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Module Tag	SED & PG II

Principal Investigator	Co-Principal Investigator	Co-Principal Investigator
Prof. Talat Ahmad ***Vice-Chancellor*** Jamia Millia Islamia Delhi	**Prof. Devesh K Sinha** Department of Geology University of Delhi Delhi	**Prof. P. P. Chakraborty** Department of Geology University of Delhi Delhi
Paper Coordinator	**Content Writer**	**Reviewer**
Prof. P. P. Chakraborty Department of Geology University of Delhi Delhi	**Prof. Subir Sarkar** Department of Geological Sciences, Jadavpur University, Kolkata	**Prof. D. M. Banerjee** INSA Honorary Scientist Department of Geology University of Delhi Delhi

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1. Learning outcomes

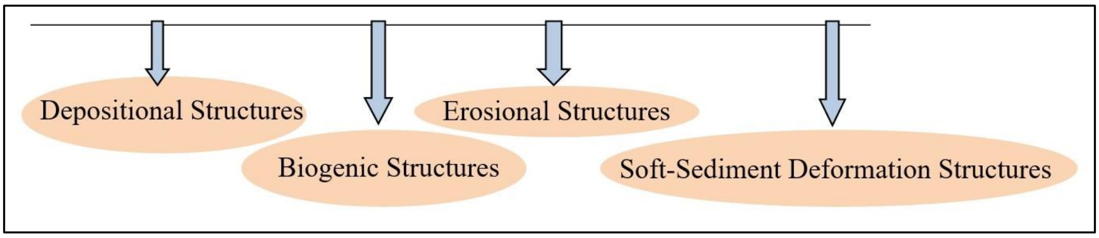
After studying this module, you shall be able to:

- Know about the sedimentary structures formed during or immediate after deposition of the sediment.
- Understand about the mechanisms of formation of different types of primary structures.
- Learn about the hydrodynamic condition of the depositional environment, as inferred from these structures.

2. Introduction

Primary sedimentary structures are both inorganic as well as organic in origin, formed during sedimentation or immediately after sedimentation but prior to lithification. Hence, primary sedimentary structures in sediment piles are of diverse origin and of different timings with respect to sedimentation. Structures formed during sedimentation, bear the signature of flow dynamic processes involved in sedimentation. These are the overwhelming and omnipresent primary structures, and can be divided into depositional and erosional structures. Organically influenced structures record the organism-substratum interaction history. Soft-sediment deformation structures, on the other hand, encompasses all the deformation structures, which have formed during or after deposition but prior to lithification, and completes the spectrum of primary sedimentary structures. Among these syn-depositinal or syn-sedimentary deformation structures include those formed along with sedimentation, and reflect substratum condition during deposition. Others formed close to, but after, sedimentation is called penecontemporaneous or metadepositional deformation structures.

Primary Sedimentary Structures



Usually the primary sedimentary structures do not have any depositional environmental bias; although very few of the structures, which are restricted to a particular depositional environment. Desiccation cracks, rootlet marks and structures associated with evaporates are significant examples. Usually primary structures represent a particular formative mechanism, which can be shared by different depositional environments.

Desiccation cracks from a modern environment

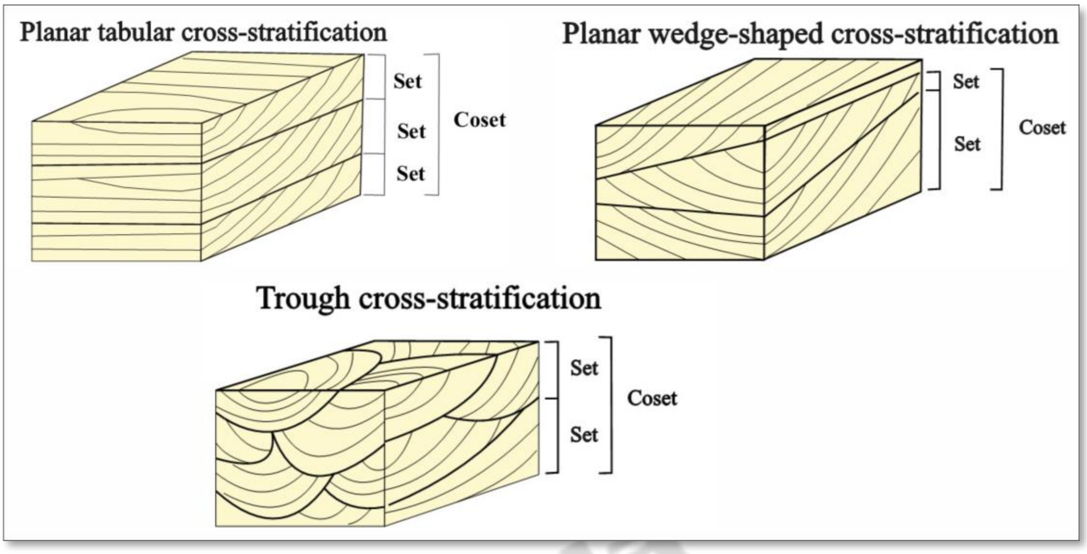
Desiccation cracks from rock

Rootlet marks from rock record

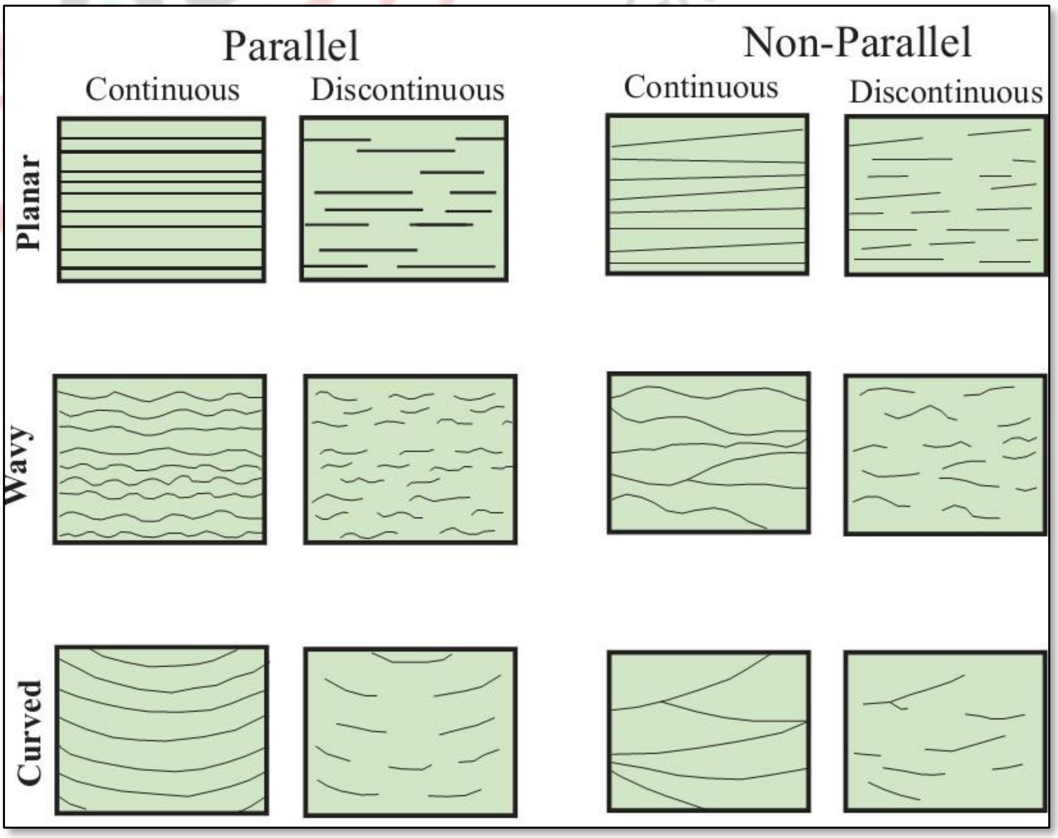
3. Primary Sedimentary Structures

3.1 Introduction to Bedform

Primary structure of fundamental importance is **bed** because bed represents individual flow. It's a sedimentation continuum delimited below and above by omission surfaces, erosional or non-depositional in nature. The thickness of a bed indicates the magnitude of the event though conventionally, strata thicker than 1 cm are referred to as beds. Beds are the basic building blocks of successions and are thus of foremost importance as primary sedimentary structure. Beds are generally tabular or lenticular in geometry that has lithologic, textural, or structural unity that clearly distinguishes them from layers above and below. Bounding surfaces of beds are known as **bedding planes** or bedding surfaces. They represent either erosion, or non-deposition, or an abrupt change in depositional conditions. Bedding planes can be of various types, even, wavy, or curved. The gross geometry of a bed (tabular or lenticular) depends upon the relationship between bedding-plane surfaces, which can be either parallel or nonparallel. Geometric forms of beds can vary enormously, some common descriptive terms include uniform-tabular, tabular-lenticular, curved tabular, wedge-shaped and irregular. Groups of similar beds or cross-beds are called **bedset** (or **set**). A simple bedset consists of two or more superimposed beds characterized by similar composition, texture and internal structures. A group of two or more sets is called **cosets**. A **composite bedset** refers to a group of beds differing in composition, texture, and internal structures but associated genetically. Marked discontinuities within beds are called amalgamation surfaces.



