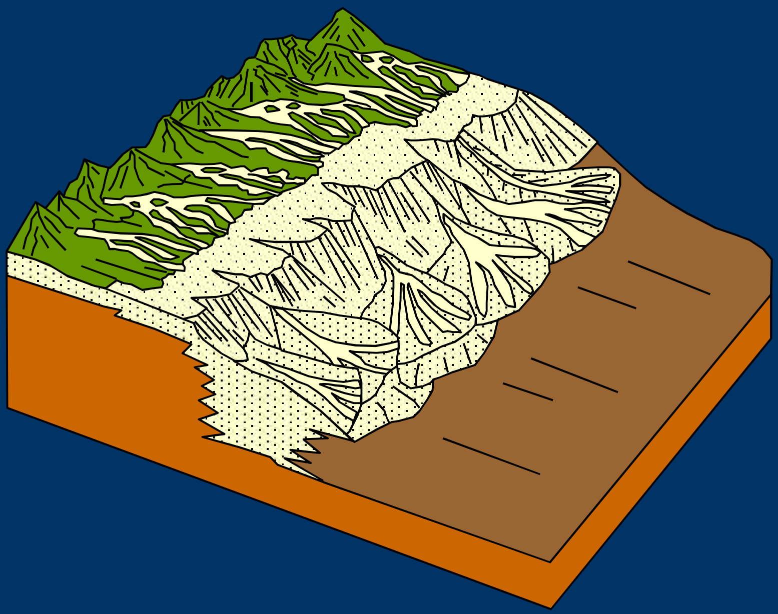
Deepwater Sediments

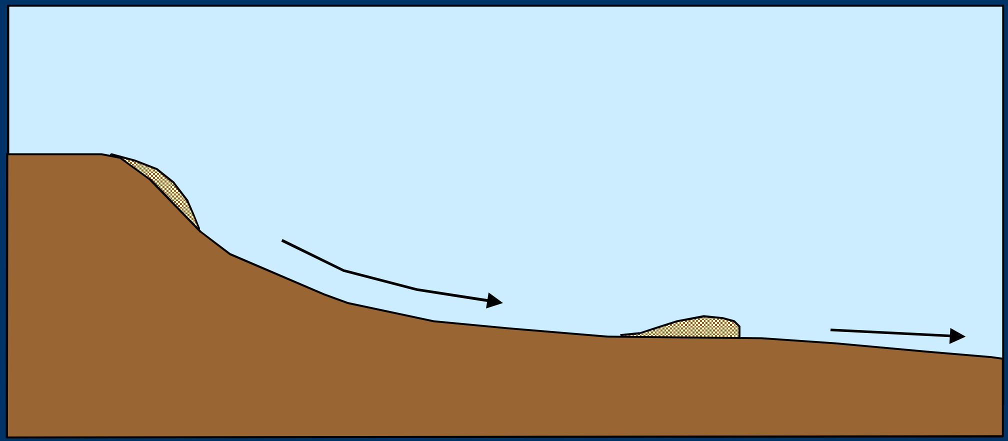
Sedimentary Processes

Reservoir quality sandstones are deposited in deep water environments by two main processes. They are the types of *Sediment Gravity Flows* known as *Turbidity Currents* and *Debris Flows*. As the name implies, sediment gravity flows are mixtures of fluid and sediment flowing down slope



Sediment gravity flows are often initiated by slumping or some other form of failure at the shelf edge or on the continental slope. This will happen more frequently whenever there is rapid deposition at the shelf edge, as at sea level lowstands

Slope failure mixes a large amount of sediment of varying grain size with water, resulting in a mass with a density that is greater than that of the surrounding fluid. Gravity causes the mass to move downslope and the density difference keeps it on the water bottom. Flow size varies with the amount of sediment in the slope failure

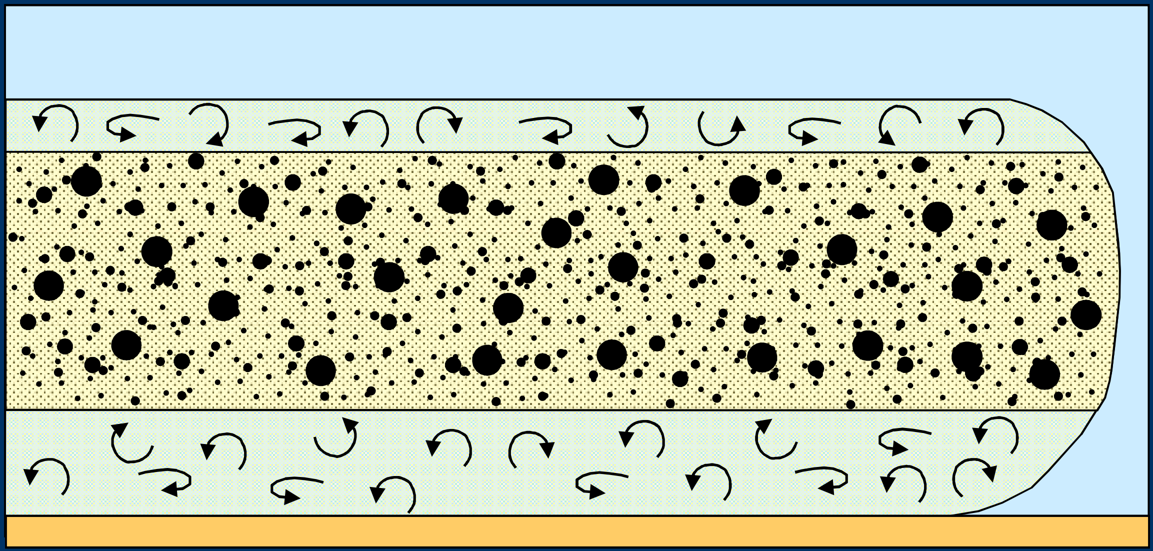


(after Mulder *et al*. 1997)

Debris flows can transport large amounts of very coarse sediment by a mechanism that is not well understood

When a fluid with a large amount of clay particles in suspension is strongly sheared, it develops an internal strength that allows it to carry large clasts

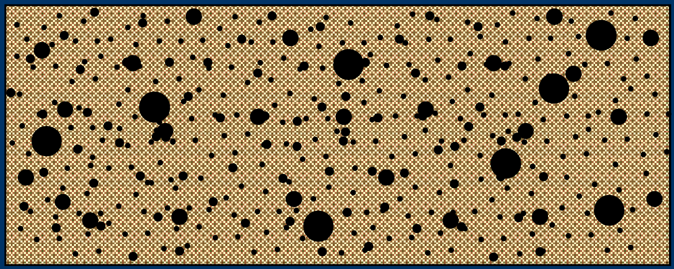
The clasts are suspended in a clay or sand matrix that forms a rigid plug in the middle of the flow. There is turbulent mixing of fluids above and below the plug and the debris flow rides the lower turbulent layer



(after Middleton and Hampton 1973)

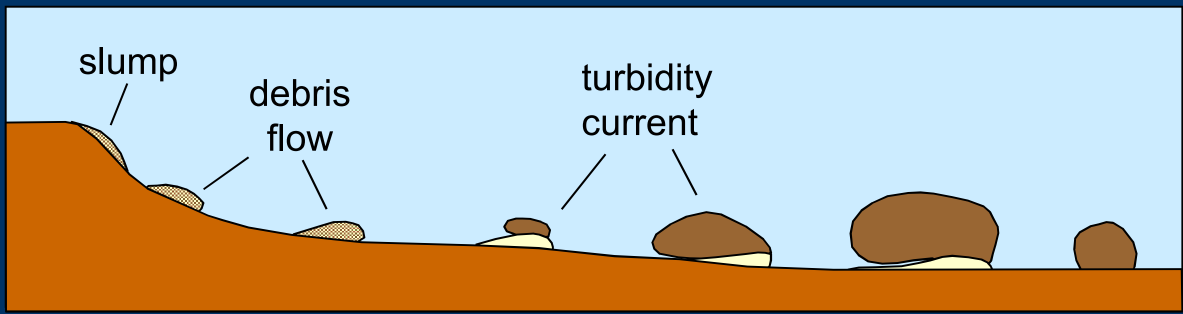
Steep slopes are required to generate the shear necessary to maintain the debris flows. When the slope decreases below a threshold value, the debris flow collapses and the plug is deposited very rapidly

The product is a *Matrix-Supported Conglomerate* where individual clasts are not in contact with each other and there is no grain fabric



The requirement for strong shearing causes debris flows to be deposited close to the base of a slope

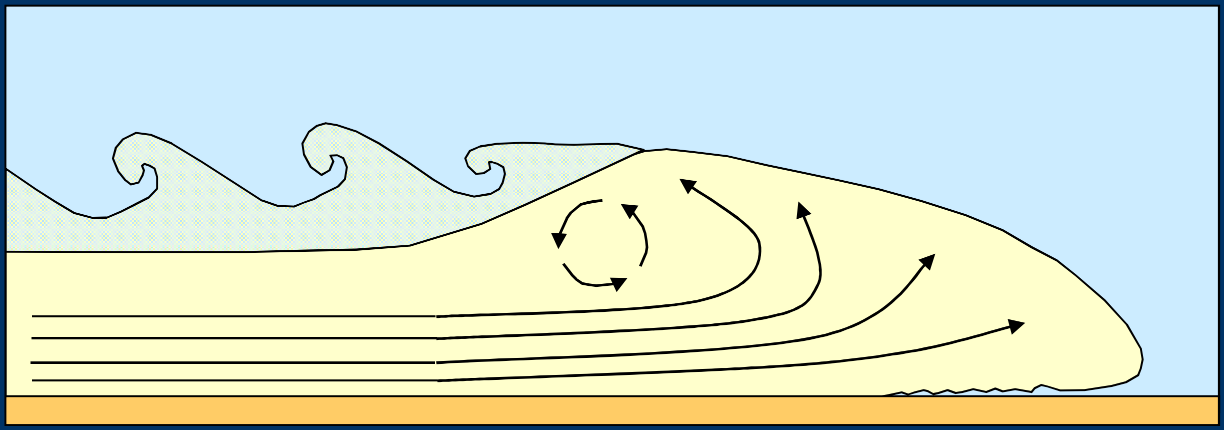
Debris flow collapse often will generate a turbidity current that continues down the low gradient slope and eventually dissipates on the basin floor



(after Mulder *et al*. 1997)

Turbidity currents are the most important process for transporting sand to the deep sea; their deposits are called *Turbidites*.

The flow properties and transport mechanisms in a turbidity current have many similarities with flow in a river or tidal channel but there are some very important differences



(after Middleton and Hampton 1973, and Simpson 1987)

Flow velocity depends on the density difference between the flow and the surrounding fluid, plus there is significant friction at the top of the flow as well as at the bottom. The Chezy equation for velocity becomes $U = \sqrt{8g' d \sin\alpha / f_o + f_i}$

where f_o and f_i are the friction factors at the bottom and top of the flow respectively and g' is the gravitational constant adjusted for density by $g' = g \times \Delta\rho / (\rho + \Delta\rho)$

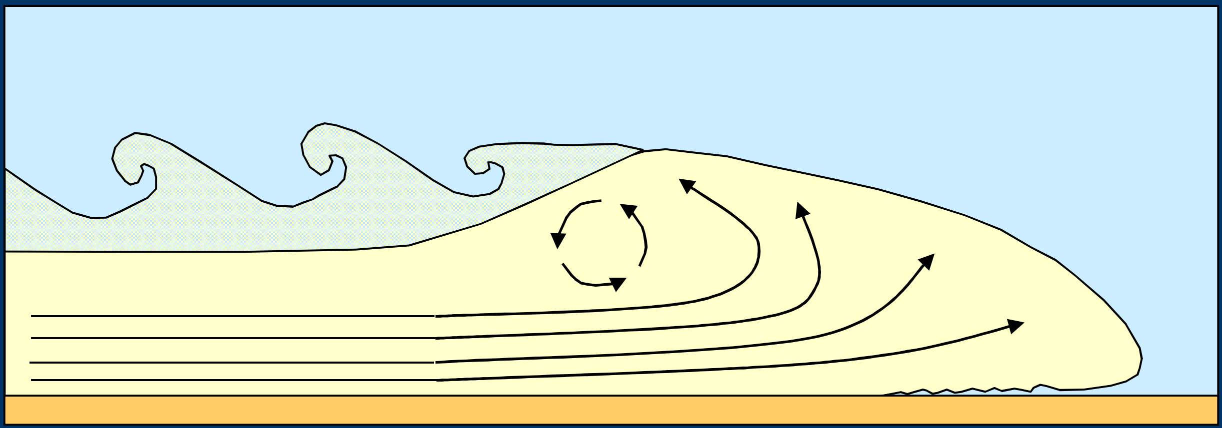
where $\rho + \Delta\rho$ is the density of the flow

Froude number also has to be adjusted for density in the same way. The equation becomes $Fr' = U/\sqrt{g' d}$

which is called the densiometric Froude number

The density difference controls the gravity component of motion. As flow density increases, so does velocity. Velocities can be high; up to 20 m per second has been documented from submarine cable breaks. This means that upper flow regime conditions can develop.

