Chapter three (transportation and sedimentation)

Transportation: is the movement of eroded particles by flowing water, air, ice or dense mixtures of sediment and water.
Sedimentation is the settling out of solid materials in a liquid.
Sedimentary processes include both transportation and sedimentation; they include the work of water, wind, ice, and gravity.

Transportation and deposition of sediments are governed by the laws of physics.

FUNDAMENTALS OF FLU I D FLOW

Matter occurs in three phases: solid, liquid, and gaseous. The physicist considers gases and liquids together as **fluids.**

Fluids are substances that change shape easily under their own weight. Air, water, and water containing various amounts of suspended sediment are the fluids. The basic physical properties of these fluids are **density** and **viscosity**. Differences in these properties markedly affect the ability of fluids to **erode** and **transport sediment**.

Fluid density is a mass per unit fluid volume. Density varies with different fluids and increases with decreasing temperature of a fluid. The density of water (0.998 g/mL at 20°C) is more than 700 times greater than that of air. This density difference influences the relative abilities of water and air to transport sediment; e.g., water can transport particles of much larger size than those transported by wind.

Fluid viscosity is a measure of the ability of fluids to flow. Fluids with low viscosity flow readily and fluids with high viscosity flow sluggishly. For example, the air has very low viscosity and ice has very high viscosity. Water has low viscosity; honey has high viscosity. The viscosity of water is greater than that of air. Viscosity increases with decreasing temperature of the fluid.

The behavior of granular solids in liquids and gases is comparable. Thus, water and wind form similar bedforms and structures. The similarity of the bedforms and structures of windblown and water-laid deposits are the root problem of differentiating them in sedimentary rocks.

Stokes' law

States that the settling velocity of a particle is related to **its diameter,** and to the **difference between the particle density** and the **density of the fluid**. Considered at its simplest a small particle (in case same density) or denser one (in case same diameter) will settle faster.

The behavior of particles in fluid:

1. **Reynolds number** a dimensionless number that is proportional to the ratio between **inertial** and **viscous** force in the fluid. It typically used to differentiate between **laminar** and **turbulent** flow.

$$R = \frac{Udp}{\mu}$$

Where R is the Reynolds number, U is the velocity of the particle, d is the diameter of the particle, p is the density of the particle, and μ is the viscosity of the fluid.

2. **Froude number** a dimensionless number that expresses the relation between **inertial** and **gravity** force in the fluid. It typically applied to **flow regime (**tranquil and rapid flows) **and generation of bedforms** (ex. ripples, dunes).

$$F = \frac{U}{\sqrt{gL}}$$

Where U is the velocity of the particle, L is the force of inertia (i.e., the length traveled by the particle before it comes to rest), and g is the acceleration due to gravity.

Flow regime; is the relationships that exist between various flow conditions and bedforms at sediment/water interface and the water surface.

Bedform; is a morphological feature formed by the interaction between a flow regime and sediment on a bed (for example, ripples in the flowing stream and sand dune in desert).

The behavior of fluids and particles in fluids:

The behavior of fluids and particles in fluids classified into a laminar flow and turbulent flow (Fig. 3.1):

A- Laminar flows, all molecules within the fluid move parallel to each other in the direction of transport. It is characterized by:

1. There is no mixing of the water or grains (or ice) and there is no sorting of grain sizes.
2. It takes place only at low Reynolds numbers and at very low fluid velocities over smooth beds.
3. It occurs in some mudflows, in moving ice and in lava flows.

B- Turbulent flows, molecules in the fluid move in all directions but with a net movement in the transport direction. The general characters are:

1. There is a mixing of the fluid and particles with variable degree of sorting.
2. It takes place at high Reynolds numbers and at high fluid velocities over rough beds, which tend to produce random eddies and vortices.

3. It occurs in the most flow of air and water.

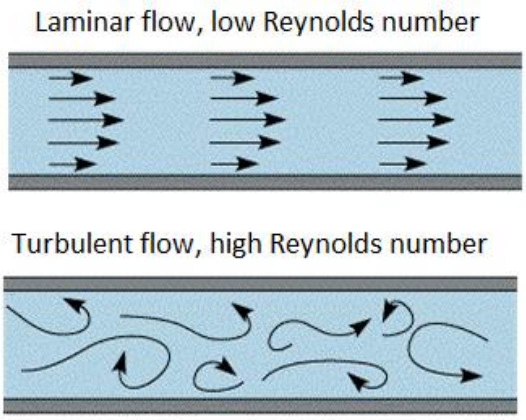

Fig. 3.1 Types of fluid flows

<u>There are four main agents (or media) of sediment transport:</u>

1- **Water**

The most important agents for transporting the products of weathering and erosion processes. Sediment moved by water can be larger than sediment moved by air (due to density difference). These flows may be strong enough to carry coarse material along their base and finer material in suspension.