Laminae are the building blocks of bed and represent fluctuations within a single flow. Some other informal terms are also in use. They may be parallel or non-parallel, continuous or discontinuous and curved, either wavy or planar.



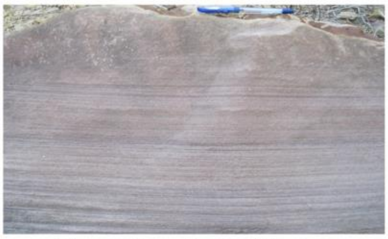
Layers- thicker than laminae, separated by minor but distinct discontinuities in texture or composition.

Divisions- characterized by a particular association of sedimentary structures.

Bands and lenses- subdivisions of a bed based on color, composition, texture, or cementation.

Beds are produced under essentially constant physical, chemical, and biological conditions. Beds can be produced rapidly by a single flow, which results in the formation of **massive beds**; while slow deposition leads to the formation of either graded or laminated beds. The grain size within a graded bed ranges from coarser at the bottom to finer at the top; and hence, graded beds may be used as "up indicators". Graded bedding implies slow deposition from a highly sediment-laden waning flow (such as turbidity current) where the sediment load is essentially suspension load. **Laminated beds** can be of two basic kinds-**Planar laminated and Cross-laminated.** In case of Planar laminated bed, internal laminae of a bed are essentially parallel to the bedding planes while internal laminae are deposited at an angle to the bedding planes for cross-laminated beds.


Cross laminated beds

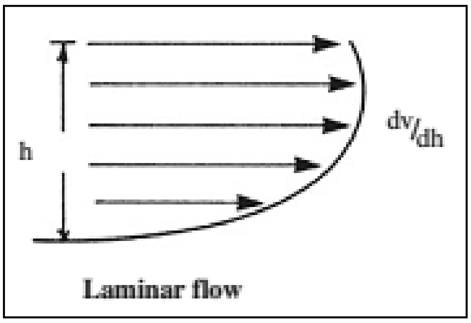

Planar Laminated beds

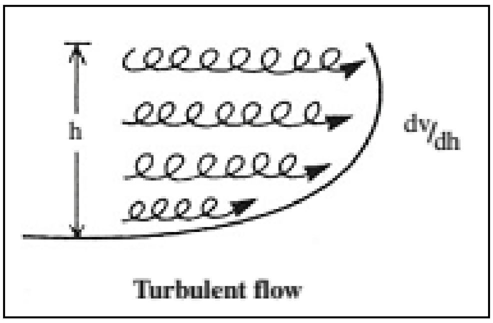

Massive beds

Bedforms are the bedding surface features developed at the sediment-water (or air) interface due to local deposition and erosion in response to the interaction of flowing or oscillatory current of water (or air). A **bedform** is produced as soon as flow attains a force sufficient to entrain particles from the bed, and start transporting sediments through formation of a set of structures. If buried and preserved, bedforms will form sedimentary structures. A bedform can be made up of a single bed or succession of beds. Variables influencing bedforms are nature of flow (unidirectional or oscillatory), flow depth (d), flow strength (velocity, U, shear stress,τ or, stream power, $\mu\tau$), fluid viscosity (μ), fluid density (ρ_f), sediment size (D), sediment density (ρ_s) and acceleration due to gravity (g).To understand the dynamics of the bedforms one should have some ideas regarding the **Flow Regime concepts**. Flow regime is relation between the flow parameters, nature of sediments and the bedforms or their internal structures. The flow regime concept is primarily applicable for products of channelized water flows with free upper surface (not for those formed in pipes or tunnels), although the concept may extend to include some special kinds of flows, such as turbidity currents. Relevant data are derived from studies in the field of fluid dynamics, hydraulic engineering, geomorphology and physical oceanography where a direct observation between relevant factors is feasible.

3.2 Flow Regime Concept

Some idea regarding the hydrodynamic principles of the flow is to be needed to understand the nature of sediment surface configuration. There are mainly two types of flow in nature namely laminar flow and turbulent flow. In Laminar flow, each point in the liquid moves along a straight line parallel to the bed but in case of turbulent flow, each point follows an irregular path so that eddies can form.





The nature of a flow (whether it is laminar or turbulent) is measured by Reynold's number ***(R_e)***. It is a dimensionless number expressed by-

$$R_e = h.v.\ \rho / \mu$$

Where, v is the mean velocity, h is the depth of a channel or the diameter of a pipe in which fluid is flowing, ρ is the fluid density and μ its viscosity. If $R_e > 2000$ the flow is a turbulent flow while in case of laminar flow $R_e < 2000$. In nature, flows in rivers or channels are always turbulent.

For flows in open channels, the most important coefficient of fluid dynamics is the Froude number (***F***). F can be considered as the ratio between inertial force acting on the fluid and the gravity force action on the water surface. This is essentially the ratio between the force required to stop a moving particle, that is, the inertial force and the force of gravity.

It can be represented by: $F = v / (g \cdot h)^{1/2}$

Where h is the depth of the channel, v is the mean velocity and g is the gravitational acceleration. A Froude number of 1 (or 0.84) separates two distinct types of fluid flow in open channels; each type used to represent set of particular flow conditions known as **flow regime.** Each flow regime generates specific bedforms and primary sedimentary structures.

Flow Regime	Bedforms	Characteristics
Lower	Lower flow regime plane bed, ripples, dunes	**F**<1(or 0.84), low rate of sediment transport dominated by contact load, bedforms out of phase.
Upper	Upper plane bed, in-phase waves, chutes and pools	**F**>1 (or 0.84), High rate of sediment transport, Bedforms in-phase with the water surface

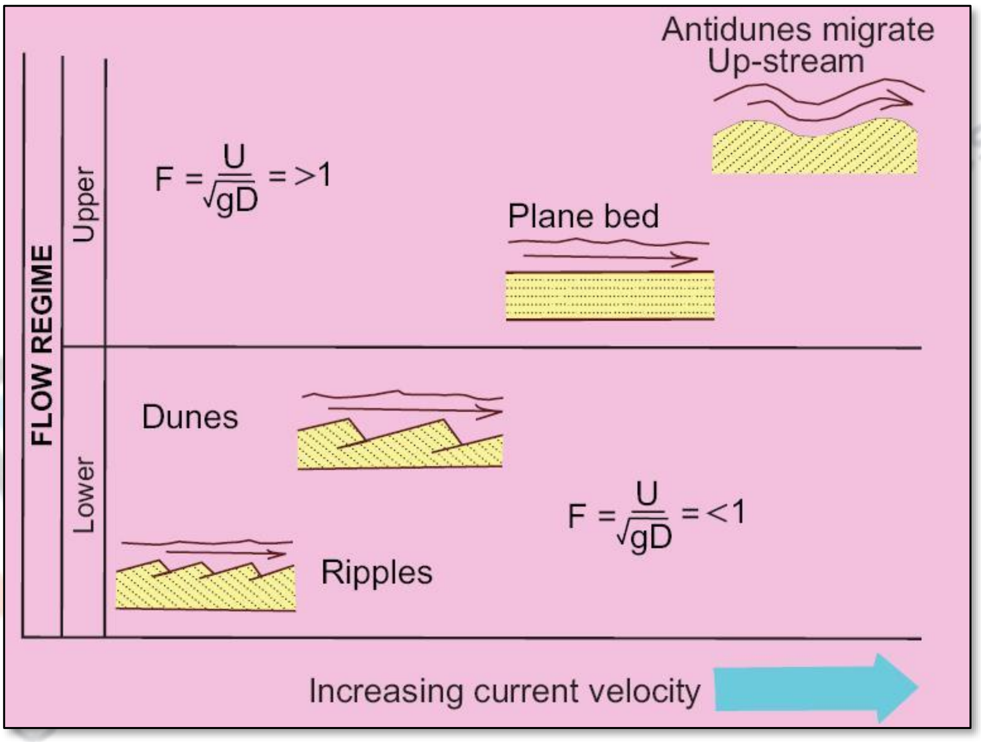


Diagram showing the basic sedimentary structures formed within each flow regime (after Harms and Fahnestock, 1965).

