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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	**Dr. Soumik Mukhopadhyay** 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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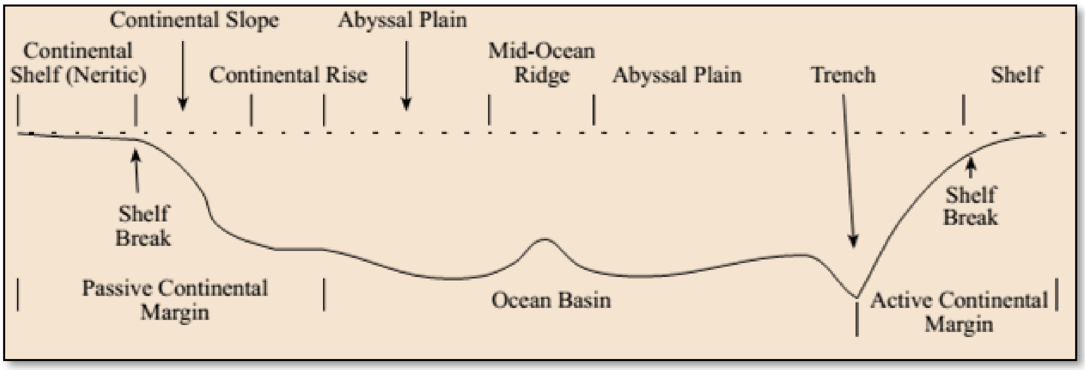
1. Learning outcomes

After studying this module, you shall be able to:

- Know about deep marine environments.
- Learn about characteristic sediments, as well as sedimentation processes and patterns operative in this environment.
- Know about the different sub-environments including submarine fan systems, their character and varieties.
- Know about the nature of products of this environment, its characteristic criteria for recognition in geological record and types of successions they form in the rock record.

2. Introduction

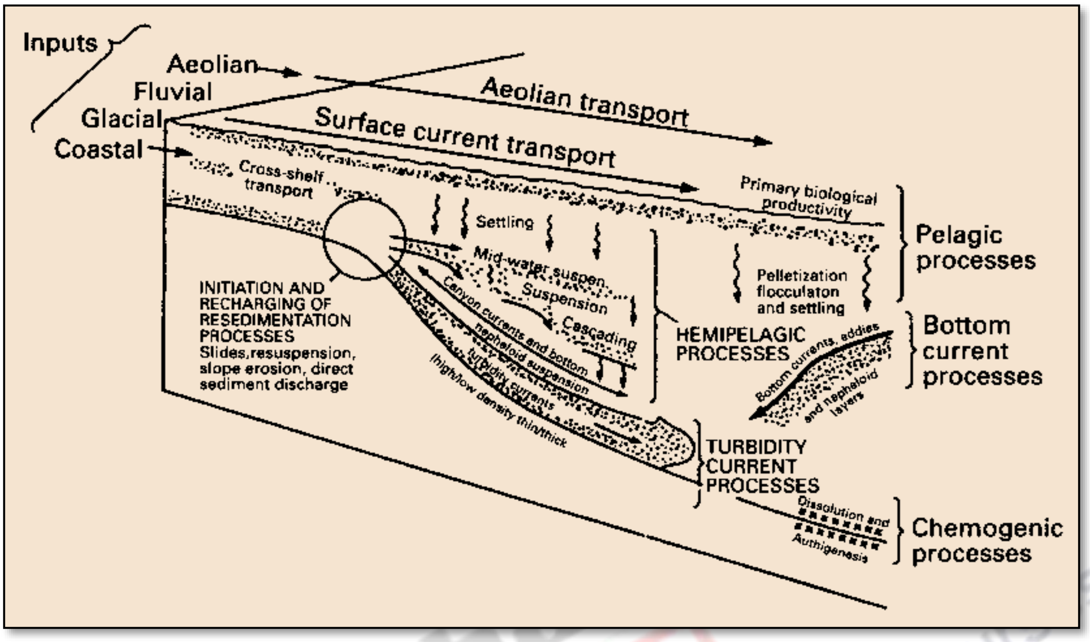
Deep marine environments cover the largest area of the earth's crust, but as the sedimentation rate is very low the amount of sediment deposited within the deep marine environment is not significant, compared to other environments. Marine environments, as a whole can be grouped into two broad categories, shallow marine environments and deep marine environments. The edge of the continental shelf makes a natural break between shallow and deep marine environments. Deep marine environments include the continental slope and the abyssal plain.