2- Air: Wind.

The next most important transporting media. Wind blowing over the land can pick up (hold) dust and sand and carry it to large distances. The capacity of the wind to transport material is limited by the low density of air, the Size of the transported sediment by air is fine sand (<1 mm) and smaller.

3- Ice: Glaciers and icebergs.

Consider ice as a fluid because over a long time it moves across the land surface very slowly. Ice is a rather high – viscosity fluid which is capable of transporting large amounts of clastic debris. It is significant in polar ice caps and mountainous areas with permanent or semi-permanent glaciers.

4- Gravity:

Sediments move downslope under the direct action of gravity. Gravity can occur on sloping surfaces in general, including hill slopes, scarps, cliffs, and the continental shelf—continental slope boundary. Sediments transported by gravity, represent **Rockfalls, slide** and **sediment gravity flows.**

Transportation effects:

Transport of sediments (by rivers, wind, and ice) has several effects, which increase with transport distance:

1. Reducing of grain size. 2. Rounding of grains. 3. Sorting of grains.4. Weathering of minerals, by dissolution or alteration. 5. Mixing of grains from different origins.

Types of grain movement in the fluid

There are three types of grain movement in the fluid**.** These include **rolling**, **saltation** (bouncing) and **suspension** (Fig. 3.2). In a given situation, the heaviest particles are never lifted from the ground. They remain in contact with their colleagues but are rolled along by the current. At the same velocity, lighter particles move down current with saltation, while the lightest particles are borne along by the current in suspension.

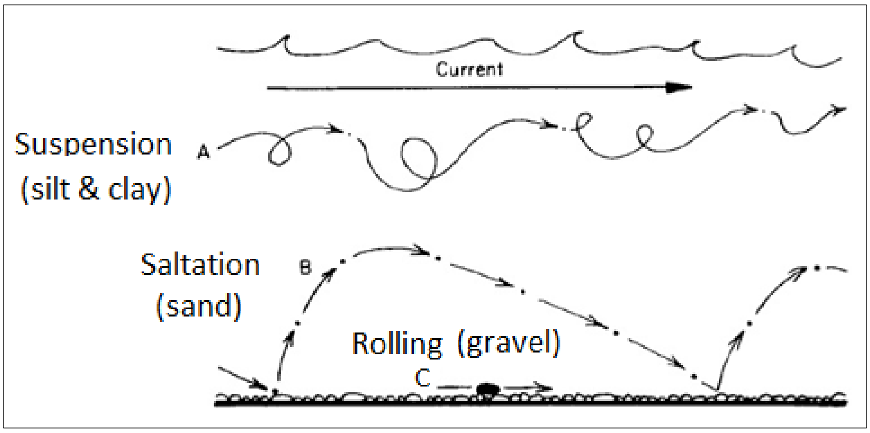

Fig. 3.2 The mechanics of particle movement. (A) Suspension. (B). Saltation (Bouncing). (C) Rolling.

In a situation such as a river channel, therefore, gravel will be **rolling** along the bottom, sand will sedately **saltate**, and silt and clay will be carried in **suspension**.

The critical flow velocity needed to start a particle into motion:

The beginning of grain movement is mainly determined by **Hjustrom's diagram**, Fig. 3.3. The critical fluid flow increases with grain size. An exception to this rule is noted for cohesive clay bottoms. Because of their resistance to friction, they need rather higher velocities to erode them and commence movement than for silt and very fine sand. This anomaly termed the "**Hjulstrom effect**".