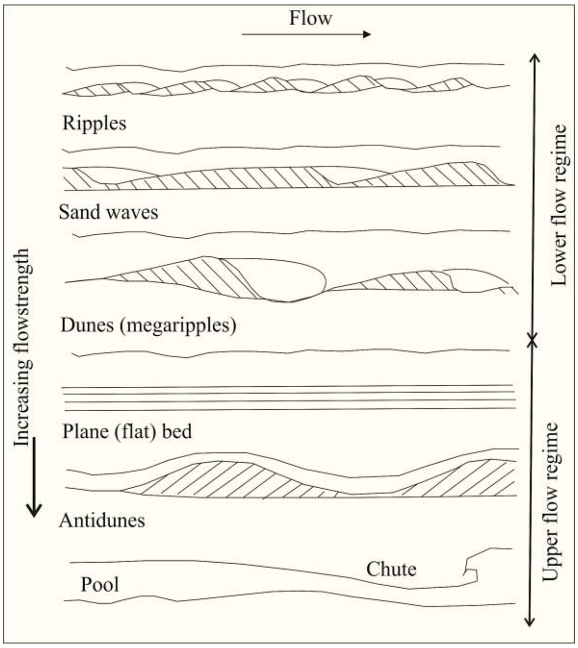
3.3 Lower Flow regime plane bed

These bedforms are flat and almost featureless, internally planar laminated and generally present both in silt and fine sand. The sediment mainly transport as suspension load, rarely as bed load. Suspension fall-out is the major depositional mechanism in case of fine sand or silt and can be formed both in unidirectional or oscillatory flow. The structures are present in different environment, starting from deep marine to fluvial flood plains. In case of bed load sediments, depositional mechanism appears to be the migration of low-relief ripples in the lower-flow regime under shallow-flow conditions, where lack of avalanche faces within the low-relief ripples prevent formation of cross-laminae. This mechanism is more active under subaerial condition than subaqueous one.

Lower flow regime planar beds

3.4 Bedforms produced by Unidirectional Flow

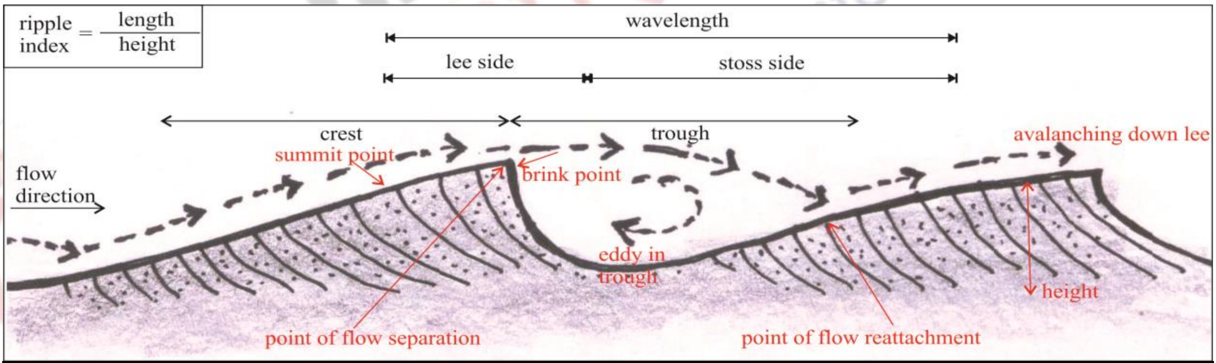
An array of bedforms can be generated by the unidirectional flow depending upon velocity, grain size and depth of flow; ripples are the most common amongst them. Within sand finer than 0.7 mm, the first feature to form is ripples, typically, their spacing is 10 to 20 cm or less, and their height is less than a few centimeters. As flow



velocity increase the ripples enlarge until they form sand waves, and finally dunes, which have spacing from 0.5 to 10m or more and heights of tens of cm to a meter or more. At higher velocity, plane beds are replaced by antidunes of up to 5m spacing. Low dip angles of 10 degrees or less, eventually produced chutes and pool.

Ripples

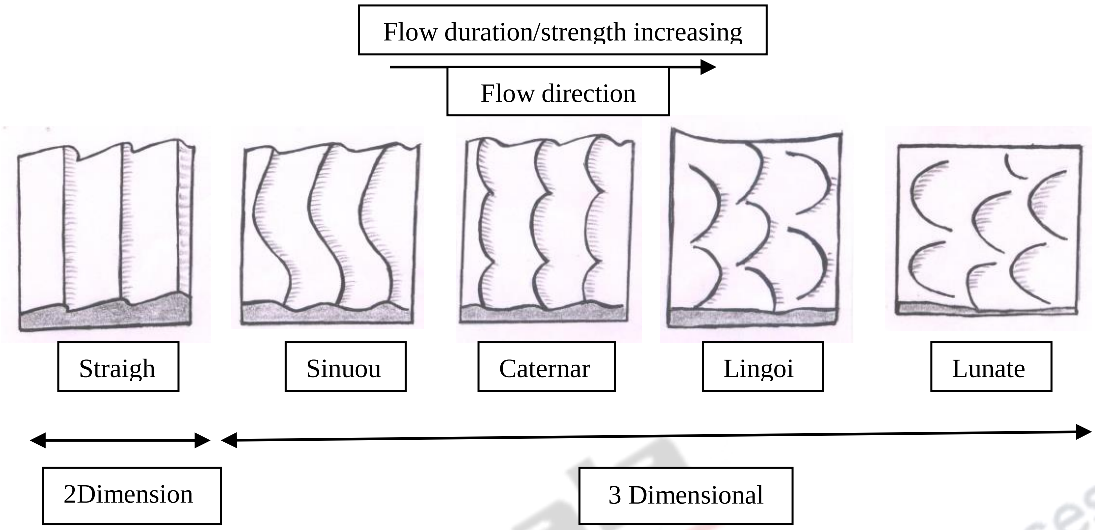
As mentioned earlier ripples are very common primary structures are of two types viz., Current and Wave ripples. Current Ripples are the commonest bedforms encountered within the lower flow regime unidirectional flow conditions. They are dominantly formed by bedload movement. They are asymmetric with a steeper, downstream-facing lee side and a gentle upstream-facing stoss side.



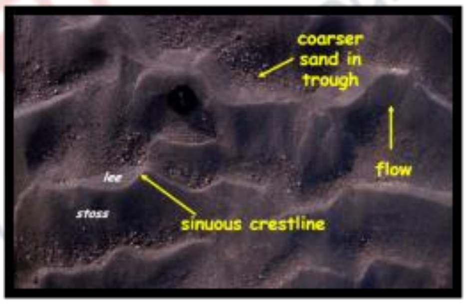
Current ripples on the basis of crest-line geometry and correlation with flow parameters

Mostly they erode the upstream side (stoss side) and accrete on the downstream side (lee side).Avalanching along the lee side takes place after sediment accumulation on crest reaches to the angle-of-repose. The wavelength and amplitude of a ripple is dependent on current velocity, grain size and water depth.

Current Ripples can be classified on the basis of crestline geometry and correlation of the flow parameters.



Asymmetric ripples



Curved crested 3D ripples

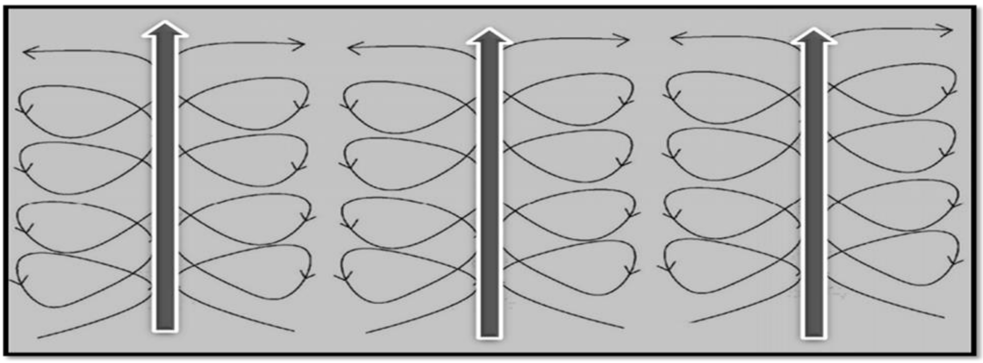
Dunes are large, asymmetric bed forms, dynamically different from that of ripples, commonly forming sand coarser than0.15 mm. They are larger bedform with wavelengths of 1m or more and heights of several 10's of centimeters. The shape of the ripples and dunes is described as two-dimensional if the crests are straight, or three-dimensional, if the crests are curved. The overall planform varies with flow strength. In the lowest flow, strength dunes have straight to sinuous crests (2-D dunes) transforms gradually into 3-D dunes with increasing flow strength.