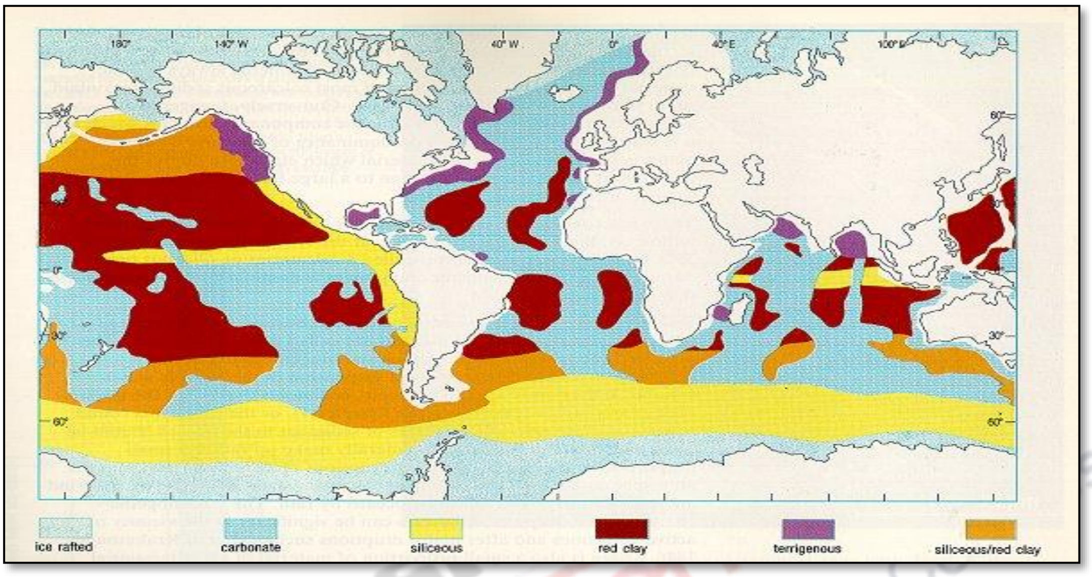
Ocean floor bathymetry

3. Deep sea sediments and sedimentation processes

Deep-sea Sedimentation has two main sources of sediment; External- terrigenous materials from the land and Internal- biogenic and authigenic materials from the sea. Major sedimentation processes in the deep sea include slow but continuous suspension fall-out of fine particles (biogenic, terrigenous as well as cosmogenous- cosmic dust falling over vast seas) and local authigenic deposits of biogenous or hydrogenous material (chemical precipitation from water), with occasional emplacement of coarse clastics through sediment gravity flow processes, mainly debris flows and turbidity currents. Materials deposited from the suspension fall-out are divided into two groups, pelagic and hemipelagic sediments. These two types of sediments along with the authigenic deposits of deep marine realm account for the typical deep marine sediments. The rate of sedimentation of these deep marine sediments is very slow, but the lateral extent is huge, as these sediments cover bulk of the deep marine environment. The other variety of deep marine sediments are the coarser clastics, both terrigenous as well as biogenous in nature, which get emplaced occasionally within the deep marine realm through sediment gravity flows originating at the continental shelf or continental slope area. These characteristically have higher rate of sedimentation, but lower aerial extent, restricted within near vicinity of the continental slope. Some distal turbidity currents can run for hundreds of kilometers though, through the abyssal plain.



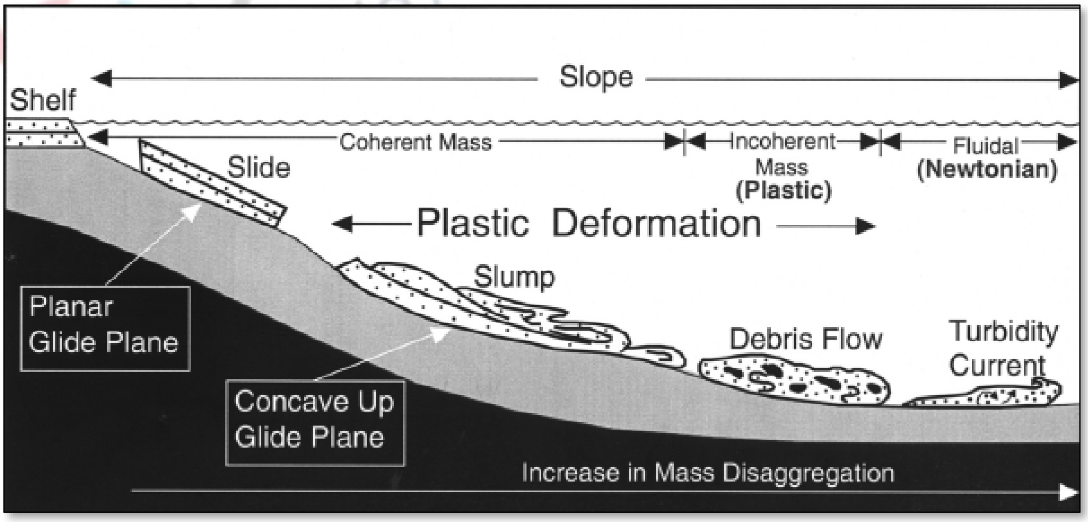
Pelagic-sediments by definition are composed of fine material, which has at some stage been floating in the water. Such sediments get deposited through a very slow but continuous suspension fall-out from the ocean water, like a rain of finer particles. Pelagic materials are usually small in size although remains of larger marine organism or rare drop stone can also be present in this pelagic setting. Pelagic materials are mostly biogenic (nektonic and planktonic organisms, which floats in water but sinks to bottom after death) with considerable amount of fine-grained wind-blown terrigenous (including volcanic ash) and cosmogenous material. As a whole, pelagic material is mainly clay and fine silt mixed with organic carbonate or siliceous remains and can be classified into two major varieties; calcareous/siliceous clays and biogenic oozes. Sediments with less than 30% biogenic component are termed as calcareous or siliceous clays. Red clays are typically made up of kaolinite, chlorite, quartz, feldspar and lack organic remains; whereas black shales contain about 1-15% organic-matter and formed under an abundant, supply of organic material and/or anoxic bottom condition. Greenish or dark colored shale contain organic materials in variable proportions. Calcareous or siliceous muds with greater than 30% biogenic component, is known as biogenic 'oozes'. They are primarily composed of marine microfossil remains. Divided either into $CaCO_3$ (calcium carbonate) or SiO_2 (silica) dominated systems; producing **calcareous** or **siliceous oozes**, respectively.



Calcareous oozes are formed by the accumulation of calcium carbonate hard parts from dead microscopic plankton, mainly cocolithophores and foraminifera. Calcareous oozes principally deposit in relatively shallow, low- to mid-latitude regions of deeper ocean. Deposition takes place above CCD (carbonate compensation depth) and in warmer waters. Siliceous oozes are produced by the accumulation of dead shells of silica-secreting organisms, mainly diatoms and radiolaria. Siliceous oozes are restricted within the higher latitudes and prefer cooler waters. Concentrations of siliceous oozes are upwelling and nutrient-supply controlled and favored below CCD. Consolidated siliceous ooze gives rise to a hard siliceous rock, chert. Deep-sea cherts are thinly bedded in nature.