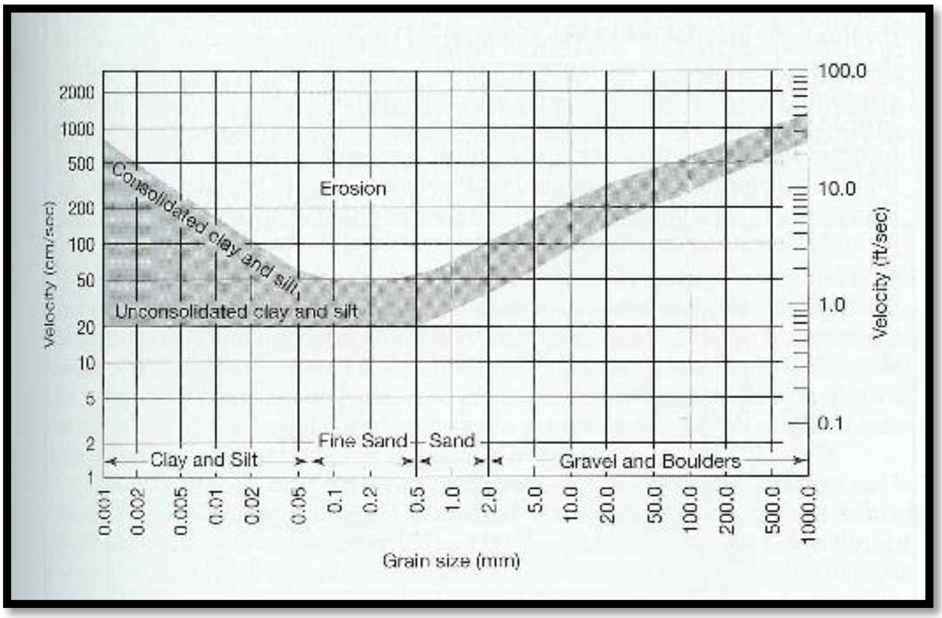

Fig. 3.3 Hjulstrom diagram

Types of sediment loads (bedload transport):

There are four kinds of sediments load (Fig. 3.4):

1. BedLoad (traction); made up of coarse clastic material moved by **rolling** and **saltation** (jump) along the bed (very close to the bed).

2. Suspended Load; made up of fine-grained clays and silts. This sediment transported higher up in the main flow.

3. Wash load; fine grains (clays) in continuous suspension derived from riverbank or upstream.

4. Dissolve load; this represents the dissolved ions in solution that transported within the fluid such as (Ca, Mg, Na, K, Cl, SO4…..etc.) ions.

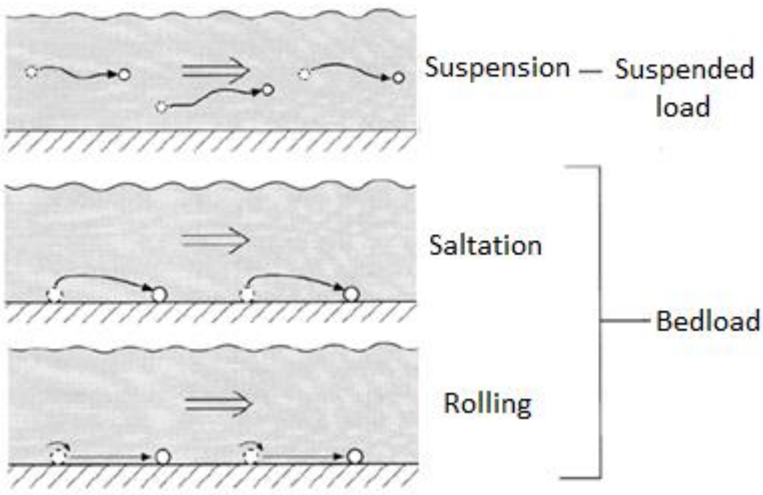

Fig. 3.4 Main types of sediment load

Types of deposits resulted from different types of fluid flow:

A. **The traction deposits (carpet);** are generated by bedload transport (traction) from traction currents (mainly by rolling and saltation) and deposited as traction carpet deposits. They are characterized by:

1. Sedimentary structures such as cross-beds, ripple marks, and pebble imbrication (paleocurrent indicators).
2. Traction currents may be generated by gravity (e.g.; river sand), or by wind (e.g.; Desert sand dunes) or tidal forces in the sea.

B. **The density current deposits** originate from a combination of traction and suspended load transport and deposited by the direct action of gravity. They are characterized by:

1. Mixtures of sand, silt, and clay, which lack cross-bedding and typically show graded bedding.
2. Density currents are caused by differences in density between sediments and the surrounding water.

C. **The suspension deposits** include those that settle out from suspension. These are :

1. Fine-grained silts and clays and include windblown silts (loess) and the pelagic detrital muds.
2. Sediments deposited from suspension are commonly characterized by *fine laminations*

The relationships between Bedforms and sedimentary structures for different flow regimes (Fig. 3.5):

The basic approach to understanding traction-current sedimentation has been made through experimental studies of unidirectional flow in confined channels which can be summarized as follows:

Small ripples begin to develop in sandy sediment as soon as the critical entrainment velocity for the sediment is reached. (Fig 3.5) **Ripples** are the smallest bedform, ranging in length from about 5 to 20 cm and in height from about 0.5 to 3 cm. They form in sediment ranging in size from silt (0.06 mm) to sand as coarse as 0.7 mm. Larger bedforms with spacing or wavelength, ranging from under 1 m to over 1 000 m are called dunes (Ashley, 1 990). Dunes are similar in general appearance to ripples except for size. They form at higher flow velocities in sediment ranging in grain size from fine sand to gravel. In the lower part of the dune stability field, ripples may be superimposed on the backs of dunes.