Dune height is primarily influenced by water depth while that of ripples are influenced more by grain size. Ripples are sometimes superimposed on dunes to form **compound dunes.** Flow separation over the dune crest leads to the development of an eddy that may produce a high enough upstream velocity over the bed to produce upstream-migrating ripples (**back-flow ripples**).Ripples and dunes occupy separate fields in bedform stability diagram. As flow strength increases dunes becomes longer and lower (**Washed-out dunes**), washing out into the next bedform, the upper flow regime planar beds.

Sand waves are low appearing to be the transitional phase between these two bedforms namely ripples and dunes. Sand waves are low, straight to sinuous crested bed forms with well-defined lee surface and stoss sides. Sand waves wavelength can be up to 100 m or more and the index is much higher than ripples and Dunes.

3.5 Upper Flow regime Plane Beds

These Plane beds are flat bed with intense sediment transport. Flow parallel mounds known as current lineations or parting lineations, characterized by flow parallel ridges (with a few grain diameter height) and intervening furrows, arranged in en-echelon fashion along the length of the flow. Minute flow parallel eddies, moving along helically coiled path, develop on the sediment-flow interface and the coarse grains settle between uprising eddies forming minute parallel ridges produces parting lineations. Such ridges remain parallel to the flow direction.

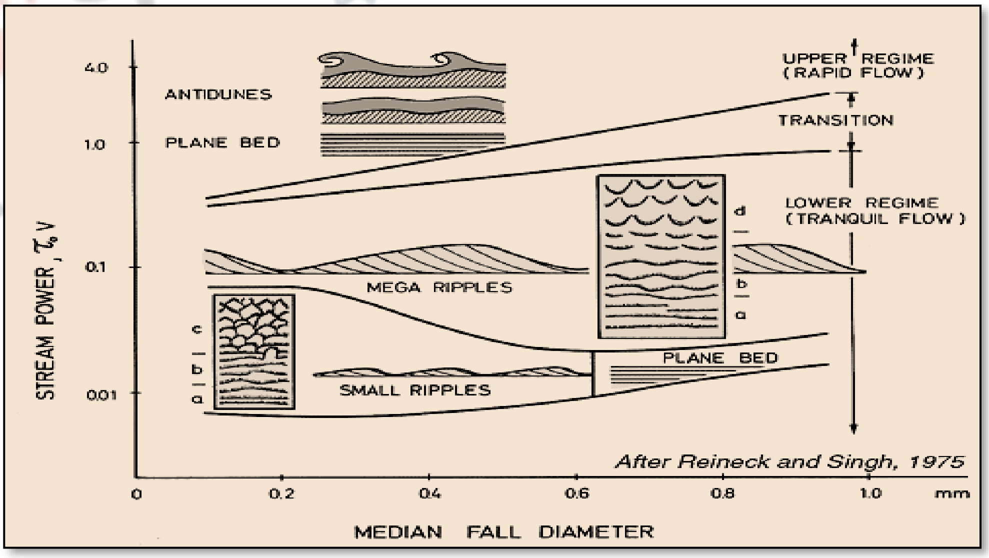


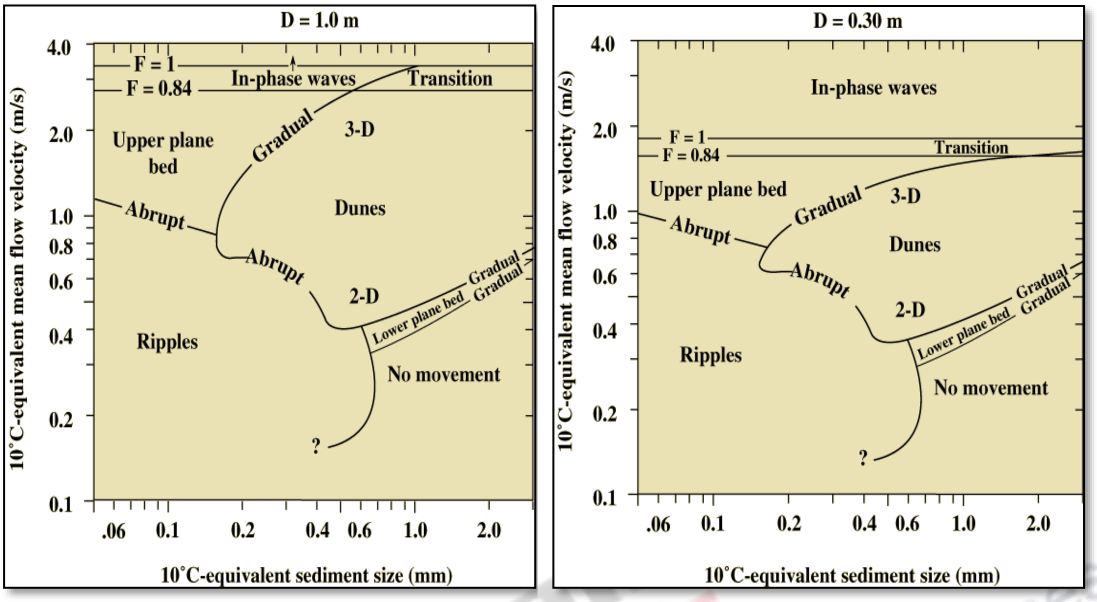
Antidunes

Antidunes formed with further increase in flow strength produced under rapid flow conditions (F>1). Antidunes are gently sloping, long-crested undulatory bedforms with low relief (RI~7 to 100).Internally low angle cross beds directed upstream are discernible. When the surface waves break and collapse giving a flat-water surface from which new waves grow move upstream formed the antidune.

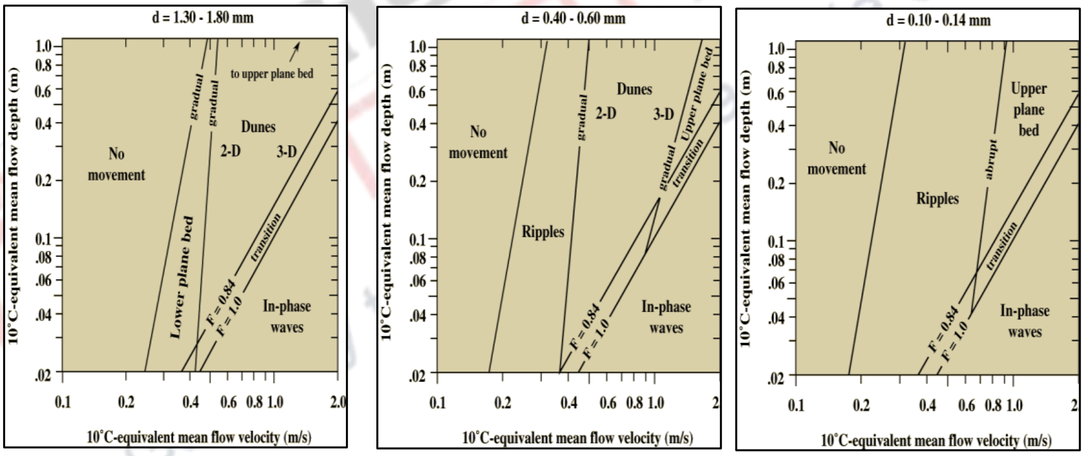
3.6 Bedform Stability Diagram

The three major controlling factors for generation of different types of bedforms are mean velocity or stream power, grain size of sediment load and depth of the flow. The conditions, under which a given bed form will develop, depend on a combination of fluid and sediment properties. The conditions are flow velocity, flow depth, water temperature (specifically fluid density and viscosity), grain Size, grain density. Besides, sediment sorting coefficient and particle shape have also considered being of secondary importance.





Variations in field of stability of different bedforms with changing depth of flow.

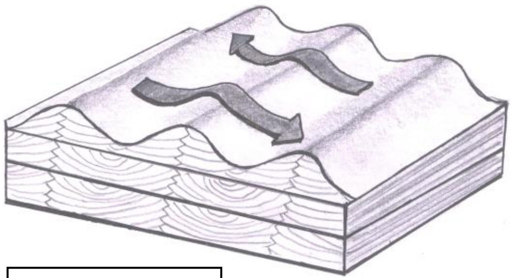


Variations in field of stability of different bedforms with changing grain-size of the sediment load.

