Istituto Nazionale di Oceanografia e di Geofisica Sperimentale

Università degli studi di Trieste

LAUREA MAGISTRALE IN GEOSCIENZE

Classe Scienze e Tecnologie Geologiche

Curriculum: Esplorazione Geologica

Anno accademico 2022 - 2023

Analisi di Bacino e Stratigrafia Sequenziale (426SM)

Docente: **Michele Rebesco**

Module	Topic	Teacher	Date
1.1	Introduction to the course	Rebesco	03/10/22
1.2	Methods (geophysics, but not only)	Volpi/Rebesco	06/10/22
6.1	Visit to the icebreaker Laura Bassi (along with Geologia Marina)	Rebesco	10/10/22
1.3	Mechanisms of basin formation (geodynamics, tectonics…)	Lodolo	13/10/22
1.4	Seismic interpretation, facies and primary structures	Rebesco	17/10/22
	No lesson: 20th October		
1.5	Energy storage & CCUS	Volpi/Donda	24/10/22
	No lesson: 27th		
2.1	Sedimentary processes in river & deltas	Rebesco	31/10/22
	No lesson: 3rd November		
2.2	Action of tides and waves, wind and ice	Rebesco	07/11/22
2.3	Density currents, bottom currents and mass transport	Lucchi/Rebesco	10/11/22
3.1	Alluvial deposits, lakes and deserts	Rebesco	14/11/22
3.2	Barrier systems and incised valleys	Rebesco	17/11/22
3.3	Continental shelves (wases, storms, tsunamis)	Rebesco	21/11/22
3.4	Submarine fans (gravity flows on the continental slope)	Lucchi/Rebesco	24/11/22
3.5	Sediment drifts (bottom currents along the continental slope)	Rebesco	28/11/22
3.6	Mass transport deposits	Ford	01/12/22
3.7	Abyssal plains (hemipelagic fallout) and continental margins	Rebesco	05/12/22
	No lesson on Thursday 8 th December		
3.8	Glacial depositional systems	De Santis	12/12/22
3.9	Carbonatic environments, faults, volcans	Rebesco	15/12/22
4.1	Sequence stratigraphy: introduction	Rebesco	19/12/22
	No lessons from 23 rd December to 8 th January		
4.2	Sequence stratigraphy: closer view	Rebesco	09/01/23
4.3	Sequence stratigraphy: applications (e.g. hydrocarbon reservoirs)	Rebesco	12/01/23
5	Excercise	Rebesco	13/01/23
6.2	Visit to CoreLoggingLAB (along with Geologia Marina)	Rebesco	20/01/23
6.3	Visit to OGS and SEISLAB (along with Geologia Marina)	Rebesco	27/01/23

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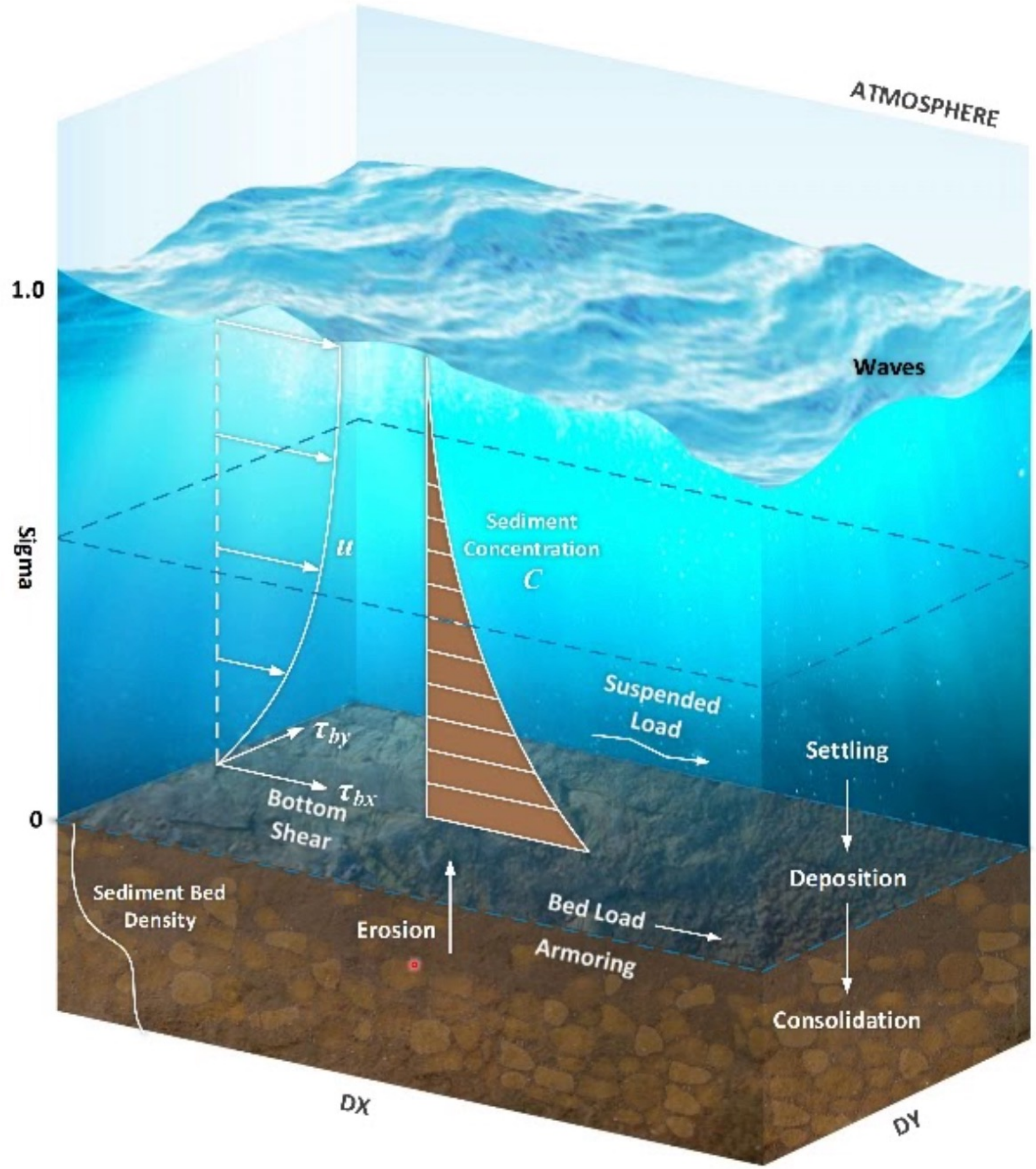
Module 2.1
Fluvial & deltaic sedimentary processes

Outline:
- Sediment transport
- Fluid flow dynamics
- Types of transport
- Fluvial transport
- Flows in deltas

Sediment transport

Sediment transport is the movement of solid particles (sediment), typically due to a combination of gravity, and the movement of the fluid in which the sediment is entrained.

After erosion, the particles are available for transportation. **Water, wind, ice and gravity** are the main agents for sediment transport. Gravity can act alone or associated to other agents.

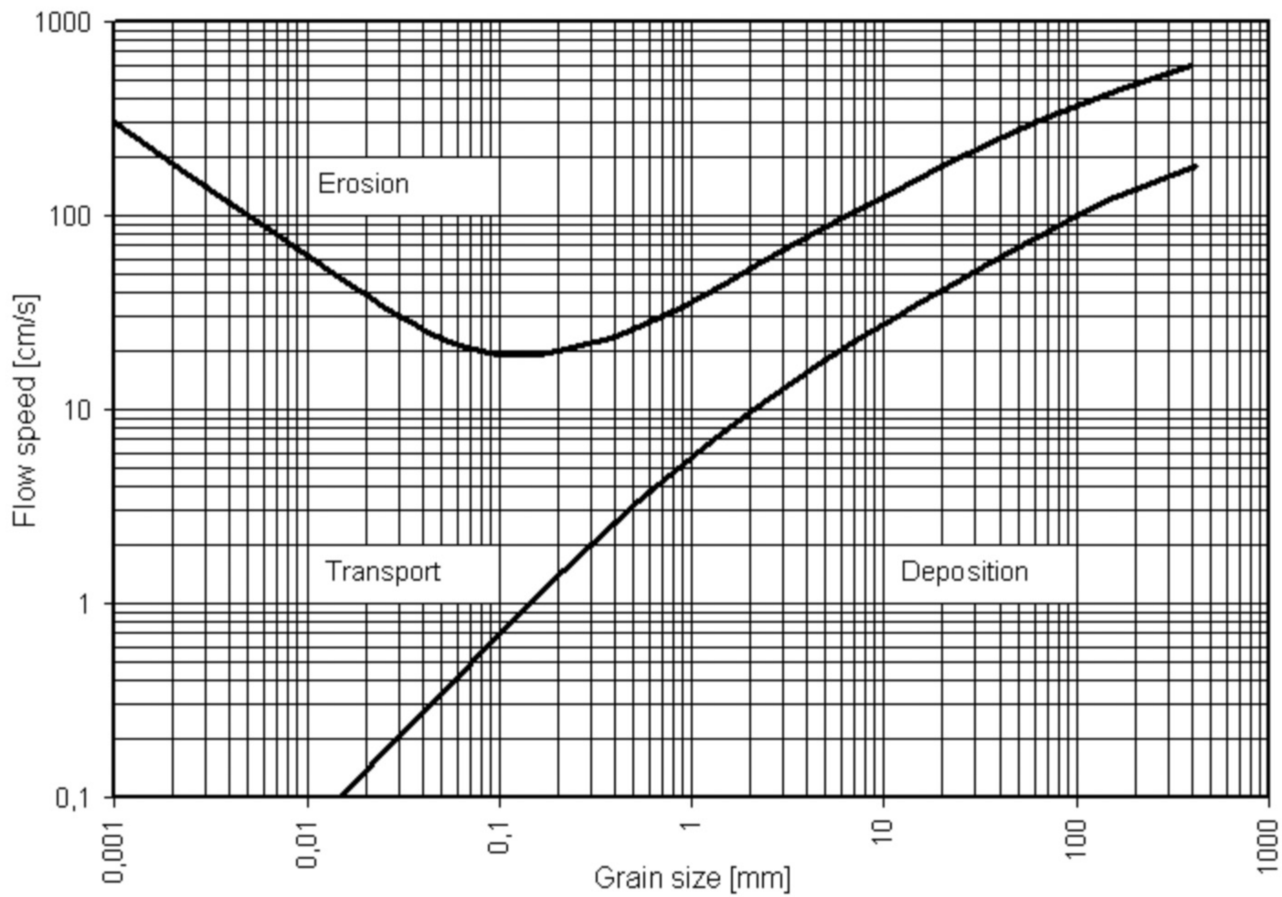


Hjulström Diagram

For a fluid to begin transporting sediment that is currently at rest on a surface, the boundary (or bed) shear stress exerted by the fluid must exceed the critical shear stress for the initiation of motion of grains at the bed.