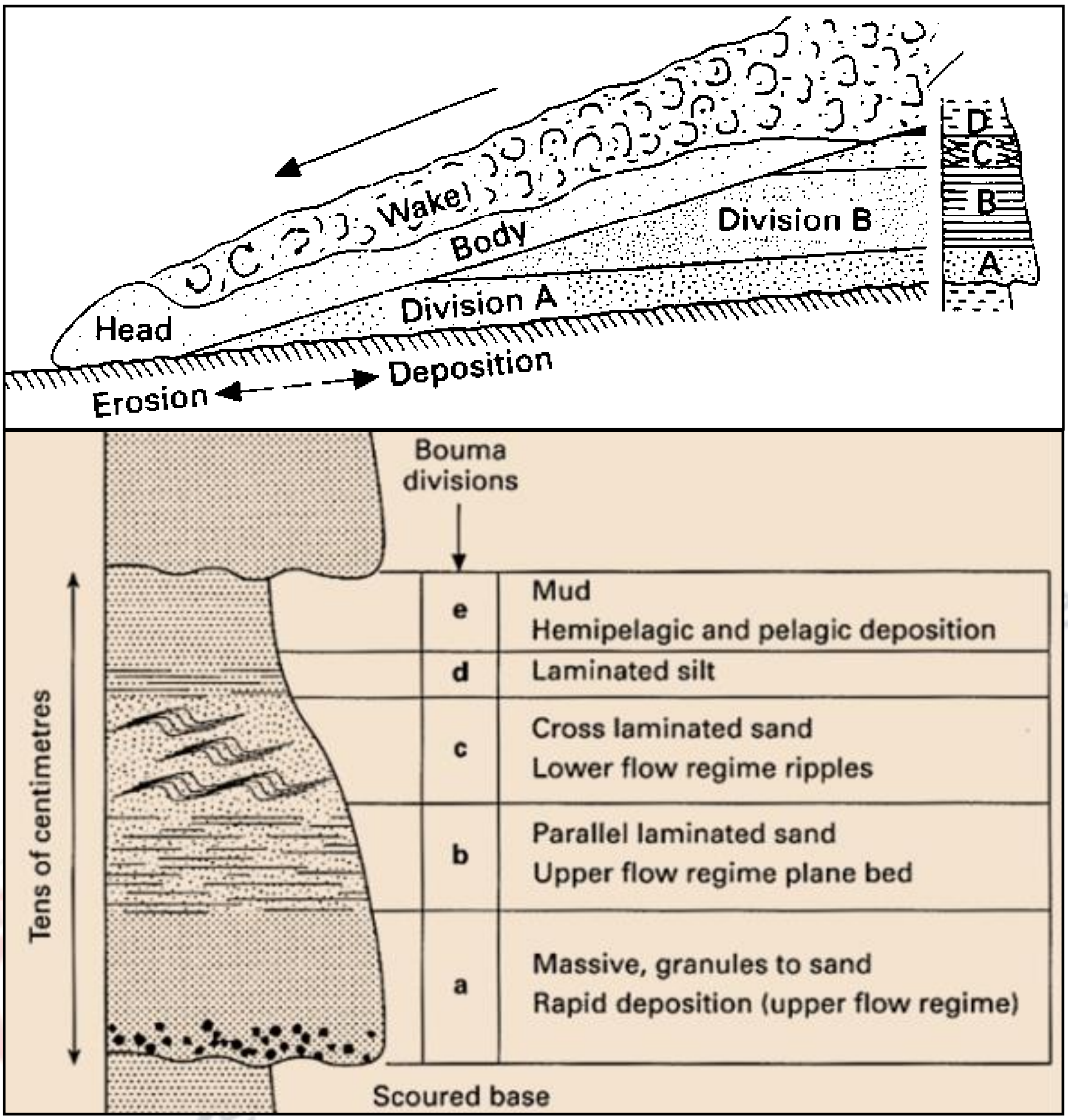
Hemipelagic sediments refer to at least 25% of fine-grained (muddy) terrigenous materials from shelf, redeposited within deep marine realm by storm-generated plumes or short-distance turbidity currents. These materials are temporarily held in suspension by the storm-generated currents before final deposition in deeper waters, but often within near vicinity of the continental slope. Depositional mechanism includes suspension fall-out from storm-generated plumes and during terminal stages of turbidity currents. Distal, muddy turbidites merge gradationally into hemipelagic deposits. Eolian dust is an important component (~50%) of hemipelagic (and pelagic) sediments.

Authigenic (Hydrogenous) deposits are essentially solid chemical or biochemical precipitates from seawater. They accumulate on sea floor, with very slow rate. Carbonates, ferromanganese nodules and phosphorites are common products. Carbonate precipitation from calcium carbonate supersaturated seawater can take place with or without biogenic influence. Common non-biogenic form includes short aragonite crystals and oolites. Ferromanganese nodules are deposits of manganese, iron, copper, cobalt and nickel. Such nodules accumulate in areas of low sedimentation rate only (e.g., the Pacific) with an extremely slow precipitation rate (1 to 10 mm/million years). Phosphorites are phosphate crusts having greater than 15% concentration of P_2O_5. These crusts generally formed by transformation of unoxidized organic phosphorous, settling out on the ocean floor in large quantities. Most phosphorite grains are sand size although particles greater than 2 mm may be present. These larger grains, referred to as nodules, can range up to several tens of centimeters in size. Such nodules are restricted within continental shelf and upper continental slope areas, in regions of high productivity.



Mass transportation at deep marine realm

Coarse clastics found within the deep marine realm are transported from the continental slope area through subaqueous mass movements, mostly sediment gravity flows. Owing to higher gradient of continental slope area, such slump-generated mass movements initiate at the base of the slope. Such mass movements can also take place along the submarine canyons and produce submarine fans. Important types of mass movements are turbidity currents, cohesive debris flow, fluidized/liquidized flows, grain flows and contourites. Commonest among these processes are **turbidity currents**. Generation of turbidity currents characteristically require thick column of water overhead, hence, these kinds of flows are mostly restricted within deep marine environments, though some large lakes can also produce similar flows. **Turbidites** are typical products of turbidity current, and frequently encountered in deep marine realm. Debris flows plays the next important role in mass movement, but such flows are restricted within the continental slope regions mostly. Any external trigger, ranging from seismic jerks to storm wave pounding can trigger mass transport at the continental shelf-slope junction. Usually the mass transport initiates as a **slide**, a coherent translational mass transport of a block or strata on a planar glide plane (shear surface) without internal deformation, at the top of continental slope. As the material moves downslope, a slide generally get transformed into a **slump**, which represents a coherent rotational mass transport of a block or strata on a concave-up glide plane (shear surface) with internal deformation. Upon addition of fluid during further downslope movement, slumped material may get transformed into a **debris flow**, which transports sediment as an incoherent body in which inter-granular movements predominate over shear-surface movements. A debris flow behaves as a plastic flow with strength. As fluid content increases further in a laminar debris flow, the flow may evolve into a Newtonian **turbidity current**. Although not all turbidity currents evolve from debris flows, some may evolve directly from sediment failures at the continental slope. **Contourites** are the product of contour parallel current (parallel to continental margin). This is the only mass transfer product, which is governed by fluid-gravity flows. Contour currents rework and redeposit turbidites to produce contourites.