Friction at the upper surface causes turbulence and fluid mixing, both of which increase as slope increases



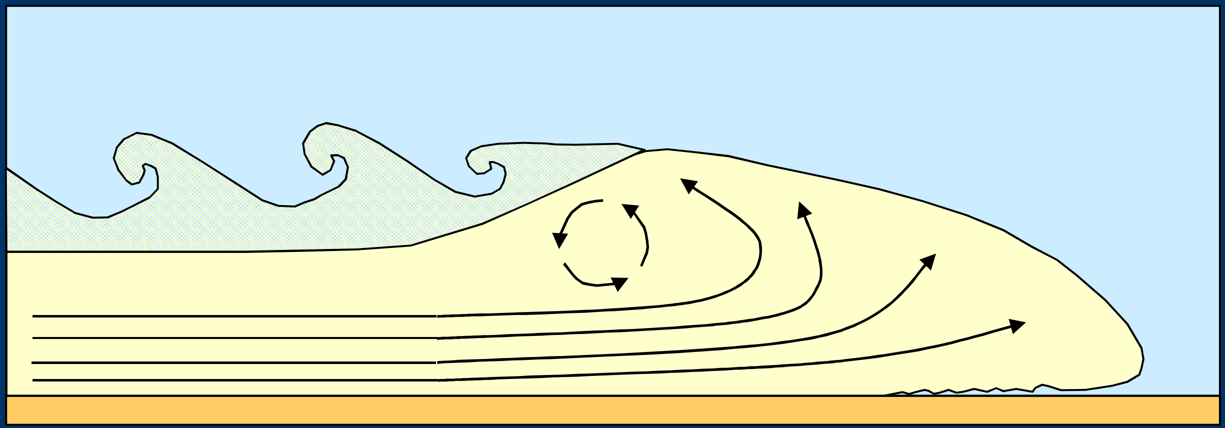
(after Middleton and Hampton 1973, and Simpson 1987)

Turbidity currents must displace water as they move downslope. The frictional flow resistance caused by the displacement creates a well-defined head that is much thicker than the main part of the flow

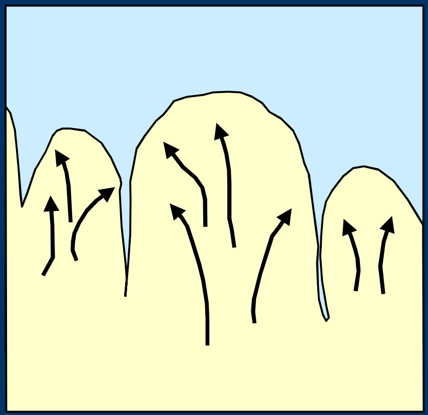
Turbulence is very high in the head. It is the area of highest energy and is often erosive. In three dimensions, it is lobate

Bottom shear stress continually decreases behind the head because the flow gradually becomes thinner

Once deposition begins at any point, it continues until the entire flow has passed



(after Middleton and Hampton 1973, and Simpson 1987)

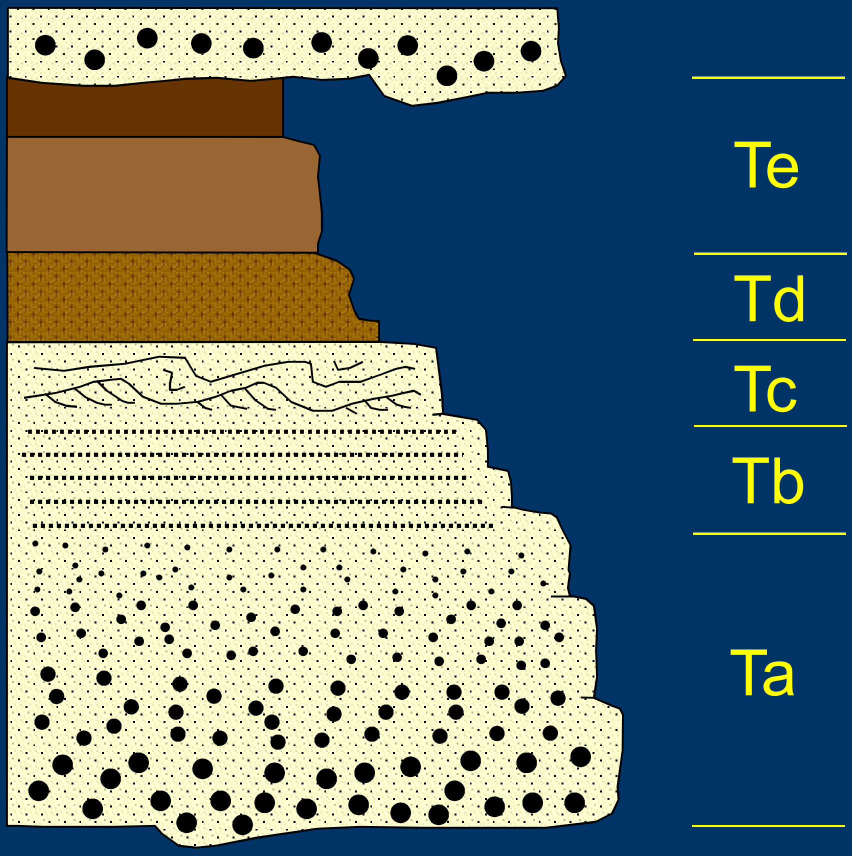


(after Kneller and Buckee 2000)

This raises a fundamental difference between sediment gravity flows and surface currents. Surface currents transport sediment with them while sediment is part of a sediment gravity flow.

As deposition occurs, flow density and velocity decrease continually and the flow eventually dissipates. This also means that sediment is continually and rapidly added to the bed during deposition

Continually decreasing velocity results in a deposit that indicates progressively lower energy upward with respect to grain size and sedimentary structures

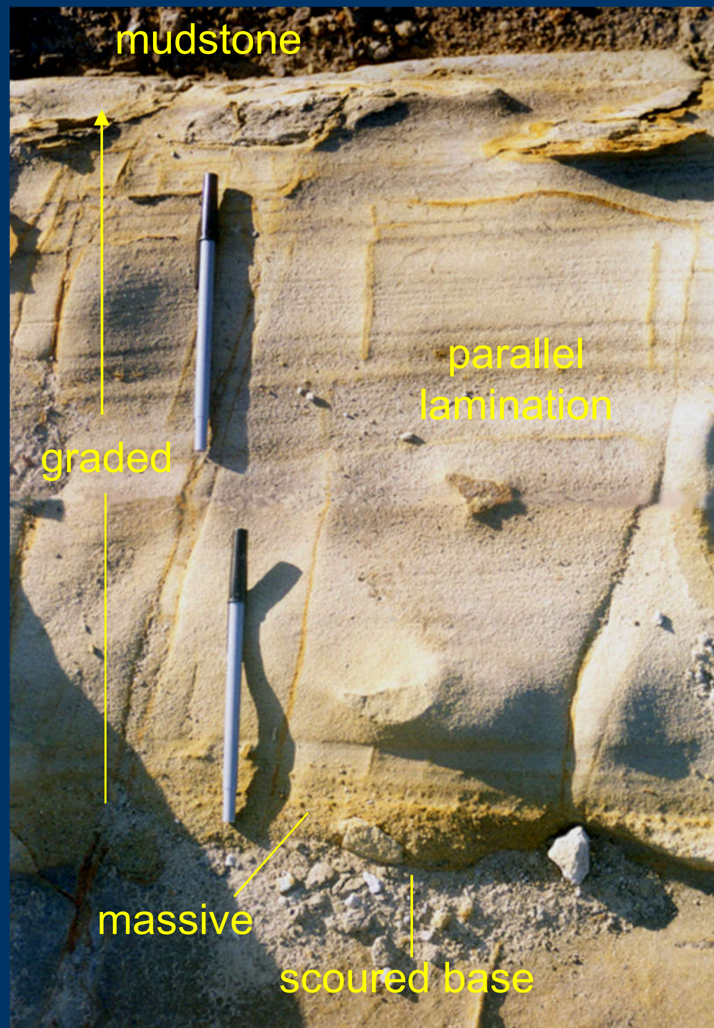


(after Bouma 1962)

This forms the basis of the *Bouma Sequence* that describes the product of one turbidity current

An ideal Bouma sequence has five subdivisions, each with a different sedimentary character, and designated by the nomenclature Ta – Te

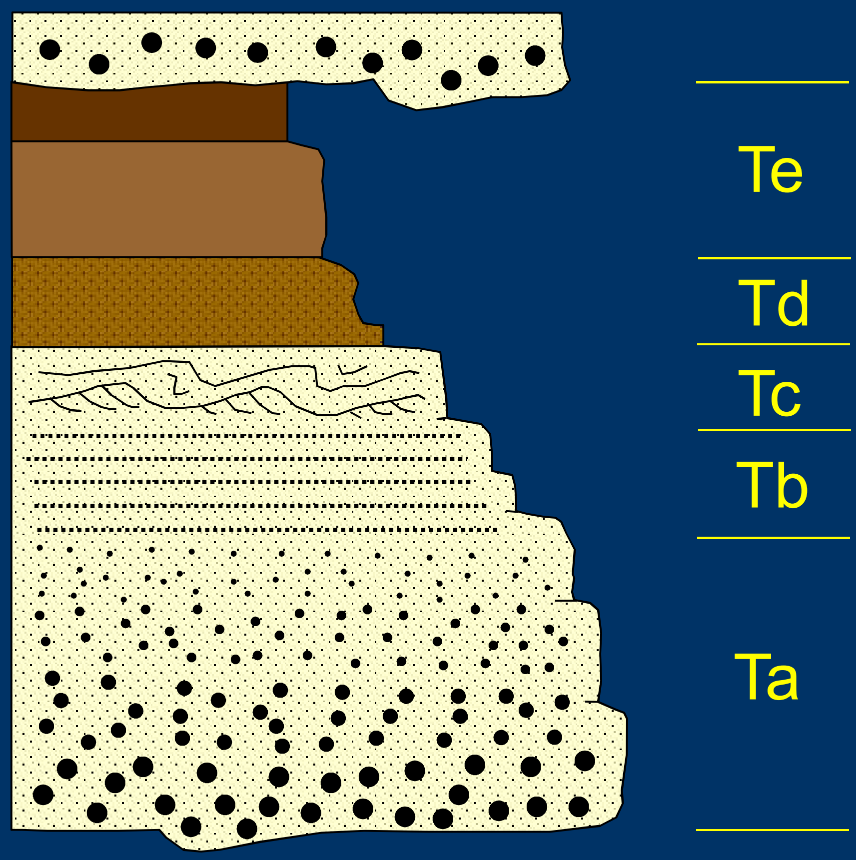
The basal unit (Ta) is the coarsest. It has an erosional base, often with sole marks, and is structureless but normally graded. It passes gradationally into parallel-laminated sand (Tb)


