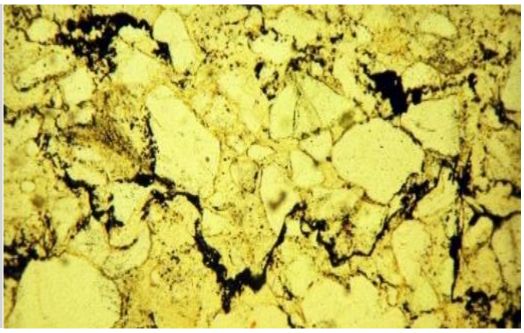
- ***By increasing burial depth*** ductile (mica) fractured or pseudoplastic deformed & bending around Qz & Fs
- ***Increasing burial depth (to 1000-1500m)*** compaction is replaced by pressure solution. Quartz subjected to high effective pressure that causes preferential solution (concavo-convex & sutured contacts developed)

Qz grain suffering from P-solution & with sutured contact & bending of muscovite flake



- ***By subsequent increase of burial depth***: microstylolites developed in sutured quartz
- **Microstylolites**: zigzag cross-cut quartz grains, & cements, visible in thinsection because marked by concentration of insoluble material (P-solution product)

Microstylolite in Qz arenite (PPL)

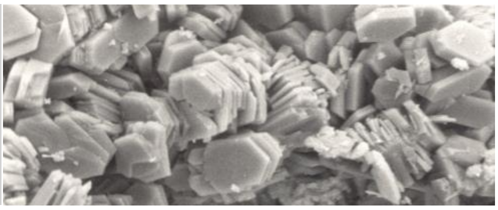


- If the sediment was early cemented, or there is a much matrix, pressure solution is not developed, because the load is distributed over large areas rather than points or small areas, & the contact-pressure is reduced

Chemical diagenesis

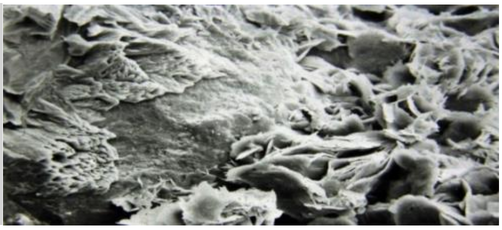
- Silica cement, Feldspar authigenesis, Carbonate cement, Fe-oxide cement, & Clay minerals authigenesis
- **Silica cement**: as ***quartz overgrowt*** which characterized by ***dust line*** & If there is no dust line, it is difficult to distinguished & a ***cothodoluminescence*** is required
  - **Dust line:** is a coat of Fe-oxides or clay minerals
  - **The origin**: P-solution, biogenic silica (radiolaria, diatoms, sponge), silica dust & silicates dissolution, groundwater, & transform of feldspar into kaolinite
  - **Silica cement forms:** micro-quartz, mega-quartz, chalcedonic-quartz, & opaline-silica
- **Feldspar authigenesis**: in form of **feldspar overgrowth**, & Common on K-feldspar than detrital plagioclase
  - characterized marine (not fluvial) because requires alkaline pore water rich in Na^+, K^+, Al^{3+}, or Si^{4+}
- **Clay mineral** (illite, kaolinite, smectite, montmorillonite, & chlorite) precipitated as authigenic or as cements, & filling pore spaces or as caly rims around detrital grains
  - The diagenitic clay studied by: X-ray diffraction, SEM, polarizing transmitting microscope
  - **Kaolinite**: books of stacked pseudohexagonal plates

Kaoloinite with book-like aggregate of pseudo-hexagonal plates (SEM)



  - **Illite** in clay rims forms: flakes, fibers, & whiskers

Illite crystals (central right) formed adjacent to detrital grain & stacked irregularly



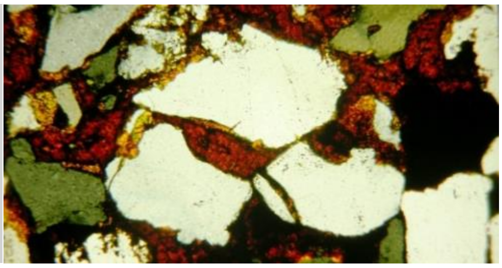
  - kaolinite & illite produced by:

1. **Precipitation** of materials derived from alteration of labile detrital minerals (feldspars)
2. **Replacement** of silicate minerals along fractures & cleavage planes (feldspar-kaolinite, glass-smectite)
3. **Recrystallization** of other clay minerals