The hydraulic conditions that generate **ripples** and **dunes** take place at Froude numbers < ~ 1. Under these flow conditions, either the water surface shows little disturbance or the water waves are out of phase with bedforms, and flow is said to be in the lower flow regime {Simons and

Richardson,1961). Downstream migration of ripples and dunes leads to the formation of *cross-lamination* and *cross-bedding* respectively that dips downstream at angles of up to about 30°.

With further increase in flow velocity, dunes are destroyed and give way to an upper flow regime stage of flow, which takes place at Froude numbers > ~1, Sheetlike, rapid flow of water takes place, which generates surface water waves that are in phase with bedforms. Intense sediment transport results, over an initially relatively flat bed, during what is referred to as the **plane-bed** stage of flow. Plane-bed flow gives rise to internal *planar lamination* in which individual laminae range in thickness from a few millimeters to a few centimeters.

At still higher velocities of flow, plane beds give way to **antidunes**, which are low, undulating bedforms up to 5 m in length. Antidunes form in very fast, shallow flows. They migrate upstream during flow, giving rise to *low-angle* (< 10 °) *cross-bedding* directed upstream.

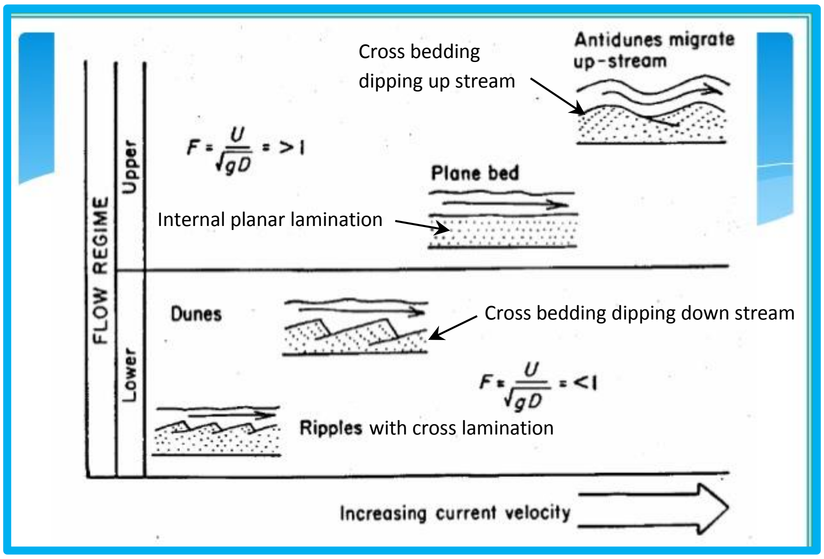

Fig. 3.5. Bedforms and sedimentary structures for different flow regimes. (After Harms and Fahnestock, 1965, and Simons *et al.,* 1965.

Most important of all, it is an experimental observation that the ripple phase is absent in sediments with a fall diameter of more than about 0.65 mm. (Fig. 3.6) (The fall diameter is a function of the particle diameter and the viscosity of the fluid). The fall diameter of a particle decreases with increasing viscosity. It is a matter of field observation that cross-lamination is absent in sediments with a particle diameter of over about 0.5 mm.

A second important point to note is the way in which temperature affects sediment structures. Harms and Fahnestock (1965), in their study of reaches of the Rio Grande, showed how, for similar discharges, either plane bed or dunes could be present. The main controlling variable seemed to be temperature. This controlled the fluid viscosity and hence the fall diameter of the sediment.