mudstone
parallel
lamination
graded
massive
scoured base

Te

Tb

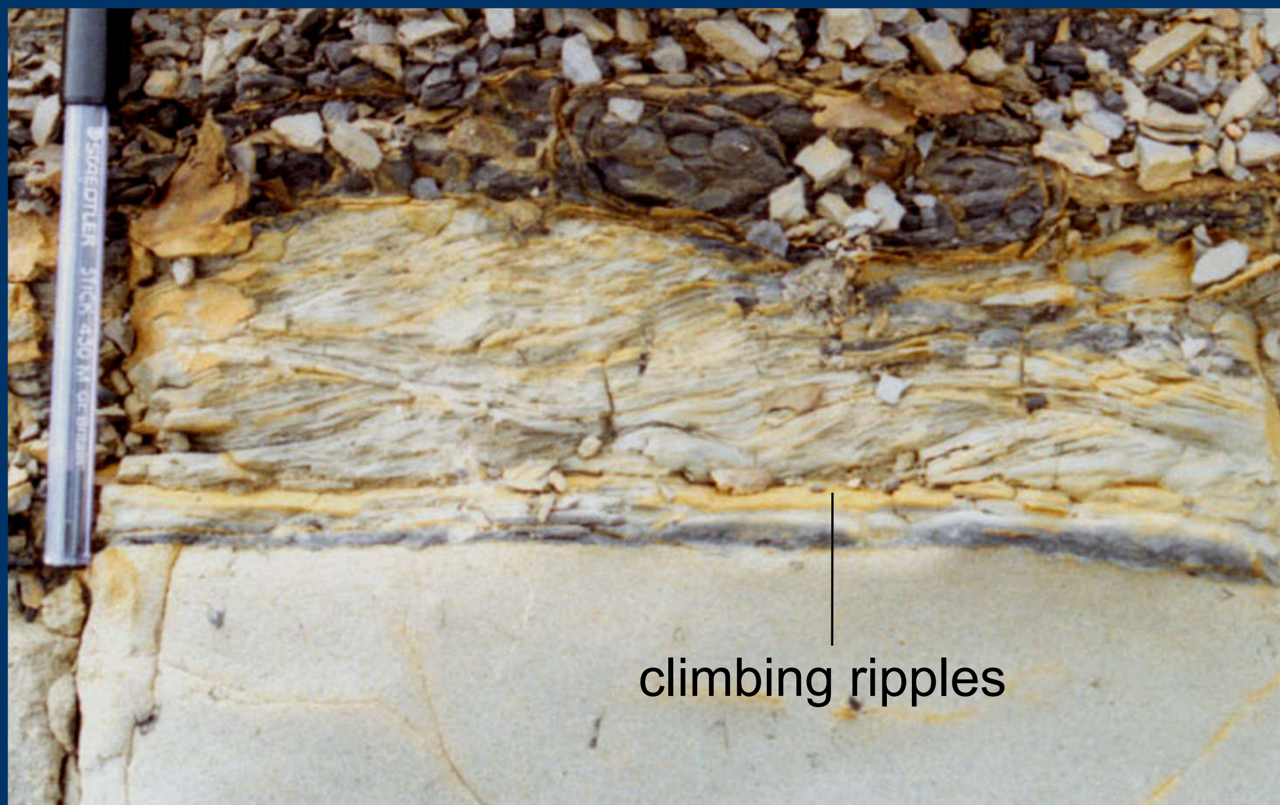
Ta



(after Bouma 1962)

Rippled and/or convoluted sand comprise the overlying Tc unit; rapid sedimentation often forms climbing ripples in this interval. Parallel-laminated silt and mud form the next unit (Td) and the top layer (Te) is mud partly from the turbidity current and partly from hemipelagic deposition

Complete Bouma sequences are rarely found in the sedimentary record. Most turbidites consist of partial sequences with some of the units missing

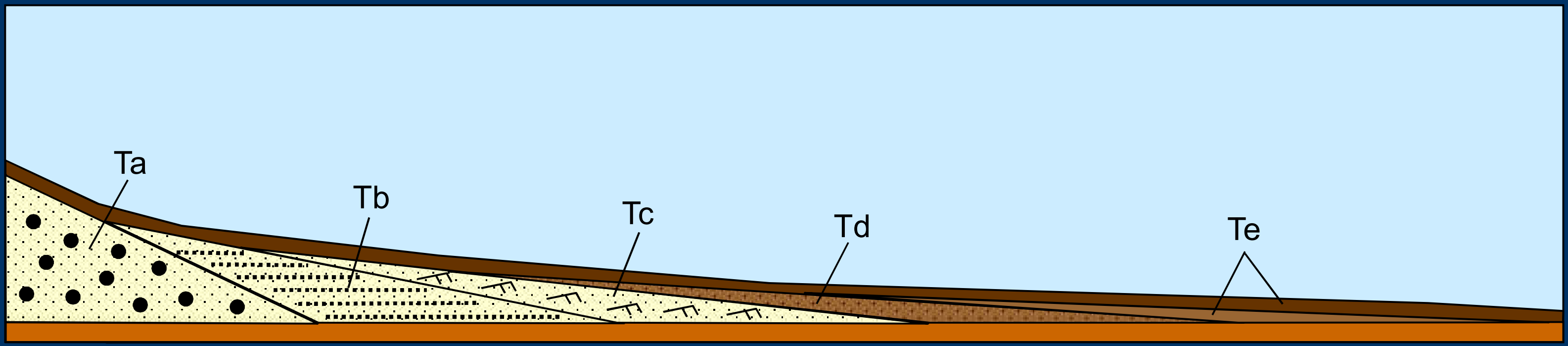

climbing ripples


convolute bedding

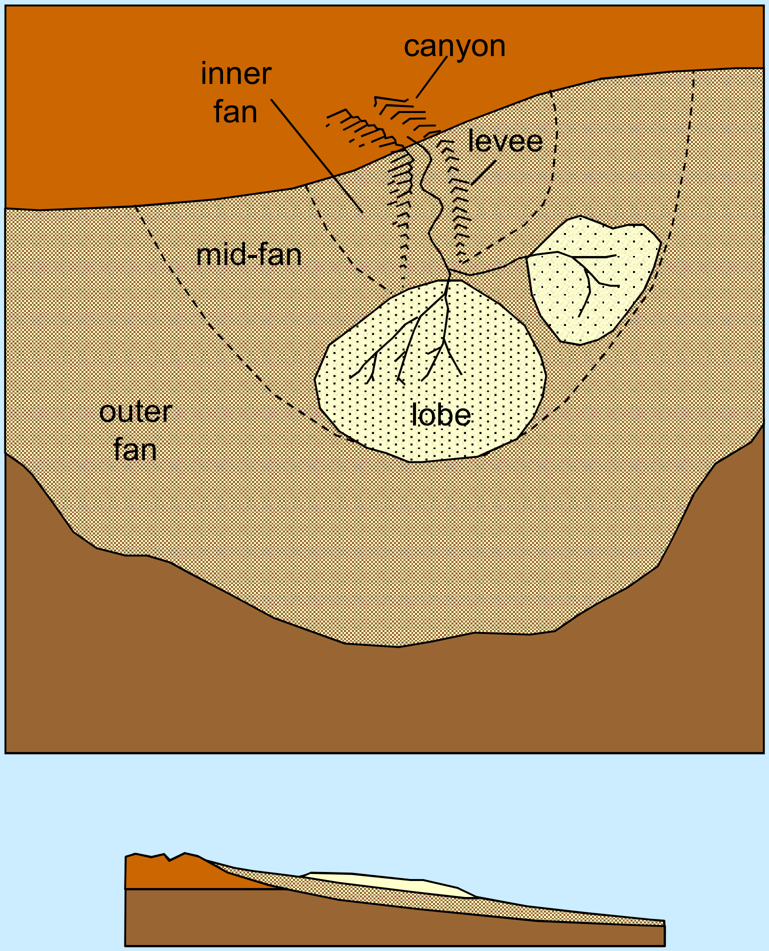
This is because the highest energy units are lost successively as the turbidity current travels basinward

Ta sediment is deposited first laterally as well as vertically, followed in order by Tb, Tc, Td and the turbidity current portion of Te as the flow wanes

The concept of *Proximal* and *Distal* turbidites as an indication of relative distance from the slope comes from observing beds with mostly higher energy units (proximal) as opposed to beds with exclusively low energy units



(after Allen 1985)