  - For authigenesis of
    1. **Kaolonite**: Acid water with low K^+ are required that achieved through flushing the sandstone by fresh water during early stage of diagenesis
    2. **Illite**: Neutral to alkaline pore fluids with sufficient K^+, Al^{3+}, Si^{4+} are required

- **Fe-oxide:** red color (hematite), occur as pore- lining or filling, & rim coating detrital grains, & stain authigenic clay & feldspar grains along fractures or cleavage planes

Fe-oxide (hematite) cement filling pore spaces between detrital Qz



  - Hematite replaces biotite flakes along cleavage planes, ranging from scattered spots to complete replacement of flake, which is identified as a former detrital biotite flake on base of fan- or flake- shape

Types	Formed through/by
Detrital hematite (amorphous)	Weathering in humid tropical region, transported, deposited, & Finally converted (aged) into hematite
Yellow-brown coats	Chemical weathering & ageing into the hematite after deposition
Pure diagenetic	Intrastratal fluid of ferromagnesian silicate, in oxidizing env form hematite or hydrated oxide

- **Carbonate cementation** calcite (common) or dolomite
  - **Calcite**: poikilotopic cement, margins of the sand grains replaced & corroded by calcite, so appear to float in a sea of calcite
  - **drusy calcite** equant calcite crystals that fill the pore spaces, increase in size towards the center of cavity
  - **Dolomite** pore-filling microcrystalline rhombs to coarse anhedral mosaics & large poikilotopic
  - **Ferroan dolomite (Fe-rich dolomite)** common in sandstone that underwent reducing conditions

DEPOSITIONAL ENVIRONMENTS

- **Facies**: is a body of sedimentary rock with characteristic features that distinguishes it from other facies
  - **Features**: lithology (lithofacies), & fossil (biofacies)

Depositional environment of siliciclastic sediments	
Continental	Fluvial (Alluvial fans & rivers), deserts, lakes, glaciers
Marginal marine	Deltas, beaches (barrier) bars, lagoons, & tidal flats
Marine	Shallow marine shelves, epeiric seas, continental margins, & deep-water basins

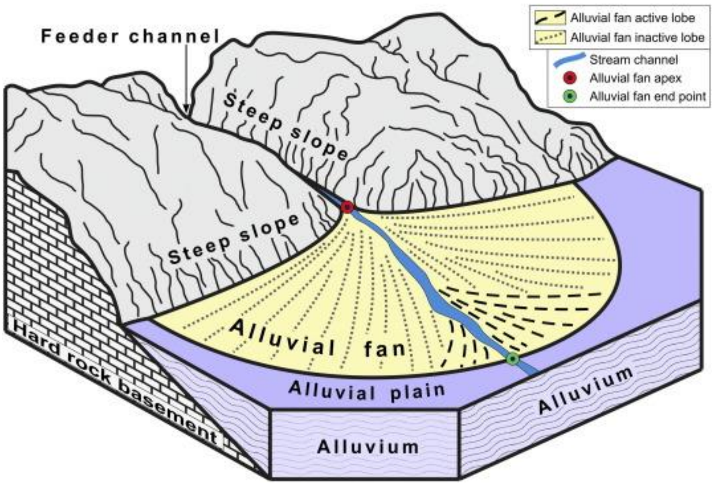
CONTINENTAL ENVIRONMENTS

Fluvial system

- **Fluvial**: complex systems of erosion, transportation, & deposition which give rise to different landforms
  - **Include**: alluvial fan, braided rivers (low sinuosity stream network), & meandering rivers (high)

Fluvial sediment: conglomerates, sandstones, & mudrocks	
Conglomerate	Lenticular, cross-bedding, extra- & intra-formational clast, & pebble-support fabric
Sandstones	Lenticular or laterally, sharp-based & cross-bedded, contain soil horizons & free off fossils but with plant debris, &