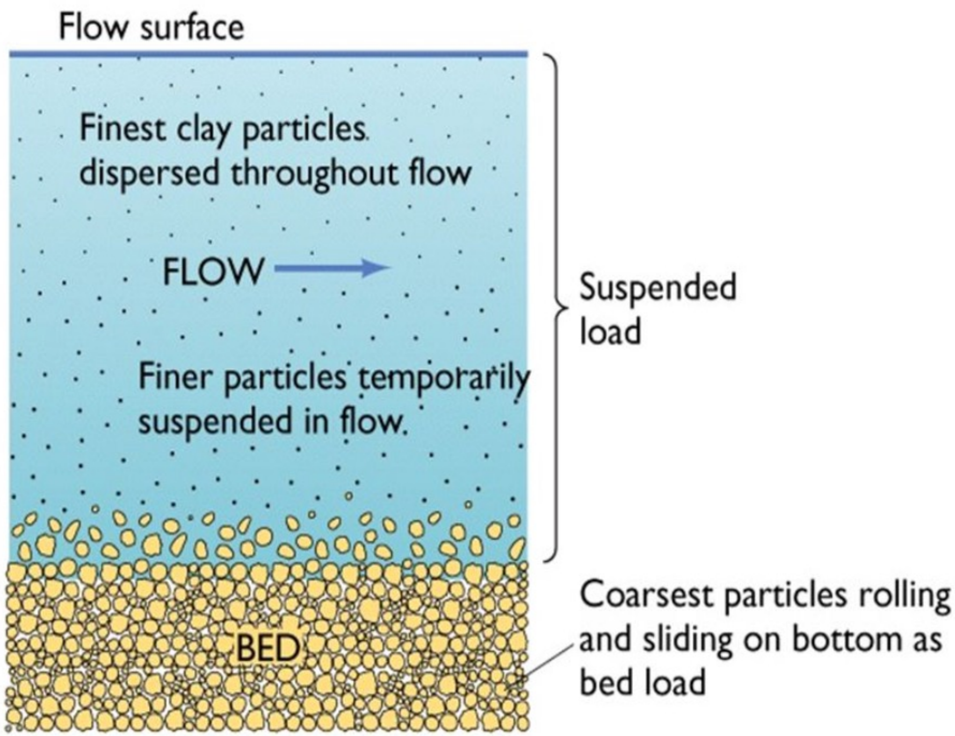
Created by Filip Hjulström in 1935, this graph shows the relationship between the size of sediment and the velocity required to erode, transport, or deposit it.

The logarithmic Hjulström curve



Fluid-flow dynamics: competence & capacity

Sediment transport can be classified according to its competency (related to the transported grain size), its capacity (related to the amount of sediment that the agent can transport) and the load (amount of sediment that the agent effectively carries). A river capable of carrying particles larger than sand sized is a highly competent agent. Also, the greater the volume flow of the river, the greater the load in motion and, therefore, the greater its capacity.

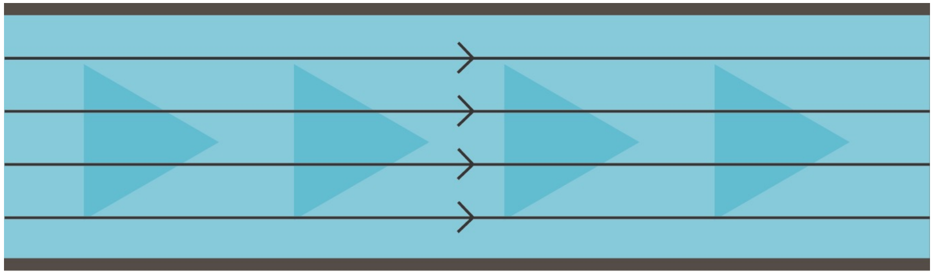


The force that moves the particles during transportation is provided by fluids, and depends mainly on their velocity and **viscosity**. The flow of fluids can be separated into 2 types: **laminar flow** and **turbulent flow**. In laminar flows, the particles immersed in the fluid move parallel to each other, in the direction of transportation. In turbulent flow, however, the particles immersed in the fluid move in all directions, but with a displacement parallel to the transportation direction. This type of flow has a much greater erosion power than laminar flow. As velocity increases, the flow tends to become turbulent.

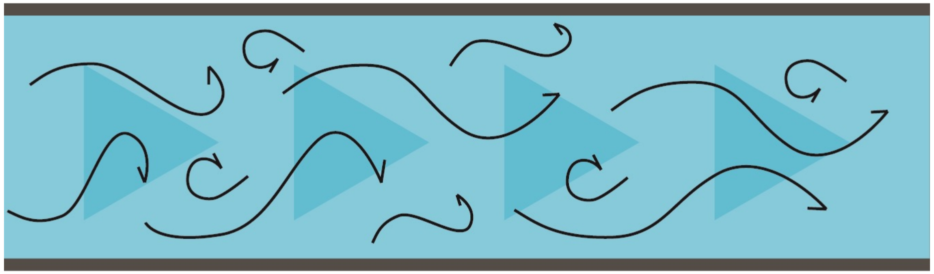
Reynolds Number

A dimensionless parameter called Reynolds Number (Re), named after Osborne Reynolds, who studied fluid dynamics during the nineteenth century, indicates the intervals at which a flow of fluid is laminar or turbulent. The Reynolds number is proportional to the velocity of the flow (V) and to the depth of the channel or diameter of a pipe (L), as well as to the ratio between the density (d) and the viscosity of the fluid (u), according to the equation:

$$Re = V \times L \times \frac{d}{u}$$



Laminar flow



Turbulent flow

For values of Re < 500, the flow is laminar, whereas for values of Re> 2000, it is turbulent. Laminar flows are common in high viscosity or low velocity fluids. Wind flow is, therefore, essentially turbulent due to the low viscosity of air. Water flows can be laminar when their velocity is very low. However, significant volumes of sediment are usually transported by turbulent water flows.

https://www.endeeper.com/blog/

Froude Number

In addition to the effects of fluid viscosity and inertial forces, gravity also influences the way a fluid transfers waves or moves sediment dunes. The Froude Number (Fr), which can be considered the ratio between the average velocity of the flow and the velocity of a wave contained therein, is also a useful dimensionless value for sedimentology studies, expressed as:

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

where U represents the average velocity of the flow, L the depth of water and g the acceleration due to gravity.

When Fr value is less than 1, the flow is considered subcritical or quiet and a wave can move upstream (against flow). If the value is greater than 1, the waves cannot propagate upstream and the flow is considered supercritical or fast. In addition to being used to define the critical velocity from which a flow is considered subcritical or supercritical at a given depth, the Froude Number is also related to different flow regimes, which are related to characteristic bedforms.

The Froude number enters into formulations of the **hydraulic jump** (rise in water surface elevation).

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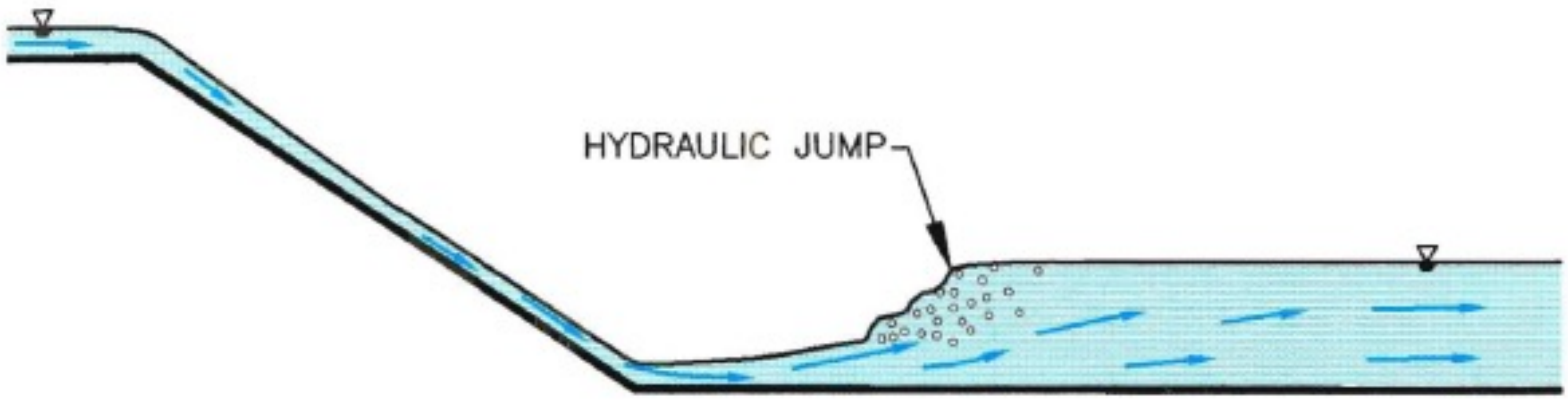
hydraulic jump

A hydraulic jump is a phenomenon in the science of hydraulics which is frequently observed in open channel flow such as rivers and spillways. When liquid at high velocity discharges into a zone of lower velocity, a rather abrupt rise occurs in the liquid surface. The rapidly flowing liquid is abruptly slowed and increases in height, converting some of the flow's initial kinetic energy into an increase in potential energy, with some energy irreversibly lost through turbulence to heat. In an open channel flow, this manifests as the fast flow rapidly slowing and piling up on top of itself similar to how a shockwave forms.