Schematic diagram showing different parts and processes of turbidity flow (above). Bouma sequence (below)

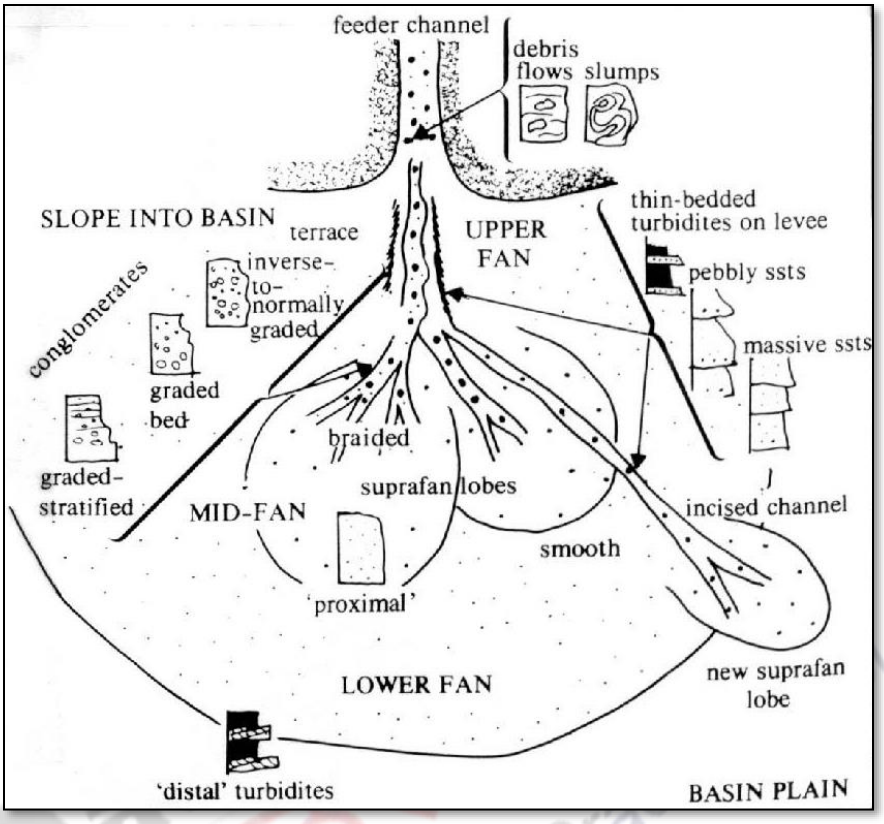
Debris flow products are usually coarse-grained in nature, with matrix-supported framework and randomly oriented angular grains, often protruded above the upper surface. Bodies are internally massive and poorly sorted with lenticular body geometry. Turbidites, on the other hand, exhibits a distinct proximal to distal fining in grain-size. Graded bedding is common in turbidity current deposits. Turbidite beds commonly show a fining upwards facies architecture, the details of which was first noted by Bouma (1962), and consequently known as 'Bouma sequence'. An 'ideal' turbidite contains five divisions; A: Rapidly deposited, massive sand; B:

Planar stratified (upper-stage plane bed) sand; C: Small-scale (climbing ripple) cross-stratified fine sand; D: Laminated silt and E: Homogenous mud. These divisions are most distinguished for medium-grained, sand-mud turbidites. High-density and low-density turbidity currents give rise to incomplete, coarse-grained (A) and fine-grained (D-E) turbidites, respectively. Contourites are just like turbidites but lacking the high-energy facies. Characteristically made up of clay, silt and fine sand grade material, deposited in parallel/wavy laminated to cross-laminated, broadly lenticular cm-sale bodies. These deposits are common in modern oceans but rare in rock record, as they are hard to distinguish from fine-grained turbidites, the only distinction being the shore parallel paleo-current directions.

The only other important geomorphic element within the deep marine realm is the submarine fan.