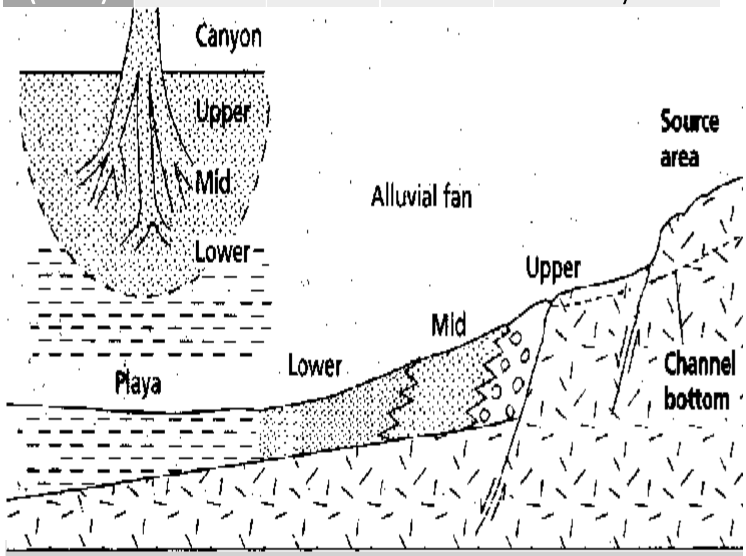
- **Alluvial fans**: aprons of sediments located adjacent to upland areas which bounded by faults



- **Fan apex:** located at the mouth of a canyon or wadi
- The surface of a fan is dissected by a **network of channels** radiating out from the fan apex, which grade downslope into **braided rivers**, **playas**, **lakes**, **coastal plain**, or sea forming **fan-deltas**
- Radius 5-15km depending on catchment basin size
- **Common in** semiarid regions where there is periodic or heavy rainfall, & **Deposition** take place from debris flows, stream floods, & sheet floods

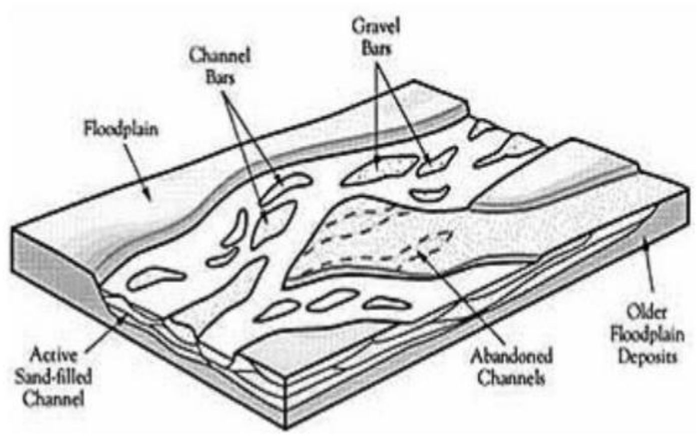
Place	Viscosity	Give rise to
Debris (mud)	High	Conglomerates with Matrix–supported fabric (Fine sediment & boulder clasts)
Stream flood	Low	Pebble-supported (Cross-bedded sand & lenticular gravel),confined to channel
Sheet flood	Shallow, Extensive	Planar & cross stratification (Thin bed of sand & gravel)

Alluvial fans subdivisions				
Fan	**Slope**	**Size**	**Sorting**	**Lithology**
Proximal (upper)	Steepest	Coarse	Poorly	Poorly developed structures
Mid-fan	Gentler	Intermediate		Planar, cross-bed, imbrication
Distal (lower)	Gentlest	Fine	Better	Sand & gravel interlayers



Facies diagram of alluvial fan show gravel & coarse sand in upper fan that pass down to pebbly sand & finer sediments of the mid to lower fan, which in turn grade into playa muds

- **Braided rivers (Braided fluvial):** low sinuosity stream network, characterized by sand & gravel bars, sand flats, & islands (divide water flow into smaller channels)

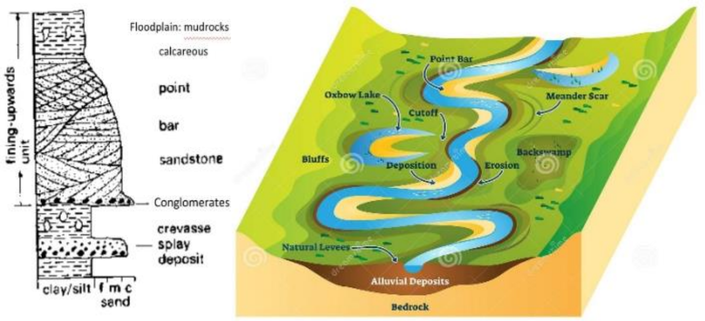


- **Conditions**: high slope area, coarse sediment, high & variable water discharge, & scarce vegetation, which **controlled by** climate, tectonic, source-area