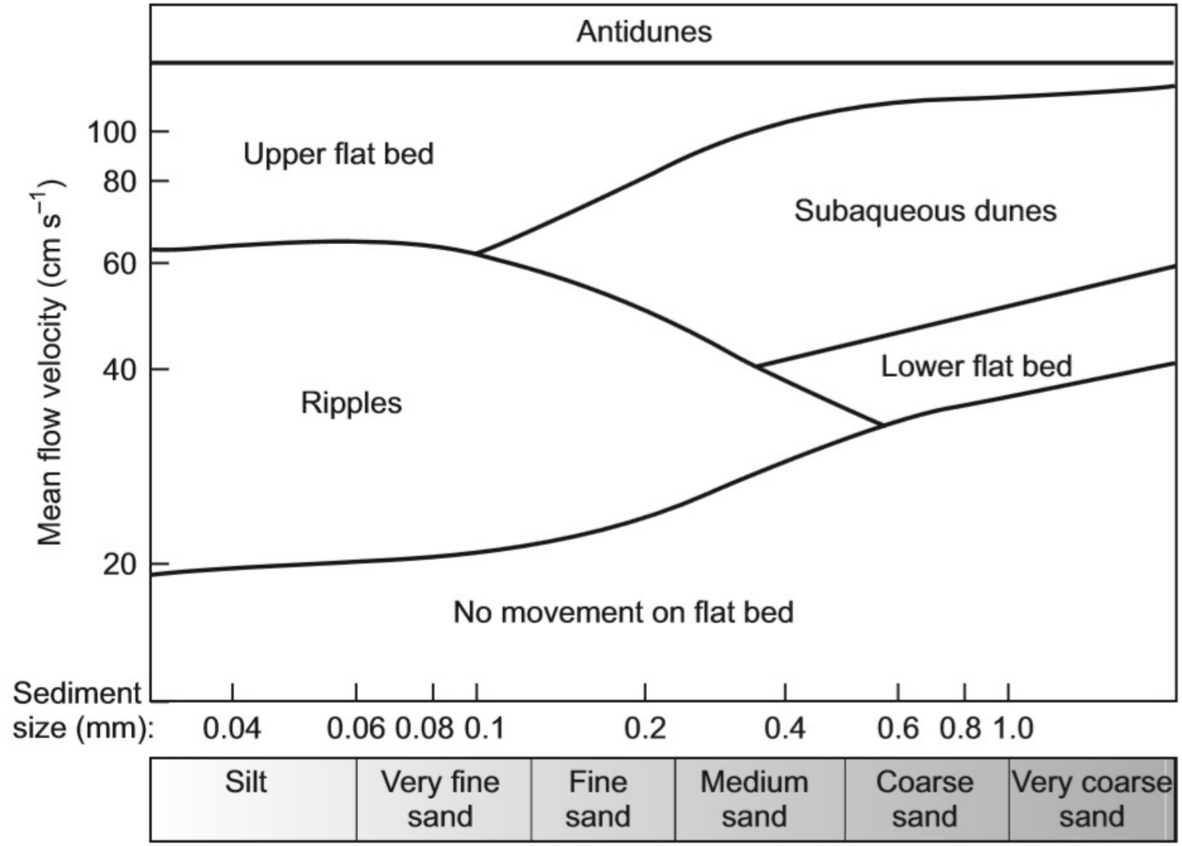


Courtesy of Wright Water Engineers, Inc. and ASDSO.
Source: Wright, Kenneth R., Kelly, Jonathan M., Houghtalen, Robert J., & Bonner, Mark R. "Emergency Rescues at Low-Head Dams." Paper presented at Dam Safety 1995, the 12th annual conference of the Association of State Dam Safety Officials, Atlanta, GA, September 1995.

Flow regimes

Two flow regimes are recognized: lower and higher. The lower flow regime comprises a subcritical flow in which ripples, dunes and plane-parallel type stratifications are formed. The upper flow regime, in turn, comprises a supercritical flow, in which antidunes and plane-parallel stratifications are stable.

This can be understood from a bedform stability diagram. The use of this diagram allows obtaining velocity estimates or identifying changes in velocity or type of flow that resulted in deposition of sediments according to their depositional structures.



Bedform stability diagram for particles under a given water flow (Nichols, 2009).

https://www.endeeper.com/blog/

Types (agents) of sedimentary transport

Water flows tend to make the sustrate into motion. In a simplified way, sediment particles will be transported if the energy of the stream overcomes the weight of the particles (and the cohesive force for finer particles).

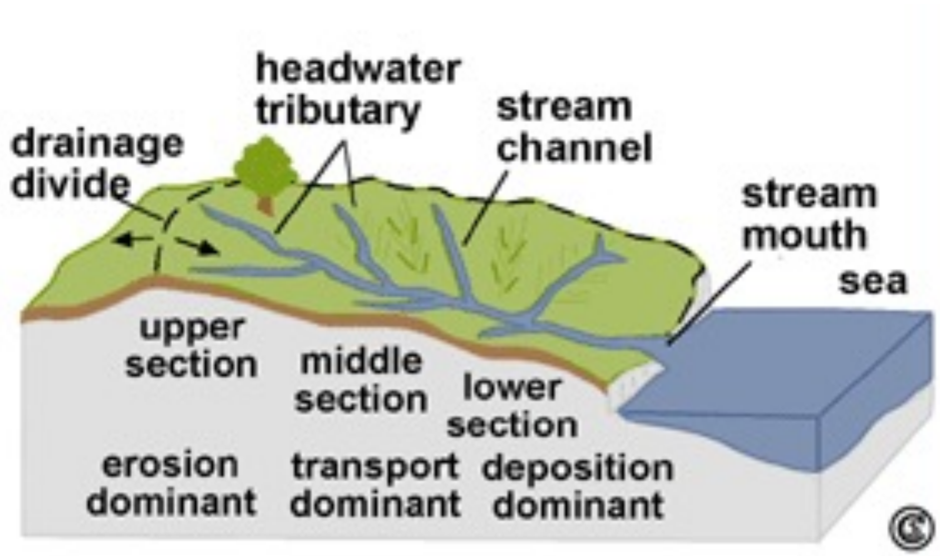
Ice is a fluid with very high viscosity that have a very slow and laminar flow. It may transport large amounts of suspended sediments of all sizes.

Air is a fluid of very low density and viscosity. Usually, air is capable of transporting in suspension only particles below the fine sand size, while coarser sediments are transported by rolling and saltation. Transport occurs at relatively high speeds, in a turbulent way.

Gravitaty flows/density flow: Sediment gravity flows are mixtures of water and sediment particles where the gravity acting on the sediment particles moves the fluid. These flows are differentiated by their dominant sediment support mechanisms.

Fluvial processes

Water flowing through a river perform three kinds of work:
erosion
transport
deposition.
Which of this three processes are at any time predominant depends on the local conditions. The river always tries to adjust on the existing conditions. In general, erosion is predominant in the headwater areas, transport in the middle reaches and deposition in the lower reaches of the respective watershed



Processes occuring in a river
Image Credit: Anette Stumptner 2007 after Bradshaw and Weaver 1995, 250

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Fluvial erosion

Fluvial erosion is the detachment of material of the river bed and the sides.
Erosion starts when the flow energy of the water exceeds the resistance of the material of the river bed and banks. Flow energy depends on depth of water and gradient and thus of stream velocity. The point in time when material is set in motion is regarded as critical state. The corresponding stress is termed '**critical shear stress**'. This varies for different particles. Hjulström already recognised 1935 the relation between flow velocity and particle size of the eroded, i.e. the moved material.
Fluvial erosion proceeds in two ways:
vertical erosion: a river erodes its river bed, i.e. it is deepen.
lateral erosion: a river erodes its bank; i.e. the river broadens.
The eroded material is transported by the river.

River bed of Adirako showing severe bank erosion in alluvial and colluvial infills; watershed of Adirako Dam in Ethiopia. Image Credit: Schütt, B. and Thiemann, St. 2001

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Fluvial transport

The material transported in a river is termed (stream) load. This can be separated into three components, each of them transported by diferent mechanisms.

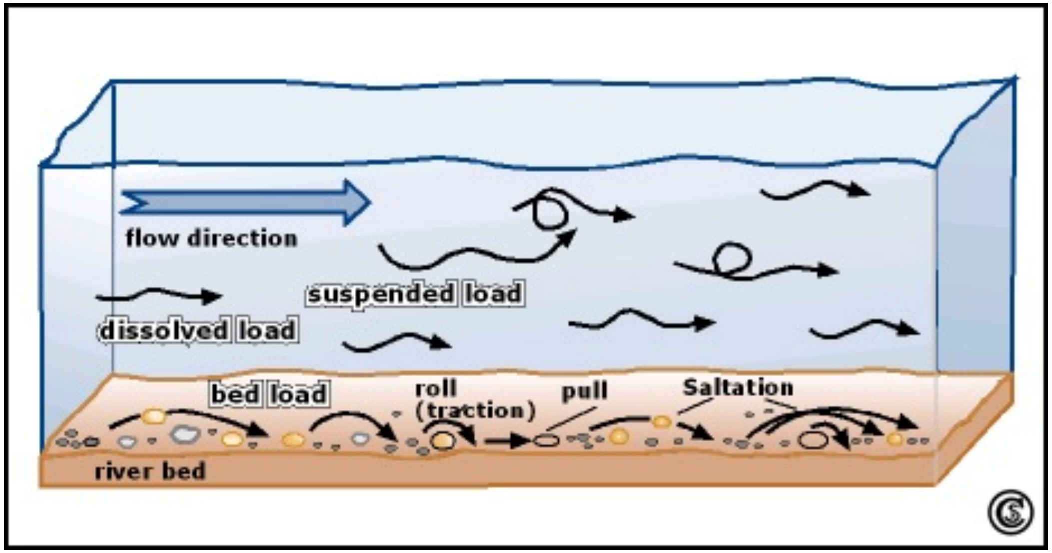
dissolved load: solution of solid substances carried in solution.

suspended load: particles which are small and light enough to be held in suspension.

bedload: particles which are transported on the river bed by traction and saltation.

During the transport the particles are gradually reduced in size and rounded (attrition = logoramento).

The ability of the river to transport its load oceanward is related exponentially to the flow velocity. If the flow energy is decreasing, the river deposits its load.



Different transport mechanisms occuring in a river
Image Credit: Anette Stumptner after Christopherson 1994, 424

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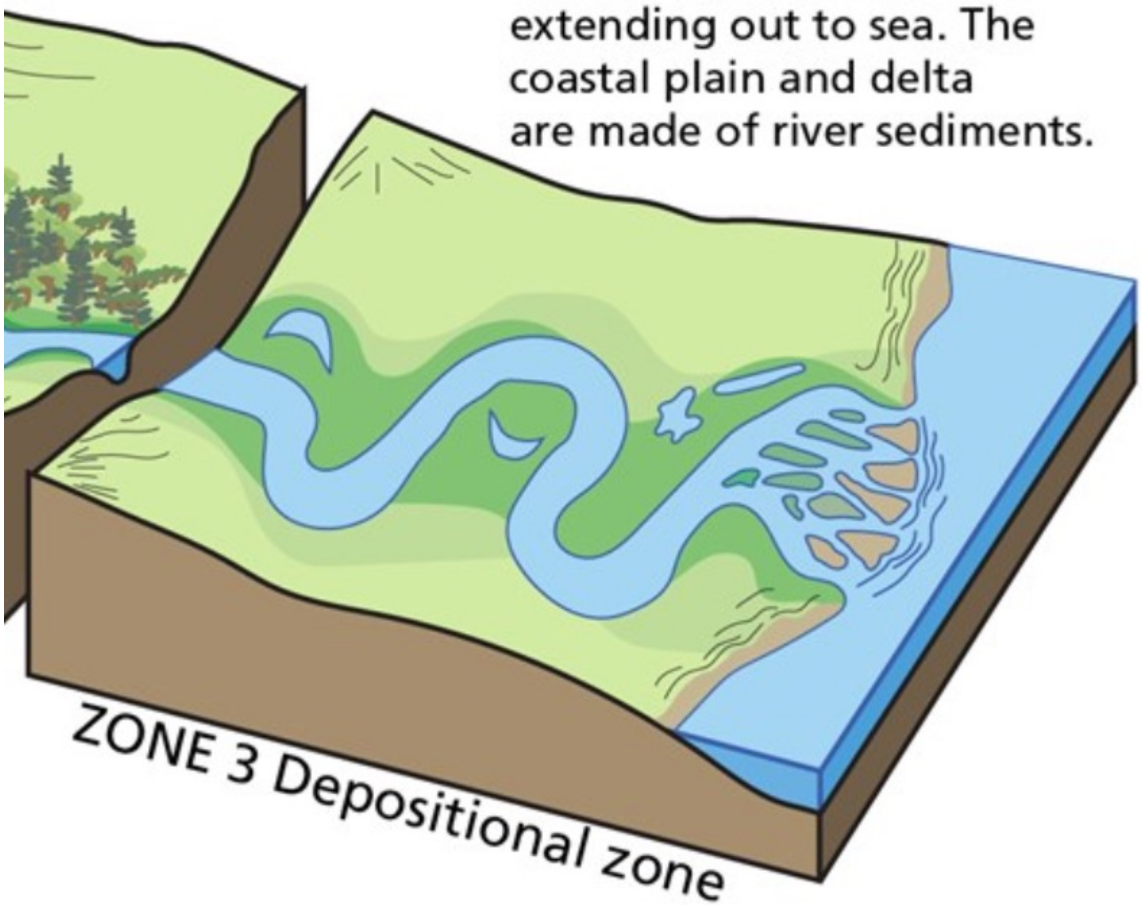
Fluvial deposition

If the friction force decreases deposition of the transported load starts. At these locations the load is deposited in different forms such as gravel cone.