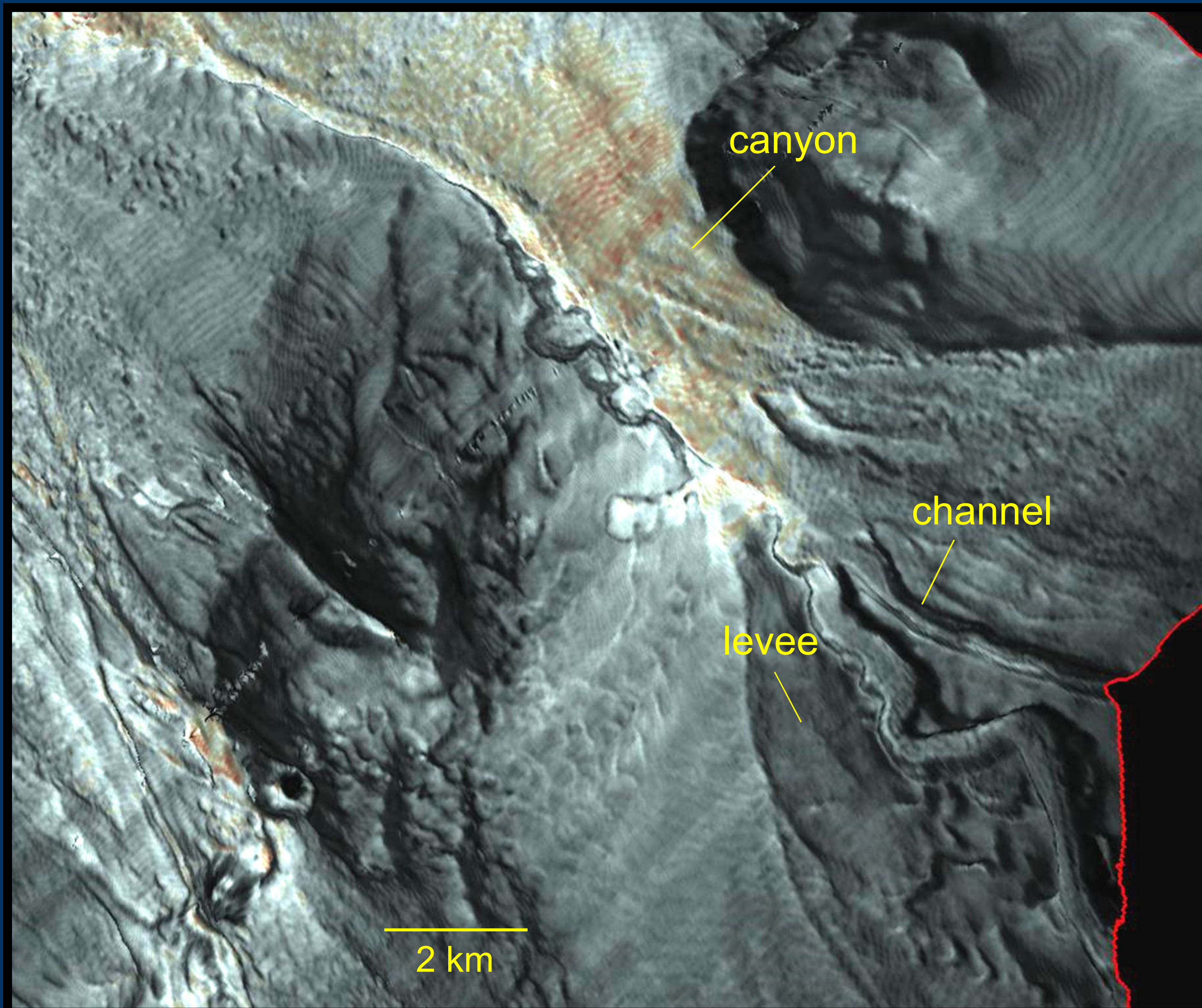


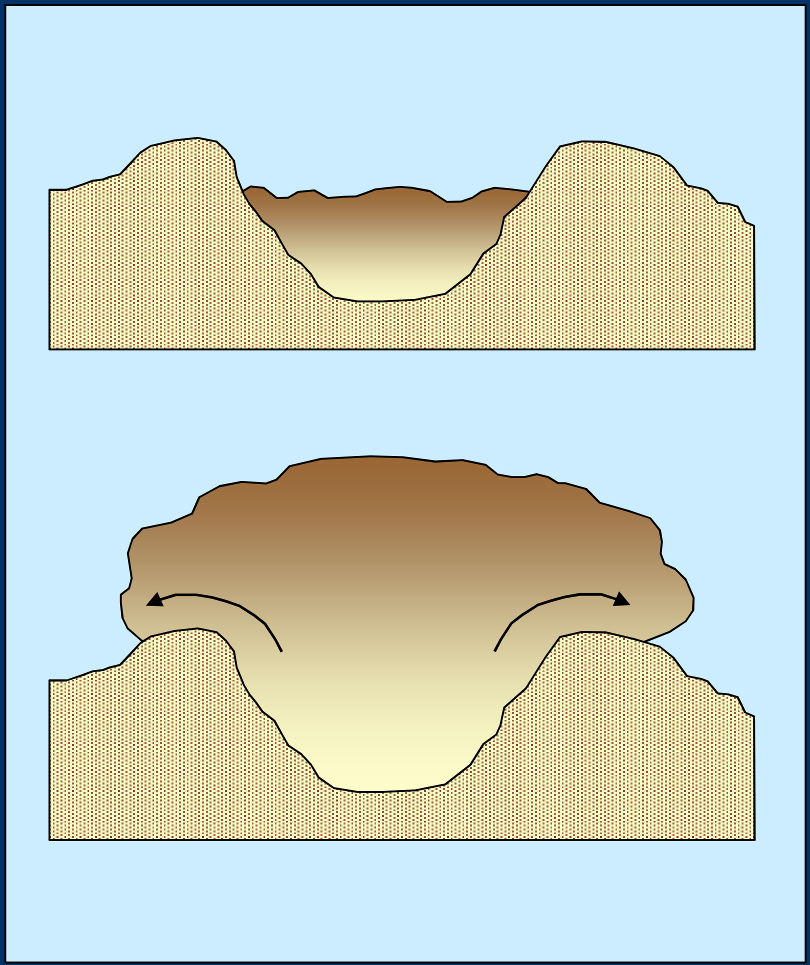
(after Normark 1978)

Turbidity currents usually flow downslope within a canyon which creates a point source for deposition

Turbidite deposition begins at the base of the slope and extends onto the adjacent basin floor

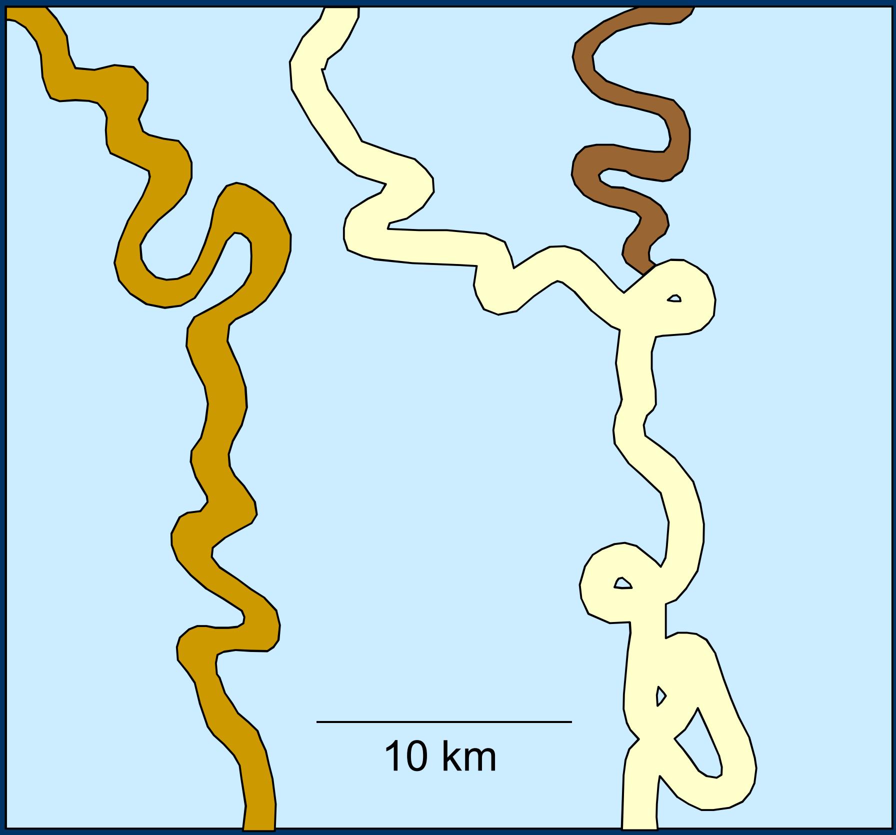
The deposits of successive flows form a *Submarine Fan* that progrades across the basin floor


canyon
channel
levee
2 km



Turbidity currents are traveling at high velocity when they exit a submarine canyon so they erode a large channel into the most proximal part of the submarine fan

Most flows are confined within the channel but some are large and spill over the channel margins, building large levees and depositing fine-grained overbank sediment

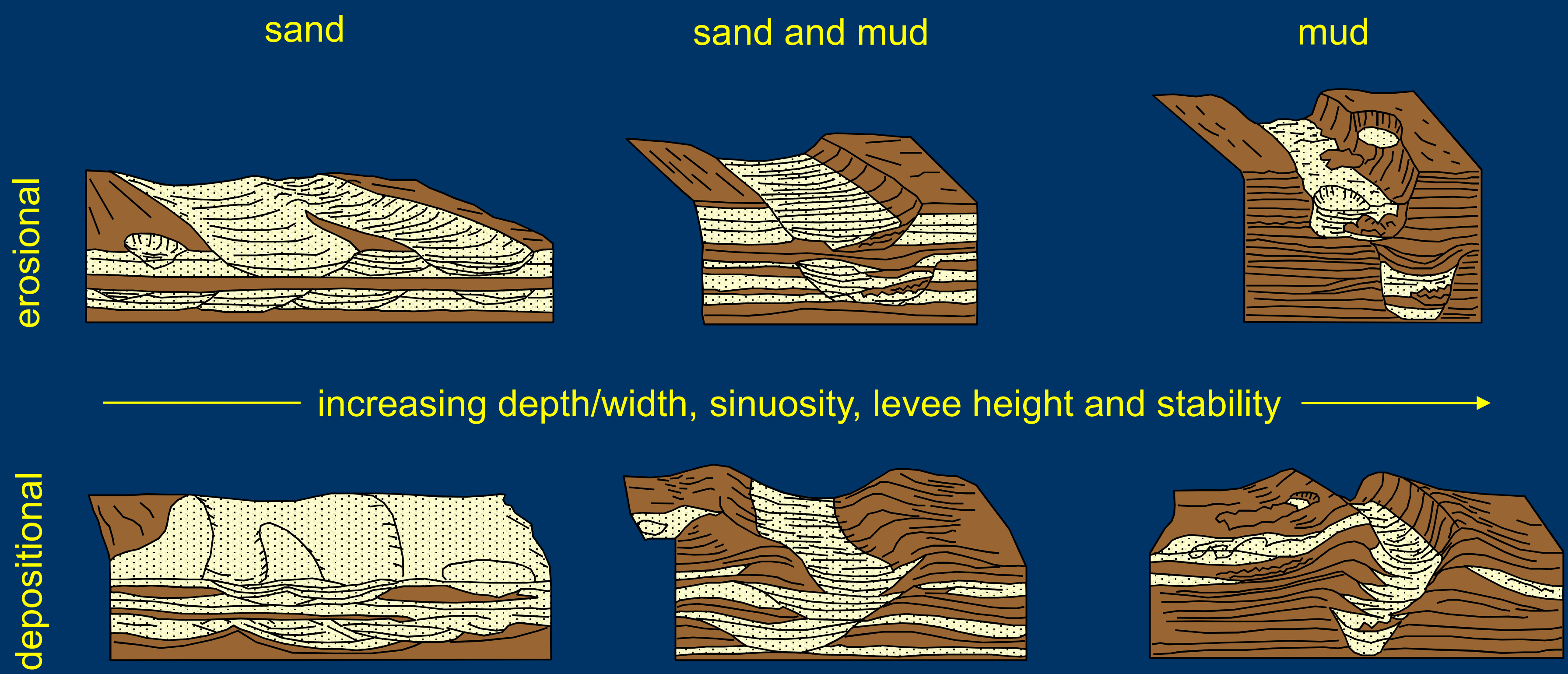


(after Damuth *et al*. 1988)

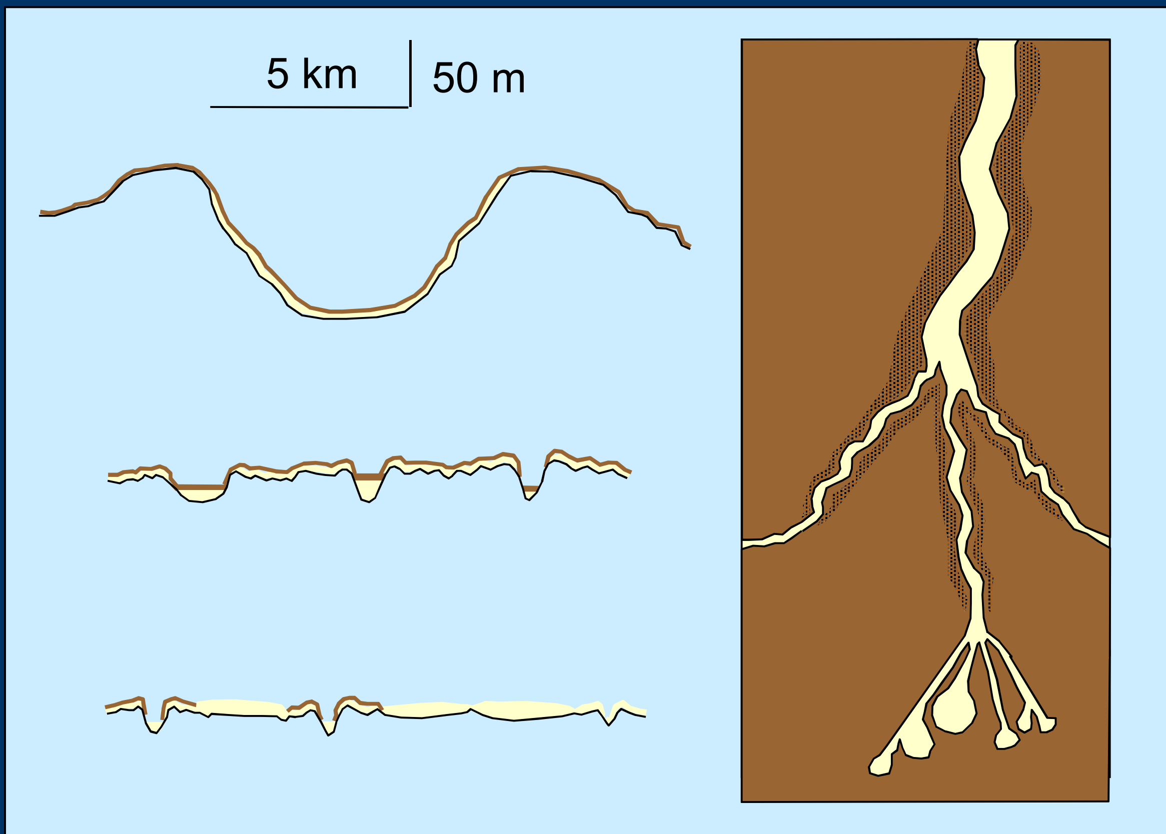
Studies on modern submarine fans indicate that channels are highly sinuous with abundant meander loops and abandoned channel segments that have been cut-off

Note that submarine channels are very large in comparison to rivers. They typically are several kilometres wide and more than 100 m deep