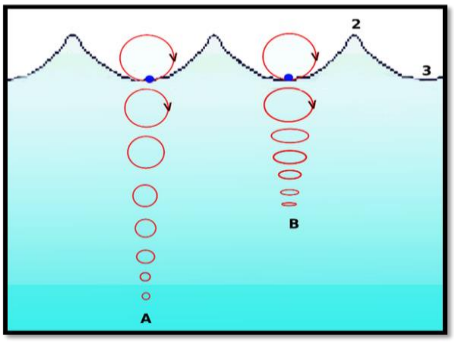
3.7 Bedforms produced by Multidirectional Flow

Multidirectional flows can be of oscillatory and bidirectional in origin. Bidirectional flows are typically indicative of tidal influence, but the constituent bedform is asymmetric ripples mostly, moving in mutually opposite direction and in course producing different kinds of cross-stratification. On the other hand, oscillatory flows typically produce wave ripples. Wave ripples are generally symmetrical to slightly asymmetrical due to eddies or orbital velocity difference. If the orbital velocity difference is less than 1 cm/s, symmetrical bedforms will produce while the difference greater than 5 cm/s give rise to asymmetrical bedforms. Crests are straight to sinuous, sharpened bifurcate, their migration rate is less, and accretion dominates mostly.

Oscillatory flows are often combined with current components. In shallower depths, wave pathway gets flattened and eventually breaks in to current after touching the sediment-water interface. The flattened wave pathways indicate combined flow condition, that is, oscillatory motion is coupled with current component. Breaking of wave indicates total transformation to current component near sea or lakeshore. In very shallow water, different wave sets can coexist and their interference produces a complex pattern of ripple set, known as interference ripples. Interference ripples can be made up of both coexisting symmetrical as well as asymmetrical ripple sets. Superimposed ripples are one kind of interference ripple where both the sets are not formed simultaneously; instead, latter minor set is superimposed over the former more dominant ripple set.

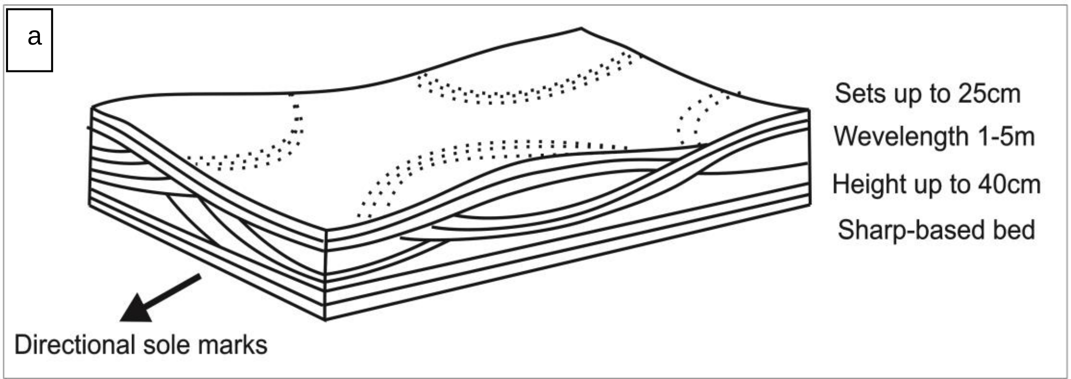


Wave ripples



3.8 Hummocks & Swales

An undulating bedding, which is thought to be formed by wave-generated oscillatory flows or combined flows (waves plus currents).The bedform shows dome shaped elevated areas separated by depression. The lower bounding surface is erosional and undulatory; sediments drape over that surface to give an undulatory dome-basin like appearance. Domal elevated areas are known as hummocks and depressed areas in-between are swales. Wave-current combination is most efficient in throwing sand population in suspension. Erosion results wavy surface and vertical fall out of sand from suspension gives rise to such bedform. Directional scours may present under the lower bounding surface. Upper surfaces are often rippled. Symmetric 'dunes' move back and forth (rather than downstream) and produces such bedform. Internally it is characterized by undulating sets of cross laminae with both concave-up (swales) and convex-up (hummocks) segments, known as Hummocky cross-strata (HCS). Decapping of hummocks leaves only the swales. This structure is formed by strong surges of varied direction (oscillatory flow) that are generated by relatively large storm waves. These bedforms are common within shallow marine or lacustrine environment, between the storm water wave-base (where wave touches the sediment-water interface during storm).



a- Hummocky cross-stratification (schematic diagram); b- Hummocky cross stratification from rock record.

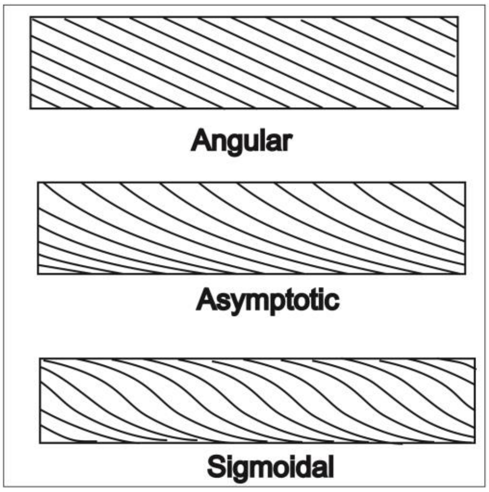
3.9 Cross-stratifications

All stratification deposited at an angle to the main depositional surface due to primary processes are known as cross stratification, normally bounded between bounding surfaces. Conventionally, if the individual inclined layers are thicker than 1 cm, the cross-stratification may be referred to as cross-bedding. Thinner inclined layering is called cross-lamination.

Cross-strata set: a single set of similar cross-strata

Cross-strata co-set: sets of cross-strata of the same type in vertical sequence and separated by bounding surfaces.

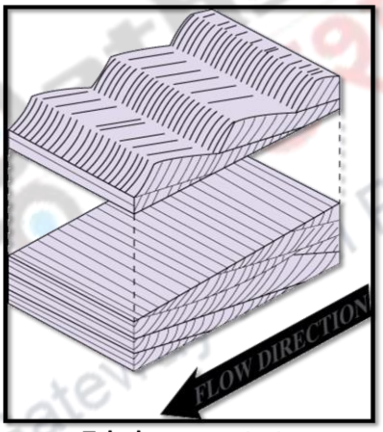
Cross-stratification is very much common in rock record as its preservation potential is much higher than that of the bedforms themselves (because the tops of bedforms tend to be planed off by subsequent current or wind erosion). Cross-stratification forms primarily by migration of ripples and dunes (in water or air).It can also be formed by filling of scour pits and channels, by deposition on the point bars of meandering streams, and by deposition on the inclined surface of beaches and marine bars. Cross-stratification thus can be formed under many depositional environments.



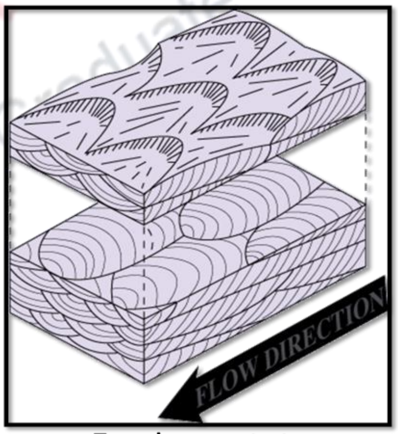
Ripple or dune migration leads to formation of dipping foreset laminae owing to avalanching or suspension settling in the zone of separation on the lee sides of these bedforms. Horizontal bottom- and top sets, along which the inclined foreset meets, are usually produced by suspension fall-out. If suspension load is negligible (in case of coarser than sand-sized sediments mostly), avalanching of the bedload sediment down the lee side of the ripple will produce steep and straight foreset laminae, having approximately the same angle as the angle of repose; such internal cross-strata is known as angular cross-strata. Similar cross-strata can also form in presence of suspension load, if the height of the lee side is large compared to the total flow depth, resulting concentration of the suspension fall-out within the base of the lee slope only; as in case of large eolian dunes. If the suspension load is considerably high, or if the height of the lee slope is small compared to flow depth, suspended sediment will pile up at the base of the lee slope rapidly enough to keep pace with growth of the avalanche deposits; causing the lower part of the foreset laminae to curve outward and approach the bottom set laminae asymptotically. If the suspension load is very high, then they fall along the foreset, over the lee and part of crest area, hindering erosion of the crest and produce sigmoidal type of cross-strata, where both the lower as well as the higher part of the foreset laminae approach the bottom- and topset laminae asymptotically. They are common in tidally influenced environments. Deposition over point bars of meandering rivers typically produces large-scale sigmoidal cross-strata, known as epsilon cross-strata. Most of the cross-strata are good palaeocurrent indicator.