Lithology	Notes
Lenticular cross-stratification, Planar cross-bedding	Formed by downstream migration ripples, sands, point bars, & dunes
Internal erosional surfaces	Between layers
Elongate or sheet multistory sand	On large scale rivera

- **Channel fills:** fining-upwards of grain size
- **Palaeocurrent:** unimodal with low variance degree

- **Meandering (high sinuosity stream network)**: possess distinct channel & overbank subenvironment & process



- The channel occupies a small part of alluvial plain, migrates laterally through bank erosion & point bar
- Sand is moved as dunes on the channel floor & lower part of point bar & as ripple on upper part

Lithology	Formed by
Trough cross-bedding	Down-migration of dunes
Cross-Lamination	Migration of ripples at top of bar
Erosive-based, cross-stratific.	Lateral accretion of point bars
Epsilon (Large cross-bedding)	Periodic lateral accretion surfaces
Fine-grained member (overlying point bar)	Vertical accretion of suspended load in a floodplain

- **Characterizes by** fining-upward sedimentary cycle
- **Palaeocurrent sands**: have greater dispersion than braided river deposition (higher variance degree)
- **Floodplain**: water flows over the banks of river, is a site of soil formation, marches, & swamps under humid climate, & salt precipitation under arid
- Some sand deposited on levees adjacent to channel when the river overtops its banks, or on floodplains as a result of crevassing, as river breaches its banks (occur as intercalations within the floodplain muds)

Deserts & Aeolian Environments

- **Desert**: areas of intense aridity, with subtropical belts
  - **Sand**: alluvial fans, ephemeral streams, desert lakes (playas), & bare rocks
  1. **Texturally**: Fine-to-Coarse-graind, Good-Sorted, Well-Rounded, +ve skew, mature to supermature (due to grain collisions)
  2. **Compositionally:** mature to supermature(arenites), Red-color (due to hematite pigmentation)
  3. Fossils absent (except vertebrate bones & footprint)
- **Aeolian sands:** large-scale, high angle cross-bedding
- **Playa (desert lakes) sediments**: mudrocks & evaporites
- **Ergs (aeolian desert sands):** vary from a thin, impersistent cover to extensive sand seas

Lakes Environment

- **Texturally**: moderately sorted & subrounded due to low wave activity, absence of tides
- **Structurally:**
  1. Wave-formed ripples, polygonal desiccation, & syneresis cracks
  2. **Graded beds with scoured bases**: on floors of lakes
  3. **Laminated sediment (rhythmites):** centers of lake-basin (by dilute density current & settling clays)
- **Deposited along:** shorelines, deltas, & deep basin floor
- **Silisiclastic lacustrine sediments:** based on the absence of marine fauna & association with certain minerals (sepiolite, palygorskite, corrensite clay mineral) & rocks

Glacial Environment

- Range of depositional settings (continental - marine, subgalcial - supraglacial, glaciofluvial – galciolacustrine)
- **Till & Tillite**: sediment deposited directly from a glacier
- **Subglacial till & tillite:** lower part of the glaciers
  1. Massive, extensive lateral continuity, 10cm thick
  2. Lack stratification, & have much matrix that is largely comminuted (ground) rock fragments
  3. some have striations & facets
  4. contain clasts of local & exotic origin
- **glaciation evidence:** cracked boulders, impression, & striated pavements on bedrock
- Lenticular & stratified detrital rock interbedded within tillites, These are water-laid deposits resulting from ***glaciofluvial processes*** (river receives glacial meltwater)
- ***Glaciolacustrine*** (lake receive glacial meltwater) ***sediments***: sands & gravels deposited by streams entering & constructing deltas, rhythmically laminated mudrocks (***varves***), with some scattered clasts dropped from rafted ice, deposited in deeper parts of the lake
- As ice sheets reach the sea, till is deposited on the sea floor & reworked by marine processes
- ***Galciomarine till*** contain fossils, & dropstones which are clasts released from icebergs calved from the ice sheet margin