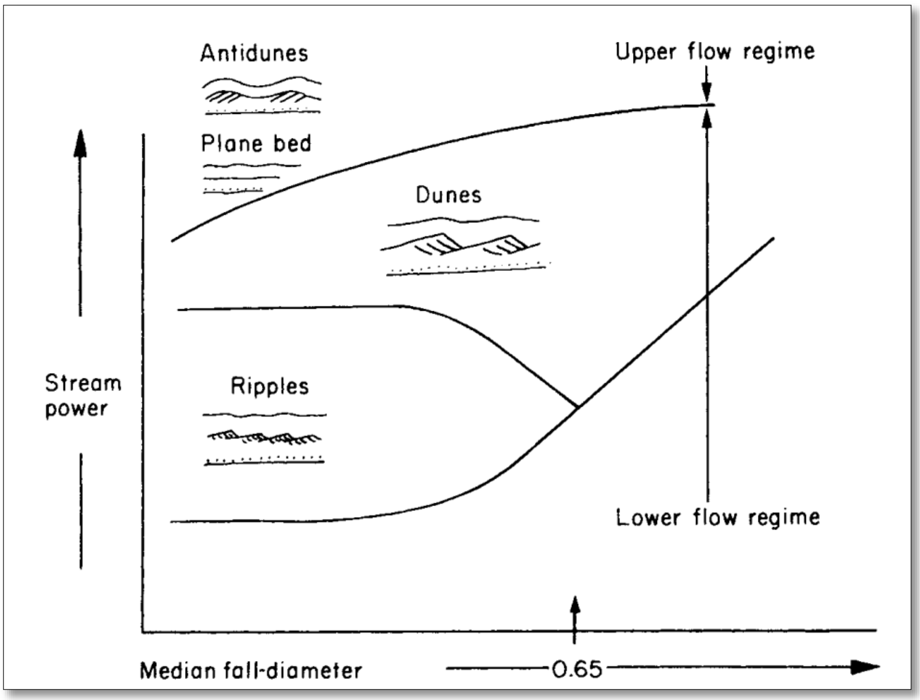

Fig. 3.6. The relationship between stream power, fall diameter, bed form, and sedimentary structure in a unidirectional traction current system. (After Simons *et al.*, 1965. Courtesy of the Society for Sedimentary Geology.)

Transport by wind (Aeolian processes):

Wind considered a very low density, low viscosity "fluid" that capable of flowing and bringing about sediment transport.

The difference between aeolian and aqueous transport:

1) In aeolian transport, grain ballistics (the bed is bombarded with grains) and intergranular collisions are much important than fluid turbulence. Transport takes place at relatively high wind velocity, and the flow is commonly turbulent.

2) The size of the transported sediment by air is less than <1 mm (0.1. to 1.0 mm) Water, by contrast, can transport particles of much larger size than those transported by wind.

The wind moves only sand-sized particles as bedload (by traction "surface creep" and saltation), dust-size particles (by suspension). Suspended loads carried by wind are called **dust loads**.

Modes of transport by wind:

There are three modes of transport by wind. These are a creep, saltation, and suspension (Fig. 3.7).

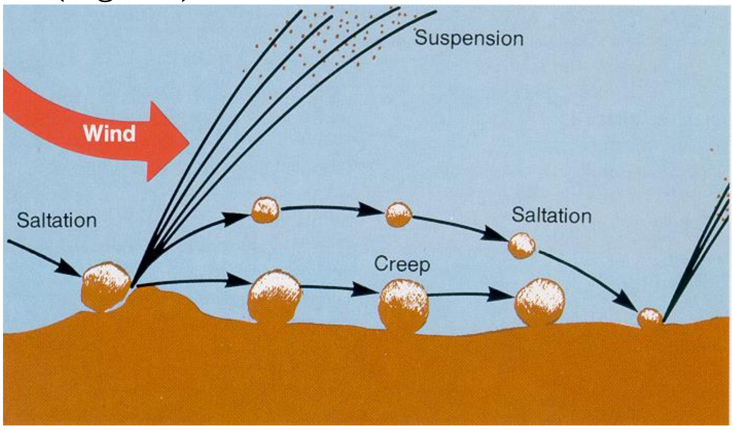

Fig. 3.7 Modes of transport by wind.

Kinds of aeolian deposits:

The transporting and sorting action of wind tend to produce three kinds of deposits:

1. Sand deposits; are commonly well-sorted and lack clay. They may form various bedforms including ripples, dunes and plane beds (sand sheet).
2. Dust (silt) deposits "loess"; commonly accumulate far from the source. They are massive and occur in laterally extensive layers.
3. Lag deposits; consisting of gravel-size particles that are too large to be transported by wind

Wind transport and deposition generate many of the same kinds of bedforms and sedimentary structures-such as *ripples*, *dunes* (Fig. 3.8) and *plane beds*-as those produced by water transport. The bedforms range from ripples few centimeters high to dunes hundreds of meters high.

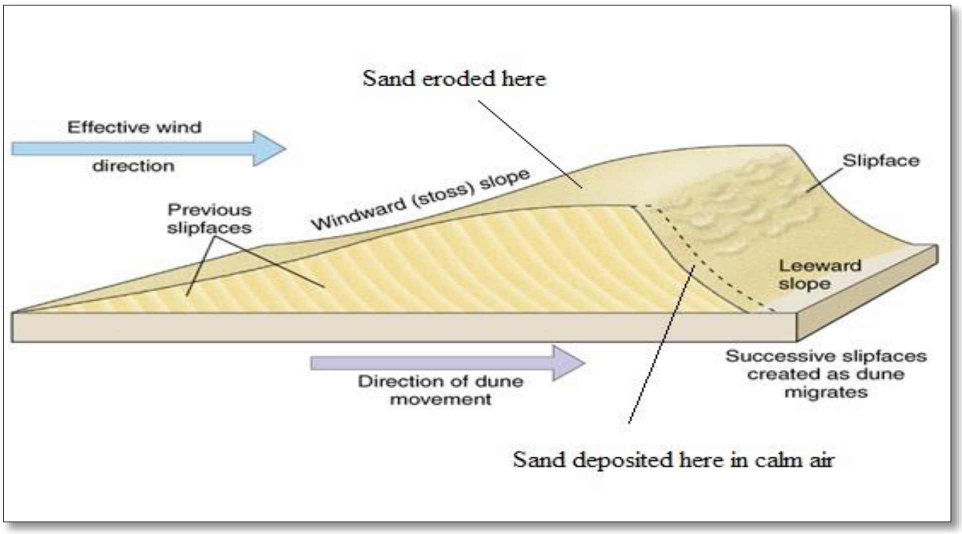

Fig. 3.8 Across-section of an idealized dune

Morphological types of sand dune:

The barchan or lunate dune; is arcuate in a plan, convex to the prevailing wind direction, with the two horns pointing downwind (Fig. 3.9A). They are bedforms of transportation, not of net deposition. It is **unlikely** to preserve in the geological record.

Stellate or pyramidal dunes; consist of a series of sinuous, sharp, rising sand ridges, which merge together in a high peak from which wind often blows a plume of sand, (Fig. 3.9B). They are sometimes hundreds of meters high. They often form at the boundary of sand seas

Longitudinal or seif dune; are long, thin, sand dunes with sharp median ridges (Fig. 3.9C). Individual dunes may be traced for up to 200 km,

Transverse dune; are straight, or slightly sinuous, crested dunes that strike perpendicular to the mean wind direction (Figs. 3.9D). Their steep slip faces directed downwind. Transverse dunes are the Aeolian bedform that actually deposits sand. The other three dune types seem largely transportation bedforms.

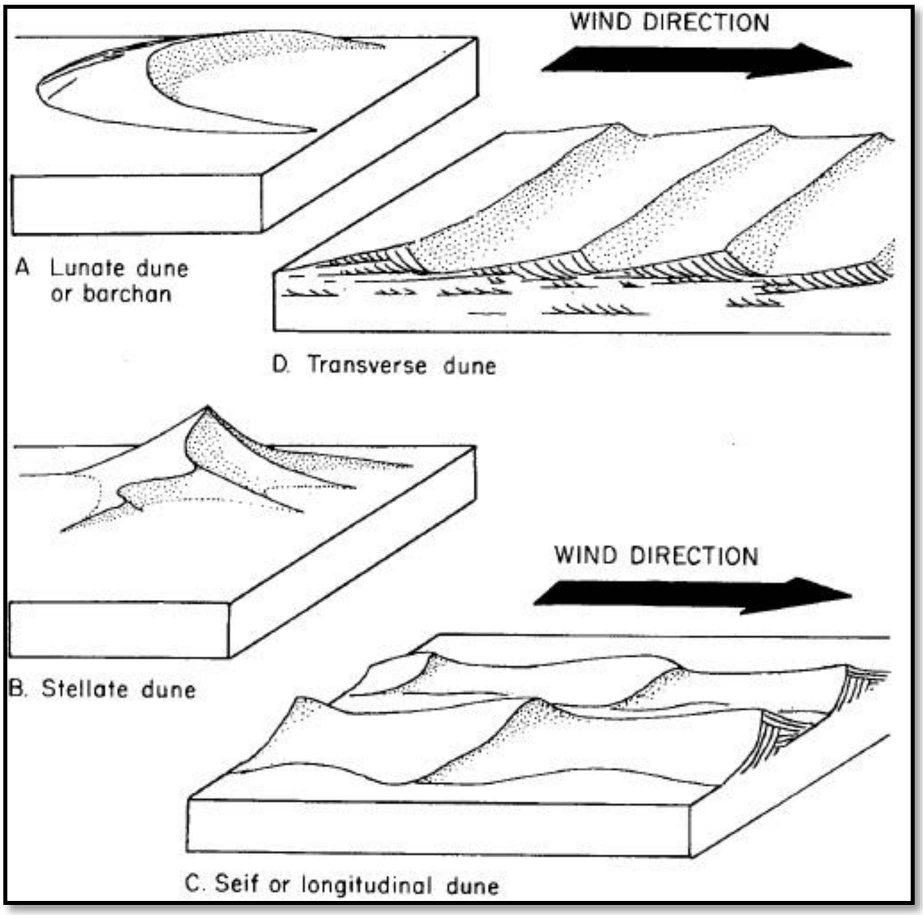

Fig. 3.9 the four main morphological types of a sand dune

Deposits of Fluid flows (summary):
Water and air are responsible for most sediment transport by fluid flow; however, ice may account for local transport of large volumes of sediment and particles of a very large size.