Channels that are depositing sediment have a much different morphology than those that are erosional. Channel morphology also varies considerably with the grain size of the sediment load



(after Galloway and Hobday 1996)



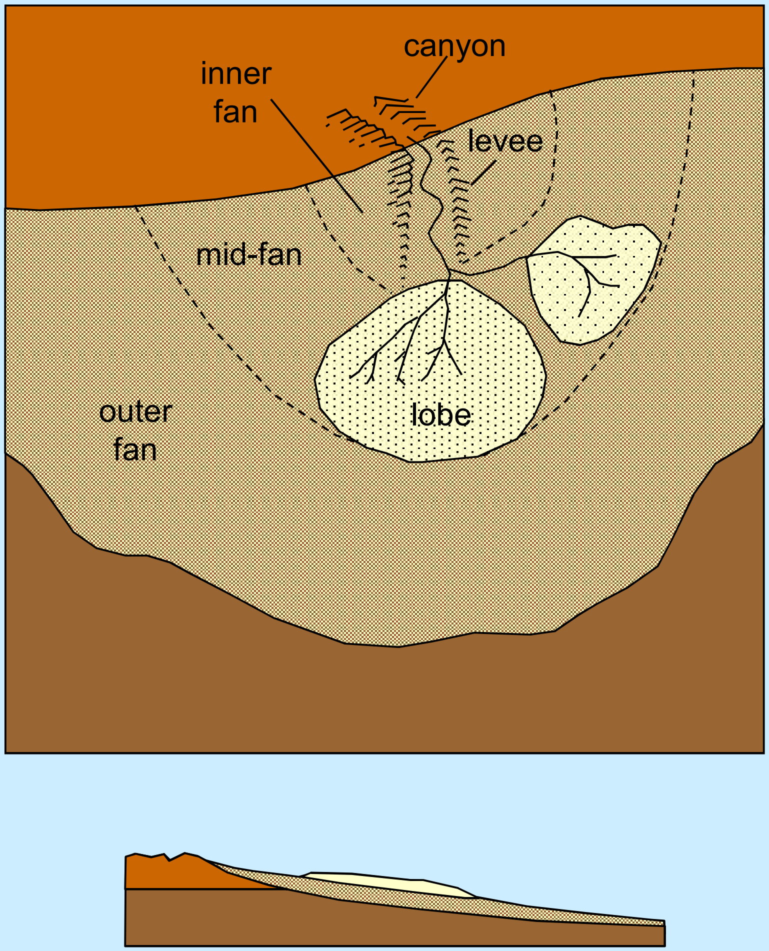
(after Kolla and Coumes 1987)

Channel morphology changes basinward as the flow begins to dissipate

The channel splits into several smaller channels with much smaller levees

Sandy sediment is deposited in the overbank areas as well as within the channels, forming a lobe

Further basinward the channels terminate in smaller lobes that deposit sheet sands

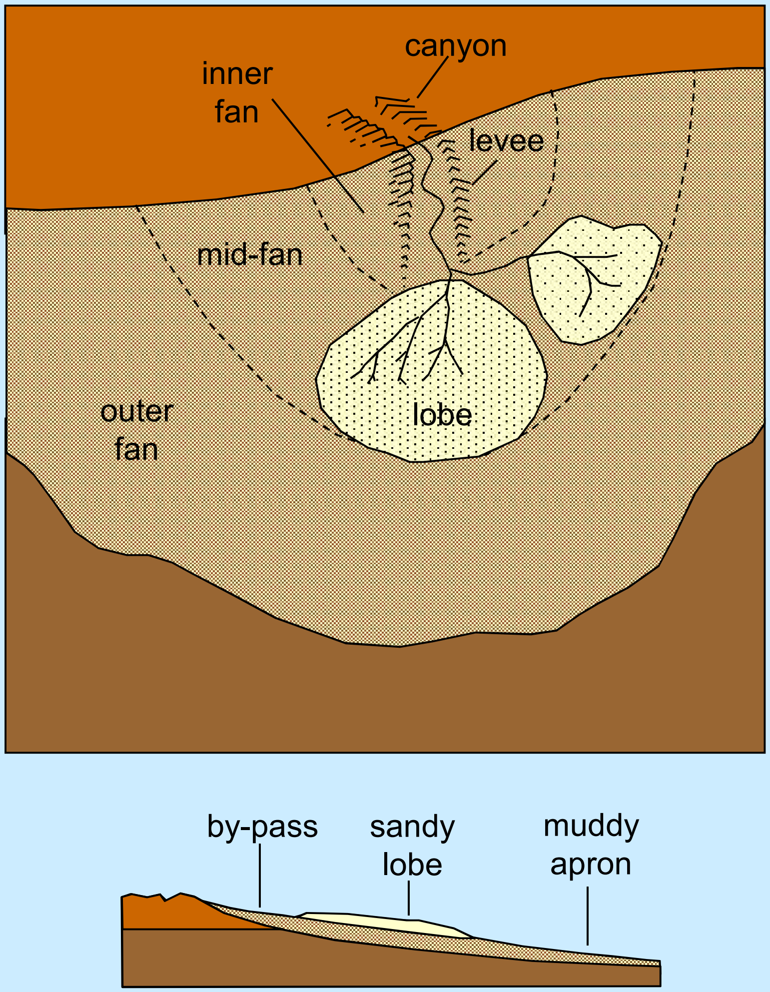


(after Normark 1978)

The turbidity current continues basinward from the channel terminations as an unconfined flow that deposits thin, fine-grained distal turbidites until it finally dissipates

The fan-shaped geometry evolves by an autocyclic process that is similar to delta lobe switching

As one channel and lobe system grows basinward, the slope is decreased until subsequent turbidity currents shift their course to follow a steeper slope

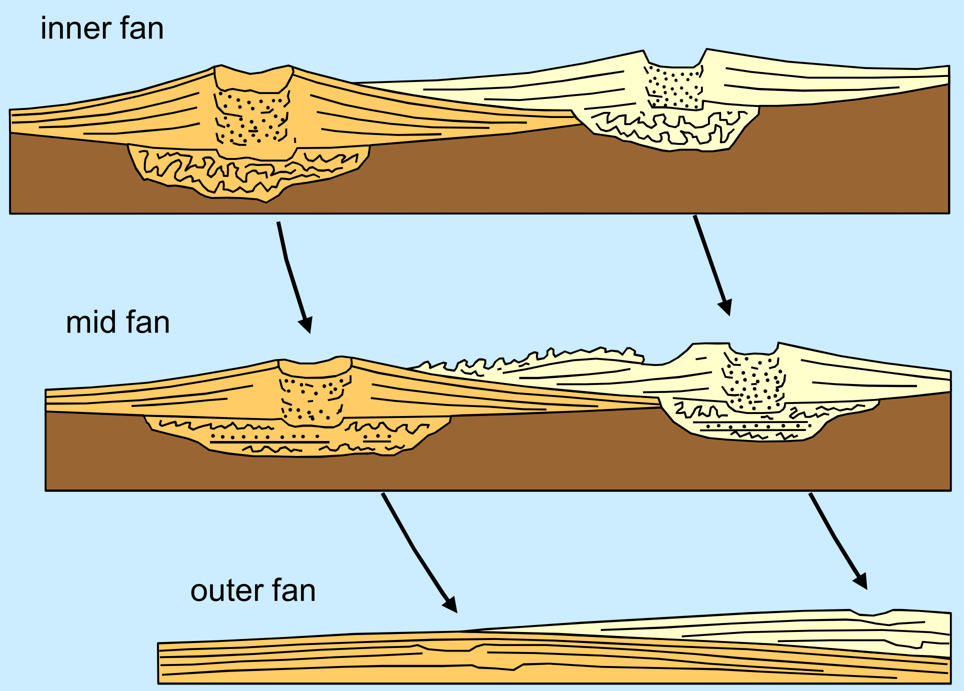


(after Normark 1978)

Submarine fan models commonly divide fans into components with different depositional styles

The *Inner Fan* has the channel and levee system and is largely a sediment by-pass area, except for overbank and levee deposits plus sands deposited in the channel by small flows. Channel meandering greatly reduces their preservation potential

Most deposition, especially of sand, occurs on the lobes that develop in the *Mid-Fan* as flow velocities drop and the channel system breaks down. The *Outer Fan* is an apron of fine-grained distal turbidites deposited by unconfined flows

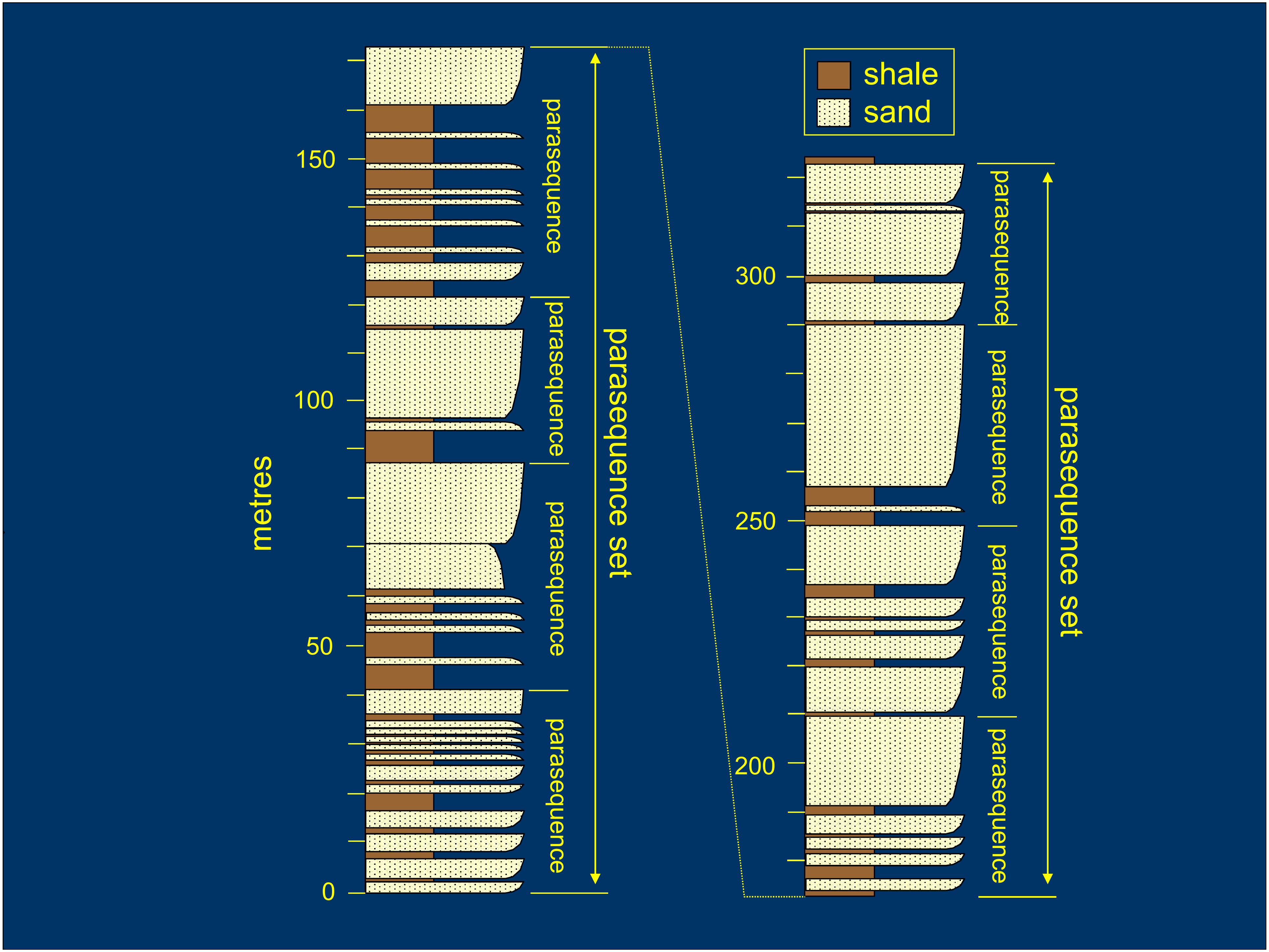


(after Walker 1992)