A large part of work is done during flood events. During these events the most and largest particles can be eroded and transported by the water – and much destructed.

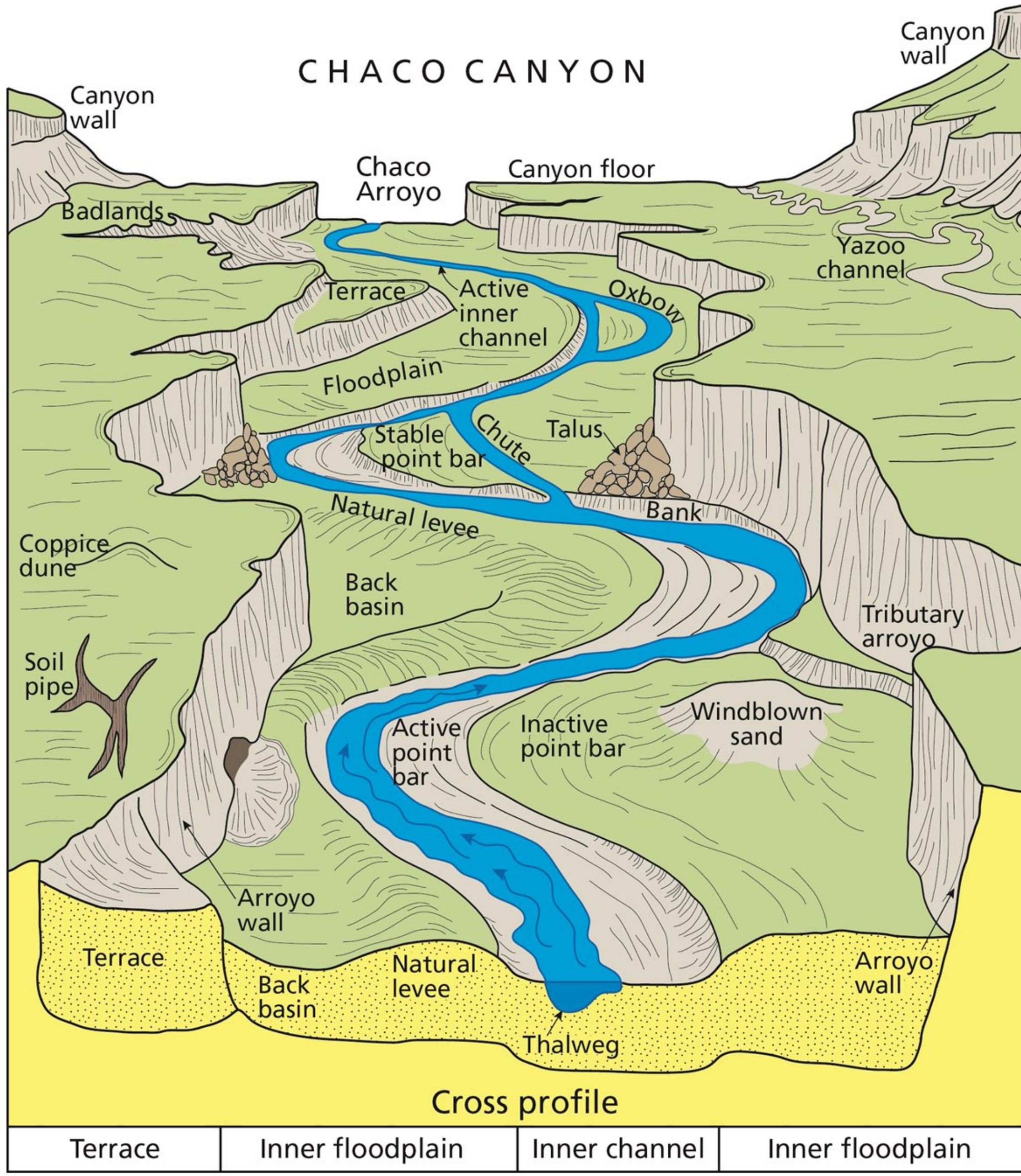
Fluvial deposition
Alluvial cone in miniature in the highlands of Ethiopia
Image Credit: Schütt, B. 2001

Depositional zone



floodplain

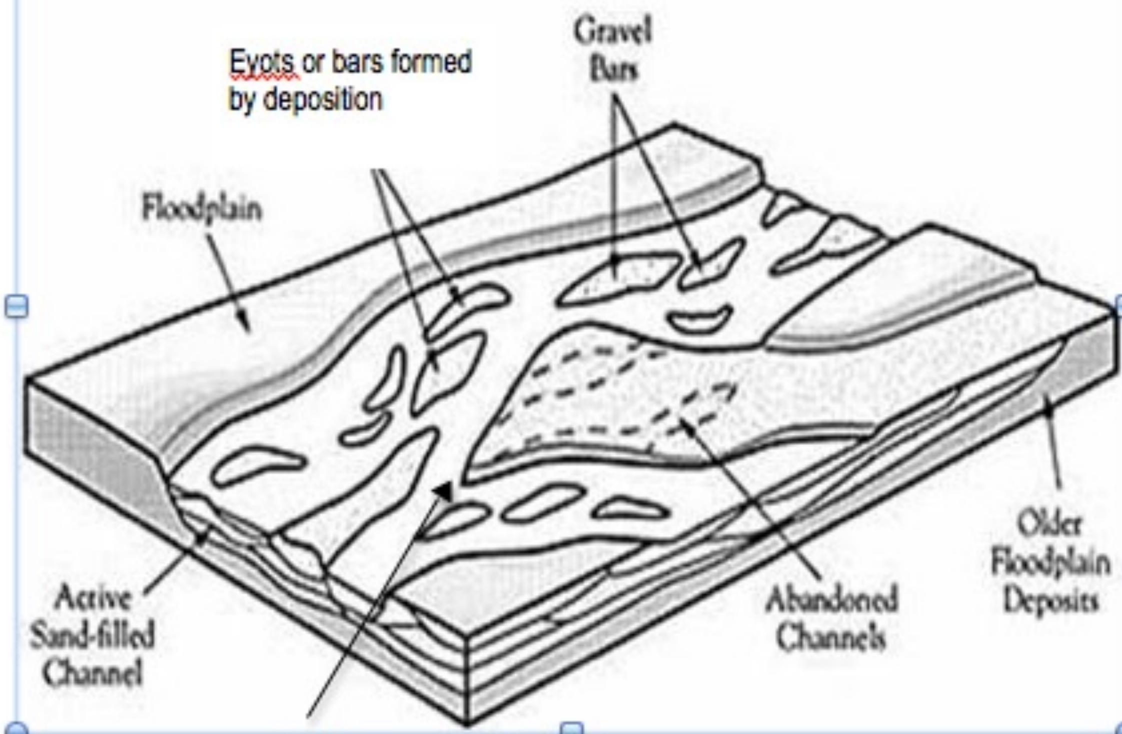
A floodplain is the relatively flat surface adjacent to the river or stream. During floods, when the stream overflows its banks, water flows over the floodplain and deposits sediment. Through fluvial processes, streams construct floodplains that accommodate their maximum flood capacity.



Braided channels

Braided channels can form nearly anywhere along the course of the river but are most commonly found in the upper course. Braided channels are common river regimes, which are characterised by significant fluctuations in discharge and resulting capacity to transport bedload.

They are common in Alpine rivers with significant snow melt as well as in dry/wet tropical climates that experience extreme rainfall events. Many arid and semi-arid regions have braided river channels.