Sediments deposited by the fluid flow of water or wind commonly characterized by:
1. layers or beds of various thickness, scarcity of vertical grain-size grading, grain-size sorting ranging from poor to excellent depending upon depositional conditions, and a variety of sedimentary structures.
2. Sediments deposited from traction currents commonly preserve sedimentary structures such as cross-beds, ripple marks, and pebble imbrication that display directional features from which the direction of the ancient fluid flow can be determined.
3. The wind is competent to transport and deposit particles in the size range of sand to dust (clay) only. By contrast, the grain size of sediment deposited by water may range from clay size to cobbles or boulders tens to hundreds of centimeters in diameter.

These variations in grain size reflect the wide range of energy conditions of wind and water that prevail under natural conditions and the variations in relative competence of wind and water to initiate and sustain sediment transport.

Mass-transport processes (Gravity mass movement):

It refers to the flow of sediments or sediment-fluid mixtures under direct action of gravity in both subaerial and subaqueous environments. They include rock falls, slides and sediment gravity flows.

(A) Rockfalls and/or Slides and slumps:

Rockfalls; free fall of rock and sediment from cliffs or steep slopes. Rockfalls may occur both on land and under the sea. They may be triggered by earthquakes and, on land, by heavy rain and freeze-thaw action in cold climates. The resultant sediment is **scree** composed of poorly sorted angular boulders with high primary porosity.

Slides and slumps; occur on gentler slopes than rock falls. The sedimentary processes of sliding involve the lateral transportation of sediment along subhorizontal shear planes.

(B) Sediment gravity flows:

The types of sediment gravity flows and deposits:

1. Debris Flows:

Fine sediment and fluid support large particles **(matrix-supported flow)** composed of highly concentrated poorly sorted mixtures of sediment (range in size from clay to boulders) and water that behave in a different manner than fluid flows.

Debris flows occur in a wide range of environments, ranging from deserts to continental slopes. In the former (deserts) situation, heavy (torrential) rainfall is generally required to initiate movement; in the latter, earthquakes, tide, or storm surges are required. In all situations, a slope is a necessary prerequisite.

Debris flow deposits

Chaotic mixtures of particles that may range in size from clay to boulders. They are typically poorly sorted, matrix-supported sediments, with random clast orientation (Fig.3.10 and Fig.3.13A).

Fig.3.10. Debris flow deposits (Palaeocene, Kirikkale, Turkey).

2. Turbidity Currents:

A type of density current that flows downslope along the bottom of an ocean or lake because of density contrasts **(density difference)** with the surrounding water and the sediment becomes suspended in water owing to turbulence.

Turbidites, the deposits formed by turbidity currents, are typically normally graded, ideally composed of five units (*Bouma sequence*). They show the following features:

• They are generally thick sequences of regularly interbedded sandstones and shales.

• They typically occur in submarine fans (in orogenic belts or in fault-bounded marine basins).

• **<u>Bouma sequence</u>** (Bouma, 1962) (Fig. 3.11_and Fig.3.13B). This ideal sequence of turbidities consists of five zones from A to E.

• They have been interpreted in terms of the **flow regime**; they record the decay of flow strength of a turbidity current with time and the progressive development of different sedimentary structures and bedform from upper flow regime to lower flow regime as current-flow velocity wanes.

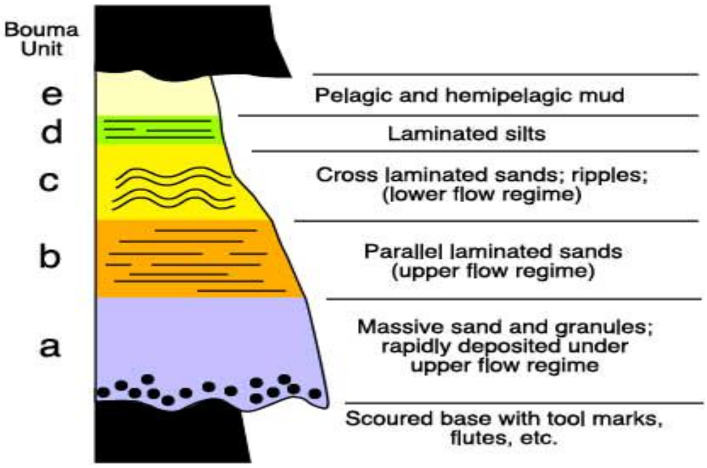

Fig. 3.11. Turbidite unit showing the complete Bouma sequence and its interpretation in terms of flow regimes.

3. Grain flows:

<u>A type of sediment gravity flow in which the sediment is supported by direct grain-to-grain interactions</u> **(grain interactions)** especially on steep slopes that approach the angle of repose for the sediment.

Grain flows occur on a sand dune in the desert (Fig. 3.12) and in the deep sea, on submarine canyons. Grain flow beds are massive or faintly bedded with clasts up to cobble size, scattered throughout them and are not graded (Fig.3.13C).