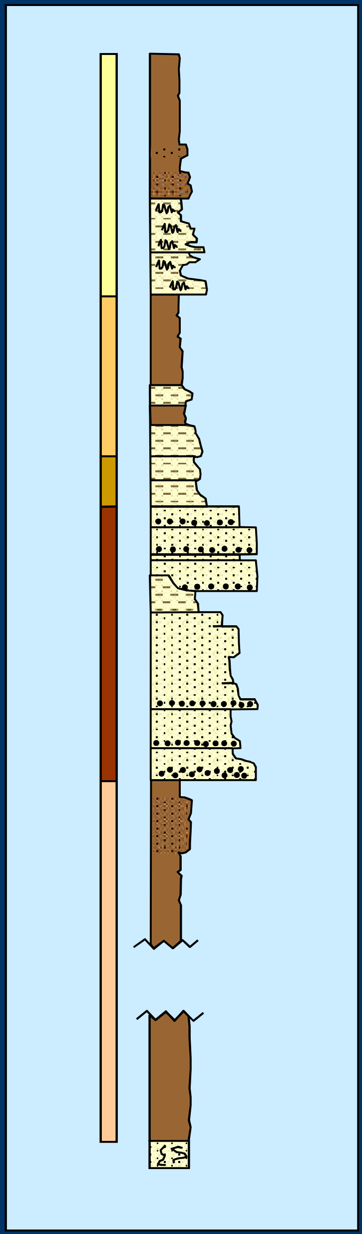
The submarine fan becomes larger and progrades basinward with each subsequent turbidity current

Because most deposition occurs in the mid-fan, it builds upward and outward primarily as a series of stacked, coarsening upward, laterally coalescing lobe and channel systems

Relief decreases and overbank deposits become more abundant basinward, until eventually the subdued lobate geometry of the outer fan prevails

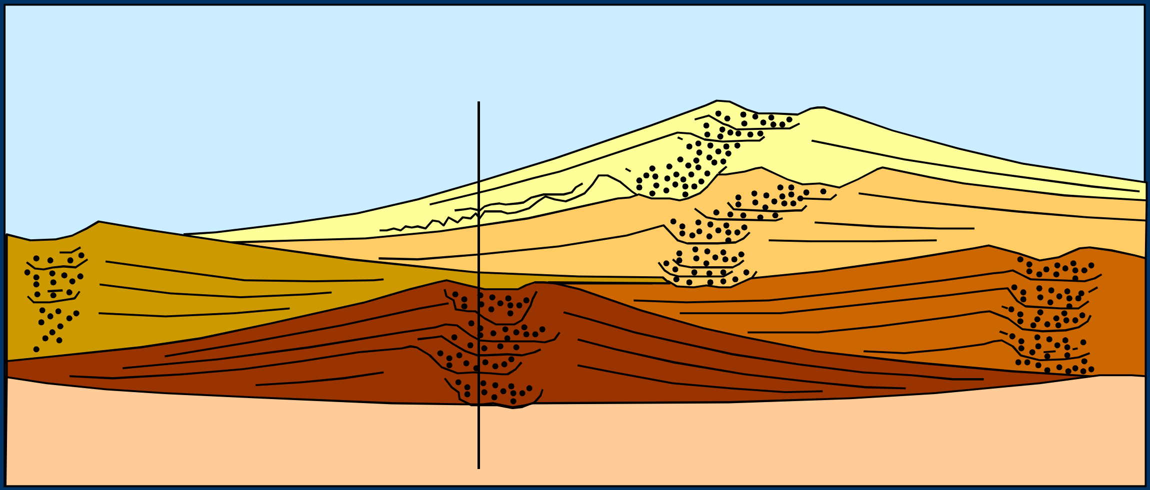


shale
sand
metres
0
50
100
150
200
250
300
parasequence
parasequence
parasequence
parasequence
parasequence set
parasequence
parasequence
parasequence
parasequence
parasequence set

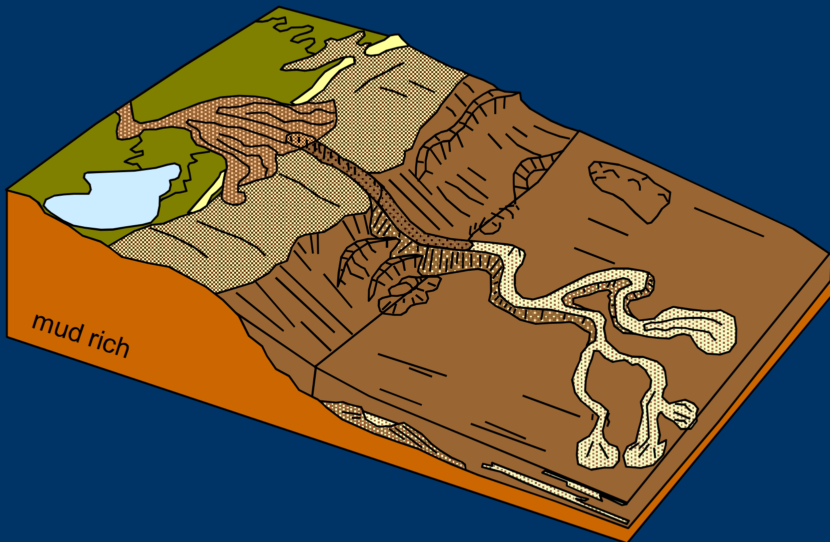


The stratigraphic column exposed in Wheeler Gorge, California was constructed from multiple channel and levee systems

It illustrates how the proportion of sand to mud in a column varies laterally so that careful facies analysis is required to determine reservoir potential accurately

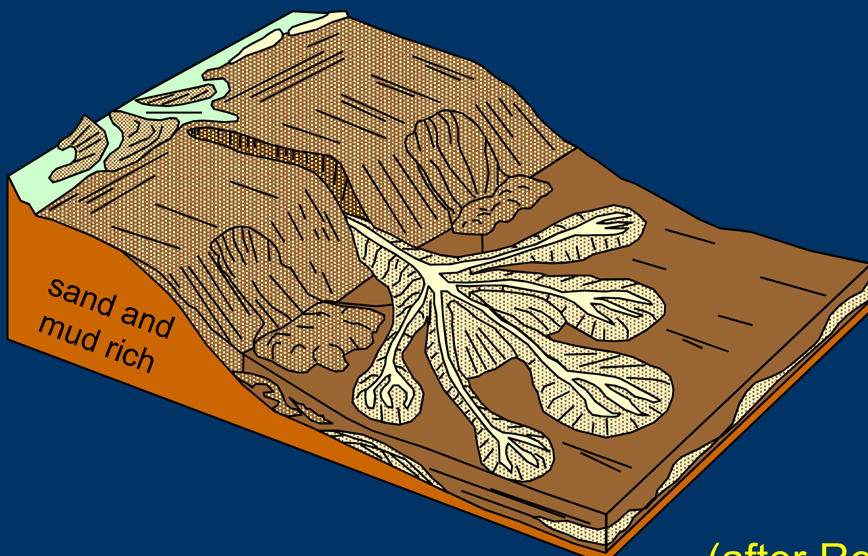


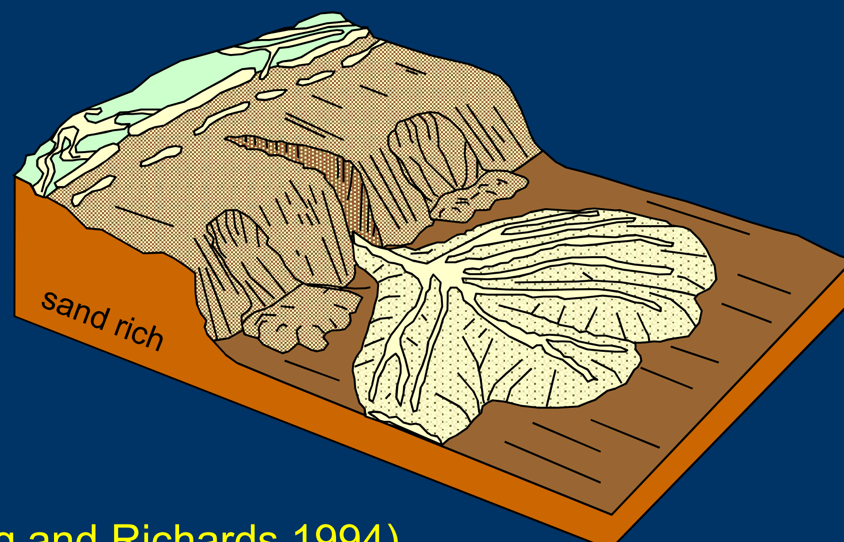
(after Walker 1992)



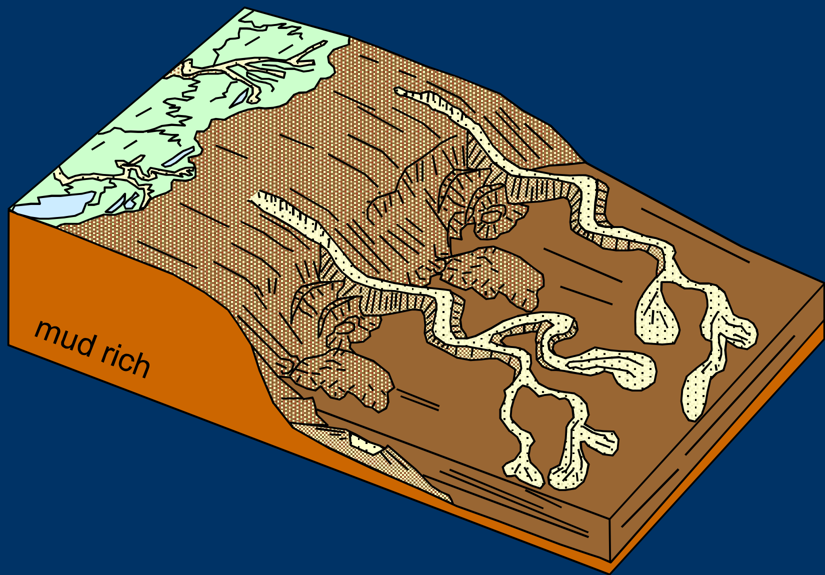
Reservoir sands can occur in most submarine fans but their abundance, geometry and reservoir quality vary greatly with the grain size of the sediment supply and the morphology of the continental margin

Generally, fan lobes become bigger and tend to coalesce more, increasing reservoir potential, as the amount of sand increases relative to mud

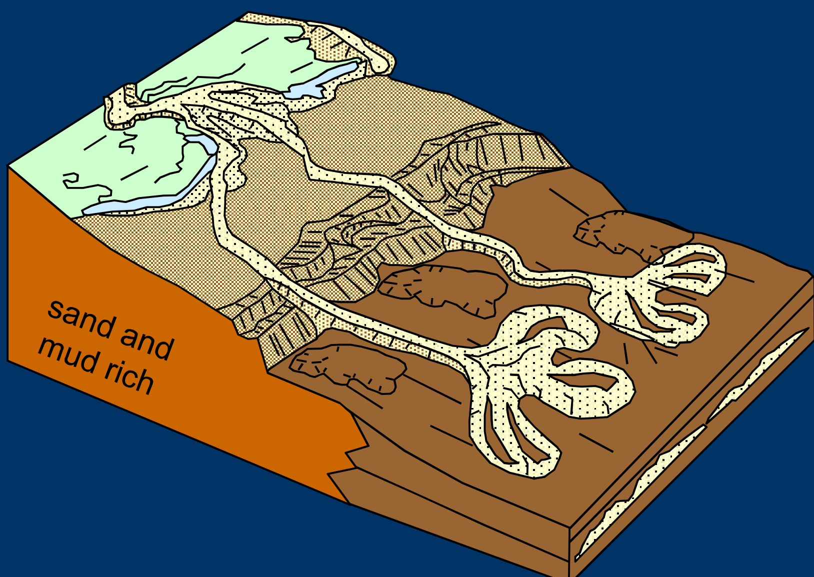


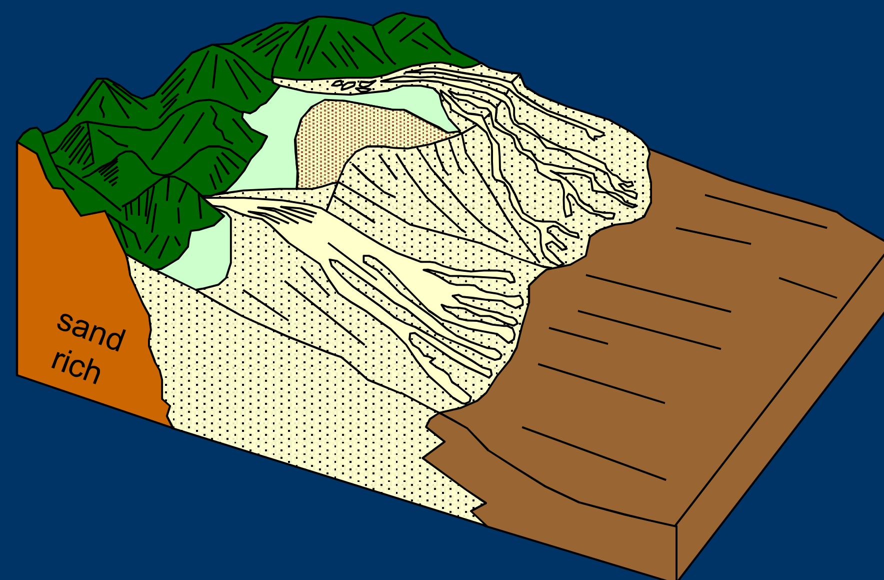


(after Reading and Richards 1994)