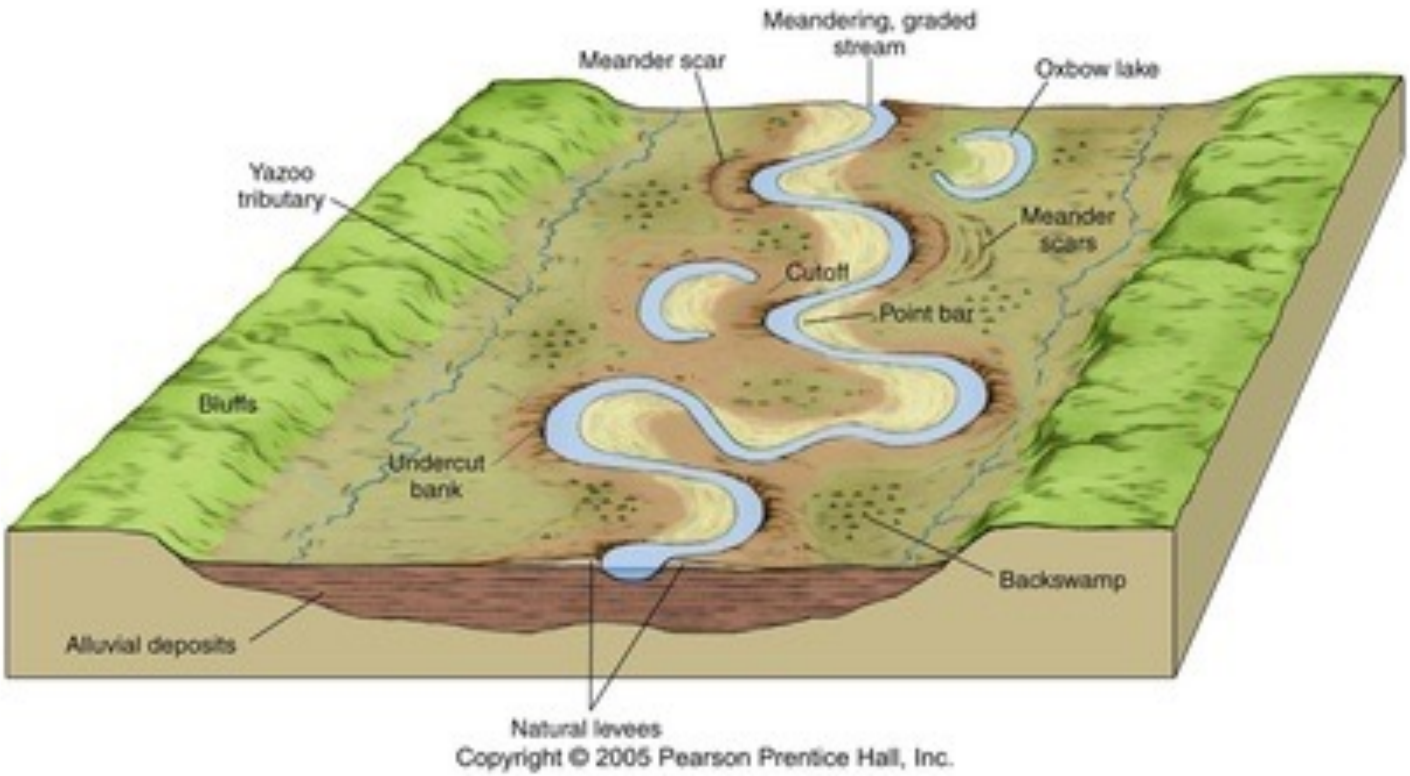


http://thebritishgeographer.weebly.com/

Meanders and floodplains

Rivers increase in discharge as they move downstream. This in turns creates a wider, deeper and more sinuous channel. Intermittently, the rivers discharge will exceed the capacity of the river channel and overflow the river banks. A river cuts out its floodplain as its channel migrates.

Meanders are sweeping bends in the lower course of the river. Meanders form through a combination of intrinsic factors (river's attempt to balance its energy, velocity, bedload and discharge) and extrinsic factors (channel gradient and roughness).



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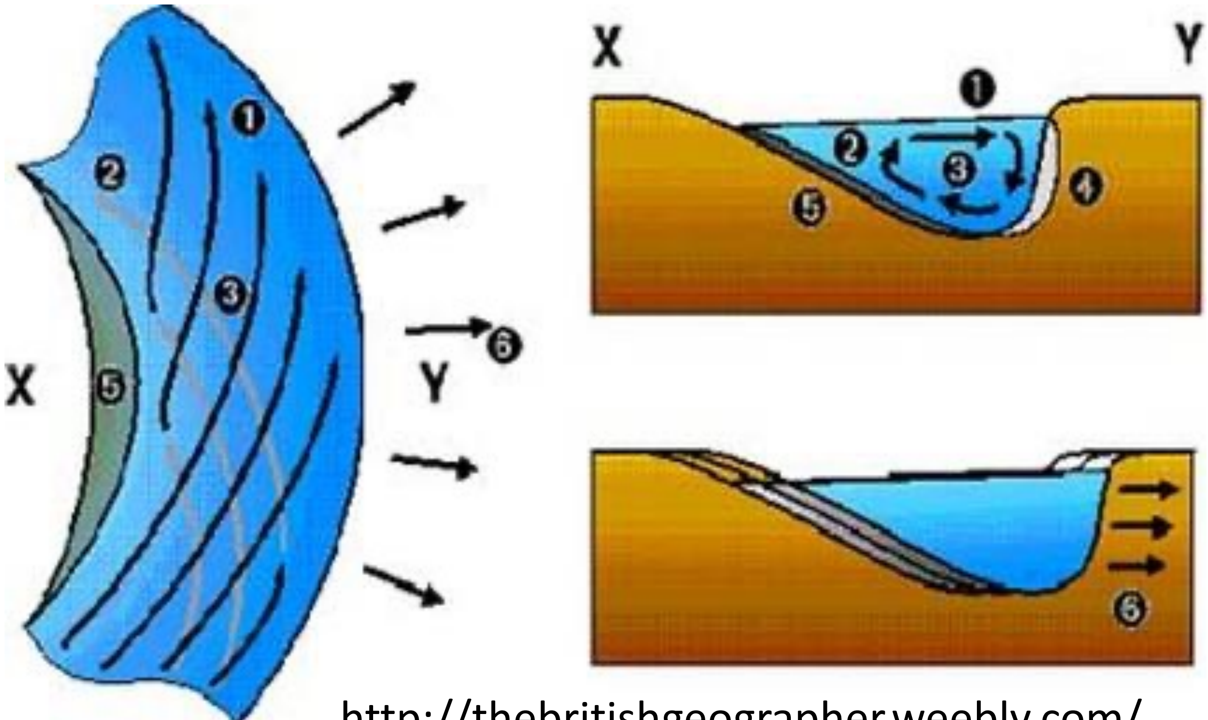
Helical flow

Higher velocity chutes within a stream tend to be driven to the outside of a meander. On the outside of the meander, the surface of the water has a tendency to be slightly higher because it has gained momentum and acceleration, in the same way as centrifugal force works. Here, the flow is forced down the outer bank which results in the scouring of the bank and bed. It returns to the surface toward the inside of the meander where flow is less turbulent. This flow across the channel is known as the secondary cell.

The helical flow continues to erode the outside of the bend and to deposits it on the inside. This continuous process cause meanders to migrate and contract at their neck (untill the river cuts directly through, forming a channel cut-off and incipient ox-bow).



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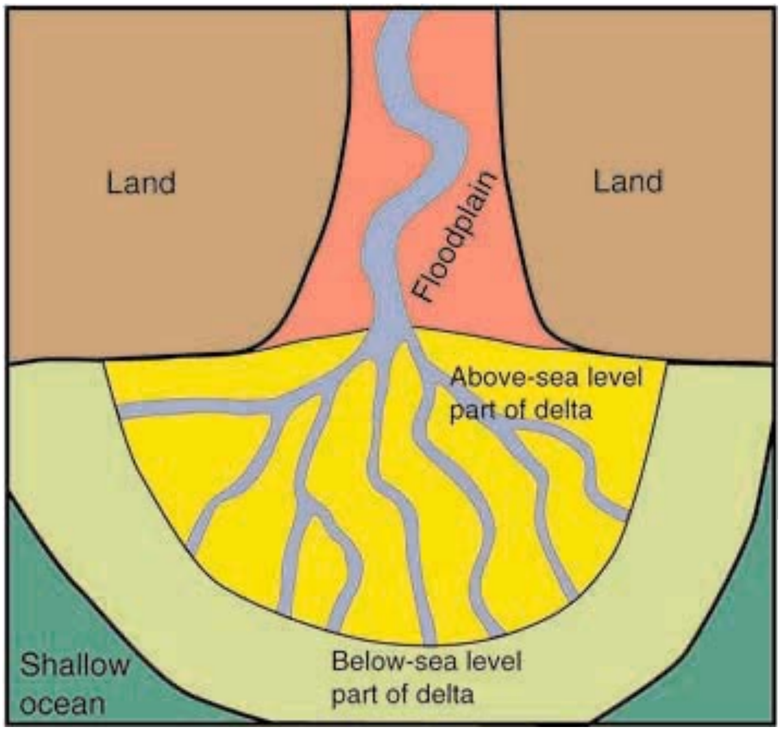
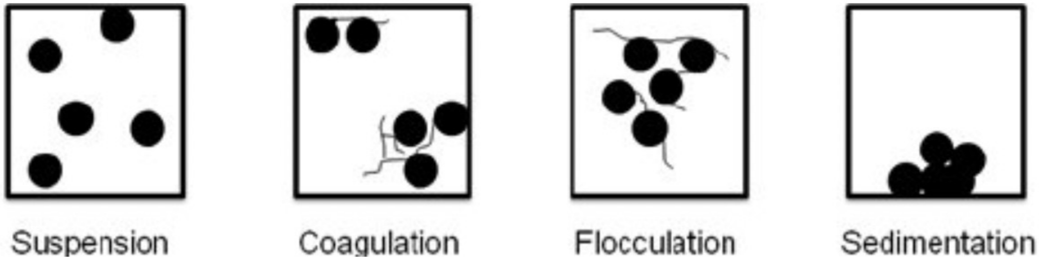
Deltas

At their mouth the river may form a delta. Deltas only form in areas where the amount of sediment supply exceeds the rates at which it is removed. The extent to which sediment is removed is an important factor therefore in determining the delta shape. When rivers with high capacity reach the sea they encounter opposing tidal and wave currents.

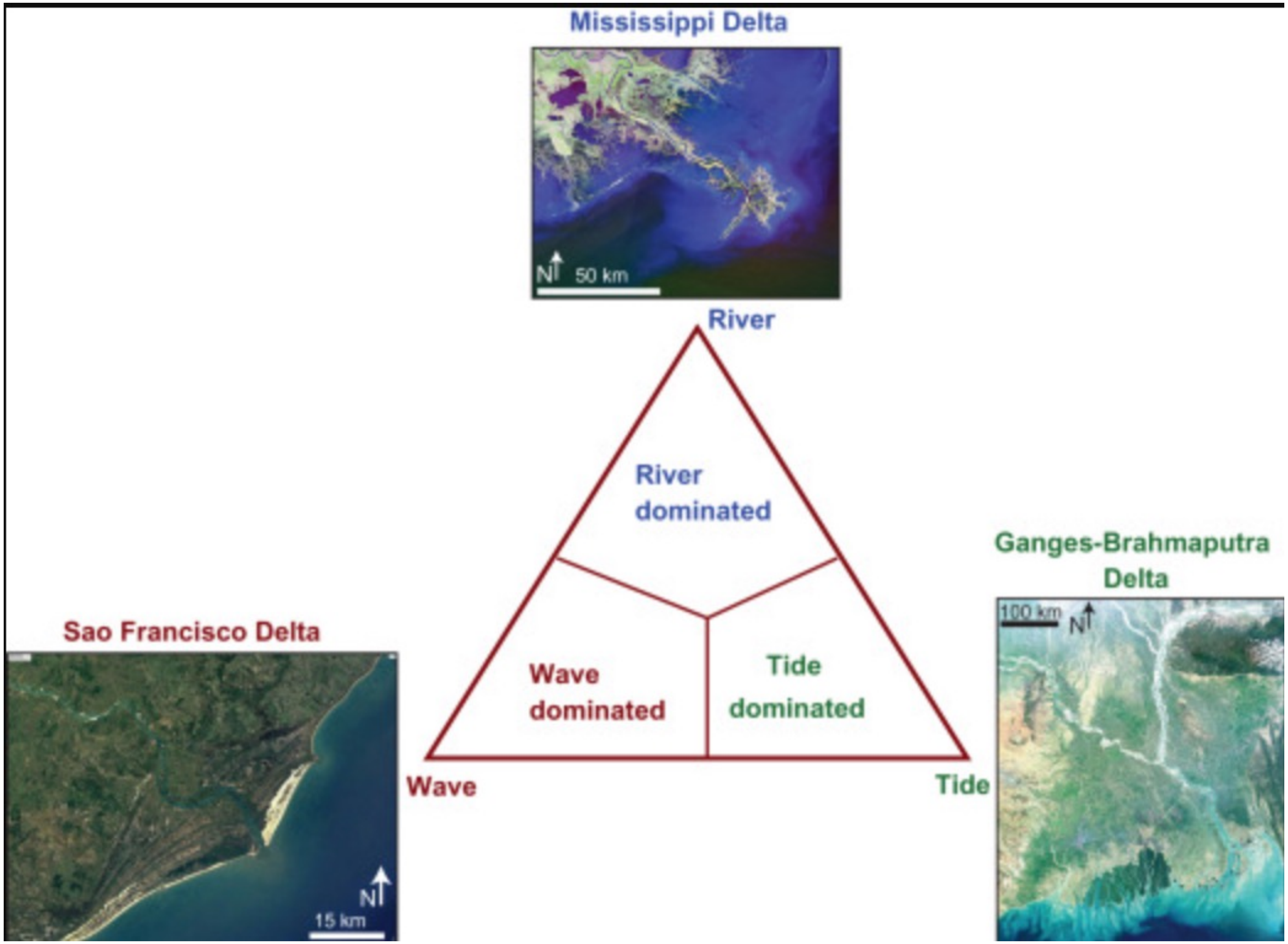


In the marine environment freshwater is also coming into contact with salt water, known as brackish water. At this interface, fine muds and clays transported in suspension coagulate with salt in a chemical reaction called **flocculation**. This process makes them heavier and they sink to the bottom. This process produces a varied composition of sediment in the Delta.