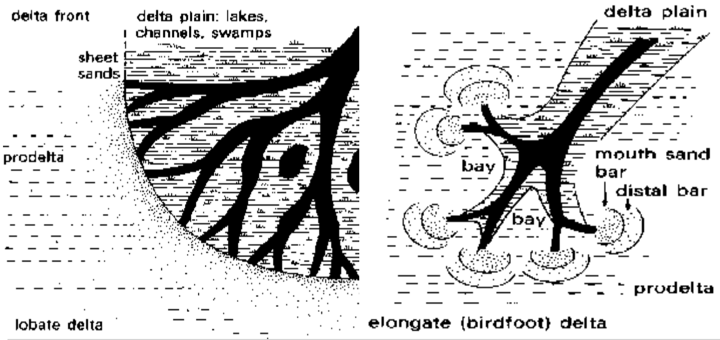
MARGINAL MARINE ENVIRONMENTS (SHORELINES)

- **Sites of deposition of much siliciclastic sediments**
- **Factors affect sedimentation**: sediment supply, tidal range, wave action, sealevel, tectonic activity, & climate
- **Beaches & barriers** are best developed in areas of moderate to high wave action
- **Tidal flats** characteristic of areas with high tidal range

Deltas

- **Delta:** rivers enter the sea, main siliciclastic deposition, where main factors controlling sediments distribution
- **Delta interplay between** river regime, tides, wave action, climate, water depth, & subsidence rate

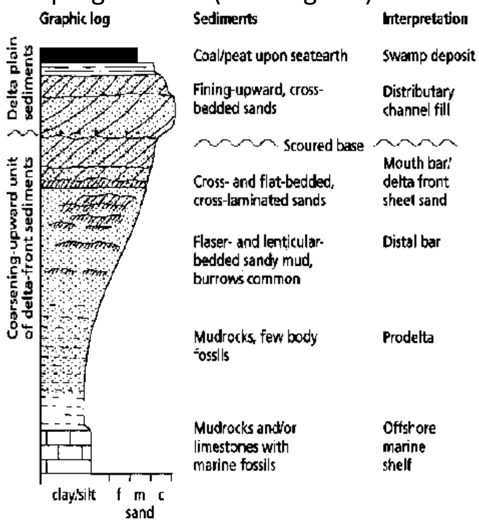
Delta parts	
Plain (top)	• The area landward of the shoreline 1. **upper plain:** dominated by river processes 2. **lower plain:** some marine influence • **Subenvironments:** swamp, interdistributary bay, distirbutary channel, floodplain's marche
Front	The subaqueous mouth sand bars & distal silt to fine sand bars in front of the distributary channels
Pro	Is the part of delta in the deepest offshore region



Subenvironment of lobate delta (right) & birdfoot delta (left)

Delta types	
Lobate	numerous radiating & dividing distributary channels
Birdfoot	Just one or several major distributaries & well-developed interdistributary bays

- **The characteristic of deltaic sediments**: vertical sequence of coarsening-upward units, produced by progradation (building out) of the delta front

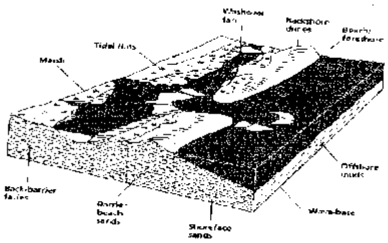


Sketch graphic log and interpretation of typical coarsening-upward sequence produced by delta progradation

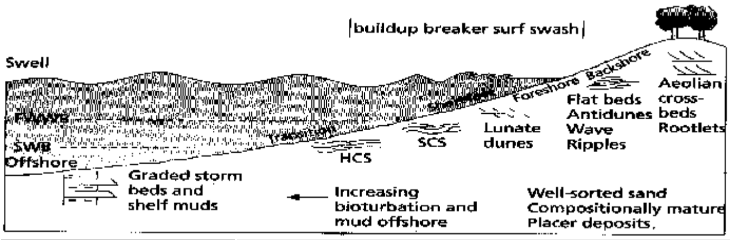
- **Thickness of sequences** depends on the size & type of delta, water depth, & subsidence rate (generally > 30 m)
- **Sands deposited** at distributary mouths gradually build out over prodelta muds, **Delta plain** deposits in the form of seatearths (clays below coal) & coals
- **Thin coarsening-upward** formed by infilling of inter-distributary bays, occur above the delta front sequence
- **Mouth bar & channel sands** show cross-stratification & planar bedding while **flaser & wavy cross-bedding** is common in distal bar & prodelta deposits