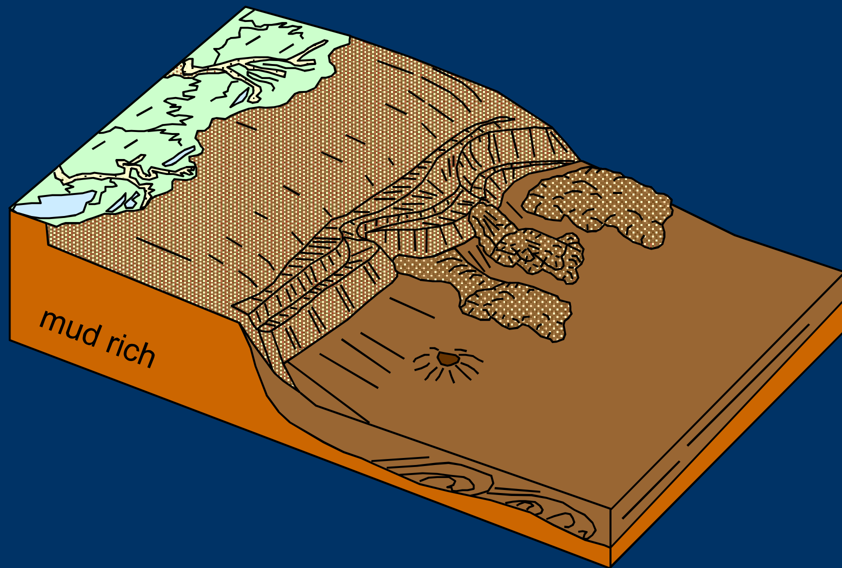


Reservoir potential varies greatly as a function of sediment supply on ramped margins. Sandy ramps develop large vertically and laterally continuous sand bodies but mixed and muddy margins accumulate smaller, isolated sands

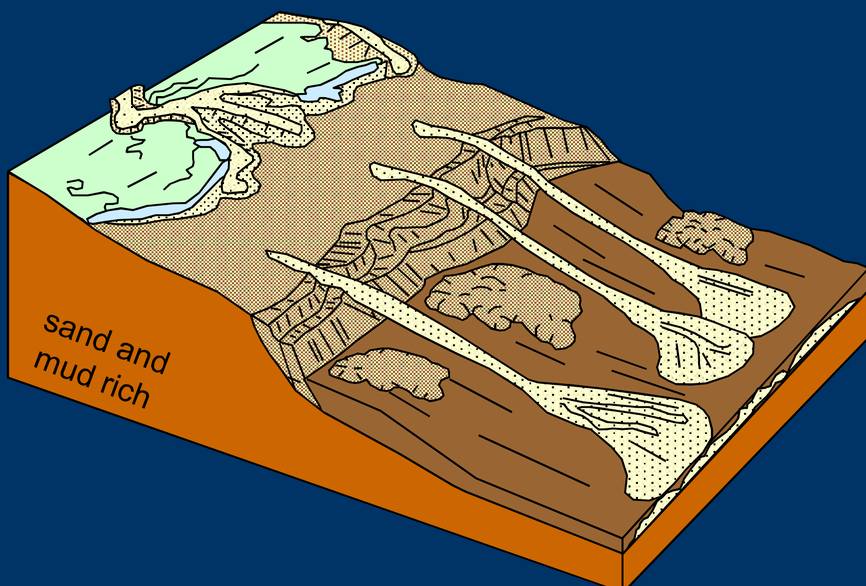


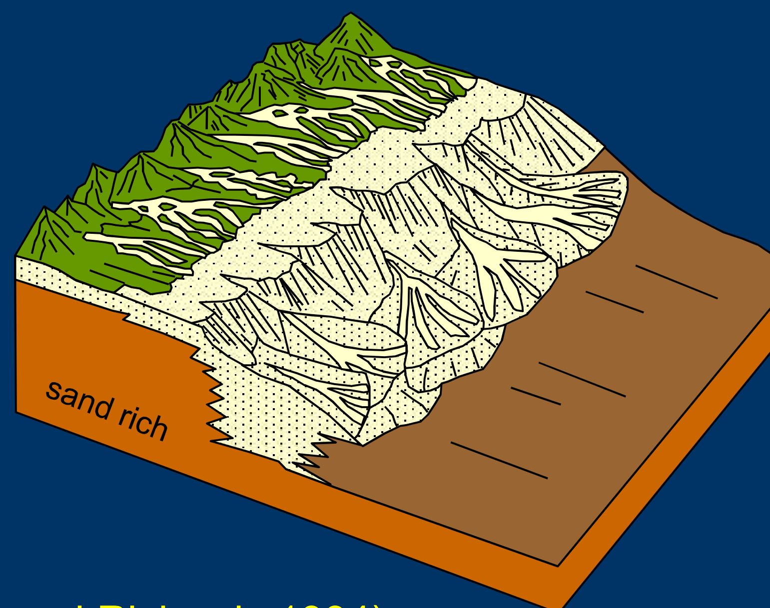


(after Reading and Richards 1994)

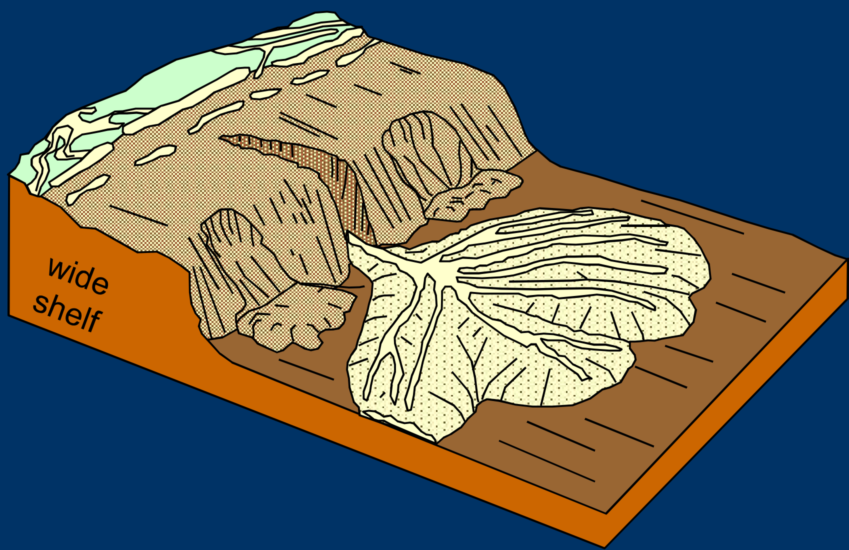


Very little, if any, sand makes it to the deep sea on a mud-rich margin with a narrow shelf and steep slope but a sandy *Slope Apron,* with excellent reservoir potential, will develop on a sand-rich steep margin

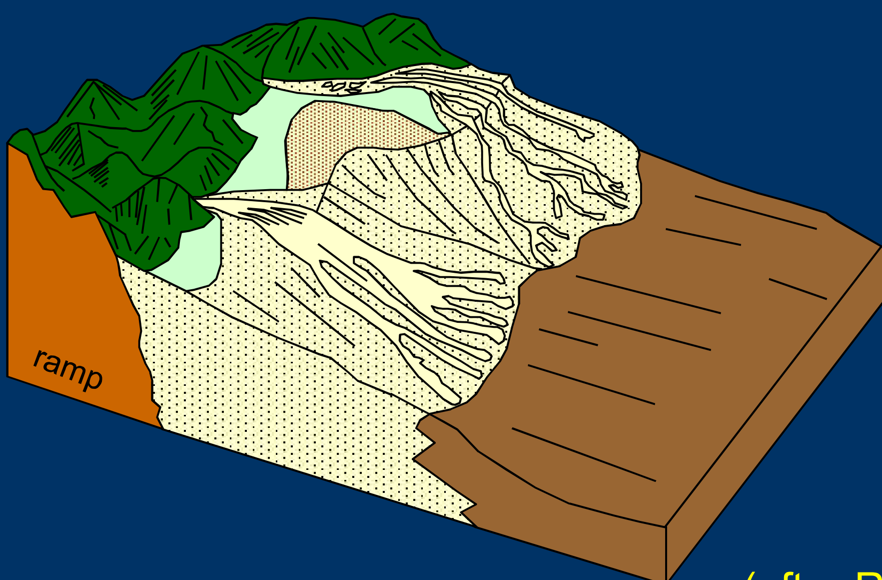


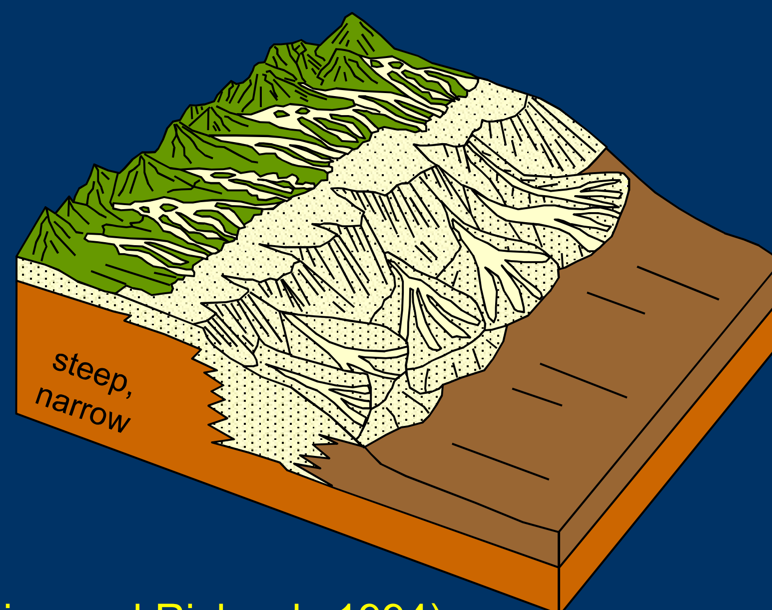


(after Reading and Richards 1994)