Three types of deltas

Galloway, W., (1975). Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional system. SEPM, Special Publication No. 31. 127-156.



Fluvially-Dominated Deltas

Fluvially-dominated deltas are primarily controlled by the water density difference between the inflowing river water and the standing water on the basin. Different flow types that determine the distribution of sediment and sedimentary structures formed in the delta are:

homopycnal flow, hyperpycnal flow, and hypopycnal flow. When investigating coastal areas with low tide and wave energy, the deltas in this situation can be **inertia-dominated, friction-dominated, or buoyancy-dominated.**

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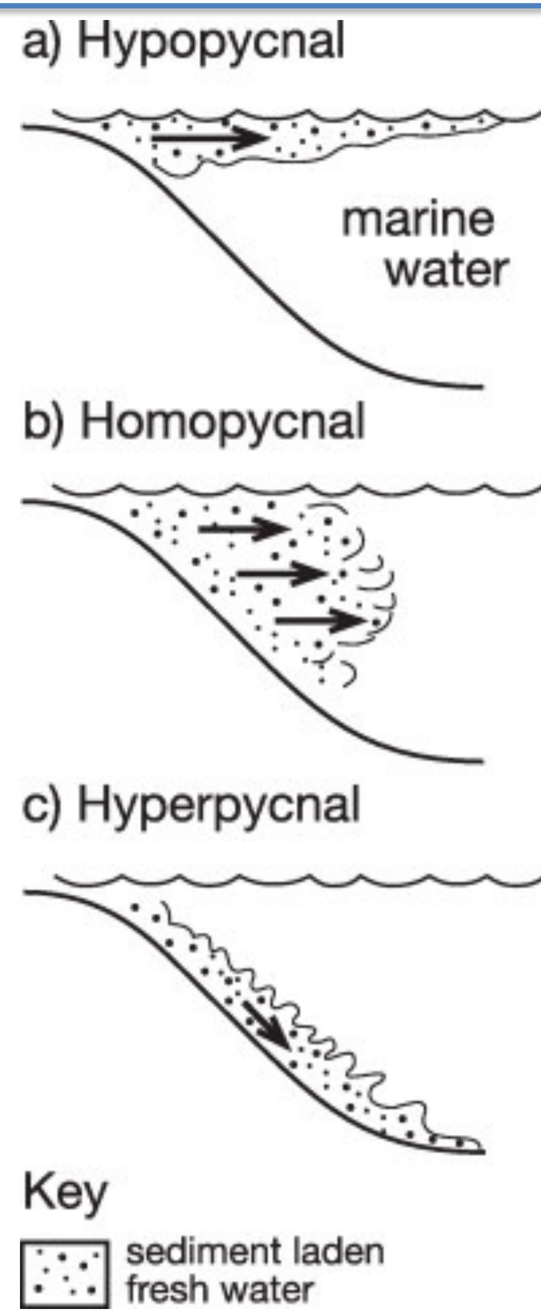
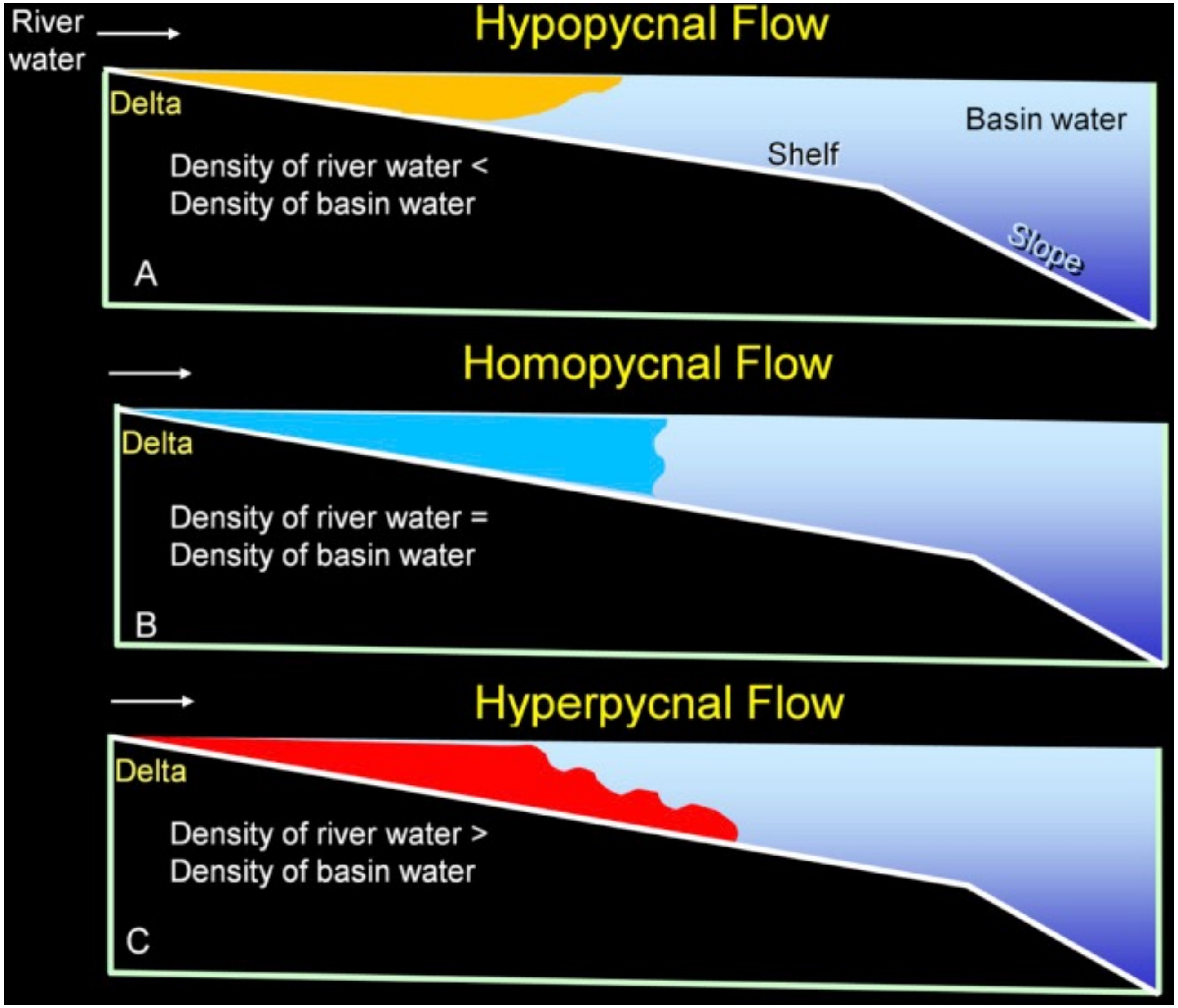
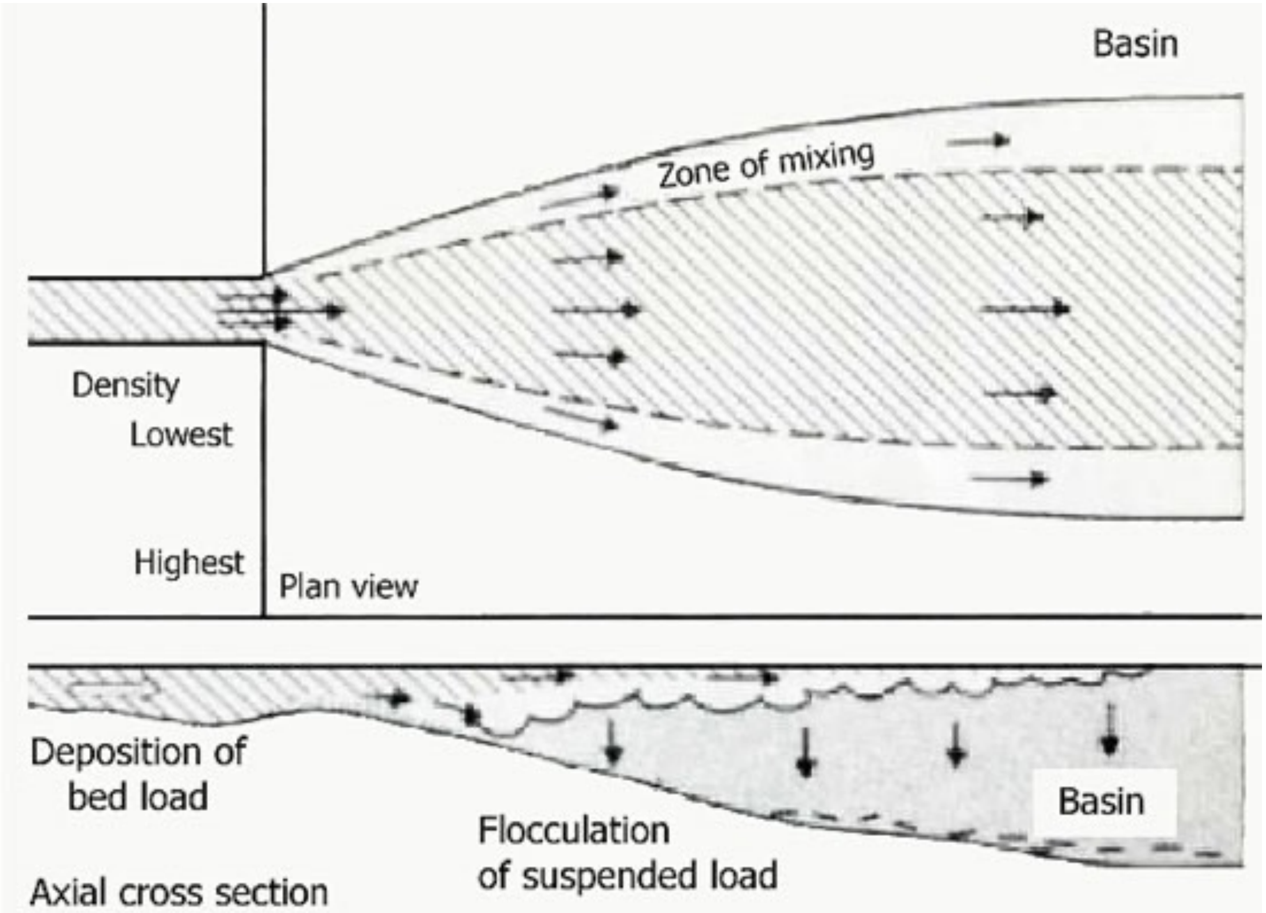