Cross-strata are divided into two principal types on the basis of formative depositional mechanisms-Tabular cross-strata and Trough cross-strata.

Tabular cross-strata forms due to migration of 2-d or straight crested ripples and dunes; avalanching is the dominant mechanism for migration; it is formed under lower flow regime. Trough cross-strata, on the other hand is formed by migration of 3d ripples and dunes; formed under comparatively higher flow conditions. Depending upon the overall geometry and the nature of the bounding surface tabular cross-strata can be of two types, planar tabular cross-strata and planar wedge-shaped cross-strata. **Trough cross-strata**, on the other hand, is characterized by curved bounding surfaces having trough-shaped sets consisting of an elongate scour filled with curved foresets having asymptotic bases.



Tabular cross-strata



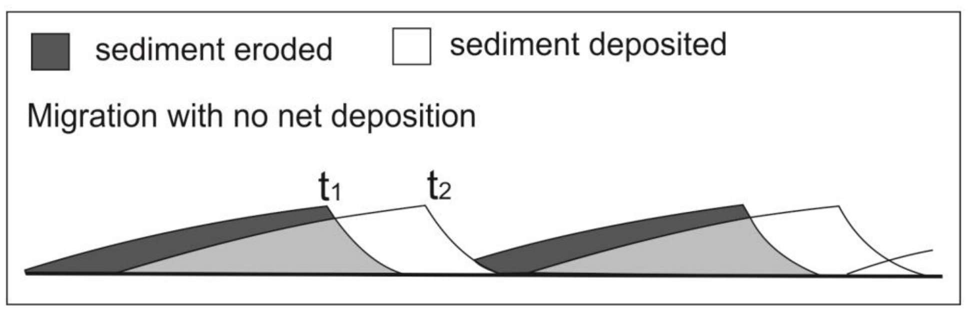
Trough cross-strata

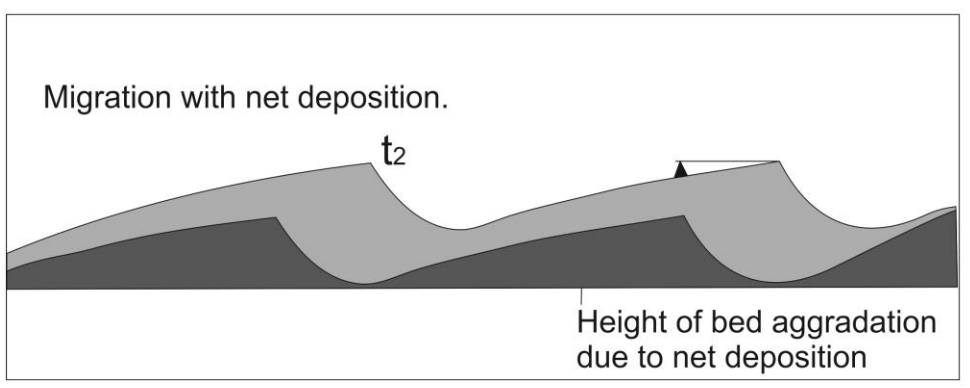

Tabular cross-strata


Trough Cross stratification

3.10 Formative processes for cross-stratification

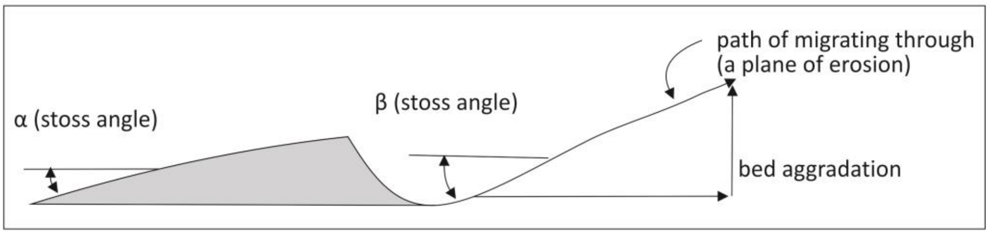
Cross-stratification reflects episodic deposition on the bedform and presence of heterogeneity within the sediment load made cross-stratification discernible. As a bedform migrates, there is erosion in the trough and stoss slope and deposition on the lee slope. For preservation of the internal cross-stratification in rock record, it requires preservation of part of the bedform. Without net deposition (aggradation) on the bed form, the bedforms will migrate through each other and preserve only a thin veneer in the migrating troughs. So net deposition is the prime requisite to preserve a cross stratification. With net deposition, the bed aggrades and the internal deposits of the bed forms are preserved. Proportion of the preserved internal structure of a bedform depends on the stoss slope angle and the angle of climb of the bed form.





3.11 Ripple cross-laminations

Ripple cross-lamination (climbing ripple cross-lamination) forms when net deposition (aggradation) takes place very rapidly during migration of current ripples. During aggradation, ripples climb one on another in such a manner that the crests of vertically succeeding laminae are out of phase and appear to be advancing upslope. Some ripple laminae may be in-phase (one ripple crest lies directly above the other), which indicate no migration of ripples.



Three kinds of ripple cross-laminations are observed depending upon the relationship between stoss angle and the angle of climb-

Subcritical climb: angle of climb <stoss angle.

Critical climb: angle of climb = stoss angle.

Supercritical climb: angle of climb >stoss angle.

3.12 Flaser & Lenticular Beddings

Flaser bedding is a type of ripple bedding in which thin streaks of mud occur between sets of cross-laminated sandy or silty sediment. Mud concentrate mainly in the ripple troughs, but may also partly cover the crests. Flaser bedding suggests deposition under fluctuating hydraulic conditions; periods of current activity, resulting deposition of rippled sand due to traction transport, alternate with periods of quiescence, when mud is deposited. **Lenticular bedding** is formed by interbedded mud and ripple cross-laminated sand, where sand lenses are discontinuous and isolated in both vertical and horizontal directions. Lenticular bedding indicates dominance of mud-depositing conditions interspersed by occasional traction current deposits of current or wave origin. Wavy bedding is a typical structure, where amount of traction deposit and suspension fall-out is almost equal. These structures indicate deposition from cyclically alternating hydraulic conditions, as common in tidally influenced areas. Transitions from flaser to lenticular bedding pointed towards gradual increase in suspension fall-out in expense of traction deposits.

3.13 Cross-stratification formed under oscillatory flows

Internal structures of the cross-stratification formed under oscillatory flows are relatively less common compare to unidirectional current. Wave ripple is the most common example. To-and-fro grain movement of the flow gives rise to bimodal cross-strata because of vertical building up of the bedforms. In natural condition, a current component usually coexists with oscillation. Wave-current combination is most efficient in throwing up sand in suspension; consequently, structures like offshoots and draping arise in wave ripples. Erosion results wavy surface and vertical fall out of sand from suspension gives rise to wavy parallel laminations. In case of large waves, as encountered in storms, erosion is more pronounced followed by suspension, which produce hummocky (HCS) or swaley cross-strata (SCS). Hummocky cross-stratification is characterized by undulating sets of cross-laminae that are both concave-up (swales) and convex-up (hummocks). The erosion surface is, however, dome-like in geometry and thus hummocky cross-laminae dip centripetally.

4. Erosional Structures

Erosional structures created by a flow immediately before it allows sedimentation, are often preserved at sole of beds. Erosional grooves created by flow vortices include flutes and longitudinal ridges. Some other non-erosional structures, such as mud cracks or rain prints or setulfs also occur on top of the bed. Particle movement in the flow gives rise to diverse kinds of structures, like, groove, prod, bounce mark, brush mark, chevron mark. All these structures are very useful indicators of palaeotop as well as sense of palaeocurrent with or without the direction. Erosional structures can be grouped into two classes- current formed structures and tool formed structures. In former case, vortices within shooting current flows erode the substrate, forming grooves or small channels or scour like structures.In latter case, scours or depressions are resulted from the action of objects or tools, carried by the current by intermittently or continuously making contact with the substrate.

Sole marks formed by currents

- ***Obstacle marks:*** Form where a barrier such as a pebble or boulder has disrupted a flow, a shadow zone of slow deposition occurs in the lee of the obstacle and erosion occurs on the up-current side of the obstacle. A common example is current crescents, frequently observed in beaches.
- ***Flutes:*** Flute marks are special kinds of asymmetrical depression in which the steepest and deepest part of the depression is oriented upstream. When the depression is filled-up, the filling forms a positive-relief structure on the sole of the following bed, with a bulbous nose oriented upstream. It is generally developed over muddy substrates. Such structures are known as flute casts. The plan-view shape of flutes varies from nearly streamline, bilaterally symmetrical forms to more elongate and irregular forms, even twisted. They are common at the base of storm or other event beds and also in turbidites.