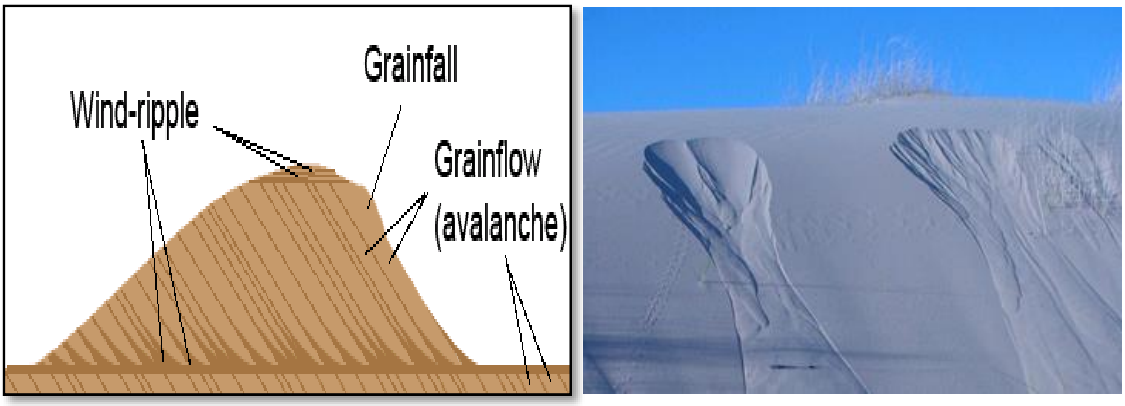

Fig. 3.12. Grain flow on the lee slopes of sand dunes

4. Fluidized Flows:

Sediment particles are moved by the upward flow of fluid escaping between grains (fluid escape). They Form when loosely packed sand is shocked, this causes grains to become shortly suspended in their own pore fluid.

The deposits of fluidized flow are typically thick, poorly sorted sand units. They are characterized particularly by fluid escape structures, such as the dish structures, pipes, and sand volcanoes (Fig.3.13D).

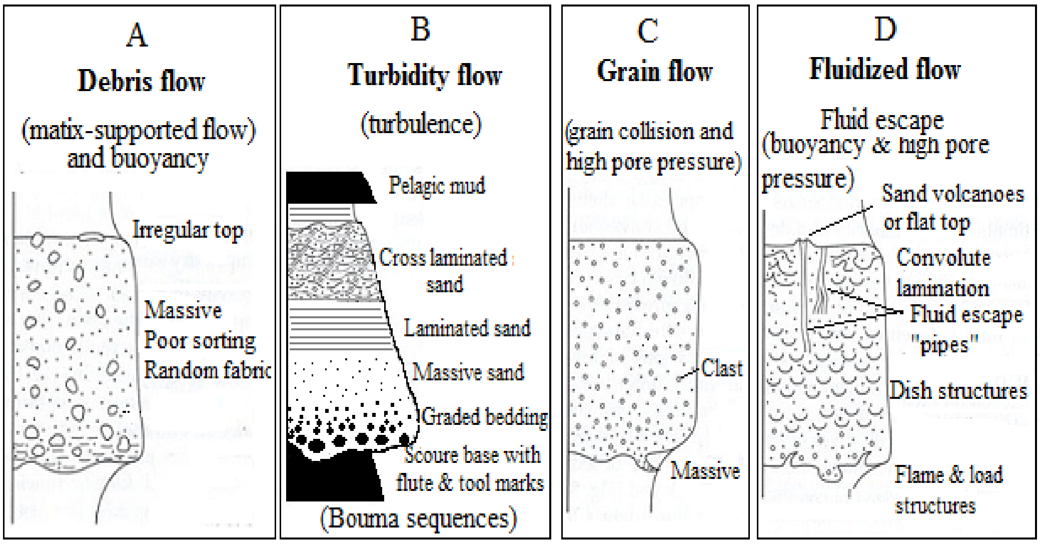

Fig.3.13 Types of sediment gravity flows

Transport of sediments by glacial ice (GLACIAL PROCESSES):

A glacier is anybody of flowing ice that has been formed on land by compaction and re-crystallization of ice gradually, the snow transitions to glacier ice through a combination of compaction and re-crystallization of the ice.

Sediments move within glacial ice very slowly owing to its high viscosity. The flow of the ice is laminar, and flow velocity is greatest near the top and center of the glaciers. Velocity decreases toward the wall and floor.

Sediments deposited by glaciers are characteristically poorly layered and extremely poorly sorted, with particles ranging from meter-sized boulders to clay-sized grains. When the front of a glacier melts, the sediment load is dumped as unsorted, poorly layered **glacial moraine.**

Diamictite. This is a poorly sorted sediment from boulders to clay. The boulders, are angular and show **striations** (Fig.3.14).

Tillites; are Ancient diamictites of a glacial origin.

Fig.3.14 Striations in glacial deposits.