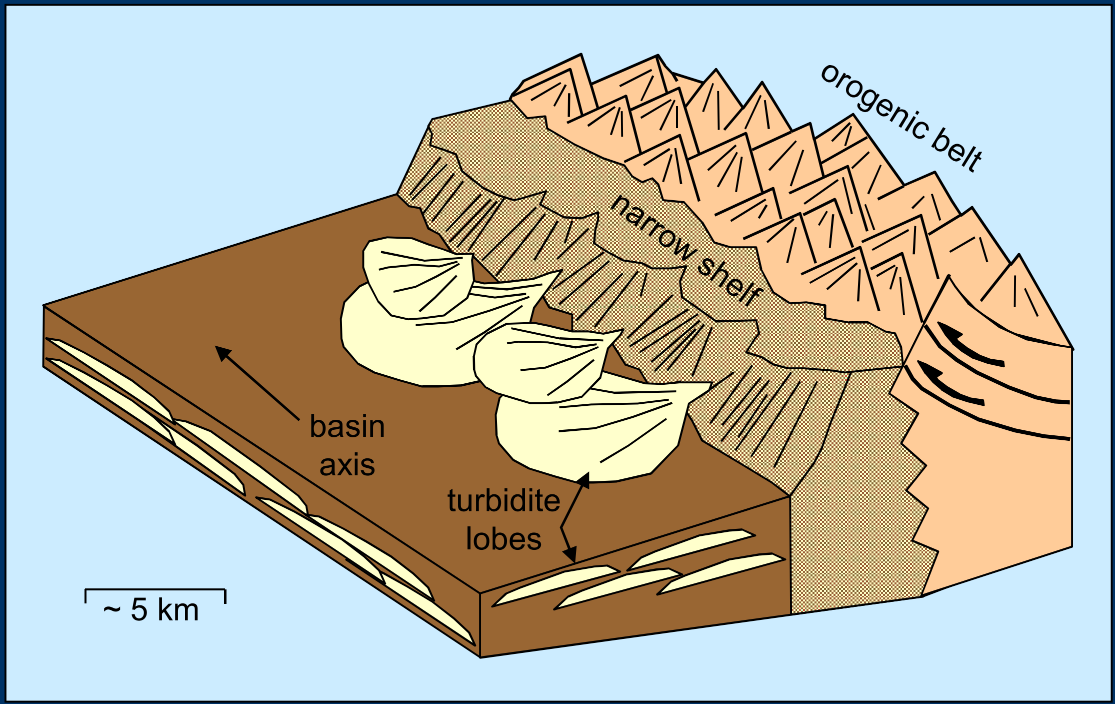


Fans that develop at the base of wide continental shelves tend to be muddier with less vertical and lateral reservoir continuity in coalesced sand bodies than those that are deposited on ramped margins or as slope aprons on steep, narrow margins





(after Reading and Richards 1994)

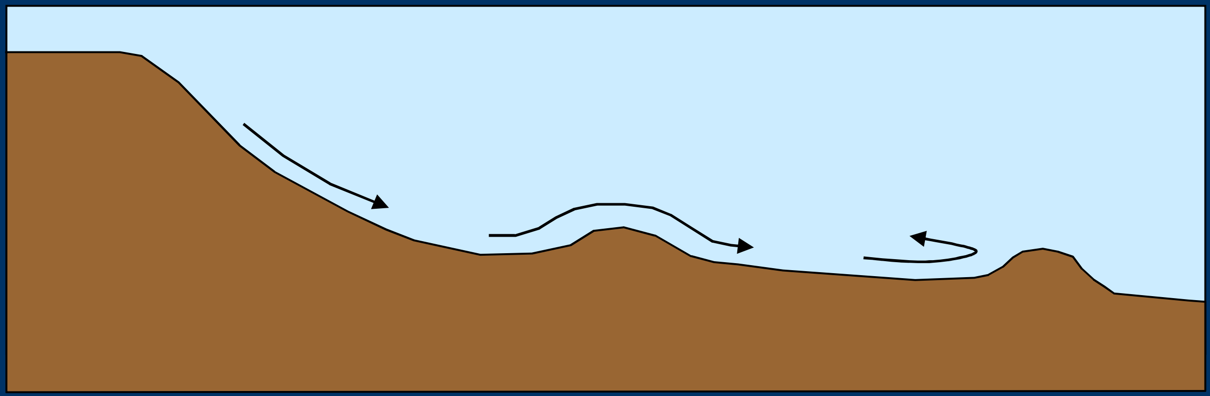


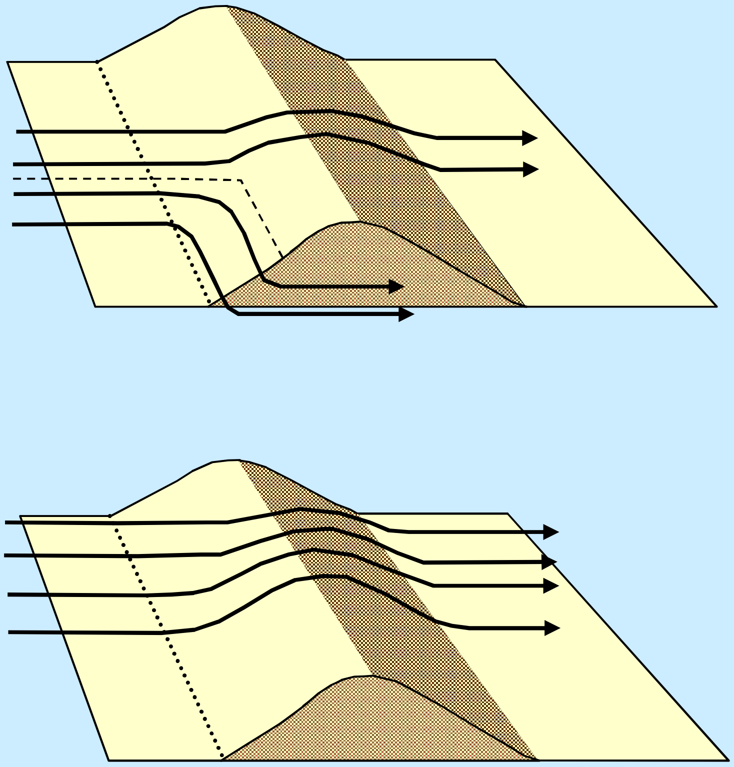
(after Williams 2001)

These models assume a smooth slope that decreases basinward. Real slopes often have topography that changes the slope locally

When encountering a topographic feature, a turbidity current can either continue over it, be deflected by it or ponded against it.

The exact response depends on the size and velocity of the flow relative to the slope and height of the topographic obstacle



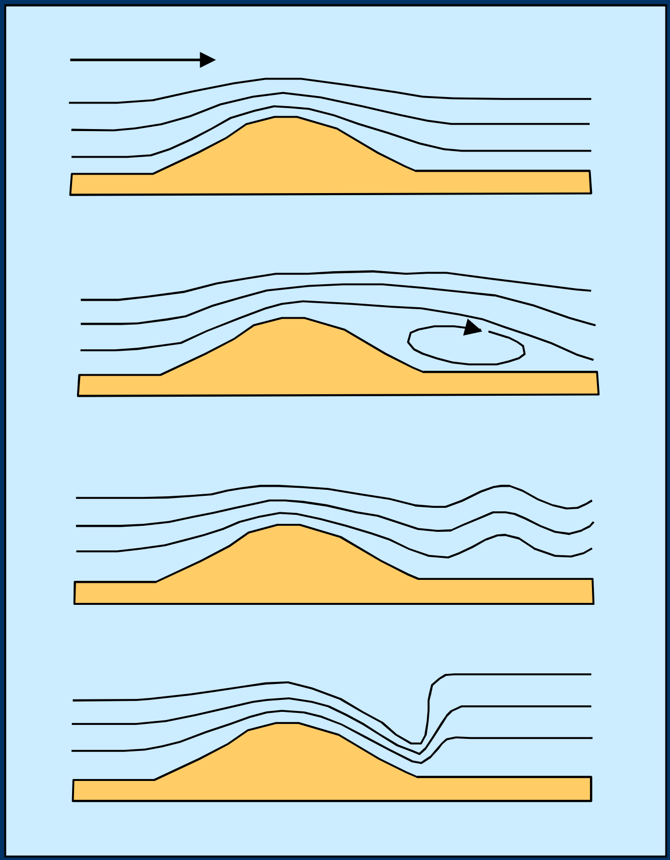


(after Kneller and Buckee 2000)

The response can be complex

The lower part of a flow with its coarse grained sediment can be deflected while the upper part oversteps the topography

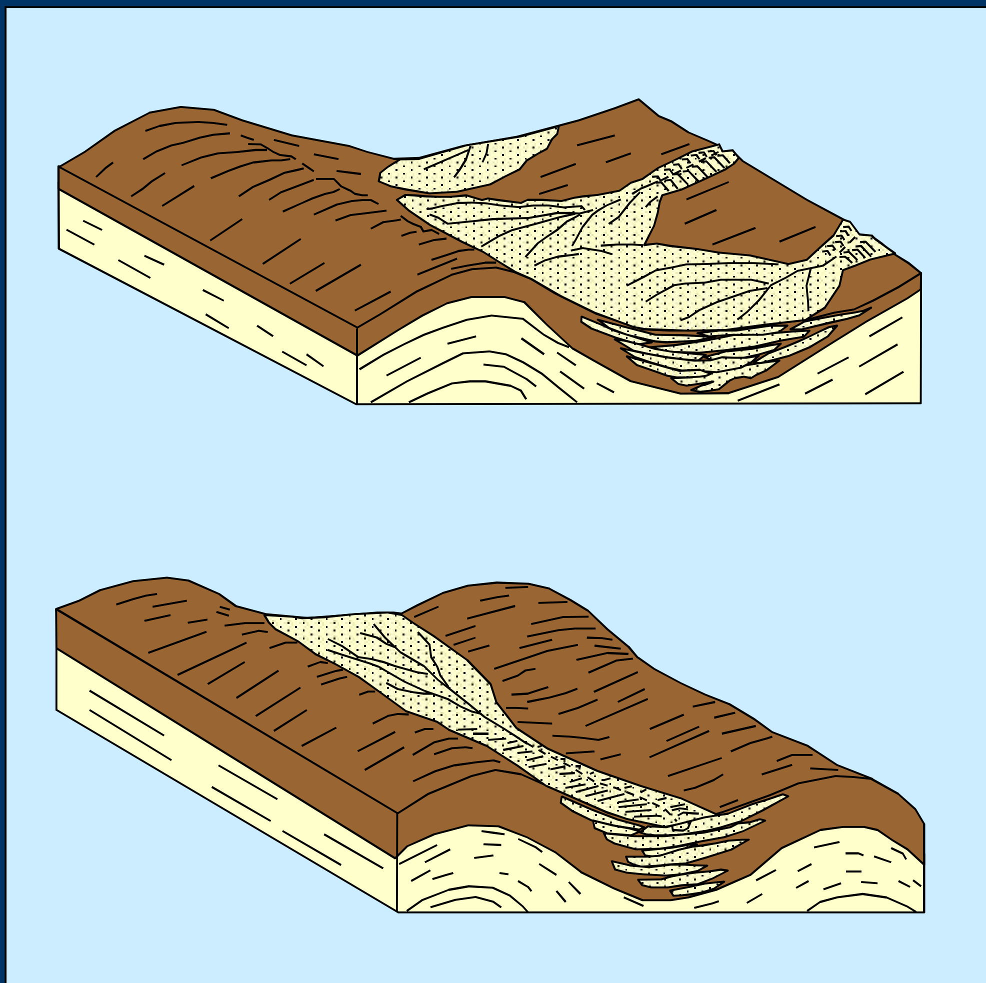
High velocity flows continue across an obstacle without any deflection



(after Kneller and Buckee 2000)

Flow characteristics can be modified significantly when a turbidity current flows over a positive topographic feature

The exact flow pattern depends on the relative height of the topographic obstacle plus the velocity of the flow



(after Scott and Tillman 1981)

Fan shape and orientation are strongly modified by bottom topography and turbidity current deflection

Consequently sand body geometry is highly variable in ponded turbidites

Key Points

- Turbidity currents and debris flows are the most important of the sedimentary processes that transport sandy sediment to the deep sea
- Debris flows deposit channelised, chaotic beds that can have good reservoir potential
- The grain size and sedimentary structures within the deposit of a single turbidity current indicate waning flow upward and basinward; bed thickness and grain size decrease basinward
- Turbidites form extensive submarine fans that are built by prograding lobes that coarsen upward.
- Reservoir potential varies with sediment supply and basin configuration but is often excellent in clean, laterally extensive sandy turbidites