Beaches & barrier islands

- **Beaches**: linear belts of sand along the coast
- **barrier islands**: sand ridges, from land by a lagoon, connected to the sea by tidal inlets or channels



- Mud flat sand marches common around lagoon
- Going *from land through silisiclastic shoreline to the deeper part of the sea*: **backshore, foreshore, shoreface, transitional area, offshore (deep sea)**



From Beache & barrier island **to offshore**	Gran size & bedform decrease (due to change wave condition)
Offshore from the shoreface	Sands with hummocky cross-stratification generated by storm waves & occur between fair-weather & storm wave-base (depth of sea bottom, storms affect sea bed) • **Shreface structure:** burrow, cross-stratification • In deeper water hummocky passes to muddy sands with ripples, bioturbation, graded sand layer (tempestite)&shell lags produced by storm current
In Backshore **(area covered by water only during storm & highs)**	Wind dunes are active & give rise to large aeolian cross-bedded sand, landward oriented, with root traces & some land organism burrows
Foreshore zone	wave action towards the shore (swash) & backward return of water towards the sea (backwash) causing deposition of flat bedded & planar laminated fine sand, & corresponds to the intertidal zone (sea bottom depth from high tide level to low tide level) in shores with high tidal activity
Shoreface (subtidal) zone	From low tide level to the fair-weather wave base (FWWB) which is the depth of sea bottom where normal waves begin to affect sea bed, characterized by deposition of symmetrical & asymmetrical wave-formed ripples & lunate dunes that give rise to planar & trough cross-bedding & cross-lamination

- Barrier islands & beaches migrate seawards & landwards, depend on state of sealevel (static or rising), supply of san, & rate of subsidence
- **Coarsening-upward sequence** by seaward progradation

Tidal flats

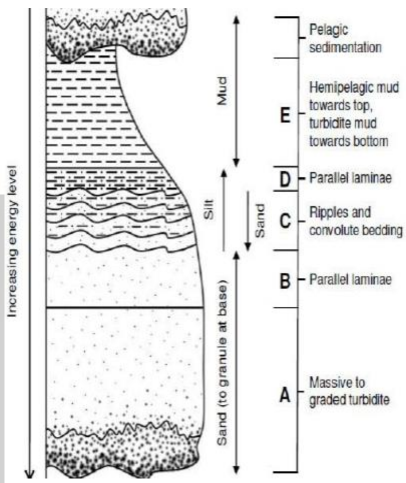
- **Tidal flats**: developed in shorelines characterized by a high range between the low tide & the high tide
- **Occur** around lagoons, behind barriers, & in estuaries
- **grain size decrease** across the flat from sand in the lower intertidal zone to silt & clay in the higher part
- Progradation of tidal flat sediments forms a **fining-upward sequence** (thickness determined by paleotidal)

Low tidal flat	• Cross-bedded sands with herringbone structure • Burrows & grazing trace fossils
In mid-upper tidal flat	• Ripples with interference patterns • Flaser-wavy-lenticular bedding • Bioturbation & trace fossils
High intertidal to supratidal	• Desiccation crack (depend on climate, marshe) • sabkhas occupy the supratidal area