4. Submarine Fan

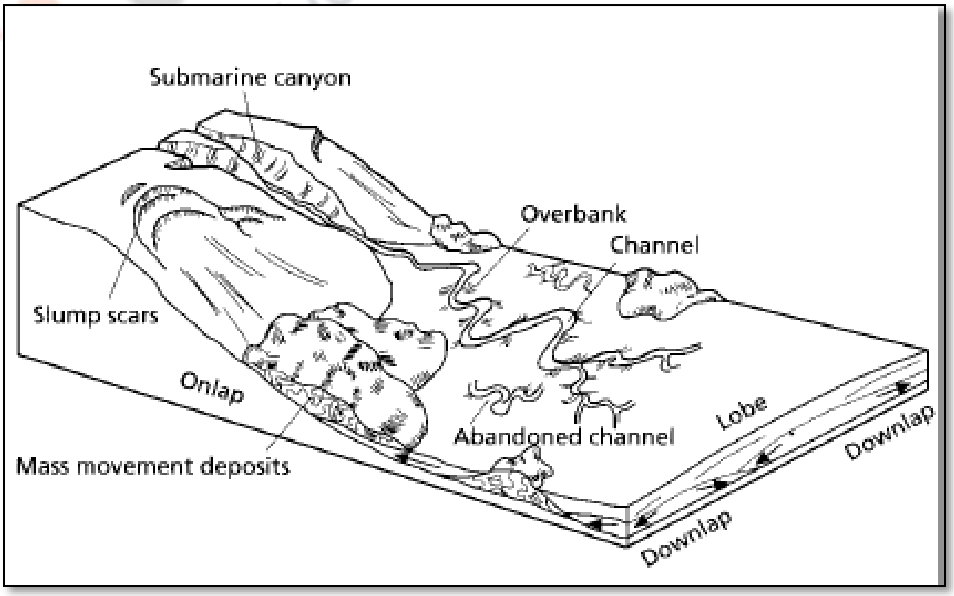
Submarine Fans are a fan-shaped sediment accumulation, radiating away from the feeder system, at the base of the continental slope, building out into the ocean basin. Submarine canyons at the shelf edge are connected to submarine fans on the ocean floor, acting as the feeder system of submarine fans. Submarine canyons are ubiquitously present along the continental slope of both active and passive basinal margins. They typically cut through the edge of the continental shelf and terminate on the deep abyssal floor, some 5,000 or more feet below sea level. Some extend landward across the continental shelf. Turbidity currents, along with other less important mass transfer mechanisms, intermittently flush sediments through the canyons to build up depositional fans where the flows reach the lower gradient of the ocean floor. The size of submarine fans is inversely related to dominant grain size (i.e., mud-dominated submarine fans are 104-106 km^2, sand or gravel-dominated submarine fans are 101-102 km^2).



Divisions and characteristic sediments at different parts of submarine fan

Submarine fan develops when mass of clastic sediments are supplied to the shelf margin. Sea-level fall facilitates submarine fan development by reducing the extent of the shelf region and/or by increasing the amount of sediment load in rivers. Formation of submarine fan during high sea level is also not impossible, if rivers can build deltas across shelf, owing to either high sediment influx (e.g. Mississippi) or narrow shelf configuration (e.g. Congo). Where sediment supply is high, deltas may buildout to the edge of the shallow marine shelf. Further sediments can bypass the shelf and are supplied directly down the continental slope to the deep marine realm to produce submarine fans, especially in comparatively steeper shelves.

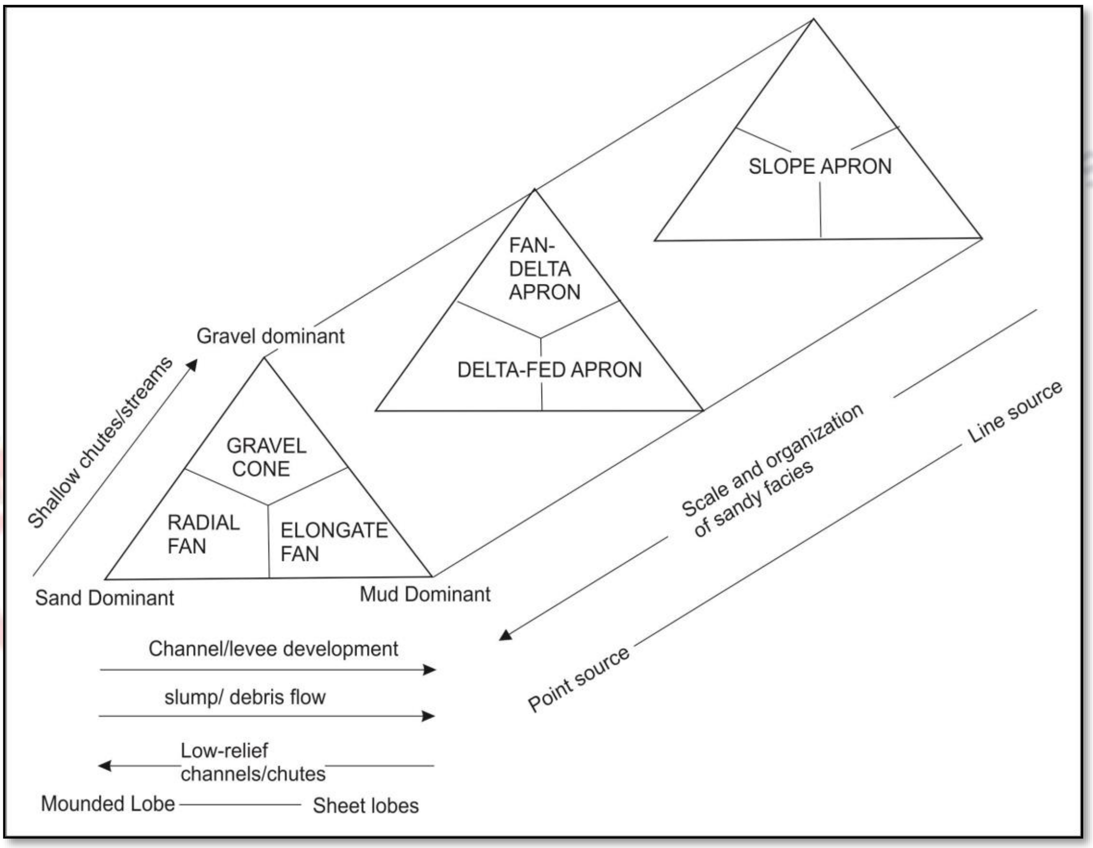
Submarine fans share several characteristics with deltas; they consist of a feeder channel that divides into numerous distributary channels bordered by natural levees ('channel-levee systems') and are subject to avulsions. Modern findings envisaged submarine fans are much larger and complex in nature, than that of previously thought, with major components including incised channels (submarine canyons, slope channels), leveed channel systems, mass transport complexes, frontal splays and distal lobes. Major three divisions can be established; **Upper Submarine Fan (trunk channel)**; **Middle Submarine Fan (lobes)** and **Lower Submarine Fan**. **Incised channels** and **channel-levee systems** with occasional **mass transport complexes** characterize upper fan region, while the middle fan region is represented by **channel/lobe systems** on **frontal splays**. The lower fan region is typified by **turbidite-dominated distal lobes**. The upper fan channel-levee systems are characterized by braided (within the canyon) to meandering (on upper fan) river systems. Both high as well as low sinuosity shallow meandering channels are reported from modern submarine fans. In rock record upper fan region is characterized by amalgamated sandstone (may be pebbly) bodies, resulted from vertical aggradation of channels. In-channel turbidites, upto 170m thick and 20km across, made up of coarse sand and/or gravel, are reported from modern fans. Typical products are thick, structure less or crudely graded beds (an interval dominates); finer sediments may get deposited but subsequently eroded by later turbidity currents. Lateral migrations of channels producing sheet sandstone bodies are common. In areas of high spillover, rate sandstone bodies are rather narrow, ribbon-like though, surrounded by levee deposits.