Three types of flows

Schematic diagrams showing three types of density variations in river water in deltaic environments. (Based on concepts of Bates (1953), from Shanmugam (2012): Elsevier Books. Handbook of Petroleum Exploration and Production, Volume 9



Hypopycnal flows



(Boggs, 1995)

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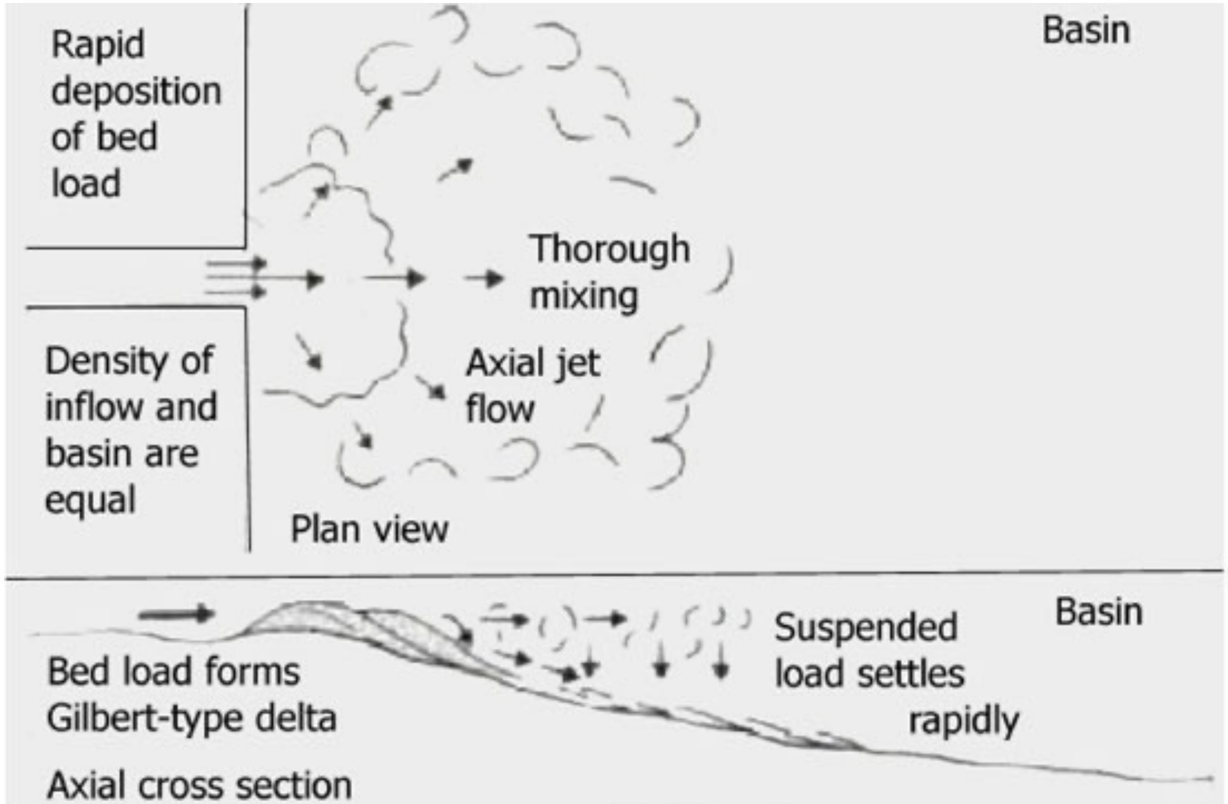
hypopycnal flow is associated with a lower river water density entering a higher density standing water density in the basin. Under these conditions, the river water will flow out over the standing water gradually depositing the suspended clay portion of the sediment load to the prodelta. The clay particles settle out of suspension through the process of **flocculation** (the clumping of clay particles together due to a positive-negative charge relationship created by the seawater).

Plumes (pennacchi)

A plume is defined as a fluid enriched in sediment (or ash, biological or chemical matter) that enters another fluid (e.g. a river entering in a basin)

Homopycnal flows



(Boggs, 1995)

homopycnal flow occurs when the density of the river water is equal to the density of the standing water in the basin. This type of flow is associated with rapid mixing throughout the general flow. There is also abrupt deposition of the sediments carried to the basin by the river as the two water sources meet.

Boggs Jr., Sam, Principles of Sedimentology and stratigraphy, Prentice Hall, New Jersey, 1995.

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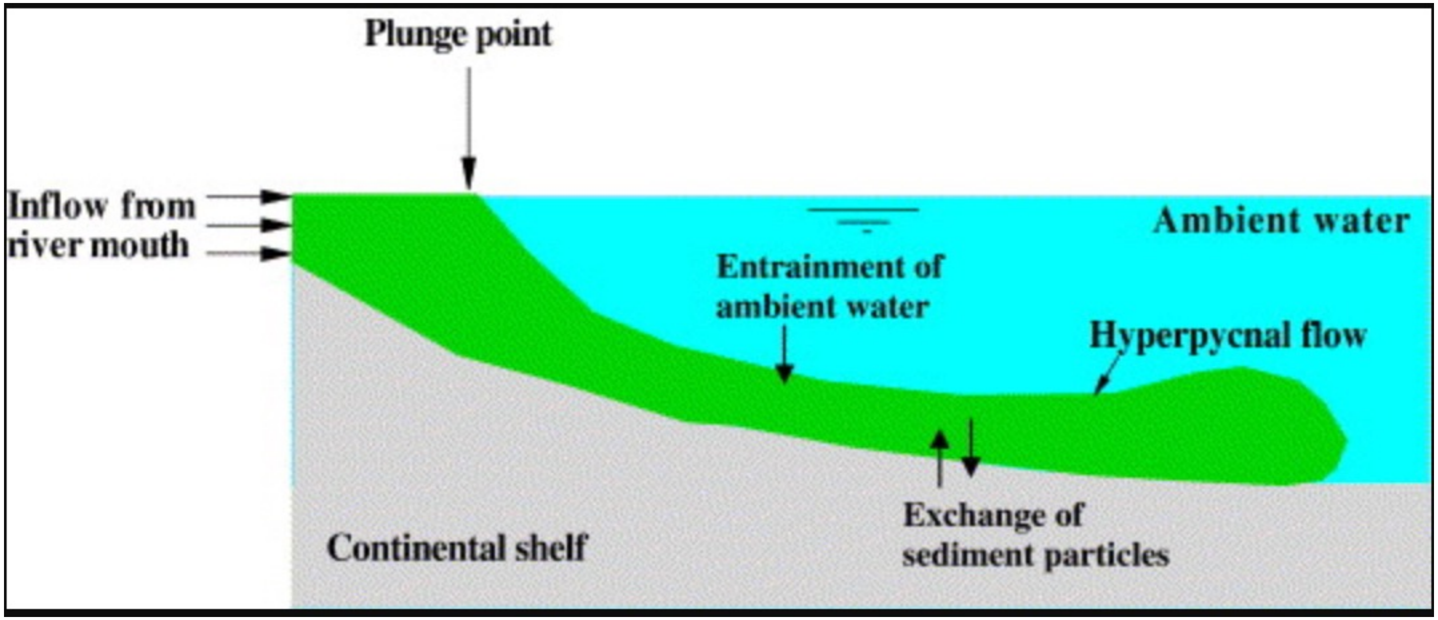
Hyperpycnal flows

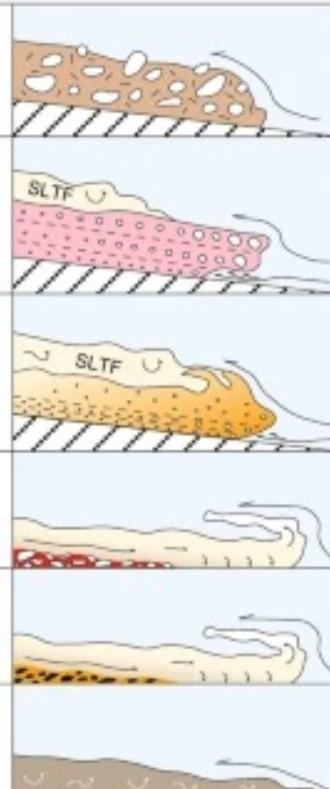


…versus **Sediment Gravity Flow** (definition: Sediment gravity flows are mixtures of water and sediment particles where the gravity acting on the sediment particles moves the fluid, in contrast to rivers, where the fluid moves the particles; synonyms: Density currents; Gravity currents; Mass flows; Sediment flows)

Can we label long lived hyperpycnal flows as a kind of sediment gravity flow?