Flute casts

➢ ***Longitudinal scours:*** Formed by helical flow eddies in fast moving shallow water, generally run parallel to the direction of current. Parting lineations are product of such scouring. They are associated with upper flow regime plane beds. Ridge and furrow structures also form by similar process, only the scale is larger. Longitudinal dunes in Aeolian field are also formed by similar process with further enlarged scale.

➢ ***Gutters:*** Generally occur as elongated ridges at the sole of sandstones, generally symmetrical but asymmetrical are not uncommon.

Gutter cast

Sole marks formed by tool

Tool marks can be formed by rolling, bouncing, skipping, or dragging of tools (like pieces of wood, the shells of organisms, or any similar object) over the substrate; well preserved over muddy substrate. When it is filled-up by sediment, the filling forms a positive-relief structure on the sole of the following bed, known as casts.

➢ ***Grooves (continuous):*** Groove casts are elongate, nearly straight ridges.

➢ ***Chevrons (continuous):*** Chevrons are a variety of groove casts made up of continuous V-shaped crenulations with the V pointing in a downstream direction.

➢ ***Prod, Bounce, Skip, Brush marks:*** Prod, bounce, skip and brush marks are all small discontinuous marks produced by tools that make intermittent contact with the bottom. Brush and prod marks are asymmetrical in crosssection, with the deeper, broader down current end. Bounce marks are roughly symmetrical. Skip marks are repeated but discontinuous.

5. Biogenic Structures

Biogenic sedimentary structures are those, which are formed by living organisms, interacting with the sediment. Organisms may be animals, which walk on or burrow into the sediment, or they may be plants with roots, which penetrate the sediment, or they may be bacterial/algal colonies, which trap and bind the sediment to produce layered structures. Biogenic structures can be subdivided into two categories - trace fossils or ichno-fossils and bio-stratifications. ***Trace fossils*** are not true bodily preserved fossils but are simply biogenic structures that originated through the locomotion, feeding, burrowing, or resting activities of organisms. ***Bio-stratification*** structures are sedimentary layering produced through the activities of organisms. Bio-stratification structures are only represented by ***stromatolites***; which are mostly restricted within carbonate rocks, although rare reports of siliceous stromatolites are also available. These are "organo-sedimentary structures" and formed by colonies of sediment-trapping cyanobacteria (commonly called blue-green algae). Recently **MISS** (Microbial mat induced sedimentary structure) or **MRS** (Microbial mat related structure), a new category of bio-induced sedimentary structures have been reported from different siliciclastic formations across globe.

Horizontal burrow on bed surface

Stromatolite

6. Soft Sediment Deformation Structures

Soft-sediment deformation (SSD) structures include structures formed by deformation during deposition (syn-sedimentary) as well as just after deposition prior to lithification (penecontemporaneous). Deformations producing these structures can be triggered by some external cause like seismic jerks or internal cause like over pressuring due to quick dumping. If triggered by external cause, these structures are usually found to be restricted within a single sedimentation unit with lateral extension. Genetically these soft-sediment deformation structures are of following varieties:

- ***Gravitational instability:*** Density-driven soft-sediment deformation, generally restricted within a particular sedimentation unit, overlying and underlying units remain undeformed.
- ***Convolute lamination:*** Convolute lamination is a structure formed by complex folding or intricate crumpling of beds or laminations into irregular, generally small-scale anticlines and synclines. Convolutions increase in complexity and amplitude upward from undisturbed laminae in the lower, part of the unit and may either die out at the top part of the unit or be truncated by the upper bedding surface.

Convolute Lamination

- ***Load structures:*** Due to density contrast within alternate sand and mud layers, sand layer intermittently sinks into mud layer due to gravitational pull, forming load structures.
- ***Ball and pillow structures:*** Ball and pillow structures are found in the lower part of sandstone beds, and less commonly in limestone beds, that overlie

shales. They consist of hemispherical or kidney-shaped masses of sandstone or limestone within the shale unit that show internal laminations.

- ***Flame structures:*** Flame structures are wavy or flame-shaped tongues of mud that project upward into an overlying layer, which is commonly sandstone. They are probably caused by loading of water-saturated mud layers, which are less dense than overlying sands and are consequently squeezed upward into the sand layers.

Downslope movement:

- ***Slumps:*** slump structures produced by penecontemporaneous deformation resulting from downslope movement and displacement of unconsolidated or semi-consolidated sediment, mainly under the influence of gravity. Large-scale slump structures are usually related with seismic activity.
- ***Growth faults:*** Brittle failure within soft sediment indicates cohesion to hold the grains together. Wetted sand in Aeolian dunes often fails in a brittle manner.

Fluid flow:

- ***Overturned cross bedding:*** Overturning of deformation can be produced by strong shear stress exerted by the flowing fluid over semi-consolidated sediment near the surface.

Overturned cross-stratification

- ***Fluidisation & Liquifaction:*** Fluidisation & liquifaction are two important processes of soft-sediment deformation. These two processes actually facilitated all kind of soft sediment deformation structures to form by reducing the cohesion among grains. In liquefaction, fluid pressure increases by some external shock or over-pressuring, enable fluid to surround grains, so that grain-grain cohesion reduces and sediment starts to flow like a fluid. In fluidization, fluid released by external shock or over-pressuring moves upward with great velocity through the sediment column and in consequence carried the sediment along with it. The resulted structures include sand volcanoes, mud diapirs and sand dykes. Sedimentary diapiric rises are caused by fluidization. It can take place among sandy as well as muddy sediments. Such diapirs when come to surface through openings mud or sand volcanoes result. Dish and Pillar structures are primarily produced by liquefaction. Dish structures are thin, dark-colored, sub-horizontal, flat to concave-upward, clayey laminations that occur principally in sandstone and siltstone units. Pillars are vertical to near vertical, crosscutting columns and sheets of structure less or swirled sand that cut through either massive or laminated sands. These structures are commonly associated with sediment-gravity flow deposits.

7. Primary Sedimentary structures and Depositional Environment

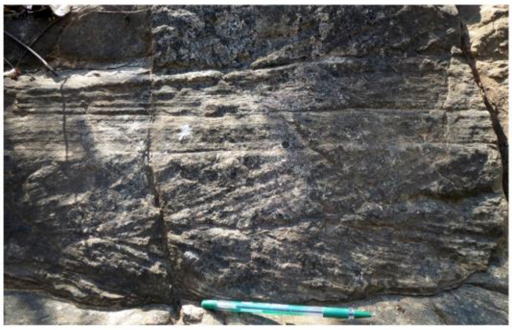
Although attempts to correlate common kinds of primary structures with depositional environment often ends with dissatisfaction, an attempt can be made to evaluate the potential of primary sedimentary structures as environmental indicator in broad terms.

Frequent occurrence of wave structures in a sedimentary body most certainly indicates deposition in a wave agitated environment, viz., shallow marine or lake. In a lake, tide, without synchronization with open-ocean tide, has amplitude only up to a few centimeters. No tidal bedform is thus expected in lacustrine deposits. River water entering a lake is often muddy and of higher density than the lake water. As a result, underflows are common in lake successions. Graded siltstone or fine sandstone beds are typical products of such underflows. Lake turbidites are thinner than marine turbidites. Mm-scale varves, typical of lakes, are subjected to climate extremities.

Herringbone cross-strata, sigmoids, thick-thin lamina alternations, mud drapes, double mud drapes, cyclic variation in foreset geometry are the features that help to establish tidal influence with variable degree of confidence.

Thick-thin lamina alternation

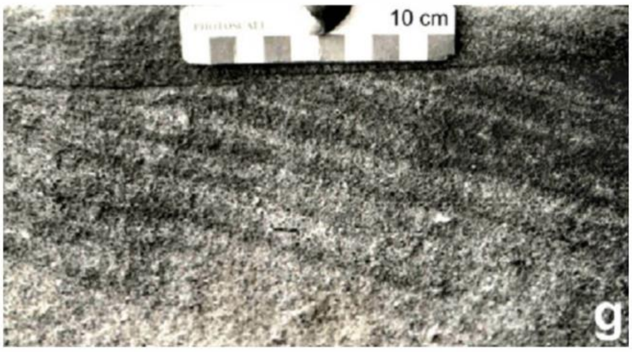
Double mud drape layers



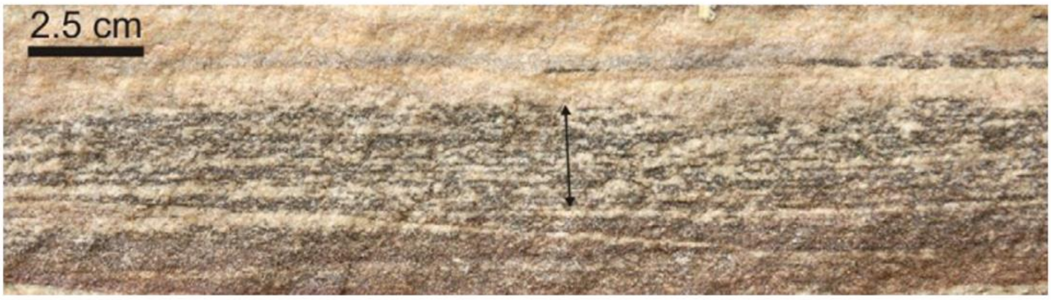
Herringbone cross-strata

However, the most convincing proof of tidal action is derived from demonstration of lamina-thickness variation in periodicities corresponding to those of tides.