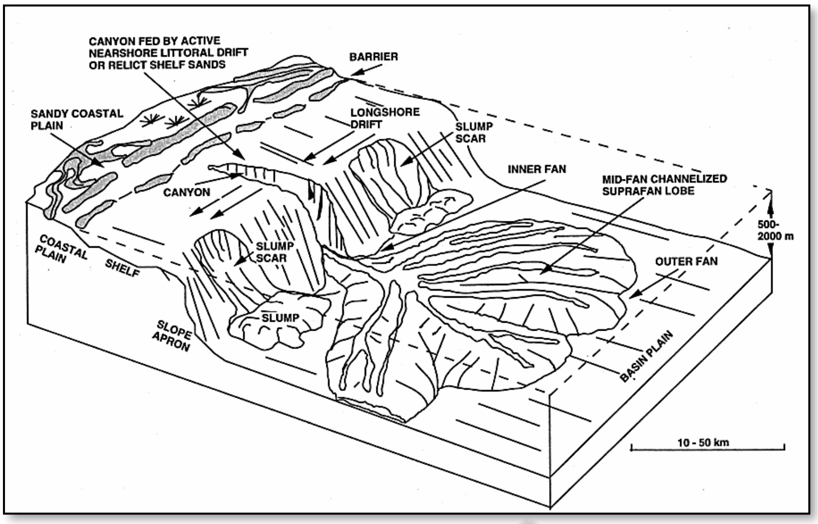
Different components of submarine fan

Levee deposits are made up of interbedded turbidites (representing the spillovers) and shale (background sedimentation). Mass transport complexes form owing to occasional slumping along the continental slope region. Products are typically chaotic in nature and made up of various kinds of sediment gravity flows, depending upon the gradient of the continental slope and nature of reworked sediments. Soft sediment deformation structures like convolutes or slump folds are frequent. Debrites (products of debris flow) are most common in occurrence along with proximal turbidites. Transitions from one to another type of sediment gravity flow are common. The mid fan region is categorized by frequent turbidity currents, with minor debris flow and shallow short-lived channels. In mid-fan area, turbidity currents spread-out from the confines of the upper fan channel, and consequently lobes built up. Such lobes generally prograde outwards. Mid-fan lobe deposits often contain complete Bouma sequences and the whole succession may be tens of meters thick. An individual lobe may be kilometers or tens of kilometers across. Shifting as well as abandonment of lobes is common. Proximal to intermediate turbidites with minor debrites characterize this region. Shallow channel deposits, whatever deposited, often gets reworked by subsequent turbidity currents. Distal lobes, on the other hand, are made up of distal turbidites alternating with hemipelagic sediments. Lower fan turbidites already deposited coarser debris to proximal parts of the fans, and hence only fine sand, silt and clay gets deposited in the lower fan region (c-d-e or d-e intervals). Convex-up geometries are less prominent as they are much broader in size than higher; internally thinly bedded with sheet-like geometry.

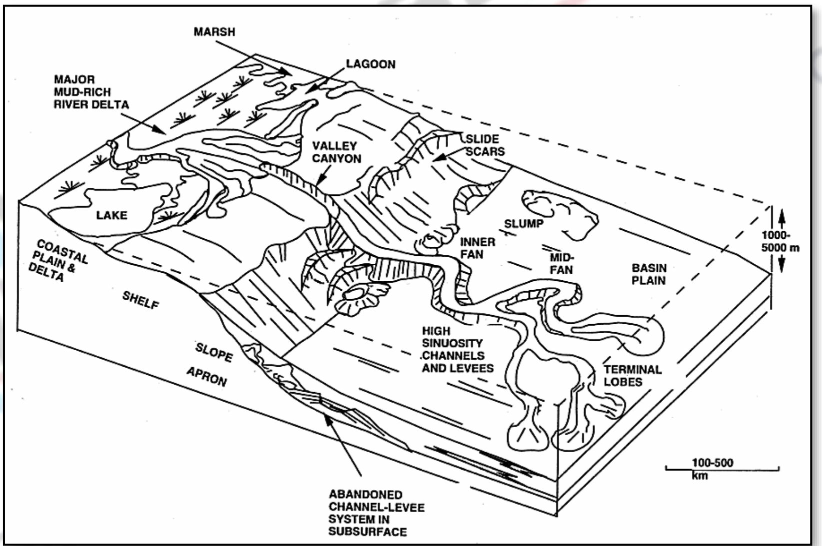
Submarine fan can be of various kinds, depending upon four main factors, namely nature of source (point or line source), dominant grain-size (can be gravelly, sandy or muddy), sea floor relief (bathymetry) and sea level change (controls the sediment supply and its rate). Point sources refer to one major feeder system, produces single submarine fan, whereas line sources refer to series of comparable feeder system, and as a result yields series of submarine fans, often amalgamated to produce an apron. Gravelly fan systems are laterally most restricted, with steepest gradients and shallow channels or chutes. Sediment gravity flows dominate. Generally, such submarine fans are known as fan deltas or gravelly domes. Sandy systems produce radial submarine fans, with intermediate size as well as gradient. Low-relieved channels and mounded lobes characterize such fans. Lobe shifting is common. Muddy systems produce largest submarine fans, with lowest gradient and extensive development of channel-levee complex. Lobes are flattened, sheet-like. Overall, the muddy fans are elongated in nature. Bathymetry controls the submarine channel networks as they follow the bathymetric lows.