Hyperpycnal flows

Types of hyperpycnal flows					Flow origin
Non-Newtonian (plastic)			Cohesive debris flows (CDF)		High-density short-lived flows entering the basin
Newtonian (Fluid flows)	Supercritical	Laminar	Hyperconcentrated flows (HCF)		- Alluvial fans - Small mountanious rivers - Flash floods
Newtonian (Fluid flows)	Supercritical	Turbulent	Concentrated (granular) flows (CF)		Require steep slopes to accelarate, incorporate ambient water, and transform into dilute turbulent flows
Newtonian (Fluid flows)	Subcritical	Turbulent	Sediment-laden turbulent flows (SLTF)	Pebbly	Low-density long-lived flows entering the basin
				Sandy	- Medium- to large-size rivers
				Muddy	No steep slopes are neccesary. Flow can travel for long distances since the flow is sustained by the river discharge



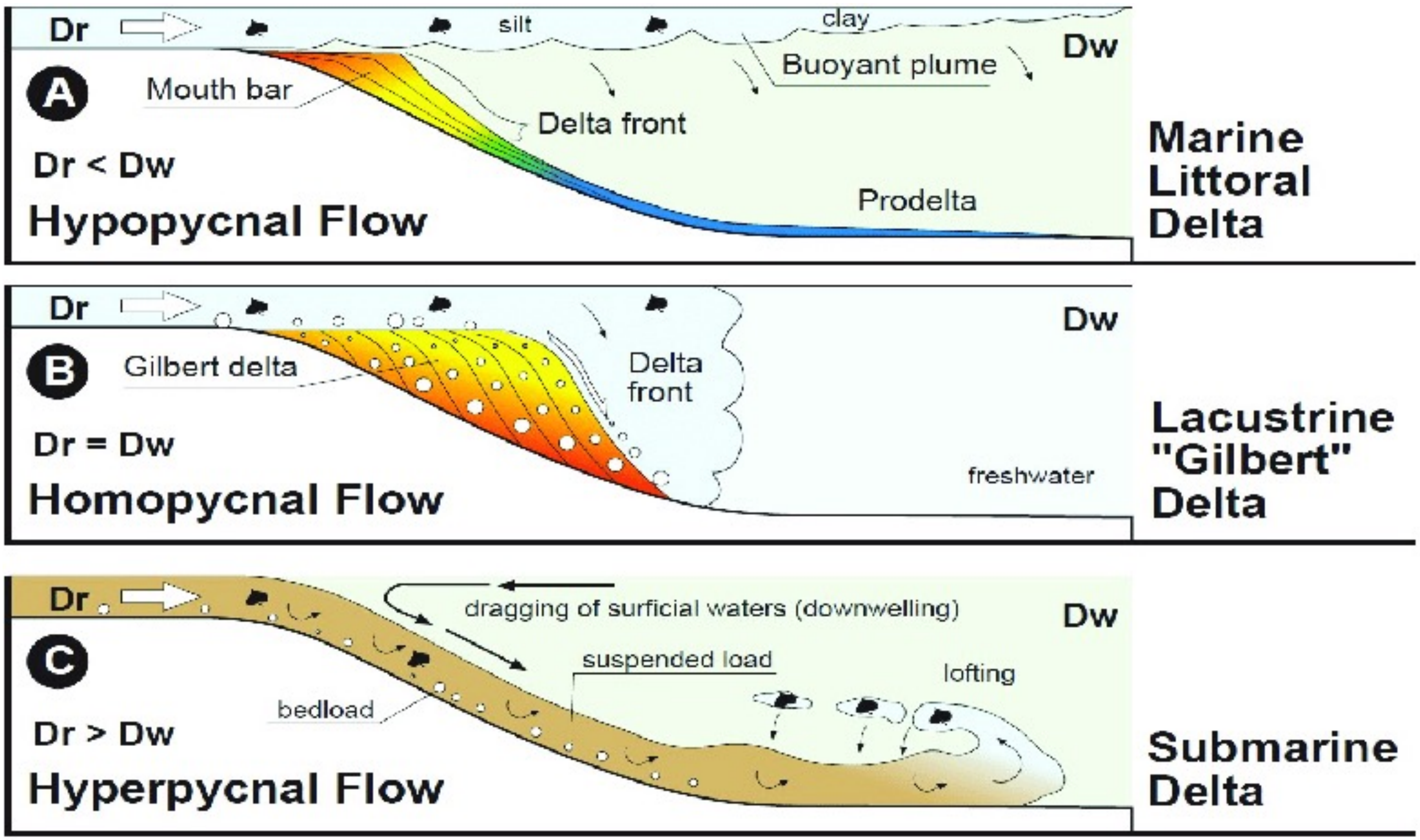
Zavala C. (2020). Hyperpycnal (over density) flows and deposits Journal of Palaeogeography 9, 17

Non-Newtonian fluid

Contrarily to e.g. water, non-Newtonian fluids do not follow Newton's law of viscosity, i.e., constant viscosity independent of stress (The viscosity of a fluid is a measure of its resistance to deformation at a given rate).

In non-Newtonian fluids, viscosity can change when under force to either more liquid or more solid. Ketchup, for example, becomes runnier when shaken and is thus a non-Newtonian fluid. Many salt solutions are non-Newtonian fluids, as are many commonly found substances such as toothpaste, starch suspensions, paint, blood, melted butter, and shampoo.

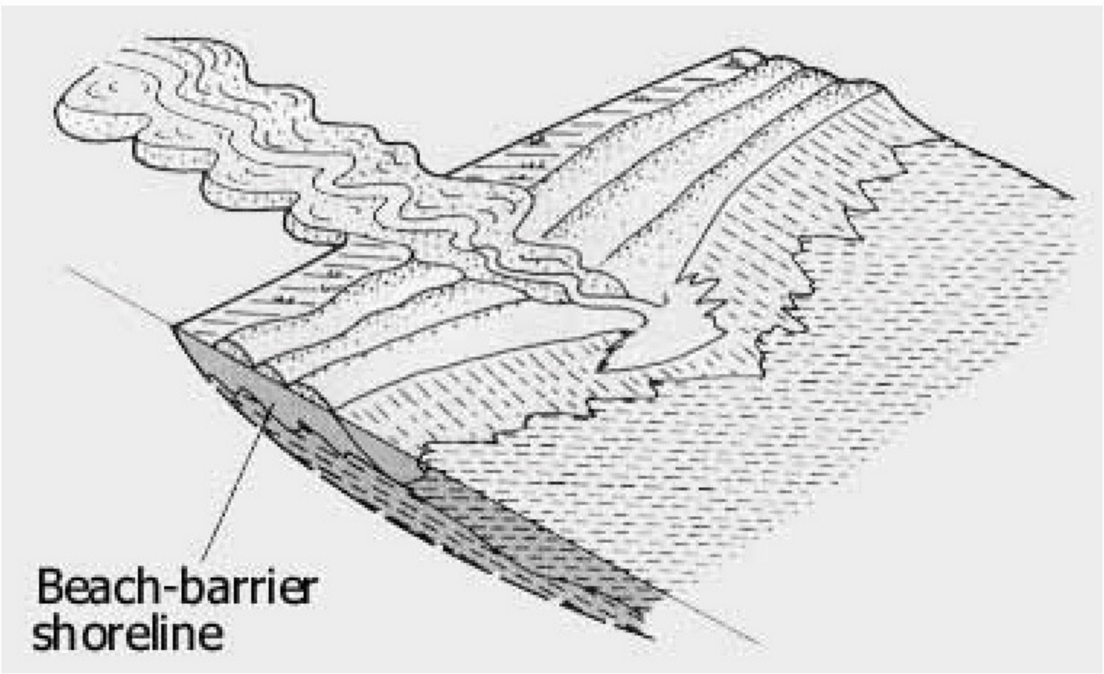
Three types of flows (summary)



Zavala C. (2020). Hyperpycnal (over density) flows and deposits Journal of Palaeogeography 9, 17

Wave-Dominated Deltas

An open ocean basin accepts more water input, with potential for greater wave energy, making deltas potentially wave-dominated. High wave interference causes conflicted or deflected river mouths.



(Carter, 1994)

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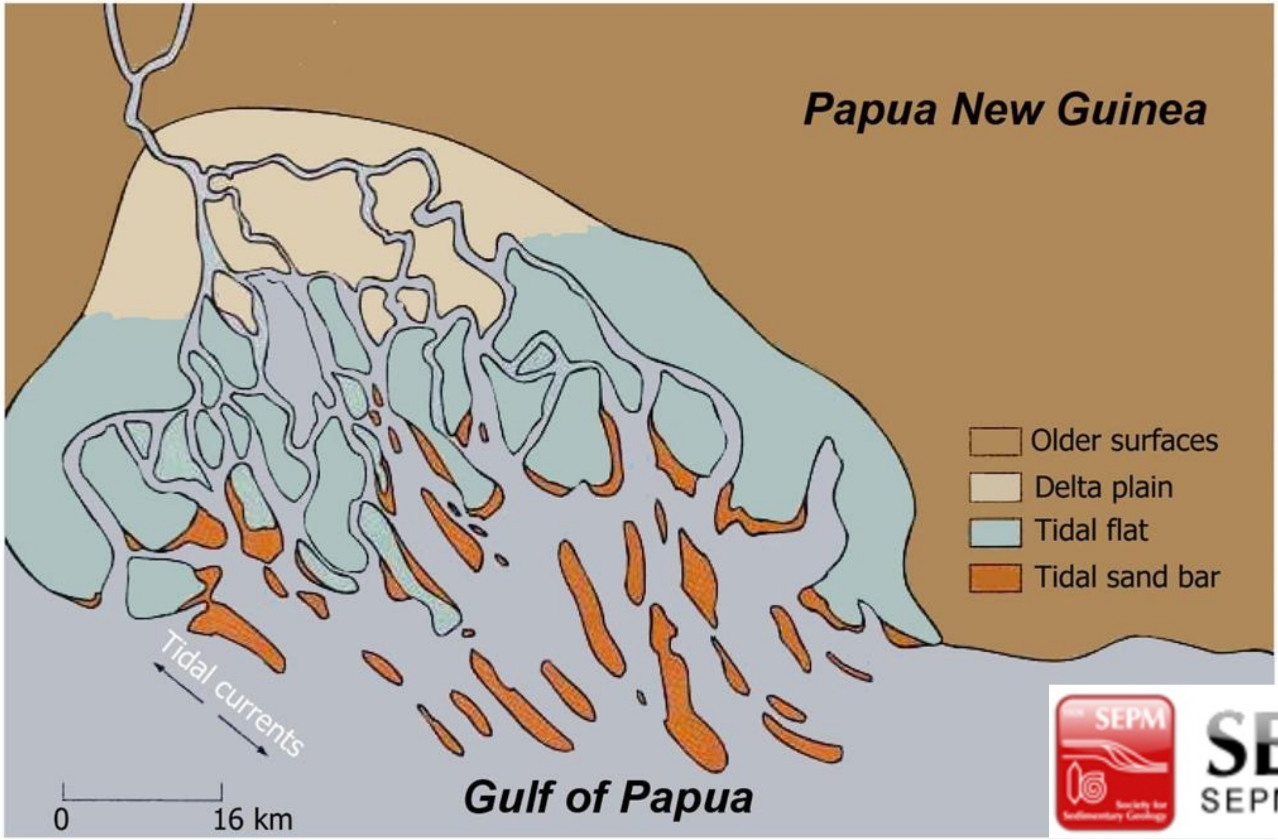
There is less influence from fluvial sources. In wave-dominated delta regions, breaking waves cause immediate mixing of fresh and salt water. Typically, the fresh water flow velocity decelerates rapidly. The wave action reworks the sediment delivered by the river and transports it along the coast.

Tide-Dominated Deltas

Deltas which undergo strong tidal interaction are classified as tide-dominated deltas. As sediment travels out of the delta into the sea, high tides and flood tides confine sediment on the delta plain and low tides carry sediment seaward. Tide-dominated deltas typically occur in locations of large tidal ranges or high tidal current speeds.



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Don Boyd, personal communication, 2007

Tide-dominated delta is that it has many linear structures parallel to the tidal flow and perpendicular to the shore.