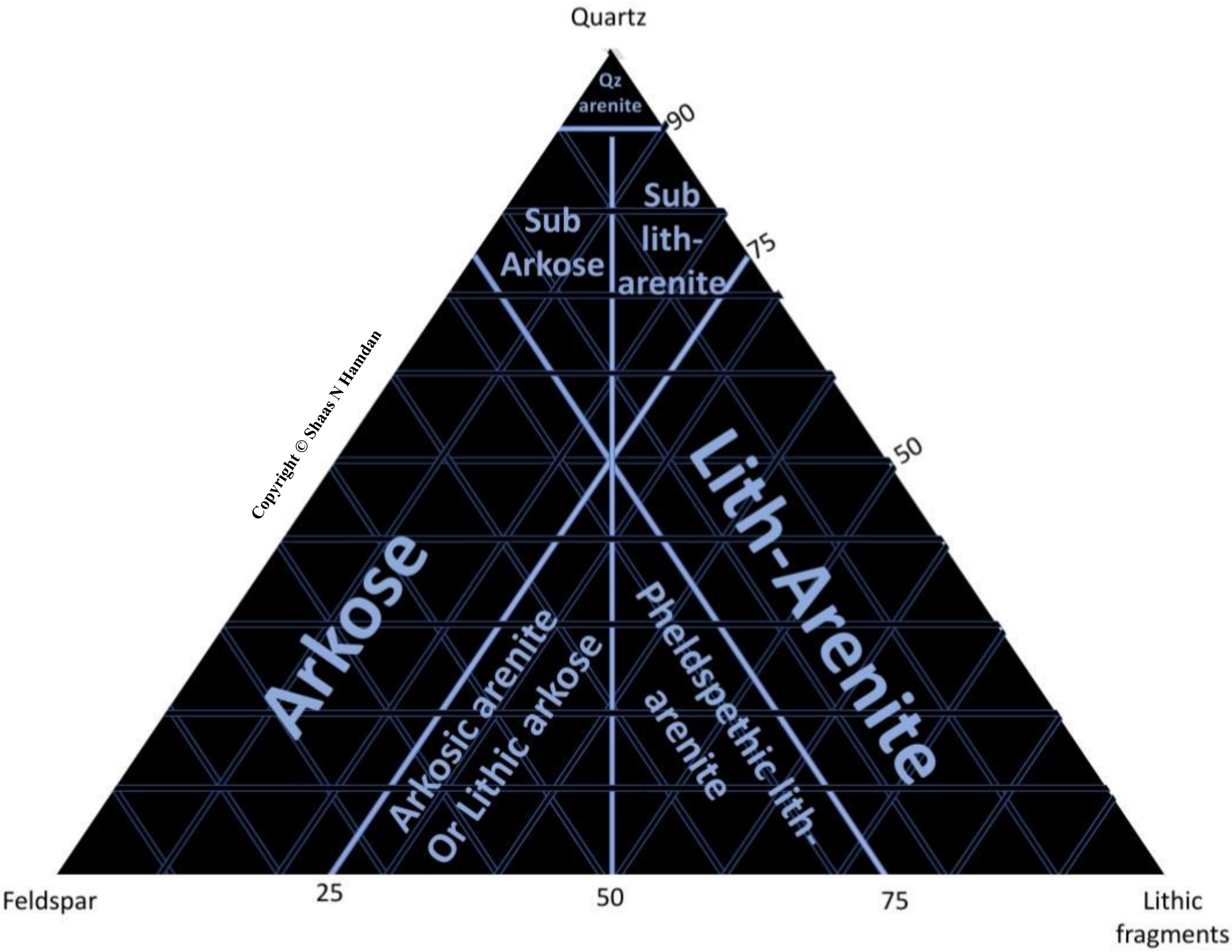
MARINE ENVIRONMENT

- **Shallow marine (shelves & epeiric seas):** away from the coastline, water depths 10-200m, sands deposited in continental shelves seas, epeiric, & epicontinental seas
  - May **tidal currents** dominate, or **wave** dominated
  - **Tidal sand body**: Deposits of tide-dominated sea & shelve, but mud more extensive because large areas of these seas have weak currents (wave-dominated)
  - **The bedforms**: ripple, dune, sand wave (mega-ripple), cross stratification, & planar bedding
  - **Marine body fossils & trace fossils are common**
  - Many shallow sandstone texturally & compositionally **mature** (arenite) **due to reworking**
- **Continental margin & deep water basin:** depositional sites of sandstones derived from slopes & shelves
  - Sand transport downslope via **sliding, slumping, & gravity** such as **turbidity currents & debris flows**
  - **deeper-water** are pelagic & hemipelagic deposit (e.g. cherts, pelagic limestone, & muudrocks)
  - **Turbidity currents**: density current of sediment that kept in suspension through fluid turbulence, are the
  - **Turbidity:** common type of deep water sandstone, form sequences 100-1000 m's with sandstone regularly alternating with hemipelagic mudrocks
  - **Turbidites sandstones deposited by** decelerating turbidity currents, **& possess well-developed sole structures**: flutes, tool marks, trace fossil, load casts
  - **Graded bedding** is **characteristic internal structure of turbidites** with **horizontal cross-lamination**
  - **Bouma sequence**: definite sequence of internal structures of **turbidites**

This sequence can be interpreted in terms of deposition from a waning flow: division A & B (upper flow regime), C (lower flow regime), D & E (deposition from suspension)



CLASSIFICATION OF SANDSTONES



Note. Use this diagram in the classification questions