Varieties and controls of submarine fan system



Facies model for sandy submarine fan system



Facies model for muddy submarine fan system

Different architectural elements are encountered within modern fans. Distributions of important architectural elements within common fan systems are listed below.

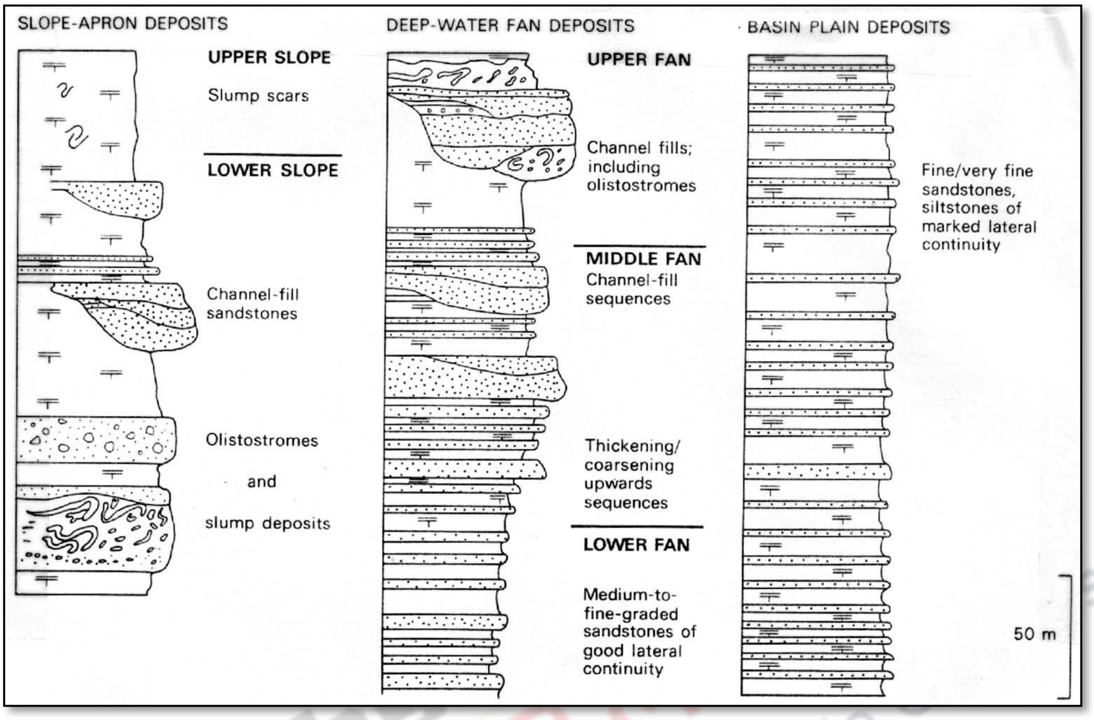
System Type	Wedges	Channels	Lobes	Sheets	Chaotic Mounds
Gravelly System	Present	Chutes	-	-	-
Sandy System	-	Braided	Channelized lobes	-	-
Muddy System	-	Channel-levee	Depositional lobes	Present	Slumps and slides

5. Vertical Succession of submarine fan and other deep marine sub-environments

Submarine fans usually progrades over the abyssal plain. Hence, the resulting succession appears to be coarsening upward. The transition from distal to proximal fan is recorded in vertical succession. Lower part of the succession is characterized by distal turbidites of lower fan region, alternating with hemipelagic background sediments. Intermediate position is occupied by mid fan lobe complexes, with intermediate to proximal turbidites and debrites. Amalgamated sand bodies of upper fan region, with occasional sediment gravity flows marks the top of the succession. Retrograding submarine fan is also reported, though rarely, from some modern setting.

Deep marine abyssal plain deposits, on the other hand, do not show any characteristic trend in vertical succession. Fine silty or muddy indigenous sedimentation from suspension fall-out (pelagic sediments), occasionally dispersed by fine sandy distal turbidites, are the typical basin plain product.

Slope apron deposits are comparatively coarse-grained. Continental slope deposits characteristically show intercalation between silty suspension fall-out deposits and coarser sediment gravity sliding or slumping products. Soft sediment deformation structures are common within such slumped beds. Occasional channel sandstones are observed restricted towards the upper part of the slope though. Lower slope deposits show more frequent slumped bodies, with rare olistostromes. Olistostromes are typical sedimentary deposit composed of a chaotic mass of heterogeneous material, such as blocks, known as olistoliths, and mud, that accumulates as a semifluid body by submarine gravity sliding or slumping of the unconsolidated sediments. Overall fining trend is discernible due to aggradation.



Typical coarsening upward succession of submarine fan. Note the difference from a slope apron succession and normal deep basinal succession.

6. Summary

- Deeper marine environments characterized by slower sedimentation rate and hence deposit comparatively lesser amount of sediments than other depositional environments.
- Edge of the continental shelf marks the extent of deep marine realm.
- Major sedimentation processes in the deep sea include slow but continuous suspension fall-out of fine particles (pelagic and hemipelagic sediments) and local authigenic precipitation (chemical or biochemical precipitation from water), with occasional emplacement of coarse clastics through sediment gravity flow processes, mainly debris flows and turbidity currents.
- Pelagic sediments are mostly biogenous, with minor wind-blown terrigenous fines, that at some stage been floating in the water. Calcareous or siliceous pelagic muds with greater than 30% biogenic component, is known as biogenic 'oozes'.