In traction current domain, it is most important to distinguish between alluvial/fluvial and eolian deposits. As grain-flow process operates more frequently, inversely graded dune cross-strata are far more common in eolian deposits. Common occurrence of regular alternations between grain-flow and grain-fall strata, translatent strata or ripple climb, adhesion laminae or ripples distinguishes eolian deposits from aqueous deposits. Wind ripples characteristically have very low amplitude, but wide wavelength. This is because of low impact angle involved in eolian grain transport.



Alternate grain flow-grain fall strata



Translatent strata followed by adhesion lamina (arrowed)

In contrast, positive evidence for alluvial process in terms of distinctive primary structures is difficult to cite. Identification of the deposits depends on consideration of structures along with textures, sediment body geometry, reconstruction of various alluvial architectural elements or meso-scale geomorphologic entities, like Point bar, Mid-channel bar, Sand flat, Levee, Epsilon cross-strata, Crevasse splay, Flood plain, Ox-bow lake, etc. The last factor obviously demands working out of interrelationships between various structural elements and lithologies. Current structures in fluvial deposits yield unimodal orientation, however wide the degree of variation may be.

Furrows, though common under glacial deposits, are equivocal as they can be generated by rock sliding during faulting or bollide impact as well. So are striations and facets on pebbles. However, multifaceted pebbles and striations on those facets are far more reliable indicator of glaciation than dropstones. Dropstones may be of volcanism or impact-related. Dropstones of subaqueous environment settle vertically and deform the sediment laminae on which they settle. Dropstones of subaerial origin however cause rupture in the underlying laminae and their curved trajectories are often recorded in their inclined passages through sediment.

Grading, normal or reverse reflects sediment gravity flow mechanism and not palaeogeography. However, deposits on fans, alluvial, deltaic, shelf or slope, contain a good proportion of sediment gravity flow deposits. While debris flows, grain flows and fluid gravity flows can operate on both subaerial and subaqueous conditions, but turbidity current is confined to the subaqueous condition. Normally graded conglomerates or pebbly sandstones are almost certainly subaqueous in origin. Such conglomerates could not have deposited from turbidity currents, since turbulence alone cannot transport grains larger than sand grade in suspension.

Primary structure does help in reconstruction of Palaeoenvironment, but form just a component of study materials. Palaeoenvironmental reconstruction should be a holistic approach. Not only inherent characteristics of deposits, including penecontemporaneous structures, but their associations should also be taken into consideration.

8. Palaeocurrent

Most of the cross beddings except some accretionary form are reliable palaeocurrent indicators. The palaeocurrent analysis is an important tool for basin analysis study. It gives the direction of the flow, which was responsible for generation of the structure.

The true dip of the forset planes reconstructed from two orthogonal sections is used for determining the palaeocurrent. In case of trough cross stratification, the bedding plane expressions or the traces of the trough on the bedding planes are very useful for measuring the palaeocurrent direction. The acute bisectrix of the two tangents drawn on two arms of the traces of trough gives reliable palaeocurrent direction. The lee of a ripple slope is also a good indicator of current direction. Besides some erosional structures, e.g. flute casts are also useful indicators of palaeoflow direction

Consistency of a current depends upon the steadiness of the flow. Long-term consistency of palaeocurrent indicates stability of the current system. In tectonically unstable setting long term, stability of the palaeocurrent is not expected. Palaeocurrent may be unimodal, bimodal, bipolar or polymodal. Unimodal palaeocurrent is expected in Fluvial depositional system. Bipolarity and bimodality are common in marine deposits. Tidal deposits generally show this pattern, though unimodal records are not uncommon. Deposits of waves also can produce bipolar palaeocurrent. Aeolian palaeocurrent is generally polymodal in nature. Shallow marine environment may also give polymodal current direction. As mentioned fluvial palaeocurrent pattern is likely to be unimodal. However, degree of consistency of the palaeocurrent also varies between meandering river, braided river and straight channels. The relation between palaeocurrent direction and dip of the depositional substrate is important for regional interpretation. Fluvial cross-strata generally have a mean direction towards dip of the depositional substrate. However, Aeolian cross bedding is not related to palaeoslope. Shallow marine palaeocurrent also does not always maintain any particular relation with palaeoslope. It may be parallel to slope, even across slope. In case of long-shore current, the direction is parallel to shoreline. Sole structure particularly flute cast, prod marks etc. also provide good information about palaeocurrent direction with sense. Some other sole features such as gutters; grove casts etc. provide direction without sense. Similarly parting lineation provides uni-direction without sense. Fossil orientation may be helpful at places but their relation with palaeocurrent is not always same. Pebble imbrications in conglomerate deposits may also be helpful for getting the palaeocurrent direction.

9. Summary

Primary sedimentary structures form during deposition or immediately after deposition of the sediment. It tells about the depositional mechanisms during the formation of the structures. Primary sedimentary structures are of diverse origin. Many primary structures bear the signature of flow dynamic processes involved in sedimentation and similar flow dynamics can be shared by the different palaeogeography. For this reason, sedimentary structures are not always helpful to determine the palaeogeography. However, there are very few structures, which are good indicators of depositional environment. Syn-depositional deformation structures that reflect substratum condition during deposition are also by definition primary. Some other sedimentary structures, deformational or not, form close to, but after, sedimentation and are called penecontemporaneous or meta-depositional structures. Determinations of palaeocurrent from some of the primary sedimentary structures are helpful to determine the flow direction, consistency of flow and occasionally dip of the depositional substrate.

Frequently Asked Questions-

Q1. How do you classify Primary sedimentary structures considering the process of their formation?

Q2. Discuss Flow regime concept considering Reynold's and Froude number?

Q3. What are the bedform produced by unidirectional flow? Discuss briefly their generations?

Q4. Discuss briefly the bedforms produced by multidirectional flow?

Q5. What is cross-lamination? How does a cross lamination can be preserved in rock record?

Q6. What are erosional primary sedimentary structures? How do they generate? Do they always indicate palaeocurrent direction?

Multiple Choice Questions-

1. Wave ripple characterized by

(a) Sharp and straight crest line
(b) Asymmetric crest line
(c) Unidirectional lee orientation

Ans: a

2. Critical climb of ripple denotes

(a) Angle of climb > stoss angle
(b) Angle of climb < stoss angle
(c) Angle of climb = stoss angle

Ans: c

3. A flow becomes turbulent when

(a) Reynolds Number (Re) <1000
(b) Reynolds Number (Re) <2000
(c) Reynolds Number (Re) >2000

Ans: c

4. Determination of palaeocurrent is possible from

(a) Gutter cast
(b) Flute Cast
(c) Longitudinal scours

Ans: b

5. Fluvial palaeocurrent is generally

(a) Unimodal
(b) Bimodal
(c) Polymodal

Ans: a

6. Tabular cross bedding is formed due to migration of

(a) 2D bedform
(b) 3D bedform
(c) Both 2D and 3D bedforms

Ans: a

Suggested Readings:

1. Collinson, J. D. and Thompson, D. B. (1982), Sedimentary Structures, Allen and Unwin Publication, ISBN 10: 0045520178 / ISBN 13: 9780045520176.
2. Reineck, H.-E., Singh, I. B. (1980), Depositional Sedimentary Environments: With Reference to Terrigeneous Clastics, 2nd Edn., Springer Publications. ISBN-10: 3540101896, ISBN-13: 978-3540101895.
3. Sam Boggs Jr. (2011). Principles of Sedimentology and Stratigraphy, 5th Edn. Pearson Education, Inc., New Jersey. ISBN: 9780321643186, 0321643186.
4. Gary Nicols (2009), Sedimentology and Stratigraphy, 2nd Edn., Wiley-Blackwell, UK. ISBN: 978-1-4051-3592-4.