- Hemipelagic sediments refer to at least 25% of fine-grained (muddy) terrigenous materials from shelf, redeposited within deep marine realm by storm-generated plumes or short-distance turbidity currents.
- Authigenic (Hydrogenous) deposits are essentially solid chemical or biochemical precipitates from seawater.
- Coarse clastics found within the deep marine realm are transported from the continental slope area through subaqueous mass movements, mostly turbidity currents and debris flows.
- Submarine Fans are a fan-shaped sediment accumulation, radiating away from the feeder system, at the base of the continental slope, building out into the ocean basin. Submarine canyons at the shelf edge are connected to submarine fans on the ocean floor, acting as the feeder system of submarine fans.
- Submarine fans share several characteristics with deltas; they consist of a feeder channel that divides into numerous distributary channels bordered by natural levees (‘channel-levee systems’) and are subject to avulsions.
- Submarine fan can be of various kinds, depending upon four main factors, namely nature of source (point or line source), dominant grain-size (can be gravelly, sandy or muddy); sea floor relief (bathymetry) and sea level change (controls the sediment supply and its rate).
- Submarine fans usually progrades over the abyssal plain. Hence, the resulting succession appears to be coarsening upward. Deep marine abyssal plain deposits, on the other hand, do not show any characteristic trend in vertical succession, and are primarily composed of pelagic sediments dispersed occasionally by fine-grained turbidites. Slope apron deposits, at the base of continental slope are characterized by pelagic and hemipelagic sediment alternations, dispersed by slumped deposits.

Frequently Asked Questions-

Q1. What are the major sedimentation processes operating in deep marine environment?

Ans: Major sedimentation processes include slow but continuous suspension fall-out along with authigenic chemical (or biochemical) precipitation and occasional sediment gravity flows, mainly turbidity currents and debris flows.

Q2. Define 'ooze'. What are the different types of pelagic oozes?

Ans: Pelagic muds with greater than 30% biogenic component, is known as biogenic 'oozes'. Major varieties include calcareous oozes and siliceous oozes. Calcareous oozes are formed by the accumulation of calcium carbonate hard parts from dead microscopic plankton, mainly cocolithophores and foraminifera. Calcareous oozes principally deposit in relatively shallow, low- to mid-latitude regions of deeper ocean. Deposition takes place above CCD (carbonate compensation depth) and in warmer waters. Siliceous oozes are produced by the accumulation of dead shells of silica-secreting organisms, mainly diatoms and radiolaria. Siliceous oozes are restricted within the higher latitudes and prefer cooler waters. Concentrations of siliceous oozes are upwelling and nutrient-supply controlled and favored below CCD.

Q3. What are Submarine fans? What are the different components of submarine fan?

Ans: Submarine Fans are fan-shaped sediment accumulation, radiating away from the feeder system, at the base of the continental slope, building out into the ocean basin.

Major components of a submarine fan include incised channels (submarine canyons, slope channels), leveed channel systems, mass transport complexes, frontal splays and distal lobes. Submarine fans can be divided into three divisions; Upper Submarine Fan (trunk channel); Middle Submarine Fan (lobes) and Lower Submarine Fan. Incised channels and channel-levee systems with occasional mass transport complexes characterize upper fan region, while the middle fan region is represented by channel/lobe systems on frontal splays. The lower fan region is typified by turbidite-dominated distal lobes. The upper fan channel-levee systems are characterized by braided (within the canyon) to meandering (on upper fan) river systems. In rock record upper fan region is characterized by amalgamated sandstone (may be pebbly) bodies, resulted from vertical aggradation of channels. In-channel turbidites, made up of coarse sand and/or gravel, are reported from modern fans. Typical products are thick, structure less or crudely graded beds (an interval dominates); finer sediments may get deposited but subsequently eroded by later turbidity currents. Lateral migrations of channels, producing sheet sandstone bodies are common. Levee deposits are made up of interbedded turbidites (representing the spillovers) and shale (background sedimentation). Mass transport complexes form owing to occasional slumping along the continental slope region. Products are typically chaotic in nature and made up of various kinds of sediment gravity flows, debrites (products of debris flow) are most common in occurrence along with proximal turbidites. Soft sediment deformation structures like convolutes or slump folds are present. The mid fan region is categorized by frequent turbidity currents, with minor debris flow and shallow short-lived channels. In mid fan area turbidity currents spread-out from the confines of the upper fan channels, and produces outward progradinglobes. Mid-fan lobe deposits often contain complete Bouma sequences and the whole succession may be tens of meters thick. Shifting as well as abandonment of lobes is common. Proximal to intermediate turbidites with minor debrites characterize this region. Lower fan region is typified by distal lobes, which are made up of distal turbidites alternating with hemipelagic sediments. Lower fan turbidites already deposited coarser materials to proximal parts of the fans; only fine sand, silt and clay get deposited in lower fan region (c-d-e or d-e intervals). Convex-up geometries are less prominent as they are much broader in size than higher; internally thinly bedded with sheet-like geometry.

Q4. What kind of facies stacking pattern one would expect in case of progradation of a submarine fan?

Ans: Submarine fans usually progrades over the abyssal plain. Hence, the resulting succession appears to be coarsening upward. The transition from distal to proximal fan is recorded in vertical succession. Lower part of the succession is characterized by distal turbidites of lower fan region, alternating with hemipelagic background sediments. Intermediate position is occupied by mid fan lobe complexes, with intermediate to proximal turbidites and debrites. Amalgamated sand bodies of upper fan region, with occasional sediment gravity flows marks the top of the succession.

Multiple Choice Questions-

1. A black shale forms under

(a) High rate of suspension fall-out
(b) Anoxic conditions
(c) High organic productivity

Ans: b

2. Deep sea cherts mainly form from

(a) Radiolarian ooze
(b) Red clay
(c) Foraminiferal ooze

Ans: a

3. Submarine fan is favored under

(a) Sea-level rise
(b) Sea-level fall
(c) Low sedimentation rate

Ans: b

4. Common non-biogenic carbonate forms as

(a) High-Mg Calcite
(b) Low-Mg Calcite
(c) Aragonite

Ans: c

5. Fluid-gravity flow generated coarse mass transport product within deep marine realm is

(a) Contourite
(b) Debrite
(c) Turbidite

Ans: a

6. Fan-deltas form within

(a) Muddy submarine fan system
(b) Sandy submarine fan system
(c) Gravelly submarine fan system

Ans: c

7. Size of a submarine fan is dependent mainly upon

(a) Gradient of the continental slope
(b) Sediment size
(c) Nature of the feeder system

Ans: b

Suggested Readings:

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